

Systemic Feedback Mapping of Indonesia's Rare Earth Element Sector: A Causal Loop Diagram Analysis

Syifa Farhatunnisa El Baehaqi

School of Business and Management, Institut Teknologi Bandung, Jl. Ganesha No. 10,
Bandung 40132, Indonesia
Email: syifa_farhatunnisa@sbm-itb.ac.id

Yos Sunitiyoso

School of Business and Management, Institut Teknologi Bandung, Jl. Ganesha No. 10,
Bandung 40132, Indonesia

To Link this Article: <http://dx.doi.org/10.6007/IJARBSS/v15-i6/25606> DOI:10.6007/IJARBSS/v15-i6/25606

Published Date: 28 June 2025

Abstract

Rare Earth Elements (REE) are essential components for various strategic sectors, such as renewable energy, electronics, and high-tech manufacturing. Indonesia has abundant REE reserves and great potential to become a global supplier. However, the development of this sector is still hampered by complex and interrelated systemic challenges in various fields. This study aims to identify the main factors and interrelationships between factors that influence the development of the REE sector in Indonesia. By using a systems thinking approach and qualitative data from interviews with stakeholders, this study maps the dynamics of the problem through three Causal Loop Diagrams (CLDs). The first CLD shows how regulatory stagnation and unclear institutional roles reinforce governance fragmentation and hamper policy coordination. The second CLD illustrates the structural inconsistency between upstream exploration and downstream industry readiness that hinders value chain integration. The third CLD highlights the strengthening of external dependency, where weak domestic capacity drives dependence on foreign technology and markets, which ultimately threatens national resilience. These findings emphasize the importance of integrated interventions to encourage sustainable and sovereign REE sector development.

Keywords: Rare Earth Elements, Indonesia, System Thinking, Causal Loop Diagram

Introduction

Rare Earth Elements (REEs) are a group of metals that play a critical role in a number of strategic sectors, including renewable energy, advanced electronics, and security technologies. The strategic relevance of REEs is increasing with the global transition to clean

energy and decarbonization. According to the International Energy Agency (IEA, 2024), the demand for REEs for clean energy applications is expected to increase significantly between 2023 and 2040, driven by rapid developments in electric vehicles, wind turbines, and semiconductors.

Despite the increasing demand for REEs, the global REE supply chain remains vulnerable and faces several challenges. China, which accounts for more than 70% of global REE production, plays a dominant role in this supply dynamic (USGS, 2023). The global dependence on Chinese REEs has created vulnerabilities, both in terms of price fluctuations, supply, and emerging geopolitical tensions (Feffer, 2024). In response to this situation, the European Union has initiated a policy to reduce dependence on REE imports from China, with a target of reducing dependence to a maximum of 65% of total consumption by 2030 (Pitt, 2024).

Indonesia has great potential in REE production, especially in the Bangka Belitung and Kalimantan regions, with abundant REE deposits—over 186,000 tons of monazite-based REE deposits are recorded in Indonesia (ESDM, 2019). However, despite this enormous potential, Indonesia's REE sector faces various obstacles, especially in terms of domestic processing facilities and dependence on foreign technology for advanced processing. These obstacles include a lack of coordination between the institutions involved, as well as policies that are not yet optimal in supporting the development of the REE sector as a whole. In 2023, the Ministry of ESDM issued Decree No. 296/2023, which classifies REE as a strategic mineral commodity, but technological constraints and limited investment are still the main obstacles to building full-scale REE processing capacity (CSIS, 2023).

The problems faced by the REE sector in Indonesia are very complex and require a more systemic approach to solving them. Therefore, the System Thinking approach is used in this study to analyze the cause-and-effect relationships in this very complex system. The Causal Loop Diagram (CLD) was chosen as a tool to understand the dynamics of the REE sector in Indonesia, identify weak points in existing policies, and provide a clear picture of the interactions between the various factors involved, such as policies, natural resources, technology, and the actors involved.

The findings of this study will provide significant contributions to the Indonesian government, especially related institutions such as the Ministry of Energy and Mineral Resources, as well as industries involved in the REE mining and processing sector. This study will provide important insights to improve inter-agency coordination, overcome technological barriers, and optimize domestic processing capacity, as well as open opportunities for the community through job creation and increasing the competitiveness of the national industry. By using a system model based on System Thinking and Causal Loop Diagram (CLD), the findings of this study are expected to produce more efficient and applicable policies in the long term, which will increase Indonesia's independence in managing REE resources and strengthen the industry's resilience to global market fluctuations. In addition, the resulting policies will support more objective and measurable data-based decision-making, which can be directly applied in the formulation of energy policies and sustainable mineral resource management, providing a significant positive impact on the industrial sector and the national economy as a whole.

Previous Research

Several previous studies have examined the condition of REE in Indonesia by highlighting various aspects such as economic potential, technological readiness, environmental risks, regulatory challenges, and processing processes. Adi (2013), through qualitative analysis, identified REE as a strategic resource with high potential but also highlighted extraction constraints that require systemic improvements before full-scale exploitation.

Nugroho et al. (2015) deepened the discussion with a case study that focused on extraction technology. This study emphasized the importance of technology investment as a prerequisite for increasing the efficiency of REE extraction in Indonesia—in line with the global trend that places technical innovation as the key to economic and ecological sustainability in the REE industry.

From the institutional side, Harsono (2019) used a policy analysis approach to evaluate the national regulatory framework. His findings highlighted the weak coordination across policies as a recurring obstacle, which exacerbated the fragmentation of roles between institutions and hampered sector development. This reinforces the urgency of the need for a systemic approach to bridging the gap between actors.

Meanwhile, Rahimi et al. (2024) raised the issue of the advancement of REE processing technology through experimental methods. The results show that despite the increase in technical capacity, challenges in technology integration and scaling remain major bottlenecks. Overall, the existing literature provides a rich but fragmented picture. Each study tends to focus on a specific dimension without an integrative approach across domains. Therefore, a holistic, systems-based approach is needed to understand the dynamics between factors as a whole and identify appropriate policy interventions. This study uses the Causal Loop Diagram (CLD) to map the dynamics of the REE management system in Indonesia and identify policy leverage points that can accelerate the sector's systemic and sustainable transformation.

Methodology

The systems thinking approach provides a powerful conceptual framework for understanding complex systems through an emphasis on the interconnections and feedback mechanisms between their constituent elements. This approach is very useful for analyzing multidimensional issues, especially in the context of public policy and resource management. Various studies show that systems thinking has been widely applied in engineering, sustainability assessment, and evidence-based policy development (Aurachman, 2021; Onat et al., 2017). In Indonesia itself, this approach is used in various contexts, ranging from education system analysis (Suryadi et al., 2020) to complex healthcare systems (Linnéusson et al., 2022), all of which emphasize the need for cross-variable understanding and strategic resource allocation.

The systems thinking approach is also considered effective in supporting the decision-making process, especially in the context of industrial and government organizations, because it provides a holistic understanding of the structure and behavior of the system that forms the basis for policy formulation (Swanson et al., 2012).

Causal Loop Diagram

A Causal Loop Diagram (CLD) is one of the main tools in systems thinking that is used to map and analyze causal relationships between variables in a system (Iannone et al., 2015). CLD allows visualization of the relationship between actors, key factors, and the direction of their influence dynamically. This diagram not only shows the cause-and-effect relationship but also reveals the existence of feedback loops that can be reinforcing or balancing, which are very important in understanding the dynamics of change and system resistance to intervention (Inam et al., 2015; Dikmen et al., 2024).

CLD also functions as a participatory tool that can be used to involve stakeholders in mapping collective understanding of a system, as well as to identify potential indirect consequences of policies or interventions (Aletta et al., 2025; Obaze, 2019). In this context, CLD becomes a qualitative instrument that is able to bridge systemic understanding across actors and sectors. This study uses CLD to map the dynamics of Indonesia's REE sector, focusing on identifying potential leverage points for policy intervention. CLD differentiates itself from the more quantitative stock and flow diagram by focusing on modeling system behavior over time (Pokharel et al., 2023).

Research Procedure

This research was conducted through a qualitative, systems-based approach with three main stages: literature review, stakeholder interviews, and CLD construction. The first stage involved a literature study from various sources, including scientific articles, government reports, and relevant news publications related to the management of the REE sector in Indonesia. The purpose of this stage is to understand the policy landscape, technical challenges, and potential for REE development from upstream to downstream.

Furthermore, preliminary interviews were conducted with key actors from the Ministry of Energy and Mineral Resources (ESDM) and a company producing rare earth metals. This interview aims to explore initial perceptions of new and renewable energy (EBT) policies and the strategic position of REE within the framework.

After the initial exploration phase, in-depth interviews were conducted with actors from various institutions and industry sectors, including research institutions such as BATAN and Tekmira, mining companies, and processing industry players. The information collected covered operational, institutional, technological, and regulatory aspects of the REE ecosystem.

The interviews were conducted in a semi-structured manner to ensure flexibility in exploring complex system dynamics. The interview questionnaire was developed based on the principles of systems thinking, covering aspects of system objectives, actor structures, control mechanisms, and coordination challenges. The questions were designed to explore the interrelationships between variables and identify potential feedback loops in the Indonesian REE system. A summary of the questionnaire and informants is presented in Table 1.

The interview data were then analyzed to compile three main CLDs that represent systemic challenges in governance, upstream-downstream integration, and external dependencies.

Each CLD describes the main feedback loops that inhibit the sustainable transformation of the REE sector.

Table 1
In-depth interview respondents

No	Position	Unit	Relevant Experience (in years)	Role
1	Subcoordinator of Mineral and Coal Production Planning	Ministry of Energy and Mineral Resources (MEMR)	11	Develop REE policies and plan national energy strategy
2	Researcher (LTJ - Rare Earth Element)	National Nuclear Energy Agency (BATAN)	15+	Develop REE processing technologies
3	Head of REE Project	PT Timah	4	Conduct exploration and manage REE projects in the field
4	Senior Geologist (Head of REE Exploration)	PSDMBP (Mineral Resources, Energy, and Geothermal)	10	Design geological exploration strategies, governance, and energy integration

The framework of this research depicted in this picture below.

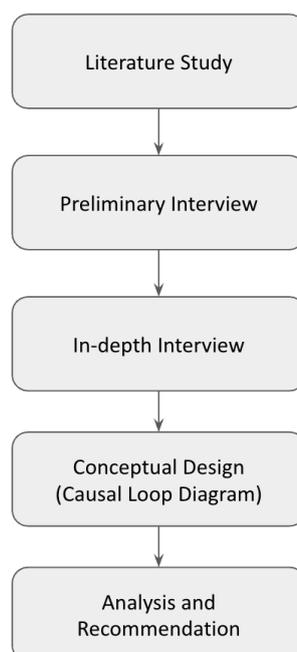


Figure 1. Research methodology

Also the table below shows the overall question delivered to the interviewees. Table below presents the interview questions designed to explore key components of the REE system in Indonesia. The questions were developed using a systems thinking approach to capture the system's purpose, structure, control mechanisms, and challenges.

Table 2
Interview questions

Topic	Questions
General Context	What is the current state of rare earth elements (REE) development in Indonesia?
	How would you describe your organization's involvement or role in the REE ecosystem?
Resource & Exploration	What are the main sources of REE in Indonesia (primary and secondary)?
	What is the current status of exploration and extraction efforts?
Technology & Processing	What technologies are available or being developed to process REE in Indonesia?
	What challenges are faced in terms of processing complexity or technological gaps?
Regulatory & Institutional Factors	What policies currently govern REE in Indonesia?
	Are there any gaps or ambiguities in the regulatory framework?
	How do inter-agency or public-private collaborations influence REE development?
Economic Feasibility	How economically viable is REE production in Indonesia at the current stage?
	What are the cost-benefit trade-offs seen from the industry's perspective?
Awareness & Strategic Priority	Do you think REE is receiving sufficient national strategic attention?
	Why might REE be less prioritized compared to other minerals like nickel?
Stakeholder Mapping	Who are the key stakeholders involved in the REE supply chain in Indonesia?
	What are the roles and influence of these actors?
Future Outlook	What is your perspective on the most urgent steps required to accelerate REE development?
	What is your hope or recommendation for the future of REE governance in Indonesia?

Analysis and result

REE Regulation

The development of Rare Earth Elements (REE) regulation in Indonesia over the years shows a gradual yet significant shift towards greater attention and policy sophistication. The timeline reveals several key phases of development in response to both domestic needs and global challenges. Here's an analysis of how REE development has progressed:

a. The Energy Law (Law No. 30/2007).

This law establishes the foundation for Indonesia's energy sector, focusing on energy diversification, security, and sustainability. It mandates the development of renewable

energy resources, including REE, to reduce dependency on fossil fuels and ensure a stable energy supply. The law also provides a framework for energy conservation and incentivizes the use of alternative energy sources, including REE for technological applications.

b. The National Energy Policy (Gov. Reg. No. 79/2014).

This regulation, part of Indonesia's broader energy strategy, sets a goal to transform the energy mix by 2025. It outlines that renewable energy, including REE resources, should make up 23% of the total energy supply by 2025. It highlights the need for policy integration, investment in renewable technologies, and effective energy management to achieve energy sustainability.

c. The Mineral and Coal Regulations (Permen ESDM No. 25/2018).

This regulation focuses on the management of mineral resources, including REE, within Indonesia. It addresses the procedures for exploration, production, and export of minerals, establishing guidelines for the refining process and environmental management. This regulation supports the independence of domestic refining capabilities for critical minerals like REE, reducing reliance on foreign processing facilities.

d. The Sediment Management Regulations (Gov. Reg. No. 26/2023).

This regulation focuses on the management of sediment related to the extraction of mineral resources, including REE. It emphasizes environmental sustainability during the mining process and addresses the issue of sediment accumulation from mining activities. It aims to minimize environmental damage and increase the sustainability of Indonesia's mining industry, including REE extraction.

e. The most recent, Critical Mineral Regulations (Kepmen ESDM No. 296/2023).

This is the most recent regulation, which recognizes REE as critical minerals essential to national security and economic growth. It outlines strategies for sustainable mining, processing, and development of critical minerals, including REE, to ensure Indonesia's competitiveness in the global market. It mandates coordination between relevant ministries and emphasizes the importance of technological advancement in processing and refining REE domestically.

Despite these regulatory developments, the prioritization of REE in Indonesia remains inconsistent when compared to other minerals such as tin (timah). Tin has historically received strong government support and clear regulatory frameworks, which have propelled Indonesia to become one of the world's leading tin producers. This prioritization has enabled significant investments in exploration, production, and downstream processing infrastructure for tin, contributing to its robust growth (Kementerian Energi dan Sumber Daya Mineral [KESDM], 2023; Putra & Santoso, 2021).

In contrast, REE has not benefited from the same level of prioritization or regulatory clarity. There exists a notable mismatch between the stated objectives of the Critical Mineral Regulations and the actual implementation of policies concerning REE. While REE is officially classified as a critical mineral, enforcement and integrated regulatory measures specifically tailored for REE are still lagging behind (KESDM, 2023; Handayani, 2022). This regulatory gap undermines the potential for Indonesia to fully capitalize on its REE resources and achieve sustainable domestic value addition. Bridging this gap requires harmonizing mineral policies and ensuring that REE receives the strategic attention needed to match its global economic and technological significance.

Actors

Based on interviews with key informants, the following table outlines the key actors involved in the rare earth elements (REE) field in Indonesia, along with their respective roles. These actors are classified into five main categories: Government, Mining Industry, Research Institutions, International Partners, and Communities. The government holds a significant and central role in Indonesia's REE ecosystem, acting as the primary policy-maker and coordinator across sectors. Ministries such as MEMR, PSDMBP, and Ministry of Industry are expected to lead strategic direction, regulatory development, and stakeholder alignment.

Table 3

Actor in REE sector

No	Category	Actor	Role
1	Government	MEMR / Ministry of Energy and Mineral Resources (ESDM)	Policy-making body responsible for overarching energy and mineral strategies, including regulation and facilitation of national REE development.
		PSDMBP – Geological Agency	Responsible for upstream activities such as geological surveys and exploration. PSDMBP also manages REE resource data.
		Ministry of Industry (Kemenperin)	Expected to support downstream REE industrial development (smelter and manufacturing), though not yet actively involved in LTJ-specific strategies.
2	Mining Industry	PT Timah	State-owned mining company focused on REE exploration and mining. Responsible for operational aspects and project management related to REE.
		Field Technicians	On-the-ground workers directly involved in REE mining operations, contributing to the technical aspects of exploration and extraction.
3	Research Institutions	BATAN (National Nuclear Energy Agency)	Conducts research on nuclear technology for REE processing, contributing technical innovations in refining technologies.
		Tekmira (Mineral and Coal Technology Center)	Focuses on technological research and development of sustainable REE processing methods and environmental management.
		University	Provides academic insights and scientific research on REE technologies and supports innovation in the extraction and refining processes.
5	Communities	Local communities	Indirect actors impacted by REE mining. Their input is critical in understanding the social and environmental consequences of mining activities.
		Local governments	Hold jurisdiction over REE-rich territories. Currently under-involved in policy and project implementation. Their engagement is crucial for licensing and regional development.

In Indonesia’s rare earth element (REE) ecosystem, key government institutions play interrelated roles. The Ministry of Energy and Mineral Resources (MEMR) serves as the central regulator, overseeing national energy and mineral policy, including REE development. Supporting this, the Geological Agency (PSDMBP) manages upstream activities such as geological surveys and exploration, and maintains critical REE resource data that informs policy and industry planning. Although not yet directly engaged in REE-specific strategies, the Ministry of Industry (Kemenperin) is expected to facilitate downstream industrial development, particularly in smelting and manufacturing. These governmental efforts are operationalized by state-owned enterprises like PT Timah, which conducts REE exploration and mining—largely as by-products of tin—while field technicians contribute essential on-site expertise in extraction processes.

The research ecosystem reinforces these operations through technological innovation. Institutions like BATAN and Tekmira focus on advancing REE refining and environmentally sustainable processing methods, while universities provide scientific insights and academic research that support continuous improvement across the value chain. At the local level, communities and governments hold both regulatory and social influence. Local communities are directly impacted by mining operations, making their feedback vital for addressing environmental and social concerns. Meanwhile, local governments govern REE-rich regions and play a key role in licensing and implementation, though their involvement remains limited. Together, these actors form an interdependent system where regulation, exploration, innovation, and community engagement must align to enable sustainable REE development in Indonesia.

Causal Loop Diagram

Lack of Cross-Institutional Coordination

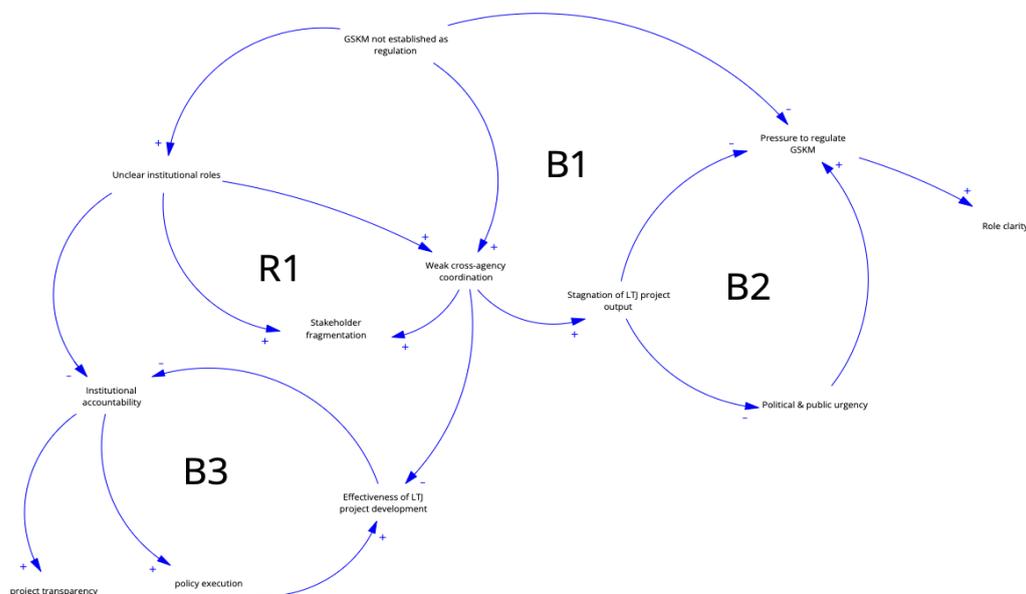


Figure 2. CLD 1 of REE Sector: Lack of Cross-Institutional Coordination

Diagram CLD 1 illustrates the systemic dynamics underlying the stagnation of the development of the rare earth metals (REE) sector in Indonesia, which is predominantly driven by fragmented governance and weak cross-agency coordination. One of the main problem nodes lies in the status of the Grand Strategy for Mineral and Coal Commodities (GSKM) prepared by the Ministry of Energy and Mineral Resources since 2021, but until now, it still has the status of a non-regulatory document. The absence of binding legal force in the GSKM has resulted in the policy not having the structural impetus to facilitate collaboration between key actors such as the National Research and Innovation Agency (BRIN), the Center for Mineral, Coal, and Geothermal Resources (PSDMBP), PT Timah, and the Ministry of Industry (Kemenperin).

Then, another problem was found the absence of a main actor acting as a cross-agency coordinator resulted in a disarticulation of roles between stakeholders. REE development initiatives were carried out partially, sectorally, and unsustainably, creating a stagnant condition that further weakened the political justification for pushing for the transformation of the GSKM into formal regulation. Under these conditions, REE projects tend to experience delays or stagnation due to the absence of a strong coordinating foundation, as well as weak accountability mechanisms and policy execution in the field.

Loop B1 (Regulatory Stagnation) shows that the unclear status of GSKM as a formal policy creates fragmentation of authority that worsens inter-agency coordination, which then has a direct impact on the hampered implementation of LTJ projects. This forms a negative cycle that weakens institutional and political pressure to promote GSKM as a binding legal instrument. Loop R1 (Fragmentation Reinforcement) strengthens this condition by increasing sectoral egos and synchrony between stakeholders, thereby deepening polarization and inhibiting cross-actor synergy.

In addition, loop B2 (Political Pressure) highlights how the lack of concrete output from REE projects reduces the attention and urgency of political and public stakeholders. The absence of short-term success reduces external pressure that should be a catalyst for policy reform, thus prolonging the status quo of GSKM. Finally, loop B3 (Accountability and Execution) illustrates that the unclear roles between institutions have an impact on weak institutional accountability, which in turn hinders the process of effective policy implementation.

Overall, these four loops form a mutually reinforcing feedback system (reinforcing-balancing mix) that explains the structural failures in the institutionalization and implementation of REE development strategies in Indonesia. This finding emphasizes the need for a systemic approach to redesign the governance of this sector holistically by placing cross-institutional coordination at the center of policy interventions.

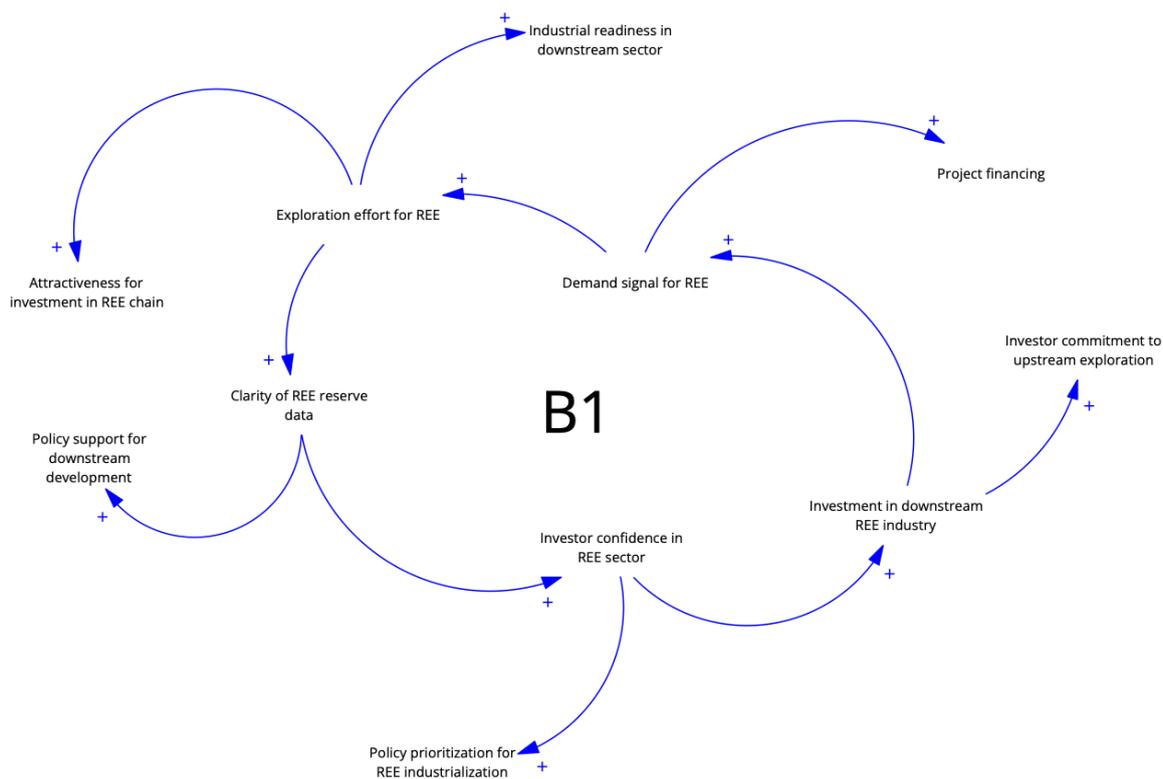
Exploration–Industrialization Disconnection

Figure 3. CLD 2 of REE Sector: Exploration–Industrialization Disconnection

The CLD 2 diagram maps the systemic dynamics between rare earth metal (REE) resource exploration activities and downstream sector development that have not been optimally integrated in the Indonesian context. This diagram highlights the reinforcing loop that explains the close but unequal relationship between the availability of exploration data and the readiness of downstream infrastructure. This dependency forms a pattern of structural stagnation that slows down the growth of the REE sector as a whole.

One of the roots of this problem is the lack of specific and sustainable REE exploration activities, which results in limited data related to national reserve estimates. The unclear data reduces the perception of commercial feasibility in the eyes of investors, especially in terms of long-term supply certainty. As a result, investment interest in building REE-based processing and manufacturing industries remains low. This condition results in a weak market demand signal for REE-based downstream products, thereby strengthening negative incentives for further exploration.

This loop shows a negative feedback pattern that prolongs the asynchrony between the upstream and downstream sectors. In the context of system dynamics, the disconnection between exploration and downstream creates policy resistance to various REE development initiatives. Low downstream investment not only holds back industrialization but also cuts off market incentives that should drive exploration. Conversely, without intensive exploration that can guarantee reserve estimates, the downstream sector remains considered high-risk

for investment, especially due to the reliance on empirical data that is not yet available or transparent.

Partial policy interventions on one side of the value chain—either exploration alone or downstream alone—tend to be ineffective in breaking this cycle. Therefore, CLD 2 emphasizes that the REE sector development strategy must be integrative and simultaneous. On the upstream side, the government needs to strengthen the intensity and quality of exploration through budget support, advanced exploration technology, and technical regulations that encourage transparency of reserve data. On the downstream side, interventions can take the form of providing fiscal incentives, guaranteeing raw material supplies, and facilitating the formation of offtake agreements to strengthen demand certainty.

By intervening on both sides simultaneously, market signals regarding REE potential will increase, thereby accelerating the pace of investment and forming a virtuous loop that supports the sustainable growth of the REE ecosystem. Overall, CLD 2 shows that the integration of exploration and industrialization is an absolute prerequisite for the success of Indonesia's REE development strategy and that a shift from a sectoral to a systemic approach is key to breaking out of the structural stagnation that has so far shackled the sector.

International Dependency and Strategic Vulnerability

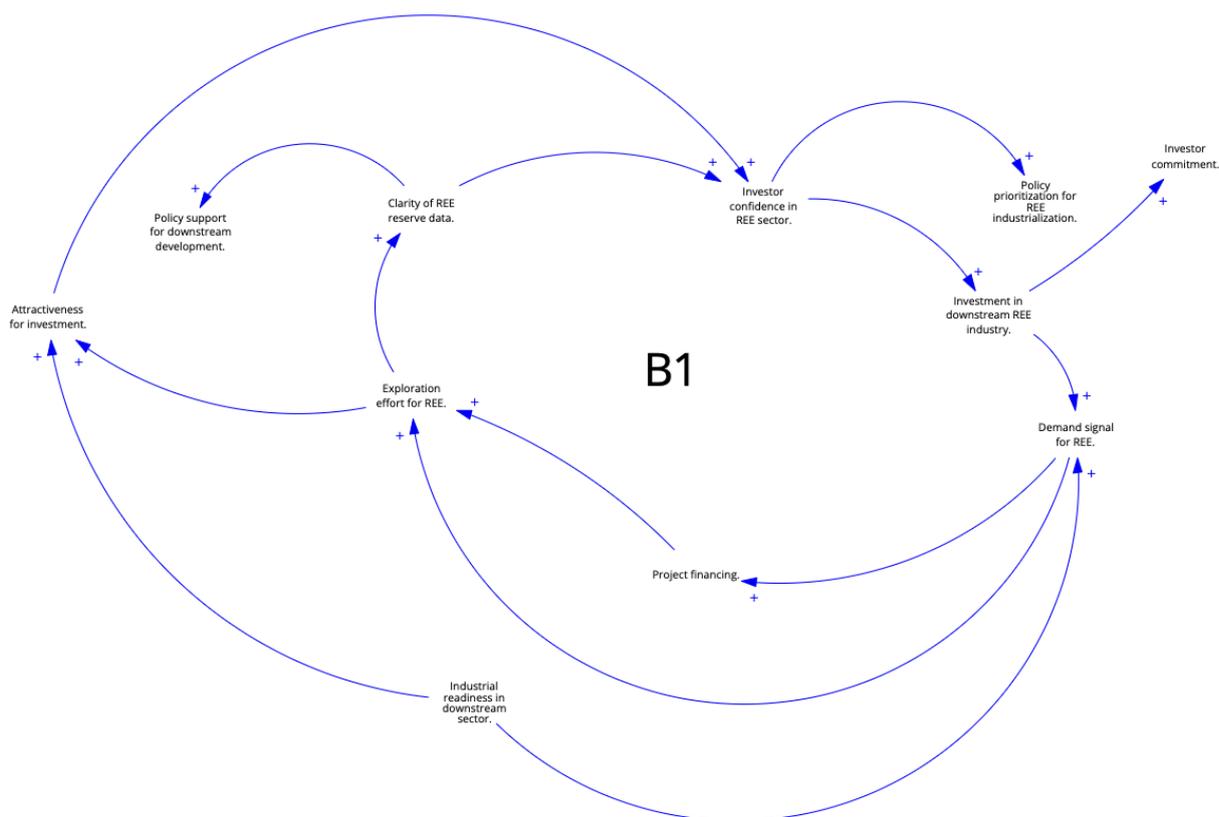


Figure 4. CLD 3 of REE Sector: International Dependency and Strategic Vulnerability

The CLD 3 diagram reveals the dynamics of systemic risk arising from the lack of domestic capacity in managing rare earth metal (REE) resources, which triggers high dependence on

external actors. When key elements in the national system—including exploration, technological capacity, regulatory framework, and downstream industrialization—are weak or underdeveloped, the strategic role vacuum in the value chain tends to be filled by foreign parties. This can be seen from the rampant practice of illegal export of associated minerals such as monazite abroad, especially to China, where foreign industries process the minerals without contributing to domestic added value.

This condition reflects a reverse value capture, where the resource country actually experiences a loss of control over its strategic resources. The unpreparedness of the domestic system opens up a gap for external domination, which occurs not only in the market aspect but also in the dimensions of technology and governance. Bilateral discussions and technology cooperation with countries such as Kazakhstan and Russia do present opportunities for technology transfer. However, long-term dependence on foreign technology providers risks strengthening technological lock-in, where internal capacity development is delayed because institutional and industrial incentives to innovate independently become low.

The reinforcing loop in CLD 3 illustrates how external dependency indirectly weakens the national capacity to make long-term investments in process technology research and engineering. When external solutions are considered faster and more efficient, both the government and domestic industry show a passive attitude in building national technological infrastructure. As a result, not only productivity and added value depend on other countries but also national strategic resilience. In a dynamic geopolitical scenario, this dependency increases the vulnerability of the national system to external disturbances, whether in the form of restrictions on technology exports, economic sanctions, or instability in the global supply chain.

Thus, CLD 3 underlines the need for systemic interventions that target structural independence in all LTJ subsystems. These efforts include building domestic research and engineering capacity, strengthening regulations on associated mineral exports, and incentives for technology transfer that are adaptive and absorptive, not passive and dependent. Without an integrated and visionary approach, Indonesia will continue to be trapped in the resource trap, where resource wealth is not transformed into national strategic advantages.

Conclusion

This study reveals that the challenges of developing the rare earth metals (REE) sector in Indonesia are systemic and interconnected, thus requiring a holistic analytical approach. Through modeling using Causal Loop Diagrams (CLD), this study successfully identified three main dynamics that hinder the sustainable progress of the REE sector.

First, fragmentation of governance and unclear institutional roles are the roots of regulatory stagnation that weakens coordination between institutions and reduces accountability for policy implementation. Second, there is a structural asynchronous between exploration and downstream, where low reserve certainty inhibits downstream investment, which in turn weakens exploration incentives—creating a mutually reinforcing inhibitory loop. Third, dependence on external actors, both in terms of technology and markets, further deepens

the vulnerability of the national system to geopolitical pressures and the loss of domestic added value.

The three CLDs show that policy reform efforts cannot be carried out partially. Systemic interventions are needed that include: strengthening coordinative leadership between institutions, focused exploration investment to clarify reserve estimates, and building domestic technological capacity so that Indonesia does not continue to be in a position of dependence.

These findings provide a basis for developing a more integrated, adaptive, and sovereign REE transformation strategy. By identifying leverage points in each loop, policymakers have the opportunity to intervene in the system in a targeted manner and break the cycle of stagnation that has so far shackled the national REE sector.

Contribution

This study provides significant theoretical and contextual contributions to the development of the rare earth metals (REE) sector in Indonesia by using the causal loop diagram (CLD) approach to describe the complex dynamics that exist. Unlike previous studies that are fragmented, this study integrates social, political, and economic perspectives, thus providing a more comprehensive understanding of the challenges faced by Indonesia. These findings enrich the theory of systems thinking, especially the causal loop diagram approach that can show the causal relationships between existing perspectives. Thus, these findings also provide valuable insights for policymakers to design more integrated and empirically data-based policies in terms of REE. Furthermore, this paper can be an important reference in improving Indonesia's competitiveness in the global market and supporting the development of a more independent and sustainable REE sector.

References

- Aletta, F., Zhou, K., Mitchell, A. D., Oberman, T., Pluchinotta, I., Torresin, S., Cerwén, G., Lam, B., Can, A., Guastavino, C., Tarlao, C., Lavandier, C., Schulte-Fortkamp, B., Cobussen, M., Burgess, M., Nooshin, L., Payne, S. R., Ratcliffe, E., Bernatek, R., & Kang, J. (2025). Exploring the relationships between soundscape quality and public health using a systems thinking approach. *Nature Sound*, 1(1). <https://doi.org/10.1038/s44384-025-00003-y>
- Aslani, A., Helo, P., & Naaranoja, M. (2014). Role of renewable energy policies in energy dependency in Finland: System dynamics approach. *Renewable and Sustainable Energy Reviews*, 37, 362–371.
- Aurachman, R. (2021). Teaching conceptual models in engineering research with mathematical model approaches. *Journal of Physics: Conference Series*, 1832(1), 012054. <https://doi.org/10.1088/1742-6596/1832/1/012054>
- Carrell, J. (2020). *Global supply chain and rare earth elements: The critical role of China in the global market*. *International Journal of Energy Economics and Policy*, 10(3), 45-57.
- Center for Strategic and International Studies. (2023). *Policy brief: Challenges in Indonesia's midstream REE sector*. Center for Strategic and International Studies. Retrieved from <https://www.csis.or.id/publication/indonesias-strategic-dependencies/>

- Dikmen, İ., Karakocak, E., & Birgönül, M. T. (2024). Communication of project risk assessment information through visuals. *Project Leadership and Society*, 5, 100141. <https://doi.org/10.1016/j.plas.2024.100141>
- Du, Y., Wang, W., Lu, Q., & Li, Z. (2020). A DPSIR-TODIM model security evaluation of China's rare earth resources. *International Journal of Environmental Research and Public Health*, 17(19), 7179. <https://doi.org/10.3390/ijerph17197179>
- Feffer, J. (2024). Rare earth politics: The new global tug of war. *Geopolitical Review*, 12(1), 55–68.
- Feffer, J. (2024). *Geopolitics of rare earths: Vulnerabilities in the global supply chain*. *World Politics Review*, 33(2), 128-144.
- Forrester, J. W. (1971). *Industrial dynamics*. MIT Press.
- Hamed, M., Al-Tamimi, H., & Kassim, R. (2024). System dynamics modeling for evaluating mineral supply chains. *Journal of Industrial Policy Studies*, 18(2), 102–115.
- Herindrasti, V. L. S. (2022). Positioning Indonesia in the international world through energy transformation. *DOAJ (Directory of Open Access Journals)*. <https://doi.org/10.52166/jsps.v3i2.109>
- Hoppmann, J., Huenteler, J., & Girod, B. (2014). Compulsive policy making in energy transitions: The case of solar PV in Germany. *Energy Policy*, 72, 663–672.
- Iannone, R., Martino, G., Miranda, S., & Riemma, S. (2015). Modeling fashion retail supply chain through causal loop diagram. *IFAC-PapersOnLine*, 48(3), 1290. <https://doi.org/10.1016/j.ifacol.2015.06.263>
- Inam, A., Adamowski, J., Halbe, J., & Prasher, S. O. (2015). Using causal loop diagrams for the initialization of stakeholder engagement in soil salinity management in agricultural watersheds in developing countries: A case study in the Rechna Doab watershed, Pakistan. *Journal of Environmental Management*, 152, 251–267. <https://doi.org/10.1016/j.jenvman.2015.01.052>
- International Energy Agency. (2024). *The role of critical minerals in clean energy transitions*. International Energy Agency. <https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions>
- Jaya, R., Machfud, M., Raharja, S., & Marimin, M. (2014). Prediction of sustainable supply chain management for Gayo coffee using system dynamic approach. *International Journal of Supply Chain Management*, 9(2), 115-128.
- Jimenez, A., Nunez, C., & Ramirez, F. (2016). A system dynamics model to support the diffusion of renewable energy in Colombia. *Renewable Energy Journal*, 88, 35–44.
- Ju, N., Gao, Y., Zhao, D., Wu, Y., Liu, B., Zhang, P., Liu, X., Shi, L., Feng, Y., Zhao, Z., Ren, Y., Wang, H., Yang, Q., Sun, Z., & Dong, S. (2025). Geology, mineralization, and development potential of rare and uncommon earth ore deposits in Southwest China. *Minerals*, 15(5), 459. <https://doi.org/10.3390/min15050459>
- Linnéusson, G., Andersson, T., Kjellsdotter, A., & Holmén, M. (2022). Using systems thinking to increase understanding of the innovation system of healthcare organisations. *Journal of Health Organization and Management*, 36(9), 179–194. <https://doi.org/10.1108/JHOM-01-2022-0004>
- Liu, S., Fan, H., Liu, X., Meng, J.-Y., Butcher, A. R., Lahaye, Y., Yang, K., & Li, X. (2023). Global rare earth elements projects: New developments and supply chains. *Ore Geology Reviews*, 157, 105428. <https://doi.org/10.1016/j.oregeorev.2023.105428>
- Maani, K. E., & Cavanagh, R. R. (2007). *Systems thinking and modeling: Understanding change and complexity*. Pearson Education.

- Ministry of Energy and Mineral Resources. (2023). *Decree No. 296/2023: Classification of critical mineral commodities*. Ministry of Energy and Mineral Resources. <https://legalhub.asia/e-lib/energy/reg-directory/regulation/keputusan-menteri-esdm-no-296kmb01memb2023>
- Obaze, Y. (2019). The transformative community-based humanitarian service ecosystem. *Journal of Humanitarian Logistics and Supply Chain Management*, 9(3), 410–429. <https://doi.org/10.1108/JHLSCM-06-2018-0039>
- Onat, N. C., Kucukvar, M., Halog, A., & Cloutier, S. (2017). Systems thinking for life cycle sustainability assessment: A review of recent developments, applications, and future perspectives. *Journal of Cleaner Production*, 150, 1-16. <https://doi.org/10.1016/j.jclepro.2017.03.013>
- Pitt, P. (2024). The European Union's policy on rare earth elements: Reducing dependence on China. *European Geopolitical Review*, 12(4), 50-63.
- Pokharel, R., Bertolini, L., & te Brömmelstroet, M. (2023). How does transportation facilitate regional economic development? A heuristic mapping of the literature. *Transportation Research Interdisciplinary Perspectives*, 19, 100817. <https://doi.org/10.1016/j.trip.2023.100817>
- Purwanto, A., Widodo, T. W., & Mulyadi, M. (2019). Understanding resource nexus in local governance: A qualitative causal model. *Journal of Indonesian Sustainability Studies*, 5(1), 1–15.
- Riva, O., Bertolini, M., & Fornari, F. (2018). Exploring electricity systems through system dynamics: A socio-economic model. *Energy Systems*, 9(1), 43–59.
- Senge, P. M. (2006). *The fifth discipline: The art and practice of the learning organization*. Doubleday.
- Severson, R., Yulianto, A., & Mahesa, D. (2023). Challenges in Indonesia's REE downstream sector. *Asian Mining and Energy Review*, 10(2), 112–126.
- Sunitiyoso, Y., Rahayu, R. A., & Damayanti, S. (2012). System thinking approach in managing energy policy in Indonesia: A case study on New and Renewable Energy (NRE). *International Journal of Energy Sector Management*, 6(4), 469–482. <https://doi.org/10.1108/IJESM-11-2019-0019>
- Swanson, R. C., Cattaneo, A., Bradley, E. H., Chunharas, S., Atun, R., Abbas, K., Katsaliaki, K., Mustafee, N., Meier, B. M., & Best, A. (2012). Rethinking health systems strengthening: Key systems thinking tools and strategies for transformational change. *Health Policy and Planning*, 27(4), 54–61. <https://doi.org/10.1093/heapol/czs090>
- Suryadi, S., Fuad, N., Sawan, F., & Fadhillah, F. (2020). Analysis of integrity index of students in national exams based on causal loop diagram model. *Advances in Social Science, Education and Humanities Research*, 384, 682–686. <https://doi.org/10.2991/assehr.k.200130.126>
- United States Geological Survey. (2023). *Mineral commodity summaries: Rare earths*. United States Geological Survey. Retrieved from <https://pubs.usgs.gov/commodity/rare-earths/>