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From Dependency to Destiny: Crafting Europe's Resilient and Green Rare Earth Revolution

Aidan So (author)[1]

Abstract

The European supply chain for Rare Earth Elements (REE) faces increasing vulnerability due to China's persistent dominance over global REE exports. Almost half (46%) of Europe's REE are sourced from China, whose government seeks to transform this crucial raw material into a geopolitical weapon. This article contends that given the improbability of China loosening its export control, and the lack of viable substitutions, Europe must urgently develop a solution that prioritises resilience and sustainability.

The proposed framework is evaluated through quantitative modelling of costs, environmental impacts, and overall feasibility. A novel metric—"safety stock building time"—is introduced to assess the supply chain's resilience under various disruption scenarios projected to 2045, with graphical illustrations of system performance. Sensitivity analysis highlights the relative influence of different supply sources, revealing that while import purchases have a significant effect on resilience in the short run, expanding domestic production is essential for long-term supply security. Through analysing the implementation

timeframe, this article investigates methods to minimize the permission time for Environmental Impact Assessment (EIA), which enhances the efficiency of the model.

Lastly, the limitations of this proposed solution are discussed, which highlights the gaps in current literature, including the lack of dynamic analysis, and the various geopolitical risks that may disrupt the supply chain.

Keywords: supply chain, rare earth elements, resilience, sustainability, Europe

Introduction

Rare Earth Elements (REE) emerge as the most sought-after raw materials globally in the 21st century. REE are defined as seventeen metallic elements comprising fifteen lanthanides, plus scandium and yttrium (Malvern Panalytical, 2025). These raw materials are highly valuable to both nations and businesses, with scandium (Sc), the most expensive REE, costing more than silver, oil, or aluminium (Love Money, 2025; Trading Economics, 2025; Long Forecast, 2025).[1] High concentration Sc metals are even more costly than gold (Standordmaterials.com, n.d.). Although sometimes the term REE+ is used to refer to all 17 elements, while REE refers to the 15 elements excluding Sc and Y, in this article, REE is defined as all 17 elements mentioned above.

From magnets to semiconductors, electric vehicles to missile defence systems, REE are essential for their production. However, the Chinese REE supply has currently established

[1] In this article, REE refer to the 17 chemical elements, including La (Lanthanum), Ce (Cerium), Pr (Praseodymium), Nd (Neodymium), Pm (Promethium), Sm (Samarium), Eu (Europium), Gd (Gadolinium), Tb (Terbium), Dy (Dysprosium), Ho (Holmium), Er (Erbium), Tm (Thulium), Yb (Ytterbium), Lu (Lutetium), Sc (Scandium), and Y (Yttrium).

itself as a monopoly in the market. REE supply is therefore used as a geopolitical weapon for Beijing to exert pressure on other countries, particularly in trading negotiations, exemplified in its countermeasures against America's tariff hikes. By controlling 7 critical REE, immediately souring alternative supplies in the underdeveloped supply chains outside of China is nearly impossible (Baskaran and Schwartz, 2025).

As China dominates the production of REE (70% of the global production) (Andrews-Speed and Hove, 2023) and processes nearly 90% of them (Perera, 2025), its rival, the USA recognises the importance of the reduction of reliance on Chinese REE supply, and has been searching for solutions since 2011 (112nd-Congress, 2011). The Pentagon's multi-billion dollar investment in MP Materials, a REE producer, is just one of the many potential solutions to deal with the Chinese dominance (Emont, 2025).

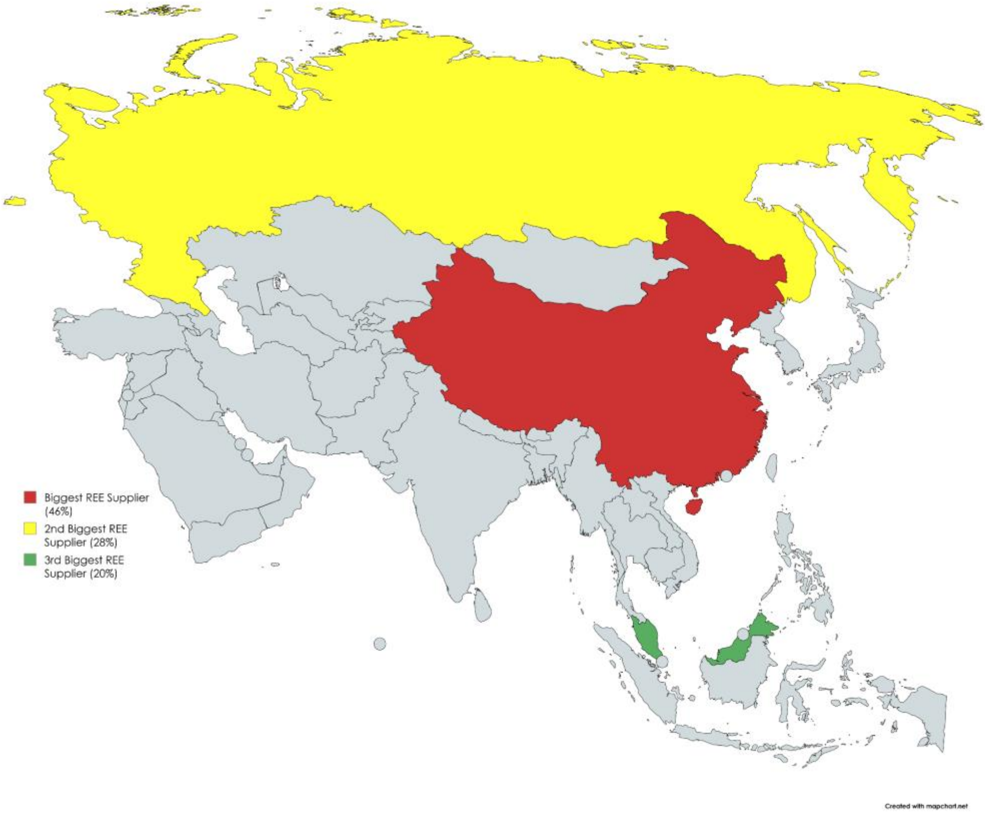
While the USA is actively pursuing domestic production and processing capabilities, the EU's lack of effective response to the problem is alarming (Brender, 2025). The current REE supply chain in the EU relies heavily on imports and suffers from low domestic production levels. Being reliant on China means that European countries receive inconsistent REE supplies, which hinders supply chain resilience. Once Beijing decides to reduce REE exports, not only are profitable sectors, such as the automobile industry negatively impacted, but the productions of crucial defence systems are also delayed, undermining national security. With the increasingly popular idea of resource nationalism in the USA, the EU supply chains risk being caught between American protectionism and Chinese coercion.

Although the creation of the supply chain ensures sufficient REE supply, it releases pollution and leads to more severe global warming (Zapp, Schreiber, Marx, and Kuckshinrichs, 2022). The poor sustainability of the existing supply chain obstructs the long-term advancements of it. Life Cycle Assessments (LCAs) confirm that REE production generates toxic wastewater, radioactive residues, and high carbon emissions (Schreiber, Marx, and Zapp, 2021). Because of these drawbacks, the incentives for forming the supply chain in the EU decrease, and its progress is often limited by environmental policies. Experts have concluded that recycling is crucial for sustainability for the REE supply chain. However, current literature lacks concrete frameworks for integrating recycled rare earth elements, which “is not yet developed at scale”, into the EU's supply chain (Rizos, Righetti and Kassab, 2022, P2).

Europe imports 98% of REE in 2024, with China as the major supplier, providing almost 50% of REE (Eurostat, 2024). Russia and Malaysia also play a crucial part in REE supplies to Europe, as demonstrated in Figure 1 (Eurostat, 2024). After being processed mainly in China, most REE enter factories producing electric vehicles, permanent magnets and wind turbines.

Figure 1

Largest partners of imports of REE+ by product code in 2024 in weight



Note. Data from Eurostat (2024, Table 1)

Within Europe, there are no active operational REE mining sites, possibly due to the strict environmental constraints and policies (ERMA, 2021). The lack of domestic mining of REE leads to the increasing reliance on imports of REE, particularly from China. Furthermore, REE requires a sophisticated separation and production process. Only one separation factory is present in Estonia (Neo Performance Materials) while the biggest REE producer, Solvay, a French company, supplies 4,000 tons of REE in 2024, which is merely 1.3% of the annual output from China (Hendrich, 2024). As depicted in Table 1, despite contributions from France and Estonia, Europe's REE demand remains too high to be met domestically and is projected to increase 5-fold by 2030 (European Commission, 2025). Clearly, Europe's REE supply chain must be improved to ensure future resilience.

Table 1

REE application and Europe Import Dependency

Application	Critical REE	EU Import Dependency
EV Motors	Nd, Pr, Dy	95% (China: 88–99%, Malaysia: 1-11% for raw materials)
Wind Turbines	Nd, Dy, Tb	98% (China: 88–99%, UK/US: 1–5% for minor processing)
Defense	Dy, Tb, Gd	100% (China: 97–100%, no European refining)
Electronics	La, Ce, Y, Eu	90% (China: 46–99%, US/Japan: 1–27%)

Note. Data from Eurostat (2024, Table 1)

Therefore, given the current limitations of the supply chain in Europe, a new model is essential. This is driven by the low likelihood of any significant reduction in China's control over REE exports, the limited willingness of immediate US collaboration with Europe on strategic mineral supply, and the difficulty of discovering REE alternatives in the near term. In this article, a novel supply chain model, illustrating the flow of material, information and finance, is developed. Two different perspectives: resilience and sustainability, are used to evaluate the model. The ultimate goal of it is to reduce the reliance on China, while balancing sustainability and resilience.

Method

Consumption and Production Projections

A complete reduction in reliance on Chinese REE supply is not possible, particularly in the short term. Nevertheless, the proposed solution aims to improve the domestic production in Europe, and increase the number of separation and processing factories and emphasises on the collaboration between countries.

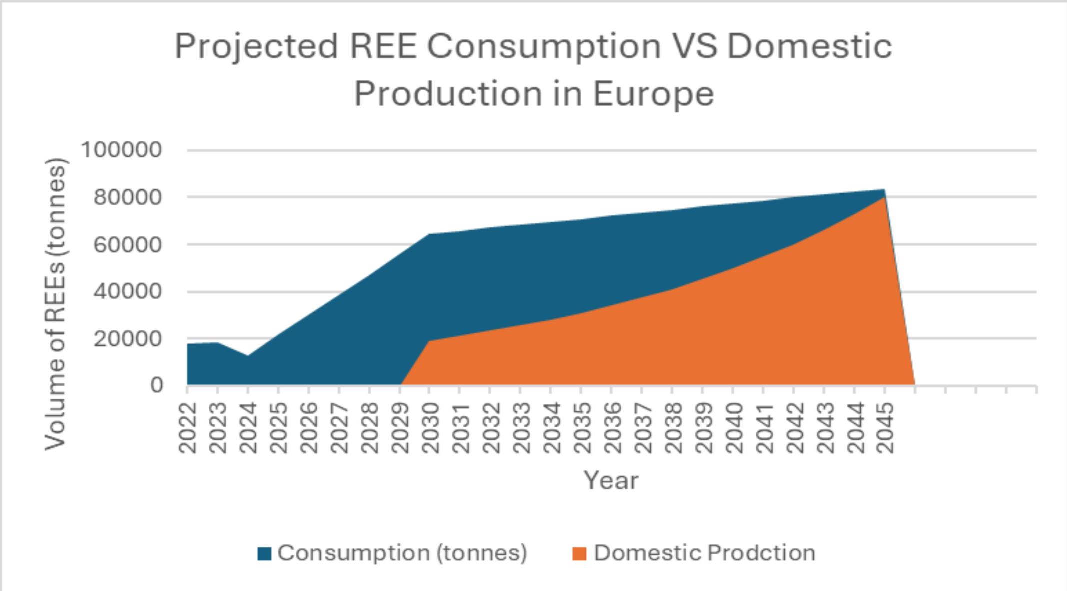
Domestic production in Europe must mainly focus on its reliability and volume flexibility, with less emphasis on their production cost (Tomlin, 2006). In case of a global geopolitical crisis, these domestic production sites increase their production volumes to cover off the decrease in exports from cheaper REE sources (i.e., China). When geopolitical risks are low, European production should operate at a slightly lower level to avoid oversupply and high costs. However, European REE producers must always maintain readiness to respond immediately if China imposes export controls.

Achieving a certain level of domestic production requires heavy investments in European countries with substantial REE reserves. Northern and Mediterranean Europe are the main development sites. In 2023, the “largest deposit” of REE in Europe was discovered in Sweden (LKAB, 2023). While REE can be produced as by-products from other mines in Finland (Eurare.org, 2022), Norway’s Fen Complex in Telemark, southeast Norway, potentially holds 8.8 million metric tons of REE (REE., 2024). Meanwhile, around the Mediterranean Sea, Greece stands out with the highest concentration of REE reserves (Tsirambides, & Filippidis, 2024). These nations are crucial players in the supply chain, responsible for raw material mining and extraction.

Sweden, Finland, Norway, and Greece collectively hold an estimated 19.2 million tonnes of rare earth element (REE) reserves (Eurare, 2022, LKAB, 2023, Teivainen, 2023, Tsirambides, & Filippidis, 2024). To capitalize on this resource, substantial government investment will be required to develop mining infrastructure, including exploration, labour mobilization, and equipment procurement. Assuming full operational capacity is achieved by 2030, a production rate of 1% of total reserves (19,000 tonnes per year) would cover approximately 30% of Europe’s projected REE demand. If production increases at an annual rate of 10%—consistent with China’s average REE production growth from 2021 to 2024—the supply-demand gap would narrow significantly (Pistilli, 2025, Briefing, 2025). Under this scenario, by 2038, Europe’s reliance on REE imports could decline to 45%, indicating that domestic production could offset Chinese imports (46.3%, Figure 1) within 13 years. This projection underscores the potential for Europe to enhance its REE self-sufficiency through sustained investment and strategic resource development. It is worth noting that all values used and projections calculated in this article, as well as graphs produced from the calculations, can be referenced from Appendix 1.[2]

Figure 2

Projected REE Consumption VS Domestic Production in Europe



Geographical Model

REE requires processing after being extracted from mining sites. The REE handling factories are arguably just as important as the mining process. In Europe, only two countries possess rare earth processing facilities: Estonia and France, which would struggle to provide sufficient infrastructure for the ambitious attempt of the REE supply chain development (Josephs, 2025). To improve the processing infrastructure, it is argued that the extracted REE

[2] https://www.dropbox.com/scl/fo/1fhzmhoh6xo421dq1mv6u/AJLk3HQFJqUp7Flc63ZBg4U?rlkey=t2165vmwj931gjmmv9bnybahg&st=6s7pp5ds&dl=0

should be transported to a limited number of strategically located refining factories (Figure 3). This centralized strategy would reduce redundant infrastructure costs and enable the deployment of advanced processing technologies at scale. Limiting the number of processing plants also decreases the release of pollution, making the model more sustainable.

The strategic refining hubs are proposed to be France, Estonia, Romania and Germany. These countries are chosen due to their investment in REE processing infrastructure and geological locations.

The distance between Estonia to Finland and Sweden is short, allowing quick transportation while minimizing cost. Moreover, the country houses Europe's largest REE processing facility. France contains Solvay's La Rochelle separation plant, aiming to establish a "robust, reliable, and sustainable" supply chain in Europe (Solvay, 2025). Its access to open sea allows transportation of REE from marine routes, from countries such as Norway or even the United Kingdom. Germany and Romania's proximity to Sweden and Greece respectively offers REE extracting countries a close partner for REE processing. Both of these countries have been developing REE processing facilities. While the German government has spent €1 billion in REE processing (MINING.COM, 2024), the Romanian Minister of Economy, Bogdan Ivan, believes that the nation can "process tens of thousands of tons of raw materials", showing its commitment to developing REE processing infrastructure (Costa, 2025).

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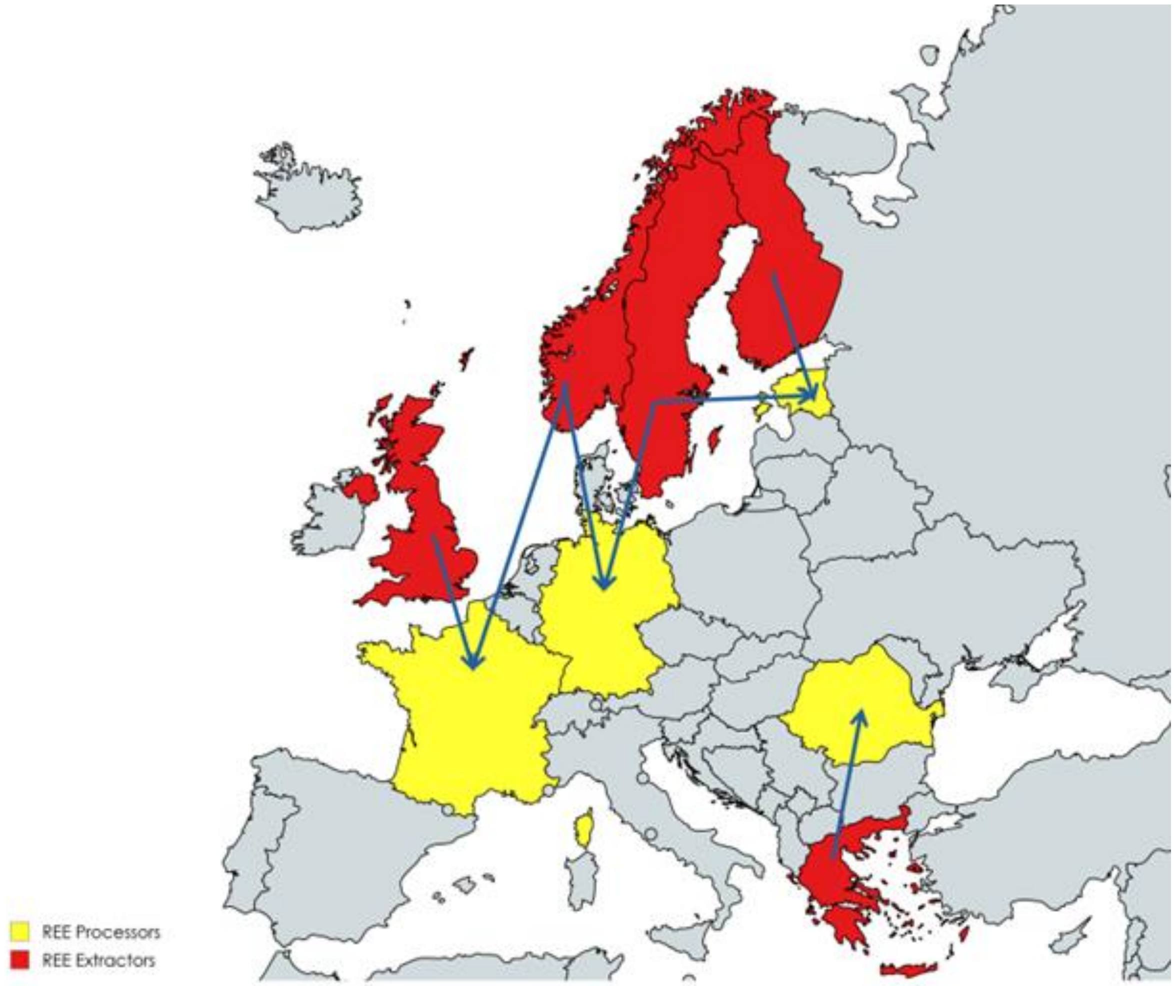
Figure 3

Mapping the Proposed Main REE extractors and Processors in Europe



Safety Stock Equilibrium Model

Resilience of the supply chain relies on the tactics for managing disruption risks, which refers to the potential export control on REE from importers. The proposal focuses on China's export control because it is by far the largest REE supplier and processor to Europe. Two main strategies for mitigation are extra REE inventory and alternative sourcing. As

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alternative sourcing has been explained in previous sections, this section focuses on inventory of REE in Europe in case of a global geopolitical crisis.

Inventory, also known as stockpiling, refers to the "accumulation and storage of a reserve supply" of REE (Quickeconomics, 2024). The inventory developed (Safety stock) helps mitigate such scenarios as the spare REE saved are used for production. The quantity of safety stock needed is given by the general formula:

$$Safety\ Stock\ =\ Monthly\ Deficit\ x\ Lead\ Time$$

For example, when China decides to cut off 100% of its exports to Europe in 2030, 46% of Europe's REE supply is stopped. In 2030, the domestic production in Europe and consumption of REE are projected to be 19,200 and 64,500 tonnes per year respectively (figure 3). Lead time for mining and processing factories to boost REE production is set as a constant at 4 months (ET Manufacturing, 2025). Thus, the safety stock required in the crisis is:

$$Safety\ Stock\ =\ [(64{,}500\ -\ 19{,}200)\ /\ 12]\ x\ 46\%\ x\ 4\ =\ 6{,}946\ tonnes$$

To introduce different strategies for a high-resilient supply chain, this article proposes a formula to calculate the time required for Europe to build the safety stock, denoted as T_s. When China completely shuts off exports to Europe, T_s increases, creating an undesirable scenario. The aim of this strategy is to limit T_s to a minimum value of approximately 4, which is the time required to ramp up production for new production capacities. To address this, the article proposes methods to reduce T_s back to its original level. The formula for T_s is given by:

$$T_s = \frac{S - I_o}{\sum_{k=1}^{3} \psi_k P_k}$$

S = Quantity of safety stock

I_o = Initial inventory level

ψ_k = Allocation ratio of REE from different sources to inventory

ψ_1: Domestic production

ψ_2: Import purchases

ψ_3: Recycling

P_k = Monthly contribution to REE safety stock from different sources:

P_1: Domestic production

P_2: Import purchases

P_3: Recycling.

Parameter Choices

The large-scale supply chain of REE in Europe is complicated. It is therefore useful to model the time for implementation to quantify the transition period. Three parameters are selected to determine the overall implementation time under 2 scenarios - the ideal (faster) scenario (Scenario A) and the slower scenario (Scenario B). The parameters are permitting and approval from policy makers, construction of mining sites, and construction of processing factories.

In this model, it is assumed that both parameters 2 and 3 are carried out immediately after parameter 1 is completed, and that parameters 2 and 3 are built simultaneously.

Permitting and approval from policy makers

Before construction of mining sites and factories can begin, companies must first obtain government approval. The length of this permitting period depends on the government's baseline review process, which may include an Environmental Impact Assessment (EIA) (Proactiveinvestors, 2023), as well as any additional delays caused by queuing.

Scenario A assumes that all procedures, such as the baseline review time, is at a minimum, while there are no delays and minimum EIA is required in the permission granting process. In 2020, an EIA permit is passed with a duration of 10 months (Poljanec and Belamarić Šaravanja, 2023), while a relatively short permit generating time is 11 months in Portugal, which has a one-stop shop system to minimize the time taken (Regueiro, 2017, P.31-32).

In Scenario B, companies are required to conduct an EIA, and potential delays are factored into the timeline. In addition, if the country operates under a more complex regulatory framework than Portugal, the overall approval period is expected to be longer. Completing an EIA potentially takes up to 24 months (Assessmentstools, 2025). Procedures in Greece are more "complex" (Sme et al., 2025, P.10), involving multiple authorization processes. It often takes around 1.5 years for the company to receive the permit (Regueiro, 2017, P.32).

Construction of mining sites and processing factories

The typical construction timeframe for a mid-sized mining operation is around 24 months, whereas larger projects can take up to 3 years to finish (DiscoveryAlert, 2025). The scale of the mining site depends heavily on resource sizes (i.e. volume and concentration of REE in the area, mining technology used, and amount of funding invested in the project. For instance, the adoption of advanced technologies, such as AI and automation, can extend the implementation timeline. These technologies also demand higher capital investment, and securing the necessary funding may further prolong the start of the project. Meanwhile, the construction timeline for REE processing factories can extend to a minimum of 24 and a maximum of 36 months (Sepro, 2024).

As mentioned above, because mining sites and processing factories are built simultaneously after the permit is received, the implementation time for parameters 2 and 3 for each scenario is determined by the longer of the two construction durations. Therefore, given the data, the implementation time for Scenario A (minimum time required) and Scenario B (maximum time required) is shown in the table below:

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Table 2

Comparison between time taken to implement the supply chain in different scenarios

Scenario	Permit approval (Years)	EIA (Years)	Mining site construction (Years)	Processing factory construction (Years)	Total time (Years)
A	0.917	0.833	2	2	3.75
B	1.5	2	3	3	6.5

Results

REE Supply Chain Resilience

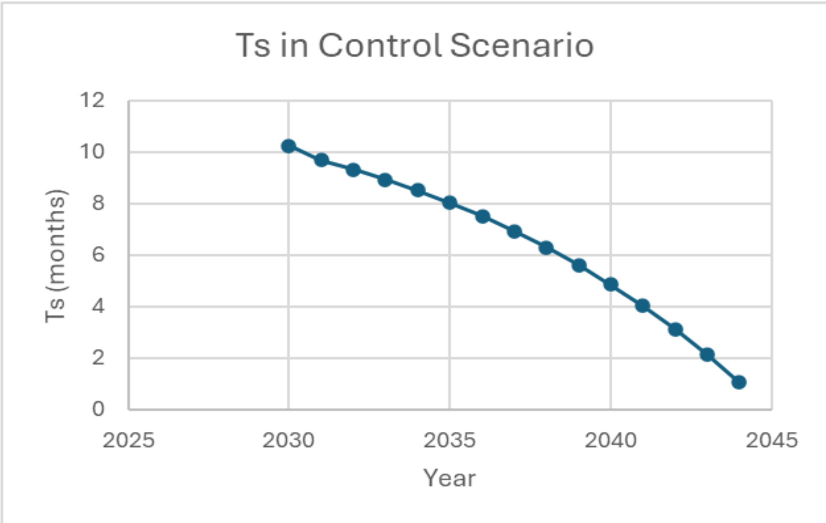
Using our safety stock equilibrium model, we evaluate Europe's REE supply chain resilience under two scenarios. The first scenario is where China maintains its 46% share of REE exports to Europe, and the second scenario is where China abruptly cuts off all REE exports to Europe.

Note that in both scenarios, it is assumed that all factories and mining sites are fully functional, and that the supply chain is working seamlessly in 2030.

As a control test, the ratio of REE supply from sources 1, 2 and 3 to the inventory stock are set as 0.1, 0.1 and 0.1 respectively. The ratio indicates that T_s, as a result, is in Figure 4:

Figure 4

T_s in Control Scenario



T_s peaks in 2030 at 10 months before gradually declining to approximately 1 by 2045. While this downward trajectory shows improvement, the initial 10-month safety stock accumulation period remains problematic, as it is much longer than the 4-month minimum factory ramp-up time required. Without China's supply (Scenario 2), T_s is even greater, as shown in Figure 5:

Figure 5

T_s Difference With and Without Chinese Supply Under Control Scenario

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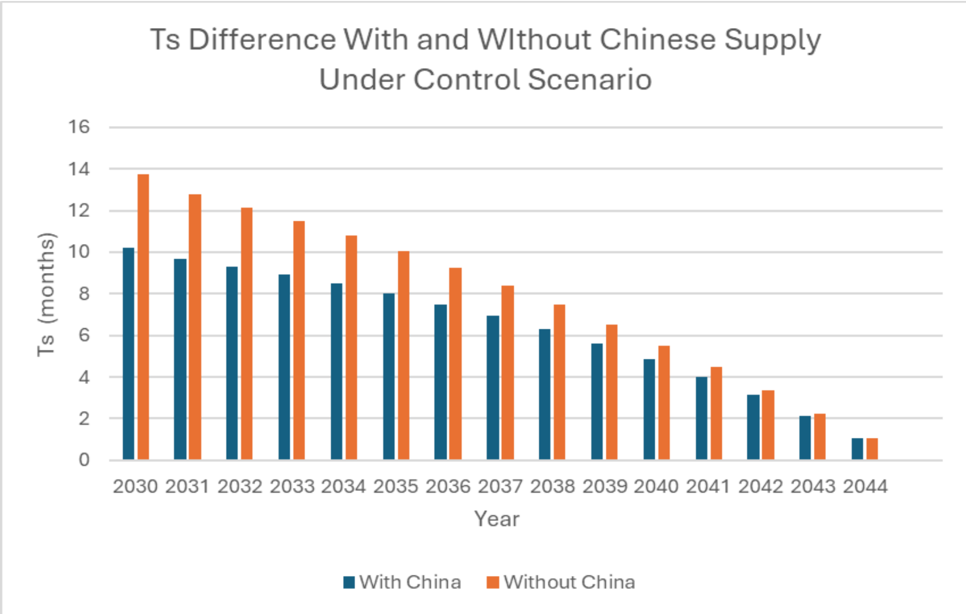

The lead time in each scenario exceeds 4 months, which indicates a potential vulnerability of a shortage of REE supply. Therefore, in order for the supply chain to be resilient, it is suggested that the value of Ts must be controlled at around 4. This ensures the inventory stock can be developed in the shortest possible time to mitigate against the Chinese export control. With multiple simulations run, it is concluded that the value $T_s \approx 4$ can be reached, with the expense of increased domestic production, which is indicated in the increase of the ratio. The suggested ratio is as follows:

Table 3

Ratios in different scenarios used in the investigation

Scenario	**ψ_1 (Domestic)**	**ψ_2 (Imports)**	**ψ_3 (Recycling)**
Control Ratio	0.1	0.1	0.1

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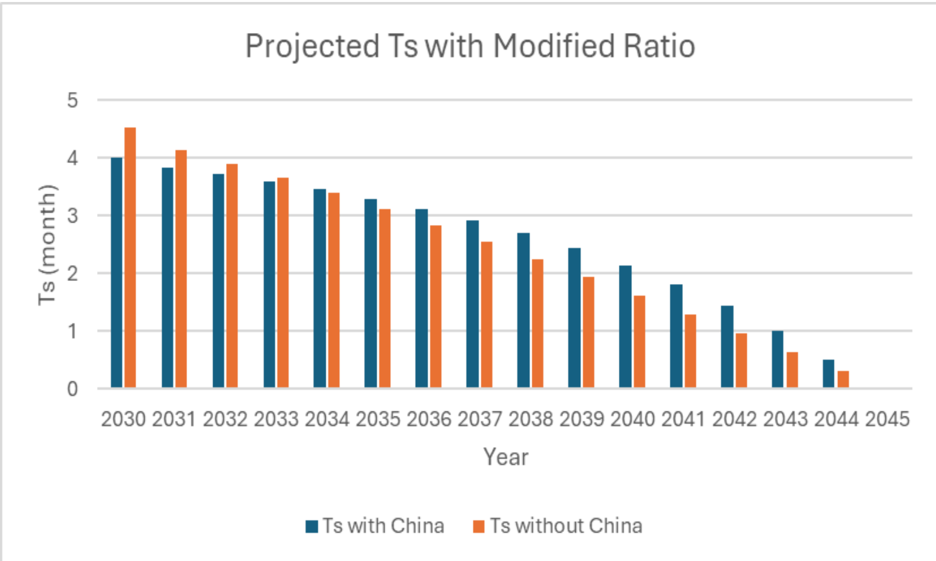
With Chinese Supply	0.2	0.3	0.2
Without Chinese Supply	0.3	0.3	0.3

Figure 6

Projected T_s with Modified Ratio



As shown in the ratio comparison table, the ratios indicate that a 20% increase in domestic production and recycling and a 30% increase in import purchases are necessary for European countries to develop the inventory stock in around 4 months when China is still willing to trade. In Scenario 2, the 20% increase in recycling production and 30% increase in import purchases remain constant with Scenario 1. However, when China refuses to export any REE, the domestic production of REE must further increase by 10% in order for the target $T_s \approx 4$ to be achieved.

Cost Analysis

Calculating the cost of the supply chain involves several 6 main areas: manufacturing cost, administration cost, warehouse cost, distribution cost, capital cost and installation cost (Pettersson and Segerstedt, 2013). Previous literature indicates that most companies tend to calculate only parts of the total supply chain cost, in particular areas that are likely to cost the most (Pettersson and Segerstedt, 2013, Figure 3). Thus, for the purpose of this article, only manufacturing cost and installation cost are investigated.

Manufacturing cost consists of two main elements - mining cost and processing cost. In China, the average cost to extract a tonne of REE is $11,370 (Pcreml.com, 2025). Assuming that the cost for extraction of REE is the same in Europe as in China, and the domestic production target is set as 19,200 tonnes in 2030 (Figure 1), the mining cost in 2030 is $218.3 million. This value is set to increase continuously as target domestic production grows exponentially. Furthermore, a study investigating 6 REE companies around the world indicates that processing plant-specific OPEX (operational expenditure) ranges between $6.1 and 15.1 per kg, which translates to $6,100 and $15,100 per tonne (Lee, 2025). Therefore, the manufacturing cost in 2030 in Europe is approximately between $335.1 million and $507.9 million. Note that these estimations do not take into account inflation, which may increase the cost.

While manufacturing cost is a main element in the cost calculation, the installation cost must not be neglected. On average, financial investment for REE for a mining site and its associated processing facilities is $600 million (Schüler et al., 2011, p.45). This figure also includes the installation of specialized machinery, environmental mitigation measures, and initial workforce training, all of which are essential for safe and efficient operations. There are currently 14 projects in Europe (ERMA, 2021, p.6). These projects may vary in scale and scope, as there are differences in ore concentration, and technological approaches. Assuming that each project has a mining site and processing factory, and that the same number of projects will be carried out in 2030, the total cost for installing all of these projects amounts to $8.4 billion in 2030.

Both manufacturing cost and installation cost include a labour cost component. Labour cost will be divided into two categories: mining labour cost, and other labour costs (covering all labour except mining). Research conducted by O'Brien and Alonso have investigated 12 REE projects outside of China in 2023. The power regression model is generated in the form of $y = ax^b$, where y is the expense estimated, x is the variable modeled, and a and b are constants determined by the regression analysis (O'Brien and Alonso, 2024). With reference to the literature (O'Brien and Alonso, 2024), where Mill Feed Rate refers to metric tonnes of REE produced per day, mining labour cost is given by the equation:

$$Mining\ labor\ cost\ per\ tonne\ =\ 7{,}126\ x\ Mill\ Feed\ Rate - 0.734$$

The Mill Feed Rate in 2030 is given by 19,200/365 = 52.6 metric tonnes/day. Mining cost per tonne is therefore $388.7 per tonne. Assuming that the employees work 365 days in a year, and a total of 19,200 tonnes of REE are produced in 2030, the total mining labour cost in 2030 is:

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$$388.7\ x\ 19{,}200\ =\ \$7.46\ million$$

Other labour costs is given by the equation (O'Brien and Alonso, 2024):

$$Other\ labour\ cost\ per\ tonne\ =\ 855\ x\ Mill\ Feed\ Rate - 0.472$$

The other labour cost amounts to $131.7 per tonne, according to the equation. Assuming that the employees work 365 days in a year, and a total of 19,200 tonnes of REE are produced in 2030, the total other labour cost in 2030 is:

$$131.7\ x\ 19{,}200\ =\ \$2.53\ million$$

Total labour cost is therefore:

$$\$2.53\ million\ +\ \$7.46\ million\ =\ \$10\ million$$

Although a large sum of human capital is needed for the successful operations of these projects, and wages of labour are more expensive in Europe than in China, the estimated total labour cost represents only 2-3% of the total manufacturing and mining cost. It is therefore concluded that manufacturing, mining and installation costs require the most financial support.

Sensitivity Analysis

The way resilience is tested relies mainly on scenarios based on the willingness of China to supply REE. Nevertheless, this section focuses on the impacts of fluctuations of the 3 sources, S_1 - domestic production, S_2 - import purchases, S_3 - recycling on T_s. The purpose of this is to identify which sources most strongly affect system recovery, thereby guiding strategies to enhance the supply chain.

Two scenarios are considered. The first scenario is where REE continues to be supplied from China at current levels, and the second scenario is where supply from China is fully restricted, simulating a severe disruption.

Within each scenario, the effects of a 10% increase and a 10% decrease in S_1, S_2, and S_3 are evaluated separately on T_s. This allows a clear assessment of how marginal changes in each supply source can affect T_s under contrasting conditions. By comparing these results, the section determines which source has the greatest leverage on resilience, which provides a quantitative basis for identifying the most effective strategies to strengthen the supply chain against external shocks and accelerate the development of the system.

Scenario 1

In this scenario, REE supplies are provided to Europe as normal. It is assumed that when one of the sources fluctuates, the tonnage of REE supplied from the other 2 sources stays constant. Figure 7 shows the difference of T_s (Baseline- T_s - T_s after fluctuation of REE sources) when volume from each source of REE is increased by 10%, while Figure 8 shows the difference when the same sources changes by -10%.

Figure 7

Difference in T_s When Sources Increase by 10% Under Scenario 1

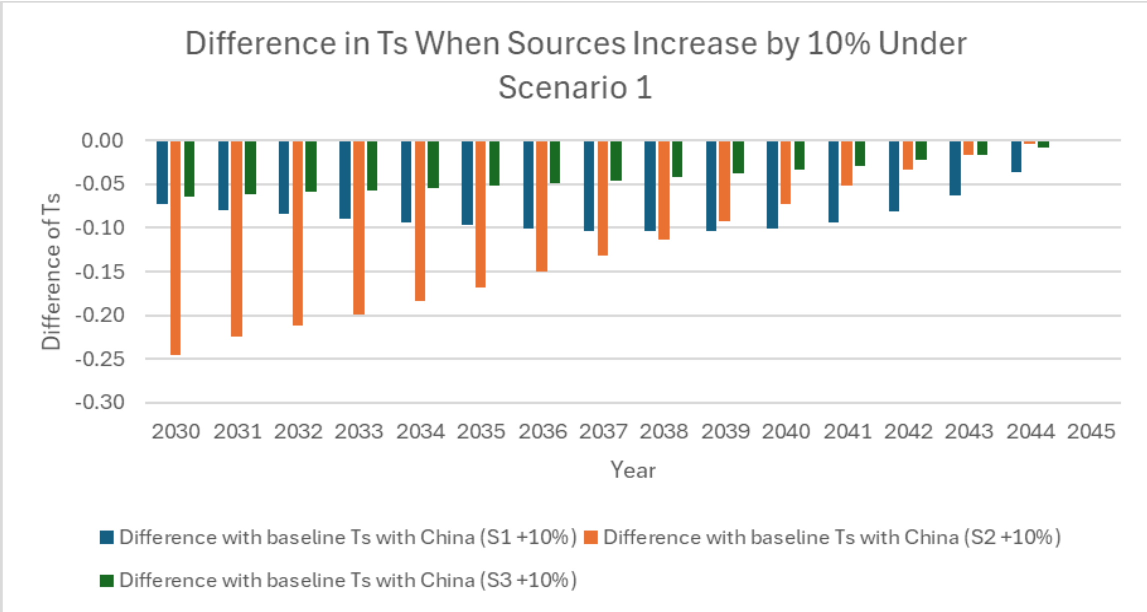
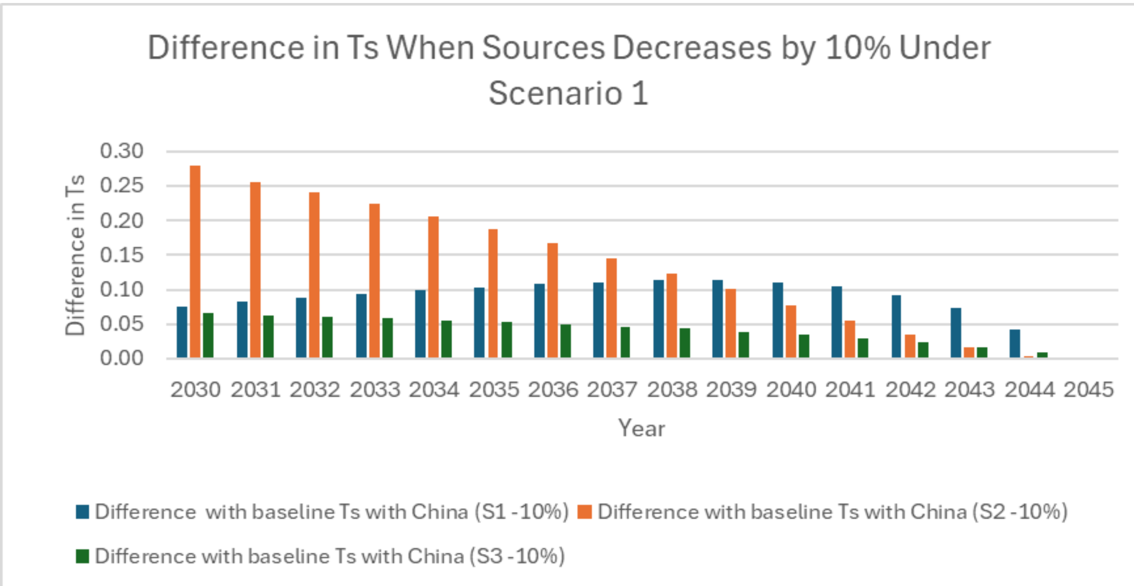


Figure 8

Difference in T_s When Sources Decrease by 10% Under Scenario 1



Both figures 7 and 8 indicate that S_1 and S_2 have a much more influential role in impacting T_s than S_3, which is nonetheless important in sustaining the supply chain. S_2, import purchases, stands out as the most influential parameter in the first 8 years of the model, up to 2038. A change of ±10% results in an approximately ±0.25 month difference in T_s. Notably there is a crossover point in the year 2038 to 2039, when S_1, domestic production, becomes the most important factor in impacting T_s. Beyond this point, increases or decreases in domestic production have a stronger effect on T_s than equivalent changes in imports. This shift suggests a transition in the system's structural reliance, from external to more internal sources.

Scenario 2

Whilst Scenario 1 illustrates the market without the occurrence of political crisis, Scenario 2 models a huge geopolitical risk from China, who decides to shut off all REE supply. This scenario may appear improbable, but the chances of it occurring, or of a comparable situation happening, is becoming greater over time, especially after the new export control rules and slow pace of approval from Beijing in May 2025 (McMorrow, Dempsey and White, 2025). Shown in Figure 9 and 10, the ±10% increase or decrease in the 3 sources have similar effects on T_s with subtle differences. It is worth highlighting that the investigation assumes ceteris paribus: despite the export control from China, other major REE sources, such as Malaysia and Russia, continue their supply of REE to Europe.

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Figure 9

Difference in T_s When Sources Increases by 10% Under Scenario 2

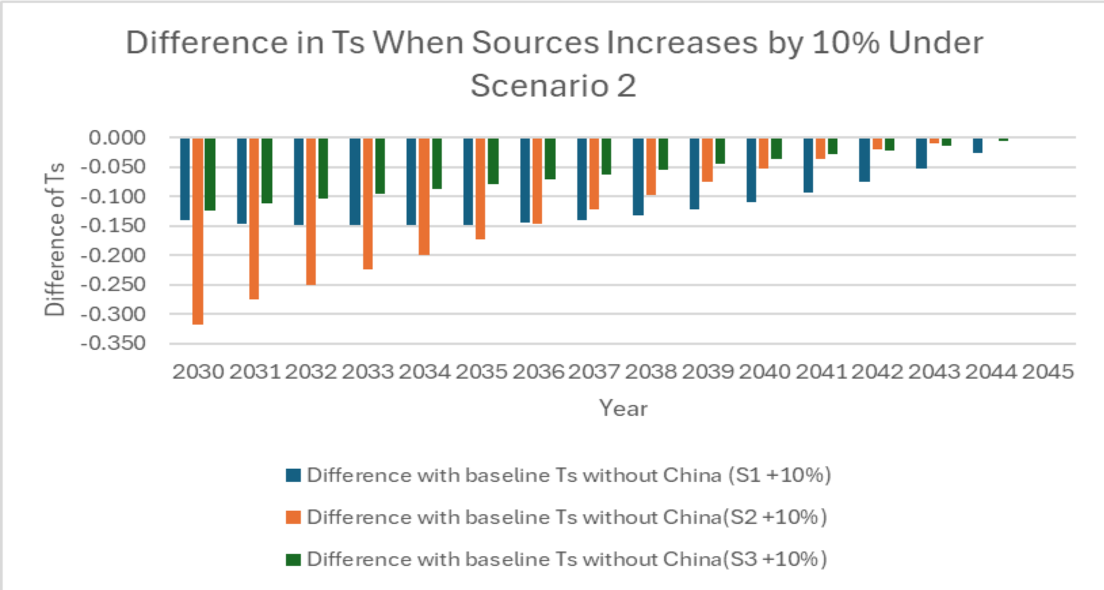
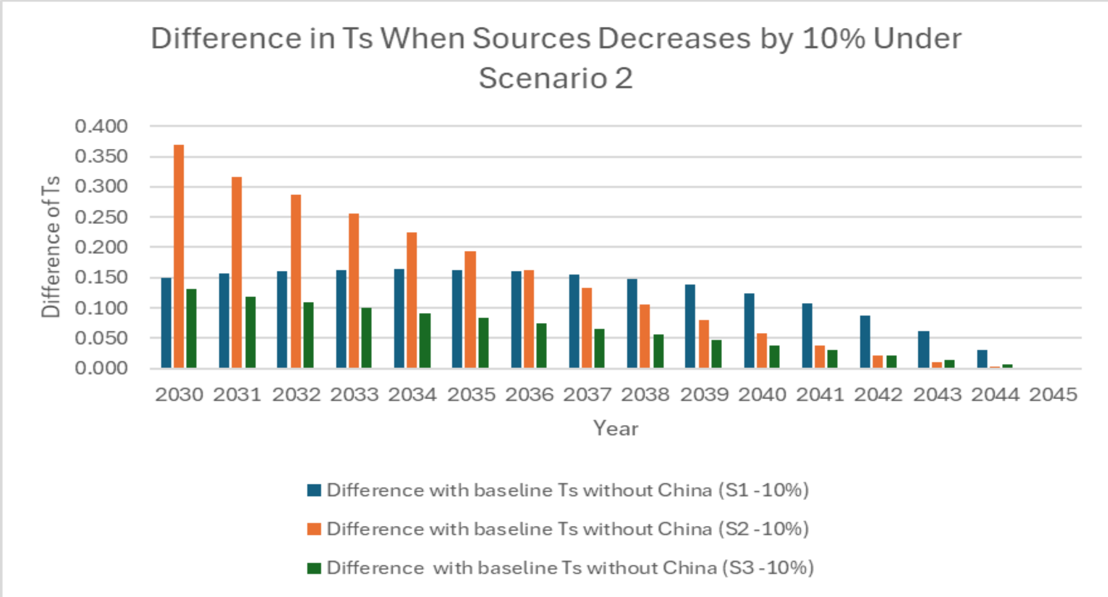


Figure 10

Difference in T_s When Sources Decreases by 10% Under Scenario 2



Similar to Figure 7 and 8, S_2 dominates the influence on T_s at first, before being surpassed by S_1. Overall, the changes to T_s are greater without Chinese supply, likely because the supply chain relies on a smaller number of sources, making each source play a more critical role in supplying REE individually. For example, compare S_2 in 2030 in Figure 7 (Scenario 1) and Figure 9 (Scenario 2): the change in T_s in Scenario 2 due to a 10% fluctuation in S_2 is 30% greater than that in Scenario 1.

Furthermore, a crossover is observed in around 2036, 2 years earlier than that crossover in the previous scenario. This suggests that the absence of Chinese supply accelerates the point at which domestic production overtakes imports as the dominant factor influencing T_s. Therefore, the system becomes increasingly dependent on internal capacity to maintain resilience.

The analysis highlights the importance of import purchases, despite the bulk of this article emphasising on domestic production, especially in the early development of the supply chain. It is suggested that governments in Europe could reach out to other countries and geopolitical groups ambitiously developing its REE supply chain. An organisation in Africa, being an REE player that is often out of the spotlight, has announced the REE advancement, which is a "beneficial socioeconomic transformation across the continent" (ASDT, 2025). Additionally, countries such as Australia and the USA represent promising partners for REE trade.

Governments must allocate even more resources onto developing domestic production just prior to the crossover point. This includes the heavy investment in mining sites and processing factories, as the dominant factor of influence in ensuring the supply chain resilience shifts towards S_2.

Recovery and CO2 Emissions

Currently, the development of REE in Europe has stalled because of stringent environmental regulations. The governments are skeptical about the environmental impacts, such as soil erosion, release of radioactive dust and river contamination that the production of REE brings about (Zapp, Schreiber, Marx, and Kuckshinrichs, 2022). While NGOs may criticize the unsustainable nature of mining, the general public are often skeptical about REE development in their own countries. Although REE are usually produced outside of Europe due to the concerns from the society, because of the potential geopolitical risks, the challenge for European governments lies in balancing the expansion of REE production with the mitigation of its environmental consequences. Therefore, it is argued that the sustainability of the supply chain, in both the mining and refining stages, must be addressed.

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Recycling REE, also called Urban Mining, offers an alternative source for raw materials. These secondary REE reserves could offset 30–50% of demand for critical elements like Nd, Dy, and Sc by 2035 (Gaustad et al., 2021). In Europe, crucial sources include coal ash, red mud and E-waste.

Coal ash is rich in REE, with scandium levels 2.9 times higher than those found in primary sources (Gaustad et al., 2021). In Europe, Poland and Germany are the leading producers of coal ash, making them ideal locations for implementing collection programs. The gathered coal ash can then be transported to nearby processing facilities in Germany, where it can be refined alongside REE extracted from primary sources.

Although red mud contains lower overall rare earth concentrations than traditional ores, it is notably richer in certain high-value elements. Specifically, it has 11 times more scandium, four times more thulium (Gaustad et al., 2021). Given that scandium is the most valuable rare earth element in today's markets, and thulium and terbium also command high prices (2nd and 3rd most expensive elements) (Love Money, 2025), red mud could become an economically viable source for these critical materials (Fu et al., 2025, Strategic Metals Invest, 2025).

For REE urban mining purposes, E-waste refers to LED bulbs and NiMH batteries that are not consumed or have not gone through recycling processes. Less than 40% of E-waste is being recycled in 2020 (European Parliament, 2020) while research highlights that E-wastes contain 3-6x more Dy, Tb and La (Gaustad et al., 2021). Since LED bulbs and NiMH batteries remain crucial in the consumer goods market, their demand and production are expected to stay steady, which ensures a consistent supply of recyclable materials. Pioneering facilities like Umicore's Belgian plant demonstrate the viability of this approach, recovering of Nd/Dy annually for renewable energy applications while cutting carbon emissions compared to conventional mining in China (Umicore, 2023). Furthermore, Europe generates the most e-waste per capita (16.2 kg per person), underscoring the opportunity for a robust e-waste recycling supply chain (DTP Group, 2025).

Global e-waste reached 62 million tonnes in 2022, with Europe contributing 13 million tonnes (21%). Projections suggest total e-waste will grow to 82 million tonnes by 2030. Assuming Europe maintains its 21% share, it will generate 17 million tonnes of e-waste by 2030 (UNITAR, 2024). REE constitutes 0.5% by weight of e-waste (Binnemans et al., 2023). Thus, the recovery potential of REE from Europe's e-waste is:

$$Recovery = 17{,}000{,}000\, tonnes \times 0.005 = 85{,}000\, tonnes$$

Thus, when Europe has a 100% recovery rate of e-waste, and assuming that the e-wastes contain all elements of the REE, the raw materials produced just by recycling not only covers, but also comfortably exceeds the European demand in 2030.

Europe's 20% collection for Electrical and Electronic Equipment suggests that an extra 17,000 tonnes of REE can be generated just from E-waste recycling (UNITAR, 2024). It is worth noting that despite the continuous increase of E-waste in Europe, the annual recycling percentage decreases. Therefore, the total mass REE generated from recycling sources is modelled as a constant of 17,000 tonnes.

While recycling increases REE supply in Europe, it also decreases CO2 emissions. In China, emissions caused by the production of Nd is 30kg CO2 per kg of Nd (Schreiber et al., 2021), while recycling Nd generates 8kg CO2 per kg of Nd (Umicore LCA report, 2023). Given these statistics, and assuming all REE processes produce the same amount of CO2, the emission reduction would be calculated as:

$$CO2\ Reduction = \ 22{,}000\ kg\ CO2/tonne \times 17{,}000\ tonnes$$
$$= 374{,}000\ tonnes\ CO2/year$$

This indicates that the CO2 emissions of the annual electricity usage of approximately 50,201 homes in the UK are reduced, highlighting the sustainable potentials of REE recycling (Environmental Protection Agency, 2015).

Government Actions

The proposed supply chain demands substantial investments in both financial and human capital. Its success, nevertheless, will depend heavily on government action. Current lengthy permitting processes for EIA, and lack of government intervention on a circular economy framework will undermine the efficiency, productivity and speed of the implementation and operation of projects. This section, therefore, explores the government's roles in ensuring the seamless operation of the supply chain.

As established above, EIA is a lengthy process, which can take on an average of to complete. This highlights that some projects are held up for a long period of time before construction starts. During the waiting process, companies' ambitions to contribute to REE supplies are often delayed. In Europe, the main problem lies with the lack of a streamlined process for EIA. It is suggested that governments should develop a standardised, online portal for EIA for all countries in Europe collaboratively.

In the online EIA application system, data of all previous EIA applications must be loaded into an AI system that compares the previous application data to the new application (IAIA, 2021). Companies are required to fill in data and information about the impacts of their projects on air, water, noise, and biodiversity. Using previous data sets, the AI system produces a priority list, ranking the potential risks for experts to review. More resources are then put into reviewing these issues. The reviewing process utilizes a parallel evaluation model, where data and information of the riskiest issues of the project are viewed by multiple experts, and different issues are being reviewed simultaneously. Feedback from them is recorded directly within the system, allowing companies to address the identified challenges and submit corrective measures where necessary. The data of environmental impact after the solved issues are entered into the system again. The process keeps iterating until the information provided is up to standard.

Governments in Europe, to support this, must collaboratively share the previous EIA data that is feeded into the AI system, while employing computer scientists to develop the system. Moreover, a training course designed to assist experts that review the application should be compulsory for all reviewers before they take on the roles. In all European countries, a law must be passed, so that using this system for EIA application is mandatory. This allows the streamlining of the EIA application process, and the integration of AI and online feedback systems would accelerate the process.

Furthermore, a "EIA Credit System" can be implemented by the government (Hu et al., 2024). It works by rewarding companies credits for desirable practices during previous EIA processes, and those which operate sustainably, such as submitting documents punctually and adapting green technology. As the credits are built up, companies are allowed to reduce the time for EIA process once the credit points reach a certain threshold. This approach would create a strong incentive for firms to build a consistent record of good environmental performance, as only those with demonstrated responsibility would benefit from accelerated approvals. However, the credits expire after a set period of time, encouraging the continuous strive for environmental improvement. Governments ensure the transparency of the system, preventing any frauds from occurring and tracking the issuing and expiring of credits. Laws must also be accepted so that any attempt to exploit loopholes could result in serious consequences.

Although the AI system streamlines approvals, mining operations remain energy-intensive. To address this, a circular framework can reduce emissions and improve resource efficiency.

Shown in Table 1, Nd, Tb, and Dy are used in the production of wind turbines, which generates renewable energy. They are capable of outputting 6 million kilowatt-hours (kWh) of electricity annually, which is equivalent to the demand of approximately 1,500 typical households (EON, 2022). Given the large amount of electricity that wind turbines can potentially produce, it is applicable to electrokinetic mining (EKM) (Wang et al., 2024). EKM extracts REE in an environmentally friendly method, which uses low-voltage electric fields to mobilize and recover rare earth elements from soils and sediments (Wang et al., 2024). Its advantage lies in its efficiency, achieving up to 95% recovery rate of REE (SciTechWay, 2025). Mined REE, in particular Nd, Tb and Dy are then refined and incorporated into the production of wind turbines, which are ideally built close to the mining site. Other mined REE and excess electricity are suitable used in other products and processes. This creates a circular, sustainable framework that reduces emission while ensuring the long-term development of the REE industry.

Governments play a massive role in the framework. They can establish regulatory policies that allow the close proximity between the mining site and the location of wind turbines, which reduces resources used in transportation of materials and transmission of electricity. Furthermore, it is recommended that governments implement fiscal policies to enhance investment incentives. By reducing taxes and lowering borrowing interest rates, individuals and businesses have increased financial capital. These policies are therefore likely to stimulate greater private sector investment in the development of REE facilities (Tutor Chase, n.d.). Greater advertisement of the REE projects should be done to promote them, raising awareness of the investors and gaining wider societal support.

Limitations

The proposed supply chain model aims to identify weaknesses in the current REE situation in Europe while exploring the potentials of REE development in the continent and strategies to mitigate geopolitical risks. However, the model contains several assumptions, and the data collected may not be an accurate representation of the full picture.

In the article, it is assumed that in all of the REE reserves in Europe, the concentrations of different REE are at a similar level. Although this allows the calculations of the overall consumption, T_s and volume of recycled REE, it may oversimplify the variability of REE concentration. Some REE, such as Nd and Dy, are used in more products than others (Table 1). This represents potential inaccuracies in the model. As this article considers data representing all REE, regardless of their importance, the supply risk of the high-demand REE may be underestimated while there may be an overestimation of low-demand REE.

Consumption of REE is assumed to increase 5-fold by 2030 and 7-fold by 2045 from the consumption in 2020. Nevertheless, the prediction assumes that all REE grow at the same rate, ignoring that the demand of some REE will expand more rapidly than others. For instance, the largest use of REE is magnetic for electric vehicles and wind turbines (ACF Equity Research, 2023), and their demand will increase at a faster rate than less used REE.

In addition, the article only explores geopolitical risks when China closes the REE trading window with Europe. This situation is investigated because of the significance of Chinese supply to Europe (46%), and a supply stoppage from China represents one of the worst situations that Europe faces. Nonetheless, other geopolitical crises may occur. Potential risks may include the unwillingness of cooperation between European countries, trade bans from partnership nations, such as the USA, and resource nationalism in African regions. These risks can severely limit development of the supply chain, in particular the build up of safety stock, reducing resilience. Moreover, if European countries refuse to cooperate with each other, the flow of REE from mining sites to processing factories, located in different countries. is cut off. This results in an undesirable interruption in the supply chain. The risks mentioned above are not tested in the model, and therefore the full potential and flaws of the supply chain remain to be investigated.

During the exploration of resilience of the supply chain, how the supply chain reacts to disruptions is investigated. However, the model does not utilize dynamic analysis to examine the supply chain under scenarios. Governments, for example, may actively anticipate supply chain crises, which incentivizes its investment and preparation from other REE sources. When this is taken into account, the resilience of the supply chain could be impacted significantly. Although this article provides a comprehensive view of the resilient abilities of the model, the lack of usage of such dynamic analysis may lead to slight inaccuracies in predictions.

The cost analysis of the supply chain only accounts for the labour cost, implementing cost, and manufacturing cost. It does not, however, cover all six areas of supply chain cost (Pettersson and Segerstedt, 2013). Thus, the estimate of supply chain cost is an underestimate. The assumption that 14 projects would be built by 2030 is not a precise projection of the number of REE projects in Europe (ERMA, 2021, p.6), especially if governments are ambitious for REE success. Although the average cost of each project is on an average of $600 million (Schüler et al., 2011, p.45), the amount of financial capital required to start up each project depends heavily on its scale and types of REE present in the mine.

Lastly, this study presumed that NGOs and local citizens accept the development of REE in their own nation. The rise of the NIMBY (Not In My Backyard) movement raises awareness of unwanted constructions in a particular region (Driscoll, 2022). Consequently, opposition from this movement poses a significant risk of hindering and delaying the supply chain's implementation, as governments must first secure public trust by demonstrating that the projects' long-term sustainability will outweigh their potential environmental impacts.

Conclusion

REE has ascended as a crucial raw material in the new "era of deglobalization" (Keller and Marold, 2023), facilitating the production of the world's most indispensable goods. This paper addresses the problem that Europe is facing – the Chinese monopoly on this strategic resource, and the lack of domestic supply chain advancement within the continent. Given that Beijing has been dominating REE supply and processing since the 1990s (Geopolitical Monitor, 2023), the solution proposed does not seek to establish a fully self-sufficient supply chain, but rather to reduce dependence on China while striking a balance between sustainability and resilience. Furthermore, this solution is even more crucial, given that China is reluctant to change its strict export control in the short term, and that other alternatives to solve the challenge are unlikely to occur.

The flow of materials is mapped in this article, and the potential reserves in Europe is estimated. With the proposed novel safety stock evaluation, the resilience of the supply chain is investigated. It is investigated that the different ramp up scenarios needed to minimise the safety stock build up time. Moreover, the analysis highlights domestic production and import purchases as the most important factors in improving the supply chain, with the influence of domestic production increasing over time. The findings presented here provide a foundation for researchers and policymakers to design effective strategies aimed at enhancing the overall productivity and resilience of the supply chain.

Sustainability, one of most concerning issues regarding the establishment of REE projects, is explored with discussions on recycling and circular resource framework. These add-ons to the supply chain ensure its long-term development. While governments may use the sustainable initiatives to persuade the acceptance of REE projects in the citizens' communities, future literatures could potentially develop concrete frameworks on how they are implemented.

The cost analysis and implementation time estimation mentioned in my article provides an approximate timeframe and investment required. Although a substantial amount of resources are needed, and the exact timeline remains uncertain, these projections offer a foundational benchmark that future studies can refine to enhance the feasibility assessment of the proposed supply chain. EIA, which initiates every REE project, requires complex stages. The article puts forward a proposal for an AI-driven, collaborative online platform encompassing all European countries, complemented by a credit system to expedite the process. Such a framework not only streamlines permit approvals but also promotes greater transparency and consistency across the continent.

Due to the weaponization of REE from China, Europe must act swiftly to counter those measures. How Europe responds will define the future of the REE market and whether the external pressures of the supply chain can be handled. Decisions made now shape the technological advancements in Europe and influence the future of national security. Using the foundation work of the proposed solution in this article, Europe can begin building a resilient and green REE supply chain.

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