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Global Supply of Rare Earth Elements: An Analysis of German Economic Dependence on China's Exports

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Abstract

This thesis explores the trade relationship between China and Germany, focusing specifically on the German economy's import of rare earth elements. Using Input-Output analysis and Leontief Inverse analysis, this research investigates the exposure and vulnerability of the German economy to the disruption of this supply chain. The findings reveal that the German economy has multiple key industries that are highly exposed to the negative effects of disruptions and suggest a significant need for protective measures to be taken to protect the greater economy. This study contributes to the literature on supply chain resilience by taking a narrow focus on the dynamics of one significant and highly affected relationship. A deeper understanding of this specific relationship could be applied to other similar and less severe cases to act as an example.

Keywords: Supply Chain Resilience, Input-Output Analysis, Leontief Inverse, Rare Earth Elements

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Chapter 1: Introduction

As technology has developed, the role of Rare Earth Elements in the economy has grown more prominent and near critical, particularly in developing technologies that are driving the green energy transition. However, these resources are often not talked about proportionally to their importance in the trade of commodities. These materials are essential in the manufacturing of electric automobiles, medical technology, wind turbines, defense systems, and many more. Germany is a globally significant manufacturer and exporter of some of these critical products, leaving them highly dependent on these Rare Earth Elements. The guiding questions for this thesis are as follows: What are the direct and indirect dependencies of German industries on REEs imported from China? Which of those industries are most dependent and thus most vulnerable? What strategies can be implemented to reduce the risk to the economy?

This thesis explores the topic of vulnerability, exploring and analyzing global data on the flow of goods to better quantify the issue of dependency. A quantitative understanding is critical to formulating effective strategies and responses to protect the economy from supply disruptions.

1.1 Problem Statement

The central problem explored by this thesis is the high degree of exposure and vulnerability that the German economy has to China's export of Rare Earth Elements. Germany is a mass importer of raw materials including Rare Earth Elements that are critical in the production of its exports. This is primarily due to the lack of availability within the country. This presents a strategic vulnerability for Germany as it leaves them highly dependent on China, who are almost monopolistic exporters of these materials. The high degree of dependence that Germany has on this supply leaves its economy exposed to many potential disruptions. Germany's economy is left vulnerable to the results of geopolitical tensions, international trade disputes, and the whim of China's export policies. Currently, Germany does not have a sufficient alternative source for this critical material. This fact makes an adequate response to any of these shocks very difficult. Due to these factors, the supply chain of Rare Earth Elements is a critical weakness in the German economy that needs to be addressed.

1.2 Objectives and Research Questions

The purpose of this research is to critically analyze the dependence of the various industries of the German economy on the supply of Rare Earth Elements (REE) imported from China. Leading to a broader understanding of the sensitivity of the German economy to disruptions in that supply chain and the specific points of vulnerability in the German economy. When only considering trade volume, Germany's dependence on imports from China is comparable and even lesser than other EU countries. However, Germany differs from these other countries with respect to strategic dependence (THE ECONOMIC RESEARCH PORTAL, 2023). This unique and critical supply chain weakness is the primary motivation behind the focus of this paper. With Germany's near singular dependence on imports from China and its critical position in the production that will drive the green energy transition, the impact of this relationship becomes far more impactful. More specifically, the primary objectives of this research are to: understand the most exposed and vulnerable industries of the German economy to this supply relationship. Using complete trade data to explore the complete, direct, and indirect, relationships in the world economy. Finally, to isolate the dependencies of each German industry on China's output of REEs, using these outputs to make recommendations of measures to mitigate risk.

Klossek et. al. (2016) characterize the effect of the economy's dependence on China's export of this raw material. They highlighted the effects of the tensions between China and Japan in 2010, in which China placed restrictions on its export of REEs. This restriction greatly increases the price of REE adversely affecting the Japanese economy. They highlight particular systemic problems in the rare earth market: "competing political-economic models, resource nationalism, market opacity, a lack of trust, weak cooperation and short-versus long-term approaches and profit orientation" (Klossek et. al., 2016). They propose a series of solutions to these problems that include a database of REEs that reduces market opacity, an increase of state involvement in the cooperation of nations in the long term, and measures to increase the free market quality of the REE value chain. These problems become particularly important as technological development is progressing in a direction that is increasingly dependent on REEs. Some rare earth elements are critical in the manufacture of magnets that are critical to many renewable energy technologies (Stegen, 2015). As a consequence of this, the global effort to develop green energy technology, the world will become increasingly dependent on REEs. This increase will further exacerbate the problems highlighted in Klosseks et. al. (2016) article. Looking at supply, China has made cuts to its exports that have greatly increased the price of raw materials, like REEs. These effects are further increased by insufficient recycling and limited substitutes for REEs in production processes; limited options for alternate sourcing drive the possibility of a crisis (Massari & Ruberti, 2013).

1.3 Significance

The impact of this strategic weakness in the German economy is extremely vast, not only for the present but for the future. In the short term, a significant part of Germany's exports will suffer a large price spike in one of their critical raw inputs. The shortage caused by this spike will negatively affect the output capability of the economy, reducing GDP and the overall health of the economy. This effect is directly reflected in the tension that China had with Japan, the consequences of which are shown by the negative effects on Japan's economy (Klossek et. al., 2016). The longer-term effect is arguably more significant and pivotal. Given the critical nature of REEs in the production of green energy technologies, a disruption in supply could delay Germany's goals to slow the effects of climate change. Germany's goal is to source 80% of its energy from green sources, like wind turbines, by 2030 (Wehrmann, 2024). A reduction in the production capability could delay this goal, increasing the time that energy production is dependent on polluting sources.

The primary value of this study is to provide empirically based strategies and policies to strengthen this vulnerable point of the German economy and increase critical resource stability. This short-term stability will then lead to long-term resource stability, which is also supported by the strategies explored. This study aims to add to the greater discourse regarding supply resilience by identifying specific points of weakness with quantified vulnerabilities.

1.4 Overview of Methodology

The methodology employed in this study consists of a multi-country Input-Output analysis that includes a Leontief inverse analysis aimed at quantifying the inter-industry dependencies. This method of analysis will provide a more complete understanding of these inter-industry/country dependencies and the full impacts of supply disruptions. The full model is then narrowed to focus specifically on the flow of REEs from China into the German economy, this narrowing will focus on the main focus of this research.

1.5 Scope and Limitations

This study intentionally takes a rather narrow focus, looking specifically at the import of REEs into the German economy from China using the most recent data available. The analysis takes into account a large number of countries in the dataset in order to output a more complete picture of the flow of goods and the indirect dependencies of specific economies. The goal of a comprehensive analysis is mainly constrained by the parameters of the data that is analyzed. Given the complexity of the data, there is a significant amount of time between the year that is represented and the present. Changes in the world economy in these years could have an effect on the results of the analysis. The analysis is ultimately trying to better understand one specific supply relationship in a greater and far more complex global supply system.

1.6 Paper Structure

This thesis is structured into 5 Chapters: Introduction, Theoretical Framework, Methodology, Results, and Discussion. The Theoretical Framework aims to present previous literature and context to the main concepts of the thesis. Providing foundational information on the Input-Output analysis method, the role of Rare Earth Elements in the modern economy, the effects of supply disruption on regional economies, and the gaps that exist in the literature. The Methodology chapter provides a description and theory of the methods used in the collection of data, the Input-Output analysis, and the specific methods used within that analysis framework. The next chapter presents the results of the analysis performed, highlighting particular weaknesses in the economy and places of high vulnerability to supply disruption. The final chapter discussed the potential methods and strategies to strengthen the economy. Including a conclusion that summarizes the findings and discusses the implications.

Chapter 2: Theoretical Framework

This section aims to give background information on the key ideas that surround this research. It will explore the analytical methods used as well as previous research into the topics that pertain to import resilience and trade disruptions. Specifically, the history and background of Input-Output analysis and the importance of Rare Earth Elements. Additionally, the effects of import disruption are explored focusing on their less observed effects on economies.

2.1 Input-Output Analysis

Input-Output (IO) analysis is an analytical framework created to understand and analyze how industries are interdependent on one another in a given economy. First developed in the 1930s by Wassily Leontief it has become a widely used tool set in economic analysis (Miller & Blair, 2009). The IO framework is grounded in a similar way to other accounting frameworks, in that it records transactions of inputs and outputs in a given economy. The fundamental equation that the framework captures is that the consumption output (final demand) in addition to the outputs used as intermediate inputs is equal to the total produced output (gross output). This equation captures the total output by all specified industries during a selected period of time. The framework also captures the carry-through effects of intermediate outputs that are later used for another industry's final consumption output. These interactions and flow of goods capture the total volume of transactions through the given economy The framework will often divide these values to represent different accounting identities. These include government purchases, and investments, along with exports and imports (Jackson, 2020). For this analysis, many of these parts of the framework will be omitted. In favor of the direct input and output data within the table.

The IO model is similar to other widely used economic models in that it presents a form of production function for the economy. However, unlike other models, the production function in this analysis is unable to see optimizing behavior. This is due to a lack of a theoretically complete representation of the supply and demand sides of the economy. The assumptions of static inputs to output ratio in each industry preclude the optimization of the supply side. In one form of the IO model, people and households are treated as industries, locking them to a static input-output ratio. This is a misrepresentation of behavior, instead of choice-making organisms they are treated as producing industries (Christ, 1995). Despite this, IO analysis is a strong tool to understand the complex flows throughout an economy. It can provide a complete picture of the ripple effects from any corner of the economy throughout its industries. It is important to understand the limitations of the method by the standards of a complete economic model. However, those who defend it say it is particularly valuable as a first look at the situation, which can provide sufficient information in some cases to take the first action. Also, that with some adjustments and developments, can inform actions in a greater number of situations. One important type of situation where IO analysis can be very valuable is a short-term situation in which there is a rapid and great change in the amount of goods or services available in the economy (Christ, 1995). This function of IO analysis makes it particularly valuable for this research. This model is also valuable in the evaluation of the regional resilience of a region, which will also be valuable for this analysis. For example, in their article Bruggeman and Giannakis (2017) used IO analysis to explore the structural changes in the production of the Greek economy from 2004-2011 to understand the effect on employment recovery of the post-2008 recession. Through the use of employment multipliers, they were able to identify the sectors of the economy that had the greatest effect on employment when stimulated (Giannakis & Bruggmen, 2017). This is one of many use cases for IO analysis in economic research.

2.2 Role of Rare Earth Elements

Rare Earth Elements (REE) are a set of raw materials that are a key part of the production process of many advanced technologies. They are a cornerstone of geo-political and economic strategy for the European Union and the Republic of China (Alves Dias et. al., 2020). The set of elements that are classified as critical raw material, the mining of which is currently dominated by China. China currently holds an effective monopoly, 97% of the mining share is controlled by the Republic of China (Morrison & Tang, 2012). Currently, China's strategic goals are to maintain this monopoly over REEs, as they are a strong point of strategic strength. As a large importer of REEs, the EU's strategic goal is to find alternate sources of REEs to loosen China's grip on the REE markets (Balaram, 2023). Despite the name, there is a relatively great supply of REEs in the Earth's crust, so there may be other undiscovered deposits. One alternate source being considered is space mining, although it is not yet cost-effective and comes with significant environmental concerns as some materials are radioactive or toxic (Balaram, 2023).

One central use case for these REEs in the EU is in the green energy transition. As climate change has become a more central issue in politics, the EU has begun to shift towards producing greener sources of energy. Unfortunately, the production of many of these technologies is dependent on REEs. Four of these REEs specifically, neodymium, praseodymium, terbium, and dysprosium all of which are dominantly supplied by China (Alves Dias et. al., 2020). Demand for these materials is predicted to increase over time which could cause supply bottlenecks that are damaging to the green energy efforts (Alves Dias et. al., 2020).

Germany is specifically vulnerable to China's dominance in REEs. Of the 30% of gross value added in manufacturing, 22% of those goods use REEs in their production. While Germany remains dependent on China for 84% of its REEs and will for the near future (KfW, 2024). This dependence on China, in REEs and other sectors, poses a significant risk to the German economy. A large economic crisis in China could have a spillover effect on Germany, lowering GDP by up to 1% a year for two years (Deutsche Bundesbank, 2024). In a survey conducted by a representative of the German Bundesbank, half of all firms in manufacturing either had direct or indirect dependence on Chinese intermediate inputs (Deutsche Bundesbank, 2024). This leaves the risk of spillover into other non-dependent or even non-German sectors quite high. There is a desire in Germany, backed by the EU, to decouple from the single-sided dependence on China. The German economic ministry is developing new raw material strategies and looking to diversify the supply chain to limit the risk surrounding critical materials imported from China (EURACTIV, 2023).

2.3 Effect of Disruptions

Trade and supply chain disruptions can have a strong effect on the productivity of economies (Attinasi et. al., 2021). If imports suddenly and drastically decrease in a country that is highly dependent, unless the country has alternatives, it can have a significant effect on the local economy (Blayney et. al., 2006). In the instance of a trade disruption, the indirect effects can greatly increase the damage of the direct effects. Particularly economies with both intersectoral linkages are vulnerable to this additional effect (JONES et. al., 1988). A similar method of IO analysis is used often when assessing an economy in this situation, to capture the full extended effect of disruptions. This is a critical capability in assessing ripple effects that occur when there is a disruption in just one section of the economy (Miller & Blair, 2009). There are significant instances in which trade restrictions have been brought down that show these effects in real economies. For instance, China restricted their export of REEs, and industries that depended on these materials suffered greatly. In a study, Wübbeke (2013) used this event to show the great vulnerability of economies and supply chains to political decisions. This was done by highlighting the dependence of specific industries on imports from China and how the greater economy was affected along with them (Wübbeke, 2013). Through the existing literature, it becomes clear that the effects of trade disruption can be extremely costly and damaging to an economy. It is also evident that there is far more to it than simply the direct effect on the industry that is import-dependent. Many other downstream and upstream industries rely on this effect for their output. It is therefore very important to get a complete understanding of the flows and connections in a vulnerable economy or one that has vulnerable industries.

2.4 Gaps in the Research

While there exists extensive research on trade disruptions and different applications of the IO framework to measure the direct and indirect effects of those disruptions; There is a lack of research that specifically explores this dependence on the relationship between the German economy and China's export of REEs. The analyses of imports from China are generally broad and look at larger economic areas, not focusing on particular points of high vulnerability to disruption. By focusing on specific countries and industries, the evaluation can become more valuable in the effort to alleviate the risk that is present. Further, by exploring the topic at this scale, the adjacent industries that may be vulnerable through indirect effects present themselves more apparent. This can help to direct efforts to protect the rest of the regional economy from strong spillover effects.

This research aims to fit into one of these more specific spaces. By focusing on the highly dependent sectors of the German economy it becomes easier to diagnose the vulnerable areas. Using IO analysis, and more specifically the Leontief inverse matrix, the complete indirect effect will be captured. This method provides a complete and more comprehensive understanding of the flows of goods through the German economy. Ultimately this study aims to perform a more narrow and focused analysis that explores one risky relationship in a greater system. This will provide a deeper understanding of the greater system and provide a more robust direction to inform future policy regarding resilience.

Chapter 3: Methodology

This research aims to reveal the greater effect throughout the German economy of a significant reduction in the availability and import of Rare Earth Elements (REE). Given these materials' nearly singular source, together with their role in the production process of significant industries; The import of REEs, if disrupted, will affect a critical portion of the German economy. It is, therefore, important to understand more clearly the effect that this disruption may have in order to effectively deploy resources and efforts to reinforce particularly vulnerable areas. Without this specific understanding, it becomes difficult for policymakers and businesses beyond those directly affected to protect themselves. The data for this analysis was taken from the University of Groningen World Input Output Table (WIOT) database. It includes an input-output table for the German economy, broken down by industry. This study uses the extracted data to perform an Input-Output (IO) analysis. The aim of the IO analysis is to model the interdependencies between sectors of the economy and understand the extended effects of specific disruptions to one part of the economy.

3.1 Input-Output Analysis Framework

Input-output analysis is a quantitative economic method that is designed to model and understand the industry interdependency in a chosen economic area. Developed by and named for Wassily Leontief, this analysis is the ideal tool to understand the complete system of connections in an economy. The results of an IO analysis are especially valuable in understanding the effects of changes in the economy. This research utilizes the methods to understand the complete effects that a reduction in the imports of rare metals will have on the German economy (Miller & Blair, 2009).

The IO analysis represents the chosen economy with a matrix, in which each row column pair represents the sectors or industries of the economy. The columns of the matrix represent the inputs required by each column's industry from each row's industry to achieve its final output. Conversely, the rows of the matrix show the output that each row's industry provides to each column's industry in the economy. Additionally, the values on the diagonal show the internal consumption of each industry, the output that one provides for itself (Miller & Blair, 2009).

A key element of the IO analysis framework is the input coefficient matrix (A). This matrix contains the input required from each industry to produce one unit of a given industry's output. The coefficients in this matrix show the direct dependency on the output of all other industries in the economy. It captures the intermediate inputs from each industry, as well as each industry's final output. This final output is captured in the IO framework as the sum of an industry's output to all other industries and its output to the final consumer. The combination of these two elements across all industries gives a complete view of the flow of economic activity through a chosen economy (Blair & Miller, 2009). Though the A matrix provides a complete understanding of direct dependencies between industries, it is not a complete understanding of the economic dependencies in the economy. To understand the indirect dependencies, the matrix is adjusted and inverted. This inversion allows the matrix to capture the direct and indirect dependencies in the economy by focusing on an increase in final demand. The total coefficients matrix, accounting for all rounds of exchange between industries, shows the increase in final output required from all industries to meet a one-unit increase in demand of a given industry. This inversion fully captures the ripple effects throughout the economy and provides a far more complete understanding of interdependencies that is critical for informed decision-making (Blair & Miller, 2009).

The benefit of the IO for this analysis is that it presents the economic flows between industries and regions in great detail. By using an IO table that includes many countries and that includes sectors with high uses of rare metals, it is possible to clearly understand the flows that affect the areas of interest for this analysis. An understanding of these relationships, along with the sensitivity of each sector to another, allows for the understanding of the effects of a significant reduction of a specific input (Miller & Blair, 2009).

To conduct this analysis, this research will construct a Leotief inverse (L) matrix, one of the key tools in the framework of the IO analysis. The L matrix contains the interdependence of industries of the economy, enabling the understanding of how an initial reduction of one factor in the economy will affect various other industries. This method allows for a complete and comprehensive understanding of the complete effect of an import reduction (Miller & Blair, 2009).

3.2 Analysis Method

As previously stated the primary tool under the umbrella of IO analysis used in this research is the Leontief inverse (L) matrix, also known as the total coefficients matrix. This matrix is constructed using the raw IO table collected and the R statistical and data visualization software. First, from the IO table, the unnecessary rows and columns are removed and the ones that are classified to the data are stored for later use. The data is converted to matrix form in R and the identity matrix is created (Miller & Blair, 2009).

The Identity matrix (I) is a matrix of the same dimensions as the IO matrix that contains 1s along the diagonal and 0s in the off-diagonal spaces of the matrix. The I matrix is an essential part of the L matrix's construction as it accounts for the sectors' self-sufficiency for the values in the final matrix.

The next step is to calculate the technical coefficients for each industry combination. The technical coefficient (a_{ij}) represents the amount of inputs bought from industry i by industry j, divided by the total production of industry j

$$a_{ij} = \frac{z_{ij}}{x_j} = \frac{Value\ of\ input\ to\ industry\ j\ from\ industry\ i}{Total\ value\ of\ industry\ output\ j}$$

This coefficient is simply interpreted to represent the value of inputs from industry i per the value of output of industry j (book). The technical coefficients for each combination are then used to create the technical coefficients matrix (A), a matrix of equal dimensions to matrix I and the original IO table. This matrix will be used to calculate the matrix that will be inverted to give the final output of the analysis, once corrected for self-sufficiency (Miller & Blair, 2009).

The next step of the analysis is to correct the matrix A by subtracting the matrix I.

$$First\ Order\ Effect = (I - A)$$

By subtraction the identity matrix from the technical coefficients matrix, the first-order dependencies of industry on each other are observable. This matrix includes the coefficients $-a_{ij}$ for all spaces on the off diagonal and the coefficient $a_{ij} - 1$ on the diagonal. This is done to see the true dependence of each industry on itself excluding the effect of self-sufficiency for each industry (Miller & Blair, 2009).

The next step of the analysis is to solve for the Leontief inverse (L) matrix by inverting the last matrix $(I - A)$. This yields the matrix:

$$L = (I - A)^{-1}$$

This matrix is also called the total requirements matrix, whether each value represents the total output required from a given sector for a single unit increase from another given sector. These values unlike those of the previous matrix $(I - A)$ capture both the direct and the indirect effects. The direct effects include the immediate requirements of each industry, as previously stated these are captured by the technical coefficient. However, importantly, the indirect effects that are captured by these new coefficients include implications along the supply chain, where the first industry requires input from the second, which in turn requires input from a third, and so on. The values of matrix L, capture the full scope of multilayered interdependencies in the economy of interest (Miller & Blair, 2009).

The final step of this analysis is to use the values of matrix L, in the framing of the restriction of interest. In this case, the industries that are most sensitive to the loss of rare metal imports in the German economy. With the inclusion of a significant number of countries economies and many of Germany's trading partners, it becomes very possible to extract an accurate sensitivity. This in turn can be used to assess the multilayered effects on the German economy of this loss of a critical input (Miller & Blair, 2009).

3.3 Data

The data for this analysis is an IO table that is a part of the World Input-Output Database (WOID) found on the Groningen Growth and Development Centre (GGDC) which is hosted by the website for the University of Groningen. This site offers a comprehensive and detailed data set that contains large sets of IO data. The original site of this data is no longer maintained and has been archived (University of Groningen, 2020).

WIOT data is perfect for an analysis such as this one as it is a highly detailed collection of resource flow through a large system of economies. The “world” scale of the data gives a more intricate insight into the dependence of industries than more narrow IO data. The data set contains flow data for 43 countries, each of which is divided into 56 industries which show their inputs and outputs to each industry in every country. The data spans in the same form from the year 2000 until 2014, this analysis takes only the data from 2014 in order to get as close to a modern perspective as possible. The data is in accordance with the 2008 System of National Accounts (SNA) and the International Standard Industrial Classification revision 4 (ISIC Rev. 4) is used in the division of each country's economy into 56 industries. This ensures that there is adequate comparability and coherence for ease of analysis (University of Groningen, 2020).

This database provides an intricate view of interactions not only within national economies but on a much larger scale. In an analysis, this will provide a more complete view of the cascading effects of different changes in any of the economies included. This type of dataset is ideal for the exploration of the effects of technological advancements, changes in national policy, and, in the case of this analysis, certain specific trade frictions (import reductions) (University of Groningen, 2020).

To increase the focus and relevance of the data several countries were removed, collapsing the IO matrix. The countries removed were Australia, Indonesia, Brazil, Canada, and Mexico. They were removed due to their distance and direct economic disconnection from the European economy. Their removal will help to enhance the accuracy of the results as it cuts extraneous data and can clear away noise from the analysis. The industry that represents the REEs produced in China is categorized as Mining and Quarrying. As the label states, this captures the mining and quarrying industry's activities in China. This captures the production of REEs, as they are collected through a mining process, it does however capture some other outputs. Although it doesn’t capture REE production alone it acts as a reasonable proxy for it.

Chapter 4: Results

This section presents the findings of the IO analysis and the values of the Leontief inverse analysis that help to understand the impact that the supply of REEs produced in China has on the German economy. The results are presented with three tools; descriptive statistics of the German industry coefficients, a histogram showing the spread of coefficients, and a graph showing the industries with greatest dependence. These three presentations are chosen to present a narrowing picture of the vulnerabilities in the German economy.

4.1 Descriptive Statists for Total Coefficients

Table 1 contains the descriptive statistics for the columns in the row of the total coefficients matrix that represent the German industry's dependence on the Chinese Mining and Quarry industry. The data in the table is in the unit of the total value coefficient, this value represents the increase in output of China's Mining and Quarry industry needed for a 1 unit increase in a given industry of another country. The coefficients that these statistics represent show the amount of output from

Chinese mining that is required for one unit increase of each of the 56 German industries. The mean value of 9,18 represents an average increase in demand for Chinese mining output of 9,18 units per one unit increase in the average German industry, this value is high but not troublingly so. However, the minimum of 0 suggests that some industries have no connection. Furthermore, the maximum value of 44,658 suggests that there is at least one industry that is extremely dependent on mining inputs for its production. The upper and lower quartile values and the median do suggest that the majority of industries have a lower dependence than the maximum values. This could mean the existence of outliers, making it easier to identify vulnerable areas.

Table 1 also contains the descriptive statistics that represent the average dependence of each industry among all EU countries on China's Mining and Quarry industry. The average dependence is lower than the dependence of Germany by a large margin. Particularly considering the maximum value, this value shows Germany has an industry that is far more dependent than the average. The column of differences shows that the German economy overall also has a greater dependence than the EU on average. This indicates that Germany is differentiated in its vulnerability.

	Germany	EU Average	Difference
Minimum	0	0	0
Lower Quartile	3,425	0,604	2,821
Median	5,922	1,021	4,901
Upper Quartile	14,355	2,035	12,32
Maximum	44,658	6,408	38,25
Mean	9,18	1,474	7,706

Table 1: Table 1 contains the descriptive statistics for the total output coefficients derived from the IO analysis. The statistics are divided into three columns, the first contains the statistics for only industries of Germany, the second contains the statistics for the average value of each industry among EU countries, and the third column contains the difference between the value of the first and third columns.

4.2 Histograms

Figure 1 is a histogram that shows the spread of industries' dependence in Germany over the range of total output coefficients. The figure shows that the data is skewed right with the majority of industries having a dependence near the mean value, with a few greater and one industry that deviates. This industry is nearer to the maximum value. The right skew is important to this analysis as it suggests the existence of specific weaknesses in the German economy due to this specific supply disruption.

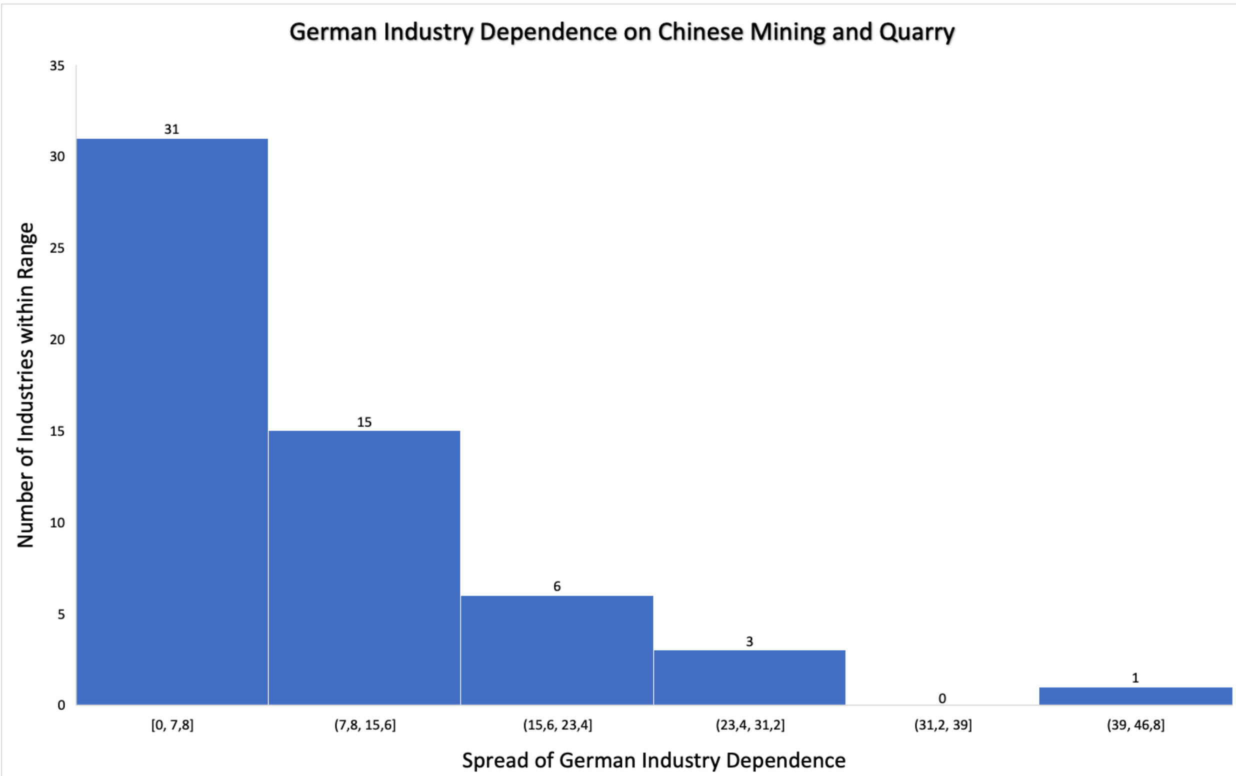

Figure 1: Figure 1 presents a histogram of the spread of total output coefficient values for industries in the German economy. The x-axis shows the ranges of coefficients and the y-axis shows the number of industries that are contained in the given range.

Figure 2 is a histogram that shows the spread of industries' average dependence among EU countries over the range of total output coefficients. The figure shows that the data is skewed right with the majority of industries having a dependence near the mean value, with a few greater and none that deviate as much as the Germany coefficient. The right skew of the histogram is significant as it shows the German economy is not different in all respects from the EU average. Although the range of values is far greater for the German economy, the first group of coefficients in Figure 1 has a range greater than the entire range of coefficients in Figure 2. Meaning that the German economy has a greater dependence on Chinese mining exports.

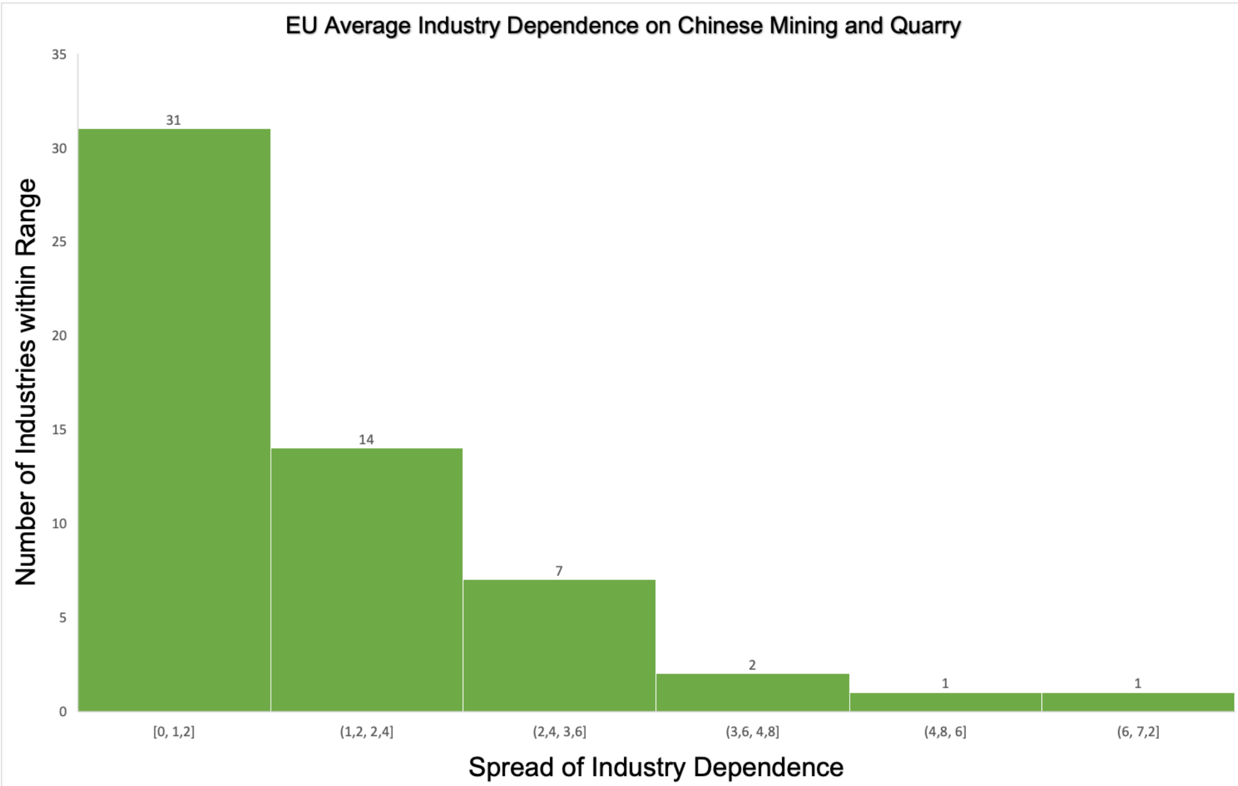

Figure 2: Figure 2 presents a histogram of the spread of total output coefficient values for the EU average of each industry. The x-axis shows the ranges of coefficients and the y-axis shows the number of industries that are contained in the given range.

4.3 Most Dependent Industries

Figure 3 displays the 10 industries, with the highest total output coefficient, in Germany with the greatest dependence on China's mining and quarry output. As well as the EU average dependency for the same 10 industries. The figure shows that, of the German industries analyzed, the manufacturing of motor vehicles, trailers, and semi-trailers stood out as the most dependent. With the text three industries clustered at about 25% lower than the first one, and the rest at about 50% lower. The motor vehicle manufacturing industry's sensitivity is particularly significant given the German economy's dependence on the export of motor vehicles. The output of this industry's significant contribution to Germany's GDP makes its dependence an important finding of this analysis. Some of the other industries on this graph seem to be ones that logically would not have a direct dependence on mining outputs. This indicates the existence of complex connections between industries, which is significant for informing strategies to address vulnerabilities in the economy. Figure 3 also shows that, when compared with the average, Germany has a far greater dependence on mining imports from China than other EU countries.

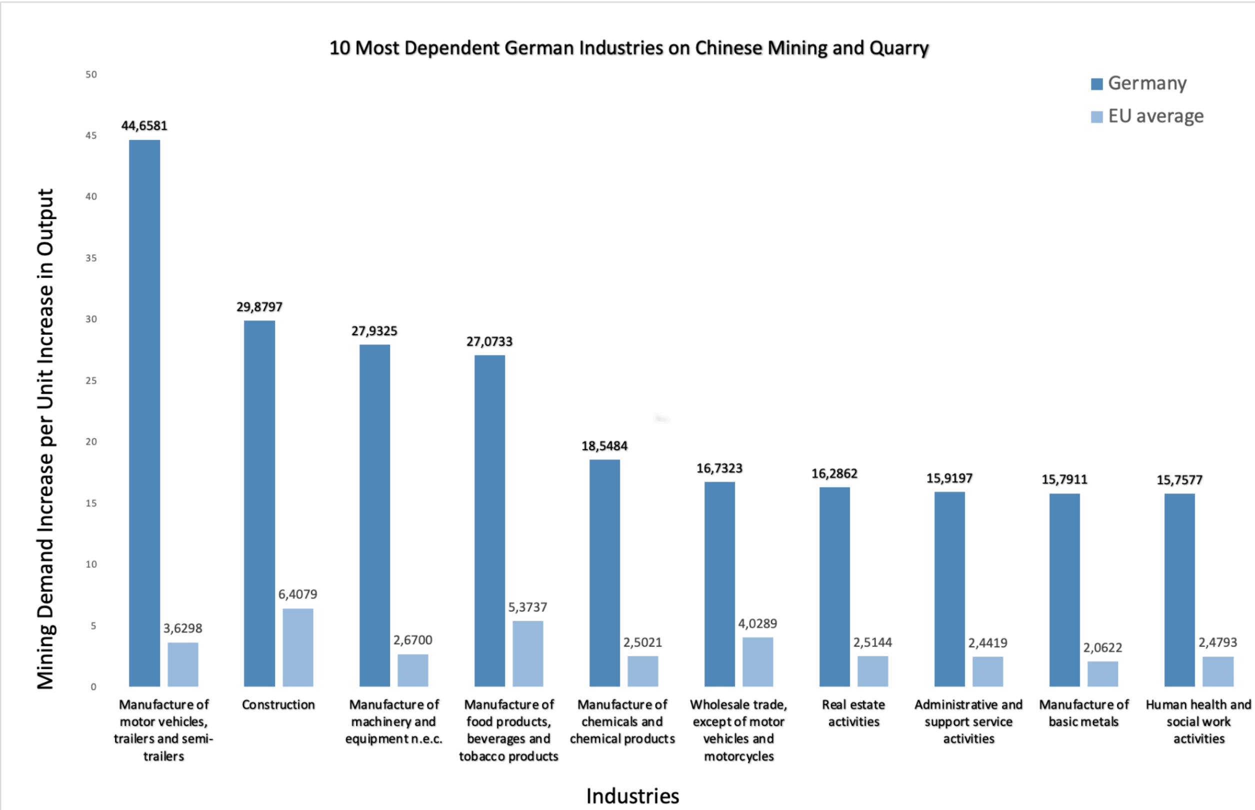

Figure 3: Figure 3 is a bar graph that shows the total output coefficient values for the ten industries with the greatest value for this coefficient, alongside the corresponding value for the EU average coefficient of each industry. The x-axis shows the industries and the y-axis shows the value of each industry's coefficient.

For comparison, figure 4 shows the 10 German industries with the greatest input coefficient, taken from matrix A. This value represents the direct input requirement from China’s mining industry to create one unit output of each German industry or the direct effect. Six of the ten industries appear on both graphs, and two of the top three are the same between the graphs. Although the manufacture of motor vehicles has a greater indirect than direct effect, this could be due to many intermediate inputs that go into the manufacturing process. It seems that Germany’s industries are largely affected by a direct dependence on China’s mining exports.

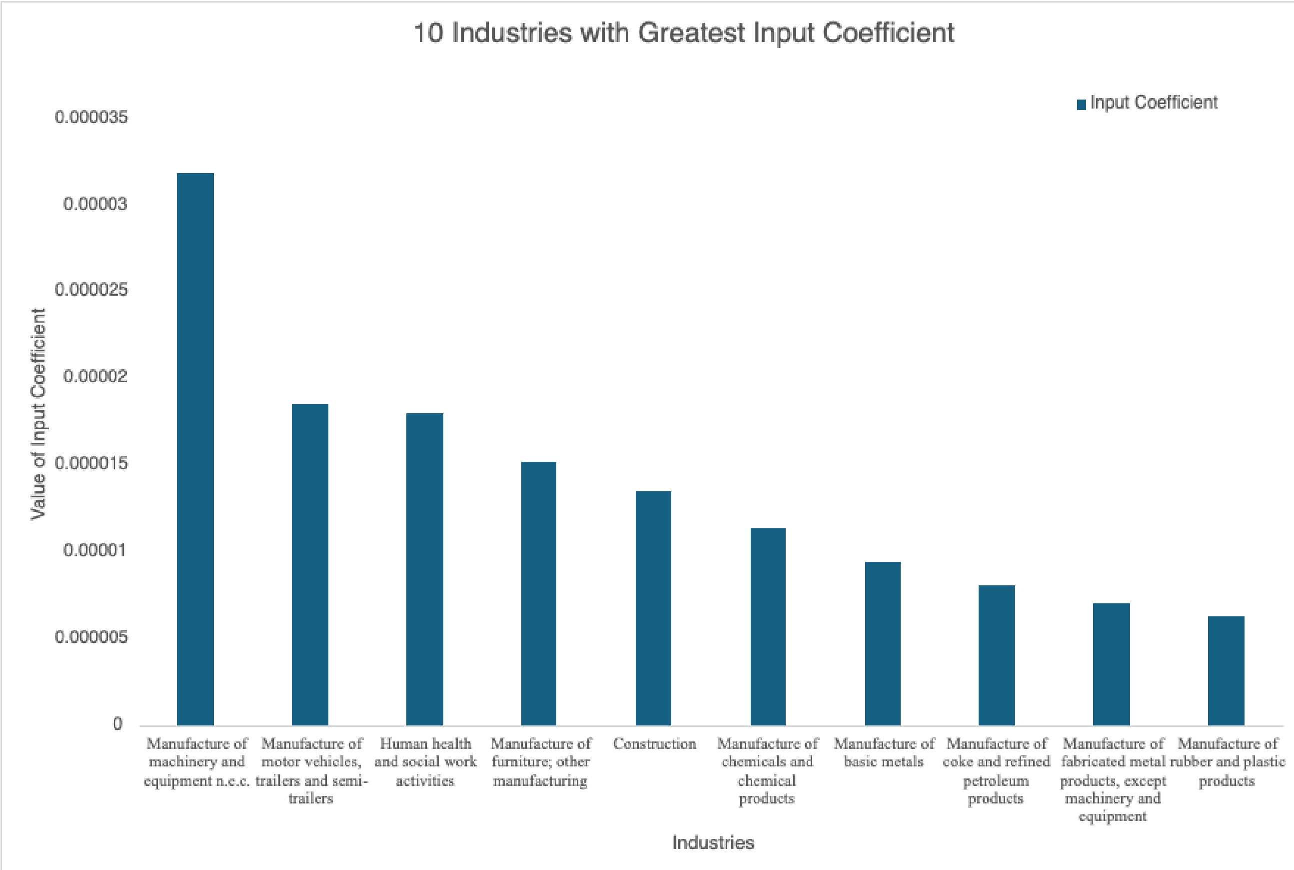

Figure 4: Figure 4 is a bar graph that shows the input coefficient values for the ten industries with the greatest value for this coefficient. The x-axis shows the industries and the y-axis shows the value of each industry's coefficient.

The results of this analysis show that the dependency of the German economy on China's mining industry has great variation. The significantly dependent industries that were identified point to a need for targeted policy and other measures to strengthen the resilience of the economy. As these sectors are important for export, growth, and economic stability it is particularly important to be swift and effective when addressing these weaknesses. Using these findings, policymakers have an empirical foundation to identify, strategically formulate, and implement changes that will effectively address these weaknesses.

Chapter 5: Discussion

This paper aimed to explore the German economy's dependence on rare earth elements imported from China. The results of the IO analysis highlight a few strategic weaknesses characterized by critical industries with high dependence. This shows a need for a comprehensive analysis and development of a strategy to strengthen the critical sectors of the economy. These strategies can include alternative sourcing, recycling programs, and stockpiling for immediate shortages.

5.1 Impact of Supply Disruption

The values of the Leontief inverse show that key industries in the German economy, like automotive manufacturing, are highly dependent on mining output imported from China. As previously stated, industries like this are critical for economic growth and stability, particularly when it comes to the transition to green energy as REEs are critical to electric car manufacturing, as well as the manufacture of many other types of vehicle manufacturing (Energy Systems Research Unit, 2017). The economy's exposure to geopolitical risk and supply volatility increases greatly with a critical industry's input dependence on a single country's output. The following will further explore this vulnerability and the potential effective strategies that can be implemented to remedy the weakness.

5.1 Alternative Sourcing of REEs

The single source dependency of the critical output is one of the most significant vulnerabilities to address. The logical first step is to explore alternative sources to spread the dependency and the risk. There are a few alternative sources that have the potential to replace a portion of Germany's dependence on China.

The first alternative source for serious consideration is deep-sea mining. Although still in the early stages of exploration, the ocean bed in some areas seems to be full of the REEs, among other critical minerals, that Germany depends on. This mining practice consists of scanning vehicles that use sonar to detect areas of the sea bed that are rich in small nodules of compacted polymetals, these nodules are small spheres that can range from the size of a golf ball to a tennis ball. Once the nodule-rich area is identified, a machine with a vacuum-like apparatus scrapes the sea floor, collects and separates the nodule, discharging silt collected with them back into the water. The current discussion around deep sea mining hails it as a part of the future of green energy and REE sourcing. However it isn't without its concerns, the primary of which is the environmental concerns. The current technology that is prepared for use in the collection of these nodules removes and returns large amounts of the sea floor. This is a problem because the areas that contain many nodules are often sites of high bioactivity. The sea floor that is removed is often returned at higher levels which creates clouds of silt that suffocate and disrupt many species (Ashford et. al., 2024). Despite this, there is already action from some mining companies to start mining. This shifts the issue to a moral problem. If Germany were to source these materials to progress green energy technology at the price of a small ecological disaster elsewhere, is it ethical? All things considered, seafloor mining is a promising alternative source for REEs however, a significant improvement is necessary to the technology to alleviate the environmental costs.

The other alternative method to source a part of the supply is electronic recycling. This solution is beneficial on two important fronts. First, it reduces the amount of overall electronic waste in the environment, much of which is very environmentally damaging. It is also a sustainable and economically viable source of REEs to help reduce dependence on imported REEs. This recycling entails the collection and processing of a growing amount of e-waste. This process will ultimately extract the REEs and other materials from the waste, minimizing its environmental impact and repurposing the raw materials. There are several different technical processes used during this process, though many still have technological issues that need to be addressed (Vuppaladadiyam et. al., 2024). Recycling initiatives within the country, contrary to deep sea mining, give the German government more control in the new sourcing process. The government can directly support the development of recycling programs through subsidies and regulations to assist the development productively. Although both of these alternative sources seem to be promising, both have a certain technological development threshold that they must pass before they become usable.

5.2 Political Measures

Given the critical nature of REEs to the German economy, the government must implement policies to support import stability. This effort will work in tandem while alternative sources are explored.

The first thing that German policymakers can do is to strengthen their connections and relationships with countries that are looking to increase their REE production. Aware of China's effective monopoly in REE, Canada is attempting to expand its mining operations to challenge the monopoly. Through survey and exploration, Canada has identified large reserves of minerals and REEs. Canada has found to have found 15.2 million tonnes of REEs that are not currently commercially mined, though it is in the process of developing the infrastructure to extract these materials (Natural Resources Canada, 2023). Australia would be another important partner in the alternative sourcing of REE. The Australian Government has announced that it will underwrite two projects aimed at extracting the key minerals. These two projects are specifically aimed at extracting and refining REE, for the explicit purpose of strengthening the supply chain. Australia is already the third-largest producer of REEs, the opening of these new projects will help Australia to take a chunk out of China's effective monopoly (Constable, 2024). If Germany were to take early action, even potentially invest in the project's success, it could help to guarantee a significant diversification in their sourcing of REEs. This diversification of their import source will take a lot of pressure off the relationship with Chinese imports. This measure would significantly lower the total output coefficient for Chinese mining of German industries and shift the weight of dependence onto other countries' exports. This would significantly alleviate the sensitivity of German industries to supply changes from China. A good first step is to address the vulnerability of German industries.

Two other measures that may have a positive supporting effect in the longer term are support for research and alternate materials for production, as well as regulatory frameworks and incentive programs. Investment in research into alternative production methods that are not dependent on REEs is another angle to reduce dependency on imports. One example of this research is the introduction of sodium batteries for electric vehicles (EVs). One of the largest factors driving the automotive industry's dependence on REEs is the fact that EV batteries are primarily Lithium-ion batteries. Lithium and other elements in the batteries' chemistry are among the elements that are imported from China. The recent development of Sodium-ion, a far more abundant element, batteries and their introduction to EV production will greatly reduce the German economy's import demands (Moztarzadeh, 2024). The switch to Sodium-ion batteries and other developments that reduce the use of REEs can also lower the demand for imports of these materials. These measures address the dependence problem from a different angle, reducing the domestic demand for REEs. These policies change the total output relationship in the opposite way to the previous measures. These policies reduce the final demand for the output that is reliant on REEs, thus reducing the exposure of the economy to the manufacturing process that has a high coefficient value. These policies would be particularly valuable to protect the manufacturing of motor vehicles (EV) and the manufacturing of machinery (turbines and other green technology) both of which are highly exposed as seen in figure 3 and 4. These policies are effective measures but will have the greatest effect when paired with the previously mentioned measures that approach the problem from a different angle.

5.3 Economic Theory and International Cooperation

A better understanding of the economic theory that drives supply chain resilience will contribute to the efficient implementation of strategies. These theories become one of the foundations of understanding the actions taken in the relationship between the suppliers and consumers of REEs. Beyond the basic theory of supply and demand, an application of game theory in tandem with an understanding of the political landscape will give a strong foundation to support the resilience of vulnerable parts of the supply chain. Another important concept to understand is the exposure of the German economy driven by commodity dependence. The high level of dependence that German industries, like machine and motor vehicle manufacturing, have on China's export of REEs leaves value-adding activities vulnerable to price and supply volatility (Van Cauwenberge et. al., 2021). Measures to diversify this singular commodity dependence would help to protect the important industries in the economy.

The theory of hypothetical extraction also provides important insight into the vulnerability of the German economy. The theory allows for an understanding of the effect on the greater economy upon the hypothetical removal of one industry (Los et. al., 2016). Germany's strongest and most important industries are those centered around high-tech manufacturing. Various manufacturing industries are significant parts of Germany's economy (United Nations Industrial Development Organization, 2024). Several of these industries have high input and total output coefficients, as seen in Figures 3 and 4. If these industries were to be hypothetically removed from the economy, which could simulate a supply crisis, there would be a large effect on the economic health of the economy overall. Diversifying the singular supply dependence would help to mitigate the effects of a supply crisis, protecting the economy and reducing exposure.

With these theories in mind, cooperation, and coalitions become powerful tools to restructure dependence in supply-demand relationships. Countries, such as Canada and Australia, are making efforts to establish new sources of supply for REE to loosen China's grip on the market. If countries that experienced risk from their dependence on China's exports of REEs collaborated, the combined effort would be far more efficient at reducing China's control and mitigating their own risk. The exposure that Germany experiences from its commodity dependence on China would be drastically reduced by this diversification of supply. This would take a great deal of political and economic cooperation but it is feasible given the high level of mutual gain from the endeavor.

5.4 Broader Implications and Future Research

The critical nature of REEs for the global transition to green energy makes the resilience of their global supply particularly important to secure. It expands the issue beyond one of just economic security but one of meeting global targets to reduce the effects of climate change. Future research could expand more in this direction, focusing on building a model to better project the effects of different scenarios on the development of the green energy transition. This would help to isolate the effect of one of the most important functions of REEs, better-informing policy and strategy that aims to support the transition.

5.5 Conclusion

This discussion gathered the results of the IO analysis, connecting them to the broader geo-political and economic context. Addressing the vulnerabilities of the German economy in this trade relationship and proposing actionable plans to elevate the risk related to the disruption of REE supply. By approaching the issue from multiple perspectives: Diversifying the sourcing of REEs through deep sea mining and advancing electronic recycling programs. Taking political action by establishing strong trade relationships and investing in emergency short-term reserves. These strategies could be supported by changes in the materials used for production. By implementing this diverse collection of strategies, Germany could create a comprehensive plan to make certain they have a strong and resilient supply of these critical REEs.

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