The University of Chicago

Mining for Influence

The European Union's Geopolitical Strategy in Critical Raw Materials

Divya Rajesh

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Faculty Advisor: Roger Myerson
Preceptor: Kara Hooser

Abstract

The relationship between the European Union (EU) and the United States (US) has long focused on issues vital to both parties' national, economic, military, and energy security. However, US officials have frequently accused the EU of free-riding on American efforts and investments to address these challenges. Today, as both parties face growing security threats due to their critical mineral supply chain vulnerabilities, the question at hand is how the EU will approach this new challenge. By using a Markov decision process, this paper argues that, for the most part, the EU will choose to free-ride off US investments but that US punishment mechanisms are an effective mechanism to prevent such defection.

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Introduction

In 1987, while visiting one of China's largest deposits of rare earth elements in Inner Mongolia, President Deng Xiaoping famously claimed that "The Middle East has oil, China has rare earths" (Johnston, Hancock, and Dempsey 2023). The quote demonstrates the remarkable foresight of Deng Xiaoping and China in understanding the enormous potential for rare earth elements (REEs), a group of seventeen metallic elements, to shape the economic, technological, geopolitical, and environmental dynamics of our global systems (Johnston, Hancock, and Dempsey 2023). Deng's statement was not just empty words but reflected a dramatic shift in China's industrial policy. The seventh National Five-Year Plan for Rare Earth Industry in 1986, made their research and production a national priority while China designated REEs as a "protected and strategic mineral" in 1990 (Nakano 2021; Tse 2011). Under these initiatives, the government set production quotas to scale up China's mining and processing capabilities, rolled out investment policies to attract and heavily control foreign capital and technology, and led research and development efforts to advance the sector (Nakano 2021; Tse 2011). In 1990, China accounted for under a third of the world's production of REEs; by 2008, they had practically established a monopoly, responsible 90% of the world's production (Nakano 2021; Keane 2018). Today, while this dominance has declined slightly, China still processes over 90% REEs, with the rest of the world still trying to catch up (Johnston, Hancock, and Dempsey 2023).

This story is not unique to REEs: China's foresight and early action have allowed them to dominate the supply chain across a range of minerals, such as lithium and cobalt, far before the rest of the world understood and appreciated the crucial role they would play. Today, a broad spectrum of industries depend heavily on these minerals: REEs are crucial for missile and intelligence systems; and lithihum, cobalt, and nickel are necessary for electric vehicle batteries and renewable energy technologies; while minerals are vital to many digital technologies including semiconductors and hard-drives (Keane 2018; Ufimtseva, Li, and Shapiro 2024; Theodosopoulos 2020). The demand for these minerals have increased rapidly over the past decade, and for the most part this is due to their role in the energy transition. For instance, in a 2021 report, the International Energy Agency found that the average quantity of minerals required for each additional unit of power generation has gone up by 50% (International Energy Agency 2022). Thus, these minerals have become hugely important for the economic, social, and environmental well-being of countries, resulting in strategies to secure their access being increasingly expressed through the language and framework of security. Along these lines, policymakers have begun grouping these minerals they consider important under the titles of critical minerals or critical raw materials (CRW). This paper explores the security implications of China's critical mineral dominance on the foreign and economic policy of the US and EU.

The criteria for what exactly defines a critical mineral is determined individually by each government and thus differs across countries. However, most frameworks classify minerals as critical if they are of high economic importance, face high supply risk, are vulnerable to political shocks, and have few substitutes (Coulomb et al. 2015; Shiquan and Deyi 2022). Consequently, there is significant overlap across lists, with minerals like lithium, cobalt, REEs, and graphite appearing on most if not all lists. The prospect of securing access to critical minerals, however, is not a straightforward task. Long-term industrial planning through state-led investment into domestic mining and processing facilities as well as investment from state-owned companies in mining projects abroad have ensured that China has dominates all parts of the supply chain (Johnston, Hancock, and Dempsey 2023; Majkut et al. 2023). Today, estimates suggest that China produces between 50-90% of the world's critical minerals (Ufimtseva, Li, and Shapiro 2024).

This dominance poses several challenges for the rest of the world. Firstly, it creates significant supply risks because any disruptions of mineral production and exports, be it intentional or otherwise, severely threatens the ability of most other countries to access critical minerals. For instance, the European Union (EU) and US import over 50% and 62% of their critical minerals from China respectively (Ufimtseva, Li, and Shapiro 2024; Theodosopoulos 2020). Several US and EU leaders have expressed concern over this dependence and have identified establishing an alternative supply chain, one in which China does not plays a dominant role, as a priority (Theodosopoulos 2020; Vivoda 2023). However, this too is a challenge. China's dominance have allowed it to develop the technology, technical know-how, and economies of scale to mine and process minerals at a lower cost than much of the rest of the world will be able to do and thus, any attempt to compete with Chinese firms will take a long time, require significant investment, and rely heavily on government support (Johnston, Hancock, and Dempsey 2023). With this in mind, the US, EU, and its allies, have adopted a strategy of ally- or friend-shoring which, in this context, can be understood as ensuring that this alternative supply chain goes through only countries with whom the US and EU are allied with (Vivoda 2023). This strategy attempts to accelerate the development of critical mineral production capacity outside China by spreading the costs and risks of investment across countries while allowing governments to pool their resources together, thus increasing investment, facilitating knowledge sharing, and increasing access to mineral deposits (Vivoda 2023).

While this approach is implicit in the several bilateral agreements between the US, EU, and its allies on joint investment in critical minerals infrastructure, the first evidence of the institutionalization of this strategy took place in 2022, with the creation of the Mineral Security Partnership (MSP) (Vivoda 2023). The MSP was formed by the US as a way to develop a "diverse and sustainable critical minerals supply chain" (United States Department of State 2022). As part of the MSP, member governments work together to identify and support critical mineral projects across the world by providing financial or diplomatic support among others (United States Department of State 2022). While the partnership promises to "accelerate" the creation of new supply chains, the capacity of the partnership to actually achieve this goal is questionable (United States Department of State 2022; Vivoda 2023). Importantly, the MSP is not a fund with a supply of capital dedicated to critical mineral infrastructure investments and does not have a mechanism to ensure that member countries are actively investing in such projects (Majkut et al. 2023). Thus, the onus is on the countries themselves to set and achieve investment targets. This opens up the possibility that countries may rely on partner nations to invest instead of investing in these projects themselves. This concern is reflective of a broader risk with the strategy of friend-shoring, where membership in the friend-shoring alliance means nations can benefit from an alternative supply chain through trade without necessarily participating and investing in its creation. This strategy is known as free-riding (Olson and Zeckhauser 1966; Buchholz and Sandler 2016). Indeed, such concerns have been at the forefront of many international partnerships including EU-US relations within the North Atlantic Treaty Organization (NATO) and global efforts to combat climate change (Wilkie 2018; Parker and Karlsson 2016). I am interested in investigating whether efforts to establish an alternative critical mineral supply chain face similar risks from the perspective of the EU. Thus, my thesis aims to answer the question:

What is the European Union's Optimal Geopolitical and Investment Strategy in the Creation of an Alternative Critical Minerals Supply Chain?

To answer this question, I use a Markov decision process (MDP) model to determine the EU's optimal strategy. Central to my paper is the argument that their dependency on China makes critical minerals a security concern for the EU and US because this framing influences the stakes of the issue and therefore the types of policy tools that both parties are willing to adopt to achieve their goals Therefore, I begin my paper with a definition and defence of this argument. I then situate critical minerals and the friend-shoring strategy within the existing literature on burden-sharing and free riding in international relations to demonstrate there is significant potential for the EU to free-ride on US investments. In this section, I also identify five key factors that I believe will determine the EU's optimal strategy. I end with the implementation of the MDP and an analysis of my results. Ultimately, I conclude that the EU will choose to free-ride off US investments but that US punishment mechanisms are an effective mechanism to prevent such defection.

Scholars have long studied the relationship between the US and EU across various dimensions, including climate and environmental policy, and my work contributes to this field by focusing on critical mineral investments. This focus reflects recent changes in government priorities and awareness of the importance of critical minerals, and thus, when placed in conversation with the work of others, can help shed light on how the growing importance of critical minerals impacts this relationship. In light of recent global events like China's imposition of controls on the export of REES in April and the signing of a critical minerals deal between the US and Ukraine, the need for research to understand how critical minerals will shape international relationships, trade policy, and foreign policy is now more relevant than ever (Kullab 2025; Butts 2025). This paper thus seeks to contribute to filling this gap in the literature.

Critical Minerals and Security

The idea of critical raw materials as a security issue is not a new one. Raw materials have always played an integral role in the global economy, responsible for energy production, manufacturing, transportation, and technological development and so the drive to secure access to these materials have long been linked to a nation's economic, defence, technological, and energy sovereignty (Theodosopoulos 2020; Colgan 2020). Historically, this concern has revolved around attempts to secure access to fossil fuels, primarily oil, but the drive towards decarbonisation and the growing role of digital technologies have forced scholars and policy-makers to redefine and expand their definitions critical materials to incorporate the new raw materials and technologies necessary for these sectors (Proskuryakova 2018). These transitions have led to the development of critical minerals, such as lithium and cobalt, as a new and separate issue of security.

Although existing literature on oil as a security issue offers valuable insights and analytical frameworks for examining critical minerals, key differences between fossil fuels and critical minerals make it necessary to approach the security of critical minerals as a distinct topic. Most crucially, the position of China as a monopolist in the production of the critical minerals is one that we don't see with oil, where instead several countries control the oil fields. China's dominance gives them a much greater degree of control over the market for critical minerals while depriving other nations uninhibited access to those resources. This serves as a major source of what Morgenthau calls national power (1948, p. 73). This refers to the ability of a country to use their resources and strengths to influence the actions of another nation for their benefit. Therefore, the lack of availability of critical minerals within the US and EU can be considered a source of relative weakness for both entities because their access to critical minerals depends entirely on China (Morgenthau 1948, p. 82). Controls by China on the trade and availability of critical minerals thus directly threaten US and EU access to these minerals and can, and have in the past, be employed as a leverage in negotiations or a tool for retaliation (Ufimtseva, Li, and Shapiro 2024). This can impact the US and EU directly through export bans, which make it more difficult for them to import the minerals directly, and indirectly because China's market share allows it to control global mineral prices and influence the global development of downstream industries that use critical minerals by setting the terms of export and trade (Ufimtseva, Li, and Shapiro 2024).

Formalising Critical Minerals as a Security Issue

Drawing on the work of Arnold Wolfers (1962), Hans Günter Brauch highlights how traditional theorists break down the idea of security into two parts (2008). The first is an objective sense of security, which refers to the extent to which something is a threat or vulnerability to various functions or sectors in a state, such as its economy or military capabilities. The second part is a subjective sense of security, which refers to perception amongst government officials, the media etc. that something poses a threat to a country. We can map this construction of security to the case of critical minerals as follows. China's dominance in critical minerals can be considered a security issue in the objective sense for the US and EU, in times when measures like export or price controls are implemented by the Chinese government. Their dominance can also be considered a security issue in the subjective sense because even when none of these measures are implemented, the ability of China to weaponize their dominance in this way has been perceived and framed by US and EU government officials as something that poses a threat to their respective countries. Indeed, we see this in the way these minerals are classified as critical but also in statements from government officials and various reports from the White House and EU Commission that frame China as an adversary upon which they are overly and dangerously reliant on (Ufimtseva, Li, and Shapiro 2024).

We can further develop this idea by exploring how critical minerals link to narrower and more specific concepts of security. Securing access to critical minerals have been discussed by scholars as relating closely to a state's national and economic security. Along the dimension of national security, the reliance on critical minerals for the manufacturing of defence technologies and goods necessary for the functioning and success of the US economy makes the US vulnerable to diplomatic and military threats from China. Indeed, the threat of being denied access to critical minerals can limit and constrain the ability of the US to push through and promote its agenda on the global stage by deterring the US from pursuing policies that China disagrees with (Morgenthau 1948, p. 84). Moreover, this reliance means that policies to restrict US access to critical minerals can weaken the US' military capacity, its economy, and its ability to foster technological development, thus threatening the US' self-adopted position as a global leader (Shiquan and Deyi 2022). We see this clearly in the context of China's recent imposition of export controls on REEs, where the US lacks the infrastructure and stockpiles to fill the supply disruptions created by the controls (Butts 2025). Thus, supply vulnerabilities in REEs have direct implications for US military readiness and their ability to develop and upgrade its military technologies (Butts 2025). Moreover, the high economic importance and low substitutability of critical minerals means that China's critical minerals policy has direct implications on the US and EU economy and its determinants including the growth of industry, cost of living, employment opportunities, availability of transportation, and access to energy. In other words, critical minerals are quickly becoming the backbone of the modern economy. Thus, reliance on China for critical minerals has been framed by scholars as threatening the economic sovereignty of the EU and US (Theodosopoulos 2020, p. 1).

Finally, it is worth discussing the issue of reliance on China for critical minerals as an energy security issue for the US and EU. The framing of energy security has significant overlap with the ideas of national and economic security because access to energy and electricity forms the backbone of the global economy and trade today. Thus, threats to the supply of energy also threaten the functioning of nations, the quality of life of its residents, and its sovereignty thus creating national and economic security threats (Shiquan and Deyi 2022; Brauch 2008). However, adopting a framework of energy security allows us to apply and bring in existing literature to better understand what it means secure access to critical minerals. Scholars have traditionally framed energy security around four key aspects: availability, accessibility, affordability, and acceptability (Cherp and Jewell 2014). On the other hand, international organizations like the IEA have often focused much more closely on the idea of energy availability and affordability (Cherp and Jewell 2014). Thus, from the perspective of the EU and the US, the drive to secure access to critical minerals can be understood as a drive to ensure that industries within both nations can ensure a reliable supply of critical minerals for its industry, where supply chain disruptions are limited and access to critical minerals can be maintained at low prices. To domesticate energy production and reduce reliance on fossil fuel imports for energy, countries are increasingly turning to renewable energy to ensure that energy is available and accessible with limited scope for disruption (Kuzemko et al. 2022). With critical minerals crucial to renewable energy development, the focus of energy security thus turns to securing the critical mineral supply chain. This largely echoes the way ensuring oil security has been discussed by policymakers and scholars (Colgan 2020). Thus, net importers of an energy source – be it oil or critical minerals – have often made it a government priority to minimize vulnerabilities in the supply and cost of these resources and, in the case of oil, have justified and motivated economic and military interventions to ensure that producers of those resources are unable to leverage their control over resource markets to pursue other aims (Colgan 2020).

Across all three frameworks that relate critical minerals to security, the vulnerabilities and threats to each conception of security all stem from the fact that China, who they view as an adversary, has almost monopoly power in influencing the availability and price of critical minerals. Thus, the EU and US governments have identified the solution to this problem as creating alternative supply chains that allow them to diversify their supply away from China. Doing so would reduce China's market power and therefore overcome those vulnerabilities. At the same time, this security framing suggests that the US considers critical minerals to be an issue of elevated importance, and thus may be more willing to take more drastic actions to ensure the creation of an alternative critical minerals supply chain, such as economic sanctions.

A Case Against a Broader Definition of Security

Several other strands of the literature, broadly grouped under critical theory, frame the issue of security and critical minerals differently. Here, scholars have pushed back against accepted definitions of security, suggesting instead that the phrase means different things for different people and across different facets of energy and so should be defined contextually (Brauch 2008). This thesis, however, adopts the narrower conception of security espoused by traditional security theorists. I justify this choice because the traditional notion better reflects the way the EU government defines security for itself. For instance, despite the mining industry and EU government often emphasising the importance of minimising the environmental and social damage that can be caused by mines, analysis of European mining activities has shown that this message is not reflected in practice (Hoxha, Symochko, and Pinheiro 2024). Thus broader notions of security, such as the environmental security and the social security of communities living close to mines, does not fall within the EU government's definition of security.

Burden Sharing in International Alliances

The attempt to create an alternative supply chain requires the nations participating in and benefiting from this project to contribute invest significant capital into building critical minerals infrastructure. However, this asks questions about the willingness of nations to invest in these expensive projects, when they can instead just trade with those who do.

The study of burden-sharing and free-riding in international alliances has long been a topic of interest to scholars. The literature defines free-riding as a process by which nations are able to benefit from consuming a common good without contributing to the costs of providing it (Olson and Zeckhauser 1966; Buchholz and Sandler 2016). The success of this strategy stems from two key factors. Firstly, common goods are defined as such because they are accessible by all members of the agreement and thus the benefits of investment by one actor are felt by all members (Olson and Zeckhauser 1966, p. 267). Secondly, common goods are often characterised by a large disparity between the cost and benefits of investment, whereby the collective gain of such an investment is high but the benefit for each individual actor is much lower and can be outweighed by the high cost of investment (p. 268). Thus, actors have an incentive to invest much less than what is optimal for the group (p. 278) In other words, they are able to free-ride of the investments of others because they benefit differently from the common good: those that benefit more are more willing to invest in the common good to benefit themselves, and so everyone else in the partnership are able to also benefit without the cost of investment (Buchholz and Sandler 2016).

This theory can be used to explain free-riding within the critical mineral investments. With the alternative supply chain developed in response to China's critical mineral supply chain dominance, the US, benefits hugely from this new supply chains, by virtue of its extremely strong stance in opposition to China. Thus, with the US expected to be at the forefront of critical mineral investments, there is potential for its allies to invest minimally in critical mineral infrastructure and instead free-ride off US investments by trading closely with the US and the nations in which the US invests. Thus, they are able to diversify their critical mineral supply chain and reduce reliance on China without the cost of investment. However, the decision to free-ride comes with the potential of backlash, as actors that invest more threaten to deny other nations access to the common good withdraw from the agreements thereby (Brandt, Hauert, and Sigmund 2003). Indeed, the recent negotiations surrounding the burden-sharing of defence spending in NATO clearly exemplifies the backlash the EU could face should it be accused of freeriding from the US (Wilkie 2018).

Key Factors Influencing the EU Strategy

Thus, the EU's decision on whether or not to free-ride ultimately depends on the benefits it derives from critical mineral investments, the costs of the investments, and the extent to which access to the minerals can be hindered. I identify five key factors that could influence EU strategy.

1. Changing priorities on hard security issues
2. Ideological considerations
3. Structural Issues
4. EU's relationship with China
5. EU's relationship with the US

Changing Priorities on Hard Security Issues

The war in Ukraine highlighted the EU's reliance on imports of natural gas from Russia for their energy. Despite discussions to boycott the use of Russian gas, the EU has yet to sanction its use and continues its import (Kuzemko et al. 2022). Additionally, the war greatly increased the already high energy prices in Europe, contributing to a cost of living and energy crisis far greater than what has been experienced in the US (Evans 2024; Kuzemko et al. 2022). The response of the EU has thus been focused on reducing its dependency on Russian gas by investing heavily in renewables (Kuzemko et al. 2022). With Russia the more immediate threat to the EU, questions remain whether the EU would also choose to reduce its dependency on China at the same time. Indeed, this trade-off is important to consider because of the constrains on EU's financial resources and the importance of the government incentives to encourage greater innovation and production within the downstream sectors of the renewable energy supply chain (Kuzemko et al. 2022).

Ideological Considerations

Secondly, recent results in EU elections showed the growing popularity of right-wing, populist parties at the expense of several more left-leaning parties including the Greens (Evans 2024). Of particular note is in the increased conservatism in the German and French governments who, as two of the largest EU members, play a significant role in funding EU investment and influencing its priorities (Evans 2024). The declining popularity of the Green parties foreshadows weakening ambitions in EU's climate policy, particularly as other issues take priority (Wong 2024). Moreover, the rise of conservative governments reflect a shift in the way energy security is discussed and prioritised, with energy security now being understood as domesticating greater parts of the energy supply chain through protectionism instead of investing in mining projects across the world, as an alternative supply chain would require (Coulomb et al. 2015).

Structural Issues

Critical mineral investments also face significant structural issues due to the long lead times and high uncertainty associated with these investments. On average, mines take 16 years from the decision to invest in the mine to the first production of minerals. However, newer estimates suggest that in recent times mine lead times are increasing to 18 years due to increasing mineral demand and longer permitting processes (Manalo 2024). Combined with high upfront costs, the long lead times reduce the incentives for firms to invest and governments to encourage such invest. Additionally, mineral deposits are often located in countries impacted by non-market forces including higher rates of corruption, violence, and alignment with China, which increases the uncertainty over the success of the projects (Coulomb et al. 2015). However, it may be because of these same features that the EU government views critical mineral investments as a priority, because of the necessity of investing in minerals now to benefit from their access 16 years later.

EU's Relationship with China

Fourthly, the EU has sometimes benefitted from growing tensions between the US and China. For instance, during the US-China trade war, Chinese firms redirected their exports to the EU markets, of which France and Germany are the most likely to benefit (Goulard 2020; C. Brown 2024). This reflects the broader geopolitical relations with between the three nations regarding foreign investments by Chinese state-owned companies with the US taking a much stronger anti-China stance compared to EU nations, some of which have accepted Chinese investment under the Belt and Road Initiative (Goulard 2020).

EU's Relationship with the US

Lastly, despite several alliances and a common understanding of the threat that China's CRM dominance poses, the US and EU are not unified in their energy security strategy. Aside from CRM policy, energy security policy has largely emerged as protectionism, with the Inflation Reduction Act and the EU Green Deal having significant provisions and stipulations that technologies be manufactured domestically (Smith 2023). The EU thus views US energy policy as an America first strategy highlighting the gulf between the nations and opening the possibility that any alternative supply chain created by the US will be created with the same US first ideology (Goulard 2020).

Methodology

Scholars have long used decision-theory to model behaviour within formal and informal alliances. I follow this line of work by applying decision theory to model a relatively new focus of EU-US relations in critical minerals. Following the rationale of Zhu (2022, I treat the EU as a single player because it exists as an actor in its own right in most critical mineral treaties and joint-investment agreements. Furthermore, it often speaks on behalf of its members on matters of trade policy and in diplomatic negotiations (European Commission 2024). Crucially, the EU has its own budget and therefore has the capacity to allocate spending to critical mineral infrastructure (European Commission 2024). Thus, it is reasonable to focus on the EU when analysing investment strategies. While individual European countries may have differing critical mineral policies, incorporating these differences would greatly increase the complexity of the decision model beyond the scope that the length of this thesis affords by introducing many new parameters, considerations, and priorities. Further research on this topic can look into the heterogeneity between EU nations and in relation to the European Commission and investigate how this impacts the development of a cohesive European strategy as well as relations with the US.

Model Overview

To solve the decision theoretic problem, I use a Markov Decision Process (MDP) model to model the actions and behaviour of the EU. MDP models are used to determine how an actor maximises their long-term utility when making a sequence of decisions (Chen et al. 2014). At every step in the process t, the actor chooses their decision from the set of actions available to them, $a \in A$, which moves them from their current state s to a new state, s' (Chen et al. 2014). In a MDP, the outcome of the action is probabilistic and uncertain, which means that the actor could move to one of several potential states s' within the same initial conditions (Chen et al. 2014). The probability that a specific s' is chosen depends on the current state, s, and the chosen action, a and is known as the stationary transition probability (Chen et al. 2014). My model uses a first-order MDP, and so the EU's history doesn't affect the stationary transition probabilities, only their current state s and choice of action in that state, a is relevant.

The decision theory model adopted in this paper is an adapted version of the two-stage repeated public goods game where the strategy of the US is already specified. Within the traditional construction of the game, each player is given a certain endowment to invest towards a communal fund from which they all benefit (Brandt, Hauert, and Sigmund 2003). Each player chooses how much of their endowment to invest and does so without telling other players of their choice (Brandt, Hauert, and Sigmund 2003). This allows players to benefit from the investment of others without contributing themselves (Brandt, Hauert, and Sigmund 2003). In other words, they can free-ride. My player of interest is the EU, who chooses how much to invest in developing critical mineral infrastructure projects domestically and abroad across both mineral mining and processing. I then follow the structure from Brandt, Hauert, and Sigmund (2003) and Podder, Righi, and Pancotto (2021) to allow the US to respond to the EU's action in the second step of the game by punishing free-riding. I justify the use of a two-stage game because there is a time lag between the EU's decision and the US' response, with the US choosing their course of action after witnessing the EU's decision. Furthermore, this construction preserves my assumption that players are acting with perfect information. I justify this assumption for several reasons. Firstly, serious and successful attempts by European firms to invest in critical mineral projects with the EU and outside it are almost always made public. Thus, the US has complete information about the EU's efforts in investing in critical mineral infrastructure when deciding their action. Secondly, through interacting with the US across several dimensions of international relations, the EU can accumulate information about the US' strategy towards them. Therefore, it can be assumed that the EU will have an accurate idea of the US' response to their actions and the scope for punishment.

The decision model is visually represented in the figure below.

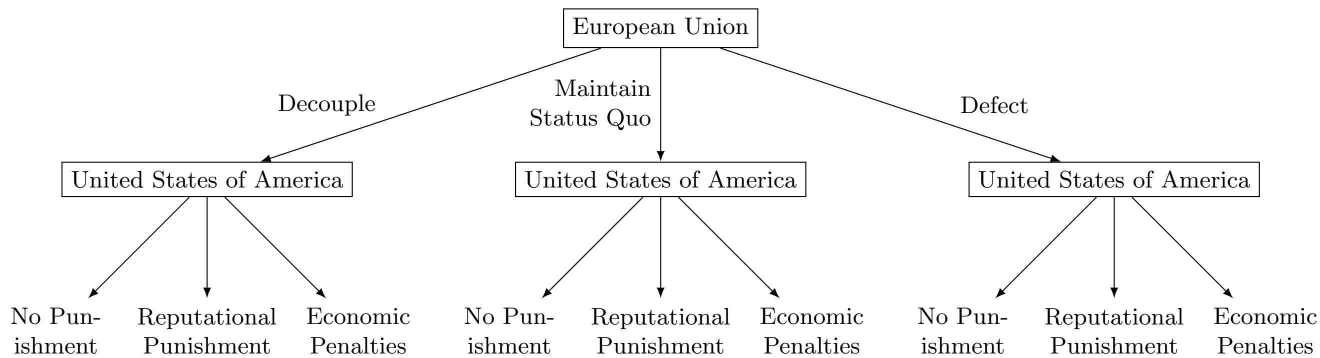

Figure 1: Visual Representation of the Decision Model

I choose this method even though several other studies use a game theoretic model instead. In my MDP model, I assume the strategy of the US to be pre-determined and static and then analyse the strategy of the EU. I don't look at how the EU's strategy could impact the US' strategy. A game theory model would require me to also analyse how the EU's strategy impacts the US and find what its best strategy is to respond to the EU. This approach is much more dynamic and likely more representative of decision-making in the real-world. However, following a MDP approach allows me to analyse how the EU's optimal strategy changes when domestic priorities and the strength of its relationship with the US changes. Through this method, I can compare across several strategies to tease out how the payoff structure and the EU's priorities influence their strategy. These comparisons are particularly insightful given that geopolitical decision-making depends crucially on context, including the norms that are shared by participants, competing interests, and perceptions of what the future looks like (Axelord and Keohane 1985, p. 232, 238).

My choice of model also adds to existing literature because it builds on more classical applications of the public goods model. This departure occurs on two fronts. Firstly, I take inspiration from Podder, Righi, and Pancotto (2021) in including a reputational scorecard which allows for actions to have reputational costs that are still relevant and punishable far into the future. This is often not included in classical public goods games, where these types of reputational impacts are considered only in the current and subsequent time period (Podder, Righi, and Pancotto 2021). Secondly, critical mineral investments present a different type of excludability problem to the traditional free rider problem. In widely studied interactions on security issues, the geographical characteristics of the EU and their shared perspective and goals of global geopolitical relations are important factors that drive US cooperation with the EU on those fronts. For instance, the EU's proximity to Russia and their mutual suspicion of first the USSR and then Russia greatly encouraged US involvement in NATO (Office of the Historian, Foreign Service Institute 2016). However, the EU has few deposits of critical minerals and so, unlike in the case of defense spending in NATO, it does not necessarily have the same leverage upon which it can free ride. As a result, the costs to the US of punishing the EU may be lower in previously studied cases of the free-rider problem and so the conclusions from this paper may differ from previous studies of similar topics (Brandt, Hauert, and Sigmund 2003).

Defining the Set of Actions

The EU's investments are likely officially pursued under one of several agreements between the EU and US and its allies, or as part of a domestic policy initiative that closely relates to these international agreements. However, all such investments are important to consider because they contribute to the creating of an alternative critical minerals supply chain. Furthermore, while the level of investment that the EU chooses to make is of course a continuous variable, I have chosen to model the EU's choice into three discrete categories to represent the three levels at which the EU can commit to the creation of an alternative supply chain.

1. **Decouple from China**: This decision represents strong commitment through significant domestic investment in developing mineral processing capabilities and investment abroad to develop new mines. Thus, the EU aligns strongly with the US.
2. **Maintaining the Status Quo**: This represents more middling commitment, where the EU maintains a more middle-ground relationship with the US and China through limited investments in the CRM supply chain while relying on the US to spearhead efforts to create alternate CRM supply chains.
3. **Defecting**: The EU make little to no investment in developing a CRM supply chain, instead relying entirely on China and the US for their source of minerals. Any very limited investments that the EU make are largely made with domestic economic and political goals in mind, such as providing new opportunities for European firms and increasing energy security.

The second stage of the game occurs after the first, and allows the other player, in this case the US, the opportunity to punish players who defected from their commitments. Punishment can be costly, often for economic and reputational reasons, but has proven to be a popular and efficient way of promoting cooperative behaviour (Brandt, Hauert, and Sigmund 2003). As with the EU, the US can choose its course of action from a continuous spectrum, but I have grouped these into three categories to reflect the three degrees of harshness with which the US can respond to the EU's chosen action.

1. **No Punishment**: The EU's chosen action produces no response on the part of the US to either praise the EU for contributing or chastising the EU for not contributing. In other words, this maintains the status quo of their relationship.
2. **Reputational Punishment**: US officials issue public statements and use diplomatic meetings and summits to criticise the EU for their history of actions. This type of punishment may damage the closeness and strength of the relationship between the US and EU. However, this doesn't directly impose any economic penalties.
3. **Economic Penalties and Exclusion**: This is the harshest response. The US rolls out more protectionist trade policies such as tariffs on imports from the EU or export quotas. These can be enforced in two ways key ways. Firstly, such measures may be directly applied to critical minerals trades, threatening EU access to the alternative critical mineral supply chain. Alternatively, the US may take advantage of issue linkages to punish the EU, by imposing penalties on goods entirely unrelated to minerals (Axelrod and Keohane 1985, 239).

I justify the categorization of US responses into these three buckets on several fronts. The first two decisions are responses that previous US administrations have often employed on issues they consider of high security priority. Famous examples include public criticisms from the White House regarding insufficient spending on NATO by EU members (Wilkie 2018) and unhappiness with the EU's lack of support to US policy in the Red Sea (Allard, Bianco, and Droin 2024). The third response, that of economic penalties and exclusion, is much harsher and has been less used by the US. However, on high security issues, when other punishment efforts like reputational punishment and diplomatic negotiations have failed the US has turned to these harsher penalties to force an EU response. For instance, the 2018 tariffs imposed on imports of EU steel and aluminium are widely believed to be linked to dissatisfaction with the level of NATO funding from EU nations (C. P. Brown 2018). Through my framing of critical minerals as a security issue, I argue that they are now, and will continue, to be viewed a high security issue by the US. Therefore, the US will be willing to evoke harsh, economic punishments when driven primarily by critical minerals policy disputes. Indeed, signs of this linkage are already appearing, with the US tying its military, security, and financial support to Ukraine on the signing of a critical minerals deal (Kullab 2025).

Incorporating the Lagged Effect of Reputation

The EU's choice of action at any stage can impact how it is viewed by the US as an ally. For instance, consistently choosing to invest in critical mineral infrastructure and decouple from China is likely to be interpreted by the US as evidence that the EU is a valuable ally. By contrast, choosing to defect may anger the US and cause them to take more punitive action through reputational or economic punishments. I incorporate this into my model by introducing a reputational system in line with the one adopted by Podder, Righi, and Pancotto (2021). This system defines an EU action as either good, neutral, or bad and assigns a reputational score to that action accordingly r_t. From the US' perspective, cooperative actions are considered good while decisions to defect are considered bad, giving the following scores:

1. **Decoupling from China** [$r_t = -1$]: the EU aligns closer to the US and is committed to the friend-shoring strategy, demonstrating willingness and ability to invest in critical mineral infrastructure.
2. **Maintaining the Status Quo** [$r_t = 0$]: EU actions move them neither closer to the US nor the China in alignment and so their reputation from the perspective of the US is as it was before.
3. **Defecting** [$r_t = 1$]: the EU chooses to free-ride off US investments instead of contributing themselves. This also suggests that they are willing to maintain close ties with and remain dependent on China which goes directly against the US' position on the matter.

The cumulative reputational effect of each action is captured by the EU's total reputational score, R_t and calculated by aggregating the individual reputational score of the EU's history of actions. This represents the US' opinion on the EU's reputation as an ally within the context of critical minerals. R_t is calculated as follows:

$$R_t = \sum_{i=1}^{t} r_i \tag{1}$$

Of course, the US' view of the EU's reputation is not just a function of the EU's action on critical minerals but is also influenced by the EU's actions across a range of topics. I account for this through the use of a 2x2 framework which distinguishes between circumstances where the US generally views the EU through a better or worse lens and thus captures these external effects. This will be discussed further later. My inclusion of a reputational score is intended to isolate the impact of the EU's critical mineral investment decision on the US' choice of response.

Determining the Payoffs

The Utility Function

The payoffs for the EU of a particular action and strategy depends on its benefits and costs as well as the significance that the EU attaches to those outcomes. Each benefit and cost is weighted depending on the significance the EU attaches to it in each state of nature. The benefits and costs of the mineral investment can be summarised as follows:

1. **Security Benefits**: This comes from the dual effect of decreased reliance on China and the diversification of the supply chain of critical minerals. The former reduces the EU's vulnerability to volatility in the supply and price of critical minerals caused by China's intentional weaponisation of its monopoly power. The latter reduces China's monopoly power entirely, by opening new supply lanes of critical minerals. While this also reduces China's ability weaponise critical minerals, it also reduces the EU's exposure to unintentional volatility in price and supply by China, caused by external changes in production costs, environmental factors, or broader economic factors. Doing so also increases energy independence, because EU ownership over critical mineral infrastructure allows for the domestication of a much greater part of the supply chain for several renewable energy technologies. Greater investment in critical minerals increases
2. **Energy and Social Benefits**: These benefits come about because of the correlation between greater critical mineral investment and the acceleration of the energy transition. Investment enables the construction of new mines, creating access to new mineral deposits, and increase competition in the upstream and midstream parts of then critical mineral supply chain. This competition will spur technological developments, by encouraging research and development, while also increasing worldwide capacity to meet the ever-growing demand for critical minerals from clean energy technologies further downstream. Thus, expansion in critical mineral access directly increases the ability to produce downstream clean technologies like renewable energy and electric vehicles. The acceleration of the transition then more quickly lowers pollution levels and addresses global warming, which brings social benefits including health benefits and reduced risk of natural disasters.
3. **Economic and Opportunity Costs**: Investments in critical mineral infrastructure are extremely costly, characterised by high upfront costs, increasingly long lead times for construction, susceptibility to significant delays, and a lengthy return-on-investment timeline (Manalo 2024; Majkut et al. 2023). Moreover, there are several non-financial costs play a significant role, including opaque mineral markets, low price transparency, price volatility and strong environmental and social concerns (Majkut et al. 2023; Coulomb et al. 2015). Furthermore, mineral deposits are often located in politically unstable regions, and susceptible to coups and policy changes by the government (Coulomb et al. 2015). These factors all serve to increase the actual cost of investment. This further increases considering opportunity costs. Critical minerals is one of many areas to invest in both for energy transition technology and, more generally, in defense and digital technologies. Furthermore, minerals are not the only part of the energy, military, and digital technologies supply chain in which the EU is reliant on China. For instance, China plays a dominant role in the EV battery and solar panels supply chains (Shiquan and Deyi 2022).
4. **US response**: This can negatively impact the EU if the US decides not to go with a no punishment response. The severity of the cost depends on the harshness of the US' action with no punishment being the least costly and exclusion being the costliest. Importantly, under both a no punishment and reputational punishment response, the EU still maintains uninhibited access to US investments in the alternative mineral supply chain. As the US chooses its response after the EU has made its decision, the US' choice depends entirely on the state, s', which is the state that the EU is in once the reputational effects of its decision have been accounted for.

In this model, the states are entirely determined by the EU's reputation. This is because the only component of the EU's decision that changes depending on its state is the US' response to its action. Thus, the EU's strategy must be defined at every reputational score. Moreover, because the impact the EU's action on its reputational score is deterministic, so is the EU's next state, s'. Thus, for every state-action pair, the EU moves to one particular, s' with probability 1 and all the other states with probability 0. This is summarised below:

$$s' = R_t + r_t \tag{2}$$

The payoff of a particular decision $a(s)$ in state s, $u_{s,a}$, thus is given by the following formula:

$$u_a(s, s') = \omega_1 \beta_{1,a} + \omega_2 \beta_{2,a} + \omega_3 C_a + \omega_4 \gamma_{s'} \tag{3}$$

where

$$\omega_i \in \{1,2\} \text{ are the weightings attached to each benefit and cost}$$
$$\beta_{i,a} \in \{1,0.5,0\} \text{ are the payoffs from each benefit for } i \in \{1,2\}$$
$$C_a \in \{-4,-2,0\} \text{ is the economic and opportunity cost of investment}$$
$$\gamma_{s'} \in \{2,1,-1\} \text{ is the payoff from the US response}$$

$\omega_i = 1$ if a factor is considered less important while $\omega_i = 2$ means it is considered highly important. The value of ω_i is determined by the context and is independent of s, s', a. The decision to decouple from China is the most costly ($C_a = -6$) but has the largest benefits ($\beta_{i,a} = 1$). The decision to defect requires no investment and is the least costly ($C_a = 0$) but therefore brings no direct benefits ($\beta_{i,s} = 0$). A US response of no punishment gives the greatest benefit to the EU ($\gamma_{s'} = 2$) while a response of economic penalties and/or exclusion is the most harmful ($\gamma_{s'} = -1$). The payoffs from the benefits and economic cost depend only on the action chosen, and not the current or next state, while the impact of the US response depends only on the next state, s'.

I justify my choice of payoffs as follows. Firstly, for the same action, the economic costs are much higher than either of the benefits. This is chosen because the costs of mineral investment are high, immediate, and much more certain than the corresponding benefits such an investment brings because of the risk that mining facility falls through or is significantly delayed. Investing the same capital elsewhere could produce quicker returns and also accelerate the energy transition, particularly when targeted towards other vulnerable sectors. The second significant choice is the decision to place greater value in access to the alternative supply chain as compared to the benefits from investing heavily in minerals. This is chosen precisely because the strategy of friend-shoring allows nations to benefit from investments that they alone cannot make, through the coordination of resources which increases the pool of capital to be invested and thus increases the number of new infrastructure projects funded (Vivoda 2023). Additionally, despite the cost of a reputational punishment, the EU still maintains uninhibited access to these benefits, and thus the payoff of 1 was chosen. Finally, the payoffs from the decision to decouple are double that of the decision to maintain the status quo, representing the gulf in commitment between the two actions.

The Value Function

The EU's decision is determined by the present discounted value of its strategy when the actor starts from state s (Chen et al. 2014). In the equation below, δ is the time discount factor while $P(s'|s,a)$ is the probability of reaching state s' given that the actor is currently in state s and is choosing action a. As has been established earlier, $P(s'|s,a) \in 0,1$. Within this model, I have chosen that each time period represents 2 years to account for the fact that the decisions-making process for to invest in new mineral infrastructure projects is often long due to extensive permitting and regulatory requirements (Manalo 2024). Consequently, I assign $\delta = 0.4$ to capture how short term lengths of EU officials in relation to this encourages them to focus on initiatives that produce shorter term benefits that will support future re-election campaigns.

$$V(s) = u_a(s,s') + \delta \sum_{s'} P(s'|s,a)V(s') \tag{4}$$

The 2x2 Framework

I use a 2x2 framework to establish the conditions under which the EU is making its decision. On one axis, I vary the cooperativeness of the US and the extent to which they value an alliance with the EU. In practice, the difference between both states is in their reputational threshold for escalating the harshness of punishment. In a high cooperative scenario, the US places greater value on a strong relationship with the EU, and so is less willing to punish the EU (Brandt, Hauert, and Sigmund 2003). This is reflected by higher thresholds before the US imposes harsher punishments. Commitment and reputation is also assumed to be reciprocal and so if the EU sees that the US values their relationship more they too will attach greater weight to it.

On the other axis, I vary the importance of critical minerals to the EU government, scientific community, and the public. A high importance scenario means that the security and environmental benefits of investing in clean technology, including critical minerals, are valued far more. In a low importance scenario, other factors like economic and opportunity cost, and are prioritised instead. Indeed, we can see the low importance scenario as one where factors like structural issues, right-wing ideological considerations, and changing priorities on hard security issues take precedence, even if critical minerals remain a security issue. A summary of this framework is given in Table 1, below.

Table 1: The 2x2 Framework

	EU Priority	
US	High Cooperativeness x High Priority	High Cooperativeness x Low Priority
Cooperativeness	Low Cooperativeness x High Priority	Low Cooperativeness x Low Priority

Assigning Weights

Under a scenario where the US is highly cooperative, the EU elevates the significance of the security threats caused by over reliance on China for critical minerals as well as a strong, positive relationship with the US as compared to a low cooperation scenario. Additionally, when the EU places high priority on critical minerals, the government elevates the importance of the energy benefits of a larger critical minerals supply chain while minimising the significance of its economic costs when compared to a scenario where critical minerals have a lower priority. Consequently, in each the four scenarios, the weights are attached as follows:

High Cooperativeness x High Priority

- **High importance**: Security Benefits, Energy and Social Benefits, US Responses
- **Low importance**: Economic and Opportunity Costs

High Cooperativeness x Low Priority

- **High importance**: Security Benefits, Economic and Opportunity Costs, US Responses
- **Low importance**: Energy and Social Benefits

Low Cooperativeness x High Priority

- **High importance**: Energy and Social Benefits, Economic
- **Low importance**: Security Benefits, Opportunity Costs, US Responses

Low Cooperativeness x Low Priority

- **High importance**: Economic and Opportunity Costs
- **Low importance**: Security Benefits, Energy and Social Benefits, US Responses

Determining the Strategies

The US Strategies

The US decides to change its response to the US based on reputational thresholds. Under a high co-operative scenario, the US government adopts the following strategy.

1. While $R < 3$, the US chooses to take no punishment action against the EU.
2. When $R = 3$, the US escalates to reputational punishment and maintains that response.
3. When $R = 5$, the US escalates to implement economic penalties and maintains that response.

Under a low cooperative scenario, the US government adopts the following strategy.

1. While $R < 1$, the US chooses to take no punishment action against the EU.
2. When $R = 1$, the US escalates to reputational punishment and maintains that response.
3. When $R = 2$, the US escalates to implement economic penalties and maintains that response.

The higher thresholds and larger jumps between thresholds in the high co-operation scenario reflects how the US values its relationship with the EU for other factors, including strong trade and economic relations and the EU's role as an ally against geopolitical adversaries such as China and Russia. Thus the US is more patient and lenient with the EU as compared to a low co-operation scenario. This therefore captures the impact of the EU's decisions in other other issue areas.

Determining Optimality

Solving equation 4 allows for the calculation of the present-discounted value of the EU's strategy when the EU starts from state R, as listed in Appendix A. To determine the optimality of EU's strategies, I utilise the one deviation property to test whether deviating from the strategy is beneficial for the EU. This property states that the EU's strategy is an equilibrium if and only if a decision to deviate from the strategy at a particular step t and then continue with the original strategy does not yield a higher value for the EU (Osborne and Rubinstein 1994, p. 99, 153). To show this, it is thus sufficient to show that deviating from strategy at the very first step, $t = 1$ is not beneficial. As shown in Appendix A, I use this property to calculate the present discounted value of deviation for each state R. As the EU chooses from three actions, at every state R there are two such deviations to check.

Results and Analysis

Results Overview

Solving the model gives a set of strategies that is optimal for the EU to follow under each of the four scenarios. This is summarised in Table 2.

Table 2: The EU's Optimal Strategy Across all Scenarios

	The EU Strategy			
State (R)	**High Cooperativeness x High Priority**	**High Cooperativeness x Low Priority**	**Low Cooperativeness x High Priority**	**Low Cooperativeness x Low Priority**
0	Status Quo	Defect	Defect	Defect
1	Status Quo	Defect	Status Quo	Defect
2	Decouple	Defect	Decouple	Defect
3	Decouple	Defect	Decouple	Defect
4	Decouple	Status Quo	Defect	Defect
5	Decouple	Decouple	Defect	Defect
6	Decouple	Defect	Defect	Defect
7	Decouple	Defect	Defect	Defect
8	Decouple	Defect	Defect	Defect
9	Decouple	Defect	Defect	Defect
10	Decouple	Defect	Defect	Defect
11	Decouple	Defect	Defect	Defect
12	Defect	Defect	Defect	Defect
13	Defect	Defect	Defect	Defect

From Table 2, it is clear that the EU's optimal strategy across all four scenarios differs dramatically. Under a high cooperation x high priority scenario, it appears to be in the EU's best interest to always invest in critical minerals, even when their reputation score is such that it will take several periods of high to regain uninhibited access to the minerals produced and processed by the US. This is clearly visible in the way the EU's optimal strategy in column 2 is *decouple* even when $R > 5$. In complete contrast, Table 2 suggests that the EU's best option is always to defect when it attaches low importance both to uninhibited access to US critical mineral infrastructure and to a strong relationship with the US. This suggests that the economic and opportunity costs of maintaining and ensuring both is not worth the benefits that they bring. Indeed, this conclusion is reasonable because critical mineral infrastructure projects involve high upfront capital costs and are plagued by risks regarding their successful construction and ability to recover initial investment costs (Manalo 2024; Coulomb et al. 2015). Finally, the prominence of defection in the EU's optimal strategy under the last two scenarios are demonstrative of this precise cost-benefit trade-off. Unlike the high co-operation x high priority scenario, when the EU faces no risk of punishment it always chooses to defect and thus free-ride. Only when faced with punishment, does it choose to invest both to maintain access to the alternative supply chain and to benefit from a strong relationship with the US.

The Propensity to Free-Ride

The earlier discussion of burden-sharing in international relations highlighted how an actor would always choose to defect when large differences between the cost of investment and individual benefit as well as differences between actors in how they would benefit from the same investment allowed them to free-ride off the investments made by others. We see that is also the case for the EU in the context of critical minerals under three of the four scenarios. Aside from the high co-operation x high priority case, the EU always chooses to defect when doing so does not incite any punishment. Under all three scenarios, this decision makes sense. When the priority regarding critical minerals is low, their security and energy benefits are further minimised because the EU likely prioritises other economic, social, and security issues over critical minerals, making their cost of investment appear prohibitive. Even under the low cooperation x high priority scenario, this decision can be justified because the security benefits of a diversified supply chain are reduced. Although maintaining dependence on China exposes the EU to weaponisation, the fact that EU tends to maintain a more friendly relationship with China reduces this threat. This is furthered by the increased distance between the US and EU enforced under a low cooperation scenario by reducing the risk that any attempts by China to weaponise critical minerals against the US, amidst a deteriorating relationship, does not spillover to the EU. Instead, such distancing could benefit the EU as demonstrated by the EU's ability to distance itself from the US during the US-China trade war during President Trump's first term in office (Goulard 2020). Under a similar low cooperation scenario, a closer relationship with China could allow the EU to access critical minerals more cheaply by taking advantage of the lower costs at which these minerals are mined and produced by China compared to the rest of the world.

However, the high cooperation x high priority scenario demonstrates an interesting break from this trend. Notably, the EU always chooses to invest in critical minerals, even when defecting induces no punishment from the US and does not threaten the EU's access to US investments in the alternative supply chain. Under, this scenario, the weighting both the security and energy benefits highly suggests that investment is always the better choice as doing so would accelerate the realisation of these benefits. Moreover, a comparison with columns 3 and 4 highlights how it is the combined effect of both benefits that pushes this strategy: under column 3, the EU still prioritised the security benefits of decoupling from China while under column 4, the energy benefits were prioritised highly while the cost of investment was a low priority. While the necessity of prioritising both benefits to ensure investment is reflective of the high costs of investment, it also suggests that these costs are not prohibitive. Instead, as critical minerals increasingly become the focal point of most conversations surrounding defense, digitisation, energy security, and economic growth, the elevation of critical minerals to a high priority by EU governments implies that the mineral infrastructure will begin to see more and more investment. That being said, the decision to invest in line with the status quo, and do just enough to keep the US satisfied, suggests there is a degree of free-riding in the EU's strategy and highlights the continued pull of other policy considerations on the EU budget.

Strength of the Punishment Mechanism

Another interesting pattern is differences in the effectiveness of the punishment mechanism across the four scenarios. Brandt, Hauert, and Sigmund 2003) suggested that punishment mechanisms are an effective way to ensure co-operation, and with the exception of the low cooperation x low priority scenario, the results in Table 2 support this claim. Notably, under the other 3 scenarios, when the EU was just under the threshold for a punishment escalation, the EU rarely defecting and accepting the costs of punishment is rarely the optimum choice. Instead, it appears that the cost of investing in critical minerals infrastructure was worth enduring for the benefits that this investment provided and the ability to avoid punishment from the US.

In the case of economic penalties, the EU's decision to avoid obstacles in their access to the minerals produced by US and allied investments in the alternative supply chain is demonstrative of the importance of being able to benefit from the friend-shoring approach. Notably, this is indicative of the fact that the costs of investment to ensure access to the alternative supply chain are largely dwarfed by the cost the EU would have to incur should it attempt to achieve this diversification by itself, as column 2 suggests it would pursue, or to lose out on this access completely, as is stipulated under the column 3 of Table 2. Under column 2, the desire to avoid economic punishment could be reflective of two key factors. Firstly, the low priority of critical minerals suggests that the opportunity cost of such an investment is much more significant. Thus, ensuring that the EU maintains uninhibited access to investments by other nations would allow it to satisfy any internal security or energy concerns about complete reliance on China while allowing it to focus its capital and efforts on more pressing areas of policy. Secondly, this could reflect the spillover benefits of a strong relationship with the US on other areas of EU-US interactions. These can include the US' commitment to NATO, support for the EU's efforts to combat climate change, and diplomatic support of EU interests in international forums like the United Nations.

More interesting is the EU's desire to avoid reputational punishment under both scenarios where critical minerals are a high priority. Indeed, incurring a reputational punishment would not limit the EU's access to US investment in the energy supply chain and thus, even under a low cooperation scenario, this suggests that the EU places great value on a very strong relationship with the US. This is a significant departure from the EU's approach to other issues of security, such as defense spending under NATO and response to the 2023-2024 attacks in the Red Sea by the Houthis. Under both scenarios, the EU demonstrated willingness to endure the US' reputational condemnations and censures, and in the case of NATO even economic penalties imposed by the Trump administration in response to what was perceived as continued EU defection (Wilkie 2018; Allard, Bianco, and Droin 2024; C. P. Brown 2018). Moreover, column 3 suggests that under a high cooperation scenario, reputational punishments are not an effective enforcement mechanism, which the greater significance of the energy and social benefits as well as the relatively low importance given to the costs of investment are driving the desire to avoid reputational punishments.

Attempts to Repair Reputation

Lastly, the EU decision to invest heavily and decouple when exactly at the threshold of punishment escalation suggests its willingness and desire to try repair its relationship with the US under all but the low cooperation x low priority scenario. Following the discussion above on the benefits of maintaining secure access to the alternative supply chain and having a strong relationship with the US, this conclusion is no longer surprising but is more evidence of how those benefits outweigh the investment cost. More interesting is the extent to which this belief lasts. Under the high cooperation x high priority scenario described in column 2 of Table 2, the EU's preferences for continuing to decouple until $R = 11$ reflects the belief that even when mending this relationship is extremely costly and time consuming, the significant benefits for the EU justify this continued and consistent investment even when the EU is present biased. In contrast, the decision to defect in states 6 and 4 respectively imply that the benefits of investments are capped when the costs of repairing the relationship increase even slightly. This is likely also reflective of the degree to which the EU is present-biased and is further evidence of the fact that policy issues with faster solutions are likely to be prioritised.

Under all four scenarios, the decision to defect is an absorbing state once the EU's reputation crosses a certain threshold. This is perhaps indicative of the fact that the EU is better off strengthening its relationship with China through increased mineral trade, which makes sense because the EU's increasingly frosty relationship with the US means that China is less likely weaponise the EU's critical mineral dependency as it sees the EU as a much stronger ally.

Limitations

While this methodology has allowed for nuanced analysis, there are several limitations that must be addressed. These include simplifications of the real-world and assumptions about the payoff structure.

Simplifications

Throughout this thesis I refer to critical minerals as a single object of investment on which the EU and US have complete agreement. In reality, the term refers to a group of many minerals where the exact criteria for determining criticality varies between the EU and US. This leads to differences in their list of critical minerals as well as different perceptions on what minerals are more important for investment. Such heterogeneity can come because these nations have different mineral deposits and because they attribute different economic importance to the same mineral (Coulomb et al. 2015). Thus, the US' response to the EU's strategy will likely depend on both the EU's investment in the minerals the US considers most important and the EU's investment across all minerals it considers critical. By simplifying critical minerals to a single object, this paper ignores the impact of individual investments as well as the interaction between both determinants that could complicate the payoff values and the US response. This is furthered by the fact that heterogeneity in the economic cost, security benefit, and energy and social benefit between minerals means that the strategy pursued by the EU may differ by mineral.

Additionally, my construction of the US response parameter assumes that the nature of each response is the same across low and high co-operation scenarios. This is also a simplification, as evidenced by the difference in how the Obama, Trump, and Biden Administrations pursued their reputational punishment of the EU. Notably, both President Donald Trump and President Joe Biden focused on distinguishing their policy and rhetoric from their previous administration, and this extends to the harshness of their language towards EU (Singh 2024; Wilkie 2018). Thus, the nature and harshness of the reputational punishment itself may change the EU's strategy, independent of the threat of economic sanctions and exclusion.

Moreover, the model focuses on the EU and US as actors – other allies and China are treated as stationary actors who don't interfere with the EU strategy. To some extent, the actions of these nations are already incorporated into the model by determining the conditions under which the model is executed (i.e. high vs. low priority for the EU). However, the actions of these nations can change the payoffs of the benefits and costs over time while also impacting the extent to which the US views critical minerals as a high priority issue, changing reputational thresholds and influencing the nature of the US response to the EU's investment strategy. This speaks to a broader limitation where the US' strategy is assumed to be fixed depending on the cooperativeness of the administration. In reality, changing domestic and foreign priorities means that there is much more variation in the US strategy towards EU mineral investment.

Determining the Payoffs

Another potential limitation arises in my method for determining the payoffs attached to the benefits, economic costs, and US responses to EU behaviour. In determining the values of the payoffs, I relied heavily on qualitative studies, that discussed the relative importance of critical minerals to military, energy, and digital technologies, the structural and economic costs associated with this investment, and impact of US responses on the EU. While these provided a strong foundation from which to determine the relative payoffs between each parameter, supporting this evidence with quantitative analysis that compares the monetary benefit of these three factors would provide more precise and, perhaps, more representative values for the benefits and costs. Carrying out this exercise, however, is challenging for several reasons. Firstly, the relative value of all four parameters depends on the individual and their priorities; for instance some may view the 15-year lead times for new mines as more costly than other depending on their present-bias. Additionally, and more significantly, the rapid growth in importance of critical minerals as a policy issue, constant technological innovation, and changes over time in the minerals considered critical mean that few studies have quantified and compared these values. To do this myself would thus be beyond the scope of this thesis.

What's Next for Global Critical Mineral Investments?

Through this study, I investigate the EU's optimal strategy to address the security challenges caused by its dependence on China for its source of critical minerals. I find that existing theories on free-riding and burden sharing in international relations are extremely applicable to the critical mineral context, with the EU choosing to free-ride on US investments under three of the four scenarios discussed. At the same time, by situating the critical mineral supply chain vulnerabilities within the framework of security theory, I find significant support for the effectiveness of punishment at encouraging cooperative behaviour. The only situation in which this does not hold is when both the relationship with the US and issue of critical minerals are of low importance to the EU. Ultimately, this paper demonstrates the strong impact of domestic priorities and the geopolitical landscape on the EU's optimal strategy.

This being said, the critical minerals space is a fast evolving and ever-growing industry. Focus from international agencies, government discourse, environmentalists, and others have encouraged innovation and investment in this field at an unprecedented rate. Thus, this field is not static, but one where awareness of the benefits of critical minerals, the relative importance of each mineral, and the costs of investment are extremely dynamic and rapidly changing. Thus, while the findings of this paper are significant and should be further studied, the assumptions on which it is built merits consistent review and updating.

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Appendix A: Tables of Results

The following tables give the reward matrix for the EU in each of the four scenarios. The EU's optimal strategy has been highlighted in bold.

Table 3: High Co-operation x High Priority

R	Decouple	Status Quo	Defect
0	6.6666667	**6.6666667**	6.6666667
1	6.6666667	**6.6666667**	6.6666667
2	**6.6666667**	6.6666667	4.6666667
3	**6.6666667**	4.6666667	3.8666667
4	**4.6666667**	3.8666667	-0.4533333
5	**3.8666667**	-0.4533333	-2.1813333
6	**-0.4533333**	-2.1813333	-2.8725333
7	**-2.1813333**	-2.8725333	-3.1490133
8	**-2.8725333**	-3.1490133	-3.2596053
9	**-3.1490133**	-3.2596053	-3.3038421
10	**-3.2596053**	-3.3038421	-3.3038421
11	**-3.3038421**	-3.3333333	-3.3333333
12	-3.3333333	-3.3333333	**-3.3333333**
13	-3.3333333	-3.3333333	**-3.3333333**

Table 4: High Co-operation x Low Priority

R	Decouple	Status Quo	Defect
0	1.41066667	3.9106667	**6.026667**
1	1.41066667	3.5266667	**5.066667**
2	1.02666667	2.5666667	**2.666667**
3	0.06666667	0.1666667	**1.666667**
4	-2.33333333	**-0.8333333**	-3.333333
5	**-3.33333333**	-5.8333333	-3.333333
6	-8.33333333	-5.8333333	**-3.333333**
7	-8.33333333	-5.8333333	**-3.333333**
8	-8.33333333	-5.8333333	**-3.333333**
9	-8.33333333	-5.8333333	**-3.333333**
10	-8.33333333	-5.8333333	**-3.333333**
11	-8.33333333	-5.8333333	**-3.333333**
12	-8.33333333	-5.8333333	**-3.333333**
13	-8.33333333	-5.8333333	**-3.333333**

Table 5: Low Co-operation x High Priority

R	Decouple	Status Quo	Defect
0	2.200000	2.700000	**3.000000**
1	2.200000	**2.500000**	1.800000
2	**2.000000**	1.300000	-0.680000
3	**0.800000**	-1.180000	-1.666667
4	-1.680000	-2.166667	**-1.666667**
5	-2.666667	-2.166667	**-1.666667**
6	-2.666667	-2.166667	**-1.666667**
7	-2.666667	-2.166667	**-1.666667**
8	-2.666667	-2.166667	**-1.666667**
9	-2.666667	-2.166667	**-1.666667**
10	-2.666667	-2.166667	**-1.666667**
11	-2.666667	-2.166667	**-1.666667**
12	-2.666667	-2.166667	**-1.666667**
13	-2.666667	-2.166667	**-1.666667**

Table 6: Low Co-operation x Low Priority

R	Decouple	Status Quo	Defect
0	-3.146667	-0.1466667	**2.1333333**
1	-3.146667	-0.8666667	**0.3333333**
2	-3.866667	-2.6666667	**-1.6666667**
3	-5.666667	-4.6666667	**-1.6666667**
4	-7.666667	-4.6666667	**-1.6666667**
5	-7.666667	-4.6666667	**-1.6666667**
6	-7.666667	-4.6666667	**-1.6666667**
7	-7.666667	-4.6666667	**-1.6666667**
8	-7.666667	-4.6666667	**-1.6666667**
9	-7.666667	-4.6666667	**-1.6666667**
10	-7.666667	-4.6666667	**-1.6666667**
11	-7.666667	-4.6666667	**-1.6666667**
12	-7.666667	-4.6666667	**-1.6666667**
13	-7.666667	-4.6666667	**-1.6666667**

Appendix B: R Code

```
#--- Load Necessary Packages -----
library(dplyr)
library(MDPtoolbox)

##--- Initializing the Parameters ----------------
n_states <- 11
n_actions <- 3
delta <- 0.4
```

```r

        #Strategies
        hh <- c(2, 2, 1, 1, 1, 1, 1, 1, 1, 1, 1)
        hl <- c(3, 3, 3, 3, 2, 1, 3, 3, 3, 3, 3)
        lh <- c(3, 2, 1, 1, 3, 3, 3, 3, 3, 3, 3)
        ll <- c(3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3)

        #Payoffs
        security <- c(1, 0.5, 0)
        environmental <- c(1, 0.5, 0)
        economic <- c(-4, -2, 0)
        no_punishment <- 2
        reputational_punishment <- 1
        economic_penalty <- -1

        #Weights
        hh_w <- c(2, 2, 1, 2)
        hl_w <- c(2, 1, 2, 2)
        lh_w <- c(1, 2, 1, 1)
        ll_w <- c(1, 1, 2, 1)

        #US Strategy
        high_threshold <- function(s_prime) {
          if (s_prime >= 1 && s_prime <= 3) return(no_punishment)
          if (s_prime >= 4 && s_prime <= 5) return(reputational_punishment)
          if (s_prime >= 6) return(economic_penalty)
        }

        low_threshold <- function(s_prime) {
          if (s_prime >= 1 && s_prime <= 2) return(no_punishment)
          if (s_prime >= 3 && s_prime <= 3) return(reputational_punishment)
          if (s_prime >= 3 && s_prime <= 11) return(economic_penalty)
        }

        ##--- Defining the Formulas for Computing the Payoffs ----------------
        #High Reputation Threshold
        high_payoffs <- function(strategy, weights) {
          payoffs <- numeric(length(strategy))
          for (s in 1:n_states) {
            a <- strategy[s]
            # Determine next state
            if (a == 1) {
              s_prime <- max(1, s - 1)
            } else if (a == 2) {
              s_prime <- s
            } else {
              s_prime <- min(n_states, s + 1)
            }
            # Get reputational response
            d_val <- high_threshold(s_prime)
            # Calculate reward
            reward <- weights[1] * security[a] + weights[2] * environmental[a] + weights[3] * economic[a] + weights[4] * d_val
            payoffs[s] <- reward
          }
          return(payoffs)
        }

        high_vf <- function(strategy, payoffs, delta, weights, tol = 1e-6, n_states = 11) {
          action_values <- matrix(0, nrow = n_states, ncol = 3)
          for (s in 1:n_states) {
            for (a in 1:3) {
              # Find s prime
              s_prime <- if (a == 1) max(1, s - 1) else if (a == 2) s else min(n_states, s + 1)
```

```
      # Payoff at s
      d_val <- high_threshold(s_prime)
      immediate_reward <- weights[1] * security[a] + weights[2] * environmental[a] + weights[3] * economic[a] + weights[4] * d_val
      # Payoff from all future s primes
      future_value <- 0
      discount <- delta
      current_state <- s_prime
      for (t in 1:1000) {
        reward <- payoffs[current_state]  # strategy-implied immediate reward
        future_value <- future_value + discount * reward
        # advance to next state under strategy
        next_action <- strategy[current_state]
        next_state <- if (next_action == 1) max(1, current_state - 1)
        else if (next_action == 2) current_state
        else min(n_states, current_state + 1)
        # Break if state is absorbing
        if (next_state == current_state && abs(delta * reward) < tol) {
          break
        }
        #Updating the values for the next time period
        current_state <- next_state
        discount <- discount * delta
      }
      action_values[s, a] <- immediate_reward + future_value
    }
  }
  return(action_values)
}

#Low Reputation Threshold
low_payoffs <- function(strategy, weights) {
  payoffs <- numeric(length(strategy))
  for (s in 1:n_states) {
    a <- strategy[s]
    # Determine next state
    if (a == 1) {
      s_prime <- max(1, s - 1)
    } else if (a == 2) {
      s_prime <- s
    } else {
      s_prime <- min(n_states, s + 1)
    }
    # Get reputational response
    d_val <- low_threshold(s_prime)
    # Calculate reward
    reward <- weights[1] * security[a] + weights[2] * environmental[a] + weights[3] * economic[a] + weights[4] * d_val
    payoffs[s] <- reward
  }
  return(payoffs)
}

low_vf <- function(strategy, payoffs, delta, weights, tol = 1e-6, n_states = 11) {
  action_values <- matrix(0, nrow = n_states, ncol = 3)
  for (s in 1:n_states) {
    for (a in 1:3) {
      # Find s prime
      s_prime <- if (a == 1) max(1, s - 1) else if (a == 2) s else min(n_states, s + 1)
      # Payoff at s
      d_val <- low_threshold(s_prime)
      immediate_reward <- weights[1] * security[a] + weights[2] * environmental[a] + weights[3] * economic[a] + weights[4] * d_val
      # Payoff from all future s primes
```

```
            future_value <- 0
            discount <- delta
            current_state <- s_prime
            for (t in 1:1000) {
              reward <- payoffs[current_state]  # strategy-implied immediate reward
              future_value <- future_value + discount * reward
              # advance to next state under strategy
              next_action <- strategy[current_state]
              next_state <- if (next_action == 1) max(1, current_state - 1)
              else if (next_action == 2) current_state
              else min(n_states, current_state + 1)
              # Break if state is absorbing
              if (next_state == current_state && abs(delta * reward) < tol) {
                break
              }
              #Updating the values for the next time period
              current_state <- next_state
              discount <- discount * delta
            }
            action_values[s, a] <- immediate_reward + future_value
          }
        }
        return(action_values)
      }

      #--- Calculating the Values of the Value Function ---------------
      #High x High
      hh_payoffs <- high_payoffs(hh, hh_w)
      hh_results <- high_vf(hh, hh_payoffs, delta, hh_w)
      print(hh_results)

      #High x Low
      hl_payoffs <- high_payoffs(hl, hl_w)
      hl_results <- high_vf(hl, hl_payoffs, delta, hl_w)
      print(hl_results)

      #Low x High
      lh_payoffs <- low_payoffs(lh, lh_w)
      lh_results <- low_vf(lh, lh_payoffs, delta, lh_w)
      print(lh_results)

      #Low x Low
      ll_payoffs <- low_payoffs(ll, ll_w)
      ll_results <- low_vf(ll, ll_payoffs, delta, ll_w)
      print(ll_results)
```