Modeling the supply of strategic raw materials for Europe's 2030 hydrogen target: analyzing dynamics, risks, and resilience

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Abstract

Keywords—

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Nomenclature

Type	Description	Unit
Set and index		
$e \in \mathcal{E} = \{1, \dots, E\}$	Exporter, index by e (1…Major exporter)	
$e' \in \mathcal{E}' = \{2, \dots, E\}$	Fringe exporter/supplier, index by e'	
$\underline{\boldsymbol{e}} \in \underline{\mathcal{E}} \subseteq \mathcal{E}$	Exporter subject to an embargo for the European market, index by $\underline{\boldsymbol{e}}$	
$m \in \mathcal{M} = \{M1, M2\}$	Market, index by m M1…European market, M2…Global market	
$t \in \mathcal{T} = \{2025, \dots, 2040\}$	Time step, index by t	
$t' \in \mathcal{T}' \subseteq \mathcal{T}$	Time step without starting year 2025	
Decision variables of the lower-level problem		
$q_{e,m,t}$	Supply quantity per e, m, and t	ton
$\bar{q}_{e',t}$	Available supply capacity e' and t	ton/year
$\bar{q}^{add}_{e',t}$	Added available supply capacity per e' and t	ton/year
$\bar{q}^{retire}_{e',t}$	Retired supply capacity per e' and t	ton/year
$q^{arb}_{M1,M2,t}$	Arbitrage of supply quantity between the European market $M1$ and the global market $M2$	ton
$q^{del}_{1,m,t}$	Delivered supply quantity of the major exporter 1 per m and t	ton
$q^{arb}_{1,m,t}$	Arbitrage quantity of the major exporter 1 per m and t	ton
$q^{stock,in/out}_{M1,t}$	Quantity in or out of the stock for the European market $M1$	ton
$q^{stock,stored}_{M1,t}$	Stock stored for the European market $M1$ per t	ton
Decision variables of the upper-level problem		
$c_{1,t}$	Marginal supply cost of the major exporter 1 per t	€/ton
$\bar{q}_{1,t}$	Available supply capacity of the major exporter 1 per t	ton/year
Parameters (selection)		
$c^{gen}_{e,t}$	Marginal supply cost per e and t	€/ton
$c^{main}_{e'}$	Specific maintenance cost per e'	€/ton/year
c^{stock}	Specific stockpiling cost	€/ton/year
$d_{m,t}$	Demand per m and t	ton/year
α	Maximum supply share of the major exporter 1 at the European market $M1$	%

1 Introduction

The EU initiated the development of a robust hydrogen (H2) ecosystem through the European Commission (EC) Hydrogen Strategy in July 2020, emphasizing H2 as a vital component of its energy mix. H2 is gaining attention as an energy carrier crucial for transitioning to a low-carbon economy and ensuring energy security in Europe. To this end, the 2022 REPower EU plan highlights investments in renewable energy, with a 10 bcm H2 production target by 2030, leading to a projected sharp increase in electrolyzer and fuel cell capacity between 2030 and 2050 (IEA, 2022).

The production of H2 involves specific metal needs, with Critical Raw Materials (CMR) playing a pivotal role in the EU's H2 economy and security. As many CRMs are geographically concentrated, the EU is significantly dependent on single countries, including China, Democratic Republic of Congo, Russia, Turkey, and South Africa, for more than 75% (up to 100% for some rare earth elements (REE)) of its supply. The uncertainties regarding the evolution of CMR demand beyond 2030, evolving from being negligible in 2020 to an expected 3.95kt in 2030 (Eurometaux, 2023), aligned with most countries' H2 production targets, emphasize the need for strategic planning.

Different types of electrolyzers, primarily Alkaline and PEM, have distinct mineral requirements. Projections indicate an average increase in demand for platinum (+24 %), iridium (+43 %), and scandium (+68 %) from the H2 sector by 2030 (IEA, 2022). Challenges in producing these materials stem from their status as by-products, limiting flexibility in scaling up production, and geological conditions inhibiting new mines, as seen in the case of iridium in the EU.

In Europe's ongoing transition toward a cleaner future in the coming decades, the strategic importance of REEs is rising, posing challenges related to their availability. Aside from the ongoing "balancing problem" of aligning demand with supply, the growing demand for REEs since the mid-1920s is compounded by the monopolistic structure of the REEs supply market. China has dominated the global REEs market in upstream and mid-stream activities since the 1990s due to abundant reserves, lower operational and regulatory costs, and environmental considerations (Fard et al., 2023; Zou et al., 2022; Zhou et al., 2017).

Given the competition between state-capitalist and market-based economies shaping the REE market, it becomes imperative for resource-poor and import-dependent countries like Europe to prioritize securing a stable supply of these materials and attaining independence in importing throughout the entire critical mineral supply chain as a critical step toward strategic autonomy (Klossek et al., 2016).

To address the challenges posed by the emerging clean transition, the EC has taken actions to ensure global competitiveness and a stable supply for European industries while avoiding imbalanced import structures for materials needed in clean solutions and minimizing the EU's vulnerability to supply risks. This initiative began with the Raw Material Initiative in 2008 and culminated in the Critical Raw Material Act in 2023. The EU's strategy focuses on building a resilient CRM supply chain, promoting CRM production within Europe, and safeguarding the domestic market through recycling initiatives and storage (Girtan et al., 2021).

This effort aims to mitigate the risks of economic coercion from primary producers and asymmetric dependencies in supply structures. These aspects were ignored until recently, with China, which is dominating the up and mid-stream activities for CRMs, withdrawing VAT refunds on the export of unimproved CRMs in 2007, imposing export quotas on a few raw materials from 2008 to 2015, implementing a more stringent licensing system from 2015, and banning exports to Japan in 2010, resulting in market uncertainty and price spikes (Mancheri, 2015). .

Focusing on the need for CRMs in the hydrogen economy uptake, the study addresses three pivotal questions at the convergence of geopolitics, market dynamics, and regulatory frameworks within the CRM sector. The investigation delves into the strategic behavior of the market-dominant player and its impact on the EU supply chain, specifically platinum, a key component for hydrogen production. It explores the interplay between the dominant player in the platinum market and the EU within the CRM market, considering the repercussions of supporting policies. Additionally, the research evaluates the CRM Act's potential contribution to fortifying Europe's CRM supply chain, especially concerning the challenges linked to ambitious hydrogen production targets by 2030.

In particular, it seeks to provide insights into how supply chain dependency, vulnerability to disruptions, and potential limitations in technological innovation unfold under the dominance of a single market player, thereby investigating the implications for the EU supply chain dynamics. In addition, it centers on the regulatory framework's role in mitigating dependencies on dominant players. To this end, it aims to explore the CRM Act's impact on creating a more resilient CRM supply chain and spurring technological innovation within the sector through collaborative efforts with alternative suppliers.

Lastly, it delves into understanding how these provisions, and in particular the role of stockpiling provisions outlined in the CRM Act, mitigate the impact of geopolitical tensions on the EU's CRM supply chain, contributing to supply chain resilience, while addressing challenges in meeting hydrogen production targets, and influencing strategic decision-making amid market uncertainties.

To answer these questions, the work employs a novel model that integrates a leader-follower Stackelberg game framework, considering the competitive dynamics between the dominant player and the EU. This deterministic bi-level optimization model enables a comprehensive examination of the complex interactions within the CRM market, incorporating factors such as market dominance, regulatory compliance, and geopolitical influences. Through this approach, the work aims to provide insights into the potential future trajectories of the European CRM sector under diverse scenarios, offering valuable perspectives for policymakers, and industry stakeholders, alike.

The following section focuses on the framework of the CRM Act and the techno-economic modeling studies in the context of CRMs. Section 3 details the modeling analysis and the key scenarios investigated, while Section 4 presents results. Finally, Section 5 offers conclusions.

2 Background

CRM Act and literature review here.

2.1 to be added

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2.2 Techno-economic modeling studies in the context of CRMs

As far as the proposed techno-economic modeling approach is concerned, to the best of our knowledge there is no equivalent publication. Still, the literature offers studies that are worth mentioning. One focus of these studies is certainly the modeling of the CRM demand and requirements in techno-economic, mostly large-scale energy system models. Comprehensive reviews about CRM in large-scale energy system models are given by Liang et al. [1] and Zhang et al. [2]. It seems worth remarking here, however, that the two reviews were recently published in 2022 and 2023 respectively. Tokimatsu et al. [3] look at CRM demands in the 2°C climate target using an energy system modeling approach. Peiró et al. [4] focus in their analysis on the integration of CRM demand of different sustainable energy technologies into energy systems models.

Another strand of the relevant existing literature deals with the prices of CRMs and how they might evolve in the context of an expected significant increase during the sustainable transition of the global energy system. Sun et al. [5] study the impact of widespread deployment of fuel cell vehicles (FCV) on platinum demand and price. Based on historical values, the authors show that platinum prices have been sensitive to changes in demand in the past. Combining this with scenarios for platinum recycling, they estimate the future price of platinum as a function of demand and the number of FCVs, finding an average platinum price increase by around 70 % in 2045. Schnuelle et al. [6] explore the impact of resource constraints in a hydrogen economy based on renewable energy sources. Among others, the authors describe that the availability of sufficient amounts of platinum alloys could be a bottleneck for building the hydrogen economy. Furthermore, Parra and Patel [7] deal with the techno-economic implications of the electrolyzer and their platinum demand. Robinson [8] examines the sensitivity of the future platinum price due to changes in macroeconomic variables and vice versa. Bao [9] investigates the dynamics and correlation of platinum (more precisely of platinum-group metals) spot prices in the time period between 1992 and 2019. Zhang et al. [10] focus on the effect of global oil price shocks on the platinum trade. The authors provide a national case study and look in detail at the Chinese market. Aspects of to what extent the geopolitics of oil and CRMs can be compared are given by MMånberger and Johansson [11]. The authors study the geopolitics of CRMs used for the sustainable energy transition and find that the geographic concentration of most of the studied materials will be higher than for oil.

Another interesting aspect in the context of our analysis in which the existing literature should be discussed is the aspect of secondary supply and the recycling of CRMs. The current literature already provides plenty of studies dealing, for example, with the recycling of steel and iron from a techno-economic perspective but hardly any about CRMs especially platinum. When it comes to steel and iron, we exemplarily refer to a recent study by Harvey [12] (focusing on constraints on the recycling of end-of-life steel) but also other studies could be mentioned. As mentioned, not much of comparable studies exist for CRMs and platinum. One exception in fact is the work by Tong et al. [13]. The authors study the recycling of platinum used in cars for the purpose of emission reduction potentials. In doing so, they analyze different scenarios from 2020 to 2050 and identify in their results, among others, the time lag between the peak of waste platinum (from the used fossil fuel cars) and the increasing demands from the FCVs. They conclude that it will be essential to upgrade the recycling of platinum, especially in developing countries, to secure platinum supply. A second study relevant here is presented by Sverdrup and Ragnarsdottir [14]. The authors investigate the long-term development of world primary extraction, market supply, and secondary supply such as the recycling of platinum. They use a system dynamics methodology to study the period from 1900 to 2400 and show that extraction will reach its maximum in the period from 2020 and 2050. The supply will, however, peak in 2070 to 2080. They conclude, based on the identified time lag, that recycling will play a crucial role in the future platinum supply.

3 Methodology

A deterministic bi-level optimization problem is proposed to answer the research questions. The lower-level problem considers the behavior of competitive fringe supply, in which a fixed demand is met by minimizing supply cost by the fringe suppliers, given the upper-level decisions by the major exporter (Stackelberg leader). The leader maximizes her profit and can exercise market power. The main links between the lower-level problem and the upper-level problem are the export price and quantity offered by the major exporter to the market clearing (i.e., decision variables from the upper-level problem serve as parameters for the lower-level problem) and, in the other direction, the cleared quantity and price (i.e., decision variables from the lower-level, whose dependence on the upper-level variables is recognized by the leader). In the lower-level problem, the market clearing is treated separately for the European and global markets $M1$ and $M2$ (by having two separate supply-demand equilibrium constraints), but the total cost of both is minimized. As described in detail below, this allows for the consideration of customized conditions (such as diversification of exporters), especially in finding the optimality of the European market clearing. Against this background and also taking into account the market power of the major exporter, it is assumed that there is no price discrimination between the two markets under consideration in the long run. Therefore, the mathematical formulation of the lower-level problem ensures that the market clearing prices are uniform. There are many arguments that could be used to justify why the clearing market prices are converging here. To mention just a few: price arbitrage by traders between the different markets potentially equalizes market price differences when there are no significant barriers to entry or exit; provided that the different markets are transparent, consumers have the opportunity to compare market prices, which in turn, discourages exporters and sellers from offering different prices; that the share of the transportation cost on the total cost does not dominate, as with the cost of critical raw materials, and under the fact that no demand shocks are considered (see Iwatsubo and Watkins [15]).

3.1 Lower-level problem: market clearing at minimized total cost

As is typical for bi-level optimization problems, the original formulation (or primal problem) of the lower-level problem is transformed into its dual problem using the Karush-Kuhn-Tucker (KKT) solution formalism [16]. The complete formulation of the dual problem of the lower-level problem (incl. Lagrangian function, KKT conditions, and complementarity conditions) can be found in Appendix A.1 and corresponding subsections. For easiness of reading, the main text focuses on the original formulation and the lower-level problem's primal problem.

3.1.1 Objective and decision variables

The objective of the lower-level problem is to minimize the sum of the generation cost of all exporters, the maintenance cost of fringe exporters, and the stockpiling cost of the European market when satisfying the demand of the European and global markets. Equation 1 shows the objective function while x is a vector containing all the lower-level problem's decision variables.

$$\min_x \underbrace{\sum_e \sum_m \sum_t c^{gen}_{e,t} \times q_{e,m,t}}_{\text{Generation cost of all exporters}} + \underbrace{\sum_{e'} \sum_t c^{main}_{e'} \times \bar{q}_{e',t}}_{\text{Maintenance cost of fringe exporters}} + \underbrace{\sum_t c^{stock} \times q^{stock,stored}_{M1,t}}_{\text{Stockpiling cost of European market}} \quad (1)$$

The decision variables $q_{e,m,t}$ is the supply quantity of exporter e, market m, and time step t. $c^{gen}_{e,t}$ is a parameter and describes the marginal supply cost per exporter e and time step t. Note that the latter varies over time for the major exporter only. For the fringe exporters, $c^{gen}_{e,t}$ is constant and assumed to be a single value over time. The decision variables $\bar{q}_{e',t}$ is the available supply capacity per fringe exporter e' and t. $c^{main}_{e',t}$ is a parameter and describes the specific maintenance cost per e'. In the third term, which considers the stockpiling cost of the European market $M1$, $q^{stock,stored}_{M1,t}$ is the decision variable of the stock stored for the European market per t. Again, c^{stock} is a parameter reflecting the specific stockpiling cost. The vector of decision variables is described in Equation 2.

$$x = [q_{e,m,t}, \bar{q}_{e',t}, \bar{q}^{add}_{e',t}, \bar{q}^{retire}_{e',t}, q^{arb}_{M1,M2,t}, q^{del}_{1,m,t}, q^{arb}_{1,m,t}, q^{stock,in/out}_{M1,t}, q^{stock,stored}_{M1,t}] \tag{2}$$

In addition to the decision variables described above, $\bar{q}^{add}_{e',t}$, $\bar{q}^{retire}_{e',t}$, $q^{arb}_{M1,M2,t}$, $q^{del}_{1,m,t}$, $q^{arb}_{1,m,t}$, and $q^{stock,in/out}_{M1,t}$ are introduced with x. $\bar{q}^{add}_{e',t}$ is the added available supply capacity per e' and t. $\bar{q}^{retire}_{e',t}$ is the retired supply capacity per e' and t. Both variables are directly influenced by the market clearing price of the previous time step $t-1$. This is explained in more detail in the Section 3.1.2 below. $q^{arb}_{M1,M2,t}$, $q^{del}_{1,m,t}$, and $q^{arb}_{1,m,t}$ are decision variables used solely to ensure uniform clearing prices between markets, as mentioned above. Essentially, this decision variable prevents exporters from engaging in price discrimination between the two markets. The quantity delivered to the market and used for arbitrage is explicitly considered for the major exporter ($q^{del}_{1,m,t}$, and $q^{arb}_{1,m,t}$), while an aggregate is considered for the sum of all the fringe exporters $q^{arb}_{M1,M2,t}$. A separate consideration for the major exporter is needed to ensure that major exporters' market share restrictions can be ensured when solving the model. $q^{stock,in/out}_{M1,t}$ is the quantity in or out of stock for the European market per t. Finally, note that $\bar{q}_{1,t}$ for the major export is a parameter for the lower-level problem, while it is a decision variable for the upper-level problem (see Section 3.2 in detail).

3.1.2 Constraints

The constraints of the lower level's primal problem are described below. For each constraint, the equation is given together with its applicability and the variable of the dual problem in parentheses. To help the reader understand the mathematical formulation of the model, the dual variables are numbered consecutively according to the equation number (see superscript of the dual variables). A distinction is also made between equality and inequality equations. Lambda (λ) is used for equality equations and mu (μ) for inequality equations. Table 1 outlines the most relevant mathematical formulations of the lower-level problem.

Equation 3 ensures that the supply quantity is less than the available supply capacity per e and t (capacity restriction). Equation 4 is the balance constraint of the major exporter per m and t, ensuring that the supply quantity is either directly delivered to a market or through arbitrage to the other considered market.

$$\left[\sum_{m} q_{e,m,t}\right] - \bar{q}_{e,t} \leq 0 \quad : \forall e, t \quad (\mu^{3}_{e,t}) \tag{3}$$

$$q^{del}_{1,m,t} + q^{arb}_{1,m,t} - q_{1,m,t} = 0 \quad : \forall m, t \quad (\lambda^{4}_{m,t}) \tag{4}$$

The Equations 5 and 6 are the supply balance constraints of the European market $M1$ and the global market $M2$. Note that they differ in the way in which the European market allows stockpiling.

$$\left[\sum_{e'} q_{e',M1,t}\right] - q^{arb}_{M1,M2,t} + q^{del}_{1,M1,t} + q^{arb}_{1,M2,t} + q^{stock,in/out}_{M1,t} - d_{M1,t} = 0 \quad : \forall t \quad (\lambda^{5}_{t}) \tag{5}$$

$$\left[\sum_{e'} q_{e',M2,t}\right] + q^{arb}_{M1,M2,t} + q^{del}_{1,M2,t} + q^{arb}_{1,M1,t} - d_{M2,t} = 0 \quad : \forall t \quad (\lambda^{6}_{t}) \tag{6}$$

The demand of the European and global market per t is $d_{M1,t}$ and $d_{M2,t}$ respectively. Equation 7 considers the embargo on all exporters $\underline{\boldsymbol{e}}$ at the European market $M1$. Equation 8 considers the share restriction on the major exporter at the European market $M1$. The supply share of the major exporter is limited by the share of α of the total annual demand $d_{M1,t}$.

$$q_{e,M1,t} = 0 \quad : \forall \underline{\boldsymbol{e}}, \quad (\lambda^{7}_{\underline{\boldsymbol{e}},t}) \tag{7}$$

$$q^{del}_{1,M1,t} + q^{arb}_{1,M2,t} - \alpha \times d_{M1,t} \leq 0 \quad : \forall t \quad (\mu^{8}_{t}) \tag{8}$$

Equation 8 takes into account that the initial stock at the European market $M1$ is zero. Equation 10 is the stock balance constraint.

$$q^{stock,stored}_{M1,2025} = 0 \quad (\lambda^{9}) \tag{9}$$

$$q^{stock,stored}_{M1,t'} - q^{stock,stored}_{M1,t'-1} + q^{stock,in/out}_{M1,t'-1} = 0 \quad : \forall t' \quad (\lambda^{10}_{t'}) \tag{10}$$

The equations 11 to 17 ensure the non-negativity of decision variables.

$$-q_{e,m,t} \leq 0 \quad : \forall e, m, t \quad (\mu^{11}_{e,m,t}) \tag{11}$$

$$-\bar{q}_{e',t} \leq 0 \quad : \forall e', t \quad (\mu^{12}_{e',t}) \tag{12}$$

$$-q^{del}_{1,m,t} \leq 0 \quad : \forall m, t \quad (\mu^{13}_{m,t}) \tag{13}$$

$$-q^{arb}_{1,m,t} \leq 0 \quad : \forall m, t \quad (\mu^{14}_{m,t}) \tag{14}$$

$$-q^{stock,stored}_{M1,t} \leq 0 \quad : \forall t \quad (\mu^{15}_{t}) \tag{15}$$

$$-\bar{q}^{add}_{e',t} \leq 0 \quad : \forall e', t \quad (\mu^{16}_{e',t}) \tag{16}$$

$$-\bar{q}^{retire}_{e',t} \leq 0 \quad : \forall t \quad (\mu^{17}_{e',t}) \tag{17}$$

The dual variables λ^5_t and λ^6_t (below just λ_t) are crucial to the following description of the upper-level problem. Both variables are directly incorporated in the objective function of the upper-level problem and thus in maximizing the profit of the major exporter. In order to consider the impact of the market price not only on the decision and the resulting outcome of the major exporter in the top-level problem, the following approach is also chosen: The available supply capacity $\bar{q}_{e',t}$ of all fringe exporters is assumed to be a function of the market clearing price λ_t. The Equation 18 describes this relation. For simplification, it is assumed that more exporter's capacities are economically viable and can be made available to the market when market prices rise (for example, due to the profit maximization strategy of the major exporter).

$$\bar{q}_{e',t'} = \bar{q}_{e',t'-1} + \bar{q}^{add}_{e',t'} - \bar{q}^{retire}_{e',t'} \quad \text{with } \bar{q}^{add}_{e',t'} = f_{e'}(\lambda_{t'-1}) \quad : \forall e', t' \tag{18}$$

The available supply capacity of the major exporter is not affected by the market clearing price, nor is it a decision variable in the lower-level problem. Before a detailed description of the upper-level problem is given, a few thoughts are added here to underscore the proposed approach, especially the relationship between the market-clearing price and the available supply capacity of exporters. Since there is little historical and empirical data on the evolution of markets for critical raw materials (including their prices), a look at other markets can be useful. An example is the oil market. This market can serve as an example since similar market conditions can be assumed as in the markets for critical raw materials (e.g. high production concentration and thus market shares of a few exporters). A paper that explicitly examines the question of why oil prices jump is published by Wirl back in 2008 [17]. The author shows that the main reason for jumping oil prices is the strategic behavior (i.e. pricing) of exporters with market power. More specifically, he reveals that they seek hysteresis in the clearing price to maximize profits by crowding out other (smaller) exporters. Such jumping of prices is not only observed for the oil markets but also for other markets, such as the natural gas market (see for example Mason & Wilmot [18]).

3.2 Upper-level problem: profit maximization of the major exporter

As is often the case with bi-level optimization, the upper-level problem is much simpler than the lower-level problem. This leads in the case here to the fact, that the upper-level problem, which is the profit maximization of the major exporter (index 1 with refer to the lower-level problem from above) to the fact, that there are only two equations. The first, Equation 19, is the objective function of the problem. It shows the profit maximization of the major exporter by setting its decision variables.

$$\max_{\mathcal{Y}} \sum_{m} \sum_{t} q_{1,m,t} \times (\lambda_t - \tilde{c}) \tag{19}$$

The decision variables are summarized by $\mathcal{Y}$ and include the variables $c_{1,t}$ and $\bar{q}_{1,t}$. This is also described in Equation 20. As a reminder, $c_{1,t}$ is the marginal supply cost and $\bar{q}_{1,t}$ is the available supply capacity of the major exporter 1 at time step t. Both variables are parameters in the lower-level problem.

$$\mathcal{Y} = [c_{1,t}, \bar{q}_{1,t}] \tag{20}$$

Essentially, the major exporter sets both variables so that the product of the cleared quantity delivered to the markets and the market clearing prices are maximized. Thereby, the only constraint is that the offered supply capacity is equal to or smaller than the real supply capacity ($\tilde{q}_1$) which is assumed to be static over time. This is described in Equation 21.

$$0 \leq \bar{q}_{1,t} \leq \tilde{q}_1 \tag{21}$$

Further details on the mathematical formulation of the upper-level problem can be found A.2. Especially this section explains how the non-linear term $q_{1,m,t} \times \lambda_t$ is linearized.

Table 1: Summary of the mathematical formulation of the lower-level problem (market clearing at minimized total cost)

Equation			Qualitative/high-level explanation of the mathematical equation	
No.	Dim.	Dual var.	Keyword	Brief description
1	1	-	Objective	Minimize the sum of generation (all exporters), maintenance (fringe exporters), and stockpiling (European market $M1$) cost
3	$\lvert\mathcal{E}\rvert \times \lvert\mathcal{T}\rvert$	$\mu^3_{e,t}$	Capacity	Restrict supply quantity by available export capacity
4	$\lvert\mathcal{M}\rvert \times \lvert\mathcal{T}\rvert$	$\lambda^4_{m,t}$	Generation	Generation balance constraint of the major exporter 1
5	$\lvert\mathcal{T}\rvert$	λ^5_t	Market $M1$	Supply balance of the European market $M1$
6	$\lvert\mathcal{T}\rvert$	λ^6_t	Market $M2$	Supply balance of the global market $M2$
7	$\lvert\underline{\mathcal{E}}\rvert$	$\lambda^7_{\underline{e},t}$	Embargo	Embargo on exporters at the European market $M1$
8	$\lvert\mathcal{T}\rvert$	μ^8_t	Share	Restriction on the supply share of the major exporter 1 at the European market $M1$
9	1	λ_9	Initial stock	Set initial stock at the European market $M1$ zero
10	$\lvert\mathcal{T}'\rvert$	$\lambda^{10}_{t'}$	Stock balance	Stock balance constraint at the European market $M1$

3.3 Scenarios

Scenario 1: Strategic Dominance by the main player (Base case scenario)

Context: This scenario envisions the dominant player leveraging its dominant position in the REEs market to influence strategic decisions and gain maximum economic benefit. The EU adapts to the market conditions set by the dominant player.

Key Assumptions:

1. The dominant player maintains its dominant market position.
2. The EU relies heavily on dominant player REEs due to limited alternative sources.
3. The CRM Act has limited effectiveness in mitigating the dominant player's market dominance.

Expected Outcomes:

1. Supply Chain Dependency:
   - The EU becomes heavily dependent on the dominant player REEs.
   - The dominant player exercises market power to influence prices and dictate supply terms.
1. Vulnerability to Supply Disruptions:
   - The EU faces heightened vulnerability to supply disruptions due to its reliance on a single dominant player.
   - The dominant player strategically controls supply to maximize its economic interests.
1. Limited Technological Innovation: Innovation in REEs extraction and processing technologies may be stifled as the dominant player maintains control over the market.

Research Question from scenario 1: How does the main player's strategic dominance in the REEs market influence the EU's supply chain dynamics, particularly in terms of supply chain dependency, vulnerability to disruptions, and the impact on technological innovation, and what are the long-term implications for the European CRM sector?

Scenario 2: CRM Act Provision Compliance and Effectiveness/Diversification

Context: In this scenario, the CRM Act proves highly effective in promoting the diversification of CRM sources for the EU. The EU actively seeks alternative suppliers and reduces dependency on any single market player.

Key Assumptions:

Provisions Compliance:

1. All countries, including the dominant player, adhere strictly to the provisions outlined in the CRM Act.
2. The 65% limit for REE exports to the EU is respected by all nations.

Effectiveness/Diversification:

1. The CRM Act encourages diversification and reduces entry barriers for alternative suppliers.
2. The EU invests in exploring new sources of platinum

3. Strategic partnerships are formed with multiple countries to ensure a diversified and resilient supply chain.

Expected Outcomes:

1. Reduced Dependency on the dominant player:

   - The EU successfully reduces its dependency on the dominant player's REEs.
   - Alternative suppliers contribute to a more balanced market.

1. Resilient Supply Chain:

   - The CRM supply chain becomes more resilient to market fluctuations and supply disruptions.
   - Diversification ensures stability even in the face of geopolitical uncertainties.

1. Technological Innovation: Increased competition and collaboration with alternative suppliers stimulate technological innovation in the CRM sector.

Research Question from scenario 2: To what extent does the CRM Act, through provisions compliance and effectiveness in promoting diversification, contribute to reducing the EU's dependency on the dominant player REEs, creating a more resilient CRM supply chain, and fostering technological innovation in the platinum sector?

Scenario 3: Geopolitical Tensions/Supply Disruptions and Stockpiling
Context: This scenario explores the impact of heightened geopolitical tensions between the dominant player and the EU, resulting in disruptions to the REEs supply chain.
Key Assumptions:

1. Escalation of Geopolitical Tensions: Geopolitical tensions between the dominant player and the EU escalate due to trade disputes, political differences, or other geopolitical factors.

1. Supply Chain Disruptions:

   - Geopolitical tensions result in disruptions to the REEs supply chain, including trade restrictions, export bans, or other geopolitical actions.
   - Traditional supply routes are affected, leading to delays and shortages in REEs availability.

1. Stockpiling Provisions of the CRM Act:

   - The CRM Act includes provisions on stockpiling as a strategic response to potential supply disruptions.
   - The EU, guided by these provisions, initiates stockpiling efforts to build reserves of critical REEs.
   - The EU successfully establishes a safe level of union stock with cross-border accessibility, as mandated by the CRM Act.

Expected Outcomes:

1. Strategic Stockpiling and Supply Chain Resilience:

- The EU, in response to supply disruptions, activates the stockpiling provisions of the CRM Act.
- Strategic stockpiling enhances the resilience of the EU's REEs supply chain by creating a buffer against short-term disruptions.

1. Mitigation of Hydrogen Production Challenges:

   - While disruptions occur, the strategic stockpiles help the EU mitigate challenges in meeting its hydrogen production targets.
   - Essential REEs for hydrogen production remain accessible during periods of supply chain uncertainty.

1. Market Uncertainties and Volatility:

   - Prices in the global REEs market become volatile due to the geopolitical tensions.
   - Market uncertainties impact both the dominant player and the EU, leading to challenges in strategic planning and decision-making.

1. Rethinking Strategic Partnerships:

   - Both China and the EU reassess their strategic partnerships in the wake of geopolitical tensions and disruptions.
   - Alternative arrangements, such as exploring diversified sources or establishing more resilient supply chain networks, are considered.

Research Question from scenario 3: How do the stockpiling provisions of the CRM Act mitigate the impact of geopolitical tensions and supply disruptions on the EU's REEs supply chain, and to what extent do these provisions contribute to the resilience of the supply chain, address challenges in meeting hydrogen production targets, and influence strategic decision-making amid market uncertainties and volatility?

3.4 Data

MAX

4 Results and discussion

5 Conclusion

Declaration of Competing Interest

The authors report no declarations of interest.

Acknowledgement

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Appendices

A Mathematical formulation of the bi-level optimization problem

A.1 Lower-level problem: market clearing at minimized total cost

A.1.1 Primal decision variables

$$x = [q_{e,m,t}, \bar{q}_{e',t}, \bar{q}^{add}_{e',t}, \bar{q}^{retire}_{e',t}, q^{arb}_{M1,M2,t}, q^{del}_{1,m,t}, q^{arb}_{1,m,t}, q^{stock,in/out}_{M1,t}, q^{stock,stored}_{M1,t}] \tag{22}$$

A.1.2 Objective function

$$\min_{x} \underbrace{\sum_{e}\sum_{m}\sum_{t} c^{gen}_{e,t} \times q_{e,m,t}}_{\text{Generation cost of all exporters}} + \underbrace{\sum_{e'}\sum_{t} c^{main}_{e'} \times \bar{q}_{e',t}}_{\text{Maintenance cost of fringe exporters}} + \underbrace{\sum_{t} c^{stock} \times q^{stock,stored}_{M1,t}}_{\text{Stockpiling cost of European market}} \tag{23}$$

A.1.3 Constraints (primal problem)

Equality constraints

$$q^{del}_{1,m,t} + q^{arb}_{1,m,t} - q_{1,m,t} = 0 \quad : \forall m, t \quad (\lambda^4_{m,t}) \tag{24}$$

$$\left[\sum_{e'} q_{e',M1,t}\right] - q^{arb}_{M1,M2,t} + q^{del}_{1,M1,t} + q^{arb}_{1,M2,t} + q^{stock,in/out}_{M1,t} - d_{M1,t} = 0 \quad : \forall t \quad (\lambda^5_t) \tag{25}$$

$$\left[\sum_{e'} q_{e',M2,t}\right] + q^{arb}_{M1,M2,t} + q^{del}_{1,M2,t} + q^{arb}_{1,M1,t} - d_{M2,t} = 0 \quad : \forall t \quad (\lambda^6_t) \tag{26}$$

$$q_{e,M1,t} = 0 \quad : \forall \underline{\boldsymbol{e}}, \quad (\lambda^7_{\underline{\boldsymbol{e}},t}) \tag{27}$$

$$q^{stock,stored}_{M1,2025} = 0 \quad (\lambda^9) \tag{28}$$

$$q^{stock,stored}_{M1,t} - q^{stock,stored}_{M1,t-1} + q^{stock,in/out}_{M1,t-1} = 0 \quad : \forall t' \quad (\lambda^{10}_{t'}) \tag{29}$$

Inequality constraints

$$\left[\sum_{m} q_{e,m,t}\right] - \bar{q}_{e,t} \leq 0 \quad : \forall e, t \quad (\mu^3_{e,t}) \tag{30}$$

$$q^{del}_{1,M1,t} + q^{arb}_{1,M2,t} - \alpha \times d_{M1,t} \leq 0 \quad : \forall t \quad (\mu^8_t) \tag{31}$$

$$-q_{e,m,t} \leq 0 \quad : \forall e, m, t \quad (\mu^{11}_{e,m,t}) \tag{32}$$

$$-\bar{q}_{e',t} \leq 0 \quad : \forall e', t \quad (\mu^{12}_{e',t}) \tag{33}$$

$$-q^{del}_{1,m,t} \leq 0 \quad : \forall m, t \quad (\mu^{13}_{m,t}) \tag{34}$$

$$-q^{arb}_{1,m,t} \leq 0 \quad : \forall m, t \quad (\mu^{14}_{m,t}) \tag{35}$$

$$-q^{stock,stored}_{M1,t} \leq 0 \quad : \forall t \quad (\mu^{15}_{t}) \tag{36}$$

A.1.4 Dual decision variables

$$\lambda = [\lambda^4_{m,t}, \lambda^5_t, \lambda^6_t, \lambda^7_{\underline{e},t}, \lambda^9, \lambda^{10}_{t'}] \tag{37}$$

$$\mu = [\mu^3_{e,t}, \mu^8_t, \mu^{11}_{e,m,t}, \mu^{12}_{e',t}, \mu^{13}_{m,t}, \mu^{14}_{m,t}, \mu^{15}_t] \tag{38}$$

A.1.5 Lagrangian function

$$
\begin{aligned}
\mathcal{L}(x,\lambda,\mu) = & \sum_e \sum_m \sum_t c^{gen}_{e,t} \times q_{e,m,t} + \sum_{e'} \sum_t c^{main}_{e'} \times \bar{q}_{e',t} + \sum_t c^{stock} \times q^{stock,stored}_{M1,t} \\
& + \sum_m \sum_t \lambda^4_{m,t} \times \left\{ q^{del}_{1,m,t} + q^{arb}_{1,m,t} - q_{1,m,t} \right\} \\
& + \sum_t \lambda^5_t \times \left\{ \left[\sum_{e'} q_{e',M1,t} \right] - q^{arb}_{M1,M2,t} + q^{del}_{1,M1,t} + q^{arb}_{1,M2,t} + q^{stock,in/out}_{M1,t} - d_{M1,t} \right\} \\
& + \sum_t \lambda^6_t \times \left\{ \left[\sum_{e'} q_{e',M2,t} \right] + q^{arb}_{M1,M2,t} + q^{del}_{1,M2,t} + q^{arb}_{1,M1,t} - d_{M2,t} \right\} \\
& + \sum_{\underline{e}} \sum_t \lambda^7_{\underline{e},t} \times \left\{ q_{\underline{e},M1,t} \right\} \\
& + \lambda^9 \times \left\{ q^{stock,stored}_{M1,2025} \right\} \\
& + \sum_{t'} \lambda^{10}_{t'} \times \left\{ q^{stock,stored}_{M1,t'} - q^{stock,stored}_{M1,t'-1} + q^{stock,in/out}_{M1,t'-1} \right\} \\
& + \sum_e \sum_t \mu^3_{e,t} \times \left\{ \left[\sum_m q_{e,m,t} \right] - \bar{q}_{e,t} \right\} \\
& + \sum_t \mu^8_t \times \left\{ q^{del}_{1,M1,t} + q^{arb}_{1,M2,t} - \alpha \times d_{M1,t} \right\} \\
& + \sum_e \sum_m \sum_t \mu^{11}_{e,m,t} \times \left\{ -q_{e,m,t} \right\} \\
& + \sum_{e'} \sum_t \mu^{12}_{e',t} \times \left\{ -\bar{q}_{e',t} \right\} \\
& + \sum_m \sum_t \mu^{13}_{m,t} \times \left\{ -q^{del}_{1,m,t} \right\} \\
& + \sum_m \sum_t \mu^{14}_{m,t} \times \left\{ -q^{arb}_{1,m,t} \right\} \\
& + \sum_t \mu^{15}_t \times \left\{ -q^{stock,stored}_{M1,t} \right\}
\end{aligned}
\tag{39}
$$

A.1.6 Karush–Kuhn–Tucker conditions

$$
\frac{\partial \mathcal{L}}{\partial q_{e,m,t}} = \begin{cases}
c^{gen}_{1,t} - \lambda^4_{M1,t} + \lambda^7_{1,t} + \mu^3_{1,t} - \mu^{11}_{1,M1,t} = 0 & : \forall t, \text{ if } 1 \in \underline{\mathcal{E}} \\
c^{gen}_{1,t} - \lambda^4_{M1,t} + \mu^3_{1,t} - \mu^{11}_{1,M1,t} = 0 & : \forall t, \text{ if } 1 \notin \underline{\mathcal{E}} \\
c^{gen}_{1,t} - \lambda^4_{M2,t} + \mu^3_{1,t} - \mu^{11}_{1,M2,t} = 0 & : \forall t \\
c^{gen}_{e',t} + \lambda^5_t + \mu^3_{e',t} - \mu^{11}_{e',M1,t} = 0 & : \forall e' \notin \underline{\mathcal{E}}, t \\
c^{gen}_{e',t} + \lambda^5_t + \lambda^7_{e',t} + \mu^3_{e',t} - \mu^{11}_{e',M1,t} = 0 & : \forall e' \in \underline{\mathcal{E}}, t \\
c^{gen}_{e',t} + \lambda^6_t + \mu^3_{e',t} - \mu^{11}_{e',M2,t} = 0 & : \forall e', t
\end{cases}
\tag{40}
$$

$$
\frac{\partial \mathcal{L}}{\partial \bar{q}_{e',t}} = c^{main}_{e',t} - \mu^3_{e',t} - \mu^{12}_{e',t} = 0 \quad : \forall e', t \tag{41}
$$

$$\frac{\partial \mathcal{L}}{\partial q^{arb}_{M1,M2,t}} = -\lambda^5_t + \lambda^6_t = 0 \quad : \forall t \tag{42}$$

$$\frac{\partial \mathcal{L}}{\partial q^{del}_{1,m,t}} = \begin{cases} \lambda^4_{M1,t} + \lambda^5_t + \mu^8_t - \mu^{13}_{M1,t} = 0 & : \forall t \\ \lambda^4_{M2,t} + \lambda^6_t - \mu^{13}_{M2,t} = 0 & : \forall t \end{cases} \tag{43}$$

$$\frac{\partial \mathcal{L}}{\partial q^{arb}_{1,m,t}} = \begin{cases} \lambda^4_{M1,t} + \lambda^6_t - \mu^{14}_{M1,t} = 0 & : \forall t \\ \lambda^4_{M2,t} + \lambda^5_t + \mu^8_t - \mu^{14}_{M2,t} = 0 & : \forall t \end{cases} \tag{44}$$

$$\frac{\partial \mathcal{L}}{\partial q^{stock,in/out}_{M1,t}} = \lambda^5_t + \lambda^{10}_{t+1} = 0 \quad : \forall t \setminus \{t_{end}\} \tag{45}$$

$$\frac{\partial \mathcal{L}}{\partial q^{stock,stored}_{M1,t}} = \begin{cases} c^{stock} + \lambda^9 - \lambda^{10}_{2026} - \mu^{15}_{2025} = 0 \\ c^{stock} + \lambda^{10}_{t'} - \lambda^{10}_{t'+1} - \mu^{15}_{t'} = 0 & : \forall t' \setminus \{t_{end}\} \\ c^{stock} + \lambda^{10}_{2040} - \mu^{15}_{2040} = 0 \end{cases} \tag{46}$$

$$0 \leq \mu^3_{e,t} \quad \perp \quad \left[\sum_m q_{e,m,t}\right] - \bar{q}_{e,t} \leq 0 \quad : \forall e, t \tag{47}$$

$$0 \leq \mu^8_t \quad \perp \quad q^{del}_{1,M1,t} + q^{arb}_{1,M2,t} - \alpha \times d_{M1,t} \leq 0 \quad : \forall t \tag{48}$$

$$0 \leq \mu^{11}_{e,m,t} \quad \perp \quad - q_{e,m,t} \leq 0 \quad : \forall e, m, t \tag{49}$$

$$0 \leq \mu^{12}_{e',t} \quad \perp \quad - \bar{q}_{e',t} \leq 0 \quad : \forall e', t \tag{50}$$

$$0 \leq \mu^{13}_{m,t} \quad \perp \quad - q^{del}_{1,m,t} \leq 0 \quad : \forall m, t \tag{51}$$

$$0 \leq \mu^{14}_{m,t} \quad \perp \quad - q^{arb}_{1,m,t} \leq 0 \quad : \forall m, t \tag{52}$$

$$0 \leq \mu^{15}_t \quad \perp \quad - q^{stock,stored}_{M1,t} \leq 0 \quad : \forall m, t \tag{53}$$

A.1.7 Complementarity condition linearization

The complementarity conditions in Equations 47 to 53 are linearized using the well-known linear expressions (see [19]) as follows, where u is a binary decision variable and M is a parameter large enough to ensure complementarity (both indexed accordingly).

$$\begin{aligned} 0 \leq \mu^{3}_{e,t} \leq M^{3} \times u^{3}_{e,t} \quad &: \forall e,t \\ 0 \leq \left[\sum_{m} q_{e,m,t}\right] - \bar{q}_{e,t} \leq M^{3} \times \left(1 - u^{3}_{e,t}\right) \quad &: \forall e,t \end{aligned} \tag{54}$$

$$\begin{aligned} 0 \leq \mu^{8}_{t} \leq M^{8} \times u^{8}_{t} \quad &: \forall t \\ 0 \leq q^{del}_{1,M1,t} + q^{arb}_{1,M2,t} - \alpha \times d_{M1,t} \leq M^{8} \times \left(1 - u^{8}_{t}\right) \quad &: \forall t \end{aligned} \tag{55}$$

$$\begin{aligned} 0 \leq \mu^{11}_{e,m,t} \leq M^{11} \times u^{11}_{e,m,t} \quad &: \forall e,m,t \\ 0 \leq q_{e,m,t} \leq M^{11} \times \left(1 - u^{11}_{e,m,t}\right) \quad &: \forall e,m,t \end{aligned} \tag{56}$$

$$\begin{aligned} 0 \leq \mu^{12}_{e',t} \leq M^{12} \times u^{12}_{e',t} \quad &: \forall e',t \\ 0 \leq \bar{q}_{e',t} \leq M^{12} \times \left(1 - u^{12}_{e',t}\right) \quad &: \forall e',t \end{aligned} \tag{57}$$

$$\begin{aligned} 0 \leq \mu^{13}_{m,t} \leq M^{13} \times u^{13}_{m,t} \quad &: \forall m,t \\ 0 \leq q^{del}_{1,m,t} \leq M^{13} \times \left(1 - u^{13}_{m,t}\right) \quad &: \forall m,t \end{aligned} \tag{58}$$

$$\begin{aligned} 0 \leq \mu^{14}_{m,t} \leq M^{14} \times u^{14}_{m,t} \quad &: \forall m,t \\ 0 \leq q^{arb}_{1,m,t} \leq M^{14} \times \left(1 - u^{14}_{m,t}\right) \quad &: \forall m,t \end{aligned} \tag{59}$$

$$\begin{aligned} 0 \leq \mu^{15}_{t} \leq M^{15} \times u^{15}_{t} \quad &: \forall t \\ 0 \leq q^{stock,stored}_{M1,t} \leq M^{15} \times \left(1 - u^{15}_{t}\right) \quad &: \forall t \end{aligned} \tag{60}$$

A.2 Upper-level problem: profit maximization of the major exporter

A.2.1 Decision variables

$$\mathcal{Y} = [c_{1,t}, \bar{q}_{1,t}] \tag{61}$$

A.2.2 Objective function

$$\max_{\mathcal{Y}} \sum_{m} \sum_{t} q_{1,m,t} \times (\lambda_t - \tilde{c}) \tag{62}$$

A.2.3 Constraints

$$0 \leq \bar{q}_{1,t} \leq \tilde{q}_1 \quad : \forall t \tag{63}$$

A.2.4 Linear reformulation

- Of the non-linear term $q_{1,m,t} \times \lambda_t$ (see Equation 62)
- With m,n in [($M1$, 5), ($M2$, 6)] (see Equations 25 and 26)
- With the following new variables: $\sigma_{e',m,t}$ (binary), $\tilde{\lambda}^n_{e',t}$ (continuous), $\tilde{\sigma}_{e',m,t}$ (binary)
- With the following new parameters: $\tilde{\beta}$ (large enough), ϵ (small enough)

$$\lambda_t = \lambda^n_t = \sum_{e'} c_{e'} \times \sigma_{e',m,t} \quad : \forall t, m, n \tag{64}$$

$$\sum_{e'} \sigma_{e',m,t} = 1 \quad : \forall t, m \tag{65}$$

$$\tilde{\lambda}^n_{e',t} = c_{e'} \times \tilde{\sigma}_{e',m,t} \quad : \forall e', t, m, n \tag{66}$$

$$q_{e',m,t} \leq \tilde{\beta} \times \tilde{\sigma}_{e',m,t} \quad : \forall e', m, t \tag{67}$$

$$q_{e',m,t} \geq \epsilon \times \tilde{\sigma}_{e',m,t} \quad : \forall e', m, t \tag{68}$$

$$\sigma_{e',m,t} \leq \tilde{\sigma}_{e',m,t} \quad : \forall e', m, t \tag{69}$$

$$\lambda^n_t \geq \tilde{\lambda}^n_{e',t} \quad : \forall e', t, n \tag{70}$$

- Introducing the following new variable $z_{e',m,t}$ (continuous) and parameter β (large enough)

$$z_{e',m,t} \leq \beta \times \sigma_{e',m,t} \quad : \forall e', m, t \tag{71}$$

$$z_{e',m,t} \leq q_{1,m,t} \quad : \forall e', m, t \tag{72}$$

$$z_{e',m,t} \geq q_{1,m,t} - \big(1 - \sigma_{e',m,t}\big) \times \beta \quad : \forall e', m, t \tag{73}$$

$$z_{e',m,t} \geq 0 \quad : \forall e', m, t \tag{74}$$

A.3 Completed optimization problem

$$\max_{x,\lambda,\mu,u,y,\sigma,z} \sum_{e'} \sum_{m} \sum_{t} c_{e'} \times z_{e',m,t} - \sum_{m} \sum_{t} q_{1,m,t} \times \tilde{c}$$

$$\begin{aligned} \text{s.t. } & (40) - (46) \\ & (54) - (60) \\ & (64) - (74) \\ & (63) \\ & (18) \end{aligned} \tag{75}$$

B Data

MAX

B.1 Assumptions regarding the potential of recycling platinum