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Critical Materials to Meet Europe's 2030 Hydrogen Target: Modeling Supply Dynamics and Market Power Risks

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Abstract:	The central role of hydrogen in the EU's decarbonization strategy has increased the importance of critical raw materials. To address this, the EU has taken legislative steps, including the 2023 Critical Raw Material Act (CRMA), to ensure a stable supply. Using a new model based on a leader-follower Stackelberg game framework, we analyze critical raw material market dynamics, compliance with CRMA regulations, value chain resilience, and geopolitical influences. Our results identify potential for strategic behavior by major exporters while stressing the value of diversified export sources and stockpiling to ensure supply stability. The analysis provides insights into the EU's efforts to secure critical raw material supplies, which are key to achieving decarbonization goals and fostering a sustainable energy transition. Additional research is needed to explore alternative approaches to reducing supply costs and exporter market power and the broader implications of pricing mechanisms, market outcomes, and consumer welfare.
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April 2, 2024

Dear Professor Tol,

On behalf of my co-authors, I wish to submit an original research article entitled "Critical Materials to Meet Europe's 2030 Hydrogen Target: Modeling Supply Dynamics and Market Power Risks" for consideration by Energy Economics.

In the present manuscript, we provide an original perspective on the rising importance of critical raw materials (CRMs) in the context of hydrogen uptake by 2030. Our work introduces a novel model utilizing a leader-follower Stackelberg game framework to comprehensively analyze critical raw material market dynamics, compliance with regulations, value chain resilience, and geopolitical influences.

What has emerged from the work is the importance of strategic behavior among major exporters, diversified supply sources, recycling practices, and stockpiling for stability in critical raw material markets globally and in Europe, noting a potential shift in dominance towards fringe competitors like Russia due to production cost disparities. Furthermore, it is emphasize the critical role of diversified export sources and recycling in Europe, alongside demand resilience to price fluctuations and the potential of recycling to mitigate resource constraints despite capacity challenges. Stockpiling is highlighted as crucial for supply stability and price mitigation in Europe, with optimal sizes around twice the annual demand. Overall, the work reveals the complexity of the CRMs market dynamics and highlights the importance of strategic planning, diversified sourcing, and regulatory interventions for a stable and sustainable supply chain for critical raw materials in the context of Europe's energy transition goals.

We believe that this manuscript is appropriate for publication by Energy Economics because it offers insights into the economic aspects of securing a stable supply chain for CRMs in the renewable energy sector. The work employs a strong methodological approach that combines market dynamics and policy provisions. Its findings have direct policy implications for policymakers. It also drives home the need to investigate further under-researched issues that could have significant implications for policy design on market outcomes and consumer welfare.

I confirm that this manuscript has not been published elsewhere and is not under consideration by any other journal. I also confirm that all authors listed on the title page have approved the manuscript and agree with its submission to Energy Economics. The data will be published as open source: Sesini, M., Zwickl-Bernhard, S., Münchmeyer, M., & Hobbs, B. F. (2024). Modeling Europe's 2030 Hydrogen Target: Raw Material Supply Dynamics, Risks, and Resilience - Data (v.1) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.10865913 [embargoed until publication]. We have no conflicts of interest to disclose.

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Thank you for your consideration.
Kind regards,

Marzia Sesini

(Marzia Sesini)

Critical Materials to Meet Europe's 2030 Hydrogen Target: Modeling Supply Dynamics and Market Power Risks

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Abstract

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Keywords— Hydrogen Strategy, Critical Raw Materials, Supply Dynamics, Regulatory Compliance, Value Chain Resilience

Analyzing Europe's 2030 Hydrogen Target: Raw Material Supply Dynamics, Risks, and Resilience

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Highlights:

- EU's hydrogen goals hindered by specific countries' raw material supply dominance.
- Analyzed market dynamics blending game theory and the Critical Raw Material Act.
- Market dominance might shift to fringe competitors due to production cost gaps.
- Critical role of diversified export sources and recycling in Europe.
- Stockpiling is highlighted as crucial for supply stability and price mitigation.

Critical Materials to Meet Europe's 2030 Hydrogen Target: Modeling Supply Dynamics and Market Power Risks

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1 Introduction

The EU initiated the development of a robust hydrogen (H2) supply sector 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, and, therefore, the materials needed in their manufacture International Energy Agency (2023a).

In particular, producing H2 involves specific metal needs, with Critical Raw Materials (CMRs) playing a pivotal role in the EU's H2 economy and security. As the production and processing of many CRMs are geographically concentrated, the EU is increasingly dependent on individual countries, including China, Democratic Republic of Congo, Russia, Turkey, and South Africa, for more than 75% of its supply, and as much as 100% for some rare earth elements (REEs). Uncertainties regarding the evolution of EU demand for CMRs beyond 2030, evolving from negligible levels in 2020 to an expected 3.95kt in 2030 Liesbet (2023), aligned with most countries' H2 production targets, emphasize the need for strategic planning.

Different types of electrolyzers, primarily Alkaline and Proton Exchange Membrane (PEM), have distinct mineral requirements. Projections indicate an average increase in demand for platinum (+24 %), iridium (+43 %), and scandium (+68 %) from the EU H2 sector by 2030 International Energy Agency (2023a) . Challenges in producing these materials stem from, first, their status as by-products, limiting flexibility in scaling up production, and, second, from geological conditions inhibiting new mines, as seen in the case of iridium in the EU, which is often found as a by-product of nickel or platinum mining).

The study focuses on platinum, which is part of the eponymous set of Platinum Group Metals (PGMs). In addition to platinum, the group comprises ruthenium, rhodium, palladium and iridium. These metals are commonly found and mined together Commission (2023a). Currently, platinum is primarily used in the automotive industry, where it is needed for manufacturing catalytic converters for vehicles using an internal combustion engine. While an increasing penetration of electric vehicles in the EU is likely to reduce the automotive industry's demand for platinum, on the other hand that metal will become increasingly important for the EU's supply of green hydrogen. As mentioned above, platinum is needed for PEM electrolyzers, which are expected to account for approximately 55% of the electrolyzer market in 2030 and 35% in 2050 Commission et al. (2023). The Joint Research Center (JRC) thus estimates that, in a high-demand scenario with conservative material efficiency assumptions and in which the climate objectives of the EU are met, the platinum demand for electrolyzers will increase from 0.02 tonnes per year in 2020 to 16.6 tonnes in 2030 and 33.6 tonnes in 2050 Commission et al. (2023).

Known global reserves of platinum are highly concentrated, with the Republic of South Africa possessing 63 million of the 71 million tonnes of known PGM reserves and accounting for 120 out of a total of 180 tonnes of global platinum mine production in 2023 US Geological Survey (2024). With Europe's ongoing transition toward a cleaner future in the coming decades, the strategic importance of CRMs will rise, and supply availability will be increasingly challenging. The growing demand for CRMs since the mid-1960s is compounded by the monopolistic structure of the CRMs supply market. China has dominated the global CRMs 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 CRMs market, it becomes crucial 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 and vulnerability for supply risks 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. The EU largely disregarded these concerns until two decades ago, with China especially, which dominates the up and mid-stream activities for CRMs. More recently, China has taken several actions, including 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). It is against this legislative, technological, and geological background that this study assessses possible measures that the EU can take to maintain its strategic autonomy and competitiveness in platinum as it pursues its hydrogen production objectives to 2030 and beyond.

To undertake this assessment, this work starts by proposing a novel model that integrates a leader-follower Stackelberg game framework, considering the competitive dynamics between the dominant player in the platinum supply chain 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 potential future trajectories of the European CRMs sector under diverse scenarios, offering potentially valuable perspectives for policymakers and industry stakeholders alike.

Focusing on the need for CRMs to support growth of in the hydrogen economy, the study addresses three pivotal issues at the convergence of geopolitics, market dynamics, and regulatory frameworks within the CRM sector. First, the investigation delves into strategic behavior of the market-dominant player and its impact on the EU supply chain, for platinum. It then explores the interplay between the dominant player in the platinum market and the EU within the CRMs market, considering the impacts of EU policies on those interactions. Thereby, the research evaluates the CRM Act's potential contribution to fortifying Europe's CRMs supply chain, especially concerning the challenges of meeting ambitious hydrogen production targets by 2030.

In particular, this analysis centers on the regulatory framework's role in mitigating dependencies on dominant players. With the first issue, the work seeks to provide insights into how supply chain dependency, vulnerability to disruptions, and potential limitations in technological innovation could unfold under the dominance of a single market player, investigating their implications for the EU's CRMs supply chain dynamics. With the second issue, it aims to explore the CRM Act's impact on creating a more resilient CRM supply chain and spurring of technological innovation within the sector through collaborative efforts with alternative suppliers. Lastly, with the third issue, the work addressed concerns on how the provisions of the CRM Act, and in particular the role of its stockpiling provisions, mitigate the impact of geopolitical tensions on the EU's CRM supply chain, contributing to supply chain resilience.

The paper is organized as follows. The next section positions the work in the literature and focuses on the framework of the CRM Act and the previous techno-economic modeling studies of CRMs markets. Section 3 details the modeling framework and the key scenarios investigated, while Section 4 presents results. Finally, Section 5 offers conclusions.

2 Background

Although, the literature underscores the role of CRMs in the modern industrial landscape, highlighting challenges such as supply chain vulnerabilities, dependence on specific countries for crucial materials, and the necessity for circular strategies to ensure sustainability and resilience in the face of global economic shifts and technological advancements, many work also examine the dynamics of global trade, supply chain management, and strategic considerations, particularly in response to a dominant player's dominant position in the market (i.e., China). They highlighting the complexities and challenges faced by alternative suppliers and the broader implications for industrial development and international trade.

Particularly, in recent years authors have reflected on the high technological and economic importance of CRMs. To this end, two main streams of literature can be identified. On one hand, the role of CRMs in the energy transition has been discussed with particular emphasis on resource availability and the constraints it poses to the technological deployment. To this end, Pommeret et al. (2022) reflects on CRM scarcity, accounting for technology substitutes, material recycling, and policy constraints. That paper aims to enhance societal welfare by exploring political economy aspects and sub-optimal policy design. In addition, Islam et al. (2022) proposes strategies to optimize mineral imports for clean energy goals. It analyzes mineral import demand in response to clean energy transitions, noting variations in copper and nickel prices and diverse impacts of income levels across OECD countries. Other studies focus on particular technologies necessary for a hydrogen-based economy, such as fuel cells and electrolyzers. These include studies that: assess potential resource constraints on a hydrogen economy that relies on those technologies Kleijn and van der Voet (2010); examine the demand for critical materials for stationary and mobile fuel cells Wittstock et al. (2019) and for water electrolysis Kiemel et al. (2021); and , to a lesser extent, consider more niche technologiesWatari et al. (2019), with, for instance,Pihl et al. (2012) presenting a detailed analysis of material constraints for concentrating solar-thermal power technology.

On the other hand, other literature discuss the role of CRMs in global supply and demand dynamics from both a value chain perspective (from production to recycling), and from the point of view of global markets and trade. Some authors have focused on circularity Hool et al. (2022), some others on security of supply Shiquan and Deyi (2023), supply risks and dependenciesRabe et al. (2017), and on social acceptance Mateus and Martins (2021), while still others have emphasized domestic production potential benefits Guzik et al. (2021), failures Park et al. (2023), alternative routes Machacek and Fold (2014) and industrial structure of CRMs Xia et al. (2023) . Additinal studies have examined the impact of CRMs price shocks on microeconomic indicators Considine et al. (2023) and how the critical mineral trade network influences renewable energy development, highlighting the positive impact of trade-center status on fostering renewable energy progress, mediated by advancements in renewable energy technology and varying effects of trade patterns based on country-specific economic development Zhu et al. (2022).

Exploring the relationship between CRMs and the development of renewable energy sources necessitates a comprehensive understanding of mineral trade patterns, import demand dynamics, market disturbances, and policy implications, as well as the demand-pull from green consumers and government renewable subsidies. Such understanding is essential for facilitating the global transition towards clean energy and sustainable resource management. However, there is a gap in CRMs research concerning how the specific regulations of the CRM Act affect global trade dynamics and the costs and ability of the Eu's energy economy to transition towards renewable gas.

2.1 Legislative Response to Geopolitical Dynamics: The European Union's Critical Raw Materials Act in Context

The legislative and policy framework for this study is provided by the European Union's recent efforts to take more decisive action in order to maintain its competitiveness and reduce its strategic dependencies as it pursues the European Green Deal's target of achieving carbon neutrality by mid-century. The Russian invasion of Ukraine, which exacerbated the European energy crisis that had started to manifest in late 2021, provided the impetus for a closer examination of the EU's import dependencies in the energy sphere and beyond. This has led to renewed debate about the EU's so-called *strategic autonomy*, a broad and context-dependent concept, but with a common denominator of the Union preserving its ability to pursue its domestic and geopolitical objectives independent from third countries, that is without another country having the opportunity to influence EU action through economic or political means. (On the concept of strategic autonomy more generally, see Damen (2022); on its use in the energy sector, see Hancher and De Hauteclocque (2024)). A closer reflection upon the EU's priorities and competitiveness has highlighted current and future vulnerabilities in supply chain structures and risks that will become increasingly acute as the EU's "twin transition" of digitalization and decarbonization proceeds Commission (2023e). In 2022, at the EU State of the Union, the link between fossil fuel and raw material dependencies was made explicit, with the Commission President highlighting the necessity of steering clear of the dependency pattern observed in the case of oil and gas Commission (2022).

The Commission's recent decisive action on CRMs was spurred on by China's above mentioned dominance, particularly at the processing stage, in the supply of several CRMs such as heavy REEs. While a sudden, potentially politically motivated import disruption of CRMs would have less immediate and more narrow impact on the EU economy than is the case for Russian natural gas, it could nonetheless jeopardize the EU's decarbonization objectives in the long term by preventing the roll-out of clean tech at the speed and scale needed to realize the objectives of the European Green Deal Le Mouel and Poitiers (2023). In addition to these political concerns, the Commission was also concerned that, without dedicated action in the CRM sphere, the EU would be ill-placed to compete with other global players and benefit from the projected substantial increase in demand for clean tech and for the raw materials necessary to manufacture these technologies. This concern was heightened by when other global actors passed legislative measures to strengthen domestic clean tech and raw materials supply chains. Certainly, a key event in this regard was the passage of the Inflation Reduction Act (IRA) in the United States Law (2022). The IRA seeks to support the American cleantech industry through substantial tax cuts. The best known of these measures is the subsidies provided to first-time buyers of electric vehicles, which is tied to local content requirements Marconi et al. (2024)Scheinert (2023). In addition to limits on the household income and the value of the electric vehicle in question, buyers only qualify for the maximum available tax credit of $7,500 if the vehicle has undergone final assembly in North America. Also, for vehicles purchased in 2024, 50% of the critical minerals contained in the battery must be extracted or processed in the US or a country with which the US has a free trade agreement. Further, 60% of the value of the battery's components must be manufactured or assembled in North America. Electric vehicles that use critical raw materials or components manufactured in a Foreign Entity of Concern (FEOC), a category which includes China, are not eligible for the tax credit Marconi et al. (2024) U.S. Department of the Treasury (2024).

Against this background of (i) a projected exponential increase in demand for critical raw materials beyond 2023 Commission et al. (2023), (ii) an increasing wariness of overdependence on imports, and (iii) mounting competition from other global players, the Commission decided to take legislative action. The fifth list of critical raw materials for the EU, a document which the Commission had published every three years since 2011, was thus accompanied by a proposal for a regulation "*establishing a framework for ensuring a secure and sustainable supply of critical raw materials*" Council (2023), the so-called Critical Raw Materials Act (CRM Act). Together with the proposals for a Net-Zero Industry Act Commission (2023d) and electricity market design reform Commission (2023c), published in March 2023, the CRM Act forms part of the legislative implementation of the Green Deal Industrial Plan Commission (2023b). This plan aims to create an enabling environment for the manufacturing of net-zero technologies in Europe, thereby enhancing the EU's competitiveness and reducing dependencies through the scaling up of domestic extraction, processing and manufacturing capacities.

Table 1: Strategic Raw Materials (SRMs) identified in the CRM Act

Bauxite, Alumina, Aluminium	Bismuth	Boron (metallurgy grade)	Cobalt
Copper	Gallium	Germanium	Lithium (battery grade)
Magnesium metal	Manganese (battery grade)	Graphite (battery grade)	Nickel (battery grade)
Platinum Group Metals	Rare Earth Elements for magnets (Nd, Pr, Tb, Dy, Gd, Sm, and Ce)	Silicon metal	Titanium metal
Tungsten			

From the list of 34 CRMs identified by the European Commission, including PGMs, the CRM Act identifies a subset of 17 Strategic Raw Materials (SRMs) listed in Annex I to the regulation (Council 2023, Annex I). These are shown in Table 1 According to the Act, SRMs are defined as:

raw materials that are of high strategic importance for the functioning of the internal market, taking into account their use in strategic technologies underpinning the green and digital transitions or for defence or aerospace applications, that are characterised by a potentially significant gap between global supply and projected demand, and for which an increase in production is relatively difficult, for instance due to long lead-times for new projects increasing supply capacity Council (2023).

The SRMs are subject to certain, special provisions and objectives. The Act specifies a set non-binding benchmarks for SRMs Council (2023). Member States should collectively ensure that, by 2030, Union capacity "approaches or reaches":

- 10% of EU annual consumption of SRMs at the extraction stage of the value chain;
- 40% of EU annual consumption of SRMs at the processing stage of the value chain; and
- a recycling capacity that can produce 25% of EU annual consumption of SRMs.

In addition, the CRM Act stipulates that the Commission and Member States should take steps to diversify EU imports of SRMs with the objective of ensuring that, by 2030, the EU does not rely on a single third country for more than 65% of each SRM at any stage of processing.

Projects within and outside of the Union that improve the EU's SRM supply security and which are expected to be operational within a "reasonable timeframe" can be designated "Strategic Projects" Council (2023). These projects are to be considered first for investment and, if located in the Union, benefit from expedited permitting procedures, which are not to exceed 27 months for extraction projects and 15 months for processing and recycling Council (2023).

The CRM Act further includes provisions on stockpiling of SRMs. Starting in 2026, Member States should report their strategic stocks of SRMs to the Commission every year (Council (2023)with an exemption from reporting possible where disclosing strategic stocks could compromise a Member State's defence and national security). The Commission will then propose a benchmark for what may be deemed a "safe level of Union stocks" for each SRM, which must subsequently be adopted by a new governance body established by the CRM Act, the Critical Raw Materials Board, comprising representatives from all Member States and from the Commission Council (2023).

It is against this legislative, technological, and geological background that the work reviews possible pathways for the EU to maintain its strategic autonomy and competitiveness in platinum as it pursues its hydrogen production objectives to 2030 and beyond. As the concept of energy strategic autonomy evolves and gains significance in the context of Europe's ever-growing energy dependencies and decarbonization future pathways, so too does the role of the CRM Act's regulatory framework and its implications for both the EU's supply chain resilience and the behavior of market dominant players. The work explores these dynamics in the context of H2 production targets for platinum and South Africa, and put a focus on the EU's imports of unprocessed platinum, asking whether and how the import diversification benchmarks provided by the CRM Act can be achieved.

2.2 Techno-economic modeling studies in the context of CRMs

Although, to our knowledge, that are are no game-theoretic/techno-economic based models of strategic behavior in CRMs supply chains, there is significant related work that our modeling framework and data base builds upon. One focus of previous studies is on modeling of CRMs demand and requirements in techno-economic, mostly large-scale energy system models. Comprehensive reviews of CRMs in large-scale energy system models are given by Liang et al. (2022) and Zhang et al. (2023). Meanwhile Tokimatsu et al. (2017) look at CRMs demands implied the 2°C climate target using an energy system modeling approach. Peiró et al. (2022) also 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 CRMs prices and how they might evolve in response to significantly increased demand resulting from the transition of the global energy system. Sun et al. (2011) study the impact of widespread deployment of fuel cell vehicles (FCV) on platinum demand and price. They show that platinum prices have been sensitive to changes in demand in the past. Combining this with scenarios for platinum recycling, they estimate future prices of platinum as a function of demand and the number of FCVs, finding an average platinum price increase of approximately 70 % in 2045. Schnuelle et al. (2019) explore the impact of resource constraints in a hydrogen economy based on renewable energy sources. Among other CRMs, the authors posit that the availability of sufficient amounts of platinum alloys could be a bottleneck for building the hydrogen economy. Parra and Patel (2016) focus with the techno-economic implications of the electrolyzer and its platinum demand. In contrast to these technology focused studies, Robinson (2017) examines the sensitivity of the future platinum price due to changes in macroeconomic variables and vice versa. Other empirical studies include Bao (2020), which investigates the dynamics and correlation of spot prices of platinum (more precisely PGMs) between 1992 and 2019. Zhang et al. (2018) 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. The comparability of oil and CRMs geopolitics is the subject of Månberger and Johansson (2019). That study addresses the geopolitics of CRMs used for the sustainable energy transition and finds that the geographic concentration of most of the studied materials will be higher than for oil.

Also relevant to this work is the potential for secondary supply and the recycling of CRMs. The current literature already includes several studies dealing with other materials, for example, with the recycling of steel and iron from a techno-economic perspective. Just one example of many is a recent study by Harvey (2021) (focusing on constraints on the recycling of end-of-life steel). However, there are a few studies about CRMs recycling, especially platinum. One is the work by Tong et al. (2022), who study the recycling of platinum used in automobile catalytic converters. In doing so, they analyze various scenarios from 2020 to 2050, and identify in their results, among others, a time lag between the peak of waste platinum (from used gasoline-fueled cars) and increasing demands from the FCVs. They conclude that it will be essential to upgrade the recycling of platinum, especially in developing countries, to secure sufficient platinum supply. A second study relevant here is presented by Sverdrup and Ragnarsdottir (2016). The authors investigate long-term development of platinum supply chains, including world primary extraction, market supply, and secondary supply such as recycling. 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 issues posed in Section 1. 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, in one direction, the export price and quantity offered by the major exporter to the supply-demand balance in the lower level (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.

It is assumed that there is no price discrimination between the two markets under consideration to arbitrage. Therefore, the mathematical formulation of the lower-level problem ensures that the market clearing prices are equal. There are many arguments that could be used to justify why the clearing market prices converge 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; and the share of total cost made up by transport expenses is minor, as is typically the case with critical raw materials (see e.g., Iwatsubo and Watkins (2022)).

The following sub-section discusses the process of data collection and assumptions. Then, sub-section 3.2 delves into the development of the bi-level optimization problem, explaining its formulation and key components. Following that, sub-section 3.3 elaborates on the analysis of the investigated supply chain dynamics, outlining the variables and factors considered.

3.1 Data

The most important data source for this study was the dataset accompanying the JRC's 2023 report *Supply Chain Analysis and Material Demand Forecast in Strategic Technologies and Sectors in the EU: A Foresight Study* Carrara et al. (2023). This dataset provides platinum demand for 2020, as well as projections to 2030 and 2050, for several key technologies investigated in that report (i.e.,Li-ion batteries, fuel cells, electrolysers, wind turbines, traction motors, solar PV, heat pumps, data storage and servers, smartphones, tables and laptops) Commission et al. (2023). The technologies of fuel cells, electrolysers, and smartphones, tablets and laptops are those relevant to platinum demand. Data and projections are provided for world demand, as well as for regional demand for the EU, USA and China. The JRC provides demand data for both a high-demand scenario (HDS) and a low-demand scenario (LDS) for 2030 and 2050. The HDS assumes rapid technology deployment in line with reaching the targets of the EU Green Deal and REPowerEU. The HDS also assumes a near-stable material intensity for these technologies until 2050. The LDS assumes greater material efficiencies, but also a slower rate of technology deployment in which Green Deal and REPowerEU objectives are not met. Since we are examining platinum supply developments in light of the EU's 2030 REPowerEU hydrogen production targets, for the purpose of this work we used HDS data, which aligns with the achievement of those objectives Carrara et al. (2023).

3.1.1 Demand

Based on these demand projections for key strategic technologies, we make formulated estimates for total platinum demand worldwide, in the EU, in China and in the USA. To do so,2020 platinum demand data for the more traditional applications of platinum from Johnson Matthey (2023) was used. The sectors covered by this dataset are automotive, chemical, dental & biomedical, electrical & electronics, glass, investment, jewellery, petroleum, pollution control, as well as 'other' applications, the latter amounting collectively to approximately 7.7% of total world demand in 2022 Johnson Matthey (2023).

To arrive at platinum demand projections for 2030 and 2050, it was assumed that demand for those sectors, excluding automotive would remain constant and only adjusted these figures for population growth, using UN data United Nations Population Division (2022). However, in the automotive applications of platinum, an increasing penetration of electric vehicles is expected to lead to a decline in the platinum demand in that sector Joint Research Centre (2023), where platinum is at present principally used in catalytic converter manufacturing for cars with internal combustion engines.

Given the focus on a scenario in which the Green Deal's mid-century carbon neutrality objective is achieved, for 2050 it was assumed that by that year, all manufacturing of internal combustion engine (ICE) vehicles will have ceased, following the International Energy Agency's Net Zero Roadmap, which presents a scenario in which no new ICE cars are sold after 2035, with a phase-out of sales of ICE trucks by 2045 International Energy Agency (2023c). Therefore, platinum demand from catalytic converter manufacturing is given as zero in 2050. For 2030, projections for the increase of the market share of battery electric vehicles (BEVs) were used as a proxy for decline in manufacturing of vehicles that require catalytic converters, that is ICE vehicles and plug-in hybrid electric vehicles (PHEVs). Data from the International Energy Agency's global EV data explorer International Energy Agency (2023b) were used, which provides 2020 data, as well as 2030 projections, for electric vehicle (BEVs and PHEVs) combined as well as 2030 BEV and PHEV sales in absolute numbers at global and regional level. In a first step, based on the sales number projections, the share of EVs sold in 2030 that are BEVs and thus do not require a catalytic converter was calculated. Using this percentage, we then the 2020 figures and 2030 projections for the EV share in total vehicle sales were adjusted to arrive at the BEV-only share in 2020 and projected vehicle sales, and thus the percentage of cars with catalysts (PHEVs and ICE vehicles) sold in 2020 and 2030. We calculated by how much the market share of vehicles with catalysts will decline between 2020 and 2030 and then reduced the Johnson Matthey figures for 2020 automotive platinum demand by the same percentage to arrive at an estimate of 2030 automotive sector platinum demand. The IEA provides disaggregated data for buses, cars, trucks and vans. In reducing automotive sector platinum demand, the median value of market share was reduced over time for vehicles with catalysts to arrive at an estimate of the decline of such vehicles across the entire vehicle fleet.et.

To the adjusted values for the demand from the automotive and other, more traditional platinum applications in 2030 and 2050, the JRC projections for platinum demand for the production fuel cells, electrolysers, and smartphones, tablets and laptops was added to arrive at total platinum demand projections for the World, China, USA, and the EU (see data, sheet "demand"). The resulting 2050 total global demand estimate of 305 tonnes is close to a recent projection by the US Department of Energy (DoE), which projected a global platinum demand of approximately 375 tonnes by 2050. The higher estimate by the DoE is partly due to a slower decline in demand for autocatalysts US Department of Energy (2022).

The above calculations are subject to some limitations due to data availability. It should be noted that the IEA's 2030 and 2050 projections for EV sales were not available for the Net Zero Emissions by 2050 Scenario (NZE), which would have been a closer match for the JRC's HDS. The figures we use instead relate to the Announced Pledges Scenario (APS), which assumes that net-zero objectives will be met when set by countries, but does not foresee a decarbonization pathway as rapid as the NZE. A further limitation of the approach are the differences in regional scope used by the different datasets. The JRC uses the regions of EU, USA, and China. Johnson Matthey meanwhile, provides data only for "EU+", meaning the European Union plus the United Kingdom and Turkey and for North America, defined as Canada and the USA, rather than for just the latter. It should, however, be noted that the JRC itself uses Johnson Matthey EU+ data in recent studies on platinum demand Joint Research Centre (2023). The IEA dataset does provide data for the US only, but defines Europe as the EU, plus Tukey, Iceland, Israel, Switzerland and Norway. All the datasets provide data for China and the World total.

3.1.2 Production and maintenance costs

Average production costs (cash costs plus capex) for the major producing countries and regions of North America, South Africa, Zimbabwe, Russia, as well as the global average production costs, were taken from the 2019 Refinitiv GFMS Platinum and Palladium Survey Alexander et al. (2019). This report shows the high production costs of South African mines relative to other major platinum producers. Production costs for South African platinum were USD 985 per troy ounce in 2018, substantially higher than the major producers with the next highest production costs, North America and Zimbabwe, which reported USD 800 and USD 787 per troy ounce, respectively. The main two reasons given for high production costs in South Africa in the report are labour disruptions as well as a crisis at the public utility Eskom, which resulted in high electricity prices. South African mining consultancy Minxcon further provides that "*High costs can, inter alia, be attributed to the fact that a large percentage of the mines have been operating for decades, thus increasing maintenance costs on the shafts and machinery , as well as the fact that the depth of some of the platinum mines in South Africa are the deepest in the world*" Minxcon (2023). Historic mine production data for South Africa, USA, Canada, Zimbabwe, Russia as well as world totals were retrieved from the US Geological Survey US Geological Survey (2023); US Geological Survey (2024). Maintenance cost per tonne was calculated using data from Anglo American, the world's largest producer of platinum Anglo American (2023), which provides figures for cash operating cost per troy ounce of PGM produced. Following Robatto Simard et al. (2023) who cite a maintenance cost range estimate of 30-50% of a mining operation's annual budget (citing Topal and Ramazan (2010) and Christiansen (2018)), it was assumed a conservative 30% of that operating cost to be maintenance cost.

3.1.3 Stockpiling

Stockpiling cost for platinum was calculated following a 2012 report investigating raw materials stockpiling that was prepared by the consultancy Risk & Policy Analysts Limited (2012). The findings of this report have recently also been used in a study commissioned by the European Parliament's ITRE Committee Rietveld et al. (2022). The Risk & Policy Analysis report estimates that storage costs for PGMs will amount to an average of 0.125% of stock value per year. This allowed to calculate the stockpiling cost per tonne of platinum, based on the 2023 average platinum price retrieved from Johnson Matthey Johnson Matthey (2024).

3.2 Bi-level optimization model

3.2.1 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 (see exemplarily Pozo et al. (2017)). The complete formulation of the dual problem of the lower-level problem (including Lagrangian function, KKT conditions, and complementarity conditions) can be found in Appendix B.1 and corresponding subsections. In the interest of readability, the main text gives preference to a basic description of the model, excluding selected details of the mathematics

Table 2: Overview of the key equations of the lower-level problem (market clearing at minimized total cost)

Equation			Qualitative/high-level explanation	
No.	Dim.	Dual var.	Keyword	Brief description
1	-	-	Objective	Minimize the sum of generation costs (for all exporters), maintenance costs (for fringe exporters), and stockpiling costs (for the European market $M1$)
3, 4	$\lvert\mathcal{T}\rvert$ (each)	λ_t^1, λ_t^2	$M1$, $M2$	Supply balance for the European market $M1$ and global market $M2$
5	$\lvert\mathcal{T}'\rvert$	$\lambda_{t'}^3$	Stockpiling	Stock balance
10	$\lvert\underline{\mathcal{E}}\rvert \times \lvert\mathcal{T}\rvert$	$\lambda_{\underline{e},t}^8$	Embargo	Imposed on exporters operating within the European market $M1$
11	$\lvert\mathcal{E}'\rvert \times \lvert\mathcal{T}'\rvert$	$\lambda_{e',t'}^9$	Capacity evolution	Evolution of available export capacity, encompassing expansions and retirements
15	$\lvert\mathcal{E}\rvert \times \lvert\mathcal{T}\rvert$	$\mu_{e,t}^3$	Capacity restriction	Imposed by the total available export capacity
13	$\lvert\mathcal{E}\rvert \times \lvert\mathcal{T}\rvert$	$\mu_{e,t}^1$	Share restriction	Maximum share of an exporter within the European market $M1$
14	$\lvert\mathcal{E}\rvert$	μ_e^2	Reserves	Total export volumes across all time steps constrained by reserves

of both the upper and lower problems. For a comprehensive overview of the equations pertaining to the lower-level problem, reference is made to Table 2.

Objective and decision variables: The objective of the lower-level problem is to minimize the sum of the generation cost of all exporters, the cost of maintaining the existing capacity of fringe exporters, and the stockpiling cost of the European market when satisfying the demand of the European and global markets. Investment costs are implicitly accounted for, operating under the assumption that they are subsumed within the relatively higher maintenance costs, distinct from the aggregate of the other cost elements. Equation 1 shows the objective function while x is a vector containing all the lower-level problem's decision variables.

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

The decision variables $q_{e,m,t}$ represent the supply quantity of exporter e, market m, and time step t. $c_{e,t}^{supply}$ 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, $c_{e,t}^{supply}$ 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. $c_{e',t}^{main}$ is a parameter and describes the specific maintenance cost per e'. In the third term, which considers the stockpiling cost of the European market $M1$, $q_{M1,t}^{stock,stored}$ 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.

$$x = \left[q_{e,m,t}, \bar{q}_{e',t}, \bar{q}^{add}_{e',t}, \bar{q}^{retire}_{e',t}, q^{stock,in}_{M1,t}, q^{stock,out}_{M1,t}, q^{stock,stored}_{M1,t}\right] \quad (2)$$

In addition to the decision variables described above, $\bar{q}^{add}_{e',t}$, $\bar{q}^{retire}_{e',t}$, $q^{stock,in}_{M1,t}$, $q^{stock,out}_{M1,t}$ 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 3.2.1 below. $q^{stock,in}_{M1,t}$ and $q^{stock,out}_{M1,t}$ is the quantity in and out of stock for the European market per t respectively. 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 3.2.2 in detail).

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. A distinction is also made between equality and inequality equations. Lambda (λ) is used for equality equations and mu (μ) for inequality equations.

Equality The Equations 3 and 4 represent the supply balance constraints of the European market $M1$ and the global market $M2$, respectively. It is important to note that stockpiling is explicitly considered only for the European market.

$$d_{M1,t} - \left[\sum_{e} q_{e,M1,t}\right] - q^{stock,out}_{M1,t} + q^{stock,in}_{M1,t} = 0 \quad : \forall t \quad (\lambda^1_t) \quad (3)$$

$$d_{M2,t} - \left[\sum_{e} q_{e,M2,t}\right] = 0 \quad : \forall t \quad (\lambda^2_t) \quad (4)$$

The demand of the European and global market at time step t is denoted as $d_{M1,t}$ and $d_{M2,t}$, respectively. Equation 5 represents the stock balance constraint, while Equation 6 guarantees that the initial stock is empty.

$$q^{stock,stored}_{M1,t'} - q^{stock,stored}_{M1,t'-1} + q^{stock,out}_{M1,t'-1} - q^{stock,in}_{M1,t'-1} = 0 \quad : \forall t' \quad (\lambda^3_{t'}) \quad (5)$$

$$q^{stock_stored}_{M1,t_{start}} = 0 \quad (\lambda^4) \quad (6)$$

Equations 7, 8, and 9 impose constraints on the utilization of stock during the initial and final time steps.

$$q^{stock,in}_{M1,t_{end}} = 0 \quad (\lambda^5) \quad (7)$$

$$q^{stock,out}_{M1,t_{start}} = 0 \quad (\lambda^6) \quad (8)$$

$$q_{M1,t_{end}}^{stock,out} - q_{M1,t_{end}}^{stock,stored} = 0 \quad (\lambda^7) \tag{9}$$

Equation 10 accounts for the embargo imposed on all exporters $\underline{\boldsymbol{e}}$ within the European market $M1$.

$$q_{e,M1,t} = 0 \quad : \forall \underline{\boldsymbol{e}}, \quad (\lambda^8_{\underline{\boldsymbol{e}},t}) \tag{10}$$

Equation 11 represents the evolution of export capacity, while Equation 12 establishes the initial export capacity as equivalent to its existing value.

$$\bar{q}_{e',t'} - \bar{q}_{e',t'-1} + \bar{q}^{add}_{e',t'} - \bar{q}^{retire}_{e',t'} = 0 \quad : \forall e', t' \quad (\lambda^9_{e',t'}) \tag{11}$$

$$\bar{q}_{e',t_{start}} - \bar{q}^{init}_{e'} = 0 \quad : \forall e' \quad (\lambda^{10}_{e'}) \tag{12}$$

Inequality Equation 13 accounts for the share restriction imposed on each exporter within the European market $M1$. Specifically, it constraints the supply share of the major exporter to be limited by a fraction α of the total annual demand $d_{M1,t}$.

$$q_{e,M1,t} - \alpha \times d_{M1,t} \leq 0 \quad : \forall t \quad (\mu^1_{e,t}) \tag{13}$$

Equation 14 represents the constraint on total export volumes across all time steps, imposed by the reserves per exporter Q_e.

$$\sum_m \sum_t q_{e,m,t} - Q_e \leq 0 \quad : \forall e \quad (\mu^2_e) \tag{14}$$

Equation 15 incorporates the export restriction imposed by the total available export capacity.[1] Additionally, Equations 16 and 17 address the expansion and retirement of export capacity, respectively. Note that β^{add} and β^{retire} are parameters designed to control the rate at which export capacity changes between time steps. These parameters play a crucial role in regulating the speed of capacity expansion and retirement processes.

$$\left[\sum_m q_{e,m,t}\right] - \bar{q}_{e,t} \leq 0 \quad : \forall e, t \quad (\mu^3_{e,t}) \tag{15}$$

$$\bar{q}^{add}_{e',t} - \beta^{add} \times \sum_m q_{e',m,t} \leq 0 \quad : \forall e', t \quad (\mu^4_{e',t}) \tag{16}$$

[1] In the model, only the available supply capacity of the fringe exporters are decision variables in the lower-level problem. Before a detailed description of the upper-level problem is given in Section 3.2.2, 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 (fringe) exporters. Since there is little historical and empirical data on the evolution of markets for CRMs (including their prices), a look at other markets can be useful. An example is the oil market. That market can serve as an example since similar market conditions can be assumed as in the markets for CRMs (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 (2008). 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 exemplarily Mason and Wilmot (2014)).

$$\bar{q}^{retire}_{e',t} - \beta^{retire} \times q^{init}_{e'} \leq 0 \quad : \forall e', t \quad (\mu^5_{e',t}) \tag{17}$$

Equation 18 imposes a restriction on the inflow into the stock, constraining it to be in line with the annual demand. This limitation ensures a more realistic pace of stock filling.

$$q^{stock,in}_{M1,t} - d_{M1,t} \leq 0 \quad : \forall e, t \quad (\mu^6_t) \tag{18}$$

The equations 19 to 25 ensure the non-negativity of decision variables.

$$-q_{e,m,t} \leq 0 \quad : \forall e, m, t \quad (\mu^7_{e,m,t}) \tag{19}$$

$$-q^{stock,stored}_{M1,t} \leq 0 \quad : \forall t \quad (\mu^8_t) \tag{20}$$

$$-q^{stock,out}_{M1,t} \leq 0 \quad : \forall t \quad (\mu^9_t) \tag{21}$$

$$-q^{stock,in}_{M1,t} \leq 0 \quad : \forall t \quad (\mu^{10}_t) \tag{22}$$

$$-\bar{q}_{e',t} \leq 0 \quad : \forall e', t \quad (\mu^{11}_{e',t}) \tag{23}$$

$$-\bar{q}^{add}_{e',t} \leq 0 \quad : \forall e', t \quad (\mu^{12}_{e',t}) \tag{24}$$

$$-\bar{q}^{retire}_{e',t} \leq 0 \quad : \forall e', t \quad (\mu^{13}_{e',t}) \tag{25}$$

3.2.2 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 a few equations. The first, Equation 26, is the objective function of the problem. It shows the profit maximization of the major exporter by setting its decision variables.

$$\max_{\mathcal{Y}} \sum_m \sum_t q_{1,m,t} \times (c_{1,m,t} - \tilde{c}) \tag{26}$$

The decision variables are summarized by $\mathcal{Y}$ and include the variables $c_{1,m,t}$ and $\bar{q}_{1,t}$. This is also described in Equation 27. As a reminder, $c_{1,m,t}$ is the marginal supply cost and $\bar{q}_{1,t}$ is the available supply capacity of the major exporter. Both variables are parameters in the lower-level problem.

$$\mathcal{Y} = [c_{1,m,t}, \bar{q}_{1,t}] \tag{27}$$

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 28.

$$0 \leq \bar{q}_{1,t} \leq \tilde{q}_1 \tag{28}$$

Further details on the mathematical formulation of the upper-level problem can be found in Appendix B.2. The section there explains how the non-linear term $q_{1,m,t} \times c_{1,m,t}$ is linearized. Before delving into the detailed description of the proposed methodology, it is important to address certain aspects regarding the mathematical formulation of the objective function. As previously outlined, the objective of the major exporter is to maximize profit. This is assumed to be achieved by maximizing the product of the supply (export) quantity and the offered export (production) cost to the different markets. It is assumed that the true production cost of the major exporter, including maintenance costs, remains fixed. Therefore, in our optimization, the major exporter gains revenues based on the offered cost to the market clearing (i.e., pay as bid), rather than the clearing price itself. However, navigating this terrain presents notable challenges in at least two respects.

- Firstly, the selected methodology offers a viable means to resolve the model within a reasonable timeframe. Conversely, an alternative approach, such as maximizing the product of the quantity retrieved from major exporters and the clearing price, substantially escalates computational demands. We conducted thorough testing on this matter. Consequently, and for various other rationales (elaborated in the subsequent paragraph), we opted for a compromise aimed at maximizing the product of the quantity offered by major exporters and their offered price, which markedly improved computational efficiency.

- Secondly, and acknowledging this point which we have rigorously deliberated internally, this approach contradicts to some degree the previously assumed homogeneity of clearing prices across markets and the underlying assumptions concerning the behavior of exporters and consumers (i.e., arbitrage). Nonetheless, it remains imperative to highlight that it remains feasible to determine the market clearing price by adjusting the offered price accordingly. In essence, the major exporter retains the theoretical capability to set the offered price to align with the clearing price.

Moreover, the aforementioned approach aligns more closely with the market clearing mechanism of the lower-level problem, where market clearing with pay as bid could be assumed under certain conditions. In summary, the objective of the major exporter is to maintain the offered cost to the market clearing as high as possible while ensuring that a high share of the offered quantity is still cleared. This strategy maximizes the profits of the major exporter. Alternatively, one could consider using the product of the supply quantity of the major exporter and the market clearing price (i.e., dual variables of the demand balance constraint) as the objective function. However, this formulation is significantly more computationally intensive, as the model was attempted to be run with it as well . Due to the multitude of factors that can influence the running time of optimization models, strong causal conclusions are not drawn here. Ultimately,a somewhat pragmatic approach has been adopted by using the initially described objective function. Nevertheless, room for improvement is acknowledge in this area and leave it for future exploration.

3.3 Investigated supply chain dynamics

The present work investigates to what extent diverse strategies affect EU's CRMs supply chain dynamics and resilience moving forward with the uptake of hydrogen in the EU net-zero economy. It also reflects on the strategic interplay between major market players and regulatory frameworks within the evolving dynamics of critical raw materials. A total of three distinctive dynamics were examined: (1) CRM supply chain dependencies and vulnerability to disruptions, (2) the effectiveness of compliance with the CRM Act provisions and their impact on supply chain diversification, and (3) geopolitical tensions and the outcome of the use of strategic stock on the market's dominant behavior. To this end, the work seeks to answer multiple questions.

- The first probes into the impact of the dominant player's strategic behaviour on the EU's supply chain dynamics. This exploration aims to uncover the long-term implications for the European CRMs sector.
- The following question studies to what extent the CRM Act, through provisions compliance and effectiveness in promoting diversification, contributes to reducing the EU's dependency on South African PGMs, creating a more resilient EU's CRMs supply chain through diversification of CRMs sources for the EU, reducing dependency on any single market player and fostering technological innovation in the platinum sector.
- Finally, the third question delves into the effectiveness of the CRM Act's stockpiling provisions in mitigating geopolitical tensions and supply disruptions in the EU's CRMs supply chain, examining their contribution to supply chain resilience and strategic decision-making and addressing challenges in meeting hydrogen production targets.

Therefore, starting from a basic dynamic that captures the market's dominant behavior in the absence of competitors (i), the work then continues to include CRM Act provisions on limits upon CRMs import to the EU (ii) and stockpiling (iii) to evaluate the effectiveness of the EU strategic vision on CRMs and value chain resilience. The three analyzed dynamics underscore the complex interplay of geopolitical dynamics, regulatory responses, and strategic decision-making, necessitating further exploration of challenges and potential pathways towards resilience in the EU's CRMs supply chain.

Base case dynamic envisages a landscape where South Africa assumes a dominant role as a major player in the PGMs market. Within this framework, South Africa strategically wields its dominant market position, exerting influence over strategic decisions to maximize economic gains. The EU, in turn, adjusts its approach to align with the market conditions. This dynamic unfolds against the backdrop of key assumptions. Firstly, it posits that South Africa maintains its stronghold as a dominant market player in the CRM sector. Secondly, it was assumed that the EU finds itself heavily reliant on South African PGMs due to a scarcity of alternative sources. Lastly, the EU efforts to mitigate South Africa's market dominance are assumed to have limited effectiveness. Delving into the insights of this dynamic, the work explores how the EU might be integrally involved in a supply chain heavily dependent on South African CRMs. In this dynamic, South Africa exercises considerable market power, influencing prices and dictating the terms of supply. It demonstrates the EU's increased vulnerability to supply interruptions, having to deal with South Africa's strategic management of supply to optimize its economic interests. Beyond immediate market dynamics, the *base case* was introduced to investigate the potential dampening effect on technological innovation in the CRMs extraction and processing domain, as innovation may be stifled as South Africa maintains a firm grip on market dynamics. The exploration raises significant questions about the long-term implications for the European CRM sector in a scenario where a dominant player dictates the course of the CRMs market.

Compliance dynamic navigates a landscape shaped by the effective implementation of the CRM Act, fostering compliance and diversification within the CRM market. This dynamic envisions a proactive stance by the EU, wherein the CRM Act emerges as a significant instrument promoting adherence to its provisions and encouraging diversification of CRM sources. Assumptions underlying this dynamic posit strict adherence to CRM Act provisions by all countries, including the dominant player. This adherence includes respecting the 65% CRM export limit to the EU. Consequently, the dynamic looks into the EU's pursuit of alternative suppliers, aiming to reduce dependency on any single market player. By examining the decreased reliance on South African CRMs to develop a more diversified and resilient CRM supply chain, the work seeks insights into whether the CRM Act positions the EU toward a more diversified, resilient, and technologically innovative CRM sector, moving away from reliance on a single dominant market player. The study assesses whether the EU, by effectively implementing the CRM Act, successfully transitions from dependence on a dominant player to alternative suppliers, to enhance market stability amidst geopolitical uncertainties, making the EU more resilient to fluctuations and disruptions.

Disruption dynamic: examines a landscape marked by heightened geopolitical tensions between the EU and a dominant player (i.e., South Africa) leading to disruptions in the CRMs supply chain, evaluating the EU's security measures to respond to it. Underlying assumptions in this dynamic posit that the intensification of geopolitical tensions, potentially triggered by trade disputes, political differences, or other geopolitical factors, results in significant disruptions to the CRMs supply chain. Traditional supply routes are affected, introducing delays and shortages in the availability of materials. In response to these challenges, the EU activates the stockpiling provisions outlined in the CRM Act, strategically building reserves of critical materials. The insights sought from this dynamic focus on strategic stockpiling to enhance the resilience of the EU's supply chain under the CRM Act. By activating stockpiling provisions, the EU aims to mitigate short-term disruptions and ensure the availability of essential CRMs for hydrogen production amid supply chain uncertainties. Additionally, the dynamic seeks an understanding of the effectiveness of stockpiling provisions in addressing challenges and influencing strategic decision-making in the face of market uncertainties and volatility, with global prices influenced by geopolitical tensions. This poses challenges for strategic planning and decision-making for both the dominant player and the EU, prompting future reconsiderations of strategic partnerships, with both players exploring diversified sources to establish a more resilient supply chain network.

4 Results and discussion

This section presents selected modeling results concerning different aspects of supply chain dynamics, and it is structured as follows. Initially, it portrays South Africa's dominant behavior in the PGMs market through the projected marginal supply cost of the European market for 2040. Subsequently, it delves into the development of global export and supply capacities and the role of stockpiling within the European market. This is accomplished by incorporating CRM Act provisions on limiting CRM imports to the EU up to 65% and stockpiling in the model, elucidating the impact of policy measures on value chain resilience.

4.1 Marginal supply cost of the European market by 2040

Examining the marginal supply curve development in the European market, which reflects global trends due to uniform pricing, provides insights into the strategic behaviors of major exporters and their impact on market equilibrium. Our analysis reveals a consistent pattern wherein the strategic behavior of the major exporter, namely South Africa, influences marginal supply costs, often aligning them with the assumed threshold of inelastic demand at 67 MEUR/tons. This strategic alignment ensures that marginal supply costs remain below the threshold, preventing demand reduction and consumer surplus. Consequently, major exporters effectively extract consumer rent, eliminating any surplus for consumers (Figure 1).

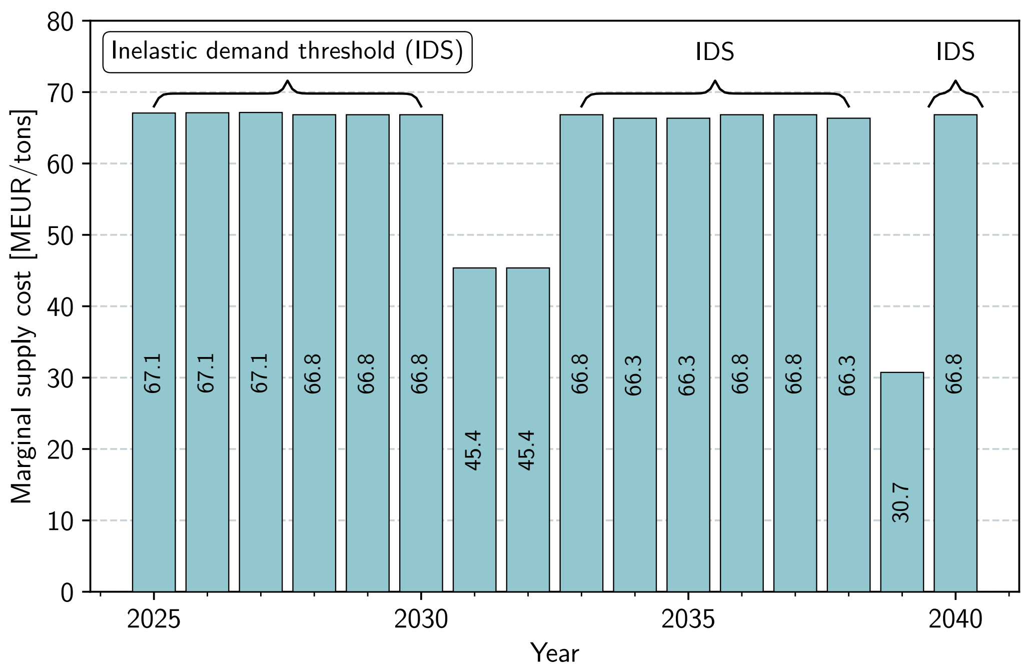

Figure 1: Development of marginal supply costs of platinum over time

Further exploration of supply dynamics, as indicated in Table 3, highlights fluctuations in the market shares of major and fringe exporters over time. By 2030, the major exporter commands a significant share of approximately 40%, followed by a drop to 25% before a subsequent increase to 35% in 2040. These fluctuations are closely tied to the inelastic demand threshold assumption, anchored at 68 MEUR/tons, the historical peak of platinum market prices in 2008 BullionVault (2023), reflective of an indicative relationship between price dynamics and market behavior. Albeit its limitations in capturing the complexities of real-world market dynamics, assuming inelastic demand when analyzing market players' behavior provides valuable insights into pricing strategies and market dynamics and prompts further investigation into market power dynamics.

Table 3: Supply share to the European market by 2040

Supply share	Description	2025-2030	2030-2035	2035-2040
North America	Fringe exporter	13.6 %	14.2 %	28.2 %
Recycling	-	31.5 %	37.2 %	4.0 %
Russia	Embargoed	0.0 %	0.0 %	0.0 %
South Africa	Major exporter	36.7 %	25.8 %	35.2 %
World	Fringe exporter	3.5 %	6.5 %	6.5 %
Zimbabwe	Fringe exporter	14.7 %	16.3 %	26.1 %
Elastic demand	Unmet	0.0 %	0.0 %	0.0 %

The analysis further highlights an interplay between market forces and strategic behaviors, evidenced by the shifting market shares over time. While competition initially dominates, with around 75% of the market share by 2025-2030, the major exporter stages a recovery by 2035-2040, exhibiting a non-monotonic trend. Possible explanations for this trend include the major exporter's unique spare capacity, rising demand, potential limitations among fringe exporters, higher maintenance costs associated with mine production and export capacity, as well as recycling of supply (see Table 3).

As Figure 2 showcases, the supply capacity of recycling fluctuates over time, peaking in 2030 before declining due to high maintenance costs. Additionally, the emergence of competitively priced export capacity from Russia, Zimbabwe, and North America (i.e., the US and Canada) contributes to market dynamics, particularly considering their lower production costs compared to South Africa. Notably, maintenance costs significantly impact mine production and export capacity, influencing the supply matrix.

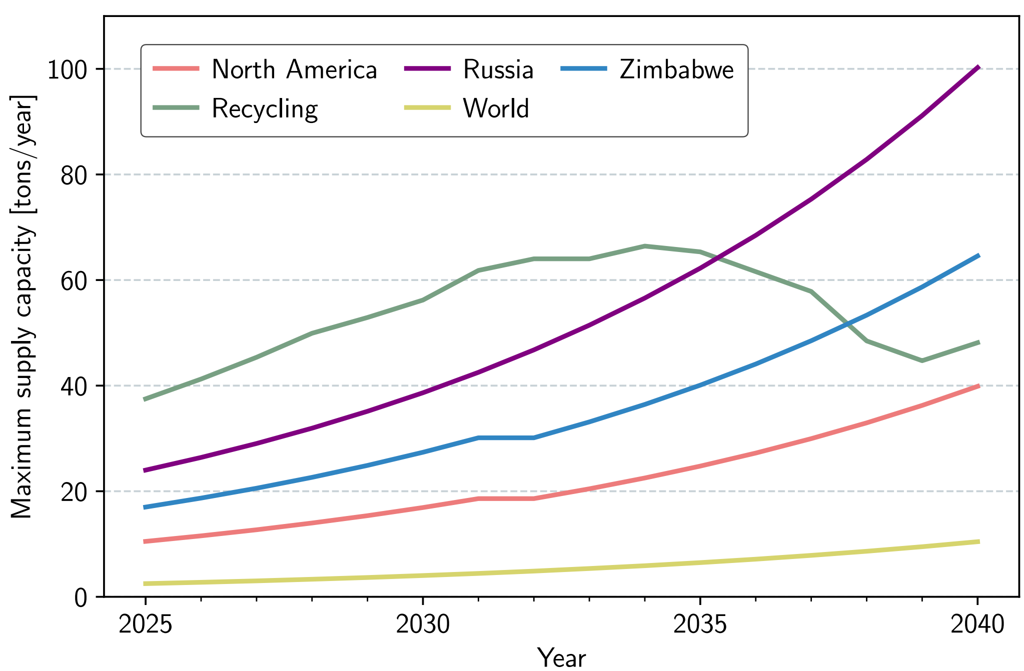

Figure 2: Temporal global evolution of minimum supply capacity for platinum

However, the limitations inherent in recyclable resources need to be mentioned. Analogous to challenges faced in steel recycling amid efforts to decarbonize, there exists a finite pool of recyclable materials. As demand remains steady or grows, the depletion of readily available resources necessitates increased reliance on primary extraction methods. This phenomenon mirrors the concept of picking low-hanging fruit in recycling without replenishment, hinting at the necessity for continuous innovation in resource management. Existing literature points to a projected maximum recyclable materials capacity by 2035-2040, coinciding with a peak in demand. Nevertheless, a detailed modeling of recycling dynamics is constrained by limited available information and data. Assumptions surrounding maintenance costs of both export capacities and recycling processes underscore the complexities of forecasting in this domain.

4.2 Development of the global export and supply capacities

Building upon the investigation of supply scarcities among exporters and recycling dynamics, this section investigates the development of global export and supply capacities. It provides insights into the evolution of global export capacities and its implications for the market power dynamics of major exporters, particularly highlighting the diminishing power position of the major exporter (i.e., South Africa) by 2040, primarily due to the significant increase in export capacities by the largest fringe exporter (i.e., Russia). Figure 2 illustrates a significant uptake in export capacity, particularly from Russia, attributed to its comparatively low production costs compared to other exporters. This surge in export capacities is mirrored to some extent by Zimbabwe and, to a limited extent, North America. While there is also a moderate increase in world export capacity, this is limited by resource constraints and assumptions concerning data availability.

Subsequently, Figure 3 delves into the offered capacity of the major exporter, assuming the cost of export capacity for the major exporter from 2023.

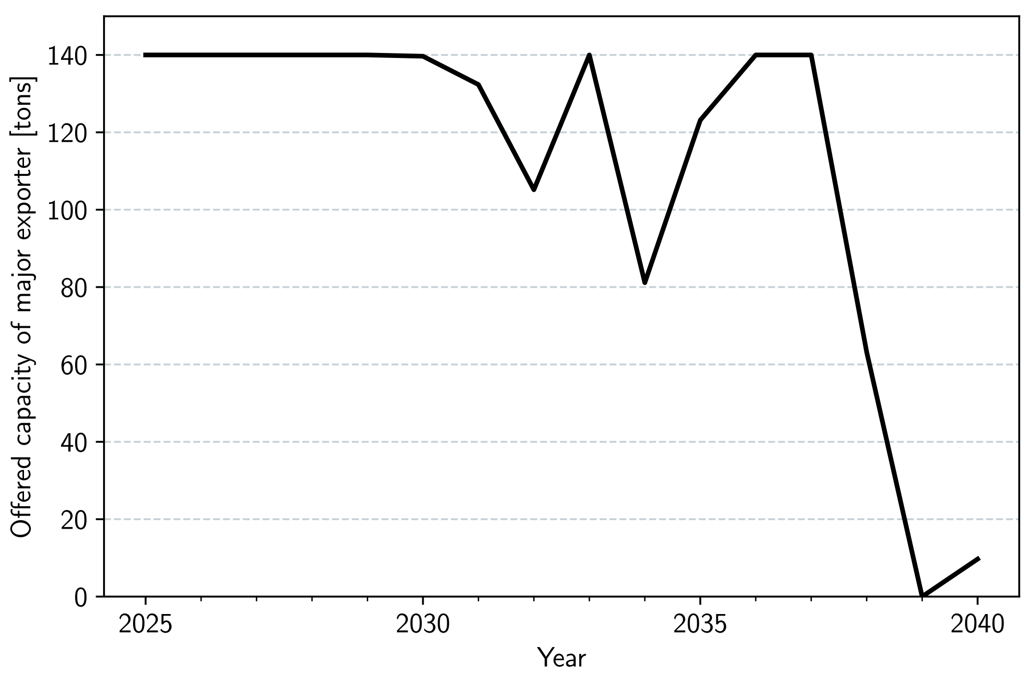

Figure 3: Evolution of South Africa's offered platinum capacity over time

The observed fluctuations in offered capacity reflect strategic decisions aimed at maximizing profits while maintaining market-clearing prices at the level of inelastic demand. Reductions in export capacities exert downward pressure on prices, a phenomenon further elucidated by the presence of stockpiling in the EU market, as illustrated in Figure 5 (see Section 4.3 for more details). The dynamic nature of prices, despite a reduction in export capacity from South Africa, can also be attributed to the stockpiling activities within the EU market, which serve to mitigate potential price spikes. The dynamic highlights the role of market mechanisms in stabilizing prices amidst fluctuations in supply capacities.

In particular, the analysis of the offered capacity in 2039 reveals a significant disparity between prices and the marginal production cost from South Africa. This gap signals the evolving market dynamics catalyzed by the emergence of new exporters such as Russia, Zimbabwe, and North America. Consequently, prices have plummeted to levels that are incompatible with South Africa's high production costs and maintenance expenses, rendering it non-competitive within the market. This market shift is visually represented in Figure 4, which illustrates the significant difference in supply capacity between South Africa and both the largest and the fringe exporters. Over time, South Africa's market power diminishes as other exporters, driven by lucrative prices, expand their export capacities (See Figure 4 and Table 4).

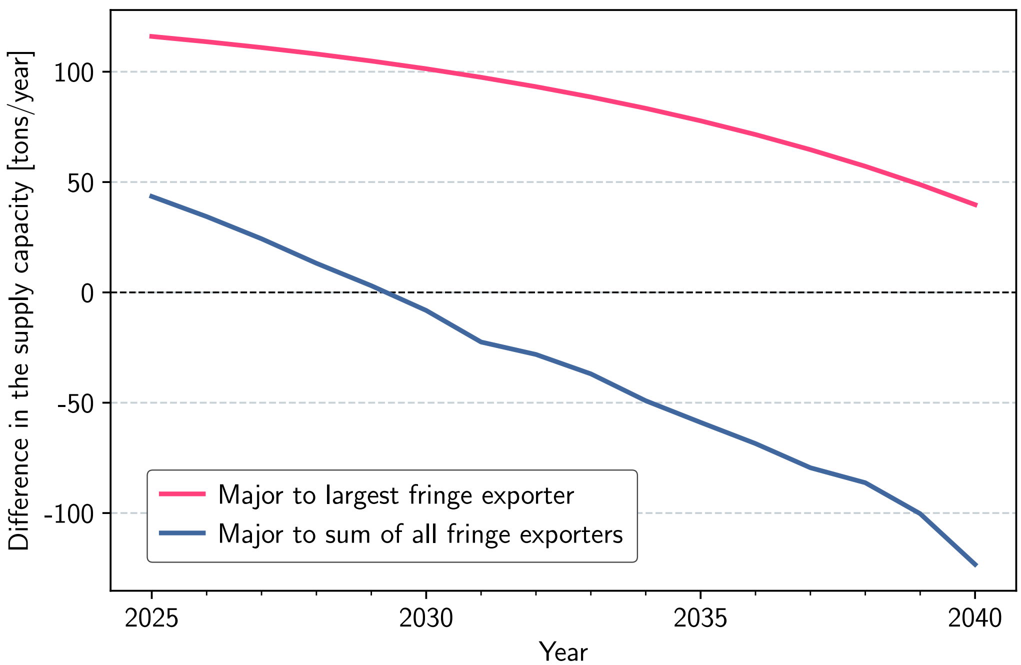

Figure 4: Supply capacity disparity between major and fringe exporters over time

The absence of offered capacity by South Africa in 2039, depicted in Figure 3, can be attributed to the saturation of the market with low-priced goods by other exporters and the strategic decision of the major exporter to optimize long-term profits, adjusting its capacity offerings accordingly to maximize profits over an extended period, rather than respond solely to short-term market conditions. To this end, the high production costs of South Africa, particularly substantial maintenance costs, labor costs, labor disputes, expensive and unreliable electricity, and aging mines (being among the oldest and deepest), contribute to its reliance on high prices to maintain competitiveness. Moreover, the finite nature of reserves, coupled with the absence of new, easily exploitable reserves in the country, point out the challenges it faces in sustaining its market position.

4.3 Stockpiling in the European market

Stockpiling dynamics within the European market offer valuable insights into supply costs and pricing strategies. While the absence of a comparative analysis between scenarios with and without stockpiling raises questions regarding causality, a single model run focused on stockpiling enables an understanding of its impact on prices and supply costs.

Table 4: Relative numbers from Figure with the magenta and blue line

Relative differences	2025	2030	2035	2040
Major to largest fringe exporter	83 %	72 %	56 %	28 %
Major to sum of all fringe exporters	34.6 %	−2.3 %	−42.1 %	−88.0 %

Figure 5 provides a comprehensive overview of stockpile development, revealing its potential to minimize supply costs for Europe. To this end, the activation of stockpiling during years of low prices, such as 2030 and 2038, indicates strategic responses to market conditions. This observation underscores the strategic role of stockpiling in the market, suggesting its utility in mitigating supply costs and bolstering market stability.

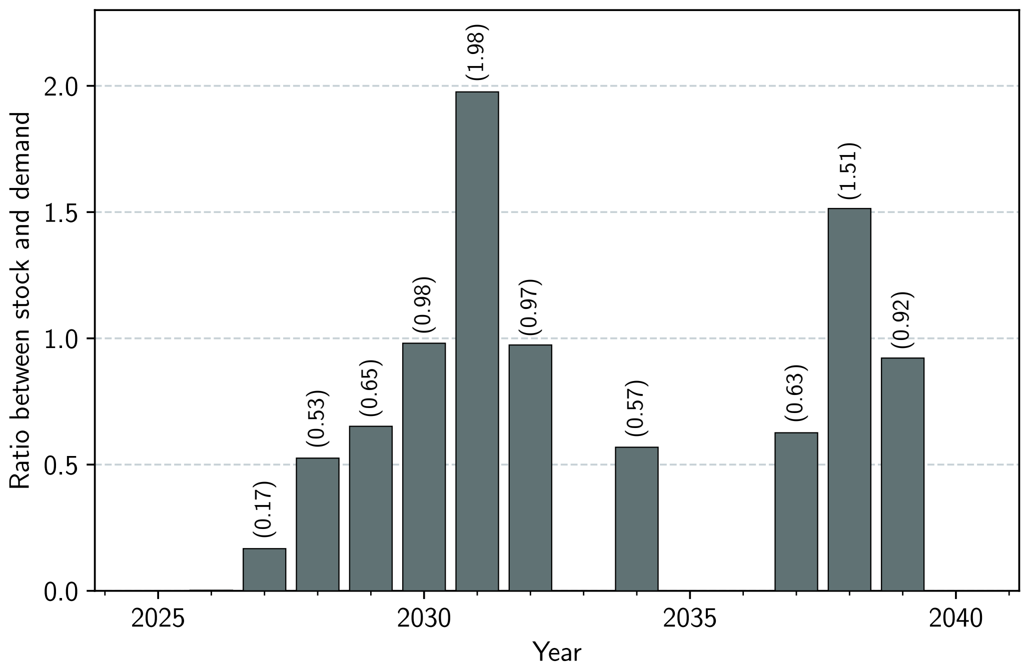

Figure 5: Temporal development of stock availability and market demand

Further analysis, as depicted in Figure 6, offers a deeper insight into the ramifications of stockpiling on the weighted average supply cost of Europe. Weighted to account for quantity and supply costs, this analysis reveals that in 2031, when the EU market demand is met through the stockpile, the resultant price of platinum is computed at 42.04 MEUR/tons. The optimal costs required to fill the stockpile or storage, based on the supply imports through Europe at that time, have been computed to track the expenses necessary to meet both the initial demand and the stockpile requirements. This includes expenditures for covering the initial demand, filling the stock, and maintaining the stockpile. In the absence of imports to Europe during this specific year, the stockpile, together with recycling (see Table 2), plays a crucial role in meeting the demand within the region. Consequently, the stockpile serves as a strategic cost-effective component in the optimization of the lower-level problem, influencing market dynamics and facilitating the fulfillment of all demand in Europe. By ensuring market clearance of the lower-level problem, the optimization process prioritizes the utilization of the most economical options to their full capacity before considering alternatives. This rationale stresses the significance of presenting the weighted average supply costs to elucidate the lower-level problem and its impact on market clearing based on marginal costs.

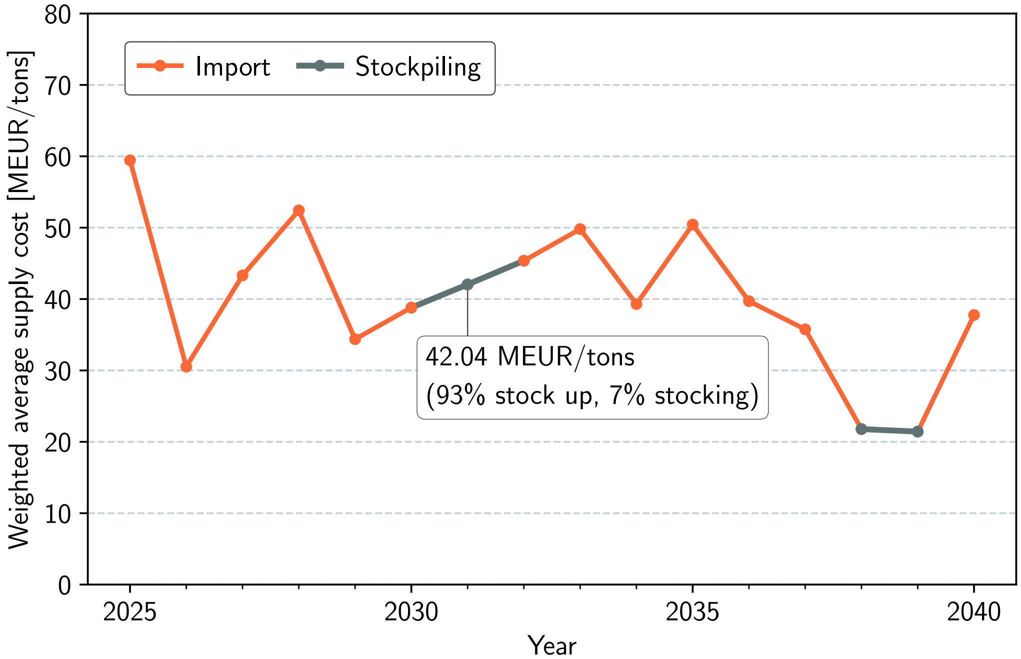

Figure 6: Impact of stockpiling on weighted average supply costs in Europe

In particular, a cyclical behavior in stockpile utilization, characterized by alternating periods of decreasing and increasing supply costs, is observed, and it emphasizes the dynamic nature of the market. This cyclical pattern can be attributed to two primary factors. Firstly, the high maintenance costs associated with capacities significantly contribute to the cyclicality. These maintenance expenses, being notably high relative to production costs, impose substantial financial burdens on maintaining export capacities, thereby influencing the fluctuations in supply costs. Secondly, the imperative of ensuring uniform prices between the global and European markets exerts a strong influence on the observed variation in prices. This emphasis on price uniformity impacts the optimization process, leading to the necessity of keeping prices consistent across markets. Additionally, the EU's diversification of importers and stockpiling options further complicates the market dynamics, contributing to the observed cyclical behavior.

5 Conclusion

In the context of Europe's decarbonization strategy, the importance of critical raw materials will increase in the coming decades. Looking at the hydrogen uptake foreseen by 2030, global competitiveness and a stable supply of platinum group metals will be crucial. To this end, the EU published the Critical Raw Material Act to create a framework for a secure and sustainable supply of critical raw materials.

To fill the knowledge gap regarding Critical Raw Material Act 's provisions and the dynamics of global trade in the EU's energy transition to renewable gas, this study presents a novel model that uses a leader-follower Stackelberg game framework to thoroughly analyze the competitive dynamics, regulatory compliance, and geopolitical influences within the critical raw material market to offer insights to industry stakeholders and policymakers. To this end, the analysis considers three distinct dynamics: (1) strategic behavior of major exporters and emergence of new players in a landscape where South Africa is a dominant player in the platinum group metals market (*base case dynamic*); (2) importance of diversified export sources for the European market, in line with the provision of the critical raw material act of limiting at 65% the EU's annual consumption of each critical raw material from a single third country (*compliance dynamic*); (3) implications of stockpiling on supply stability and market dynamics as foreseen by the critical raw material act (*disruption dynamic*).

Results have shown that:

- Within the international trade dynamics in the context of critical raw materials, strategic behavior plays a pivotal role in shaping the landscape. Our modeling results reveal the strategic behavior of major exporters, particularly exemplified by South Africa. As per current projections, the major exporter is poised to maintain its dominant position to safeguard its market share. However, the model suggests a shift, with the rise of other players, in particular Russia, whose importance in the global market is expected to increase significantly. Analysis of marginal clearing prices demonstrates a strategic focus from the dominant player on maximizing quantities to optimize profit margins while keeping prices at levels approaching the threshold of inelastic demand. However, amidst this strategic behavior, results reflect a significant shift in the global landscape, with other exporters, notably Russia, gaining prominence. This transition is propelled by the advantage of lower maintenance and production costs. Furthermore, the diminishing gap between fringe exporters and major players over time highlights the increasing competitiveness in the market, accentuated by the higher production costs faced by South Africa, which has largely exhausted its cost-saving measures, signaling a diminishing availability of low-hanging fruits in terms of cost-saving measures.

- Within the European market context, results emphasize the critical role of diversified export sources and recycling in ensuring a stable supply. Exporters such as Zimbabwe and North America, coupled with the adoption of recycling practices, emerge as key contributors to safeguarding supply reliability. Moreover, recognizing the inelastic nature of demand, market clearing mechanisms are anticipated to be predominantly influenced by demand-side factors, shaping the equilibrium between supply and demand, hence providing insights into the extent to which demand remains resistant to price fluctuations. Additionally, the discussion delves into the role of recycling as a critical component of the supply chain. Recycling can help reduce resource constraints, especially considering rising demand, yet limited recycling capacity poses a significant obstacle, worsened by variations in recycling methodologies across industries and the wide range of technologies required. In particular, platinum group metals serve as a case in point, with established recycling practices driven by their presence in emission catalysts for mobility applications. They can be recycled indefinitely without loss of performance or quality, highlighting the promise of a circular economy approach. The analysis also highlights the uncertainties surrounding recycling capacity, with market shares fluctuating due to industry immaturity, particularly outside the automotive sector, and the need for concerted efforts to bolster recycling infrastructure, enhance technological capabilities, and adopt sustainable practices to ensure a steady recycled material presence in the EU's critical raw material annual consumption mix in compliance with the 25% specified in the Critical Raw Material

- In addition to demand dynamics, the role of stockpiling emerges as a critical factor in ensuring supply stability and mitigating price volatility. Our investigation into stockpiling within the European market unveils its profound impact on crisis mitigation and supply cost stabilization to ensure a consistent supply of the commodity, as in the case of natural gas strategic storage and oil strategic reserves. In instances where imports are disrupted, stockpiling serves as a crucial mechanism to stabilize quantities and clearing prices, mitigating the adverse effects of supply chain disruptions. However, the feasibility of stockpiling is not without challenges. The European market faces significant hurdles in replenishing stocks due to the high costs associated with filling storage, particularly in comparison to exporters with lower production costs. Similar to gas storage scenarios, stockpiling necessitates a careful cost-benefit analysis, particularly in light of potential "high-impact, low-probability" events. Our findings suggest that optimal stockpile sizes, approximately twice the annual demand, offer a benchmark for effectively managing supply stability within the European market. However, the optimal balance between stockpiling size and welfare implications warrants further exploration to mitigate potential adverse effects.

Limitations of the methodology used, particularly in the context of the Stackelberg game model, are recognized. While this approach allows us to capture the strategic behavior of the major exporter, it overlooks the strategic responses of fringe exporters. These fringe exporters, driven by the objective of maximizing their profit margins, may behave differently in the market, potentially impacting supply dynamics and pricing strategies. Incorporating the strategic behavior of fringe exporters into our model would necessitate a different methodological approach. It is to be recognized that the pursuit of profit maximization extends beyond the major exporter, with fringe players also seeking to optimize their market positions.

Furthermore, the potential implications of different market structures, such as discriminatory pricing versus market clearing pricing, on supply dynamics and consumer costs are acknowledged. While it focuses on optimizing the profit of the major exporter, future research could explore how alternative pricing mechanisms and policies, such as stockpiling, demand reduction, or elastic demand, may influence market outcomes and consumer welfare.

Finally, the importance of fostering long-term partnerships with fringe producers to ensure more favorable terms for Europe is identified. While this may require negotiation and leveraging bargaining power, it could lead to more stable and cost-effective supply arrangements in the long run. In future works, there might be room to consider often excluded fringe producers, attempting to secure long-term agreements with terms more advantageous to Europe compared to the current scarcity-driven pricing seen in the short term, in discussions about strategic partnerships, which are encouraged by the Critical Raw Material Act.

The analysis provides valuable insights into the dynamics of the European market, but future research should explore alternative methodologies and consider the broader implications of different pricing mechanisms and policy interventions on market outcomes and consumer welfare. Hence moving forward, several avenues for future research are identified. These include delving deeper into the dynamics of inelastic/elastic demand, exploring the potential of recycling initiatives, and assessing the developmental trajectory of production costs among fringe exporters as they scale up their export capacities. Furthermore, the exploration of long-term contracts, market clearing mechanisms, and the implications of discriminatory practices on market outcomes remain mature areas for investigation.

Declaration of Competing Interest

The authors report no declarations of interest.

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Appendices

A Nomenclature

Type	Description	Unit
Set and index		
$e \in \mathcal{E} = \{1, \ldots, E\}$	Exporter, index by e (1…Major exporter)	
$e' \in \mathcal{E}' = \{2, \ldots, E\}$	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	
$t \in \mathcal{T} = \{2025, \ldots, 2040\}$	Time step, index by t	
$t' \in \mathcal{T}' = \{2026, \ldots, 2040\}$	Time step, index by t'	
Decision variables of the lower-level problem		
$q_{e,m,t}$	Supply quantity per e, m, and t (export)	ton
$q_{M1,t}^{stock,stored}$	Stock within the European market $M1$ per t (stockpiling)	ton
$q_{M1,t}^{stock,out}$	Quantity out of stock within $M1$ (charge)	ton
$q_{M1,t}^{stock,in}$	Quantity to the stock within $M1$ (discharge)	ton
$\bar{q}_{e',t}$	Supply capacity per e' and t (available)	ton/year
$\bar{q}_{e',t}^{add}$	Added supply capacity per e' and t	ton/year
$\bar{q}_{e',t}^{retire}$	Retired supply capacity per e' and t	ton/year
Decision variables of the upper-level problem		
$c_{1,m,t}$	Offered supply cost of the major exporter 1 per m, and t	€/ton
$\bar{q}_{1,t}$	Offered supply capacity of the major exporter 1 per t	ton/year
Parameters (selection)		
$c_{e,t}^{supply}$	Marginal supply cost per e and t	€/ton
$c_{e'}^{main}$	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 $M1$	%
β^{add}	Proportion of the maximum added supply capacity relative to the overall supply capacity	%
β^{retire}	Proportion of the maximum retired supply capacity relative to the existing supply capacity	%

B Mathematical formulation of the bi-level optimization problem

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

B.1.1 Primal decision variables

$$x = \left[q_{e,m,t}, \bar{q}_{e',t}, \bar{q}^{add}_{e',t}, \bar{q}^{retire}_{e',t}, q^{stock,in}_{M1,t}, q^{stock,out}_{M1,t}, q^{stock,stored}_{M1,t}\right] \tag{29}$$

B.1.2 Objective function

$$\min_x \underbrace{\sum_e \sum_m \sum_t c^{supply}_{e,t} \times q_{e,m,t}}_{\text{Generation cost of all exporters}} + \underbrace{\sum_{e'} \sum_t c^{main}_{e'} \times \bar{q}_{e',t}}_{\text{Maintenance cost of fringe exporters}} + \underbrace{\sum_t c^{stock} \times q^{stock,stored}_{M1,t}}_{\text{Stockpiling cost of European market}} \tag{30}$$

B.1.3 Constraints (primal problem)

Equality constraints

$$d_{M1,t} - \left[\sum_e q_{e,M1,t}\right] - q^{stock,out}_{M1,t} + q^{stock,in}_{M1,t} = 0 \quad : \forall t \quad (\lambda^1_t) \tag{31}$$

$$d_{M2,t} - \left[\sum_e q_{e,M2,t}\right] = 0 \quad : \forall t \quad (\lambda^2_t) \tag{32}$$

$$q^{stock,stored}_{M1,t'} - q^{stock,stored}_{M1,t'-1} + q^{stock,out}_{M1,t'-1} - q^{stock,in}_{M1,t'-1} = 0 \quad : \forall t' \quad (\lambda^3_{t'}) \tag{33}$$

$$q^{stock_s tored}_{M1,t_{start}} = 0 \quad (\lambda^4) \tag{34}$$

$$q^{stock,in}_{M1,t_{end}} = 0 \quad (\lambda^5) \tag{35}$$

$$q^{stock,out}_{M1,t_{start}} = 0 \quad (\lambda^6) \tag{36}$$

$$q^{stock,out}_{M1,t_{end}} - q^{stock,stored}_{M1,t_{end}} = 0 \quad (\lambda^7) \tag{37}$$

$$q_{e,M1,t} = 0 \quad : \forall \underline{\boldsymbol{e}}, \quad (\lambda^8_{\underline{\boldsymbol{e}},t}) \tag{38}$$

$$\bar{q}_{e',t'} - \bar{q}_{e',t'-1} + \bar{q}^{add}_{e',t'} - \bar{q}^{retire}_{e',t'} = 0 \quad : \forall e', t' \quad (\lambda^9_{e',t'}) \tag{39}$$

$$\bar{q}_{e',t_{start}} - \bar{q}^{init}_{e'} = 0 \quad : \forall e' \quad (\lambda^{10}_{e'}) \tag{40}$$

Inequality constraints

$$q_{e,M1,t} - \alpha \times d_{M1,t} \leq 0 \quad : \forall e, t \quad (\mu^1_{e,t}) \tag{41}$$

$$\sum_m \sum_t q_{e,m,t} - Q_e \leq 0 \quad : \forall e \quad (\mu^2_e) \tag{42}$$

$$\left[\sum_m q_{e,m,t}\right] - \bar{q}_{e,t} \leq 0 \quad : \forall e, t \quad (\mu^3_{e,t}) \tag{43}$$

$$\bar{q}^{add}_{e',t} - \beta^{add} \times \sum_m q_{e',m,t} \leq 0 \quad : \forall e', t \quad (\mu^4_{e',t}) \tag{44}$$

$$\bar{q}^{retire}_{e',t} - \beta^{retire} \times q^{init}_{e'} \leq 0 \quad : \forall e', t \quad (\mu^5_{e',t}) \tag{45}$$

$$q^{stock,in}_{M1,t} - d_{M1,t} \leq 0 \quad : \forall t \quad (\mu^6_t) \tag{46}$$

$$-q_{e,m,t} \leq 0 \quad : \forall e, m, t \quad (\mu^7_{e,m,t}) \tag{47}$$

$$-q^{stock,stored}_{M1,t} \leq 0 \quad : \forall t \quad (\mu^8_t) \tag{48}$$

$$-q^{stock,out}_{M1,t} \leq 0 \quad : \forall t \quad (\mu^9_t) \tag{49}$$

$$-q^{stock,in}_{M1,t} \leq 0 \quad : \forall t \quad (\mu^{10}_t) \tag{50}$$

$$-\bar{q}_{e',t} \leq 0 \quad : \forall e', t \quad (\mu^{11}_{e',t}) \tag{51}$$

$$-\bar{q}^{add}_{e',t} \leq 0 \quad : \forall e', t \quad (\mu^{12}_{e',t}) \tag{52}$$

$$-\bar{q}^{retire}_{e',t} \leq 0 \quad : \forall e', t \quad (\mu^{13}_{e',t}) \tag{53}$$

B.1.4 Dual decision variables

$$\lambda = \left[\lambda^1_t, \lambda^2_t, \lambda^3_{t'}, \lambda^4, \lambda^5, \lambda^6, \lambda^7, \lambda^8_{\underline{e},t}, \lambda^9_{e',t,t'}, \lambda^{10}_{e'}\right] \tag{54}$$

$$\mu = \left[\mu^1_{e,t}, \mu^2_e, \mu^3_{e,t}, \mu^4_{e',t}, \mu^5_{e',t}, \mu^6_t, \mu^7_{e,m,t}, \mu^8_t, \mu^9_t, \mu^{10}_t, \mu^{11}_{e',t}, \mu^{12}_{e',t}, \mu^{13}_{e',t}\right] \tag{55}$$

B.1.5 Lagrangian function

$$
\begin{aligned}
\mathcal{L}(x,\lambda,\mu) = & \sum_{e}\sum_{m}\sum_{t} c_{e,t}^{supply} \times q_{e,m,t} + \sum_{e'}\sum_{t} c_{e'}^{main} \times \bar{q}_{e',t} + \sum_{t} c^{stock} \times q_{M1,t}^{stock,stored} \\
& + \sum_{t} \lambda_t^1 \times \left\{ d_{M1,t} - \left[\sum_{e} q_{e,M1,t}\right] - q_{M1,t}^{stock,out} + q_{M1,t}^{stock,in} \right\} \\
& + \sum_{t} \lambda_t^2 \times \left\{ d_{M2,t} - \left[\sum_{e} q_{e,M2,t}\right] \right\} \\
& + \sum_{t'} \lambda_{t'}^3 \times \left\{ q_{M1,t'}^{stock,stored} - q_{M1,t'-1}^{stock,stored} + q_{M1,t'-1}^{stock,out} - q_{M1,t'-1}^{stock,in} \right\} \\
& + \lambda^4 \times \left\{ q_{M1,t_{start}}^{stock_stored} \right\} + \lambda^5 \times \left\{ q_{M1,t_{end}}^{stock,in} \right\} + \lambda^6 \times \left\{ q_{M1,t_{start}}^{stock,out} \right\} \\
& + \lambda^7 \times \left\{ q_{M1,t_{end}}^{stock,out} - q_{M1,t_{end}}^{stock,stored} \right\} \\
& + \sum_{\underline{e}}\sum_{t} \lambda_{\underline{e},t}^8 \times \{ q_{e,M1,t} \} \\
& + \sum_{e'}\sum_{t'} \lambda_{e',t'}^9 \times \left\{ \bar{q}_{e',t'} - \bar{q}_{e',t'-1} + \bar{q}_{e',t'}^{add} - \bar{q}_{e',t'}^{retire} \right\} \\
& + \sum_{e'} \lambda_{e'}^{10} \times \left\{ \bar{q}_{e',t_{start}} - \bar{q}_{e'}^{init} \right\} \\
& + \sum_{e}\sum_{t} \mu_{e,t}^1 \times \{ q_{e,M1,t} - \alpha \times d_{M1,t} \} \\
& + \sum_{e} \mu_e^2 \times \{ q_{e,m,t} - Q_e \} \\
& + \sum_{e}\sum_{t} \mu_{e,t}^3 \times \left\{ \left[\sum_{m} q_{e,m,t}\right] - \bar{q}_{e,t} \right\} \\
& + \sum_{e'}\sum_{t} \mu_{e',t}^4 \times \left\{ \bar{q}_{e',t}^{add} - \beta^{add} \times \sum_{m} q_{e',m,t} \right\} \\
& + \sum_{e'}\sum_{t} \mu_{e',t}^5 \times \left\{ \bar{q}_{e',t}^{retire} - \beta^{retire} \times q_{e'}^{init} \right\} \\
& + \sum_{t} \mu_t^6 \times \left\{ q_{M1,t}^{stock,in} - d_{M1,t} \right\} \\
& + \sum_{e}\sum_{m}\sum_{t} \mu_{e,m,t}^7 \times \{ -q_{e,m,t} \} + \sum_{t} \mu_t^8 \times \left\{ -q_{M1,t}^{stock,stored} \right\} \\
& + \sum_{t} \mu_t^9 \times \left\{ -q_{M1,t}^{stock,out} \right\} + \sum_{t} \mu_t^{10} \times \left\{ -q_{M1,t}^{stock,in} \right\} \\
& + \sum_{e'}\sum_{t} \mu_{e',t}^{11} \times \left\{ -\bar{q}_{e',t} \right\} + \sum_{e'}\sum_{t} \mu_{e',t}^{12} \times \left\{ -\bar{q}_{e',t}^{add} \right\} \\
& + \sum_{e'}\sum_{t} \mu_{e',t}^{13} \times \left\{ -\bar{q}_{e',t}^{retire} \right\}
\end{aligned}
\tag{56}
$$

B.1.6 Karush–Kuhn–Tucker conditions

$$
\frac{\partial \mathcal{L}}{\partial q_{1,M1,t}} = c_{1,M1,t} - \lambda_t^1 + \mu_{1,t}^1 + \mu_{1,t}^3 - \mu_{1,M1,t}^7 = 0 \tag{57}
$$

$$\frac{\partial \mathcal{L}}{\partial q_{1,M2,t}} = c_{1,M2,t} - \lambda_t^2 + \mu_1^2 + \mu_{1,t}^3 - \mu_{1,M2,t}^7 = 0 \tag{58}$$

$$\frac{\partial \mathcal{L}}{\partial q_{e',M1,t}} = \begin{cases} c_{e'}^{supply} - \lambda_t^1 + \mu_{e',t}^1 + \mu_{e'}^2 + \mu_{e',t}^3 - \mu_{e',t}^4 \times \beta^{add} + \lambda_{e',t}^8 - \mu_{e',M1,t}^7 = 0 & (\text{if } e' \in \underline{\mathcal{E}}) \\ c_{e'}^{supply} - \lambda_t^1 + \mu_{e',t}^1 + \mu_{e'}^2 + \mu_{e',t}^3 - \mu_{e',t}^4 \times \beta^{add} - \mu_{e',M1,t}^7 = 0 & (\text{if } e' \notin \underline{\mathcal{E}}) \end{cases} \tag{59}$$

$$\frac{\partial \mathcal{L}}{\partial q_{e',M2,t}} = c_{e'}^{supply} - \lambda_t^2 + \mu_{e'}^2 + \mu_{e',t}^3 - \mu_{e',t}^4 \times \beta^{add} - \mu_{e',M2,t}^7 = 0 \tag{60}$$

$$\frac{\partial \mathcal{L}}{\partial \bar{q}_{e',t}} = \begin{cases} c_{e'}^{main} - \mu_{e',t}^3 - \lambda_{e',t+1}^9 + \lambda_{e',t}^{10} - \mu_{e',t}^{11} = 0 & (\text{if } t = t_{start}) \\ c_{e'}^{main} - \mu_{e',t}^3 + \lambda_{e',t}^9 - \mu_{e',t}^{11} = 0 & (\text{if } t = t_{end}) \\ c_{e'}^{main} - \mu_{e',t}^3 + \lambda_{e',t}^9 - \lambda_{e',t+1}^9 - \mu_{e',t}^{11} = 0 & (\text{else}) \end{cases} \tag{61}$$

$$\frac{\partial \mathcal{L}}{\partial q_{M1,t}^{stock,stored}} = \begin{cases} c^{stock} - \lambda_{t+1}^3 + \lambda^4 - \mu_t^8 = 0 & (\text{if } t = t_{start}) \\ c^{stock} + \lambda_t^3 - \lambda^7 - \mu_t^8 = 0 & (\text{if } t = t_{end}) \\ c^{stock} + \lambda_t^3 - \lambda_{t+1}^3 - \mu_t^8 = 0 & (\text{else}) \end{cases} \tag{62}$$

$$\frac{\partial \mathcal{L}}{\partial q_{M1,t}^{stock,out}} = \begin{cases} -\lambda_t^1 + \lambda_{t+1}^3 + \lambda^6 - \mu_t^9 = 0 & (\text{if } t = t_{start}) \\ -\lambda_t^1 + \lambda^7 - \mu_t^9 = 0 & (\text{if } t = t_{end}) \\ -\lambda_t^1 + \lambda_{t+1}^3 - \mu_t^8 = 0 & (\text{else}) \end{cases} \tag{63}$$

$$\frac{\partial \mathcal{L}}{\partial q_{M1,t}^{stock,in}} = \begin{cases} \lambda_t^1 - \lambda_{t+1}^3 - \mu_t^{10} + \mu_t^6 = 0 & (\text{if } t = t_{start}) \\ \lambda_t^1 + \lambda^5 - \mu_t^{10} + \mu_t^6 = 0 & (\text{if } t = t_{start}) \\ \lambda_t^1 - \lambda_{t+1}^3 - \mu_t^{10} + \mu_t^6 = 0 & (\text{else}) \end{cases} \tag{64}$$

$$\frac{\partial \mathcal{L}}{\partial \bar{q}_{e',t}^{add}} = \begin{cases} \mu_{e',t}^4 - \mu_{e',t}^{12} = 0 & (\text{if } t = t_{end}) \\ \mu_{e',t}^4 - \lambda_{e',t+1}^9 - \mu_{e',t}^{12} = 0 & (\text{else}) \end{cases} \tag{65}$$

$$\frac{\partial \mathcal{L}}{\partial \bar{q}_{e',t}^{retire}} = \begin{cases} \mu_{e',t}^5 - \mu_t^{13} = 0 & (\text{if } t = t_{end}) \\ \mu_{e',t}^5 + \lambda_{e',t+1}^9 - \mu_t^{13} = 0 & (\text{else}) \end{cases} \tag{66}$$

$$0 \leq \mu_{e,t}^1 \quad \perp \quad q_{e,M1,t} - \alpha \times d_{M1,t} \leq 0 \quad : \forall e, t \tag{67}$$

$$0 \leq \mu_e^2 \quad \perp \quad \sum_m \sum_t q_{e,m,t} - Q_e \leq 0 \quad : \forall e \tag{68}$$

$$0 \leq \mu^3_{e,t} \quad \perp \quad \left[\sum_m q_{e,m,t}\right] - \bar{q}_{e,t} \leq 0 \quad : \forall e, t \tag{69}$$

$$0 \leq \mu^4_{e',t} \quad \perp \quad \bar{q}^{add}_{e',t} - \beta^{add} \times \sum_m q_{e',m,t} \leq 0 \quad : \forall e', t \tag{70}$$

$$0 \leq \mu^5_{e',t} \quad \perp \quad \bar{q}^{retire}_{e',t} - \beta^{retire} \times q^{init}_{e'} \leq 0 \quad : \forall e', t \tag{71}$$

$$0 \leq \mu^6_t \quad \perp \quad q^{stock,in}_{M1,t} - d_{M1,t} \leq 0 \quad : \forall t \tag{72}$$

$$0 \leq \mu^7_{e,m,t} \quad \perp \quad - q_{e,m,t} \leq 0 \quad : \forall e, m, t \tag{73}$$

$$0 \leq \mu^8_t \quad \perp \quad - q^{stock,stored}_{M1,t} \leq 0 \quad : \forall t \tag{74}$$

$$0 \leq \mu^9_t \quad \perp \quad - q^{stock,out}_{M1,t} \leq 0 \quad : \forall t \tag{75}$$

$$0 \leq \mu^{10}_t \quad \perp \quad - q^{stock,in}_{M1,t} \leq 0 \quad : \forall t \tag{76}$$

$$0 \leq \mu^{11}_{e',t} \quad \perp \quad - \bar{q}_{e',t} \leq 0 \quad : \forall e', t \tag{77}$$

$$0 \leq \mu^{12}_{e',t} \quad \perp \quad - \bar{q}^{add}_{e',t} \leq 0 \quad : \forall e', t \tag{78}$$

$$0 \leq \mu^{13}_{e',t} \quad \perp \quad - \bar{q}^{retire}_{e',t} \leq 0 \quad : \forall e', t \tag{79}$$

B.1.7 Complementarity condition linearization

The complementarity conditions in Equations 67 to 79 are linearized using the well-known linear expressions (see Ruiz and Conejo (2009)) as follows, where u is a binary decision variable and M is a parameter large enough to ensure complementarity (both indexed accordingly).

$$\begin{aligned} 0 \leq \mu^1_{e,t} \leq M^1 \times u^1_{e,t} \quad &: \forall e, t \\ 0 \leq -q_{e,M1,t} + \alpha \times d_{M1,t} \leq M^1 \times \left(1 - u^1_{e,t}\right) \quad &: \forall e, t \end{aligned} \tag{80}$$

$$
\begin{aligned}
0 \le \mu^2_e \le M^3 \times u^2_e \quad &: \forall e \\
0 \le -\sum_m \sum_t q_{e,m,t} + Q_e \le M^2 \times \left(1 - u^2_e\right) \quad &: \forall e
\end{aligned} \tag{81}
$$

$$
\begin{aligned}
0 \le \mu^3_{e,t} \le M^3 \times u^3_{e,t} \quad &: \forall e, t \\
0 \le -\left[\sum_m q_{e,m,t}\right] + \bar{q}_{e,t} \le M^3 \times \left(1 - u^3_{e,t}\right) \quad &: \forall e, t
\end{aligned} \tag{82}
$$

$$
\begin{aligned}
0 \le \mu^4_{e',t} \le M^4 \times u^4_{e',t} \quad &: \forall e', t \\
0 \le -\bar{q}^{add}_{e',t} + \beta^{add} \times \sum_m q_{e',m,t} \le M^4 \times \left(1 - u^4_{e',t}\right) \quad &: \forall e', t
\end{aligned} \tag{83}
$$

$$
\begin{aligned}
0 \le \mu^5_{,t} \le M^5 \times u^5_{e',t} \quad &: \forall e', t \\
0 \le -\bar{q}^{retire}_{e',t} + \beta^{retire} \times q^{init}_{e'} \le M^5 \times \left(1 - u^5_{e',t}\right) \quad &: \forall e', t
\end{aligned} \tag{84}
$$

$$
\begin{aligned}
0 \le \mu^6_{,t} \le M^6 \times u^6_t \quad &: \forall t \\
0 \le -q^{stock,in}_{M1,t} + d_{M1,t} \le M^6 \times \left(1 - u^6_t\right) \quad &: \forall t
\end{aligned} \tag{85}
$$

$$
\begin{aligned}
0 \le \mu^7_{,t} \le M^7 \times u^7_{e,m,t} \quad &: \forall e, m, t \\
0 \le q_{e,m,t} \le M^7 \times \left(1 - u^7_t\right) \quad &: \forall e, m, t
\end{aligned} \tag{86}
$$

$$
\begin{aligned}
0 \le \mu^8_{,t} \le M^8 \times u^8_t \quad &: \forall t \\
0 \le q^{stock,stored}_{M1,t} \le M^8 \times \left(1 - u^8_t\right) \quad &: \forall t
\end{aligned} \tag{87}
$$

$$
\begin{aligned}
0 \le \mu^9_{,t} \le M^9 \times u^9_t \quad &: \forall t \\
0 \le q^{stock,out}_{M1,t} \le M^9 \times \left(1 - u^9_t\right) \quad &: \forall t
\end{aligned} \tag{88}
$$

$$
\begin{aligned}
0 \le \mu^{10}_{,t} \le M^{10} \times u^{10}_t \quad &: \forall t \\
0 \le q^{stock,in}_{M1,t} \le M^{10} \times \left(1 - u^{10}_t\right) \quad &: \forall t
\end{aligned} \tag{89}
$$

$$
\begin{aligned}
0 \le \mu^{11}_{e',t} \le M^{11} \times u^{11}_{e',t} \quad &: \forall e', t \\
0 \le \bar{q}_{e',t} \le M^{11} \times \left(1 - u^{11}_{e',t}\right) \quad &: \forall e', t
\end{aligned} \tag{90}
$$

$$
\begin{aligned}
0 \le \mu^{12}_{e',t} \le M^{13} \times u^{12}_{e',t} \quad &: \forall e', t \\
0 \le \bar{q}^{add}_{e',t} \le M^{12} \times \left(1 - u^{12}_{e',t}\right) \quad &: \forall e', t
\end{aligned} \tag{91}
$$

$$
\begin{aligned}
0 \le \mu^{13}_{e',t} \le M^{13} \times u^{13}_{e',t} \quad &: \forall e', t \\
0 \le \bar{q}^{retire}_{e',t} \le M^{13} \times \left(1 - u^{13}_{e',t}\right) \quad &: \forall e', t
\end{aligned} \tag{92}
$$

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

B.2.1 Decision variables

$$\mathcal{Y} = [c_{1,m,t}, \bar{q}_{1,t}] \tag{93}$$

B.2.2 Objective function

$$\max_{\mathcal{Y}} \sum_{m} \sum_{t} q_{1,m,t} \times (c_{1,m,t} - \tilde{c}) \tag{94}$$

B.2.3 Constraints

$$0 \leq \bar{q}_{1,t} \leq \tilde{q}_1 \quad : \forall t \tag{95}$$

B.2.4 Linear reformulation

- Of the non-linear term $q_{1,m,t} \times c_{1,m,t}$ in Equation 94
  - Product of two continuous variables
- With the discrete parameter $n \in \mathcal{N} = \{0.5 \dots 30.0\}$
  - $|\mathcal{N}|$ tailored to replicate the export costs of all fringe exporters adequately
  - In this specific case $\pm 5\%$
- With the binary variable $\sigma_{m,n,t}$, continuous variable $z_{m,n,t}$, and parameter γ (large enough)

$$q_{1,m,t} \times c_{1,m,t} = \sum_{n} n \times q_{1,m,t} \times \sigma_{m,n,t} \tag{96}$$

$$\begin{aligned} z_{m,n,t} &\leq \gamma \times \sigma_{m,n,t} && : \forall m, n, t \\ z_{m,n,t} &\leq q_{1,m,t} && : \forall m, n, t \\ z_{m,n,t} &\geq q_{1,m,t} - (1 - \sigma_{m,n,t}) \times \gamma && : \forall m, n, t \\ z_{m,n,t} &\geq 0 && : \forall m, n, t \end{aligned} \tag{97}$$

B.3 Completed optimization problem

$$\begin{aligned} \max_{x,\lambda,\mu,u,y,\sigma,z} \sum_{m} \sum_{n} \sum_{t} n \times z_{m,n,t} - \sum_{m} \sum_{t} q_{1,m,t} \times \tilde{c} \\ \text{s.t. } (31) - (53) \\ (57) - (66) \\ (80) - (92) \\ (11), (97) \end{aligned} \tag{98}$$