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Strategic autonomy in practice: Ukraine's critical raw materials, growth accounting and shift-share evidence, 2010–2023

Introduction

Critical raw materials (CRMs) occupy a pivotal place at the intersection of economic growth, technological change and geopolitics. A material is conventionally deemed "critical" when high economic importance coincides with supply risk and limited substitutability. In policy and scholarly usage, the terms *critical* and *strategic* are often employed interchangeably because the sources of risk – market concentration, technological lock-ins, and coercive state action – are themselves strategic in nature. Modern industrial systems, from advanced

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manufacturing and aerospace to defense and the green-energy complex, are structurally dependent on secure flows of such inputs (Pangsy-Kania and Flouros 2022). In Europe, this dependence has been thrown into sharp relief by Russia's aggression against Ukraine and by longstanding mid-stream bottlenecks in global mineral processing.

Ukraine's resource endowment has therefore re-entered Europe's strategic vocabulary. Significant deposits of graphite, lithium, titanium and manganese are documented across the Ukrainian Crystalline Shield, with additional occurrences of other materials relevant to EU critical-raw-material and strategic value-chain policy, including germanium, vanadium, zirconium/hafnium and gallium, at a smaller scale. Recent assessments highlight the potential for Ukraine to supply a material share of Europe's CRM needs once investment and security conditions permit (Kõrts 2023). Yet endowment alone is not decisive. Power in CRM value chains is exercised at processing nodes and through standards and contracts that govern access to them (Gereffi et al. 2005). In a European Union that pursues "strategic autonomy" via *de-risking* rather than *decoupling*, the relevant policy question is whether Ukraine can anchor itself as a trusted supplier inside EU-centred chains, reducing asymmetric dependencies while financing reconstruction (European Union 2024). The Commission's RESourceEU Action Plan further reinforces this logic by framing CRM supply security around de-risking, diversification and strategic partnerships (European Commission 2025).

This article addresses that question with two transparent tools suited to political economy. First, we augment standard growth accounting by introducing a composite CRM production index, defined as a fixed-weight physical-output index (2018 = 100) for graphite, ilmenite concentrate, and manganese concentrate. This index is used to estimate the contribution of natural capital to real-GDP growth alongside the residual, interpreted as total factor productivity (TFP). Second, we apply a shift-share decomposition to Ukraine's CRM exports to separate changes due to benchmark demand, product mix and competitiveness. The two perspectives are read through the lenses of asymmetric interdependence and weaponized interdependence, which explain how control of chokepoints in networked systems translates into leverage (Keohane and Nye 2012; Farrell and Newman 2019). The empirical basket is focused on graphite, titanium (ilmenite), and manganese; lithium is discussed contextually given current data limitations.

Graphite, titanium (ilmenite), and manganese are the focus of the analysis due to their combined high economic relevance, strategic importance for the European Union, and Ukraine's established production capacity. These three materials rank among the most significant critical raw materials (CRMs) in terms of their role in key industrial and energy transition value chains, including batteries, aerospace, and steel production, while Ukraine is already a globally relevant supplier or possesses substantial reserves of each.

The study tests three hypotheses.

- H1: Ukraine's CRM endowment can make a positive and measurable contribution to potential growth, conditional on processing capacity, logistics, and credible governance.

- H2: the reorientation of Ukraine's CRM trade can lower Western dependence on concentrated suppliers, provided the product mix shifts toward segments where Europe internalizes more value added.
- H3: wartime and geopolitical shocks constrain effective utilization of CRM via volatility in logistics, finance and regulation, which should manifest as a weaker competitiveness component in export performance.

By linking an economy-wide growth perspective to a trade-performance decomposition within a single framework, this paper offers a compact bridge between potential and realized outcomes.

The remainder proceeds as follows. Section 1 sets out the theoretical lenses. Section 2 summarizes Ukraine's endowment and the available data. Section 3 details data and methods. Section 4 reports results from growth accounting and shift-share, with sensitivity checks. Section 5 discusses geopolitics and policy design under the EU's de-risking paradigm. Section 6 concludes with limitations and avenues for further research.

1. A political-economy framework for Ukraine's strategic minerals

The study develops a concise framework that links Ukraine's critical raw materials (CRMs) to both growth and power. In measurement terms, natural capital is treated as a measurable input within a transparent growth-accounting setup rooted in standard macroeconomics (Solow 1956; Mankiw et al. 1992). In political-economy terms, production and trade are analyzed through asymmetric and weaponized interdependence, which explain how control of chokepoints in networked systems translates into leverage (Keohane and Nye 2012; Farrell and Newman 2019). Finally, bargaining power is located within global value-chain governance and the EU's strategic autonomy agenda, where outcomes are shaped by rules, contracts, and mid-stream capacity rather than ore ownership (Gereffi et al. 2005; European Union 2024).

1.1. Critical raw materials as a factor of economic growth

In the growth-accounting tradition, output depends on reproducible inputs with a residual capturing technology and institutions (Solow 1957). Augmentations that add additional inputs – classically human capital – improve explanatory power while remaining transparent (Mankiw et al. 1992). Extending this logic, natural capital is treated as a measurable factor consistent with national-wealth accounting, as reflected in the World Bank's changing-wealth framework and recent EU analyses of natural capital in production functions (World Bank 2021; European Commission, DG ECFIN 2023).

Operationally, the resource factor is proxied by a composite CRM production index (2018 = 100) that aggregates graphite, titanium in the form of ilmenite concentrate, and manganese concentrate. The baseline uses equal 2018-based weights and physical quantity series. A price-weighted variant using 2018 unit prices and a value-weighted export index is reported as robustness in the Appendix. The year 2018 is adopted as the baseline due to its position as a recent pre-disruption reference point, preceding the major structural shocks associated with the COVID-19 pandemic and Russia's full-scale invasion of Ukraine in 2022. This allows for the analysis of Ukraine's critical raw materials sector under relatively stable economic and trade conditions, providing a consistent benchmark for assessing subsequent changes and disruptions. In addition, 2018 offers the most recent year for which harmonized and comparable datasets on production, trade flows, and reserves are broadly available across the studied materials.

Data for quantities and prices come from standard public sources used in the CRM literature, including USGS Mineral Commodity Summaries and Minerals Yearbook, IndexMundi and Ukrstat for production, and UN Comtrade for trade values and volumes; details and concordances are documented in section 4 and the Appendix (Gereffi et al. 2005; USGS 2018; UN Comtrade n.d.).

In this notation, $\gamma \cdot \Delta \ln N$ is the estimated contribution of the CRM production index to real-GDP growth, while the residual captures changes not explained by the CRM term and is interpreted as total factor productivity (TFP). This distinction allows us to separate extraction-led changes from broader productivity movements and to relate the results to the resource-curse literature (Mehlum et al. 2006; Frankel 2010; van der Ploeg 2011).

1.2. Interdependence and power in CRM supply chains

In a world of complex interdependence, power stems less from autarkic control than from the structure of mutual dependencies (Keohane and Nye 2012). Where those ties are asymmetric, the less dependent actor can shift adjustment costs onto the more dependent one and thus extract concessions. In critical raw materials (CRMs), Europe's longstanding reliance on extra-EU processing – especially in rare earths – creates precisely such asymmetries, with vulnerability concentrated in mid-stream stages rather than at the mine mouth (European Union 2024).

Farrell and Newman (2019) generalize this logic for networked systems, showing how actors who control central nodes can weaponize chokepoints ("chokepoint effect") or information flows ("panopticon effect"). Applied to CRMs, separation, refining, and first-stage metal making function as such hubs: geographic concentration at these nodes magnifies leverage even when upstream extraction is more diversified. The politics of CRMs thus turns from "who owns the ore?" to "who controls processing nodes and standards?", which is where coercive capacity and resilience risk actually sit (Farrell and Newman 2019; IEA 2021; IEA 2024).

Empirically, concentration is highest not only in extraction but especially in processing, refining and separation. IEA assessments show that several energy-transition minerals have more concentrated processing than mining, with rare-earth separation and battery-material refining representing particularly strong chokepoints (IEA 2021; IEA 2024). For Europe, this implies that de-risking cannot be achieved by new mines alone, because dependency is often decided in mid-stream capacity and in the compliance regimes that govern access to it. These interdependence dynamics correspond directly to the empirical tools used below: shift-share separates benchmark demand, product-mix and competitiveness effects, while growth accounting separates the estimated CRM contribution from the residual productivity term.

1.3. GVC governance and the EU's quest for strategic autonomy

The EU's turn to strategic autonomy reframes openness around resilience within governed chains. The Critical Raw Materials Act (CRMA) operationalizes this with quantified 2030 targets: at least 10% of EU annual consumption extracted in the Union, 40% processed in the Union, 25% recycled in the Union, and no more than 65% of any strategic raw material supplied from a single third country. These targets create a regulatory pull to re-anchor processing and recycling within a trusted perimeter (European Union 2024).

In practical governance terms, bargaining power resides in mid-stream capacity and verifiable standards. Due-diligence regimes and contract architectures determine access to processing nodes and the bankability of offtakes, which in turn mediate exposure to coercion and shocks. This is the logic of de-risking rather than decoupling: diversify away from concentrated suppliers, internalize more value added in trusted jurisdictions and harden the compliance layer that binds chains together (Keohane and Nye 2012; Farrell and Newman 2019; IEA 2021).

For Ukraine, the implication is straightforward. Geological options are necessary but not sufficient. Durable leverage requires credible mid-stream projects aligned with CRMA thresholds, transparent due diligence compatible with EU practice, and bankable logistics that can absorb wartime volatility. The empirical design tests these governance claims in two steps. The growth-accounting exercise asks whether Ukraine's CRM production contributes measurably to real-GDP growth, while the shift-share decomposition asks whether Ukraine gains or loses CRM export share in global and EU-27 markets. The results are interpreted against Europe's de-risking strategy and the CRMA framework (European Union 2024).

2. Ukraine's CRM endowment and context

Ukraine's resource base in critical raw materials (CRMs) is unusually diversified for a European neighbor of the EU. Commercially relevant occurrences of graphite, lithium, titanium (ilmenite/rutile) and manganese are documented across the Ukrainian Crystalline Shield and associated basins, with additional materials relevant to EU critical-raw-material and strategic value-chain policy, including germanium, vanadium, zirconium/hafnium and gallium, present at smaller scale (European Union 2024; WEF 2024; BGK 2025; FES 2025).

This geological endowment matters not simply because deposits exist, but because the EU's de-risking agenda focuses on mid-stream security in precisely those value chains where Ukraine could become a proximate, trusted supplier once security and infrastructure constraints ease (European Union 2024). Global demand trends reinforce that option value: clean-energy deployment and defense/dual-use manufacturing raise the long-run call on CRM inputs (IEA 2021).

This section establishes the factual baseline for the empirical work that follows. First, the state of knowledge on deposits, production, and trade coverage is summarized, with transparency provided where public statistics are thin (Section 2.1). Subsequently, short commodity profiles are provided for graphite, lithium, titanium, and manganese (Sections 2.2–2.5). The section closes with a brief note on other strategic metals and the institutional setting, followed by a compact "takeaway" that links the descriptive material to the methods and results. Throughout, interpretation is kept to a minimum; quantitative attribution and policy design are reserved for Sections 4 and 5.

2.1. Overview and data gaps

Publicly available evidence supports three high-level statements. First, the empirical basket covers four CRMs for which Ukraine has documented resource potential: natural graphite, lithium, titanium raw materials, and manganese. The baseline production index is limited to the three CRMs for which sufficiently consistent annual physical production series can be validated: graphite, titanium ores/concentrates, and manganese ore/concentrate. Lithium is retained for the qualitative discussion and forward-looking scenarios only.

Second, the production and export footprint was materially disrupted after 2022 by physical damage, power-price spikes, and logistics rerouting, with partial recovery visible in selected lines. Third, statistical coverage is uneven across minerals and stages (mining vs. processing vs. trade), which affects what can be said with precision in annual panels (USGS 2020–2021; WEF 2024; BGK 2025; FES 2025).

For the purposes of sections 3–4, three conventions are standardized. Where reliable annual production series exist (e.g., graphite, ilmenite, manganese concentrates), quantities are used to build the CRM composite index with a 2018 base; where production is missing or inconsistent, export values serve as a transparent proxy, clearly flagged in the data dictionary. For the trade benchmark, results are reported against both the world market and the EU-27 import aggregate, given the policy relevance of the EU perimeter.

Several definitional issues require explicit handling. "Titanium" in public sources may refer to ilmenite/leucoxene concentrates (HS 2614), titanium slag (HS 2620.99 in some customs mappings), or metallic titanium (HS 8108); the concentrate definition is maintained for comparability with production series, while metals are included only in a narrative context. For manganese, a distinction is made between ore/concentrate statistics and ferroalloy output, with only the former entering the CRM index. Lithium is not included in the baseline production index because no consistent annual production series comparable to the other CRMs could be validated for the full sample. It is therefore discussed qualitatively and used only in forward-looking scenarios. Employment series after 2016 and capital stock measures are incomplete; the growth-accounting implementation therefore reports the resource term and the residual, with K and L added when vetted series become available.

2.2. Inventory and geography of Ukrainian critical raw materials

Figure 1 locates documented occurrences of graphite, ilmenite and manganese across the principal ore belts. The pattern is spatially concentrated along the central-southeastern corridor of the Ukrainian Crystalline Shield, with manganese basins further south-east. In operational terms, titanium mining is associated primarily with heavy-mineral sand deposits and mining-concentration operations around Irshansk and Vilnohirsk/Vilnohirske, while manganese production is concentrated in the Nikopol manganese basin in south-eastern Ukraine (USGS 2023a, b, 2024; WEF 2024; FES 2025).

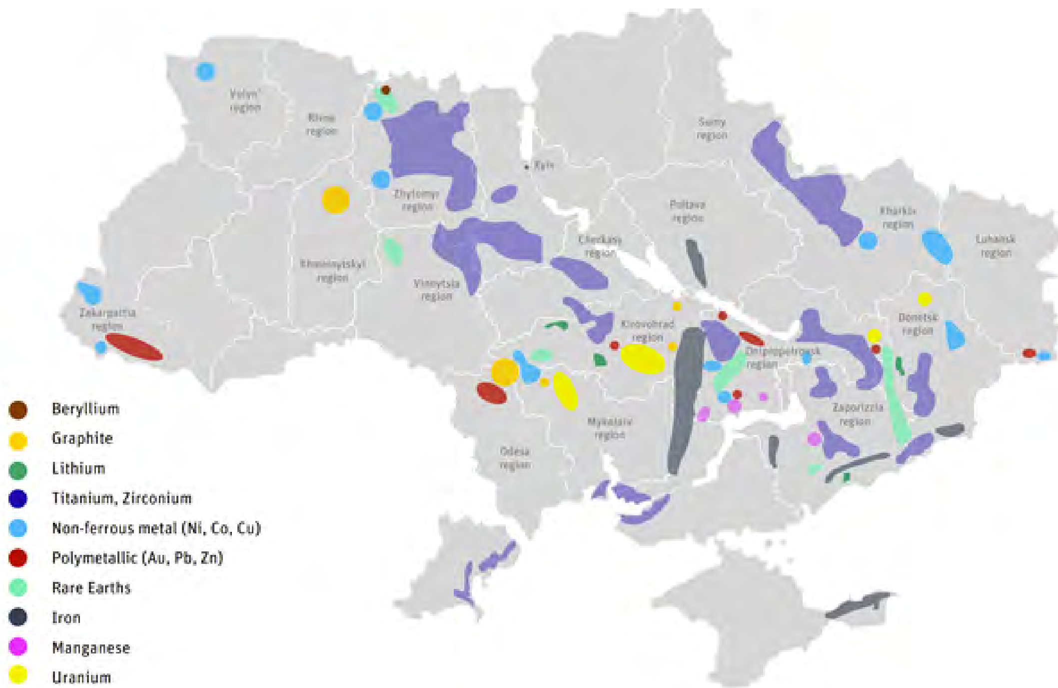

Fig. 1. Map of critical raw materials in Ukraine (schematic distribution by resource family)
Source: Ukrainian Geological Survey, Mining Investment Opportunities: Critical Raw Materials, slide 4

Rys. 1. Mapa surowców krytycznych w Ukrainie (schematyczny rozkład według grup surowców)

The map is illustrative. It shows the approximate geography of relevant deposits and occurrences, but it is not a reserve map and does not assess deposit quality, economic viability, or current mineability.

Table 1 reports indicative in-situ volumes and a simple control-status split (government-controlled vs occupied) compiled from secondary syntheses. Reserve classifications differ across sources; concordances are listed in the Appendix.

Table 1. Ukraine's critical raw materials: indicative in-situ volumes and deposit control status, status as reported in 2024–2025 sources

Tabela 1. Surowce krytyczne Ukrainy: orientacyjne zasoby w miejscu występowania oraz status kontroli nad złożami, zgodnie z danymi podanymi w źródłach z lat 2024–2025

Resource	Indicative in-situ volume as reported by sources*	Deposits: government-controlled/occupied	Notes
Graphite	13.58 million	4/2	Large occurrences in the Ukrainian Crystalline Shield; principal sites include Zavalivske, Balakivske, Burtyne.
Lithium	1.60 million	3/1	Occurrences (e.g., Polokhivske, Shevchenkivske) with petalite/spodumene mineralogy.
Titanium (ilmenite/rutile ores)	8.40 million	25/0	Long-standing ilmenite stream; industrial output disrupted in 2022.
Manganese	430 million	3/2	Nikopol manganese basin; significant pre-war contribution to metallurgical supply.

* Volume expressed mostly in metric tonnes (ore/resource basis unless stated otherwise). Volumes are indicative in-situ quantities compiled from secondary sources and refer to ore/resource volumes as reported by those sources, not to contained pure element or refined metal content unless explicitly stated. They are not directly comparable to CRIRSCO/JORC "reserves". Control status reflects the classification reported in the 2024–2025 source materials and may change with the security situation. The manganese entry reflects classified resources in the Ukrainian A+B+C1 system (State Commission on Mineral Resources), not proven reserves. Titanium refers to USGS-reported ore reserves (ilmenite/rutile) of approximately 8.4 Mt for Ukraine; graphite figures reflect recorded reserves of approximately 13.7 Mt; lithium volumes are order-of-magnitude indications pending harmonized reporting. Classifications and concordances are discussed in Appendix A.2.

Source: WEF 2024; FES 2025.

Summary metrics of reserves, shares and global rankings, including materials not used in the empirical CRM basket, are reported in Appendix A.2.

The core CRMs analyzed empirically – graphite, titanium (ilmenite) and manganese – cluster along the Ukrainian Crystalline Shield and adjacent basins. Lithium occurrences lie in the same structural corridor but remain statistically thin. The map is schematic rather than cadastral; it signals where options exist, not operating capacity. These anchors motivate the commodity profiles that follow and frame the quantitative work in sections 4–5.

Table 1 summarizes the resource families shown in Figure 1 into indicative in situ volumes and a control-status split (government-controlled vs occupied). Classifications differ across sources; concordances are listed in the Appendix.

2.3. Graphite

Natural graphite is the best documented of Ukraine's battery-relevant CRMs. Commercial deposits align with the Ukrainian Crystalline Shield, with Zavalivske, Balakivske and Burtyne as the principal sites. Pre-war activity combined one operating brownfield with several licensed greenfields, consistent with Ukraine's top-five position by graphite reserves (WEF 2024; FES 2025).

Before the full-scale invasion, the industrial base was small but continuous: production hovered around 6–8 kt in the early 2010s, increased after 2017, and peaked at roughly 17 kt in 2021. The 2022 shock led to plant shutdowns and a collapse in output to the 1–2 kt range in 2022–2023, with only partial recovery thereafter. Trade flows mirror this pattern: exports rose with the 2017–2021 ramp-up and then fell sharply as processing and logistics were disrupted. For the empirical analysis, graphite enters the CRM composite as a quantity series benchmarked to 2018 (2018 = 100) (USGS 2023a, b, 2024; IndexMundi; UN Comtrade).

2.4. Lithium

Lithium occurrences are recorded in central Ukraine, notably in the Polokhiv and Shevchenkivskyi areas, with mineralization reported in petalite/spodumene systems. Ukraine hosts three hard-rock lithium deposits and one promising block on the Ukrainian Crystalline Shield: Polokhivske (licensed to UkrLithiumMining; petalite-dominant with about 1.21% Li_2O; pre-feasibility stage), Dobra (spodumene-petalite, circa 1.38% Li_2O; prepared for a 50-year PSA), Shevchenkivske (~1.1% Li_2O; prepared for auction, currently in or near contested territory), and Kruta Balka (~0.86% Li_2O; exploration block). As of the Atlas publication, no commercial lithium extraction is reported. (Ukrainian Geological Survey; WEF 2024; FES 2025; BGK 2025)

Reserve tonnages are classified in public sources, and no industrial extraction was established during the sample window; activity has been limited to licensing rounds, exploration work, and project preparation. This implies two consequences for the paper. First, lithium does not enter the baseline CRM index because no consistent annual production or export series exists for 2010–2023. It is discussed qualitatively in Section 6 and is included in forward-looking scenarios only. Second, the policy relevance of lithium in Ukraine hinges on mid-stream integration rather than geology alone, since any move from ore to battery-grade chemicals would require processing capacity aligned with EU standards and predictable logistics. Sources used earlier report Ukraine's share of global lithium reserves as 1–2% and note that absolute figures are not disclosed (Ukrainian Geological Survey; BGK 2025; FES 2025).

2.5. Titanium (ilmenite/rutile streams)

Ukraine's titanium industry is built around ilmenite/rutile mineralization in sands and hard-rock bodies along the central-southeastern belt shown in Figure 1. Mid-stream capacity is the binding node. On the pigment side, Sumykhimprom has nominal capacity around 45 kt TiO_2 per year (Krym Titan 80 kt TiO_2, located in occupied Crimea). On the metal side, ZTMK (Zaporizhzhia Titanium and Magnesium Combine) has sponge capacity near 12 ktpa but is cost-disadvantaged without modernization. Heavy-mineral sands at Irshanske/Vylnohirske (UMCC) anchor mining; Velta and GDF operate other ilmenite/rutile deposits (USGS 2023a, b, 2024; BGK 2025; FES 2025).

Public statistics consistently report concentrates as the main tradable output; slag and metal appear intermittently and are excluded from the empirical index. Output expanded during 2018–2021 and then contracted sharply after the full-scale invasion: the best consolidated compilations indicate a fall of roughly 42% in 2022 and a partial but incomplete recovery thereafter. Export geography reoriented toward nearby EU partners and the United States. For measurement, "titanium" denotes ilmenite/leucoxene concentrate (HS 2614), aggregated to annual totals for comparability with graphite and manganese (USGS 2023a; USGS 2023b; USGS 2024; UN Comtrade; Eurostat Comext).

2.6. Manganese (ores and ferroalloys)

Manganese ore and concentrate production is concentrated in the Nikopol manganese basin and has historically been linked to Ukraine's ferroalloy complex. As with titanium, the empirical index uses ore/concentrate quantities rather than ferroalloy tonnages in order to keep the upstream mineral basket separate from energy-intensive downstream processing. Pre-war output was relatively stable, while 2022 brought a step decline associated with hostilities, power-price spikes and logistics constraints. Ferroalloy production proved particularly energy-sensitive, with curtailed operations in 2022–2023 and only partial recovery reported afterward. Trade flows follow the same broad pattern: ore exports fell sharply and were re-routed through alternative ports and rail corridors, while ferroalloy exports remained volatile. Given these properties, manganese enters the CRM composite as an annual quantity series benchmarked to 2018 = 100. The separation of upstream ore from downstream ferroalloys is maintained throughout to align with the value-chain logic introduced in Section 2.3 and the decomposition in Section 4.5 (USGS 2023a, b, 2024; Ukrstat; UN Comtrade; FES 2025).

2.7. Other strategic metals: option value and constraints

Beyond the four focal CRMs, Ukraine hosts occurrences of several strategic metals – germanium, gallium, vanadium, zirconium/hafnium, uranium and rare earth elements – typically as by-products of larger ore systems or in specialized mineralization. Their economic relevance is conditional. In most cases, value hinges on mid-stream steps (separation, solvent extraction, alloying) that determine marketability and compliance with EU standards. Where ore grades are modest or dispersed, recovery is viable only if processing routes are integrated with existing metallurgical flows or with waste/by-product streams. The geological signal therefore confers "option value": it expands the feasible set of projects once logistics and capex constraints ease, but does not by itself guarantee commercial output. In the remainder of the paper, these metals are referenced only where they clarify supply-chain governance or institutional requirements; they are excluded from the empirical indices because comparable annual production and trade series are not available for the full sample window (WEF 2024; European Union 2024; FES 2025).

2.8. Mineral economy in macro context (2010–2024)

Ukraine's mining-metallurgical complex has been a stable, if cyclical, component of the goods economy through the 2010s. The 2014 shock marked a structural break, with output and exports adjusting to new geography and trade routes. A second, larger break followed

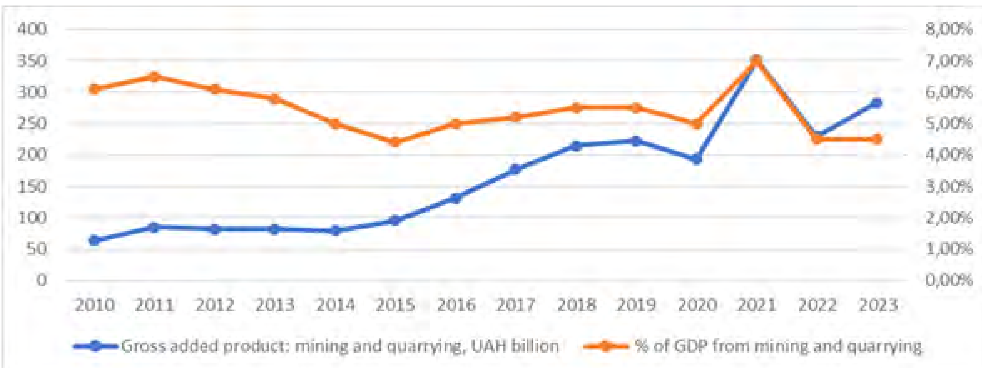

Fig. 2. Ukraine – mining and quarrying: gross value added and share of GDP, 2010–2023
The figure presents mining and quarrying (section B) only. Left axis: gross value added in current prices (UAH billions). Right axis: share of GDP (per cent).
Source: Central Statistical Service of Ukraine, BGK (2025), World Bank WDI,
Mining and quarrying value added, constant LCU (code NV.IND.MINQ.KN; latest available),
and UN Comtrade (reporter: Ukraine; partner: world; to 2023)

Rys. 2. Ukraina – górnictwo i wydobycie: wartość dodana brutto oraz udział w PKB, 2010–2023
Na wykresie przedstawiono wyłącznie górnictwo i wydobycie (sekcja B).
Oś lewa: wartość dodana brutto w cenach bieżących (miliardy UAH). Oś prawa: udział w PKB (w procentach)

the 2022 full-scale invasion, when damage to industrial assets, power-price spikes and port closures forced a rapid reconfiguration toward rail and alternative ports. The short-run effects are visible in both production and trade series: selected upstream lines (e.g., ilmenite, manganese concentrate) contracted sharply in 2022–2023, while downstream ferroalloys proved especially sensitive to energy constraints.

Figure 2 presents mining and quarrying (section B) only: gross value added in current prices (left axis) and its share in GDP (right axis), 2010–2023.

2.9. Institutions, policy signals, and investment climate

Institutional signals since 2021 point to a gradual alignment of Ukraine's extractive sector with EU frameworks. The EU-Ukraine Memorandum of Understanding on a Strategic Partnership on Raw Materials (European Commission 2021) and the EU's Critical Raw Materials Act (CRMA) define the perimeter: quantified EU targets for extraction, processing and recycling establish a regulatory pull for mid-stream capacity within a trusted space. Domestically, the licensing pipeline has shifted toward transparent auctions and production-sharing-agreement (PSA) frameworks for selected blocks, with digitization of geodata improving access to baseline information. International financial institutions have framed reconstruction finance around governance and ESG conditionality, particularly on permitting, transparency and environmental standards. None of these signals guarantees investment; they do, however, define the policy route by which geological endowment translates into marketable products. For the purposes of this study, the implication is straightforward: the mid-stream constraint identified in section 1.3 is central to both the growth contribution and the export-competitiveness patterns measured later.

2.10. Data panels feeding Sections 3–4

To make the descriptive foundation explicit without reproducing later results, two compact panels are included immediately following this subsection. Table 2 lists the annual quantities used to construct the CRM composite index (2018 = 100). Table 3 reports the 2018 and 2023 trade anchors for the shift-share benchmarks (world and EU-27).

For each mineral (graphite, ilmenite/titanium concentrates, manganese), exports from Ukraine to the world and EU-27 imports from Ukraine are reported for 2018 and 2023, along with totals. These serve as the base and end points for the constant-market-share decomposition in Section 4.

Table 2. Ukrainian CRM production (graphite, ilmenite, manganese), 2010–2023 (kt)

Tabela 2. Produkcja surowców CRM na Ukrainie (grafit, ilmenit, mangan), lata 2010–2023 (kt)

Year	Graphite	Ilmenite conc.	Manganese conc.
2010	6.0	NA	NA
2011	6.0	NA	NA
2012	5.8	NA	NA
2013	5.8	NA	NA
2014	8.0	450.0^{e}	1,526.2
2015	7.8	350.0^{e}	1,203.3
2016	6.1	350.0^{e}	1,250.0
2017	14.9	392.0	1424.7
2018	**13.0**	745.4	1521.1
2019	**13.0**	818.5	1687.0
2020	**13.0**	773.1	1887.9
2021	**17.0**	702.7	1760.0
2022	**1.7**	**0.41**	**0.95**
2023	**1.2**	200.0	**0.36**

Units are thousand metric tons (kt), gross weight. "Ilmenite concentrate" denotes ilmenite/leucoxene mineral concentrates (HS 2614). "Manganese concentrate" denotes manganese ores and concentrates (HS 2602). Superscript ^{e} marks source-documented estimates; * marks provisional entries. 2022 ilmenite (0.41 kt) and manganese (0.95 kt) are converted from tonnes to kt. Manganese ore exports fell to negligible levels in 2023, while upstream output was close to zero. Missing observations are left as NA; no interpolation is applied.

Source: USGS Minerals Yearbook country chapters for Ukraine (USGS 2023a, b, 2024), USGS Mineral Commodity Summaries (USGS 2018, for 2018 reference prices and cross-checks), IndexMundi (graphite), and Ukrstat where indicated.

2.11. Takeaways

Section 2 establishes three facts that underpin the empirical design. Ukraine's endowment in graphite, titanium concentrates, and manganese is geologically meaningful and spatially concentrated along the central-southeastern belt; lithium remains an option, with reserve tonnages classified and no industrial production established during the sample window. Wartime and energy-logistics shocks reshaped realized output and trade after 2022, with heterogeneous effects across commodities. Institutional signals since 2021 have moved policy toward EU-compatible standards and licensing, but the binding

Table 3. CRM trade anchors for shift-share (UA→World; EU-27 imports from UA), 2018 & 2023 (USD million)

Tabela 3. Główne sektory handlu w ramach CRM dla wskaźnika shift-share (Ukraina → świat; import UE-27 z Ukrainy), 2018 i 2023 r. (w mln USD)

Mineral	UA→World 2018	UA→World 2023	EU-27 imports from UA 2018	EU-27 imports from UA 2023
Graphite	4.83	0.93	4.68	0.85
Titanium ores & concentrates	125.72	82.06	32.51	36.36
Manganese ores & concentrates	3.83	0.00	3.31	0.00
Total	134.38	82.99	40.50	37.20

Current USD, millions; totals may differ from the sum of rounded components. Benchmarks correspond to the constant-market-share decomposition in section 5 and are built from two perspectives: UA→World (reporter: Ukraine; partner: world) and EU-27 imports from UA (reporter: EU-27 aggregate; partner: Ukraine). Commodity scope is restricted to graphite (HS 2504), titanium ores & concentrates (HS 2614) and manganese ores & concentrates (HS 2602).

Sources: UN Comtrade (via WITS) and Eurostat Comext (EU-27 aggregate); cross-checked with OEC (graphite 2023) and TrendEconomy (HS 2614, Ukraine exports).

constraint remains in mid-stream transformation. On this foundation, the next sections quantify:

- the contribution of the CRM composite to growth via a resource-augmented accounting identity,
- the decomposition of export changes into world-demand, product-mix and competitiveness components.

3. Methods and data

Two complementary tools suited to a political-economy analysis of critical raw materials (CRMs) are employed: a resource-augmented growth-accounting identity and a shift-share (constant-market-share) decomposition. Both are intentionally light-weight and reproducible; construction details and sensitivity grids are provided in the Appendix.

3.1. Growth-accounting setup

Real output growth is decomposed as:

$$\Delta \ln Y_t = \gamma \, \Delta \ln N_t + \Delta \ln A_t$$

↳ Y – real GDP,
N – a composite CRM production index,
A – residual interpreted as total factor productivity (TFP),
γ – resource income share.

In the baseline, $\gamma = 0.10$, with sensitivity reported for $\gamma \in \{0.05, 0.10, 0.15\}$. The CRM index is fixed-weight (2018 = 100) over graphite, titanium (ilmenite concentrate) and manganese (mineral concentrate), using equal 2018-based weights and quantity series; a price-weighted variant (USGS 2018 USD/t) and an export-value index are used for robustness. Formal definitions, weighting schemes, and the sensitivity table appear in Appendix A.4–A.6.

3.2. Shift-share decomposition

Let $X_{j,t}$ denote Ukraine's exports of CRM j. The change ΔX between 2018 and 2023 is decomposed into three components:

1) a world-growth effect N driven by overall market expansion or contraction,
2) an industry-mix effect M reflecting Ukraine's specialization across CRM segments,
3) a competitiveness effect C capturing changes in Ukraine's market share within each segment.

Calculation of the decomposition is performed against two benchmarks: the world market and the EU-27 import market. Exact formulas, aggregation conventions, and benchmark construction are detailed in Appendix A.7, together with references to the classical constant-market-share literature.

3.3. Variables, sources and coverage

The following variables and sources are used. CRM production (graphite; ilmenite/titanium; manganese concentrate): annual quantities, 2010–2023, Ukraine; base year 2018 = 100 for the composite index. Trade: annual exports by CRM, 2018–2023, with two perspectives for the shift-share benchmarks, namely UA→World (reporter: Ukraine; partner: world) and EU-27 imports from UA (reporter: EU-27 aggregate; partner: Ukraine). The 2018–2023 trade window is deliberately short because the shift-share exercise is a two-point constant-market-share decomposition rather than a time-series causality test: 2018 provides a stable pre-COVID and pre-invasion base year with harmonized trade coverage, while 2023 is the latest post-invasion year with sufficiently complete annual data for the selected HS scope.

Macroeconomic data: real GDP (constant prices) for growth-rate calculations. Primary sources and series identifiers are listed in Appendix A.2–A.3. The full data dictionary appears in Table A.1.

3.4. Baseline choices and robustness

Unless stated otherwise, results use:
- the equal-weight CRM production index,
- $\gamma = 0.10$,
- 2018 as the base year, and
- the EU-27 as the policy-relevant trade benchmark alongside the world market.

Robustness comprises:
a) alternative γ,
b) price-weighted and export-value CRM indices,
c) rebasing (2019 or 2020), and
d) basket variants (for example excluding manganese where series are sparse).

Outputs are generated by a linear, self-contained script chain; see Appendix A.8.

3.5. Limitations

Employment and capital-stock series beyond 2016 are incomplete; hence the two-term variant (CRM + TFP) is the main specification. Lithium is discussed qualitatively pending reliable series. Wartime disruptions may affect measurement because damaged infrastructure, rerouted logistics, and reporting delays can change the timing and completeness of recorded production and trade flows. Appendix A.5 documents the missing-data convention; no interpolation or zero-imputation is applied.

4. Results

This section quantifies how critical raw materials (CRMs) have shaped Ukraine's recent macro-dynamics and trade performance. The analysis begins with a resource-augmented growth-accounting exercise that attributes real-GDP growth to a composite CRM factor and a residual (TFP). Subsequently, the focus shifts to a shift-share analysis that decomposes the change in CRM exports against two benchmarks: the world market and the EU-27. Sensitivity checks (factor share γ and alternative CRM weights) and robustness notes are included to clarify the extent to which inferences depend on specific modeling choices.

4.1. Growth accounting results

Real-GDP growth is decomposed as $\Delta \ln Y = \gamma \cdot \Delta \ln N + \Delta \ln A$, where N is a composite CRM index, and A is the residual (TFP). In the baseline, the CRM income share is set to $\gamma = 0.10$. The CRM index (2018 = 100) aggregates Ukrainian production of graphite, titanium in the form of ilmenite concentrate, and manganese concentrate using equal 2018-based weights; the Ukrstat series for "≥20% Mn (dry weight)" is retained for robustness and not mixed into the main basket. The index is low and flat before 2014 (about 15), accelerates after 2017 (reflecting the ramp-up in ilmenite and manganese concentrates), and then collapses with the full-scale war: it rises from 20.5 in 2014 to 113.6 in 2021, then falls to 4.4 in 2022 and 3.1 in 2023.

Averaged over the three windows used in this paper, annual log contributions (percentage points per year) are:

- 2010–2013: $\Delta\ln Y \approx +1.83$; CRM ($\gamma \cdot \Delta\ln N$) ≈ -0.11; TFP $\approx +1.95$.
- 2014–2021: $\Delta\ln Y \approx -1.25$; CRM $\approx +2.54$; TFP ≈ -3.79.
- 2022–2023: $\Delta\ln Y \approx -14.26$; CRM ≈ -16.72; TFP $\approx +2.46$.

Table 4 presents the growth-accounting decomposition for Ukraine for the periods 2010–2013, 2014–2021 and 2022–2023.

Table 4. Growth-accounting decomposition for Ukraine, 2010–2013, 2014–2021 and 2022–2023 (percentage points per year; baseline $\gamma = 0.10$)

Tabela 4. Dekompozycja czynników wzrostu gospodarczego dla Ukrainy w latach 2010–2013, 2014–2021 oraz 2022–2023 (punkty procentowe rocznie; wartość bazowa $\gamma = 0{,}10$)

Period	$\Delta\ln Y$	CRM ($\gamma \cdot \Delta\ln N$)	TFP
2010–2013	+1.83	−0.11	+1.95
2014–2021	−1.25	+2.54	−3.79
2022–2023	−14.26	−16.72	+2.46

Period labels denote economic windows; average annual log changes are computed from the corresponding endpoint values used in Appendix A.6. Baseline uses a fixed-weight CRM quantity index (2018 = 100) over graphite, ilmenite concentrate and manganese concentrate, with equal 2018 weights and within-year re-normalization over available components. A common-availability variant (no re-normalization) is reported in Appendix A.8 and yields slightly larger CRM magnitudes in 2021–2023.

Source: authors' calculations based on World Bank WDI (real GDP) and the CRM index constructed from USGS, IndexMundi and Ukrstat series (see Appendix A.4–A.6).

Read literally, the post-2014 period shows CRMs acting as a positive engine ($\gamma \cdot \Delta\ln N > 0$), while the overall economy contracts because the residual is strongly negative – consistent with conflict-related destruction, frictions, and macro instability that offset extraction-led gains. In the wartime window, the collapse of the CRM index dominates the decomposition: the minerals term turns sharply negative and explains most of the contraction, whereas the residual turns mildly positive, consistent with partial adaptation in non-CRM tradables and services.

Figure 3 visualizes the basket dynamics: a steady pre-2014 level, a sharp post-2017 ramp-up, and a wartime collapse.

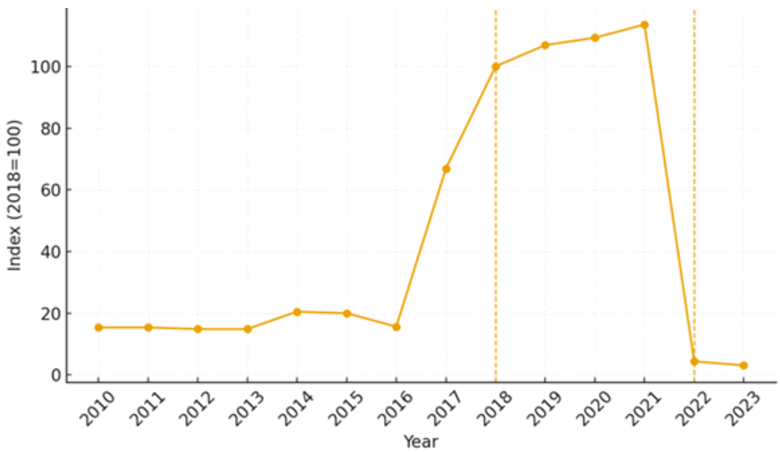

Fig. 3. Ukraine's composite CRM production index, 2010–2023 (2018 = 100)
Basket: graphite, titanium (ilmenite concentrate), manganese (mineral concentrate); equal 2018-based weights.
Source: authors' calculations from USGS/IndexMundi/Ukrstat series.

Rys. 3. Złożony wskaźnik produkcji CRM w Ukrainie, lata 2010–2023 (2018 = 100)

Results are robust to alternative γ in the range [0.05, 0.15] and to price-weighted CRM baskets using USGS 2018 USD/t; both variations scale magnitudes but leave the qualitative pattern unchanged. For transparency, the sensitivity table appears in the next section 4.2.

4.2. Sensitivity to the resource share parameter (γ)

The robustness of the resource-augmented growth-accounting results is assessed against alternative values of the CRM income share parameter γ. In the baseline, $\gamma = 0.10$, a conservative value consistent with studies that treat natural capital as a modest but non-negligible factor share in resource-rich economies. Contributions are recomputed for $\gamma \in \{0.05, 0.10, 0.15\}$, and the outcomes are reported in Table 5.

Higher γ scales the magnitude of the CRM term proportionally; it does not overturn inference. Across $\gamma \in [0.05, 0.15]$, the signs and qualitative magnitudes are invariant: pre-war the CRM term is positive; in 2022–2023 it turns sharply negative; the residual moves in the opposite direction, indicating partial adjustment outside extractives (see Table 5).

Table 5. Sensitivity of growth-accounting contributions to the CRM income share (γ), Ukraine 2010–2023 (percentage points per year)

Tabela 5. Wrażliwość wkładów związanych ze wzrostem gospodarczym na udział dochodu w ramach modelu CRM (γ), Ukraina 2010–2023 (punkty procentowe rocznie)

Period	$\Delta \ln Y$ (pp/yr)	CRM $\gamma = 0.05$	TFP $\gamma = 0.05$	CRM $\gamma = 0.10$	TFP $\gamma = 0.10$	CRM $\gamma = 0.15$	TFP $\gamma = 0.15$
2010–2013	1.83	–0.06	1.89	–0.11	1.94	–0.17	2.00
2014–2021	–1.25	1.11	–2.36	2.21	–3.46	3.32	–4.57
2022–2023	–14.26	–8.36	–5.90	–16.72	2.46	–25.08	10.82

Source: authors' calculations based on World Bank WDI (real GDP) and the CRM production index constructed from USGS, IndexMundi and Ukrstat; methods in Appendix A.4–A.6.

4.3. Data limitations and comparability notes

Two constraints are relevant for interpretation and comparability. First, the growth-accounting window is 2010–2023 and the trade-based window is 2018–2023, as defined in Appendix A.1. Second, for manganese, the USGS "mineral concentrate" series is used to maintain consistency with the titanium proxy (ilmenite concentrate) and avoid mixing ore with concentrate; the Ukrstat "≥20% Mn (dry weight)" series is retained for robustness in the Appendix. The 2017 ilmenite figure of 392 000 t is confirmed and comparable to subsequent years. Price weights, where used for robustness, are USGS 2018 USD/t; revisions would scale magnitudes but not alter signs. Employment series for 2017–2018 have been completed from official sources and are not used in the two-term GA decomposition in section 4.1. Details of preprocessing and handling of missing entries are centralized in Appendix A.3.

4.4. Transitional conclusions

The results show a clear transition from a resource engine to a resource constraint. Before 2022, the CRM sector contributes positively to growth, but aggregate performance is held back by economy-wide frictions (negative TFP). After 2021, the collapse of CRM output dominates the decomposition, coherently mapping onto the weaponized interdependence and chokepoint logic from section 1: physical control, blockade and processing bottlenecks transmit directly into macro outcomes. This motivates the policy pivot in section 5: *from extraction to resilient mid-stream* within a trusted EU-centered space under the CRMA's "de-risking" doctrine.

4.5. Results: Shift-share (World vs EU-27)

The change in Ukraine's CRM exports between 2018 and 2023 is decomposed using a standard shift-share framework (Dunn 1960; Esteban-Marquillas 1972; Barff and Knight 1988). The total change ΔX splits into a world-growth effect (N), an industry-mix effect (M), and a competitiveness effect (C). The decomposition is computed against two benchmarks: the world market and the EU-27 import market. Exact formulas and benchmark construction are in Appendix A.7.

Between 2018 and 2023, Ukraine's CRM exports fell by 51.39 million USD while world CRM trade expanded. The world-growth component is +36.67, the industry-mix is –2.35, and the competitiveness effect is –85.71 million USD. The decline is therefore dominated by a loss of market share, consistent with wartime disruption and logistics constraints.

Figure 4 shows N > 0, a small M and a large negative C, i.e., a loss of global share in 2018–2023.

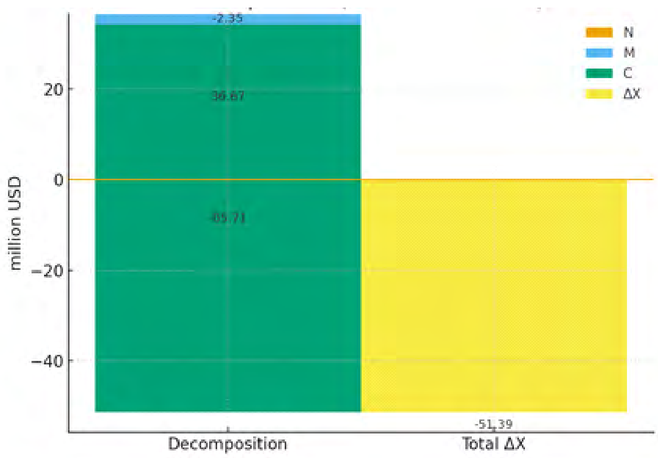

Fig. 4. 2018–2023 change in Ukraine's CRM exports: world benchmark (N/M/C; million USD)
Method: constant-market-share (shift-share) decomposition following Dunn (1960); Esteban-Marquillas (1972); Barff and Knight (1988). Query parameters (reporter/partner, HS6 breakdown, extraction timestamp) are listed in the Appendix
Source: authors' calculations based on UN Comtrade (reporter: Ukraine; partner: World; HS 2504, 2614, 2602; annual; flow: Exports; years 2018 and 2023; current USD), accessed October 18, 2025

Rys. 4. Zmiany w eksporcie ukraińskich systemów CRM w latach 2018–2023: wskaźnik światowy (N/M/C; mln USD)

Over the same period, EU-27 total imports of the basket contracted markedly, yet Ukraine's exports to the EU fell only by 3.30 million USD. The benchmark effect is −16.75, industry-mix +1.41, and the competitiveness effect +12.05 million USD. Ukraine thus gained share inside a shrinking EU market, consistent with EU de-risking and friend-shoring.

Figure 5 visualizes this pattern: despite N_EU < 0, C_EU is positive.

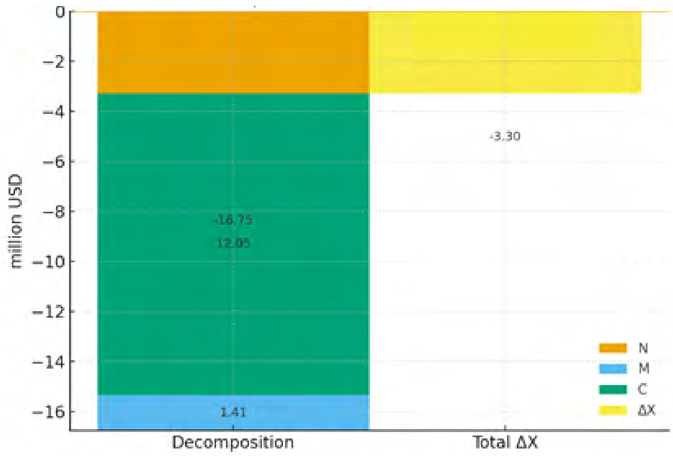

Fig. 5. 2018–2023 change in Ukraine's CRM exports to EU-27: EU benchmark (N_EU/M_EU/C_EU; million USD)
Method: constant-market-share (shift-share) following Dunn (1960); Esteban-Marquillas (1972); Barff and Knight (1988). Full query strings and conversion notes appear in the Appendix.
Source: Authors' calculations based on Eurostat Comext (Easy Comext) (reporter: EU-27 aggregate; partner: Ukraine; HS 2504, 2614, 2602; annual; flow: Imports; years 2018 and 2023; values in EUR converted to USD where indicated) and replication-compatible UN Comtrade queries on the EU-27 aggregate where available; accessed October 18, 2025

Rys. 5. Zmiany w eksporcie produktów CRM z Ukrainy do UE-27 w latach 2018–2023: wartość odniesienia dla UE (N_EU/M_EU/C_EU; mln USD)

The EU industry-mix is positive mainly due to graphite (EU demand shrank less than the whole basket), titanium stabilizes, and manganese disappears in Ukrainian export after 2021 (0 in the period of 2022–2023). The basket covers graphite, titanium (ilmenite concentrate), and manganese. Lithium chemicals are excluded from the CMS decomposition because Ukraine has no validated and comparable 2018–2023 production/export series for lithium chemicals within the empirical scope used here.

5. Policy and governance implications

The results suggest a clear ordering. Geological endowments create options, yet durable leverage is decided in mid-stream capacity, verifiable standards, and reliable logistics. In the growth-accounting lens, the CRM term is positive before the war and decisively negative in 2022–2023, while the residual moves in the opposite direction. In the shift-share lens, Ukraine loses share in the global market but gains share inside the EU-27 despite a shrinking benchmark. Read together, the binding constraint is not ore in the ground but bankable transformation of concentrates into chemicals and metals under EU-compatible rules.

5.1. Reading the results for policy

Three policy inferences follow directly. First, the complementarity between extractives and the rest of the economy was interrupted by shocks to processing and transport rather than extinguished; restoring a positive CRM contribution therefore hinges on rebuilding and upgrading mid-stream nodes, not merely reopening mines. Second, the competitiveness gain inside the EU-27 indicates credible demand for proximate, compliant supply and aligns with de-risking: fewer single-country exposures and more value added captured in trusted jurisdictions. Third, the global loss of share reflects temporary disadvantages in logistics, energy and finance rather than a structural shift in cost curves; closing those gaps is the shortest route to restored competitiveness without long-term subsidy dependence.

5.2. Priority interventions

Policy should pivot squarely to mid-stream projects aligned with the CRMA. On the titanium line, this means moving ilmenite into TiO_2 and into sponge or metal; on the manganese line, it means lifting concentrate quality toward higher-grade feedstocks. The emphasis should be on industrial-scale assets that pass bankability tests rather than pilots. Contracting must anchor these assets: multi-year offtakes with EU processors and original equipment manufacturers (OEMs) should embed price formulas, quality specifications and audit rights, and where feasible couple offtakes with prepayment or supply-chain finance.

Compliance capability matters as much as throughput. OECD-type due diligence and end-to-end traceability from pit to plant reduce risk discounts in both contracts and finance, provided verification capacity is credible and recurring. Corridors and power need hardening: pre-booked rail and port alternatives, cross-border transshipment arrangements with guaranteed slots, and ring-fenced power for electro-intensive steps cut volatility premia that currently undermine margins.

Predictability on the public side lowers the cost of capital more effectively than ad hoc incentives. Standardized permitting clocks, published data rooms and transparent competitive allocation (open auctions or PSA templates) improve pricing of risk and cycle time. Human capital is a rate-limiting factor; targeted programs for process engineers, metallurgists and maintenance teams are necessary for planned availability and recovery rates to materialize.

Finally, disciplined publication of annual quantities for graphite, ilmenite and manganese with clear metadata shortens due-diligence cycles and improves offtake pricing.

5.3. Risk matrix and mitigations

Risk is layered and interactive, so mitigation must integrate product design, contracting and infrastructure rather than treat them as separate fixes. Market cycles and the possibility of substitution threaten margins; the appropriate response is to tilt the product slate toward more processed intermediates and to embed price floors in offtake contracts, using tolling where it improves netbacks over the cycle. Logistics and security shocks at borders and ports, together with energy volatility, can erase competitiveness even when demand exists. Dual-homing of critical legs, advance reservation of rail and Danube capacity, buffer inventories at EU nodes sized to voyage time, and ring-fenced power for electro-intensive stages reduce the volatility premia that currently depress margins. Regulatory misalignment with EU practice immediately translates into price discounts or loss of access. The remedy is EU-compatible permitting and environmental compliance, plus due diligence aligned with the OECD (2016) Guidance, verified by third-party audits on a fixed cadence so that trust is exported with the product. Financing risk is amplified by wartime premia and construction risk, but can be lowered by blending international financial institutions (IFIs) and export-credit instruments with private capital, sequencing disbursements to construction milestones, and linking offtakes to prepayment or inventory finance so that the revenue line is bankable. Operational risk spans brownfield bottlenecks and greenfield ramp-up; phased commissioning with clear quality-assurance/quality-control (QA/QC) gates, vendor warranties tied to overall equipment effectiveness (OEE) and recovery rates, and predictive maintenance reduce downtime and cost creep. Finally, social and environmental frictions shape timelines and cost of capital. Early engagement, transparent baselines, funded closure plans and grievance mechanisms linked to offtake covenants limit delays and litigation. Taken together, these measures shift Ukraine's role from a vulnerable supplier of raw tonnage to a credible producer of EU-grade intermediates with contractual and institutional protection against foreseeable shocks (OECD 2016; IEA 2021; EBRD 2023; UNCTAD 2023; European Union 2024).

5.4. Partnering templates with the EU and allies

The most direct way to convert empirical advantages into durable bargaining power is to anchor mid-stream capacity inside the EU-centered regulatory and financing space. In practice, this means structuring project-financeable plants for graphite processing, ilmenite upgrading into titanium intermediates, and manganese chemicals around long-term offtakes with European industrial buyers. The Critical Raw Materials Act (CRMA) provides the legal scaffolding on the EU side for accelerated permitting, recognition as "strategic projects," and, where relevant, support instruments that lower non-market risk (European Union 2024). These instruments work best when paired with offtake contracts that are bankable: multi-year terms, minimum-volume commitments, price-band clauses to cushion down-cycles, and clear ESG representations that allow lenders to treat the revenue line as robust rather than aspirational.

Financing mixes public and private balance sheets. A typical stack layers senior loans from European IFIs, export-credit guarantees, and commercial tranches de-risked by the offtake; where feasible, mezzanine or first-loss participation by IFIs helps crowd in private lenders for assets that would otherwise be priced out by war-risk premia (EBRD 2023; UNCTAD 2023). On the compliance side, full alignment with the OECD (2016) Due Diligence Guidance is not a box-ticking exercise but a commercial asset: traceability and responsible-sourcing covenants are what make mid-stream Ukrainian output acceptable as "trusted" input in EU manufacturing (OECD 2016). A transatlantic option should be designed in at the contract stage. If product specifications and chain-of-custody data also satisfy U.S. origin and sourcing requirements under the Inflation Reduction Act, the same physical assets gain optionality across two policy blocks, expanding the buyer set and increasing project bankability (U.S. Congress 2022).

Conclusions

This article asked whether Ukraine's endowment of critical raw materials (CRMs) can be a genuine engine of growth and strategic autonomy, and under what conditions. The study combines a resource-augmented growth-accounting exercise with a trade-based shift-share decomposition, interpreting the results through the lenses of interdependence and global-value-chain governance. The two empirical lenses converge on a simple but policy-relevant message: deposits create options, but durable power is decided in the mid-stream, in processing capacity, standards and contracts that bind Ukraine into trusted European supply chains.

On the macro side, the CRM factor contributed positively to growth in the post-2014, pre-war period (2014–2021), before collapsing during 2022–2023. With a conservative income share ($\gamma = 0.10$), the minerals term turns sharply negative in wartime and explains most of the contraction, while the residual becomes mildly positive, consistent with partial adaptation in non-CRM tradables and services. Sensitivity checks over $\gamma \in [0.05, 0.15]$ and alternative weighting schemes alter magnitudes but not the sign pattern.

On the trade side, the 2018–2023 shift-share results are bifurcated. Globally, the competitiveness term is large and negative, indicating a loss of market share amid logistics disruptions and production shocks. Inside the EU-27, however, the competitiveness term is positive even though total EU demand for the CRM basket fell. That combination, $C\_EU > 0$ while $N\_EU \leq 0$, is the quantitative signature of de-risking and friend-shoring: Europe reallocates purchases toward proximate, reliable suppliers. This pattern directly informs the paper's policy logic: Ukraine's route to leverage is to move from ore exports to EU-grade intermediates, from concentrates to chemicals and metals, produced under verifiable due diligence and delivered through resilient corridors.

Taken together, the evidence provides partial confirmation of the three guiding hypotheses.

1. H1 (CRMs as a growth engine) holds in normal times but fails under conditions of acute disruption; the resource base is a necessary but insufficient condition for growth.

2. H2 (scope to reduce Western dependence) is supported in the EU case by the positive competitiveness effect in a shrinking market, which implies that Ukrainian supply can substitute for riskier sources if mid-stream capacity is credible.
3. H3 (geopolitical constraints) is strongly confirmed: wartime shocks, physical, logistical and financial, shape what portion of the geological endowment becomes a productive flow.

The analysis has limits that point to a clear research and data agenda. The analysis utilized a deliberately narrow basket (graphite, ilmenite/titanium, manganese) and volume-based weights; price-weighted indices and a broader mineral set, including lithium once reliable series are available, will further refine the estimates. Employment and capital-stock series beyond 2016 are incomplete; incorporating them would allow a full decomposition into labor, capital and natural capital rather than the two-term variant used here. On the trade side, higher-frequency data and mineral-specific quality adjustments would improve the identification of competitiveness shocks and the timing of EU policy effects.

Normatively, the results argue for a sequencing logic. First, stabilize production and logistics; second, anchor mid-stream processing under CRMA-compatible rules and bankable offtakes; third, channel rents into capabilities, metrology, engineering and compliance, that keep the competitiveness term positive when demand turns down. If those steps are taken, the macro role of CRMs can shift from a shock amplifier to a growth complement, and Ukraine's bargaining position within European supply chains can become structural rather than episodic.

Appendix. Methods

A.1. Scope, notation, periodization

This appendix documents data scope, notation, and time windows used throughout the paper. The production-based window spans 2010–2023; the trade-based window for the shift-share decomposition, also known as constant-market-share (CMS) analysis, spans 2018–2023. The composite CRM index is rebased to 2018 = 100. The empirical basket contains graphite, titanium in the form of ilmenite concentrate, and manganese concentrate; lithium is discussed qualitatively but excluded from the baseline index given current series limitations.

The trade window is limited to 2018–2023 by design. The CMS window is restricted to 2018–2023 because this is the longest interval for which the selected HS-level reporter–partner trade series are complete and comparable across both benchmarks; extending the period would require incomplete or non-final annual observations. The CMS exercise compares a stable pre-disruption base year with a post-invasion endpoint and is not intended as a long time-series estimate. Extending the window backward would mix structurally different regimes, including the post-2014 trade reorientation and earlier reporting inconsistencies, while extending it forward would require incomplete or non-final annual trade observations.

Variables and benchmarks. For the baseline production index, physical production series are used for the three CRMs with sufficiently consistent annual observations: graphite, titanium ores/concentrates, and manganese ore/concentrate. An aggregated into a fixed-weight index is used (2018 = 100). For the trade-decomposition exercise, a constant-market-share (CMS) framework is used. Two reference markets are defined: (i) Ukrainian exports to the world (reporter: Ukraine; partner: world) and (ii) EU-27 imports from Ukraine (reporter: EU-27 aggregate; partner: Ukraine). Commodity scope is restricted to HS 2504 (graphite), HS 2614 (titanium ores and concentrates, proxied by ilmenite/leucoxene), and HS 2602 (manganese ores and concentrates); HS concordances are listed in A.2. Details of index construction and weights are in A.4; preprocessing rules are in A.5.

Notation. Log-differences are denoted $\Delta\ln(\cdot)$. Growth-accounting uses

$$\Delta\ln Y_t = \gamma\ \Delta\ln N_t + \Delta\ln A_t$$

Y_t is real output, N_t the composite CRM index, A_t the residual (TFP), and the resource income share. When results are reported as percentage points per year, we compute the average annual log change over a window $[t_1, t_2]$ as $[\ln X_{t_2} - \ln X_{t_1}]/(t_2 - t_1) \cdot 100$. The baseline uses $\gamma = 0.10$; sensitivity to $\gamma \in \{0.05, 0.10, 0.15\}$ and to alternative weighting schemes is reported in A.6 and A.8.

Missing-data convention and coverage. Entries without an official annual observation are treated as missing (NA) rather than imputed or set to zero; no interpolation is applied. Where a component of the basket is missing in a given year, the index is computed on the available components with fixed 2018 weights (see the weighting and denominator conventions in A.4–A.5), and robustness on the common-availability intersection of all components is reported in A.8. Calendar year 2024 is outside the analysis windows and is therefore not used in any baseline computation.

Unit conventions, source identifiers, and any dataset-specific caveats are consolidated in A.2–A.5; robustness checks and alternative baselines are summarized in A.8. The common-availability (no re-normalization) variant is reported in A.8 as a robustness check.

A.2. Commodity scope and HS concordances

Trade statistics are drawn from harmonized tariff headings that match the physical production series used in the composite CRM index. We restrict coverage to ores and concentrates for graphite, titanium and manganese, so that trade flows correspond to the upstream quantities employed in growth accounting.

Graphite (HS 2504). Heading HS 2504 (Graphite; natural) is used at the 6-digit resolution, with 250410 and 250490 aggregated into annual totals. Articles and processed carbon products are excluded; this keeps the trade series aligned with mined natural graphite and avoids mixing downstream manufactures into the basket.

Titanium (ilmenite) (HS 2614). Titanium is proxied by HS 2614 (Titanium ores and concentrates) at the 6-digit resolution (261400). This heading covers ilmenite and leucoxene concentrates that correspond to the production series used in the CRM index. Pigments and chemicals (for example TiO_2) and titanium metal forms are out of scope for the baseline; where discussed, they appear only in the policy section and not in the empirical basket.

Manganese (HS 2602). HS 2602 (Manganese ores and concentrates) is used at the 6-digit resolution (260200). Downstream ferroalloys (HS 7202) and steel products are excluded to prevent contamination of the upstream basket with energy-intensive processing steps.

For the constant-market-share (shift-share) decomposition, two benchmarks are constructed from these concordances: UA→World (reporter: Ukraine; partner: world; trade flow: exports) and EU-27 imports from UA (reporter: EU-27 aggregate; partner: Ukraine; trade flow: imports). Values are in current USD; where Eurostat Comext reports values in EUR, these are converted to USD during preprocessing (see A.5). All series are annual and cover 2018–2023 for trade and 2010–2023 for production.

Table A.1. Supplementary reserve and global-positioning metrics for selected Ukrainian CRMs

Tabela A.1. Wskaźniki rezerwy uzupełniającej i pozycjonowania globalnego dla wybranych ukraińskich systemów CRM

Resource	Ukraine reserves (value as shown)	Share of global reserves	Global reserves ranking	Share of global production
Carbon (Graphite)	**18.6 Mt**	**6%**	**#5**	**4%**
Lithium	*(classified tonnage)*	**1–2%**	**#1 (EU)**	–
Titanium	*(classified tonnage)*	**1%**	#9	**7%**
Beryllium	**13.9 kt**	N/A	N/A	–
Uranium	*(classified tonnage)*	**2–4%**	**#1 (EU)**	**2%**
Manganese	**140 Mt**	**7%**	**#4**	**1.6%**
Iron	**6.5 Bt**	**3%**	**#8**	**1.5%**

Notes: The table summarizes publicly reported in-situ volumes and rankings for selected CRMs. Entries outside the empirical basket (for example materials beyond graphite, ilmenite/titanium and manganese) are included for context only and are not used in the CRM index or in the CMS decomposition. Classifications differ across sources; concordances are listed in A.2. "Classified tonnage" indicates that absolute reserve numbers are not publicly released; only percentage ranges or rankings are available.

Source: FES (2025); WEF (2024). Authors' compilation.

A.3. Provenance, versioning and missing-data rules

All quantity series for graphite, ilmenite (titanium) and manganese are drawn from public statistical sources that are standard in the CRM literature. The primary source for annual quantities is the USGS Minerals Yearbook country series for Ukraine, especially the "Production of Mineral Commodities" tables (USGS 2023a; USGS 2023b; USGS 2024), cross-checked against Ukrstat and IndexMundi where overlapping series exist. USGS Mineral Commodity Summaries (USGS 2018) are used for 2018 unit-price references and selected cross-checks. Trade values and quantities are taken from UN Comtrade (reporter: Ukraine; partner: world; exports) and, for the EU benchmark, Eurostat Comext (Easy Comext) (reporter: EU-27 aggregate; partner: Ukraine; imports). Access dates for all trade extractions are 18 Oct 2025. Where Eurostat reports values in EUR, we convert to USD during preprocessing (A.5).

When sources disagree, a simple precedence rule is applied, designed to preserve comparability across minerals and time: for annual quantities we retain the USGS annual totals unless a documented official revision by the national authority supersedes them; for unit prices used only in robustness weighting we use USGS 2018 USD per ton (rutile vs ilmenite explicitly distinguished), with value-share cross-checks from UN Comtrade. Headings and concordances are defined in A.2 and are kept at HS-6 aggregation (250410/250490; 261400; 260200) to align trade with the upstream production concept.

Missing-data convention. Entries without an official annual observation are treated as missing (NA). No interpolation, forward-filling, or zero-setting of missing entries is performed. For the composite CRM index, base-year weights are fixed at 2018. If a component is unavailable in a given year, the index is computed on the available subset with weights re-normalized to sum to 1 over that subset; this avoids mechanical deflation from missing components. Robustness on the common-availability intersection of all components is reported in A.8, together with a re-base check (2019/2020).

Versioning and consistency checks. All downloads are archived with their extraction timestamps; preprocessing applies uniform unit conventions (kt for quantities; current USD for trade), deduplicates reporter/partner pairs, and enforces the HS scope in A.2. Where metadata indicate quality changes (for example, manganese "ore and concentrates" vs ferroalloys), downstream products (HS 7202) are excluded from the empirical basket. Calendar year 2024 lies outside the analysis windows (2010–2023 for production; 2018–2023 for trade) and is not used in baseline computations.

A.4. CRM index construction

A.4.1. Definition and measurement

Let J = {graphite, ilmenite, manganese} denote the commodity set and $q_{j,t}$ the annual physical output of commodity j in year (metric tons). The composite CRM quantity index is a fixed-base Laspeyres-type index rebased to 2018 = 100:

$$N_t = 100 \cdot \sum_{j \in J_t} \tilde{\omega}_{j,2018,t} \frac{q_{j,t}}{q_{j,2018}}$$

where $\omega_{j,2018}$ are base weights that sum to 1 in the full basket and $J_t \subseteq J$ is the subset of commodities with an observation in year t. When a component is missing in year t, weights are re-normalized over the available subset,

$$\tilde{\omega}_{j,2018,t} = \frac{\omega_{j,2018}}{\sum_{k \in J_t} \omega_{k,2018}} \qquad \text{for} \quad j \in J_t$$

so that the index is not mechanically deflated by missing entries. In the baseline, we set equal base weights $\omega_{j,2018} = 1/3$ for all $j \in J$. All growth-accounting results in the main text use $\Delta \ln N_t$ computed from this index. In the main specification, the CRM index uses equal fixed weights for graphite, ilmenite concentrate and manganese concentrate (2018 = 100). In the baseline, equal 2018 weights are re-normalized over the set of available components in year t.

A.4.2. Weights and robustness

Baseline. The CRM index is a fixed-weight quantity index (2018 = 100) over graphite, ilmenite concentrate and manganese concentrate. Equal 2018 weights are used.

Price-weighted variant. For robustness, a price-weighted Laspeyres index with base-year value shares is also reported.

$$\omega^{p}_{j,2018} \propto p_{j,2018}\, q_{j,2018}, \qquad \sum_{j \in J} \omega^{p}_{j,2018} = 1$$

where $p_{j,2018}$ are 2018 USD/t unit prices from USGS. Because the titanium physical series is ilmenite concentrate, rutile prices would overstate titanium's share; the price-weighted benchmark therefore uses an ilmenite unit price for 2018. Table A.4.2 reports the base-year $p \cdot q$ values and the normalized weights for two informative price assumptions (rutile proxy vs ilmenite), with the ilmenite-based weights designated as the recommended price-weighted robustness.

Export-value variant. As an additional check, a trade-value index is computed using export values $v_{j,t}$ from UN Comtrade on the same HS scope (2504, 2614, 2602), with either equal shares or base-year value shares $\phi_{j,2018} \propto v_{j,2018}$. This variant aligns the basket with observed trade values and serves as a cross-validation of the quantity-based index.

Across these alternatives, results in section 4 remain sign-robust: weighting schemes scale magnitudes but do not alter the qualitative pattern over 2010–2013, 2014–2021 and 2022–2023.

Table A.2. Base-year values and normalized weights (2018) for CRM index robustness

Tabela A.2. Wartości z roku bazowego i znormalizowane wagi (2018) dla wskaźnika odporności CRM

Commodity	q_{2018} (t)	p_{2018} (USD/t)	$p \cdot q$ Variant A (rutile 1,500) USD	Weight A (%)	$p \cdot q$ Variant B (ilmenite 175) USD	Weight B (%)
Graphite (flake)	13,000	1,480	19,240,000	1.05	19,240,000	2.27
Titanium (ilmenite conc.)	745,400	1,500	1,118,100,000	60.86	130,445,000	15.36
Manganese (ore & conc.)	1,521,100	460	699,706,000	38.09	699,706,000	82.38
Total			1,837,046,000	100.00	849,391,000	100.00

Notes: Variant A uses a rutile unit price for titanium; Variant B uses an ilmenite unit price consistent with the physical series and is the recommended price-weighted benchmark. Weights are normalized to sum to 100% within each variant. Units: quantities in metric tons (t); prices in 2018 USD per ton; in USD.

Source: USGS *Mineral Commodity Summaries* (USGS 2018) for 2018 unit prices; USGS Minerals Yearbook country chapters for Ukraine (USGS 2023a; USGS 2023b; USGS 2024), IndexMundi and Ukrstat for 2018 output volumes. Authors' calculations.

A.5. Pre-processing

This section documents harmonization steps applied before index construction and decomposition. All operations are deterministic and applied uniformly across commodities and years.

Units and measurement. Production quantities $q_{j,t}$ are expressed in metric tons (t) and presented as thousands of tons (kt) in tables for readability. Trade values are in current USD; trade quantities, where used for checks, are in metric tons. Production quantities are based on USGS Minerals Yearbook country chapters for Ukraine (USGS 2023a, b, 2024), cross-checked against Ukrstat and IndexMundi where overlapping observations exist. No price deflators are applied to production quantities because the CRM index is a physical quantity index; macro aggregates used for growth accounting are taken in constant prices from WDI.

Series selection and deduplication. For production, one annual series is retained per commodity and year. Where USGS and national sources overlap, USGS annual totals are kept unless superseded by an official revision documented by the national authority. For trade, single reporter-partner pairs are used: UA→World for the global benchmark and EU-27 imports from UA for the EU benchmark. Mirror flows are not used, and re-exports are not netted out.

HS scope enforcement. Trade queries are restricted to HS-6 codes aligned with upstream production: HS 250410/250490 (graphite), HS 261400 (titanium ores and concentrates, proxied by ilmenite/leucoxene), HS 260200 (manganese ores and concentrates). Downstream products (for example, TiO_2 pigments, titanium metal, ferroalloys HS 7202) are excluded from the empirical basket.

Currency conversion (EUR→USD). Where Eurostat Comext reports values in EUR, was converted to USD using the annual average USD/EUR exchange rate for the same calendar year. The conversion is applied after enforcing the HS scope and before any aggregation. Sensitivity to alternative FX conventions (end-year, monthly averages) is negligible for the two-point CMS benchmarks used in section 5.

Outliers, estimates and flags. Source flags such as "estimated" or "provisional" are retained in the metadata. No winsorization or manual outlier removal is applied. If a year carries only an estimated value in the primary source, that value is used and flagged; any documented official revision supersedes it in the next versioned extract.

Missing data and partial-basket years. Entries without an official observation are treated as missing (NA). No interpolation, forward-filling, or setting of missing entries to zero is performed. Years with incomplete baskets are excluded in the main GA windows. For the composite index N_t we apply fixed 2018 weights and re-normalize them over the set J_t of available components in year t so that $\sum_{j \in J_t} \tilde{\omega}_{j,2018,t} = 1$. This prevents mechanical deflation when one component is unavailable. A common-availability check that restricts N_t to years in which all three components are observed is reported in A.8; results remain qualitatively unchanged.

Annualization and base year. All series are annual and aligned to calendar years. The CRM index is rebased to 2018 = 100. For growth-accounting windows, average annual log changes are computed as $[\ln X_{t_2} - \ln X_{t_1}]/(t_2 - t_1) \cdot 100$, yielding percentage points per year.

Valuation conventions in trade. No adjustment is made for FOB/CIF valuation differences across reporters; instead, the analysis is benchmarked against two internally consistent perspectives (UA→World exports; EU-27 imports from UA). Because the CMS decomposition uses two points in time (2018, 2023) within each perspective, any level bias from valuation conventions cancels out in the within-benchmark decomposition.

A.6. Growth-accounting implementation and sensitivity

Specification and windows. Real output growth is decomposed as:

$$\Delta \ln Y_t = \gamma \, \Delta \ln N_t + \Delta \ln A_t$$

where Y_t is real GDP, N_t the composite CRM quantity index (2018 = 100) defined in A.4, A_t the residual (TFP), and γ the income share of the CRM factor. Results are reported over three non-overlapping windows used in the paper: 2010–2013, 2014–2021 and 2022–2023. For any window $[t_1, t_2]$, the average annual log change of a variable X is computed as

$$\frac{\ln X_{t_2} - \ln X_{t_1}}{t_2 - t_1} \cdot 100 \text{ (percentage points per year)}$$

Real GDP series come from WDI (constant prices); is the fixed-weight quantity index over graphite, ilmenite concentrate and manganese concentrate with equal 2018-based weights (see A.4–A.5).

Baseline parameter. The baseline sets $\gamma = 0.10$, a conservative share consistent with treating natural capital as a modest but non-negligible contributor in resource-rich economies. Table A.3 reports $\Delta\ln Y$, $\Delta\ln N$ and $\Delta\ln A$ for the three windows; the baseline row ($\gamma = 0.10$) corresponds to Table 5 in the main text.

Sensitivity design. Robustness is assessed along three dimensions:

Factor share: $\gamma \in \{0.05, 0.10, 0.15\}$. Because γ multiplies $\Delta\ln N$, changing γ scales the CRM term proportionally but does not affect the residual by construction.

Weighting scheme for N_t: equal 2018-based weights (baseline); price-weighted Laspeyres using 2018 USD/t unit prices (USGS), with titanium represented by ilmenite rather than rutile (recommended variant); and an export-value index using UN Comtrade values on the same HS scope (2504, 2614, 2602).

Availability and base year: common-availability intersection of the three components versus partial-basket re-normalization (A.4–A.5); rebasing to 2019 or 2020.

Findings. Across $\gamma \in [0.05, 0.15]$, alternative weights and the availability/rebase checks, the sign pattern is invariant: the CRM term is positive in 2014–2021 and sharply negative in 2022–2023, while the residual moves in the opposite direction; conclusions in §5.1 are unaffected. Magnitudes vary mechanically with γ and modestly with weighting. Common-availability and rebase tests change levels but do not alter signs; detailed numbers are tabulated in Table A.3 and in the robustness tables of A.8.

Table A.3. Growth-accounting decomposition for Ukraine, 2010–2013, 2014–2021 and 2022–2023 (percentage points per year)

Tabela A.3. Analiza czynników wpływających na wzrost gospodarczy na Ukrainie w latach 2010–2013, 2014–2021 oraz 2022–2023 (punkty procentowe rocznie)

Period	$\Delta\ln Y$	CRM ($\gamma = 0.05$)	CRM ($\gamma = 0.10$)	CRM ($\gamma = 0.15$)	TFP ($\gamma = 0.10$)
2010–2013	+1.83	−0.06	**−0.11**	−0.17	**+1.95**
2014–2021	−1.25	+1.27	**+2.54**	+3.81	**−3.79**
2022–2023	−14.26	−9.01	**−16.72**	−27.03	**+2.46**

Notes: Period labels denote economic windows; average annual log changes are computed from the corresponding endpoint values as defined in A.6. Average annual log changes are computed as $[\ln X_{t_2} - \ln X_{t_1}]/(t_2 - t_1) \cdot 100$. The CRM term is $\gamma\Delta\ln N$ with $\gamma = 0.10$ in the baseline; sensitivity to and to $\gamma \in \{0.05, 0.10, 0.15\}$ alternative CRM weights is reported in A.8. The composite CRM index N_t is a fixed-weight quantity index (2018 = 100) over graphite, ilmenite concentrate and manganese concentrate with equal 2018-based weights; weights are re-normalized over available components in partial-basket years (see A.4–A.5).

Source: World Bank WDI (real GDP, constant prices); USGS, IndexMundi and Ukrstat (CRM quantities). Authors' calculations.

A.7. Shift-share decomposition (CMS) analysis: formulas and benchmarks

The change in exports of Ukraine's CRM basket between two dates is decomposed, t_0 = 2018 and t_1 = 2023, into three components: a world/benchmark growth effect (N), an industry mix effect (M), and a competitiveness effect (C) (Dunn 1960; Esteban-Marquillas 1972; Barff and Knight 1988). Let J = {graphite, ilmenite, manganese} and let $x_{j,t}$ denote Ukraine's exports of product to the chosen market in year (current USD). Let $B_{j,t}$ denote the benchmark market's total imports of j from all partners, and $B_t = \sum_{j \in J} B_{j,t}$. Define benchmark growth rates

$$g = \frac{B_{t_1} - B_{t_0}}{B_{t_0}}, \qquad g_j = \frac{B_{j,t_1} - B_{j,t_0}}{B_{j,t_0}} \quad (j \in J)$$

Then the total change in Ukraine's exports of the basket, $\Delta X = \sum_j \left(x_{j,t_1} - x_{j,t_0} \right)$, satisfies

$$\Delta X = N + M + C$$

with components

$$N = g \sum_{j \in J} x_{j,t_0}, \qquad M = \sum_{j \in J} x_{j,t_0} (g_j - g), \qquad C = \sum_{j \in J} \left[x_{j,t_1} - x_{j,t_0} (1 + g_j) \right]$$

Intuitively, N is the change explained by overall benchmark growth at unchanged structure and shares; M captures whether Ukraine is specialized in faster- or slower-growing CRM segments; C is the residual that reflects within-segment share gains or losses.

Benchmarks and series. The decomposition is computed for two policy-relevant benchmarks built on the HS scope defined in A.2:

Global benchmark (UA→World). $x_{j,t}$ are Ukraine's exports to the world (reporter: Ukraine; partner: world; flow: exports). Benchmark totals $B_{j,t}$ are world imports of j from all partners (standard Comtrade world aggregate).

- EU-27 benchmark (EU-27 imports from UA). $x_{j,t}$ are EU-27 imports from Ukraine (reporter: EU-27 aggregate; partner: Ukraine; flow: imports). Benchmark totals $B_{j,t}$ are EU-27 imports of from all partners.

All values are in current USD; where Eurostat Comext provides EUR, it was converted to USD in preprocessing (A.5). The basket is restricted to HS 2504 (graphite), HS 2614 (titanium ores and concentrates, proxied by ilmenite/leucoxene), and HS 2602 (manganese ores and concentrates). Aggregation is over J only; downstream products (for example TiO_2 pigments, titanium metal, ferroalloys HS 7202) are out of scope. Results are presented in section 4.5 and tabulated in the Appendix results table for CMS (same two-point window 2018–2023).

Table A.4. Constant-market-share (shift-share) decomposition for Ukraine's CRM exports, 2018–2023: global vs EU-27 benchmark (million USD)

Tabela A.4. Analiza dekompozycji przy stałym udziale w rynku (metoda „shift-share") dla eksportu produktów CRM z Ukrainy w latach 2018–2023: porównanie z rynkiem światowym i UE-27 (w mln USD)

Benchmark	ΔX	N (world growth)	M (industry mix)	C (competitiveness)
World	−51.39	+36.67	−2.35	**−85.71**
EU-27	−3.30	−16.75	+1.41	**+12.05**

Basket restricted to HS 2504 (graphite), HS 2614 (titanium ores and concentrates, proxied by ilmenite/leucoxene) and HS 2602 (manganese ores and concentrates). Components: world/benchmark growth; industry mix; competitiveness. Global benchmark uses UA→World (reporter: Ukraine; partner: world; exports). EU-27 benchmark uses EU-27 imports from UA (reporter: EU-27 aggregate; partner: Ukraine; imports). Values are current USD; where reported in EUR (Eurostat), converted using annual average USD/EUR (see A.5).

Source: UN Comtrade; Eurostat Comext (Easy Comext). Authors' calculations following Dunn (1960); Esteban-Marquillas (1972); Barff and Knight (1988).

A.8. Robustness bundle

This section summarizes sensitivity checks around the core design choices. The aim is to establish whether signs and qualitative rankings of effects are stable across reasonable alternatives; detailed numbers are provided in the robustness tables of this section and are referenced from section 5 where relevant.

Factor-share parameter (γ). The growth-accounting contributions are recomputed for $\gamma \in \{0.05, 0.10, 0.15\}$. As γ scales the CRM term mechanically, magnitudes change proportionally, but the sign pattern is invariant across the three windows 2010–2013, 2014–2021 and 2022–2023. The residual term adjusts one-for-one by construction.

Weighting schemes for the CRM index. Besides the baseline equal weights ($\omega_{j,2018}$ = 1/3), a price-weighted Laspeyres index (with 2018 USD/t unit prices) and an export-value index (using UN Comtrade values) are implemented on the HS scope defined in A.2. For titanium, we distinguish rutile versus ilmenite unit prices; because the physical series is ilmenite concentrate, rutile-based weights overstate titanium's share. Results are therefore reported with ilmenite as the recommended price proxy. Across weighting schemes, levels differ but the qualitative time profile of N_t and the signs of contributions in section 4 are unchanged.

Availability and denominator conventions. The baseline index uses fixed 2018 weights with re-normalization over available components in years with missing entries (A.4–A.5). We re-estimate on the common-availability intersection that restricts the index to years where all three components are observed. This reduces the sample but leaves the direction of changes and the main inferences intact.

Base-year choice and rebasing. Rebasing the CRM index to 2019 or 2020 shifts levels but does not affect signs of $\Delta \ln N$ over the three windows. Growth-accounting contributions move accordingly, with no change to conclusions.

Benchmark perspective and currency. The constant-market-share decomposition is computed for two internally consistent perspectives: UA→World (UN Comtrade, exports) and EU-27 imports from UA (Eurostat Comext, imports). Where Comext reports EUR, values are converted to USD using annual average USD/EUR rates in preprocessing (A.5). Using Comtrade's EU-27 aggregate as a replication check yields the same N/M/C sign pattern after currency alignment.

Time aggregation. For growth accounting, average annual log changes (percentage points per year) are reported, computed as $[\ln X_{t_1} - \ln X_{t_0}]/(t_1 - t_0) \cdot 100$. Reporting total log changes over the window yields numerically different magnitudes but the same signs and ordering; section 4 maintains the average-annual convention throughout.

Window coverage. All robustness checks respect the analysis windows 2010–2023 (production) and 2018–2023 (trade). Calendar year 2024 lies outside these windows and is not used in baseline or robustness computations.

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REFERENCES

Bank Gospodarstwa Krajowego (BGK) 2025. *The current state and prospects of extracting critical raw materials in Ukraine*. [Online:] https://www.en.bgk.pl/files/public/en/files/Reports/The_current_state_and_prospects_of_extracting_critical_raw_materials_in_Ukraine.pdf [Accessed: 2025-10-18].

Barff, R. and Knight, P. 1988. Dynamic shift-share analysis. *Growth and Change* 19(2), pp. 1–10, https://doi.org/10.1111/j.1468-2257.1988.tb00465.x.

Center for Strategic and International Studies 2025. *The consequences of China's new rare earths export restrictions*. CSIS. [Online:] https://www.csis.org/analysis/consequences-chinas-new-rare-earths-export-restrictions [Accessed: 2025-10-18].

Dunn, E.S. 1960. A statistical and analytical technique for regional analysis. *Papers and Proceedings of the Regional Science Association* 6(1), pp. 97–112, https://doi.org/10.1111/j.1435-5597.1960.tb01705.x.

EBRD 2023. *Ukraine: Reconstruction, resilience and regional integration*. European Bank for Reconstruction and Development.

Esteban-Marquillas, J.M. 1972. A reinterpretation of shift-share analysis. *Regional and Urban Economics* 2(3), pp. 249–255, https://doi.org/10.1016/0034-3331(72)90033-4.

European Commission 2021. *Memorandum of Understanding between the European Union and Ukraine on a Strategic Partnership on Raw Materials*. Brussels, 13 July 2021. [Online:] https://ec.europa.eu/docsroom/documents/46300 [Accessed: 2025-10-18].

European Commission, Directorate-General for Economic and Financial Affairs 2023. *Reflections on the role of natural capital for economic activity (European Economy Discussion Paper No. 183)*. European Commission. [Online:] https://economy-finance.ec.europa.eu/publications/reflections-role-natural-capital-economic-activity_en [Accessed: 2025-10-18].

European Commission 2025. *RESourceEU action plan: Accelerating our CRM strategy to adapt to a new reality (COM(2025) 945 final)*. Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs. [Online:] https://single-market-economy.ec.europa.eu/publications/resourceeu-action-plan-accelerating-our-crm-strategy-adapt-new-reality_en [Accessed: 2025-10-18].

European Union 2024. *Regulation (EU) 2024/1252 of the European Parliament and of the Council of 11 April 2024 establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) No 168/2013, (EU) 2018/858, (EU) 2018/1724 and (EU) 2019/1020*. Official Journal of the European Union, OJ L, 3 May 2024. [Online:] https://eur-lex.europa.eu/eli/reg/2024/1252/oj [Accessed: 2025-10-18].

Eurostat. n.d. *Comext/Easy Comext.* Dataset: EU-27 imports from Ukraine, HS 2504/2614/2602, years 2018, 2023. [Online:] https://ec.europa.eu/eurostat/web/international-trade-in-goods/data/database [Accessed: 2025-10-18].

Farrell, H. and Newman, A.L. 2019. Weaponized interdependence: How global economic networks shape state coercion. *International Security* 44(1), pp. 42–79, https://doi.org/10.1162/isec_a_00351.

Frankel, J.A. 2010. The natural resource curse: A survey (NBER Working Paper No. 15836). National Bureau of Economic Research, https://doi.org/10.3386/w15836.

Friedrich-Ebert-Stiftung (FES) 2025. *Critical Raw Materials, Local Content Policy and Ukraine's Economic Recovery. FES Ukraine*. [Online:] https://library.fes.de/pdf-files/bueros/ukraine/22223.pdf [Accessed: 2025-10-18].

Gereffi et al. 2005 – Gereffi, G., Humphrey, J. and Sturgeon, T. 2005. The governance of global value chains. *Review of International Political Economy* 12(1), pp. 78–104, https://doi.org/10.1080/09692290500049805.

IndexMundi. n.d. *Ukraine – Graphite – Production (metric tons).* (Compiled from USGS). [Online:] https://www.indexmundi.com/minerals/?country=ua&product=graphite&graph=production [Accessed: 2025-10-18].

International Energy Agency (IEA) 2021. *The role of critical minerals in clean energy transitions*. IEA. [Online:] https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions [Accessed: 2025-10-18].

International Energy Agency (IEA) 2024. *Global critical minerals outlook 2024*. [Online:] https://www.iea.org/reports/global-critical-minerals-outlook-2024 [Accessed: 2025-10-18].

International Energy Agency (IEA) 2025. *Global critical minerals outlook 2025*. [Online:] https://www.iea.org/reports/global-critical-minerals-outlook-2025 [Accessed: 2025-10-18].

Keohane, R.O. and Nye, J.S. 2012. *Power and interdependence* (4th ed.). New York: Longman.

Kõrts, M.M. 2023. *Rare earth minerals and clean technologies nexus at the background of Russia's war in Ukraine*. NATO Energy Security Centre of Excellence. [Online:] https://www.enseccoe.org/publications/rare-earth-minerals-and-clean-technologies-nexus-at-the-background-of-russias-war-in-ukraine/ [Accessed: 2025-10-18].

Mankiw et al. 1992 – Mankiw, N.G., Romer, D. and Weil, D.N. 1992. A contribution to the empirics of economic growth. *The Quarterly Journal of Economics* 107(2), pp. 407–437, https://doi.org/10.2307/2118477.

Mehlum et al. 2006 – Mehlum, H., Moene, K. and Torvik, R. 2006. Institutions and the resource curse. *The Economic Journal* 116(508), pp. 1–20, https://doi.org/10.1111/j.1468-0297.2006.01045.x.

OECD 2016. *OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas.* 3rd ed. Paris: OECD Publishing, https://doi.org/10.1787/9789264252479-en.

Pangsy-Kania, S. and Flouros, F. 2022. Rare earth elements as a huge economic challenge for the future of green economy. *In Proceedings of the 40th International Business Information Management Association (IBIMA)* (pp. 23–24). Seville, Spain. [Online:] https://ibima.org/accepted-paper/rare-earth-elements-as-huge-economic-challenge-for-the-future-of-green-economy/ [Accessed: 2025-10-18].

Pisani-Ferry et al. 2024 – Pisani-Ferry, J., Tagliapietra, S. and Zachmann, G. 2024. How to de-risk: European economic security in a world of interdependence. *Bruegel Policy Brief* 7.

Solow, R.M. 1957. Technical change and the aggregate production function. *The Review of Economics and Statistics* 39(3), pp. 312–320, https://doi.org/10.2307/1926047.

The Observatory of Economic Complexity (OEC) 2025. *Ukraine – Exports of Graphite (HS 2504), 2023.* [Online:] https://oec.world/ [Accessed: 2025-10-18].

TrendEconomy 2025. *Ukraine – Exports of Titanium ores and concentrates (HS 2614), 2018 & 2023.* [Online:] https://trendeconomy.com/ [Accessed: 2025-10-18].

U.S. Congress 2022. *Inflation Reduction Act of 2022* (H.R. 5376), Public Law No. 117–169.

U.S. Geological Survey (USGS) 2023a. *The Mineral Industry of Ukraine – 2017–2018.* [In:] *2020 Minerals Yearbook*, Europe and Central Eurasia. Reston, VA: USGS. (Table: "Ukraine: Production of Mineral Commodities").

U.S. Geological Survey (USGS) 2023b. *The Mineral Industry of Ukraine – 2019.* [In:] *2021 Minerals Yearbook*, Europe and Central Eurasia. Reston, VA: USGS.

U.S. Geological Survey (USGS) 2024. *The Mineral Industry of Ukraine – 2020–2021.* [In:] *2022 Minerals Yearbook*, Europe and Central Eurasia. Reston, VA: USGS.

U.S. Geological Survey 2018. Mineral commodity summaries 2018. U.S. Geological Survey. [Online:] https://www.usgs.gov/centers/national-minerals-information-center/mineral-commodity-summaries [Accessed: 2025-10-18].

Ukrainian Geological Survey. n.d. Mining Investment Opportunities: Critical Raw Materials. Slide deck, slide 4. State Service of Geology and Subsoil of Ukraine.

UNCTAD 2023. *World Investment Report 2023: Investing in sustainable energy for all*. Geneva: United Nations.

United Nations Statistics Division (UNSD). n.d. *UN Comtrade Database.* Queries: reporter Ukraine (partner World) and reporter EU-27 (partner Ukraine); HS 2504, 2614, 2602; years 2018, 2023; frequency annual; values USD. [Online:] https://comtrade.un.org/ [Accessed: 2025-10-18].

United Nations Statistics Division (UNSD). *UN Comtrade Database*.

van der Ploeg, F. 2011. Natural resources: Curse or blessing? *Journal of Economic Literature* 49(2), pp. 366–420, https://doi.org/10.1257/jel.49.2.366.

World Bank 2021. *The changing wealth of nations 2021: Managing assets for the future*. [Online:] https://openknowledge.worldbank.org/handle/10986/36400 [Accessed: 2025-10-18].

World Economic Forum 2024. The future of critical raw materials: How Ukraine plays a strategic role in global supply chains. [Online:] https://www.weforum.org/stories/2024/07/the-future-of-critical-raw-materials-how-ukraine-plays-a-strategic-role-in-global-supply-chains/ [Accessed: 2025-10-18].

STRATEGIC AUTONOMY IN PRACTICE: UKRAINE'S CRITICAL RAW MATERIALS, GROWTH ACCOUNTING AND SHIFT-SHARE EVIDENCE, 2010–2023

Keywords

strategic autonomy, critical raw materials (CRMs), Ukraine, growth accounting, shift-share analysis, global value chain (GVC) governance, weaponized interdependence, EU de-risking (CRMA)

Abstract

This article examines whether Ukraine's endowment of critical raw materials (CRMs) – here, graphite, titanium (ilmenite) and manganese – can support post-war growth while advancing Europe's strategic autonomy. Two transparent tools are combined. First, a resource-augmented growth-accounting identity attributes real-GDP growth to a composite CRM production index, defined as a fixed-weight quantity index (2018 = 100) for graphite, ilmenite concentrate and manganese concentrate, alongside the residual productivity term. The estimated CRM contribution is positive in 2014–2021 but turns negative in 2022–2023 as production and logistics deteriorate; signs are robust to plausible income shares and alternative basket weights. Second, a shift-share decomposition of CRM exports (2018–2023) shows a large negative competitiveness effect in global markets, consistent with wartime disruption, but a positive competitiveness effect inside the EU-27 despite a contracting EU market – evidence of selective de-risking toward proximate, trusted suppliers. Read together, deposits create options, yet durable leverage depends on mid-stream capacity, verifiable compliance and resilient corridors. Policy follows: prioritize domestic processing (concentrates into chemicals/metals) under CRMA-compatible rules and bankable offtakes; embed OECD-type due diligence; design financing and logistics to absorb shocks. Limitations include a deliberately narrow mineral basket and incomplete capital/employment series.

AUTONOMIA STRATEGICZNA W PRAKTYCE: KLUCZOWE SUROWCE KRYTYCZNE UKRAINY, RACHUNEK WZROSTU ORAZ ANALIZA SHIFT-SHARE, 2010–2023

Słowa kluczowe

autonomia strategiczna, surowce o znaczeniu krytycznym (CRM), Ukraina,
rachunek wzrostu gospodarczego, analiza shift-share,
zarządzanie globalnym łańcuchem wartości (GVC),
wzajemna zależność wykorzystywana jako broń, ograniczanie ryzyka przez UE (CRMA)

Streszczenie

W niniejszym artykule analizuje się, czy zasoby Ukrainy w zakresie surowców krytycznych (CRM) – w tym przypadku grafitu, tytanu (ilmenitu) i manganu – mogą wspierać powojenny wzrost gospodarczy, przyczyniając się jednocześnie do wzmocnienia strategicznej autonomii Europy. W analizie wykorzystano dwa przejrzyste narzędzia. Po pierwsze, tożsamość rachunkowości wzrostu z uwzględnieniem zasobów przypisuje wzrost realnego PKB złożonemu indeksowi produkcji surowców krytycznych, zdefiniowanemu jako indeks ilościowy o stałej wadze (2018 = 100) dla grafitu, koncentratu ilmenitu i koncentratu manganu, wraz z terminem produktywności rezydualnej. Szacowany wkład surowców strategicznych jest dodatni w latach 2014–2021, ale staje się ujemny w latach 2022–2023 w miarę pogorszenia się sytuacji w zakresie produkcji i logistyki; wyniki są odporne na realistyczne założenia dotyczące udziału w dochodach oraz alternatywne wagi koszyka. Po drugie, dekompozycja eksportu surowców rzadkich (2018–2023) metodą shift-share wskazuje na duży ujemny wpływ na konkurencyjność na rynkach światowych, co jest zgodne z zakłóceniami w czasie wojny, ale na dodatni wpływ na konkurencyjność w obrębie UE-27 pomimo kurczącego się rynku unijnego – co stanowi dowód na selektywne ograniczanie ryzyka poprzez zwracanie się ku bliskim, zaufanym dostawcom. W ujęciu całościowym złoża stwarzają możliwości, jednak trwała dźwignia finansowa zależy od zdolności przetwórczych na środkowym etapie łańcucha dostaw, weryfikowalnej zgodności z przepisami oraz odpornych korytarzy transportowych. Wynikają z tego następujące kierunki polityki: priorytetowe traktowanie przetwórstwa krajowego (koncentraty na chemikalia/metale) w ramach zasad zgodnych z CRMA i gwarantowanych umów odbioru; wdrożenie zasad należytej staranności typu OECD; zaprojektowanie finansowania i logistyki w sposób pozwalający na amortyzację wstrząsów. Ograniczenia obejmują celowo wąski koszyk minerałów oraz niekompletne dane dotyczące kapitału i zatrudnienia.