

Report on Critical Raw Materials in Europe's Energy Transition

A comprehensive assessment of Europe's
critical raw material dependencies,
supply chain vulnerabilities, and
options for a resilient energy transition

SEPTEMBER 2026

ENERGY COMMISSION

VOYCE Think Tank

Voice Of Youth for Change in Europe

Lead author:

Arnau M. Rodríguez Suárez, Deputy Head of the Energy Commission

Contributing authors:

Marilyn Mabel Gilbert, Federica Li Bassi, Saptarshi Mukherjee, and Sofia Rufino, Energy Commission

Contacts: arnau_rodriguez@voyceu.com, energy@voyceu.com

European Union Transparency Register:
9658947102951-42



September 2026

Reproduction is authorized provided the source is acknowledged.

Citation as: "VOYCE, Report on Critical Raw Materials in Europe's Energy Transition, 2026"

ABSTRACT

Europe's energy transition is becoming a material security challenge. Electrification, renewable deployment, batteries, hydrogen technologies, digital infrastructure, and electricity grids all require specialized raw materials whose supply chains are complex, concentrated, and slow to expand. This report examines how critical raw material dependence is reshaping energy security, industrial competitiveness, and strategic autonomy for the European Union.

This report shows that critical raw material dependence has become an issue of energy security, industrial competitiveness, and geopolitical autonomy. China is particularly central because its leverage is strongest not only in mining, but in refining, processing, and downstream manufacturing, where scale, technical know-how, and industrial coordination create bottlenecks that Europe cannot quickly replace. The Critical Raw Materials Act (CRMA) is a necessary first step, but its benchmarks and individual Strategic Projects will not by themselves create resilient European value chains.

The report concludes that Europe needs a strategy combining supply- and demand-side measures. Strengthening domestic and partner-country capacity remains necessary, but must be complemented by circularity, material efficiency, sufficiency, public legitimacy, and responsible international partnerships. The objective should not be complete self-sufficiency, but diversified, transparent, and mutually beneficial value chains aligned with climate neutrality, industrial competitiveness, and democratic legitimacy.

CONTENTS

ABSTRACT

EXECUTIVE SUMMARY

1 INTRODUCTION

1.1 Content and purpose of the report	8
1.2 Objectives and scope	9
1.3 What are critical raw materials?	9
1.4 Why critical raw materials matter for the energy transition	11
1.5 Critical raw materials in the EU's agenda	12
1.6 From raw materials to geopolitical control	13

2 THE ROLE OF CRITICAL RAW MATERIALS IN THE ENERGY TRANSITION

2.1 Why the energy transition increases material demand	14
2.2 Material requirements of key energy transition technologies	15
2.2.1 Solar photovoltaic (PV)	15
2.2.2 Wind energy	15
2.2.3 Battery energy storage systems (BESS)	15
2.2.4 Hydrogen technologies	16
2.2.5 Power grids	16
2.3 Projected demand for critical raw materials	17
2.4 Can clean technologies replace fossil fuels across sectors?	19
2.5 Reducing material dependence in key energy transition technologies	20
2.5.1 Solar PV	20
2.5.2 Wind energy	21
2.5.3 BESS	22
2.5.4 Hydrogen technologies	22
2.5.5 Power grids	22
2.6 Supply bottlenecks and risks to the energy transition	23

3 GLOBAL SUPPLY CHAINS

3.1 Extraction	25
3.1.1 Resources and reserves	25
3.1.2 Global reserves and production	26
3.1.3 Europe extraction's history and constraints	27
3.1.4 ESG risks in extraction	27
3.1.5 ESG standards and development priorities	28
3.1.6 Reducing the environmental impact of extraction	29
3.2 Refining and processing	31
3.2.1 Why refining and processing matter	31

3.2.2	Geographic concentration in refining	31
3.2.3	Why refining remains difficult to diversify	32
3.3	Manufacturing	33
3.3.1	Manufacturing as a strategic bottleneck	34
3.3.2	Battery components and cell manufacturing	34
3.3.3	Permanent magnets, solar PV, and wind turbine components	35
3.3.4	Challenges of rebuilding European manufacturing capacity	37
3.4	Recycling	38
3.4.1	Recycling as a strategic supply source	38
3.4.2	Technologies and recovery potential	39
3.4.3	Limits of recycling	39
4	CHINA AND THE GLOBAL SUPPLY OF CRITICAL RAW MATERIALS	
4.1	China's strategic positioning in the energy transition	41
4.2	China's role across the value chain	42
4.2.1	Mining	43
4.2.2	Refining and processing	44
4.2.3	Manufacturing	46
4.3	Dependency, leverage, and export controls	47
4.4	Implications for the EU	48
5	THE EU'S POSITION AND POLICY RESPONSE	
5.1	Targets, implementation, and gaps of the CRMA	49
5.2	Feasibility of Europe's ambition	52
5.2.1	Exploration, regulatory delays, and project timelines	52
5.2.2	Social acceptance and community trust	53
5.2.3	Economic constraints and the financing gap	54
5.2.4	The human capital crisis	54
5.3	Partnerships and external dependencies	55
5.3.1	Historical inequalities in producing regions	56
5.3.2	Diversification, dependency, and competition	57
5.4	The scale challenge	57
5.4.1	Material intensity and project timelines	58
5.4.2	Grid infrastructure and copper bottlenecks	58
5.5	Reducing material demand	59
5.5.1	The limits of technological innovation	59
5.5.2	Efficiency improvements in existing systems	61
5.5.3	The limits of efficiency	62
5.5.4	Energy sufficiency in practice	63
6	CONCLUSION AND POLICY RECOMMENDATIONS	
6.1	Conclusion	65
6.2	Policy recommendations	66

EXECUTIVE SUMMARY

Europe's energy transition is becoming a material, industrial, geopolitical, and social challenge. Electrification, renewable energy deployment, batteries, hydrogen technologies, digital infrastructure, and electricity grids all require specialized raw materials whose supply chains are complex, geographically concentrated, and slow to expand. As a result, energy security increasingly depends on the ability to secure, process, manufacture, recycle, and substitute the critical raw materials embedded in clean energy infrastructure.

This report examines the European Union's exposure to critical raw materials in the context of the energy transition. It analyses the material demand created by renewable energy technologies, electric vehicles, batteries, hydrogen systems, and electricity grids; the structure of global supply chains across extraction, refining and processing, manufacturing, and recycling; China's central role across several stages of these value chains; and the EU's current policy response, particularly through the Critical Raw Materials Act.

The report shows that critical raw material dependence is not only a mining problem. While extraction is important, strategic leverage is increasingly concentrated in refining, processing, and downstream manufacturing. These stages require technical know-how, industrial coordination, capital investment, skilled labour, infrastructure, and environmental management capacity. China's position illustrates this clearly. Its influence is strongest not only in domestic mining, but in the transformation of raw materials into usable industrial inputs and clean technologies, including batteries, permanent magnets, solar photovoltaics, and other strategic components. This gives China significant industrial and geopolitical leverage, particularly where alternative suppliers remain limited or cannot scale quickly.

The Critical Raw Materials Act represents an important shift in EU policy. It recognizes that critical raw materials are central to energy security, industrial competitiveness, and strategic autonomy. Its 2030 benchmarks for extraction, processing, recycling, and import diversification provide a useful direction for EU action. However, the report finds that these benchmarks and Strategic Projects will not by themselves create resilient European value chains. The targets are strategic benchmarks rather than guaranteed outcomes, and aggregate figures can hide major weaknesses in specific materials or stages of the value chain. In addition, Strategic Project status does not automatically ensure financing, permitting success, commercial viability, or social acceptance.

The feasibility of the EU's ambitions is constrained by several structural barriers. Europe faces underdeveloped exploration, long project timelines, complex permitting procedures, high energy costs, financing constraints, and the erosion of technical expertise in mining, metallurgy, and processing. Public legitimacy is also a central constraint. Mining and refining projects are unlikely to advance if communities perceive them as imposed, environmentally risky or disconnected from local benefits. Indigenous rights where relevant, meaningful participation, transparent environmental monitoring, and local value sharing are therefore essential to any credible critical raw material strategy.

External partnerships will remain unavoidable. Full self-sufficiency in critical raw materials is neither realistic nor desirable for the EU. However, partnerships must avoid reproducing extractive dependencies in producer countries. A resilient strategy should not be based only on securing access to raw materials abroad, but on supporting local processing, skills development, infrastructure, environmental governance, and responsible value creation in partner countries. This is particularly important in regions with long

histories of unequal extraction, where mining can represent both economic opportunity and environmental or social risk.

The report also highlights the scale challenge of the energy transition. Renewable technologies, electric vehicles, batteries, and electricity grids require a major expansion of physical infrastructure within a short period of time. Grid infrastructure and copper supply are particularly important bottlenecks. This means that supply expansion alone will not be sufficient. The EU must also reduce avoidable material demand through technological innovation, efficiency, circularity, and sufficiency. Technology innovation can reduce pressure on specific materials, but they often introduce new trade-offs and do not eliminate the broader relationship between clean technology deployment and material demand. Efficiency improvements are necessary, but without sufficiency, their benefits may be absorbed by growth in total consumption.

The report therefore argues that Europe needs a critical raw materials strategy combining supply- and demand-side measures.

To support this objective, the report proposes six policy recommendations:

1. **Coordinate EU critical raw material strategic security** through stronger demand forecasting, material-specific risk monitoring, strategic reserves, and crisis response mechanisms.
2. **Rebuild the European critical raw material industrial ecosystem** by connecting extraction, refining and processing, manufacturing, recycling, research, infrastructure, and skills into coordinated value-chain strategies.
3. **Put demand management at the centre of the transition** by integrating material efficiency and sufficiency into energy, mobility, grid, and infrastructure planning.
4. **Strengthen circularity, traceability, and material efficiency** by treating end-of-life products as strategic resources and improving recovery, repairability, product design, and digital traceability.
5. **Build public legitimacy and local benefits** by ensuring that Strategic Projects are linked to transparent participation, credible safeguards, local value sharing, and, where relevant, Indigenous rights.
6. **Develop strategic partnerships** for responsible value creation by diversifying imports while supporting local processing, skills, infrastructure, environmental governance, and responsible sourcing in producer countries.

Together, these measures would help the EU move from fragmented and reactive supply-risk management towards a coordinated model of material resilience. The energy transition will not succeed through renewable deployment alone. It will require industrial capability, public trust, responsible partnerships, and a realistic approach to material demand.

1. INTRODUCTION

1.1 Content and purpose of the report

This report aims to provide a clear and independent overview of the European Union’s growing exposure to critical raw materials, especially in the context of the energy transition. It seeks to analyse and complement existing European Union (EU) strategies by providing technical evidence, policy analysis, expert interviews, and VOYCE’s own research.

The purpose of the report is to help readers understand why critical raw materials matter, where the main vulnerabilities lie, and what options the EU has to reduce supply risks while supporting its energy transition. It is written for a broad audience, including policymakers, industry professionals, students, and readers who may not have a technical background in renewable energies or energy systems.

This report is structured as follows:

Chapter 1 – Introduction

Presents the objectives and scope of the report, introduces the role of critical raw materials across sectors both in Europe and globally, and explains their economic and geopolitical relevance.

Chapter 2 – Critical raw materials and the energy transition

Explains how renewable energy, electrification, and clean technologies are increasing the demand for specific materials. It also compares material needs with fossil-based technologies and discusses whether substitution of these materials is possible, limited, or unrealistic.

Chapter 3 – Global supply chains

Examines the global supply chains of the critical raw materials most relevant to the energy transition. It focuses on four key stages of the supply chain: extraction, refining and processing, manufacturing, and recycling. It also looks at geographic concentration of production and processing, historical developments, and technological constraints.

Chapter 4 – Why is China central to the critical raw materials debate?

Analyses China’s position across global critical raw materials supply chains, particularly mining, refining and processing, and manufacturing. It debates how strategic Chinese overseas investments have contributed to China’s current position in the sector. It also considers how export controls, industrial policy and vertical integration strategies are affecting global markets and, as a result, the EU.

Chapter 5 – The European Union’s position and policy response

Assesses the EU’s domestic potential, policy response, and strategic options across the entire critical raw material supply chain. This includes the Critical Raw Materials Act (CRMA), partnerships with third countries, and implementation challenges, including financing, regulation, geopolitics, and social acceptance within Europe.

Chapter 6 – Final conclusion and policy recommendations

Synthesizes the report's main findings and presents policy-oriented recommendations to strengthen the EU's resilience and strategic position in critical raw materials.

1.2 Objectives and scope

The objective of this report is to assess the European Union's vulnerabilities within its critical raw material supply chains as it undergoes its energy transition. This includes an examination of the entire supply chain, from extraction and refining to manufacturing and recycling, as well as the associated geopolitical factors that influence access to these materials. By evaluating these vulnerabilities, the report aims to explore the EU's strategic options for securing critical raw materials, whether through domestic initiatives, international partnerships, or broader industrial policy.

Furthermore, the report analyses how the EU's energy transition goals are expected to increase demand for these resources. It aims to serve as an independent reference framework for understanding the role of critical raw materials in the energy transition and for assessing how the EU can strengthen its long-term resilience. Given the rapidly changing nature of these markets and policy developments, information and data in this report reflect the best available evidence as of June 2026, unless otherwise indicated.

Because critical raw material supply chains are global, the geographical scope of this project extends beyond Europe. Particular attention is given to China, given its central role in several stages of critical raw material supply chains and its geopolitical relevance. The choice of the materials discussed is dependent on their importance in the energy transition, in relation to renewable energies, electrification, or clean technologies.

This report is designed to be independent of current political cycles and party agendas. Its aim is to contribute to an informed and long-term discussion on the EU's journey towards greater energy independence and strategic resilience. To complement the technical and policy analysis, the report draws on interviews with experts from academic, industrial, and third sector backgrounds, providing additional perspectives on the challenges and strategic choices discussed throughout the report.

1.3 What are critical raw materials?

Critical raw materials are defined by the European Union as materials that are simultaneously essential for the EU economy and exposed to a high risk of supply disruption.¹ Other factors such as geological availability, economic relevance, geopolitical exposure, and environmental and social considerations influence their criticality.²

From an economic perspective, criticality reflects how important a material is for key industrial applications and the value it generates across EU manufacturing sectors. This assessment also considers substitution, meaning whether the material can be substituted by alternatives, considering both technical feasibility and cost.³ Supply risk, on the other hand, captures the likelihood of disruptions along the supply chain. It is influenced by factors such as the concentration of production in a limited number of countries, trade agreements, and the level of import reliance. For this reason, supply risk is measured at the most vulnerable

¹ European Commission. *Critical raw materials*. https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en.

² Sofrecom. *Management Of Raw Materials Strategic Challenges For Telecom Operators*. <https://www.sofrecom.com/en/news-insights/management-of-raw-materials-strategic-challenges-for-telecom-operators.html>.

³ European Commission, *Critical raw materials*, see n. 1.

stages of the value chain, extraction or processing, while recycling and substitution are considered mitigating factors.⁴

On this basis, the European Commission regularly updates its list of critical raw materials to reflect changing market, technological, and geopolitical conditions. In 2023, the fifth EU list identified 34 critical raw materials, after assessing 70 candidate raw materials. Additionally, some of these materials are also classified as Strategic Raw Materials (SRMs) due to their relevance for the energy transition, the digital transition, space, and defence applications.

Table 1: 2023 Critical Raw Materials (*Strategic Raw Materials are shown in italics*)

aluminium/bauxite	coking coal	lithium	phosphorus
antimony	feldspar	LREE*	scandium
arsenic	fluorspar	magnesium	silicon metal
baryte	gallium	manganese	strontium
beryllium	germanium	natural graphite	tantalum
bismuth	hafnium	niobium	titanium metal
boron/borate	helium	PGM‡	tungsten
cobalt	HREE†	phosphate rock	vanadium
	copper§	nickel§	

Source: European Commission, Fifth list 2023 of critical raw materials for the EU

* Light Rare Earth Elements

† Heavy Rare Earth Elements

‡ Platinum Group Metals

§ Copper and nickel don't meet the critical raw material thresholds but are included as SRMs

While critical raw materials are often associated with renewable energy technologies, their importance extends beyond the energy sector. They are also essential for defence, space, transport, *agritech*, medicine, computing, and telecommunications.⁵ The defence domain, for example, relies on these materials for the development of emerging and disruptive technologies, which NATO explicitly recognizes as key enablers of technological superiority, strategic autonomy, and deterrence capabilities.⁶ In healthcare and pharmaceuticals, materials such as cobalt, chromium, magnesium, molybdenum, and nickel are essential components of active pharmaceutical ingredients used in antibiotics and antiviral treatments, as in COVID19 treatments. This highlights the direct link between critical raw material supply chains and public health security.⁷

Agriculture also depends on critical materials. Phosphates and potassium are fundamental to fertilizer production and soil health, while lithium, cobalt, zinc, and copper enable precision farming tools and advanced agricultural technologies.⁸ Similarly, in computing and telecommunications, materials such

⁴European Commission, *Critical raw materials*, see n. 1.

⁵Intesa Sanpaolo Innovation Center. *Industry Trends Report – Critical Raw Materials*. 2024. https://www.intesasanpaoloinnovationcenter.com/content/dam/digitalhub/documenti/202401_CriticalRawMaterials_ENG_MOST_abstract.pdf.

⁶NATO. *Emerging And Disruptive Technologies*. <https://www.nato.int/en/what-we-do/deterrence-and-defence/emerging-and-disruptive-technologies>.

⁷United Nations Economic Commission for Europe. *UNECE launches new initiative on critical raw materials*. <https://unece.org/media/press/1490>.

⁸Farmonaut. *Farmonaut*. <https://farmonaut.com>.

as silicon, cobalt, and rare earth elements are central to microchips, semiconductors, high-performance magnets, and data-processing hardware.⁹

In other words, although this report focuses on the energy transition, critical raw materials concerns extend well beyond: they are part of the material foundation of modern economies. This is why their availability, affordability, and secure supply have become increasingly important for industrial policy, technological development, and geopolitical strategy.

1.4 Why critical raw materials matter for the energy transition

The importance of critical raw materials is increasing together with a structural transformation of global energy systems. According to the International Energy Agency (IEA), the global economy is entering the “Age of Electricity”, in which electricity demand grows faster than overall energy use in all policy scenarios.^{10, 11} Electricity is increasingly at the core of modern economies, supporting industrial activity, transport, digitalization, and household consumption. And while electricity generation can draw on a diverse mix of energy sources, the infrastructure and technologies that enable electrification itself are significantly more material-intensive than conventional energy systems.

Electrification is the process in which the power supply of an activity shifts from other sources of energy (e.g. coal, gas) to electricity. This shift is creating new forms of dependence on critical raw materials. Renewable energy technologies, batteries, electric vehicles, electricity grids, and digital infrastructure all require specific critical materials whose supply chains are often complex, geographically concentrated, and difficult to scale quickly. As a result, energy security no longer means only access to oil or gas. It is also about access to these materials that are needed to build, maintain, and expand clean energy systems.

As previously mentioned, the supply chains of critical minerals are often complex, and characterized by a set of structural vulnerabilities increasing exposure to disruption. High levels of concentration, by-product dependency, and limited transparency increase the risk of disruption for many materials. Price volatility is also another important challenge. Because many critical raw material markets are relatively small and have limited liquidity, even modest changes in supply or demand can cause sharp price swings. This creates uncertainty for manufacturers, raises costs, and delays investment decisions, which can ultimately affect the wider clean energy value chains.

Diversification is therefore a central part of energy security. Yet supply chains, especially extraction, refining, and processing, are becoming increasingly concentrated in a small number of countries. This is particularly visible in the refining capacity: China is the dominant refiner for 19 out of 20 energy-related critical raw materials, with an average market share of around 70%.¹² This concentration is further aggravated by the growing use of export controls and trade restrictions. As of November 2025, more than half of energy-related strategic minerals were subject to some form of export restriction, increasing vulnerability for import-dependent regions.¹³

At the same time, critical raw materials pose an important opportunity for economic growth beyond Europe. For many resource-rich countries in Africa, Asia, and Latin America, rising demand for the materials needed in the energy transition is an opportunity to develop a stronger economy and improve its social wellbeing.

⁹SFA Oxford. *Critical Minerals In Artificial Intelligence*. <https://www.sfa-oxford.com/knowledge-and-insights/critical-minerals-in-low-carbon-and-future-technologies/critical-minerals-in-artificial-intelligence/>.

¹⁰International Energy Agency. *World Energy Outlook 2025*. <https://www.iea.org/reports/world-energy-outlook-2025>.

¹¹International Energy Agency. *Electricity 2026*. <https://www.iea.org/reports/electricity-2026>.

¹²International Energy Agency. *Global Critical Minerals Outlook 2025*. <https://www.iea.org/reports/global-critical-minerals-outlook-2025>.

¹³International Energy Agency, *World Energy Outlook 2025*, see n. 10.

Africa alone is home to around 30% of global mineral reserves relevant to the energy transition, presenting an opportunity to support economic growth, job creation, and industrial development.^{14 15} However, these opportunities will not automatically lead to sustainable development. Historical experience shows that mineral extraction has often generated limited local value, while contributing to environmental degradation, weak labour standards, land appropriation, and other social impacts. These risks are particularly salient given that an estimated 54% of energy-transition minerals are located on or near Indigenous peoples' lands.¹⁶

Attracting investment into critical raw material supply also remains difficult. New extraction and processing projects often face long lead times, high capital costs, environmental and social concerns, and regulatory uncertainty.¹⁷ Without deliberate policy action and investment facilitation, the expansion of critical raw material supply risks reproducing extractive models that fail to deliver inclusive and sustainable outcomes.

These challenges are especially relevant in the European Union. The EU faces high import dependence, limited domestic production capacity, long permitting timelines for new mining and processing projects, and strict sustainability and environmental requirements.¹⁸ At the same time, demand for critical raw materials is expected to rise sharply as the EU pursues decarbonization, industrial competitiveness, and strategic autonomy objectives. Balancing supply security, sustainability standards, and economic viability is therefore one of the central policy dilemmas of the energy transition.

1.5 Critical raw materials in the EU's agenda

The EU's transition towards a climate-neutral economy is supported by several interlinked policy frameworks. Together, these policies aim to decarbonize the energy system, strengthen industrial competitiveness, and reduce strategic dependencies. Central among these is the European Green Deal, launched in 2019, which sets the objective of making the EU climate-neutral by 2050.¹⁹ However, the Green Deal is not only a climate policy. It is also an economic transformation agenda that aligns emissions reduction with industrial policy, innovation, and the resilience of supply chains needed for clean technologies.

The Fit for 55 package turns this climate ambition into more concrete legislative measures and sets a legally binding target to reduce EU greenhouse gas emissions by at least 55% by 2030 compared with 1990 levels. To reach this target, the package revises key instruments such as the EU Emissions Trading System, renewable energy targets, and energy efficiency directives. These measures significantly increase the deployment of clean energy technologies, including wind turbines, solar photovoltaics, batteries, electrolyzers, and electric vehicles. As a result, Fit for 55 also increases the EU's need for a stable and secure supply of critical raw materials.

The REPowerEU plan, introduced in response to the energy crisis following Russia's invasion of Ukraine, further accelerates this trend. REPowerEU aims to rapidly reduce the EU's dependence on Russian fossil fuels by diversifying energy supplies, scaling up renewables, improving energy efficiency, and accelerating electrification. While primarily framed as an energy security initiative, REPowerEU also has important

¹⁴International Energy Agency, *Global Critical Minerals Outlook 2025*, see n. 12.

¹⁵Policy Center for the New South. *Africa's Minerals Will Shape the Future of Global Power*. <https://www.policycenter.ma/publications/african-minerals-will-shape-future-global-power>.

¹⁶Business & Human Rights Resource Centre. *2025 Transition Minerals Tracker*. https://media.business-humanrights.org/media/documents/2025_Transition_Minerals_Tracker_EN.pdf.

¹⁷International Energy Agency, *Global Critical Minerals Outlook 2025*, see n. 12.

¹⁸International Energy Agency, *Global Critical Minerals Outlook 2025*, see n. 12.

¹⁹Council of the European Union. *European Green Deal*. <https://www.consilium.europa.eu/fr/policies/european-green-deal/>.

implications for raw material demand, as the rapid deployment of renewable and storage technologies is inherently material-intensive.

Taken together, these policy agendas are increasing the EU's reliance on critical raw materials and making supply security a more urgent strategic issue. Against this backdrop, the Critical Raw Materials Act (CRMA) represents a pivotal shift in EU policy. Recognizing the EU's high import dependency the Act sets clear 2030 benchmarks: at least 10% of the annual EU critical raw material consumption should be extracted domestically, at least 40% processed within the EU, at least 25% supplied through recycling, and no more than 65% of any strategic raw material should come from a single third country. In this sense, the CRMA connects the EU's climate goals with industrial and security objectives and reflects the message that the energy transition will not succeed if it depends on fragile and overly concentrated supply chains.

1.6 From raw materials to geopolitical control

In critical raw material supply chains, geopolitical power is shaped less by access to geological resources than by control over processing, refining, and downstream manufacturing. These processes are technologically and chemically complex, capital-intensive, environmentally sensitive, and difficult to scale. As a result, countries that control processing capacity and technical know-how can influence supply security, pricing, and geopolitical leverage. New mining projects alone are therefore not enough to shift strategic dependence; they must be combined with investment in processing infrastructure, industrial capacity, and skilled labour.²⁰

This is an increasingly pressing challenge. Europe's shift towards a more renewable energy system depends heavily on critical raw materials, as has been mentioned throughout this section. This matters because energy infrastructure is one of the main foundations of modern economies. Oil and gas pipelines, electricity transmission grids, storage facilities, and increasingly digitalized energy systems all constitute a core pillar of political economy and national development. Investments in energy systems are closely linked to long-term economic growth strategies, as energy infrastructure not only enables production and consumption but also shapes social and political outcomes through policy choices and power relations.²¹

Reliable and affordable energy also supports industrialization, public services such as healthcare, education, and digital connectivity, and employment. On the other hand, weak or incomplete infrastructure can deepen inequalities with peripheral areas and limit economic opportunities.²²

As energy systems become more electrified, digitalized and decentralized, the link between critical raw materials and infrastructure becomes even stronger. Smart grids, batteries, renewable generation, electric vehicles, and efficiency improvements are transforming energy infrastructure worldwide, and all depend on secure access to specific materials and on the industrial capacity to process and manufacture usable components out of them.²³

²⁰Rare Earth Exchanges. *Heavy Rare Earths At The Center Of The Modern Economy Why Processing Not Mining Defines Global Power*. <https://rareearthexchanges.com/news/heavy-rare-earths-at-the-center-of-the-modern-economy-why-processing-not-mining-defines-global-power/>.

²¹Gavin Bridge, Begüm Özkaynak, and Ethemcan Turhan. *Energy infrastructure and the fate of the nation: Introduction to special issue*. In: *Energy Research & Social Science* 41 (2018), pp. 1–11.

²²World Economic Forum. *Fit For Future Building Energy Infrastructure Ahead To Drive The Energy Transition*. <https://www.weforum.org/stories/2024/12/fit-for-future-building-energy-infrastructure-ahead-to-drive-the-energy-transition/>.

²³International Energy Forum. *Infrastructure*. <https://www.ief.org/programs/infrastructure>.

2. THE ROLE OF CRITICAL RAW MATERIALS IN THE ENERGY TRANSITION

2.1 Why the energy transition increases material demand

The energy sector is a major driver of global demand for critical raw materials because the technologies needed for the energy transition are material-intensive. Renewable energy systems, batteries, electricity grids, electric vehicles, and electrolyzers for hydrogen all rely on specialized materials in significant quantities.²⁴ As decarbonization accelerates, demand for these materials is expected to rise sharply, making the energy sector central to future critical raw material supply planning.

The shift from a fossil-fuel-based system to a more renewable and electrified one changes the type of resources needed to produce energy, and therefore changes energy security priorities. Fossil fuel systems require a continuous flow of coal, oil, or natural gas. Clean technologies, on the contrary, require large amounts of materials to manufacture the systems that generate, store, and transmit energy. For example, electric vehicles use about six times more minerals than a conventional car, while wind and solar installations require larger quantities of copper and other critical raw materials per unit of capacity than conventional systems.^{25 26} The result is a different form of resource dependence. The energy transition does not eliminate resource dependence; instead, it shifts it from continuous fuel supply to materials needed to build and maintain infrastructure. Unlike fossil fuel, which can be extracted and consumed continuously, critical raw materials must be mined, processed, and embedded in infrastructure before they can serve the energy system.

This does not mean that the energy transition is less sustainable than the fossil fuel system it tries to replace. Fossil fuels still involve very large volumes of resource extraction, combustion, and greenhouse gas emissions. However, it does mean that the energy transition comes with its own challenges. Decarbonization cannot be achieved by simply deploying renewables at scale without considering the material burden behind them. Mining and refining critical raw materials also require significant energy, creating a two-way relationship: clean energy technologies require critical raw materials, but extracting and refining those materials also requires energy. This relationship must be considered in sustainability and circular economy strategies.²⁷

For this reason, understanding which technologies drive demand, how demand is predicted to evolve, and where substitution is possible is essential for assessing the resilience of the energy transition in Europe.

²⁴European Court of Auditors. *Critical Raw Materials for the Energy Transition: Not a Rock-Solid Policy*. 04/2026. 2026. https://www.eca.europa.eu/ECAPublications/SR-2026-04/SR-2026-04_EN.pdf.

²⁵IRTC. *Critical Raw Materials and the Energy Transition*. 2022.

²⁶UNECE. *Aligning Critical Raw Materials Development with Sustainable Development*. 2023. <https://unece.org/sustainable-energy/publications/un-energy-policy-brief-aligning-critical-raw-materials-development>.

²⁷IRTC, see n. 25.

2.2 Material requirements of key energy transition technologies

To understand why the energy transition increases demand for critical raw materials, it is useful to look at the technologies that drive this demand. Solar photovoltaics, wind turbines, batteries, hydrogen technologies, and power grids all require specific materials, but the quantity and type of materials they use differ.

2.2.1 Solar photovoltaic (PV)

Solar PV technology is one of the central technologies of the energy transition. Modern silicon-based solar panels, considered the industry standard, require approximately 3,000 to 5,000 kilograms of high-purity silicon per megawatt (MW), a material with an energy-intensive and geographically concentrated production. Beyond silicon, silver is used as a conductive component, with a material intensity of roughly 20 kg/MW. Although silver represents only a small fraction of the panel's mass, it accounts for a significant portion of its cost and supply risk. Other essential elements include boron, used in silicon doping. It is also geographically concentrated; the EU currently sources 99% of it from Turkey.

The recycling potential for PV is high for bulk materials such as glass and aluminium, with technical recovery rates exceeding 90%. However, recovering critical raw materials such as silicon and silver is more complex, and current commercial recycling processes achieve lower recovery rates of 70% to 80%. Improving these processes will be important for reducing the primary extraction needs and limiting dependence on imported high-purity materials.

2.2.2 Wind energy

Wind energy, particularly offshore wind, requires vast quantities of specialized materials to achieve high efficiency and operate in demanding environments. A standard 3 MW wind turbine uses approximately 4.7 tons of copper, mainly in the generator and cabling, while larger offshore turbines can see copper intensity rise to nearly 10 t/MW due to subsea wiring. The most strategically sensitive materials are rare earth elements such as neodymium, dysprosium, and praseodymium, which are used in the permanent magnets of direct-drive generators.

These magnets are important because they allow turbines to operate efficiently with compact generator designs. However, rare earth supply chains are among the most vulnerable, especially at the refining stage, which makes the wind sector especially vulnerable to supply disruptions. While the recycling of bulk materials like steel and copper in wind turbines is well-established, with potential rates over 90%, recycling rare earths from permanent magnets remains very limited, with current global rates below 1%. Scaling up specialized rare earth recycling facilities will therefore be crucial as the first generation of modern wind turbines reaches the end of its operational life.

2.2.3 Battery energy storage systems (BESS)

Battery energy storage systems are essential for grids with high shares of variable renewable energy. They are also central to electric vehicles and stationary storage. They are, however, the most mineral-intensive technology in terms of critical raw materials per unit of capacity. Lithium-ion batteries rely on several critical raw materials. In a standard nickel-manganese-cobalt battery, lithium, nickel, and cobalt are required in significant quantities, while graphite is also used in the battery anode.

The supply of these materials is exposed to significant risks. For instance, the Democratic Republic of Congo provides about three quarters of global cobalt, while China dominates natural graphite processing. On the positive side, batteries offer a strong recycling potential. Modern hydrometallurgical recycling

allows for high mineral recovery at battery-grade purity. As the first generation of electric vehicle batteries reaches end-of-life in the late 2020s, this could become an important secondary source of supply for the EU.²⁸

2.2.4 Hydrogen technologies

Hydrogen technologies, especially electrolyzers and fuel cells, are important for decarbonizing sectors where electrification is difficult, such as heavy industry and long-distance transport. However, some of these technologies depend on some of the rarest minerals on Earth. Proton exchange membrane electrolyzers, for example, use materials such as iridium and platinum. These metals are part of the platinum group metals, and their global supply is limited and geographically very concentrated, with South Africa and Russia being the primary sources.

Alkaline electrolyzers, a more mature alternative, avoid platinum group metals but require significant amounts of nickel and other materials like zirconium. This means that the technological choices in hydrogen deployment just shift the material demand from one group to another, rather than removing critical raw material dependence entirely. The recycling of platinum group metals is relatively mature, with recovery efficiencies from existing industrial catalysts already exceeding 95%. Nevertheless, dedicated recycling systems for electrolyzers will be needed to ensure that hydrogen deployment is not constrained by material availability.²⁹

2.2.5 Power grids

Power grids are the backbone of the energy transition. Expanding renewable generation, connecting remote production sites, and supporting electrification all require major investments in transmission and distribution infrastructure. This makes electricity grids highly intensive in copper and aluminium. Copper is used because of its high conductivity, particularly in underground and subsea cables. On the other hand, aluminium is increasingly used as an alternative in overhead lines because it is lighter and more abundant.

The global demand for grid-related copper is projected to double by 2040, yet primary production is struggling to keep pace. The recycling potential for the power grid is very high, as cables are large, homogenous, and easily collected during upgrades or decommissioning. Recycling rates for copper in the electricity sector already exceed 70% in some regions, and the technical potential for a closed-loop system is nearly 95%, making the grid a prime candidate for circular economy initiatives that reduce the need for primary extraction.³⁰

Compared with these clean energy technologies, traditional fossil fuel infrastructure uses relatively few of the critical raw materials discussed in this section. Offshore wind, onshore wind, and solar PV, for example, require roughly twelve, eight, and six times more minerals per MW of installed capacity than natural gas plants, and around six, four, and three times more than coal plants respectively.³¹ Rare earth elements, for example, are virtually absent from fossil fuel infrastructure, while they are essential for permanent magnets in wind turbines and electric motors. This creates entirely new supply dependencies for the energy system.

²⁸European Union. *European Critical Raw Materials Act*. 2024. https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials/critical-raw-materials-act_en.

²⁹Conrad Nichols. *Critical Material Recovery 2026-2046: Technologies, Markets, Players*. IDTechEx, 2025. <https://www.idtechex.com/en/research-report/critical-material-recovery/1124>.

³⁰International Energy Agency. *The Role of Critical Minerals in Clean Energy Transitions*. International Energy Agency, 2021. <https://www.iaea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions>.

³¹International Energy Agency, *The Role of Critical Minerals in Clean Energy Transitions*, see n. 30.

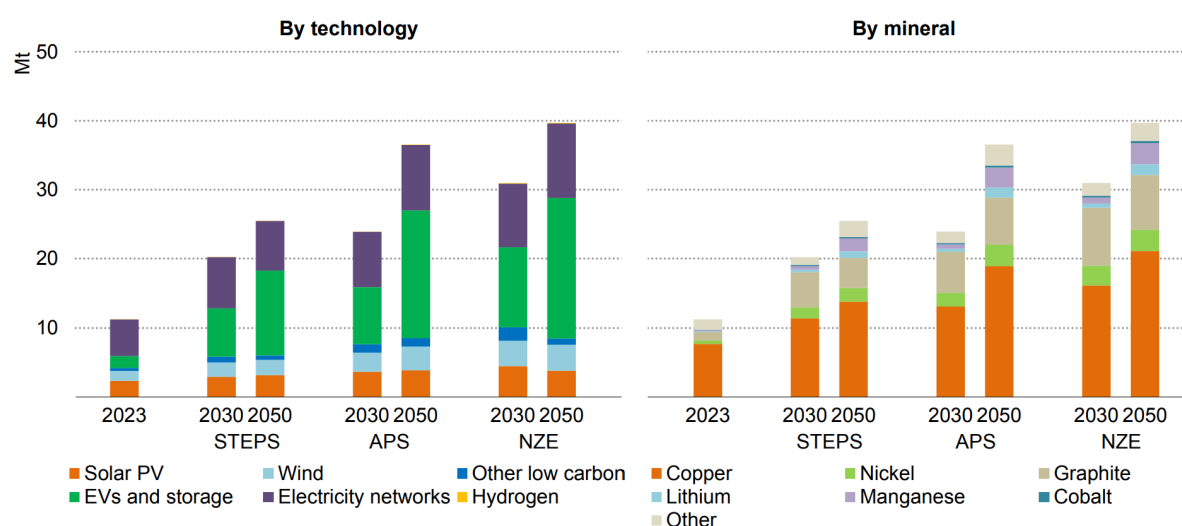
Table 2: Main critical raw materials used in key energy transition technologies

Technology	Main critical raw materials	Main use
<i>Solar PV</i>	Silicon, silver, boron, gallium, germanium	Solar cells, contacts, doping, electronics
<i>Wind energy</i>	Copper, neodymium, dysprosium, praseodymium	Cabling, generators, permanent magnets
<i>BESS</i>	Lithium, nickel, cobalt, manganese, graphite	Cathodes and anodes
<i>Hydrogen technologies</i>	Iridium, platinum, nickel, zirconium	Electrolysers and fuel cells
<i>Power grids</i>	Copper, aluminium	Transmission and distribution cables

However, this comparison requires balance. Although renewable technologies require significantly higher concentrations of specific critical raw materials like copper, lithium, or rare earths per unit of energy, the total physical mass of material extracted for fossil fuels remains vastly larger. According to the IEA's World Energy Outlook 2025, the global energy system extracted approximately 115 billion tonnes of raw materials in 2024, with coal production alone accounting for over half.³² The difference thus is not simply “more materials” and “fewer materials”, but different types of material dependence.

2.3 Projected demand for critical raw materials

The International Energy Agency (IEA) projects a strong increase in mineral demand for clean energy technologies between 2023 and 2050 under all major policy scenarios. These include the Stated Policies Scenario (STEPS), the Announced Pledges Scenario (APS), and the Net Zero Emissions by 2050 Scenario (NZE). Although the scale of demand growth changes across scenarios, the overall direction is clear: the world is heading towards a profound and sustained increase in the consumption of critical raw materials.³³



IEA. CC BY 4.0.

Figure 1: Mineral requirements for clean energy technologies by scenario. Source: Adapted from IEA (2025), Global Critical Minerals Outlook 2024, p. 92, CC BY 4.0

³²International Energy Agency, *World Energy Outlook 2025*, see n. 10.

³³International Energy Agency. *Global Critical Minerals Outlook 2024*. <https://www.iea.org/reports/global-critical-minerals-outlook-2024>.

In 2023, total mineral demand for clean energy technologies stood at roughly 10 million tonnes. Under the most conservative scenario (STEPS), this figure doubles by 2030, while under the most ambitious pathway (NZE), demand grows by almost three times within the same timeframe and reaches nearly 40 million tonnes by 2050. This increase is driven by the rapid expansion of solar photovoltaics and electricity networks, together with the growth of electric vehicles and battery storage. Hydrogen, while still a smaller contributor in absolute terms, is also expected to grow in material intensity as the technology scales.³⁴

Looking at demand by material, copper stands out as the single largest material by volume throughout the entire period, with demand expected to nearly double by 2040. This reflects its central role in electrical conductivity across clean energy technologies, from grid infrastructure to electric vehicles and wind turbines. Lithium, although smaller in absolute volume today, is projected to increase nearly ninefold by 2040, driven almost entirely by the rise in electric vehicle battery production, placing enormous pressure on a supply chain that is still developing. Graphite and nickel are also expected to follow steep growth trajectories, with graphite demand expected to nearly quadruple and nickel demand to double by 2040. Manganese and cobalt follow similar patterns, with their demand curves closely tracking the pace of EV adoption and energy storage deployment.³⁵

This demand growth is explained by two related factors. First, the large-scale deployment of energy transition technologies; and second, the material intensity of those technologies. As mentioned throughout this chapter, renewable technologies require substantial quantities of critical raw materials. However, it is important to consider how the material intensity of energy technologies is measured.

The standard metric used by institutions such as the IEA is kilograms of mineral per MW of installed capacity (kg/MW). This metric is useful for comparing the material requirements of building different technologies, but it does not measure the material required per unit of electricity actually generated. It is therefore important to distinguish between demand projections and technology comparisons. Demand projections usually account for the capacity that needs to be installed to meet future electricity needs and consider the lower capacity factors of wind and solar. However, when the material intensity of technologies is compared only in kilograms per MW of installed capacity, the comparison can be misleading.

This distinction matters because wind and solar technologies generally have lower capacity factors than conventional power plants, meaning that they generate less electricity per unit of installed capacity over a given period. Gas plants, for example, can operate continuously at high output, but wind and solar are intermittent and weather-dependent. Therefore, while demand projections already account for the capacity needed to meet future energy needs, comparisons of material intensity should be read carefully.

These material demand projections should also be considered in the context of rising electricity demand. As electrification expands across transport, heating, and industry, the amount of clean energy capacity that needs to be built will continue to grow. However, electrification is easier in some sectors than others, which raises the question: can clean technologies fully replace fossil fuels across all sectors of the economy?

³⁴International Energy Agency, *Global Critical Minerals Outlook 2024*, see n. 33.

³⁵International Energy Agency, *Global Critical Minerals Outlook 2024*, see n. 33.

2.4 Can clean technologies replace fossil fuels across sectors?

The energy transition is fundamentally a story of substitution: replacing carbon-intensive fuels and technologies with cleaner alternatives. However, this substitution does not happen in the same way across all sectors. Some parts of the economy can be electrified relatively easily, while others still depend on liquid fuels, high-temperature heat or industrial processes that are difficult to replace. This creates an uneven demand profile for critical raw materials.³⁶

Power generation

Power generation is the sector where the substitution of fossil fuels is more advanced. According to the International Energy Agency's *Renewables 2025* report, renewable sources generated approximately 9,900 TWh in 2024, representing roughly 38% of global electricity output.³⁷

This shift is primarily driven by solar photovoltaics, with 4,600 GW of new renewable capacity projected for 2025–2030, which is equivalent to the combined installed power capacity of China, the European Union, and Japan.³⁸ In this sector, therefore, the substitution of fossil fuels is well underway, with renewables meeting more than 90% of the increase in global electricity demand by 2025.³⁹

However, power generation is only one part of the energy system. In fact, electricity accounted for only 20% of global final energy consumption in 2023,⁴⁰ meaning that most final energy demand still came from direct fuel in other sectors such as transport and industry, among others. This is why the substitution of fossil fuels in electricity generation is not enough on its own.

Transport

Transport presents a more complex picture. Renewable electricity accounted for only about 12% of total transport energy in 2024, projected to reach approximately 15% by 2025.⁴¹ The IEA forecasts a 50% increase in overall renewable energy use in transport by 2030, but this relies heavily on liquid biofuels, which contribute 35% of renewable transport energy.⁴²

Road transportation is the fastest area of electrification, mainly through electric vehicles. However, other parts of the transport sector such as aviation, shipping, and heavy freight remain much harder to electrify.⁴³ As a result, the material demand profile of transport is more diverse than in power generation, as it includes not only battery materials such as lithium, nickel, cobalt, manganese, and graphite but also feedstocks for biofuels and, increasingly, green hydrogen.⁴⁴

Industry

Industry represents the most challenging sector to decarbonize. While electricity can substitute fossil fuels for process motors and low-temperature heating, high-temperature industrial processes in sectors such as

³⁶International Energy Agency. *Renewables 2025*. Paris: International Energy Agency, 2025. <https://www.iea.org/reports/renewables-2025>.

³⁷International Energy Agency, *Renewables 2025*, see n. 36.

³⁸International Energy Agency, *Renewables 2025*, see n. 36.

³⁹International Energy Agency. *Global Energy Review 2025*. Paris: International Energy Agency, 2025. <https://www.iea.org/reports/global-energy-review-2025>.

⁴⁰International Energy Agency. *Energy Mix*. <https://www.iea.org/world/energy-mix>.

⁴¹International Energy Agency, *Renewables 2025*, see n. 36.

⁴²International Energy Agency, *Renewables 2025*, see n. 36.

⁴³International Energy Agency. *Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach*. Paris: International Energy Agency, 2024. <https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-c-goal-in-reach>.

⁴⁴Energy Transitions Commission. *Material and Resource Requirements for the Energy Transition*. Energy Transitions Commission, 2023. <https://www.energy-transitions.org/publications/material-and-resource-requirements-for-the-energy-transition/>.

steel, cement, and chemicals are harder to substitute. These applications require either direct electrification at scale, green hydrogen, or new production processes.⁴⁵

Each of these pathways is material-intensive. Electrification at scale requires expanded electricity infrastructure and large quantities of copper and other conductive materials. Hydrogen production depends on electrolyzers, renewable electricity, and in many cases platinum-group metals and other critical raw materials.⁴⁶ This means that industrial decarbonization may mean increasing even more the demand for critical raw materials.

Overall, although clean technologies have the potential to fully substitute fossil fuels in power generation within the next decade, transport and industry require a more mixed portfolio of solutions. The question is therefore not only whether fossil fuels can be replaced, but which technologies will replace them and what material dependencies they will create.

2.5 Reducing material dependence in key energy transition technologies

Because supply disruptions can have such significant economic, strategic, and structural consequences, improving the resilience of critical raw material supply chains is essential. In addition to strengthening diplomatic relations with suppliers and expanding extraction and processing capacity within the EU, another important strategy is material and technological substitution, which aims to reduce reliance on scarce or highly concentrated critical raw materials.

Substitutability refers to the ability to achieve the same technological function through alternative materials or technological designs. This can occur through two main pathways:

- **Material substitution:** replacing a specific material within the same technology
- **Technological substitution:** replacing the technology itself with an alternative design that requires different materials

The degree of substitutability varies significantly across different clean energy technologies, depending on their material requirements and technological design. This section focuses on the most critical materials used in the key technologies of the energy transition. The technologies considered are solar photovoltaics, wind power, batteries (EV and BESS), hydrogen technologies, and electricity grids.

2.5.1 Solar PV

Crystalline silicon solar cells dominate global PV deployment and rely on silicon metal as the primary material, alongside smaller quantities of other materials such as silver, gallium, and germanium used in electronics. Although silicon is the second most abundant element in the Earth's crust, the production of high-purity silicon required for solar applications depends on specialized refining processes and highly pure quartzite. As a result, supply chains are highly concentrated geographically, with China currently accounting for around 70-80% of global silicon metal production and 95% of high-purity silicon manufacturing capacity.⁴⁷

⁴⁵Energy Transitions Commission, see n. 44.

⁴⁶International Energy Agency, *Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach*, see n. 43.

⁴⁷International Energy Agency, *Global Critical Minerals Outlook 2025*, see n. 12.

Substitution within silicon-based PV technology is limited, as silicon itself cannot be replaced by another material performing the same function. Rather, substitution occurs at the technological level. Thin-film technologies such as cadmium telluride (CdTe) and copper indium gallium selenide (CIGS) rely on different materials and currently represent a small share of the market, though remain less widely used due to lower efficiency. Emerging technologies like perovskites offer high efficiency but are easily degradable and are still to be deployed outside a laboratory.

With crystalline silicon technologies accounting for 95% of global PV module production,⁴⁸ the solar sector remains largely dependent on stable supply chains for high-purity silicon.

2.5.2 Wind energy

Wind turbines rely on several critical raw materials categorized by the EU as having high or very high supply risk (European Commission, 2020), particularly rare earth elements such as neodymium, dysprosium, and praseodymium used in permanent magnet generators. Other high-risk materials, such as niobium and borates, are used in structural components and composite materials such as the fibreglass in turbine blades.

According to SCRREEN, an EU-funded project focused on critical raw materials substitution pathways, material substitution for these magnetic rare earth elements is limited.⁴⁹ The main proposed approach involves replacing them with other rare earth elements, such as cerium (Ce), gadolinium (Gd), terbium (Tb), and holmium (Ho). However, given that China dominates global rare earth supply chains, accounting for over 60% of global mining output and 91% of refining capacity, substituting rare earth elements with other rare earth elements does little to reduce the overall supply risk.⁵⁰

Alternative solutions therefore focus on either replacing rare earth magnets or modifying turbine generator designs. Ferrite-based permanent magnet generators, for example, have emerged in recent years. These generators use ferrite magnets based on more abundant materials like iron oxide, reducing dependence on rare-earth materials, although they are still in early deployment stages and require larger and heavier generators due to lower magnetic strength.⁵¹ Another option is the use of electrically excited generators, a design already implemented at commercial scale by manufacturers such as Enercon. These systems rely on copper-based electromagnets rather than rare earth permanent magnets, although they require larger and heavier generators and have higher maintenance requirements.⁵² A more experimental approach is the EcoSwing project, funded by the EU Horizon 2020 programme, which investigated superconducting generators capable of drastically reducing rare earth content in wind turbines by at least two orders of magnitude.⁵³ Although technically promising, they require complex infrastructure and cooling technologies, making them difficult to commercialize.

As a result, rare earth permanent magnet generators continue to dominate due to their high efficiency and compact size, leaving the wind sector exposed to rare earth supply risks.

⁴⁸Kjeld van Wieringen and Julia Hüntemann. *Making Solar a Source of EU Energy Security*. European Parliamentary Research Service, European Parliament, 2022. [https://www.europarl.europa.eu/RegData/etudes/ATAG/2022/733587/EPRS_ATA\(2022\)733587_EN.pdf](https://www.europarl.europa.eu/RegData/etudes/ATAG/2022/733587/EPRS_ATA(2022)733587_EN.pdf).

⁴⁹SCRREEN. *Solutions for CRITICAL Raw materials – a European Expert Network*. <https://scrreen.eu/>.

⁵⁰International Energy Agency, *Global Critical Minerals Outlook 2025*, see n. 12.

⁵¹Vladimir Prakht et al. *Comparison between rare-earth and ferrite permanent magnet flux-switching generators for gearless wind turbines*. In: *Energy Reports* 6, Supplement 9 (2020), pp. 1365–1369.

⁵²Claudiu C. Pavel et al. *Substitution strategies for reducing the use of rare earths in wind turbines*. In: *Resources Policy* 52 (2017), pp. 349–357.

⁵³European Commission. *EcoSwing - Energy Cost Optimization using Superconducting Wind Generators - World's First Demonstration of a 3.6 MW Low-Cost Lightweight DD Superconducting Generator on a Wind Turbine*. 2022. <https://cordis.europa.eu/project/id/656024>.

2.5.3 BESS

Lithium-ion batteries (LIBs) dominate both electric vehicles and stationary battery energy storage systems applications, and rely on a number of critical raw materials, most notably lithium, nickel, cobalt, manganese, and natural graphite. Material substitution has already occurred through the development of different cathode chemistries. The global EV battery market is currently split between lithium iron phosphate (LFP) and lithium nickel manganese cobalt oxide (NMC) batteries, each accounting for half of the total demand. In BESS, however, LFP batteries dominate due to their lower cost, longer cycle life, and improved safety.

NMC batteries rely on nickel and cobalt to achieve high energy density, whereas LFP batteries replace these materials with iron and phosphorus. This already significantly reduces the exposure to critical raw material supply risks, while still maintaining the same lithium-ion technology.

To reduce dependency on lithium, several technological alternatives are being explored and are on their way to commercialization. Sodium-ion batteries, for example, replace lithium with sodium, which can be extracted from seawater and common salt deposits. Chinese manufacturers currently lead the development of this technology, with companies such as CATL and Changan announcing the world's first mass-production passenger vehicles powered by sodium-ion cells and grid-storage projects planned through 2026. However, according to the IEA, China is projected to hold 95% of global sodium-ion production capacity by 2030, meaning that although they may reduce lithium dependence it is unlikely to significantly diversify supply chains.⁵⁴

For stationary storage applications, redox-flow batteries represent another alternative. These systems store energy in liquid electrolytes such as vanadium and iron rather than lithium, and are particularly suited for large-scale, long-duration energy storage. However, their commercial deployment remains limited due to high cost, manufacturing challenges at scale, and low energy density compared with LIBs.

2.5.4 Hydrogen technologies

Hydrogen technologies such as electrolyzers and fuel cells rely on several critical raw materials, although the specific mineral requirements depend on the type of technology used. Alkaline electrolyzers, the most mature and widely deployed technology, avoid the use of precious metals but require significant quantities of nickel as the electrode material, and also smaller amounts of zirconium and other metals. Proton exchange membrane (PEM) electrolyzers depend on platinum group metals (PGMs) such as platinum and iridium. In hydrogen fuel cells, PGMs are also used as catalysts that convert hydrogen into electricity.

Other less-mature alternatives like solid oxide electrolysis cells (SOECs) require nickel, zirconium, and rare earths like lanthanum and yttrium. So, while technological substitution exists across hydrogen technologies, each design introduces its own material dependencies, meaning that large-scale hydrogen deployment could still be significantly affected by critical raw material supply disruptions.

2.5.5 Power grids

The electricity grid is the backbone of power systems infrastructure and plays a critical role in integrating renewable energy technologies. As electrification expands and renewable generation increases, electricity grids must grow to accommodate this higher demand. According to the IEA, the projected expansion of transmission and distribution lines worldwide over the next decade is around 80% greater than the expansion observed in the previous ten years.⁵⁵

⁵⁴International Energy Agency, *Global Critical Minerals Outlook 2025*, see n. 12.

⁵⁵International Energy Agency. *World Energy Outlook 2020*. International Energy Agency, 2020. <https://www.iea.org/reports/world-energy-outlook-2020>.

This huge growth requires a large amount of critical raw materials, especially copper and aluminium, which are the two main materials used in wires and cables. Traditionally, copper has been preferred over aluminium due to its greater electrical and thermal conductivity. However, it is more than three times heavier than aluminium and more expensive. Since there is no widely available third conductor material that can replace either at scale, material substitution in electricity networks mainly occurs between copper and aluminium. Candidates such as silver and gold are very good conductors but far too expensive, while steel is too resistive.

While aluminium is already widely used in overhead lines due to its lower weight, in recent years grid operators have increasingly explored its use in applications traditionally dominated by copper, such as underground and subsea cables. This approach reduces copper demand and raw material costs, although conductor sizes must be larger to compensate for aluminium's lower conductivity.

Technological substitution may also reduce mineral demand in the grid by adopting high-voltage direct current (HVDC) transmission systems more widely. These use two wires to transmit electricity, instead of the three wires required in conventional alternating current (AC) systems. HVDC systems are also capable of transporting more electricity, which would significantly reduce the material requirements for the projected grid expansion.

Overall, while substitution opportunities exist for some materials and technologies, many critical raw materials perform unique functions that are difficult to replicate without significant performance trade-offs. This highlights the importance of sustained investment in research and innovation within EU institutions and universities aimed at improving material efficiency, developing alternative technologies, and expanding substitution possibilities.

2.6 Supply bottlenecks and risks to the energy transition

Since substitution cannot remove material dependence entirely, supply bottlenecks remain a central risk for the energy transition. As explained throughout this chapter, clean energy technologies require significant quantities of critical raw materials, many of which are difficult to substitute without cost or performance trade-offs. In practical terms, this means that without the development of resilient and diversified critical raw material supply chains, the EU risks replacing its dependence on fossil-fuel-rich countries with a new dependence on mineral-rich countries. This would compromise the objective of strengthening energy security and independence, which has been the key driver behind the rapid expansion of the energy transition.

A resilient and diversified supply chain implies that none of its stages creates major bottlenecks that could lead to supply shortages. For critical raw materials, this includes extraction, processing and refining, manufacturing, and recycling. In such a system, disruptions affecting a single producer or exporter could be compensated by alternative suppliers. Disruptions can arise from a wide range of factors, including geopolitical tensions, trade restrictions, technical failures in mining or processing facilities, or extreme weather events.

However, this contrasts with the current global critical raw material market, where supply and processing are often highly concentrated geographically, as well as the manufacturing capacity for key technologies such as batteries and PV solar cells. According to the *Global Critical Minerals Outlook 2025*, for several battery metals and rare earths, supply from producers outside the leading country is expected to meet only around half of the remaining global demand by 2035, illustrating the fragility of current supply chains.⁵⁶

⁵⁶International Energy Agency, *Global Critical Minerals Outlook 2025*, see n. 12.

This concentration increases the risk of supply shortages and price volatility. Disruptions in mineral supply chains can therefore have wide-ranging economic consequences, affecting technology costs, industrial competitiveness, and inflation. In the energy sector in particular, such supply shocks could delay deployment, lead to major revenue and job losses across Europe, and ultimately slow progress towards binding decarbonization and energy transition targets.

The energy transition also changes the geography of energy security. Fossil fuel dependence historically centred on a limited group of *petrostates*, like Russia, Saudi Arabia, and the United States.⁵⁷ The mineral economy, however, presents a different concentration pattern. Countries such as the Democratic Republic of Congo, Australia, and Chile dominate the extraction of cobalt, lithium, and copper, while China holds a significant advantage in the processing of most energy-related critical raw materials.⁵⁸ Processing capacity is even more concentrated than mining, meaning that countries that control refining can hold a disproportionate leverage regardless of where ore is extracted.⁵⁹

The central risk is therefore that the energy transition reduces dependence on fossil fuels while creating new forms of supply chain insecurity. Understanding where this risk comes from requires a closer look at how global critical raw material supply chains are organized, from extraction and processing to manufacturing and recycling. This is the focus of the next chapter.

⁵⁷International Energy Agency, *The Role of Critical Minerals in Clean Energy Transitions*, see n. 30.

⁵⁸International Energy Agency, *The Role of Critical Minerals in Clean Energy Transitions*, see n. 30.

⁵⁹United States Geological Survey. *Mineral Commodity Summaries 2024*. United States Geological Survey, 2024. <https://pubs.usgs.gov/periodicals/mcs2024/mcs2024.pdf>.

3. GLOBAL SUPPLY CHAINS

3.1 Extraction

Extraction is the first stage of the critical raw material supply chain. It determines where minerals enter the value chain, but it does not by itself determine who captures most of its value or strategic leverage. To understand extraction, it is first necessary to distinguish between mineral resources and mineral reserves.

3.1.1 Resources and reserves

Although the terms "reserves" and "resources" are often used interchangeably when discussing minerals, they do not mean the same thing. Every reserve is a resource, but not every resource is a reserve.

A mineral resource becomes a reserve only when two main conditions are met. The first is geological certainty: there must be enough evidence to know that the deposit exists and to estimate its size and quality with reasonable confidence. The second is economic and technological feasibility: to qualify as a reserve, the material must be recoverable with existing technology and under viable economic conditions. If extraction would be subeconomic, meaning it would result in a net loss, or merely marginal, a mineral resource does not qualify as a reserve.

This distinction is therefore dynamic. If mineral prices rise, extraction technologies improve, or new infrastructure is developed, some resources can become reserves. Conversely, if prices fall, costs increase, or regulation becomes stricter, some reserves may no longer be economically recoverable and will return to being classified as resources.

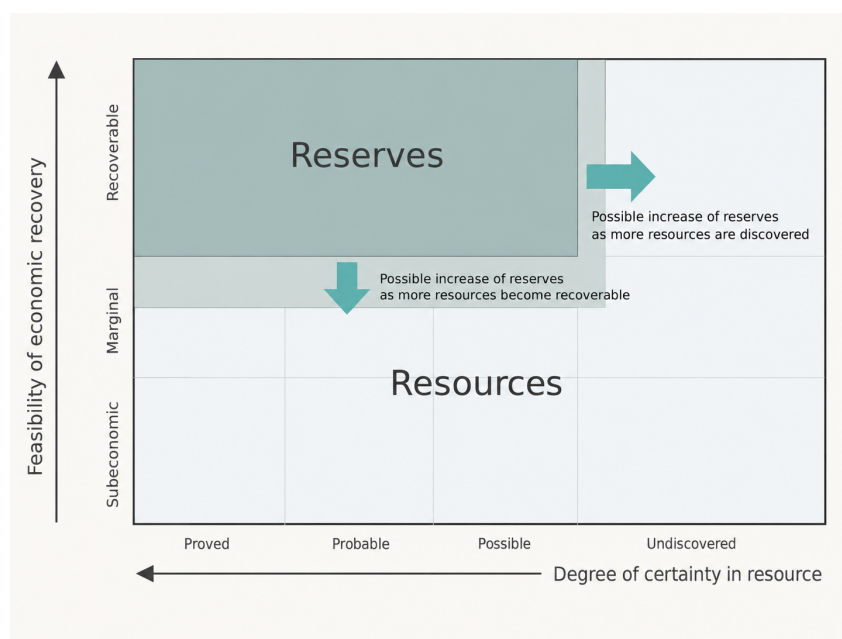


Figure 2: Difference between mineral resources and reserves. Diagram adapted from McKelvey box

The original version of this concept, developed by American geologist Vincent McKelvey, was often represented as a static classification box. In reality, however, the boundary between resources and reserves changes over time, as shown in Figure 2.

3.1.2 Global reserves and production

Mined production and reserves do not always follow the same geography. In this section, production refers to mined production: the amount of material extracted from the ground in a given year. Some countries hold large reserves but produce relatively little, while others are major producers despite holding a smaller share of known reserves. This distinction matters because supply risks depend not only on where the largest known deposits are located, but also on where extraction is currently taking place at scale.

Table 3: Material comparison of main producers and reserve holders

Material	Main producers	Main reserve holders	Key point
<i>Bauxite/aluminium</i>	Australia, Guinea, and China	Guinea, Australia, and Vietnam	China is the third largest producer despite limited reserves
<i>Cobalt</i>	DRC	DRC, Australia	DRC produces three-quarters of global supply and holds over half of reserves
<i>Copper</i>	Chile, DRC, and Peru	Chile, Peru, Australia, DRC, and Russia	Chile largest producer with one-quarter of global output
<i>Natural graphite</i>	China	China, Brazil, Mozambique, Madagascar, and Tanzania	China produces more than three-quarters of global supply while holding just one-quarter of reserves, same as Brazil
<i>Lithium</i>	Australia, Chile, and China	Chile, Australia, Argentina, and China	Production and reserves are geographically diversified
<i>Nickel</i>	Indonesia	Indonesia, Australia, and Brazil	Indonesia produces more than half global production and holds 40% of reserves
<i>Manganese</i>	South Africa	South Africa, Australia, China, and Brazil	South Africa holds one-third of global reserves and production
<i>Rare earths</i>	China	China, Brazil, India, Australia, and Russia	China dominates production, while other countries have underused reserves

Source: IEA, Global Critical Minerals Outlook 2025

Across most critical raw materials, a clear pattern emerges: mined production is often more geographically concentrated than reserves. The Democratic Republic of Congo dominates cobalt production, Indonesia is the leading producer of nickel and China dominates the production of natural graphite and rare earth elements. However, many countries holding significant mineral wealth in the ground currently produce much less, creating both opportunities and vulnerabilities in global clean energy supply chains.

In terms of reserve holdings, Australia stands out as one of the most diversified reserve countries in the world, appearing as a major holder across bauxite, cobalt, copper, lithium, nickel, manganese, and rare earths. Latin America, particularly Chile, Peru, Argentina, and Brazil, is central for lithium, copper, and natural graphite. Africa, through the DRC, Guinea, South Africa, Mozambique, and Tanzania, holds major

reserves in cobalt, bauxite, natural graphite, and manganese. China, despite dominating production across many minerals, often has a smaller reserve base than its extraction share suggests.

However, extraction is only the first stage of the supply chain. As it will be shown, the countries that mine critical raw materials are often not the same countries that refine, process, and manufacture them into clean energy technologies.

3.1.3 Europe extraction's history and constraints

Europe's mining sector has undergone a prolonged decline over recent decades. At the beginning of the twentieth century, the continent accounted for approximately 40% of global mining output; today, that figure has fallen to around 3%. This contraction reflects a combination of structural, regulatory, and economic factors, including the gradual outsourcing of extractive activities, stricter environmental standards, higher labour and energy costs, and stronger public opposition to mining projects.⁶⁰

It's important to acknowledge this decline, because the EU's energy transition depends on materials that are predominantly extracted outside Europe. As demand for critical raw materials increases, limited domestic extraction leaves the EU more exposed to external supply chains which it does not control. This energy dependency problem was brought into the spotlight by Russia's full-scale invasion of Ukraine in 2022, which prompted sweeping EU sanctions on Russian oil and gas and forced policymakers to confront the extent of Europe's energy reliance on Moscow. Determined to avoid replicating this dependency in the critical material space, the European Commission has since made reviving the domestic mining sector a strategic priority. This concern was reflected in European Commission President Ursula von der Leyen's 2022 State of the Union address, where she warned that lithium and rare earths would become increasingly important and that Europe should avoid repeating past patterns of dependence.⁶¹

However, expanding extraction within Europe remains difficult. Obtaining a mining permit in the EU can take well over a decade, reflecting administrative complexity, strict environmental and conservation legislation, and political caution. Local opposition to new or expanded mining projects adds further friction, especially when deposits are located near ecologically sensitive or protected areas. As a result, even when Europe has geological potential, turning that potential into actual mined production is slow, expensive, and socially contested.

3.1.4 ESG risks in extraction

The extraction of critical raw materials carries substantial environmental, social, and governance risks. These risks are not the same in every context. Large-scale, legally permitted mining projects can still generate serious environmental and social impacts, especially around land use, water consumption, waste management, and community consent. However, the most severe human rights abuses are often associated with informal or weakly regulated mining, particularly in conflict-affected regions or areas with limited state authority.

Environmental risks are among the most visible. More broadly, the extraction and processing of natural resources are linked to more than 90% of global biodiversity loss, highlighting the need for more sustainable resource management.⁶² In the case of mining, major operational challenges include residue management, water consumption, land disturbance, biodiversity preservation, and adaptation to climate change. Mining

⁶⁰Euronews. *Here's why Europe needs to revive its mining sector*. <https://www.euronews.com/business/2024/03/12/heres-why-europe-needs-to-revive-its-mining-sector>.

⁶¹Euronews, see n. 60.

⁶²Ellen MacArthur Foundation. *How the Circular Economy Supports Biodiversity*. <https://www.ellenmacarthurfoundation.org/topics/biodiversity/overview>.

operations also need decarbonization strategies, including the electrification of equipment and improvements in energy efficiency, if the sector is to align with broader climate commitments.

Social risks are equally important and can appear across both formal and informal mining contexts. Between 2010 and 2024, the Business and Human Rights Resource Centre recorded 178 allegations of abuse in Africa's critical raw material mining sector, accounting for more than 20% of global cases. In 2024 alone, 45 allegations were reported, up from 26 the previous year, with cobalt and copper mines in the DRC accounting for nearly half of these cases.⁶³ Reported abuses include violations of workers' rights, lack of community consent, environmental degradation, and attacks on human rights defenders. These allegations show that mining-related social vulnerabilities are not limited to illegal extraction; they can also occur where formal projects operate without sufficient oversight, community participation, or enforcement of labour and environmental protections.

Artisanal and small-scale mining can intensify these risks, especially where weak regulation, poverty, or conflict expose workers and local communities to unsafe conditions, child labour, pollution, displacement, and violence. Indigenous and marginalized communities can be disproportionately affected, facing water pollution, deforestation, loss of livelihoods, and violations of their fundamental rights.⁶⁴ To mitigate these risks, ESG standards and traceability mechanisms are essential. However, they should be designed to improve conditions in those weakly regulated mining areas, rather than simply pushing companies to source only from lower-risk regions. Otherwise, the underlying social and governance problems remain unsolved, and vulnerable communities may lose access to important sources of income.

Governance risks can reinforce both environmental and social harms. Weak enforcement, unclear legal frameworks, corruption, and inconsistent regulatory systems can contribute to conflict and to the unequal distribution of resource revenues. In some countries, overlapping responsibilities between national and regional authorities create uncertainty for investors and complicate supervision of the mining sector. Additionally, these governance weaknesses can limit the ability of resource-rich countries to turn mineral wealth into social and economic development.⁶⁵

3.1.5 ESG standards and development priorities

ESG standards are intended to reduce the environmental, social, and governance harms historically associated with mining. They serve as criteria guiding companies towards more responsible business practices, and help investors, regulators, and consumers assess whether projects meet acceptable standards on issues such as environmental protection, labour rights, transparency, and community engagement. These standards can come from voluntary frameworks such as the OECD Guidelines for Multinational Enterprises, from mandatory regulations such as the EU's Corporate Sustainability Reporting Directive, or from stock exchange requirements.⁶⁶

However, ESG standards also create complex policy tensions. In the European context, high standards are often presented as a competitive advantage and as a way to build more responsible critical raw material supply chains. In practice, they can also raise costs and lengthen project timelines, making European

⁶³Business & Human Rights Resource Centre. *New Research Reveals Rising Human Rights Risks In Africa's Transition Minerals Sector*. <https://www.business-humanrights.org/en/from-us/press-releases/new-research-reveals-rising-human-rights-risks-in-africa's-transition-minerals-sector/>.

⁶⁴Human Rights Watch. *Mining for the Energy Transition Needs to Respect Human Rights*. <https://www.hrw.org/news/2024/07/10/mining-energy-transition-needs-respect-human-rights>.

⁶⁵International IDEA. *Mineral Resource Governance in Africa: A Comparative Study*. <https://www.idea.int/publications/catalogue/html/mineral-resource-governance-africa-comparative-study>.

⁶⁶European Council on Foreign Relations. *Too Clean To Compete Why Strict Standards Keep Europeans Out Of African Minerals*. <https://ecfr.eu/publication/too-clean-to-compete-why-strict-standards-keep-europeans-out-of-african-minerals/>.

companies more reluctant to finance or participate in mining activities at all. What was intended as a tool for responsible investment has risked becoming an obstacle to building diversified supply chains.

These tensions are particularly visible in relations between Europe and African resource-rich countries. Africa is the least economically diversified continent in the world, with most countries heavily reliant on primary commodity exports and acutely vulnerable to external trade shocks. African governments do not reject ESG standards; many have developed sustainability frameworks and green taxonomies at national or continental level. However, they must weigh ESG requirements together with urgent development priorities, including job creation, industrialization, infrastructure expansion, and poverty reduction.

Field research conducted in Namibia and Zambia suggests that African stakeholders often treat ESG as one consideration among many, rather than as the primary condition for building mining partnerships over other offers. In this context, China and Gulf countries have proven more adept at aligning their offers with local priorities, emphasizing infrastructure development and employment generation alongside mineral deals.⁶⁷

There is also a mismatch between European and African approaches to ESG standards. The EU often places strong emphasis on environmental measures and compliance, whereas African stakeholders prioritize social responsibility obligations such as employment, training, local infrastructure like schools and hospitals, and broader community development. There is also a persistent misunderstanding around the governance dimension of ESG. While ESG governance refers mainly to how a company is managed, including transparency, anti-corruption measures, reporting practices, and accountability, governance risk is sometimes interpreted as a judgment on the political or institutional quality of the host country. This can increase the perceived risk of investing in some African mining projects, even when individual projects may be able to meet high standards.

This does not mean that lowering standards is the solution. Chinese companies, for example, have often been criticized for weaker labour and environmental practices in African mining operations. According to the Business and Human Rights Resource Center, between 2021 and 2022 China was linked to 102 human rights and environmental law violations, with 20% originating from mines in the DRC and Zimbabwe alone.⁶⁸ The challenge for Europe thus is not to abandon ESG standards, but to make them more practical, partnership-based and respectful of African stakeholders' priorities. Responsible extraction must be combined with credible offers on infrastructure, employment, and local value creation.

The rush for critical raw materials in the Global South has raised concerns about a new form of extractivism.⁶⁹ Communities in countries like the DRC, Chile, and Peru may often bear the environmental and social costs of mining, while much of the economic value and clean energy benefits are captured elsewhere.⁷⁰ Some academic literature describes this dynamic as "green colonialism," referring to situations where the urgency of decarbonization justifies continued exploitation of resource-rich developing nations.⁷¹ Avoiding this pattern requires partnerships that do not treat producer countries only as sources of critical raw materials but as partners in development, know-how and long-term industrial value.

3.1.6 Reducing the environmental impact of extraction

Mining operations can generate significant environmental impacts across several stages of the extraction process, including waste generation, water consumption, land disturbance, air pollution, and greenhouse

⁶⁷European Council on Foreign Relations, *Too Clean To Compete Why Strict Standards Keep Europeans Out Of African Minerals*, see n. 66.

⁶⁸Stimson Center. *Competing For Africa's Resources How The Us And China Invest In Critical Minerals*. <https://www.stimson.org/2025/competing-for-africas-resources-how-the-us-and-china-invest-in-critical-minerals/>.

⁶⁹Stimson Center, see n. 68.

⁷⁰Stimson Center, see n. 68.

⁷¹Stimson Center, see n. 68.

gas emissions. These impacts do not only come from the extraction of ore itself, but also from the energy, chemicals, transport, and infrastructure required to move and process large volumes of material.

It is also important to avoid an outdated image of mining. Modern mineral extraction is very different from the traditional image of underground coal mines. Many critical raw materials are extracted through open-pit mining, brine operations, or other specialized techniques, and legally permitted projects are increasingly subject to environmental impact assessments, monitoring obligations, waste management requirements, and land rehabilitation plans. These measures do not remove the environmental impacts of mining, and understanding where these impacts originate is essential to identifying where technological intervention can make the greatest difference.

The exact extraction process depends on the mineral, the geology of the deposit and the mining method used. In conventional hard-rock mining, operations often involve blasting, drilling, loading, and hauling, generating emissions through the use of explosives, diesel-powered equipment, and electricity-intensive machinery. Further downstream, processes such as crushing, grinding, flotation, and magnetic separation require large amounts of electricity, which can generate additional emissions when powered by fossil fuel-based systems.⁷²

A range of technological improvements can reduce the environmental footprint of extraction though. The integration of renewable energy directly lowers emissions from electricity-intensive mining operations, while electrification of equipment can reduce diesel used in drilling, loading, and hauling. Digitalization, machine learning, and automation enable more precise drilling and optimized extraction routes, reducing unnecessary energy, fuel, and water consumption. Smart ventilation systems monitor underground air quality in real time, allowing ventilation to operate only when necessary and significantly lowering energy consumption.

Alternative extraction techniques, such as in-situ leaching, bioleaching, biomining, and phytomining, can extract materials directly from ore without large-scale excavation. Biomining utilizes naturally occurring microbes to extract metals such as copper from low-grade ore, reducing reliance on harsh chemicals, while phytomining employs plants capable of absorbing metals from the soil, which are then harvested and processed to recover the mineral content. Seawater and volcanic brine mining also explore water-based sources as alternative vectors for valuable mineral extraction.

Other improvements focus on reducing land and water impacts, such as closed-loop water systems and high-efficiency filtration technologies, which reduce dependence on freshwater resources, and land rehabilitation programmes, including reforestation, which help restore ecosystems after mining operations conclude.⁷³

Finally, some more speculative approaches such as deep-sea and space mining are sometimes presented as the future sources of supply. However, these remain highly controversial or technologically immature, with major unresolved questions around environmental impact, governance, and technological feasibility.⁷⁴

⁷²M. Onifade et al. *Advancing toward sustainability: The emergence of green mining technologies and practices*. In: *Green and Smart Mining Engineering* 1.2 (2024), pp. 157–174.

⁷³Onifade et al., see n. 72.

⁷⁴Onifade et al., see n. 72.

3.2 Refining and processing

3.2.1 Why refining and processing matter

Refining and processing are often the main bottlenecks in critical raw material supply chains. Extraction determines where minerals are taken from the ground, but refining and processing determine where those mineral ores are transformed into industrial inputs usable for batteries, magnets, solar technologies, electric vehicles, and other clean energy technologies.

Interestingly, countries with the highest rate of mineral extraction do not coincide with those dominating mineral processing activities. A significant share of extracted ores and concentrates is exported for processing abroad. Global trade data from 2023 illustrates this imbalance: Australia accounted for 33% of global exports of metal ores and concentrates by value, followed by Brazil (11%), Chile and Peru (9% each), and South Africa (5%). On the import side, China alone represented 64% of global imports, while Japan and the Republic of Korea also emerged as major processing hubs despite not being leading mining countries.⁷⁵ This shows that refining capacity depends less on geological reserves than on industrial infrastructure and technology.

The establishment of mineral-processing facilities is strongly connected to the broader strength of a country's industrial and manufacturing base. Refining and processing activities rely on advanced engineering capacity, specialized technologies, skilled labour, and large-scale infrastructure. Countries with developed manufacturing sectors are therefore generally better positioned to build and operate these facilities. A strong industrial ecosystem also supports more integrated resource utilization, including the recovery of byproducts during processing, while simultaneously satisfying domestic demand through downstream industries. This relationship is evident in countries such as China, Japan, and the Republic of Korea, where some of the world's largest refineries directly feed the demand for sectors such as automotive production, electronics, and rechargeable batteries.⁷⁶ As a result, processed mineral commodities can either be directly absorbed by domestic manufacturing industries or exported into international supply chains.

Overall, while mining is primarily constrained by geology, refining is constrained by economic and technological factors. This is why a country may hold large reserves or produce mined ore but still capture limited value if it lacks the capacity to process those materials domestically.

3.2.2 Geographic concentration in refining

Refining and processing is more geographically concentrated than extraction for many critical raw materials. Rare earth elements illustrate this very well. Magnet rare earths such as neodymium and praseodymium are essential for permanent magnets used in electric vehicles, wind turbines, and other advanced industrial applications. Their mined production is already highly concentrated, with China controlling about 61% of global output. However, refining is even more concentrated, with China accounting for around 91% of global refined production, and Malaysia far behind as the second-largest producer.⁷⁷

This pattern extends beyond rare earth elements. According to the Global Critical Minerals Outlook 2025,⁷⁸ China currently dominates the refining stage of nearly all major critical raw material supply chains, being the leading refiner for 19 out of 20 strategic minerals, with an average market share of 70%. And recent

⁷⁵United States Geological Survey. *Mineral Commodity Summaries 2025*. United States Geological Survey, 2025. <https://pubs.usgs.gov/publication/fs20253038>.

⁷⁶United States Geological Survey, *Mineral Commodity Summaries 2025*, see n. 75.

⁷⁷International Energy Agency. *With new export controls on critical minerals, supply concentration risks become reality*. <https://www.iea.org/commentaries/with-new-export-controls-on-critical-minerals-supply-concentration-risks-become-reality>.

⁷⁸International Energy Agency, *Global Critical Minerals Outlook 2025*, see n. 12.

capacity additions suggest that this pattern is being strengthened rather than reversed. In several supply chains, most new capacity has been added by the already dominant producer, such as Indonesia for nickel and China for cobalt, natural graphite, and rare earth elements.⁷⁹

Compared with other minerals, copper refining remains quite diversified geographically. China accounts for around 44% of global refined copper supply, while other major players collectively represent approximately 41%, indicating a broader distribution of refining capacity. Smaller but still relevant positions also exist in other supply chains: the United States holds a modest share in rare earth refining at 5%, while Finland and Canada each account for about 6% of cobalt refining capacity respectively.⁸⁰

By 2035, projections suggest only a slight reduction in concentration, with the top three suppliers still accounting for about 82% of refined output, essentially returning to 2020 levels.⁸¹ Such heavy dependence on a limited set of suppliers heightens exposure to disruptions, whether caused by extreme weather events, operational failures, or geopolitical and trade-related shocks.

3.2.3 Why refining remains difficult to diversify

Refining is difficult to diversify because it requires much more than just access to mined ore. New facilities need specialized engineering capacity, skilled labour, energy infrastructure, water access, chemical processing plants, waste treatment systems, and transport infrastructure. Refining and processing facilities are also easier to develop where there is strong downstream industrial demand, because processed materials can be directly used by sectors such as batteries, magnets, solar technologies, electronics, and automotive manufacturing.⁸²

Capital intensity is another major barrier. Developing new processing infrastructure requires high upfront investment in chemical processing plants, hydrometallurgical and pyrometallurgical systems, waste treatment systems, energy infrastructure, and logistics networks. These projects often have long development timelines, extended payback periods, and significant commercial risks. In addition, ore grades are declining. Lower ore quality means that more material must be processed to obtain the same amount of refined output, increasing energy use, water demand, by-product generation, and operating costs.⁸³

Environmental regulation also complicates refining expansion. Refining can carry significant pollution risks, including toxic by-products, water contamination, high energy use, and complex waste-management requirements. In regions with stricter environmental standards, like Europe, projects face higher compliance costs, more complex permitting procedures, and stronger local opposition. Europe's environmental ambitions therefore create tension with domestic critical raw material industrialization.

Permitting and regulatory complexity are additional bottlenecks, as refining projects typically require environmental impact assessments, industrial permits, chemical handling approvals, water-use authorizations, emissions compliance, and hazardous waste management approvals. These procedures are necessary to protect communities and ecosystems, but they can extend project timelines significantly. Without a clearer regulatory system, Europe may struggle to scale refining capacity at the pace required for the energy transition.

⁷⁹ International Energy Agency, *Global Critical Minerals Outlook 2025*, see n. 12.

⁸⁰ Cody Good. *China Still Dominates Critical Mineral Refining in 2030*. Dec. 2025. <https://elements.visualcapitalist.com/china-still-dominates-critical-mineral-refining-in-2030/>.

⁸¹ International Energy Agency, *Global Critical Minerals Outlook 2025*, see n. 12.

⁸² United States Geological Survey, *Mineral Commodity Summaries 2025*, see n. 75.

⁸³ E. Berthet, J. Lavalley, C. Anquetil-Deck, et al. *Assessing the Social and Environmental Impacts of Critical Mineral Supply Chains for the Energy Transition in Europe*. In: *Global Environmental Change* 86, 102841 (2024).

ESG scrutiny is particularly acute in refining because it concentrates emissions, chemical hazards, labour exposure, and waste streams. As a result, future refining projects may encounter stronger public resistance, stricter investor scrutiny, and higher compliance costs. The “social licence to operate” therefore applies not only to mines, but also to smelters, refineries, and chemical processing hubs.

Global collaboration remains essential for diversifying supply sources. Resource-rich countries can co-operate with countries that have refining capabilities and downstream manufacturing demand. Major opportunities exist for cross-border partnerships in highly concentrated supply chains. For example, African nations such as Madagascar, Mozambique, and Tanzania hold around a quarter of global natural graphite resources, while Germany, Japan, Korea, and the United States possess the capacity and plans to produce natural graphite anode materials. Similarly, significant rare earth resources exist in Australia, Brazil, Viet Nam, and other countries, while Europe, Malaysia, and the United States are investing in separation facilities. Permanent magnet manufacturing capacity is also being developed in Europe, Japan, Korea, and the United States.

Mapping opportunities across the entire supply chain, rather than focusing on a single stage of the value chain, can help create partnerships in diversifying supply sources.⁸⁴ Cooperation among supply chain participants, including appropriate cost-sharing and data-sharing practices, is essential and should be supported by strong data privacy and security protocols capable of protecting business confidentiality while enabling effective information exchange.

Finally, diversification also requires better transparency across critical raw material supply chains. Traceability can support diversification by making alternative supply chains more transparent and credible to regulators and investors. As the EU seeks to work with new suppliers and processing partners, traceability systems can help verify mineral origin, processing routes, and ESG performance. This tool is especially relevant in refining and processing, since in this stage materials are transformed, blended, and chemically processed, sometimes losing a clear link to their original source.

3.3 Manufacturing

Manufacturing represents the stage of the critical raw materials value chain where processed materials are turned into high-value components and technologies. While extraction secures access to geological resources and refining transforms raw ores into usable materials, manufacturing converts these processed inputs into batteries, magnets, solar panels, wind turbines, and electric vehicles, among other technologies. This stage captures the greatest economic value and depends on sophisticated engineering, significant capital investment, skilled labour, and deeply integrated supply chains.⁸⁵

For the European Union, manufacturing capacity in critical clean energy technologies has become a central concern for energy independence and strategic autonomy. The transition to a climate-neutral economy is not only a matter of deploying renewable technologies; it also requires the ability to produce these technologies domestically or through trusted partners. Without stronger manufacturing capabilities, the EU risks remaining dependent on external actors for the very infrastructure needed to achieve its decarbonization objectives.

⁸⁴International Energy Agency, *Global Critical Minerals Outlook 2025*, see n. 12.

⁸⁵International Energy Agency, *Global Critical Minerals Outlook 2025*, see n. 12.

3.3.1 Manufacturing as a strategic bottleneck

Manufacturing is a strategic bottleneck for three main reasons. First, it captures the highest value added along the supply chain, because processed materials are transformed into finished components. Second, manufacturing capabilities require accumulated technical expertise, specialized equipment, and integrated supplier networks that cannot be rapidly built. Third, manufacturing concentration creates geopolitical leverage: countries controlling production of batteries, solar panels, or wind turbines can influence global deployment rates, pricing, and technology standards.^{86 87}

This changes the nature of energy security. A country may have abundant wind resources or solar irradiation, but without the capacity to manufacture turbines, panels, inverters, and storage systems, it cannot deploy these resources at scale. This creates a new form of dependency: not on fuel imports, but on technology imports.⁸⁸

For the EU, this dependency is particularly important. While the Union has set ambitious climate targets, the manufacturing base required to achieve these goals remains heavily concentrated outside European territory. This creates vulnerabilities that could increase costs and delay deployment. Manufacturing efficiency also depends on reliable access to refined materials, which in turn depends on mining and processing capacity. Disruptions at any stage cascade through the system, affecting downstream production.⁸⁹

To better illustrate these manufacturing bottlenecks, the following sections examine some of the most relevant technologies in the energy transition: batteries, permanent magnets, solar photovoltaics, and wind turbine components.

3.3.2 Battery components and cell manufacturing

Battery manufacturing represents one of the most strategically significant segments of clean energy technology production. Lithium-ion batteries power electric vehicles, store renewable electricity, and help stabilize the grid. The manufacturing process involves several distinct stages, including cathode manufacturing, anode manufacturing, and cell assembly, each with different material requirements and technical complexities.

Cathode materials constitute the most valuable component of lithium-ion batteries, typically accounting for 30–40% of total cell cost.⁹⁰ Different cathode chemistries require different critical raw materials: nickel manganese cobalt (NMC) batteries rely on nickel, manganese, and cobalt, while lithium iron phosphate (LFP) batteries use iron and phosphorus instead. Global cathode production remains heavily concentrated in Asia, with China accounting for almost all global LFP cathode production capacity and around three quarters of NMC cathode production.⁹¹ European cathode production remains limited, with several announced projects still in development or early construction phases.⁹²

Anode production is another major bottleneck. Graphite is the primary anode material in lithium-ion batteries, and anode manufacturing involves purification, sizing, coating, and drying processes that require

⁸⁶Marta Rivera and Eduardo Zamanillo. *Mining Is Dead. Long Live Geopolitical Mining*. <https://geopoliticalmining.com/book/>.

⁸⁷World Economic Forum. *From Chips To Turbines Europe Depends On Critical Raw Materials*. <https://www.weforum.org/stories/climate-action/from-chips-to-turbines-europe-depends-on-critical-raw-materials/>.

⁸⁸International Energy Agency. *The Role of Critical Minerals in Clean Energy Transitions*. Paris: International Energy Agency, 2021. <https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions>.

⁸⁹European Court of Auditors, see n. 24.

⁹⁰European Commission, *Critical raw materials*, see n. 1.

⁹¹DataHorizon Research. *Lithium Ion Battery Cathode Materials Market 56377*. <https://datahorizonresearch.com/lithium-ion-battery-cathode-materials-market-56377>.

⁹²International Energy Agency. *Global EV Outlook 2025*. <https://www.iea.org/reports/global-ev-outlook-2025>.

specialized equipment and quality control. Like cathodes, anode production is heavily concentrated in China, which accounts for approximately 90% of global anode material production capacity.⁹³ This concentration is difficult to overcome because graphite processing is energy-intensive and environmentally demanding. Synthetic graphite production requires temperatures exceeding 2,500°C, necessitating access to cheap electricity and robust environmental management systems. Natural graphite purification similarly involves chemical processing that generates significant waste streams.⁹⁴ New producers face high energy costs, permitting delays, and competition from established Asian producers who benefit from economies of scale and integrated supply chains.⁹⁵

Battery cell assembly is the final stage before pack integration, and requires significant capital investment, with gigafactory-scale facilities costing billions of euros to construct and equip.⁹⁶ Global battery cell production is dominated by Asian manufacturers. In 2024, Chinese companies accounted for a large share of global battery cell manufacturing capacity, with Korean and Japanese firms holding most of the remainder.⁹⁷ European cell production has grown in recent years, but remains insufficient to meet projected demand under the EU's decarbonization scenarios.⁹⁸ Production costs in the EU and the United States are currently estimated to be 40 to 50% higher than in China, due to higher labour costs, more expensive energy, less mature supply chains, and the absence of economies of scale.⁹⁹ This makes batteries one of the clearest examples of how manufacturing capacity can be a strategic dependency.

3.3.3 Permanent magnets, solar PV, and wind turbine components

Permanent magnets, solar photovoltaics, and wind turbine components represent three important manufacturing areas for the energy transition, although their supply-chain vulnerabilities differ.

Rare earth permanent magnets, particularly those based on neodymium-iron-boron alloys, are essential components in electric vehicle motors, wind turbine generators, robotics, and industrial automation systems. These magnets provide superior power density and efficiency compared to alternative technologies, making them difficult to substitute in high-performance applications.¹⁰⁰

The production of rare earth permanent magnets involves several complex stages. Rare earth oxides must first be separated into individual elements, converted into metallic form, alloyed with other elements, and processed into magnet shapes through techniques such as sintering or bonding. Each stage requires specialized equipment, technical expertise, and strict quality control.¹⁰¹ These processes have been developed over decades in established manufacturing centres, creating knowledge barriers that are difficult for new entrants to overcome.¹⁰²

⁹³ International Energy Agency. *Global Supply Chains of EV Batteries*. <https://www.iea.org/reports/global-supply-chains-of-ev-batteries>.

⁹⁴ Discovery Alert. *Graphite Anode Production Importance 2025*. <https://discoveryalert.com/graphite-anode-production-importance-2025/>.

⁹⁵ *Graphite Purification Challenges: Technologies and Future Directions*. <https://bulletin.ceramics.org/article/graphite-purification-challenges-technologies-and-future-directions/>.

⁹⁶ Junhyeok Park et al. *Overview of graphite supply chain and its challenges*. In: *Geosciences Journal* 29 (2025), pp. 329–341.

⁹⁷ Mining See. *Europes Graphite Challenge Why Anode Material Production Could Become The Battery Industrys Biggest Bottleneck After Lithium*. <https://www.miningsee.eu/europes-graphite-challenge-why-anode-material-production-could-become-the-battery-industrys-biggest-bottleneck-after-lithium/>.

⁹⁸ IndexBox. *European Union Graphite Anode Material Market Analysis Forecast Size Trends And Insights*. <https://www.indexbox.io/store/european-union-graphite-anode-material-market-analysis-forecast-size-trends-and-insights/>.

⁹⁹ Mining See. *Europes 2030 Critical Raw Materials Goals Face A Growing Delivery Challenge*. <https://www.miningsee.eu/europes-2030-critical-raw-materials-goals-face-a-growing-delivery-challenge/>.

¹⁰⁰ EV Infrastructure News. *Europe Invested 82 Billion In Gigafactories Capacity To Reach 1.2TWh By 2030*. <https://www.evinfrastructurere news.com/ev-battery/europe-invested-82-billion-in-gigafactories-capacity-to-reach-1-2twh-by-2030>.

¹⁰¹ Atiyeh Nekahi et al. *Advanced lithium-ion battery process manufacturing equipment for gigafactories: Past, present, and future perspectives*. In: *iScience* 28.7, 112691 (2025).

¹⁰² McKinsey & Company. *Unlocking Growth In Battery Cell Manufacturing For Electric Vehicles*. <https://www.mckinsey.com/capabilities/operations/our-insights/unlocking-growth-in-battery-cell-manufacturing-for-electric-vehicles>.

China dominates global permanent magnet production,¹⁰³ supported by its control over rare earth refining, which provides access to the necessary raw materials at competitive prices. European magnet production is limited, leaving European manufacturers exposed to supply disruptions and price volatility.^{104 105}

Solar photovoltaic manufacturing capacity has become increasingly concentrated in China. The manufacturing process involves polysilicon production, solar cell manufacturing and module assembly. High-purity silicon must be melted and crystallized into ingots, then sliced into thin wafers using precision cutting equipment, a process that requires significant electricity input and specialized equipment.¹⁰⁶ China currently accounts for almost the entire global polysilicon wafer production capacity, while European wafer production has declined significantly, and only a handful of facilities remain operational.¹⁰⁷

The energy intensity of wafer production presents particular challenges for European manufacturers due to high energy costs, making European wafer production economically uncompetitive compared to Asian alternatives, particularly those benefiting from state subsidies and preferential energy access.¹⁰⁸

Like wafer production, cell and module manufacturing is heavily concentrated in China, which accounts for approximately 80% of global production capacity.¹⁰⁹ European module assembly capacity exists but operates at a limited scale, primarily serving niche markets or relying on imported cells. The inability to compete on cost with Asian manufacturers has led to the closure of several European cell production facilities in recent years.¹¹⁰ Although European research institutions have made advances in next-generation PV technologies such as perovskites and tandem cells, translating laboratory progress into commercial manufacturing remains difficult.^{111 112}

Finally, wind turbine manufacturing shows a more diversified picture of the manufacturing supply chain. European manufacturers maintain competitive positions in turbine assembly, with companies such as Siemens Gamesa, Vestas, and Nordex operating significant production facilities. However, these manufacturers depend on imported components for critical subsystems, including generators, power electronics, and control systems. Direct-drive wind turbines, particularly for offshore applications, rely on permanent magnet generators that require rare earth elements, linking wind manufacturing dependencies to the magnet bottleneck described above.^{113 114}

Blade manufacturing is an area where European industry has invested significantly in supply chain diversification. Wind turbine blades require composite materials including fibreglass, carbon fibre, and epoxy resins,

¹⁰³Tim Wicke et al. *Macro Economic and Ecological Aspects of Cell Production in Europe 2030*. In: *Batteries* 11.12, 457 (2025).

¹⁰⁴Sebastian Link, Lukas Schneider, Alexander Stephan, et al. *Feasibility of meeting future battery demand via domestic cell production in Europe*. In: *Nature Energy* 10 (2025), pp. 526–534.

¹⁰⁵International Energy Agency. *Batteries and Secure Energy Transitions*. <https://www.iea.org/reports/batteries-and-secure-energy-transition/s/status-of-battery-demand-and-supply>.

¹⁰⁶International Energy Agency. *Rare Earth Elements*. <https://www.iea.org/reports/rare-earth-elements/executive-summary>.

¹⁰⁷International Energy Agency, *Rare Earth Elements*, see n. 106.

¹⁰⁸IndexBox. *European Union Rare Earth Magnets Market Analysis Forecast Size Trends And Insights*. <https://www.indexbox.io/store/european-union-rare-earth-magnets-market-analysis-forecast-size-trends-and-insights/>.

¹⁰⁹Automotive Technology. *European Auto Production Halts Amid Critical Magnet Supply Shortage*. <https://www.automotive-technology.com/news/european-auto-production-halts-amid-critical-magnet-supply-shortage>.

¹¹⁰Mining See. *Europe's Rare Earth Debate Has Moved Beyond Mines and Oxides: The Strategic Battleground Is Now the Magnet*. <https://www.miningsee.eu/europes-rare-earth-debate-has-moved-beyond-mines-and-oxides-the-strategic-battleground-is-now-the-magnet-that-is-where-geology-becomes-industrial-power-a-rare-earth-deposit-may-sit-in-norw/>.

¹¹¹European Court of Auditors, see n. 24.

¹¹²PV Manufacturing. *Polysilicon Production*. <https://pv-manufacturing.org/silicon-production/polysilicon-production/>.

¹¹³U.S. Department of Energy. *Solar Photovoltaic Manufacturing Basics*. <https://www.energy.gov/cmei/systems/solar-photovoltaic-manufacturing-basics>.

¹¹⁴International Energy Agency. *Solar PV Global Supply Chains*. <https://www.iea.org/reports/solar-pv-global-supply-chains/executive-summary>.

and their production involves moulding, curing, and finishing processes.¹¹⁵ Nevertheless, raw material dependencies remain. Carbon fibre production is concentrated in a limited number of countries, and epoxy resin production depends on petrochemical feedstocks subject to market volatility. This means that even as European blade manufacturers have invested in supply chain diversification, complete independence from external suppliers remains elusive.¹¹⁶

All in all, these examples show that manufacturing dependence varies by technology, and that bottlenecks do not only concern final assembly. Intermediate components and specialized materials are also part of the challenge.

3.3.4 Challenges of rebuilding European manufacturing capacity

Rebuilding European manufacturing capacity across critical clean energy technologies faces multiple structural challenges that extend beyond simple capital investment. Manufacturing sovereignty requires competitive energy prices, streamlined permitting, integrated supply chains, skilled workers, and access to finance. Without progress in all these areas, the EU may struggle to scale production at the pace required by the energy transition.

Energy costs are one of the most important constraints. Many clean energy manufacturing processes are energy-intensive, including polysilicon production, cathode synthesis, and magnet sintering. European energy costs have increased significantly following the disruption of Russian gas supplies, placing European manufacturers at a disadvantage compared to competitors in regions with cheaper energy access.¹¹⁷ Achieving long-term energy cost reduction will require the expansion of renewable and low-carbon electricity capacity together with improvements of energy efficiency. However, these solutions require time to implement, creating a transitional period during which European manufacturers face elevated cost pressures.¹¹⁸

Manufacturing facility construction requires permitting across multiple regulatory domains, including environmental assessment, zoning, and industrial safety. European permitting processes are often lengthy and complex, with approval timelines extending several years for large-scale facilities. This contrasts with competitors in Asia, where streamlined permitting and state coordination enable faster project deployment.¹¹⁹ Accelerating permitting may help, but it must balance speed with environmental and social safeguards that remain important to European stakeholders.¹²⁰

Supply chain integration is equally important. Manufacturing efficiency depends on integrated supply chains connecting raw materials, components, and finished products. European manufacturers currently face fragmented supply chains, requiring imports of materials and components from multiple sources. This increases logistics costs, exposure to disruptions, and difficulty responding quickly to market changes.¹²¹ Building integrated supply chains requires coordination across extraction, refining, manufacturing, and

¹¹⁵EE News Europe. *Europe sinks as China rises to lead in IC wafer capacity by 2026*. <https://www.eenewseurope.com/en/europe-sinks-as-china-rises-to-lead-in-ic-wafer-capacity-by-2026/>.

¹¹⁶Centre for Economic Policy Research. *Ukraine Invasion And Energy Crisis Comparative Advantages Equity Valuations*. <https://cepr.org/voxeu/columns/ukraine-invasion-and-energy-crisis-comparative-advantages-equity-valuations>.

¹¹⁷International Energy Agency, *Solar PV Global Supply Chains*, see n. 114.

¹¹⁸Priya Panneerselvam and Albert Alexander Stonier. *Emerging innovations in solar photovoltaic (PV) technologies: The perovskite solar cells and more*. In: *Energy Reports* 14 (2025), pp. 216–242.

¹¹⁹CleanTechnica. *A Fresh Wave Of Perovskite Solar Cell Activity Just In Time For The Next Oil Crisis*. <https://cleantechnica.com/2026/03/23/a-fresh-wave-of-perovskite-solar-cell-activity-just-in-time-for-the-next-oil-crisis/>.

¹²⁰InfinityPV. *Why Emerging Solar Cells Struggle To Scale New Data Uncovers The Missing Link Between Solar Research And Industry*. <https://www.infinitypv.com/news/why-emerging-solar-cells-struggle-to-scale-new-data-uncovers-the-missing-link-between-solar-research-and-industry>.

¹²¹Amit Kumar Harit et al. *Taking perovskite photovoltaics from promise to product*. In: *Nature Reviews Clean Technology* 2 (2026), pp. 453–466.

final assembly, creating a chicken-and-egg problem that is difficult to resolve through isolated private investment alone.¹²²

Even with the ideal industrial ecosystem, manufacturing capacity cannot expand without a skilled workforce. European manufacturers face challenges recruiting workers with experience in battery chemistry, magnet production, and semiconductor processing. Competition for these skills is global, with established manufacturers in Asia offering competitive compensation and career development opportunities.¹²³ Education and training programmes, including vocational training, university programmes, and continuing education for workers transitioning from other sectors, will therefore be essential to address skills gaps effectively.¹²⁴

Finally, large-scale manufacturing projects require substantial capital investment. Gigafactory-scale facilities and other strategic manufacturing projects can require billions of euros in upfront investment, and European manufacturers often compete with established Asian producers who benefit from state financing, preferential lending, and risk-sharing mechanisms.¹²⁵ Public financing tools, including the Innovation Fund, European Investment Bank programmes, and national support schemes, can help reduce investment risks, but they must be allocated carefully to maximize impact and ensure efficient use of public resources.¹²⁶

3.4 Recycling

3.4.1 Recycling as a strategic supply source

Recycling is becoming an increasingly important part of critical raw material supply chains. As the demand for energy transition materials like lithium, copper, and rare earth elements grows, the secondary supply market can help reduce pressure on primary mining, lower environmental impacts, and strengthen supply-chain resilience. This is why critical raw material recycling has become a growing industrial sector, not only an environmental activity.¹²⁷

Within the European Union, the recycling sector is no longer viewed only through an environmental lens but also as a strategic priority to meet the ambitious targets of the Critical Raw Materials Act (CRMA), which sets a target for at least 25% of the region's annual consumption of strategic raw materials to come from domestic recycling by 2030.¹²⁸

However, despite clear policy direction, the current situation is still characterized by a significant recycling gap. While some metals, such as cobalt and nickel, already have relatively mature recovery processes, others including lithium, graphite, and rare earths are still recovered at rates far below their potential. The sector is currently moving from pilot-scale projects towards larger industrial recycling models, designed to handle the first major wave of end-of-life electric vehicle batteries and renewable energy hardware expected by the end of this decade.¹²⁹

¹²²Interlude One. *Wind Turbines*. <https://interludeone.com/posts/2025-04-23-windturbines/wind-turbines>.

¹²³European Council on Foreign Relations. *Last Gasp Securing Europes Wind Industry From Dependence On China*. <https://ecfr.eu/publication/last-gasp-securing-europes-wind-industry-from-dependence-on-china/>.

¹²⁴Intel Market Research. *Europe Aircraft Engine Blade Market*. <https://www.intelmarketresearch.com/europe-aircraft-engine-blade-market-21064>.

¹²⁵IndexBox. *European Union Resin Impregnated Carbon Market Analysis Forecast Size Trends And Insights*. <https://www.indexbox.io/store/european-union-resin-impregnated-carbon-market-analysis-forecast-size-trends-and-insights/>.

¹²⁶Bruegel. *Adjusting Energy Shock Right Policies European Industry*. <https://www.bruegel.org/policy-brief/adjusting-energy-shock-right-policies-european-industry>.

¹²⁷Dimension Market Research. *Critical Minerals Supply Chain Market*. Dimension Market Research, 2026. <https://dimensionmarketresearch.com/report/critical-minerals-supply-chain-market/>.

¹²⁸Dimension Market Research, see n. 127.

¹²⁹Dimension Market Research, see n. 127.

Recycling of critical raw materials is also geographically concentrated, mirroring the situation seen in primary extraction and refining. The Asia-Pacific, China in particular, has developed strong recycling capabilities by building on existing refining and chemical processing capacity, holding an estimated 47.3% market share in 2026.¹³⁰ This is important because recycling is not only a waste-management activity; it also requires processing, separation, and purification infrastructure. This creates a significant challenge for the European Union, since much of the mineral-rich scrap generated within Europe is exported to regions with more established secondary processing infrastructure, a phenomenon known as “scrap leakage”. This “scrap leakage” reduces the amount of material available for domestic circular supply chains and can weaken EU strategic autonomy.

3.4.2 Technologies and recovery potential

Technologically, recycling is improving. Traditional pyrometallurgical methods, based on high-temperature smelting, have long been the industry standard due to their ability to handle mixed waste streams. However, they are characterized by being energy-intensive and often result in the loss of materials such as lithium and natural graphite into slag. In contrast, modern hydrometallurgical processes, which use aqueous chemistry to leach and separate minerals, can achieve significantly higher recovery rates often exceeding 95% for lithium, cobalt, and nickel in battery-grade purity.

2026 has seen the emergence of “AI-assisted recycling,” where machine learning and digital twins are used to optimize the sorting of complex electronic waste and predict the purity of recovered batches in real-time. For more specialized applications, such as the recovery of rare earth elements from wind turbine magnets, “long-loop” recycling technologies are being developed to decrease the energy intensity of reducing magnets back to metallic form. These innovations are crucial for achieving the high-purity standards required for recycled materials to be fed directly back into the manufacturing of new high-tech components without performance degradation.¹³¹

3.4.3 Limits of recycling

Despite these technological advancements, the recycling of critical raw materials faces fundamental limits that prevent it from fully replacing mining in the short term. The main reason is the stock-in-use time lag: many critical raw materials are currently embedded in wind turbines, electric vehicles, power grids, and batteries with lifespans of 15 to 30 years. This means they will not be available for recycling until the products reach their end-of-life, while demand for new clean energy technology deployment is rising now.

Even with an ideal collection, secondary supply is only projected to cover between 14% and 40% of the EU’s demand for battery minerals by 2030. Additionally, there are significant thermodynamic and economic limits to circularity. In thermodynamics, this refers to the “entropy limit”, which means that as minerals are used in increasingly complex and smaller technologies, the energy and cost required to separate and purify them increase exponentially. From an economic perspective, the sharp volatility in mineral prices can mean recycling projects become less profitable when primary mineral prices fall, as happened with lithium prices between 2023 and 2025. Collection systems are also still incomplete. Without better information on which products contain valuable materials, and without effective return schemes for batteries, electronics, and

¹³⁰OECD. *OECD Inventory of Export Restrictions on Critical Raw Materials 2026: Monitoring the Use of Export Restrictions Amidst Growing Market and Policy Tensions*. Paris: OECD Publishing, 2026. https://www.oecd.org/en/publications/oecd-inventory-of-export-restrictions-on-critical-raw-materials-2026_d5ca8f62-en.html.

¹³¹Sergiusz Pimenow, Olena Pimenowa, and Włodzimierz Rembisz. *Circular Economy Pathways for Critical Raw Materials: European Union Policy Instruments, Secondary Supply, and Sustainable Development Outcomes*. In: *Sustainability* 18.2, 562 (2026).

industrial equipment, many critical raw materials remain dispersed in products, stored unused, or lost in landfills.¹³²

Taken together, extraction, refining and processing, manufacturing, and recycling all show how critical raw material supply chains are not shaped by global geology alone. Strategic leverage is increasingly built in the stages where the materials are processed, transformed, manufactured, and reintegrated into the industrial loop. As this chapter has shown, one actor appears repeatedly as a central player in all stages: China. Understanding how China built this position, and what it means for the EU, is therefore essential to understanding the geopolitics of the energy transition.

¹³²Renewable Matter. *Critical Raw Materials Complex European Challenge*. <https://www.renewablematter.eu/en/critical-raw-materials-complex-european-challenge>.

4. CHINA AND THE GLOBAL SUPPLY OF CRITICAL RAW MATERIALS

4.1 China's strategic positioning in the energy transition

In 1992 Deng Xiaoping, former leader of the People's Republic of China, visited the industrial city of Baotou in Inner Mongolia and famously declared: “The Middle East has oil, China has rare earths.” At a time when critical materials merely appeared in geopolitical discussions, Chinese policymakers had already begun to identify resources as a long-term industrial and technological opportunity. China's early interest in critical materials, however, was not due to their potential in decarbonization and environmentally-friendly technologies. Rather, these materials were seen as essential for industrial modernization, for future technological development and geopolitical influence.

During the following decades, China achieved unprecedented economic growth driven by rapid industrial expansion, powered by coal and fossil fuels. While this model transformed the country into a global manufacturing powerhouse, it came at an unsustainable cost: severe pollution, rising greenhouse gas emissions, and a growing dependence on imported energy. As China's industrial expansion accelerated during the 2000s, the country became increasingly dependent on imported oil and gas, exposing Beijing to external supply vulnerabilities, maritime chokepoints, and broader geopolitical risks.¹³³ By the early 2010s, cities such as Beijing had become symbolic of the environmental costs of this development model. In January 2013's airpocalypse, PM_{2.5} concentrations in Beijing exceeded 900 $\mu\text{g}/\text{m}^3$, dramatically surpassing the daily levels recommended by the World Health Organization.¹³⁴

Chinese policymakers recognized that the fossil-fuelled growth model had reached its limits. In this context, renewable energy and clean technologies became not only climate solutions, but also tools for industrial upgrade, energy security, and economic competitiveness. Unlike many Western economies, China approached the energy transition not as an isolated environmental policy, but as part of a broader industrial strategy linking critical raw materials, manufacturing capacity and energy security. Because China had already spent decades building refining capacity and strategic control over critical raw materials, it entered the clean energy transition with a significant structural advantage.

Through initiatives such as “Made in China 2025” and the “Strategic Emerging Industries (SEI)” programme, China mobilized state resources, industrial policy, private enterprise, and financing mechanisms towards the development of clean energy technologies and strategic supply chains.¹³⁵ This long-term planning helped

¹³³Jian Zhang. *China's Energy Security: Prospects, Challenges, and Opportunities*. CNAPS Visiting Fellow Working Paper. The Brookings Institution, Center for Northeast Asian Policy Studies, 2011. https://www.brookings.edu/wp-content/uploads/2016/06/07_china_energy_zhang_paper.pdf.

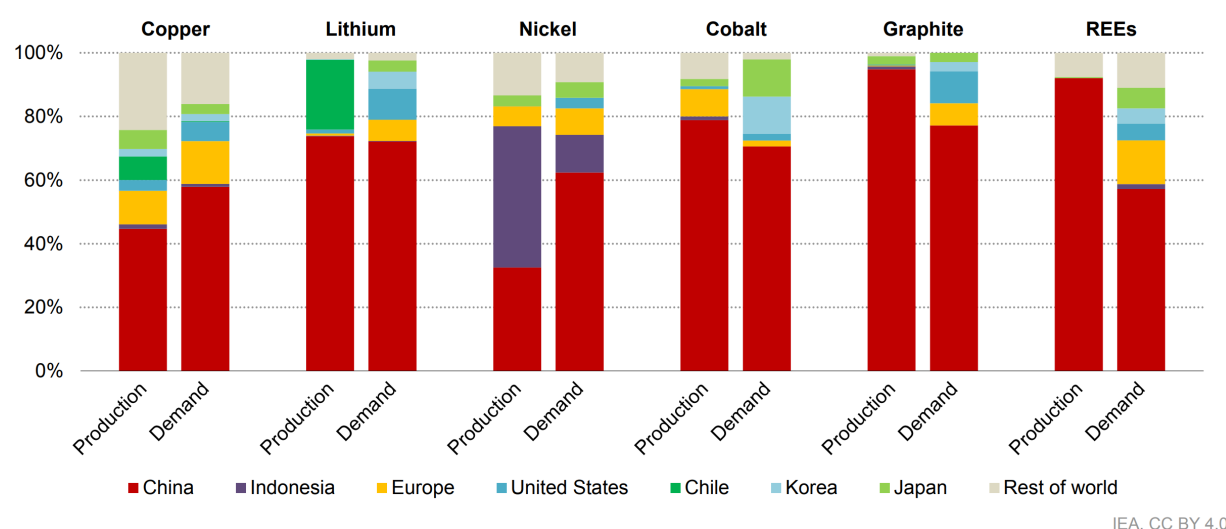
¹³⁴Wen Wu et al. *A 21-year of PM_{2.5}-related premature mortality in China (2000–2020): spatial-temporal variations and health implications*. In: *Journal of Cleaner Production* 525, 146588 (2025).

¹³⁵U.S.-China Economic and Security Review Commission. *Made China 2025 Evaluating Chinas Performance*. <https://www.uscc.gov/research/made-china-2025-evaluating-chinas-performance>.

transform the country into the world's leading producer of a wide range of renewable and electrification technologies, including batteries, electric vehicles, solar panels, and permanent magnets.

China's position in the global clean-energy supply chain is now unmatched. In 2024, the country accounted for almost two-thirds of total renewable capacity connected to the grid worldwide, and surpassed its 2030 target of 1 200 GW of combined PV and wind six years ahead of schedule.¹³⁶ China also remains the world's largest electric vehicle market, with more than 11 million EVs sold in 2024, representing two-thirds of global EV sales.¹³⁷ Beyond deployment, China has become the largest investor in clean energy globally, investing 625 billion USD in 2024 alone, 31% of the global total.¹³⁸

As a result, China is not only one of the main suppliers of critical raw materials and clean technologies, but also one of their largest consumers, as Figure 5 indicates. The country represents today the highest source of demand for several refined critical minerals, with over half the global demand for copper, nickel, cobalt, natural graphite, and rare earth elements, as well as more than three-quarters of global lithium demand. China therefore plays a central role in the energy transition, which extends far beyond manufacturing alone: it increasingly shapes the global supply, demand, and industrial structure of the clean energy economy.



IEA. CC BY 4.0.

Figure 3: Production and demand of refined critical mineral by geography, 2024. Source: Adapted from IEA (2025), *Global Critical Minerals Outlook 2025*, p. 29, CC BY 4.0

The following sections analyse China's position across the critical raw materials value chain, focusing particularly on mining, refining and processing, manufacturing capacity, overseas investment strategies, and the geopolitical implications of this growing concentration of industrial power.

4.2 China's role across the value chain

China's position in critical raw materials supply chains cannot be solely understood through mining activities. While extraction remains geographically distributed for many minerals, China's dominance becomes significantly stronger further downstream in the value chain, especially in refining, processing, and manufacturing. These stages are often more technologically complex, very capital-intensive and strongly dependent on economies of scale, making them very difficult to diversify in the short term.

¹³⁶International Energy Agency, *Global Critical Minerals Outlook 2025*, see n. 12.

¹³⁷International Energy Agency, *Global Critical Minerals Outlook 2025*, see n. 12.

¹³⁸Ember. *China Energy Transition Review 2025*. <https://ember-energy.org/app/uploads/2025/09/China-Energy-Transition-Review-2025.pdf>.

4.2.1 Mining

Despite the growing attention surrounding mining and China, extractive activities remain considerably more geographically distributed than downstream processing, with important production hubs located across Latin America, Africa, Australia, and Southeast Asia. Nevertheless, China has secured a strong upstream position in a number of minerals that are essential for renewable energy technologies.

Regarding minerals relevant to the energy transition, China currently accounts for around 22% of global lithium mining output, 61% of rare earth elements (REE) production and approximately 87% of natural graphite extraction. The country also holds significant reserves of several critical materials, including nearly half of global REE reserves and around 28% of natural graphite reserves. Rare earth elements are particularly important in this context, as they are essential for the production of the permanent magnets used in electric vehicles, wind turbines, robotics, and industrial automation systems. Unlike many other minerals, where mining activities are more geographically diversified, China combines a dominant position in REE extraction with an even stronger position in downstream refining and magnet manufacturing.

However, China's influence in mining extends far beyond its domestic territory. Over the last two decades, Chinese companies have significantly expanded their presence in overseas mining projects. Chinese firms now hold major interests in cobalt extraction in the Democratic Republic of the Congo, lithium projects across Argentina, Bolivia, and Mali, copper mining operations in Zambia, and nickel production in Indonesia.¹³⁹ Examples of this expansion include the acquisition of the Las Bambas copper mine in Peru by the Chinese state-owned enterprise China Minmetals in 2014 for approximately 7 billion USD, as well as the acquisition of the Tenke Fungurume mine in the Democratic Republic of Congo (DRC) by China Molybdenum (CMOC) in 2016, one of the largest copper and cobalt mines in the world. By 2025, Chinese entities were estimated to control between 60% and 70% of cobalt production in the DRC, a country responsible for approximately 70 to 80% of global cobalt production.

Experts interviewed for this report highlighted that China's success in securing access to African mineral resources has relied not only on financial investment, but also on infrastructure agreements and long-term industrial partnerships. According to Dr. Arnoldus, China's approach has often been perceived as less conditional and more aligned with local development priorities than Western approaches, which focus more on regulatory requirements and governance conditions.¹⁴⁰

At the same time, interviewees emphasized that one of the key differences between China and many Western economies is that China never ceased to regard mining and critical raw materials as strategic pillars of industrial development. While many countries progressively externalized mining and metallurgical activities during the late 20th and early 21st centuries, China continued investing across the different stages of the value chain, gradually developing technical expertise and industrial capabilities that are now difficult to replicate.¹⁴¹

Nevertheless, mining alone captures only a limited share of the overall value chain. In many cases, minerals extracted across Africa, Latin America, or Australia are then exported to China for refining and chemical processing before being transformed into batteries and other renewable energy technologies. As a result, China's true advantage becomes substantially more dominant further downstream in the supply chain.

¹³⁹ International Energy Agency, *Global Critical Minerals Outlook 2025*, see n. 12.

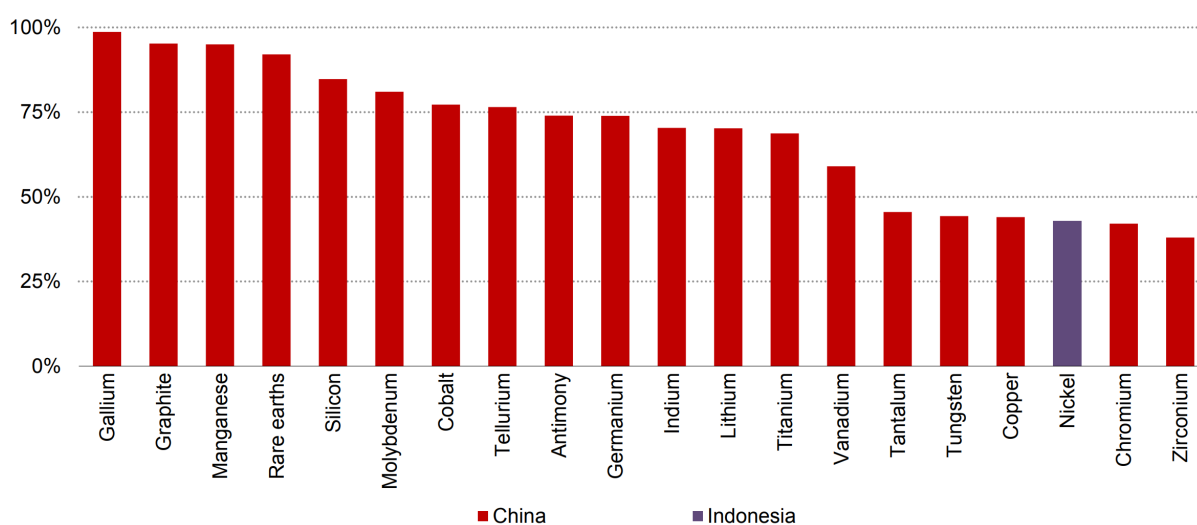
¹⁴⁰ Arnoldus M. van den Hurk Mir. *Interview*. Expert in mining and critical minerals. Unpublished interview conducted by the authors. Nov. 2025.

¹⁴¹ Eduardo Zamanillo and Marta Rivera. *Interview*. Authors of Mining Is Dead. Long Live Geopolitical Mining. Unpublished interview conducted by the authors. Feb. 2026.

4.2.2 Refining and processing

While mining activities receive the greatest political and media attention, it is the refining and processing stage that represents the principal strategic bottleneck within the critical raw materials supply chain. Experts interviewed for this report underscored this point, arguing that the conversion of raw ores into industrially usable materials represents one of the main structural advantages currently held by China.¹⁴²

China's dominance becomes very evident at this stage of the value chain. Although mentioned in the previous chapter, it is important to note that China is currently the dominant refiner for 19 of 20 critical materials analysed in relation to energy technologies, holding an average market share of around 70% for minerals refined in Chinese territory. This can be seen in Figure 4.



IEA. CC BY 4.0.

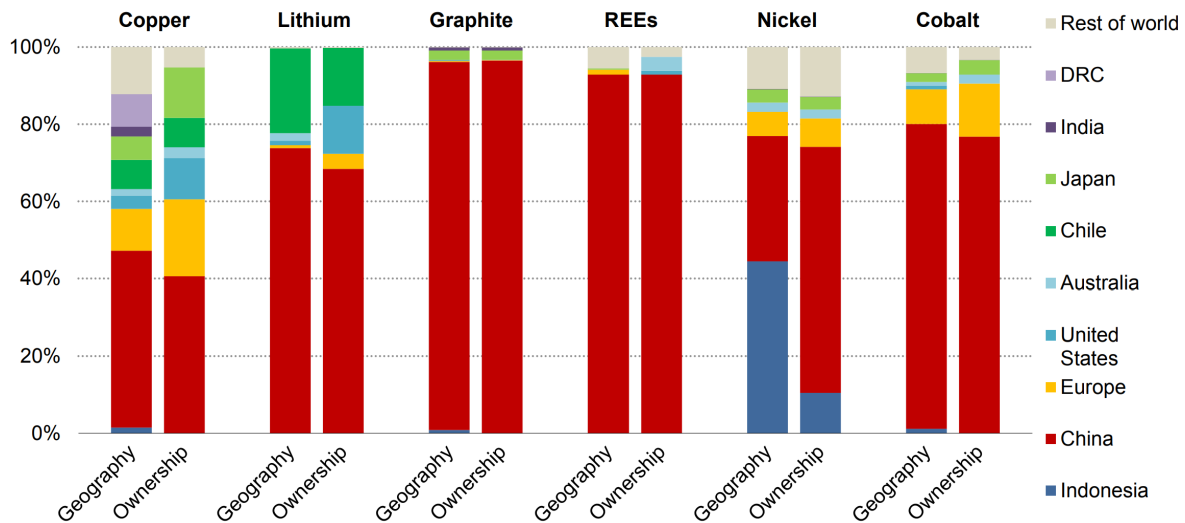
Figure 4: Share of top producer of refined energy-related strategic minerals. Source: Adapted from IEA (2025), *Global Critical Minerals Outlook 2025*, p. 252, CC BY 4.0

The concentration is especially significant in minerals essential for batteries, electric vehicles, renewable energy systems, and advanced industrial technologies. In 2024, China accounted for around 70% of lithium chemical refining and more than 90% of battery-grade natural graphite processing, as well as 78% of global cobalt refining capacity.¹⁴³ In addition, China currently accounts for around 70–80% of global silicon metal production, a key material for solar photovoltaic technologies.

As seen in Figure 5, the only refined mineral analysed by the IEA for which China is not the leading producer geographically is nickel, where Indonesia accounted for almost 45% of global refined production in 2024. Indonesian companies, however, only control 10% of this refining output, while Chinese firms own the majority of Indonesian nickel refineries, giving China control over 65% of global refined nickel production by ownership. This distinction between geographic production and ownership exemplifies how China's influence over refining extends beyond its domestic territory.

¹⁴²Hurk Mir, see n. 140.

¹⁴³International Energy Agency, *Global Critical Minerals Outlook 2025*, see n. 12.



IEA, CC BY 4.0.

Figure 5: Refining concentration by geography and ownership, 2024. Source: Adapted from IEA (2025), Global Critical Minerals Outlook 2025, p. 28, CC BY 4.0

The rare earth elements supply chain perfectly illustrates why refining remains difficult to diversify internationally. The challenges associated with refining are more obvious in the case of rare earths, whose chemical similarity with one another makes their separation into individually usable materials very complex and resource-intensive. The refining process often requires hundreds of stages of extraction and stripping cycles operating continuously to achieve the purity levels necessary for permanent magnets and advanced technologies. Moreover, these processes require large quantities of strong solvents that generate significant volumes of toxic waste, creating major environmental management requirements. Under stricter environmental regulations and higher labour costs, establishing economically competitive rare earth refining capacity outside China is very difficult without substantial state support.¹⁴⁴

Beyond infrastructure, capital intensity, and environmental trade-offs, refining also depends on accumulated expertise. As refining activities became increasingly associated with environmental costs and regulatory pressures, many Western economies progressively externalized metallurgical and chemical processing activities, while China continued investing across these stages of the value chain. Interviewees emphasized that refining capabilities, especially of REEs, rely greatly on learning-by-doing processes and cumulative industrial knowledge developed by decades of continuous operation.¹⁴⁵ As a result, many Western countries lost a great part of the technical “know-how” required to operate these large-scale refining systems efficiently, which is not easily rebuilt once the industrial ecosystem disappears.

China’s dominance in refining therefore not only reflects resource availability, but also the development of an integrated industrial environment that benefits from economies of scale, long-term planning, and decades of technological specialization.

In many cases, minerals extracted in Africa, Latin America or Australia are then shipped to China for refining and chemical conversion before being transformed into batteries, magnets, solar energy technologies, or other industrial products. Refining activities therefore capture a significantly larger share of the overall value chain than extraction alone. Australia, for example, is one of the world’s largest lithium producers, yet a

¹⁴⁴Rare Earth Exchanges. *Why Separating And Refining Rare Earth Elements Is So Difficult To Scale*. <https://rareearthexchanges.com/news/why-separating-and-refining-rare-earth-elements-is-so-difficult-to-scale/>.

¹⁴⁵Zamanillo and Rivera, see n. 141.

large proportion of the economic value associated with lithium is ultimately captured by China downstream through refining and manufacturing activities.

Access to large volumes of processed materials at competitive prices has enabled Chinese firms to develop and manufacture batteries, electric vehicles, solar photovoltaics, and permanent magnets at lower costs and larger scales than many international competitors, helping China achieve a leading global position across several strategic clean energy industries.

4.2.3 Manufacturing

China currently dominates several of the manufacturing stages most relevant to the energy transition, and this is particularly true in the battery sector. Beyond refining the minerals themselves, China also leads the production of intermediate chemical compounds necessary for advanced battery chemistries. In 2024, China produced approximately 75% of the world's purified phosphoric acid, essential for lithium iron phosphate (LFP) batteries, as well as around 95% of global high-purity manganese sulphate production, key for manganese-rich and sodium-ion battery technologies, alternatives being increasingly developed for cheaper EVs and BESS applications.¹⁴⁶

The country also dominates cathode and battery cell manufacturing. As mentioned in the previous chapter, China accounted for 98% of global LFP cathode production capacity in 2024, alongside 90% of anode material production and around 80% of battery cell manufacturing. LFP technologies are increasingly used in electric vehicles and large-scale energy storage systems due to their lower costs and greater thermal stability. China recognized the potential of LFP batteries early on and, while many Western manufacturers focused on nickel-based batteries, Chinese companies built factories, supply chains, and technical experience around LFP batteries. Current project pipelines suggest that this dominance is likely to persist in the coming decade, with China projected to account for 95% of global LFP production capacity by 2030. This means that many economies seeking to expand electric vehicles production and energy storage will remain heavily dependent on China.

According to the IEA, Chinese equipment and machinery used to produce battery and cathode material are often significantly cheaper, have shorter delivery times, and are more efficient than machinery available in other countries, particularly Korea and Japan. In some cases, Chinese industrial equipment costs between one-half to one-third of equivalent alternatives outside of China.¹⁴⁷

But China's manufacturing dominance extends also beyond batteries. In 2024, the country accounted for approximately 94% of global production of sintered permanent magnets and around 80% of bonded magnets, both essential for EVs, wind turbines, robotics, and industrial automation systems. In the same way, China currently controls close to the entirety of the world's high-purity silicon production capacity, a material critical for solar PV. As a result, many of the technologies providing the foundation for the global energy transition remain highly dependent on Chinese manufacturing companies.¹⁴⁸

One of the key reasons behind this success is the highly streamlined industrial model China has developed, connecting refining and processing with component and product manufacturing. The close geographical concentration of suppliers, processing facilities, manufacturers, and downstream industries has allowed Chinese enterprises to reduce costs, increase production efficiency, and scale manufacturing capacity much faster than international competitors.

¹⁴⁶International Energy Agency, *Global Critical Minerals Outlook 2025*, see n. 12.

¹⁴⁷International Energy Agency, *Global Critical Minerals Outlook 2025*, see n. 12.

¹⁴⁸International Energy Agency, *Global Critical Minerals Outlook 2025*, see n. 12.

China's position in clean energy manufacturing therefore reflects more than simply cheaper production. It represents decades of coordinated industrial policy, vertical integration and large-scale investment across the entire critical raw materials supply chain, where control over multiple stages of the value chain has reinforced the country's competitiveness, supply security, and geopolitical leverage.

4.3 Dependency, leverage, and export controls

Although this dominance had not gone unnoticed, for many years the concentration of critical materials supply chains was discussed as a long-term theoretical risk. However, recent events increasingly show that these vulnerabilities are already becoming a practical industrial and geopolitical reality. As electrification and renewables deployment accelerate, access to batteries, permanent magnets, solar PV, and other clean energy technologies depends more and more on undiversified supply chains in which China occupies a central role. In many cases, alternative suppliers either do not exist at scale or would require years of investment to become economically competitive.¹⁴⁹

Often this dependency translates to geopolitical and industrial leverage. Countries capable of influencing the supply and price of minerals upon which entire industries depend gain considerable bargaining power. China's recent export restrictions illustrate this. Between 2023 and 2025, China introduced export controls on several strategic materials, including gallium (semiconductors), germanium (solar cells), natural graphite, and rare earths. According to the Swedish National China Centre, following these export restrictions European gallium prices increased by 365%, germanium by around 400%, and antimony (used in batteries and electronics) by more than 430%.¹⁵⁰ These examples clearly show how concentrated supply chains can rapidly create industrial vulnerability and price volatility for importing economies.

Rare earth elements are notably important in this discussion. Following Chinese export controls on several rare earths including dysprosium and terbium, exports of rare earth magnets temporarily fell by 73% in May 2025, generating concerns among manufacturers due to the lack of alternative suppliers at scale outside China.¹⁵¹ These export controls also require exporters to provide information regarding the final use and end users of these materials before export licences are approved. As a result, international importers may face higher prices, supply shortages, and greater uncertainty regarding access to essential magnets, potentially leading to delays and production disruptions.¹⁵²

However, this relationship should not be understood as absolute unilateral control. China itself also relies greatly on imported raw materials, international export markets, and the global demand for clean and advanced technologies. Despite its dominant position in copper refining, for example, China still relies on imported copper ores from countries such as Chile, Peru, and Australia to satisfy domestic demand. At the same time, though, state-supported Chinese companies have invested extensively in overseas mining assets across Latin America, Africa, and Australia in order to secure long-term supply, particularly for copper, lithium, and cobalt. The current system should therefore be understood as one with asymmetric interdependencies, where vulnerabilities exist on both sides, although not to the same degree.

For the European Union, the issue thus extends beyond securing access to raw critical materials. It also involves rebuilding the lost industrial resilience across refining, processing, and manufacturing stages, to

¹⁴⁹International Energy Agency, *Global Critical Minerals Outlook 2025*, see n. 12.

¹⁵⁰Henrik Wachtmeister. *China's Mineral Export Restrictions: Market Impacts and Implications*. NKK Report No. 4, 2025. Swedish National China Centre, Swedish Institute of International Affairs, 2025. https://www.ui.se/globalassets/ui.se-eng/publications/other-publications/chinas-mineral-export-restrictions_market-impacts-and-implications_nkk_2025.pdf.

¹⁵¹Wachtmeister, see n. 150.

¹⁵²European Parliament. *Critical raw materials: European Parliament briefing*. [https://www.europarl.europa.eu/RegData/etudes/ATAG/2025/779220/EPRS_ATA\(2025\)779220_EN.pdf](https://www.europarl.europa.eu/RegData/etudes/ATAG/2025/779220/EPRS_ATA(2025)779220_EN.pdf).

reduce extreme dependencies on external actors and strengthen Europe's capacity to carry out the energy transition. As noted by the World Economic Forum, the EU currently lacks sufficient control over many of the critical materials' supply chains necessary to fulfil its green and digital transition targets.¹⁵³

4.4 Implications for the EU

In the short term, China constitutes an unavoidable partner for accessing many of the critical materials Europe needs for its green energy transition. Despite ongoing efforts to diversify critical raw materials supply chains, Europe faces important challenges. Rebuilding alternative supply chains and industrial capacity in Europe will require significant time, investment, and coordination across the bloc, especially in sectors where China already benefits from major economies of scale and technological maturity.

Some interviewees also stressed that Europe's challenge is not only industrial or financial, but also social and political. Public opposition to mining projects, long permitting timelines, and regulatory complexities continue to slow down the development of domestic mining and processing capacity within the EU.¹⁵⁴ This creates additional difficulties for accelerating strategic projects at the pace required for the energy transition.

Another important consideration concerns the regulatory environment under which these industries originally developed. Much of China's refining and heavy industrial capacity expanded during periods of lower environmental and permitting constraints than those currently existing in Europe. Thus, Europe today faces the challenge of rebuilding refining and manufacturing capabilities under significantly stricter environmental, social, and regulatory standards, which increase costs and extend project timelines. Once large-scale industrial environments are already established, gradually improving their environmental performance may be easier than developing entirely new supply chains from scratch under highly restrictive conditions.

However, the European Union should not focus on achieving complete self-sufficiency, which would be unrealistic in this globalized world. Rather, the real challenge stems from reducing excessive dependencies, strengthening industrial resilience, and preserving Europe's technological and industrial competitiveness without sacrificing environmental standards.

The following chapter examines the European Union's current position within critical raw material supply chains and analyses the feasibility of its mining, refining, and industrial ambitions under the Critical Raw Materials Act and the broader difficulties associated with rebuilding these capabilities.

¹⁵³World Economic Forum. *From chips to turbines: Europe depends on critical raw materials*. <https://www.weforum.org/stories/2025/10/from-chips-to-turbines-europe-depends-on-critical-raw-materials/>.

¹⁵⁴Hurk Mir, see n. 140.

5. THE EU'S POSITION AND POLICY RESPONSE

Over the past two decades the European Union has progressively transformed its approach to critical raw materials. While earlier European strategies mainly treated raw materials as inputs required for industrial competitiveness, the growing scale of the energy transition combined with recent geopolitical tensions and supply-chain disruptions have transformed critical materials into strategic assets linked to energy security and geopolitical autonomy. This evolution is reflected in the expanding EU list of critical raw materials, which increased from 14 materials in 2011 to 34 in 2023, as well as in the adoption of the Critical Raw Materials Act (CRMA) and other initiatives developed by the European Union to reduce external dependencies and strengthen supply chain's resilience.¹⁵⁵

However, translating these ambitions into reality remains very challenging. Europe faces significant disadvantages across several stages of the value chain, namely limited refining capacity, loss of industrial know-how, long permitting timelines, strong social and environmental constraints, and major cost disadvantages compared with already established ecosystems, particularly in China. Although the European Union has mineral deposits of several critical raw materials across its territory, it continues to rely heavily on imports from outside the bloc, being 100% import-dependent for 10 strategic raw materials, including lithium, magnesium, and rare earth elements. And in many cases, a single external supplier dominates the imports. In 2025, around 79% of the EU's lithium supply originated from Chile, 82% of niobium from Brazil, 97% of magnesium from China, and 98% of rare earths from China.¹⁵⁶

Yet these dependency levels cannot simply be solved by the existence of domestic geological resources. Possessing internal mineral deposits does not directly warrant extractability, since infrastructure, metallurgy, processing capacity, and socio-economic constraints often prevent large-scale domestic production. At the same time, international demand for critical materials is accelerating rapidly, while the development of mines, refining facilities, and transmission infrastructure often requires decades of investment, obtaining permission, and construction.

This chapter therefore analyses the European Union's current strategy and its feasibility under existing physical, industrial, and geopolitical constraints. It examines Europe's ambitions under the Critical Raw Materials Act (CRMA) and the limitations associated with rebuilding mining, refining, and manufacturing capacity. In addition, the chapter also explores the challenges linked to renewable deployment and infrastructure expansion together with the geopolitical dependencies and overseas investment efforts. Finally, it discusses whether part of the solution may also require reducing material intensity through energy sufficiency, changing consumption habits, and circular economy strategies.

5.1 Targets, implementation, and gaps of the CRMA

The Critical Raw Materials Act represents the EU's most important legislative response to the supply-chain vulnerabilities analysed in the previous chapters. It establishes strict rules designed to limit the bloc's

¹⁵⁵European Commission, *Critical raw materials*, see n. 1.

¹⁵⁶European Court of Auditors, see n. 24.

excessive external dependence by 2030 by strengthening domestic extraction, processing, and recycling capacity, while also diversifying imports from non-EU countries. As mentioned in the first chapter, the Act sets four strategic benchmarks for strategic raw materials: at least 10% of annual EU consumption should be extracted within the EU, at least 40% should be processed within the EU, and at least 25% should come from recycling. Furthermore, it encourages that no more than 65% of any strategic raw material should come from a third country.

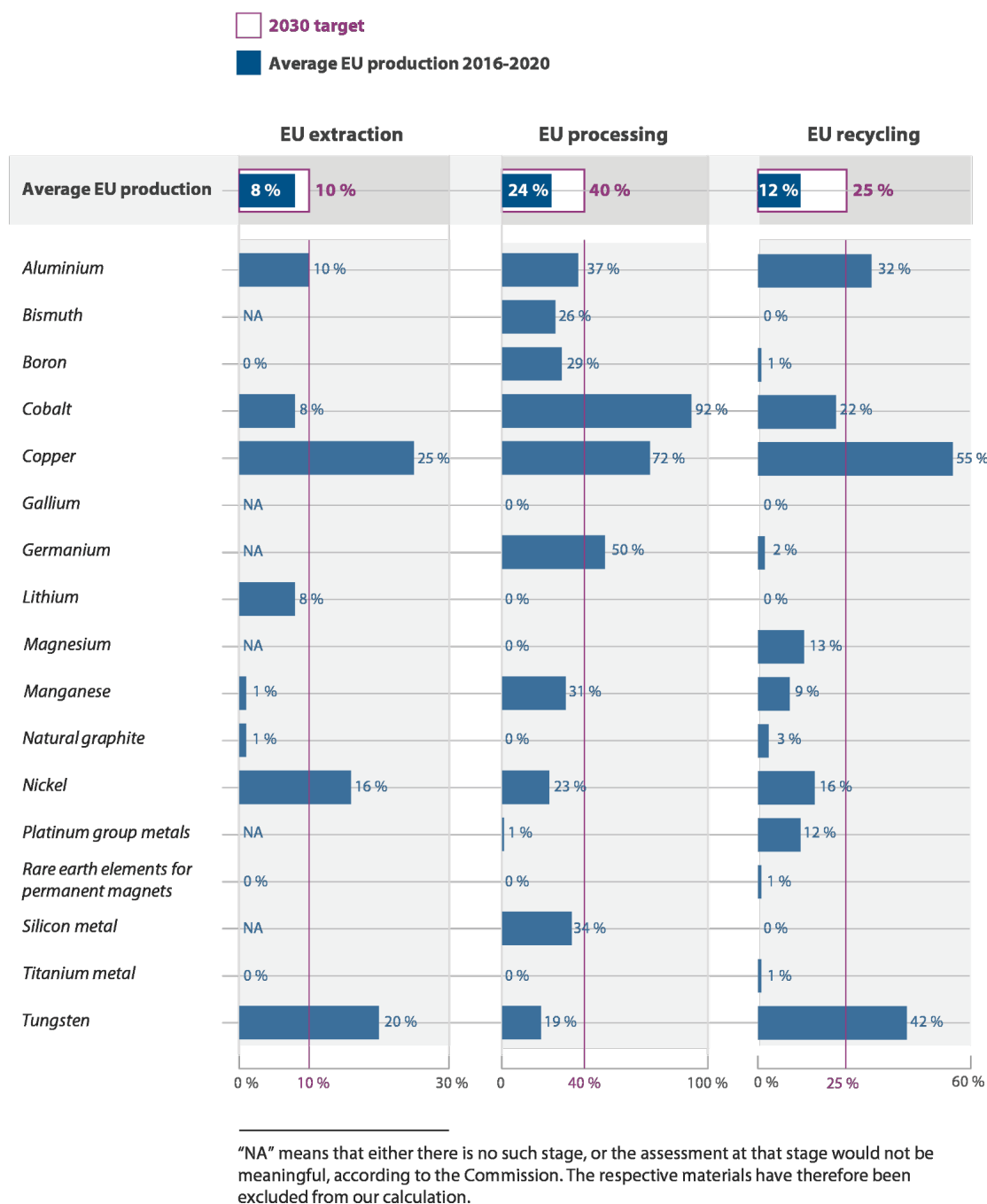


Figure 6: Average EU production capacity and progress toward CRMA 2030 targets. Source: European Court of Auditors, 2026. Modified and enhanced for readability. CC BY 4.0

However, these targets should be understood as strategic benchmarks rather than guaranteed figures. The European Court of Auditors (ECA) notes that the CRMA targets are legally non-binding, apply only to strategic raw materials (as opposed to critical raw materials), and lack a clear public justification regarding

how they were determined. In addition, these targets are accumulated across strategic raw materials, meaning that progress towards the overall target may hide major weaknesses for individual materials. This is particularly important because the EU may be relatively close to the average extraction target while still having little to no domestic capacity for central materials such as rare earth elements or natural graphite.

Figure 6 illustrates this problem. When the targets were set, the EU's average domestic production capacity was estimated at around 8% for extraction, close to the 10% target, but only around 24% for processing compared with the 40% target and around half for the recycling target. These averages show that although the EU is not starting from zero, it has large differences between individual materials, and non-existent capacity in some stages for some of the most important materials such as lithium, natural graphite, and rare earths.

To achieve these thresholds, the CRMA introduced the Strategic Projects, which are intended to strengthen supply security by accelerating permitting, administrative coordination, and increasing project visibility for investors and public institutions. The European Commission approved the first wave of projects in March 2025, including 25 dedicated extraction projects, 24 processing facilities, 10 recycling operations, and 2 material substitution innovations.¹⁵⁷ This first wave shows a strong focus on lithium, reflecting the immediate pressure created by electric vehicles, battery storage, and grid-related technologies. In June 2025, the Commission adopted a further 13 Strategic Projects located in non-EU countries, bringing the total number of CRMA Strategic Projects to 60. A second selection round was launched in January 2026, receiving more than 160 applications.¹⁵⁸

It must be noted that the CRMA does not directly address manufacturing capacity, creating a policy gap. As a result, this act can improve access to material inputs, but it does not guarantee by itself that Europe will turn those inputs into the clean technologies that must be deployed for the energy transition. Manufacturing capacity is addressed more directly through other policies such as the Net-Zero Industry Act.¹⁵⁹

Nevertheless, being selected as a Strategic Project does not automatically mean that the project is going to be built. Although these projects may benefit from faster permitting and visibility, there are several factors that affect the added value of this Act. Appeals can still delay permitting and final project timelines, and in many selected “Strategic Projects” permitting is still seen as one of the key risks by the ECA. In addition, the CRMA does not provide direct EU funding itself for the “Selected Projects”, and since financial viability is not a condition for selection, some projects may still struggle to attract investment.

The current stage of implementation is mixed. According to the ECA's analysis of 19 Selected Projects, most of them were still in early stages of development when selected in 2025, making it unlikely that they will make a meaningful contribution to the 2030 target. There were only 3 mature projects which were already at construction stage and had a high chance of contributing before 2030, while no projects in the sample were already operational. Several projects also lacked offtake agreements with a European company, raising doubts about whether their future output would actually strengthen EU supply security.¹⁶⁰

In addition, several Selected Projects have already faced strong local opposition. In Portugal, environmental groups and local residents filed a lawsuit against the European Commission over its decision to give the “strategic” status to the Barroso lithium mine project, arguing that it posed serious environmental, social,

¹⁵⁷European Commission. *Selected strategic projects under the Critical Raw Materials Act*. https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials/strategic-projects-under-crma/selected-projects_en.

¹⁵⁸Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs. *Strategic projects on critical raw materials gain momentum in second selection round for potential funding and faster permitting*. European Commission. Jan. 19, 2026. https://single-market-economy.ec.europa.eu/news/strategic-projects-critical-raw-materials-gain-momentum-second-selection-round-potential-funding-and-2026-01-19_en.

¹⁵⁹European Court of Auditors, see n. 24.

¹⁶⁰European Court of Auditors, see n. 24.

and safety risks.¹⁶¹ In Serbia, Rio Tinto's Jadar lithium projects has faced repeated local demonstrations concerned over environmental and agricultural concerns and difficulty in gaining permits.¹⁶²

5.2 Feasibility of Europe's ambition

While the CRMA sets a clear direction, its feasibility depends on whether the EU can overcome structural barriers that have accumulated over decades. A technical and socio-economic assessment of the European landscape reveals a significant misalignment between legislative ambition and operational reality. The feasibility of Europe's ambitions is therefore challenged not only by geological constraints, but also particularly by underdeveloped exploration, long project timelines, regulatory structures, a lack of social acceptance, high energy costs, financing constraints, and an erosion of technical expertise.

5.2.1 Exploration, regulatory delays, and project timelines

One of the first obstacles is the limited state of mineral exploration in Europe. The primary barrier to realizing the CRMA's extraction targets is the temporal disconnect between political timelines and the geological development cycle. Before extraction can begin, deposits must be identified, explored, assessed, financed, permitted, and developed. The European Court of Auditors notes that mineral exploration in the EU remains underdeveloped. In recent decades, member states' investment in general exploration has represented only around 2-3% of global exploration expenditure. This limits the knowledge of the EU's actual critical raw material potential and makes it harder to identify projects that could realistically contribute to the CRMA targets. Even once promising deposits are identified, targeted exploration remains a high-risk, high-cost activity, with only 1 in 1000 targeted exploration ventures leading to successful mining projects.¹⁶³

Moreover, although the Act mandates a specific permitting timeline for successfully-explored strategic projects, the European Commission's own impact assessments indicate that the average duration from discovery to production in the EU frequently exceeds a decade.¹⁶⁴ This creates a temporal disconnect between the 2030 targets and the operational reality of mineral development.

However, this delay is not only the result of bureaucratic complexity. Rivera and Zamanillo, in their analysis of Western mining dynamics, interpret European mining regulation as being driven by a form of "institutional insecurity." They argue that authorities often respond to public scepticism by adding repeated layers of control as a form of symbolic reassurance. These controls are not always introduced because of a clear additional technical evaluation, but because they make the process appear more legitimate in front of a sceptical public.¹⁶⁵

This creates a self-reinforcing dynamic: the more controls are added, the more previous controls appear insufficient. The result is a paradox, in which, driven by the fear of losing legitimacy before communities and critical public opinion, the EU builds regulatory systems so redundant and exhaustive that they ultimately erode the very efficiency and effectiveness they aim to protect.¹⁶⁶ However, legitimacy does not stem from

¹⁶¹ Reuters. *Environmental groups sue EU commission over Portugal's lithium mine*. <https://www.reuters.com/sustainability/environmental-groups-sue-eu-commission-over-portugals-lithium-mine-2026-02-05/>.

¹⁶² ABC News. *Rio Tinto Jadar Valley mine paused amid huge opposition*. <https://www.abc.net.au/news/2025-11-18/rio-tinto-jadar-valley-mine-paused-amid-huge-opposition/106020944>.

¹⁶³ European Court of Auditors, see n. 24.

¹⁶⁴ European Union. *A Secure And Sustainable Supply Of Critical Raw Materials*. <https://eur-lex.europa.eu/EN/legal-content/summary/a-secure-and-sustainable-supply-of-critical-raw-materials.html>.

¹⁶⁵ Marta Rivera and Eduardo Zamanillo, see n. 86.

¹⁶⁶ Marta Rivera and Eduardo Zamanillo, see n. 86.

accumulating regulations and controls but from transparent processes, technically sound evaluations, and progress and innovation in mining and refining processes.

5.2.2 Social acceptance and community trust

The feasibility of the CRMA is also closely linked to the social acceptance of mining within European territories. Mining is not only a matter of geology, capital, and technology. It directly affects land use, water resources, ecosystems, local economies, and cultural identities. As Rivera and Zamanillo argue, “mining is fundamentally about people and communities”.¹⁶⁷

However, the sector is increasingly perceived not as a pillar of the green transition, but as an extension of extractive practices that overlook local rights. This is particularly sensitive in regions where mineral deposits overlap with Indigenous lands. Tor Tourda, a Sámi activist interviewed for this report, articulates this sentiment, describing the current push for minerals as a movement where everything is placed under the umbrella of the ‘green transition’, making it appear unquestionable and masking the environmental and cultural costs.¹⁶⁸

This resistance is not rooted in extremism or rebellion against institutions, but emerges from a combination of social, environmental, and political factors: water contamination, soil degradation, exclusion from decision-making, and perceptions of injustice, particularly among Indigenous peoples who do not perceive tangible benefits. Tourda highlights an institutional gap: the absence of Free, Prior, and Informed Consent (FPIC) in practice. He notes that while consultation processes exist on paper, they function merely as information meetings rather than welcoming genuine participation. Companies and authorities may present projects to communities while the most significant decisions have already been taken.¹⁶⁹

This dynamic is compounded by the Swedish state’s historical “theft of land” through administrative measures, which has amplified distrust among Indigenous populations.¹⁷⁰ In this context, the EU’s ambition to secure its supply chain may be perceived as being pursued at the expense of Indigenous sovereignty, fueling a narrative that the green transition is merely reproducing the older extractive patterns instead of offering a more just and sustainable model.

But social opposition is not limited to Indigenous communities. The mining sector faces a structural mistrust that goes beyond isolated incidents or specific conflicts. According to the GlobeScan Radar 2023 survey conducted for the International Council on Mining and Metals (ICMM), mining systematically ranks among the lowest sectors regarding perceived social responsibility.¹⁷¹ Only three out of ten people associate mining with economic development or energy transition, and two out of ten with innovation or environmental stewardship. In other words, there is substantial room for narrative and symbolic growth.¹⁷²

The concept of the “social licence to operate” has, in many cases, evolved from a tool for dialogue into an informal mechanism of veto power. In contexts of low trust, even projects that have received formal approval can remain blocked by persistent opposition, creating a stalemate in which different actors can delay implementation but no institution has the authority or legitimacy to resolve the conflict.¹⁷³ To overcome

¹⁶⁷ Marta Rivera and Eduardo Zamanillo, see n. 86.

¹⁶⁸ Tor Tuorda. *Interview*. Sámi activist and advocate for Indigenous rights. Unpublished interview conducted by the authors. Feb. 2026.

¹⁶⁹ Tuorda, see n. 168.

¹⁷⁰ Human Rights Pulse. *Sweden’s troubled relationship with the Indigenous Sámi community*. <https://www.humanrightspulse.com/mastercontentblog/swedens-troubled-relationship-with-the-indigenous-smi-community>.

¹⁷¹ International Council on Mining and Metals. *Understanding Perceptions Of Mining*. <https://www.icmm.com/en-gb/research/mining-minerals/2023/understanding-perceptions-of-mining>.

¹⁷² Marta Rivera and Eduardo Zamanillo, see n. 86.

¹⁷³ Marta Rivera and Eduardo Zamanillo, see n. 86.

this paralysis, governance should move beyond traditional consultation and towards more inclusive forms of participation.

This may include structures in which communities help shape project design, participate in monitoring, share in local benefits or even co-invest in projects. As Marin and Palazzo argue, these approaches can help reduce polarization and make strategic mining more compatible with a just transition.¹⁷⁴ Without this shift social opposition in the EU such as in Sweden, Portugal, and Serbia may continue to render the CRMA's extraction targets unattainable.¹⁷⁵

5.2.3 Economic constraints and the financing gap

Economic constraints represent another major barrier to the feasibility of the CRMA. The EU has under-invested in mining and processing for several decades, partly because of high costs, permitting, social opposition, and commercial concerns.¹⁷⁶ While China has continued to expand its refining capacity and secure overseas assets, the EU is still trying to rebuild parts of the value chain that have been weakened or externalized over time. In addition, the cost of capital in Europe is also higher, as investors perceive mining projects as high-risk due to regulatory uncertainty and social opposition.^{177 178}

The European Court of Auditors also identifies financing as one of the main bottlenecks for domestic critical raw material production. As previously mentioned, although Strategic Projects may receive political visibility and administrative support, the CRMA does not itself provide direct EU funding.¹⁷⁹

This financing gap extends to the academic and research sectors, further hindering innovation. As Professors Castagliola and Lattanzi note in our interview, the field of economic geology has been largely abandoned in Italian academia because it does not produce the high volume of publications required for funding in a system driven by rapid output metrics.¹⁸⁰ "Studying a deposit in Congo may require years of work before publishing," which penalizes academic careers and reduces incentives for long-term geological research.¹⁸¹

This lack of investment in knowledge creation creates a vicious cycle. Without stronger research capacity, Europe has less ability to understand its own deposits, develop more sustainable extraction methods or improve processing technologies. At the same time, without industrial projects, there are fewer incentives for universities and young researchers to specialize in these fields. This limits the technological advancements needed to make European mining economically viable.

5.2.4 The human capital crisis

An often-overlooked constraint on the CRMA's feasibility is the erosion of human capital. The European mining and metallurgy sectors face a talent gap linked to generational change, declining academic interest, and the loss of technical expertise. The mining industry is ageing, with a workforce increasingly over 50 years old and no clear replacement on the horizon.¹⁸²

¹⁷⁴Institute of Development Studies. *Civic Power In Just Transitions Blocking The Way Or Transforming The Future*. <https://www.ids.ac.uk/publications/civic-power-in-just-transitions-blocking-the-way-or-transforming-the-future/>.

¹⁷⁵European Court of Auditors, see n. 24.

¹⁷⁶International Energy Agency, *Global Critical Minerals Outlook 2025*, see n. 12.

¹⁷⁷Marta Rivera and Eduardo Zamanillo, see n. 86.

¹⁷⁸Climate Foresight. *Moving Mining Back To Europe*. <https://www.climateforesight.eu/articles/moving-mining-back-to-europe/>.

¹⁷⁹European Court of Auditors, see n. 24.

¹⁸⁰Pilario Castagliola and Pierfranco Lattanzi. *Interview*. Experts in ore geology, mineralogy and the environmental impacts of mining. Unpublished interview conducted by the authors. Feb. 2026.

¹⁸¹Castagliola and Lattanzi, see n. 180.

¹⁸²MINING.COM Staff Writer. *Mining Industry Faces Aging Workforce and Retirement Challenges — Report*. Feb. 2023. <https://www.mining.com/mining-industry-faces-aging-workforce-and-retirement-challenges-report/>.

This is not simply a workforce shortage. Critical raw material projects depend on accumulated knowledge of deposits, processing routes, and industrial operations. Rivera and Zamanillo refer to this as a loss of "tacit knowledge": expertise that is built through experience and cannot be quickly recreated once it has disappeared.¹⁸³ Castagliola makes a similar point, stressing that "knowledge of the territory is fundamental," yet the systematic abandonment of this field in universities means Europe is losing the expertise needed to formulate future critical raw material strategies.¹⁸⁴

The problem is also cultural. In much of Europe, mining is still associated with the past, pollution, and older forms of heavy industry, rather than with innovation, strategic autonomy, or the energy transition. This weak symbolic connection between the mining industry and new generations makes it harder to attract new talent into the sector, and requires a cultural repositioning that can't be solved only by short-term incentives. As Rivera and Zamanillo argue, the West has partly lost the ability to present mining as a purposeful and modern industry.¹⁸⁵

5.3 Partnerships and external dependencies

The EU's critical raw materials strategy cannot rely only on domestic extraction, processing, and recycling. Even if the CRMA strengthens European capacity, the EU will continue to depend to varying degrees on imports from resource-producing regions and industrial partners outside its borders. Strategic partnerships are therefore central to the EU's attempt to diversify supply chains, reduce excessive dependence on China, and secure access to not only the materials required for the energy transition but also to the clean technologies enabling it.

These partnerships are not limited to one region. The EU has sought cooperation with resource-rich and strategically relevant partners in Africa, Latin America, North America, Australia, Central Asia, the Western Balkans, and neighbouring regions such as Ukraine. Each region plays a different role: some partners are important because of their reserves of lithium, copper, cobalt, nickel, or rare earth elements, while others are relevant because of their processing capacity, regulatory alignment, or political stability. Independently of their role, the EU should prioritize partnerships that support shared industrial developments, rather than simply securing raw material access for European industry. Hence, strategic partnerships in critical raw materials supply chains should not only be assessed by the volume of output they secure, but also by whether they support local value creation, skills development, infrastructure, and stronger environmental and social governance in partner countries.

Officially, EU partnerships are framed through the language of sustainability, ESG standards, local development, and mutual benefit. In principle, this represents a shift away from older extractive models. However, extraction can still remain driven by the same logic of profit maximization that characterized colonial mining economies. In the Latin American "lithium triangle", for example, lithium extraction raises concerns about water use, Indigenous rights, and negligible local participation, consultation, and consent.¹⁸⁶ Despite this, the vast majority of EU sourcing of refined lithium comes from Chile and Argentina.¹⁸⁷

This does not mean that mining partnerships should be rejected. For many resource-producing countries, critical raw materials can represent a unique opportunity for employment, infrastructure, and industrial

¹⁸³ Marta Rivera and Eduardo Zamanillo, see n. 86.

¹⁸⁴ Castagliola and Lattanzi, see n. 180.

¹⁸⁵ Marta Rivera and Eduardo Zamanillo, see n. 86.

¹⁸⁶ International Work Group for Indigenous Affairs. *A just energy transition: the impacts of lithium extraction on the Andean salt flats of Argentina, Bolivia, and Chile*. <https://iwgia.org/en/bolivia/5777-a-just-energy-transition-the-impacts-of-lithium-extraction-on-the-andean-salt-flats-of-argentina-bolivia-and-chile.html>.

¹⁸⁷ European Commission Joint Research Centre. *Lithium*. <https://rmis.jrc.ec.europa.eu/rmp/Lithium>.

development. However, the EU should ensure that its partnerships do not reinforce unequal extractive relationships under the language of the green transition. This applies not only to relations between the EU and partner countries, but also to the internal governance of extraction in producer countries, where central governments or companies may capture the benefits of extraction while local or Indigenous communities bear most of the environmental and social costs.

5.3.1 Historical inequalities in producing regions

Africa deserves particular attention because many of today's critical raw material supply chains are connected to longer histories of colonial and post-colonial extraction. As highlighted in studies such as 'Expectations of Modernity', Africa is often treated as the forgotten continent within globalization narratives: essential to global supply chains, yet marginalized in discussions of prosperity, sustainability, and technological modernity. As studied by Professor Peça, Zambia exemplifies this contradiction. While the country experienced significant economic growth during the copper boom of the 1960s and early 1970s, decades of dependency on raw material exports and external economic strategies subsequently produced economic decline, social fragmentation, and environmental degradation.¹⁸⁸

The case of Zambia shows why the design of new partnerships matters. Colonial mining economies openly considered both labour and the environment expendable in the name of economic gains.¹⁸⁹ In Zambia, the 1934 Smoke Damage Prohibition Act prohibited communities living within five miles of a smelter from claiming compensation for pollution damages, on the grounds that mining itself supposedly brought sufficient benefits.¹⁹⁰ Remarkably, this legislation remained in force until 1996.¹⁹¹ These historical examples help explain why contemporary mining projects may be viewed with distrust, particularly when local communities are not included in local participation and consultation, giving them reasons to believe that they will bear the costs while external actors capture the benefits.

Colonial spatial inequalities also had a physical dimension. African workers' settlements were often located downwind from smelters and exposed to toxic sulphur dioxide emissions, while European managers lived in safer upwind areas.¹⁹² In addition, materials extracted from African countries such as Zambia and the Congo fueled European electrification, while mining communities themselves often lacked access to electricity.¹⁹³ Although the forms of extraction are different today, the same underlying concern remains relevant. A scenario in which Europe becomes climate-neutral on paper while producer countries continue to endure pollution and land degradation would reproduce older asymmetries under the banner of the green transition.

At the same time, mining cannot be understood solely through the lens of exploitation. In many mining regions, the sector also represents the main form of stable employment, infrastructure, and hopes of modernization. Mine closures and divestment often produce economic collapse and "ghost towns," leaving populations without economic alternatives. This ambivalence is visible in practices such as the reprocessing of "black mountains", enormous waste heaps containing residual minerals. Although such activity may be informal and unsafe, local communities increasingly frame it as a form of reclaiming value from resources historically extracted by colonial powers and multinational corporations.

¹⁸⁸Iva Peša. *Interview*. Specialist in African and environmental history and principal investigator of the AFREXTRACT project. Unpublished interview conducted by the authors. Nov. 2025.

¹⁸⁹Peša, see n. 188.

¹⁹⁰I. Peša. "The Power of Pollution on the Central African Copperbelt". In: 2026. Chap. 7.2.

¹⁹¹Government of Zambia. *An Act to repeal the Actions for Smoke Damage Prohibition Act*. 1996.

¹⁹²Peša, see n. 188.

¹⁹³Peša, see n. 188.

5.3.2 Diversification, dependency, and competition

These dynamics are closely linked to the EU's broader challenge of managing external dependencies. The war in Ukraine has intensified European concerns regarding overreliance on foreign suppliers for critical raw materials, particularly in relation to geopolitical competitors such as China. Consequently, diversification has become a central objective of EU industrial and climate policy. However, diversification does not automatically resolve dependency if the underlying model remains based on securing access to raw materials abroad.

The EU needs partnerships with resource-producing countries to reduce excessive dependence on individual countries and strengthen supply security. Yet, if these partnerships are designed mainly around access, Europe may become less dependent on one dominant supplier but still remain dependent on global commodity markets, political decisions taken outside the EU, and competition from other major powers. A more resilient approach would therefore be building partnerships that support local processing capacity, skills development, infrastructure, environmental governance, and industrial participation in producer countries. Such partnerships would not eliminate external dependence, but they could make it more stable and mutually beneficial.

China's growing role in Africa and other producer countries creates pressure on the EU to secure access to resources quickly. However, while Europe's external demand for critical raw materials remains high, there is still limited political willingness to expand large-scale mining operations within European territories themselves. Mining projects in Europe are frequently met with strong environmental opposition and "not in my backyard" tendencies, reflecting the tension between the demand for critical materials and the reluctance to bear the environmental and social costs of extraction domestically.

This contradiction suggests that geographical diversification alone cannot resolve the structural problems associated with the green transition. Although some mining projects have demonstrated that more environmentally sustainable extraction may be possible under strict regulatory conditions, such models remain difficult to replicate at the scale required by current global energy demand. Ultimately, the deeper challenge lies in rethinking the relationship between modern economies, energy consumption, and extraction itself.

The material intensity of clean technologies does not undermine the case for decarbonization. Rather, it highlights how the energy transition also requires reducing the overall energy and material demand, and developing more decentralized and localized systems of energy production. Without such a transformation, the green transition risks reproducing the same extractive logics and unequal external dependencies that have historically structured relations between Europe and resource-producing regions in Africa, Latin America, and beyond.

5.4 The scale challenge

As highlighted throughout this report, clean energy technologies are significantly more mineral-intensive than conventional fossil-fuel systems. This is partly because wind and solar resources have lower average capacity factors than conventional power plants, meaning that producing the same amount of electricity often requires more installed capacity. This translates into larger infrastructure, more cable connections, and greater investment in grids, substations, storage, and control systems. Consequently, the large-scale deployment of renewable technologies, electric vehicles, batteries, and charging infrastructure under Europe's climate targets will not only significantly increase the demand for critical raw materials, but will also require an unprecedented expansion of energy infrastructure, including mining, refining, and manufacturing capacity, within a relatively short period of time.

5.4.1 Material intensity and project timelines

European climate objectives are generally framed within short political timelines, while the industrial systems required to support them operate on much longer and more uncertain timescales. This mismatch is visible in the CRMA targets. Although the EU appears relatively close to the average extraction benchmark, with domestic extraction capacity estimates at around 8% compared with the 10% target, this figure hides major differences between individual materials. For some strategic raw materials, Europe still has little or no domestic extraction capacity, while processing and recycling remain far from the 2030 goals. Yet, developing this capacity is far more complex than simply deciding to open a mine or build a refinery. New mining projects usually begin as small and risky exploration initiatives searching for economically viable mineral deposits, and only a limited number of these projects eventually become operational mines. Many fail because deposits are not profitable enough, ore grades are lower than expected, financing disappears, permits are delayed or because mineral prices change.

As discussed in Section 5.1, Strategic Project status does not guarantee that a mine or refinery will ultimately be built. In this context, the key point is that successful development of mines usually requires a much larger number of early-stage exploration projects than the final number of operational mines. As noted by Dr Arnoldus in an interview, Europe may therefore need many more exploration initiatives and significantly higher early-stage investment than current project lists indicate.¹⁹⁴

5.4.2 Grid infrastructure and copper bottlenecks

The most important bottleneck, however, lies in Europe's electricity grid infrastructure. Much of Europe's transmission and distribution network, built between the 1950s and 1980s, was designed for centralized fossil-fuel generation systems, and is becoming inadequate for the decentralized and bidirectional electricity flows associated with renewables.¹⁹⁵ This is significant because, while turbines and panels can be installed relatively quickly, the electricity they produce cannot be fully used until new transmission lines, substations, and control systems are in place. And these take years to plan, permit, and build. Until grid infrastructure catches up, many projects will remain stuck in connection queues, delaying the energy transition and potentially increasing carbon emissions.

This problem is already becoming visible in Europe. In 2024, around 1700 GW of renewable energy projects across 16 European countries were waiting in grid connection queues.¹⁹⁶ This reflects an imbalance between renewable deployment and grid investment. Since 2010, investment in renewables has nearly doubled, while global investment in grids barely changed. According to the IEA, achieving current national energy and climate targets will require adding more than 80 million kilometres of electricity grid worldwide by 2040, equivalent to rebuilding the entire existing global grid network.¹⁹⁷ This would require doubling current global investment in grid infrastructure.

And behind all this infrastructure lies copper. Transmission lines, transformers, and substations, alongside electric vehicles and renewables, depend heavily on copper due to its high electrical conductivity. However, the IEA warned in its latest Critical Raw Materials Outlook 2025 that future copper supply could struggle to keep pace with projected demand under energy-transition scenarios. Even considering all existing and

¹⁹⁴Hurk Mir, see n. 140.

¹⁹⁵VOYCE. *The EU Grid Package: grids for the energy transition*. <https://voycecommunity.eu/our-work-1/f/the-eu-grid-package-grids-for-the-energy-transition?blogcategory=Energy>.

¹⁹⁶Beyond Fossil Fuels. *Report: Final*. https://beyondfossilfuels.org/wp-content/uploads/2025/05/REPORT_FINAL.pdf.

¹⁹⁷International Energy Agency. *Electricity Grids and Secure Energy Transitions*. <https://www.iea.org/reports/electricity-grids-and-secure-energy-transitions/executive-summary>.

announced mining projects, global copper supply could face deficits of around 30% by 2035 under current policy scenarios, with even larger deficits under more ambitious net-zero pathways.¹⁹⁸

The primary reason for this is the depletion of the easiest and highest-grade deposits. Average copper ore grades have declined by around 40% since 1991,¹⁹⁹ meaning that producing the same amount of copper increasingly requires moving and processing larger quantities of material. This increases energy use, costs, environmental impacts, and project complexity. At the same time, the rate at which new large copper deposits are being discovered has slowed considerably, while new mining projects frequently end up requiring more than 15 years to develop from discovery to production.

All of this creates a structural mismatch between political ambitions and physical deployment realities. In this situation, the solution cannot rely exclusively on continuously expanding extraction, infrastructure, and material consumption. Strategies aimed at strengthening resilient critical material supply chains remain necessary, but they should be complemented by efforts to reduce overall material intensity. The following section therefore examines how material demand could be reduced from within, first through innovation in existing technologies and then through a wider discussion of the limits of efficiency and the important role of sufficiency.

5.5 Reducing material demand

The previous section discussed how the scale of the energy transition creates pressure not only on critical raw material supply chains, but also on grids, infrastructure, and industrial capacity. This section consequently explores how material demand could be reduced from within. Chapter 2 already explored material substitution and technological innovation as important tools to reduce dependence on specific critical raw materials. Building on that, this section uses selected examples of technological improvement to show that innovation remains necessary but is not sufficient on its own. It argues that these technological improvements must be complemented by broader efficiency and sufficiency measures capable of reducing avoidable demand.

5.5.1 The limits of technological innovation

As shown in previous sections, battery manufacturing is one of the largest drivers of critical raw material demand. A logical response is therefore to focus on material innovation, either by substituting the critical raw materials used or by reducing the quantities required. By drawing on three examples of battery innovation and rare-earth-free alternatives in wind turbine design, these examples show that technological innovation can reduce pressure on specific materials but often introduces new trade-offs and does not eliminate the broader scale challenge.

A significant shift is already underway from nickel-cobalt-manganese batteries toward lithium iron phosphate (LFP) batteries. LFP batteries rely on more abundant iron and phosphate and reduce dependence on cobalt and nickel, two materials with significant supply chain concerns.²⁰⁰ Research suggests that combining LFP adoption with recycling could reduce future lithium, cobalt, and nickel demand by 2060.²⁰¹

However, LFP batteries alone do not remove the material dependence problem. They still depend on lithium, and their growing deployment will continue to increase absolute lithium demand if the total

¹⁹⁸International Energy Agency, *Global Critical Minerals Outlook 2025*, see n. 12.

¹⁹⁹International Energy Agency, *Global Critical Minerals Outlook 2025*, see n. 12.

²⁰⁰PubMed Central. *PMC article*. <https://pmc.ncbi.nlm.nih.gov/articles/PMC12419118/>.

²⁰¹Mohamed Amer et al. *Critical Materials for EV Batteries: Challenges, Opportunities, and Policymakers*. In: *International Journal of Electrical Engineering and Sustainability* 3.1 (2025), pp. 119–133. <https://ijees.org/index.php/ijees/article/download/117/76>.

number and size of batteries just keeps rising. This illustrates an important limitation of substitution: it can reduce dependence on specific materials but it does not necessarily reduce overall material consumption if deployment continues to expand at the current rate.

Sodium-ion batteries (SIBs) represent a more radical form of substitution because they replace lithium with widely available sodium. They can also eliminate the need for cobalt and nickel, serving as a lower-cost alternative for stationary energy storage and short-range electric vehicles.²⁰² However, as discussed in Chapter 2, they also have limitations. Their lower energy density makes them less suitable for applications where weight and range are critical, and their supply chain is still scaling up and its production capacity remains highly concentrated in China, meaning that although SIBs reduce lithium dependence, the strategic supply chain vulnerability would remain. Global production capacity for SIBs is currently much smaller than for lithium-ion batteries, but it is expected to expand significantly by 2030.²⁰³

Solid-state batteries are another important innovation pathway. By replacing liquid electrolytes with solid alternatives, they can increase energy density and thus require less critical raw material per unit of stored energy.²⁰⁴ However, solid-state batteries do not necessarily reduce critical raw material dependence. Many designs still rely heavily on lithium, and some may require lithium-metal anodes, increasing the amount of primary lithium required compared with conventional graphite-based designs.²⁰⁵ This shows that technological improvements are not always linked to lower material demand.

A similar pattern is seen in wind turbine designs. As discussed in previous sections, most wind turbines rely on permanent magnets containing rare earth elements, which are often involved in geopolitically sensitive supply chains. The most immediate way to reduce this dependence is to change the internal architecture of the generator so it doesn't require permanent magnets.

Electrically excited synchronous generators use copper coils fed with an external electrical current to create an electromagnet. This avoids rare earth permanent magnets, but it increases copper use, generator size, and maintenance requirements. These drawbacks are especially relevant for offshore wind farms, where maintenance is more difficult and costly.²⁰⁶

Advanced induction generators offer another magnet-free option by using copper rotors and gearboxes to increase rotational speed. Gearboxes, however, add mechanical complexity and are less attractive in offshore environments, where reliability and reduced maintenance are important.

Other innovative approaches use magnets made from more abundant, non-critical materials. Iron nitride magnets, ferrite-based axial-flux generators, and high-temperature superconducting generators are examples of technologies that could reduce or eliminate rare earth use while maintaining high magnetic strength.²⁰⁷ High-temperature superconductors, which were explored in Chapter 2, could also reduce generator size and weight while reducing or even eliminating the need for permanent magnets and reducing the amount of copper needed, although they require complex cooling systems that make large-scale commercialization

²⁰² Amer et al., see n. 201.

²⁰³ Rickard Arvidsson, Julia Brunke, and Björn Sandén. *Status and Prospects of the Sodium-Ion Battery Production System Until 2030: The 2025 Update*. Chalmers University of Technology, 2026. <https://research.chalmers.se/en/publication/550820>.

²⁰⁴ Arvidsson, Brunke, and Sandén, see n. 203.

²⁰⁵ Battery Technology Online. *Lithium solid-state batteries in 2026: promise, physics and the path to commercial reality*. <https://www.batterYTECHONLINE.com/industry-outlook/lithium-solid-state-batteries-in-2026-promise-physics-and-the-path-to-commercial-reality>.

²⁰⁶ Rasul Satymov, Dmitrii Bogdanov, and Christian Breyer. *Techno-economics of offshore wind power in global resolution*. In: *Applied Energy* 393, 125980 (2025).

²⁰⁷ Baltic Wind. *Work continues on rare-earth-free generator for offshore wind turbines*. <https://balticwind.eu/work-continues-on-rare-earth-free-generator-for-offshore-wind-turbines/>.

difficult.²⁰⁸ As with batteries, the challenge is not the absence of alternatives but the trade-offs between material dependence, performance, reliability, cost, and scalability.

Taken together, these technological examples show both the importance and the limits of technological and material substitution. Each alternative involves trade-offs, and none removes the broader relationship between clean technology deployment and material demand. This is why technological innovation must be complemented by efficiency improvements and sufficiency measures.

5.5.2 Efficiency improvements in existing systems

Efficiency improvements in existing technologies can also reduce pressure on critical raw material demand. In electric vehicles, one of the most direct opportunities is to reduce unnecessary battery size. Academic models indicate that right-sizing vehicle range to meet actual consumer driving needs, rather than over-engineering large 500-mile range batteries, is one of the fastest ways to reduce absolute mineral demand. Additionally, maximizing the efficiency of the EV itself, through lighter materials, better aerodynamics, and efficient power electronics, means vehicles can travel the same distance with smaller batteries, reducing the amount of lithium, nickel, cobalt, manganese, and graphite required per vehicle.²⁰⁹

Efficiency improvements are also relevant for electricity grids. The physical expansion of transmission and distribution networks demands massive quantities of copper and aluminium. Superconductors transmit electricity with zero electrical resistance and could, in principle, transmit significantly more electricity than conventional cables within a smaller physical footprint, reducing the need for the copper-intensive grid expansion. However, as previously mentioned, their deployment still depends on cost, cooling requirements, and commercial scalability.

Smart grid technologies offer a more immediate way to improve the use of existing infrastructure. Uncontrolled EV charging during peak hours strains electricity networks and increases the need for grid reinforcements.²¹⁰ Smart charging can shift part of this demand to off-peak hours, while vehicle-to-grid systems allow electric vehicles to provide distributed storage and flexibility to the grid, minimizing the need to build separate, mineral-heavy stationary battery storage facilities.²¹¹ In parallel, AI-driven digital monitoring and advanced grid management tools can help operators use existing lines more efficiently and identify capacity constraints more accurately.²¹² These measures do not remove the need for new infrastructure, but they can delay or reduce some grid expansion and thus limit additional demand for copper, aluminium, and battery materials.

²⁰⁸European Commission Joint Research Centre. *JRC publication JRC141759*. <https://publications.jrc.ec.europa.eu/repository/handle/JRC141759>.

²⁰⁹Union of Concerned Scientists. *Making the most of EV batteries: executive summary*. <https://www.ucs.org/sites/default/files/2024-12/making-most-ev-batteries-executive-summary.pdf>.

²¹⁰Union of Concerned Scientists, see n. 209.

²¹¹London School of Economics and Political Science. *Working Paper 435: Dugoua and Noailly*. <https://www.lse.ac.uk/granthaminstitute/wp-content/uploads/2025/12/working-paper-435-Dugoua-Noailly.pdf>.

²¹²MDPI. *Energy and environmental sustainability*. <https://www.mdpi.com/2071-1050/18/8/4043>.

5.5.3 The limits of efficiency

Although the focus of many technological sectors is to improve technological efficiency to reduce total material or energy demand, this does not always happen. The economic foundation of this limitation is the Jevons Paradox, first observed by William Stanley Jevons in 1865. Jevons noted that James Watt's improvements to the steam engine made coal use more efficient, which lowered the cost of steam power. This cost reduction expanded industrial applications and increased aggregate coal consumption rather than reducing it. In modern economics, this is studied as the rebound effect: efficiency gains lower the implicit price of using a resource or service, which can induce greater demand.²¹³

This is relevant to the energy transition because many environmental policies assume that green innovation will allow economic growth to decouple from resource use and environmental damage.²¹⁴ Efficiency improvements can reduce emissions or material demand per vehicle, per battery, per kilometre, or per unit of electricity generated. However, if the number of vehicles, batteries, kilometres travelled or electricity consumed continues to rise, total material demand may still increase.

This is why the distinction between efficiency and sufficiency is important. The Intergovernmental Panel on Climate Change (IPCC) notes that solving the climate crisis requires both approaches.²¹⁵ Efficiency can be understood as doing things better, whereas sufficiency is about doing the right things.²¹⁶ For this report, the distinction is central: improving battery chemistry, wind turbine design, or grid management can reduce some material pressures, but sufficiency policies address the demand that makes those pressures grow.

Sufficiency does not mean personal sacrifice or technological regression. Modern literature increasingly defines it as a structural reconfiguration of consumption and infrastructure within social and ecological limits.²¹⁷ This idea is closely related to the "doughnut" framework, in which economic activity should remain below planetary limits, such as resource availability and carbon thresholds, while still guaranteeing a social foundation for human well-being.²¹⁸

However, sufficiency is still largely treated as individual behaviour change or as necessary exogenous trends that will need to take place, rather than as a genuine field of policy action.²¹⁹ This limits its role in energy and industrial policy. If sufficiency is understood only as a personal restraint, it remains politically weak. If it is treated as a policy framework, it can guide decisions on transport, urban planning, product lifetimes, infrastructure design, and energy demand.

For this reason, sufficiency and efficiency are not mutually exclusive; they must operate in parallel to safely navigate resource limitations.²²⁰ Efficiency remains necessary because it reduces waste and improves the performance of existing technologies. But without sufficiency, efficiency benefits may be absorbed by growth in total consumption.

²¹³Frontiers. *Energy Research article*. <https://www.frontiersin.org/journals/energy-research/articles/10.3389/fenrg.2021.686140/full>.

²¹⁴Antonio Alonso-Jimenez et al. *The Jevons Paradox and Vernon's Product Life Cycle: Evidence from Primary–Secondary Price Differentials in Copper and Aluminium (2002–2021) with 2024–2025 Market Context*. In: *Intelligent and Sustainable Manufacturing* 3.1, 10035 (2026).

²¹⁵Intergovernmental Panel on Climate Change. *IPCC AR6 WGIII: Chapter 9*. <https://www.ipcc.ch/report/ar6/wg3/chapter/chapter-9/>.

²¹⁶Intergovernmental Panel on Climate Change, see n. 215.

²¹⁷Ian Gough. *Sufficiency as a Value Standard: From Preferences to Needs*. In: *Ethics, Policy & Environment* (2023).

²¹⁸Institute of Sustainability Studies. *Understanding Doughnut Economics: A Framework for Sustainability*. <https://instituteofsustainabilitystudies.com/insights/lexicon/understanding-doughnut-economics-a-framework-for-sustainability/>.

²¹⁹Carina Zell-Ziegler et al. *Enough? The role of sufficiency in European energy and climate plans*. In: *Energy Policy* 157, 112483 (2021).

²²⁰Oskar Lindgren et al. *Exploring sufficiency in energy policy: insights from Sweden*. In: *Sustainability: Science, Practice and Policy* 19.1, 2212501 (2023).

5.5.4 Energy sufficiency in practice

In the context of critical raw materials, sufficiency means asking not only how technologies can become cleaner or more efficient, but whether the same social needs can be met with less material-intensive systems. Two examples are particularly relevant for the EU's energy transition: reducing dependence on private electric vehicles through stronger public transport, and using energy communities to align local electricity demand with local renewable generation.

EVs are among the largest drivers of critical raw material demand, as established in the previous section. It is therefore important to critically examine both the technology itself and the policies promoting it, and to consider where sufficiency-based approaches might offer a better path forward. Over 30 million electric vehicles are currently on global roads, with annual sales growing by nearly 75%. The EU has set a target of 30 million zero-emission cars by 2030 and a near-total transition by 2050.²²¹

Yet a policy focus narrowly centred on private EV adoption disproportionately benefits wealthier households. High-income households are far more likely to own a car than low-income households, meaning that subsidies or incentives focused primarily on private vehicles may leave marginalized communities underserved.²²² From an emissions and material perspective, the gap is similarly stark. Lifecycle analyses suggest that private electric vehicles can have substantially higher embedded emissions and material requirements per passenger than electric public transport due to global supply chains and vehicle utilization rates.

As an example, the average car or van in England is driven only 4% of the time, meaning it sits parked for 23 hours a day.²²³ Lifecycle assessments indicate that the emissions embedded in battery manufacturing may require one to two years, or roughly 17 000 kilometers, of driving before an electric vehicle breaks even with an internal combustion vehicle. Public buses, by contrast, operate more intensively throughout the day, amortizing their manufacturing emissions much more quickly.

The Institute for Public Policy Research has proposed a National Transport and Digital Connectivity Guarantee to reduce private car dependence, targeting peak car ownership by 2030 and a sustained decline by 2050. As governments face declining fuel-tax revenues and scale back private EV subsidies, as seen in France and Germany, reallocating fiscal resources toward public fleets may offer a higher return on investment, both environmentally and socially.²²⁴

Beyond public electric transportation, integrating energy communities with localized virtual power plants offers a complementary pillar of a sufficiency policy framework. By connecting demand-side flexibility with the legal structure of local energy cooperatives, already recognized under the EU's Clean Energy for All Europeans Package, the EU could reduce pressure on high-voltage transmission expansion and alleviate part of the copper and aluminium bottleneck.²²⁵

When electricity is generated by large, remote offshore wind farms or distant solar arrays, it must travel long distances across high-voltage lines to reach urban centres. During this transit, part of the power is

²²¹ European Commission. *Sustainable and Smart Mobility Strategy - Putting European Transport on Track for the Future*. COM(2020) 789 final. 2020. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0789>.

²²² Institute for Public Policy Research. *Shifting to Electric Vehicles Isn't Enough: Public Transport, Walking and Cycling Need Greater Role in UK's Future*, Says IPPR. June 23, 2021. <https://www.ippr.org/media-office/shifting-to-electric-vehicles-isn-t-enough-public-transport-walking-and-cycling-need-greater-role-in-uk-s-future-says-ippr>.

²²³ Emily Nagler. *Standing Still: The Way Cars Are Used in England*. RAC Foundation, 2021. <https://www.racfoundation.org/wp-content/uploads/standing-still-Nagler-June-2021.pdf>.

²²⁴ Institute for Public Policy Research, see n. 222.

²²⁵ Clean Air Task Force. *Clean Energy from the Ground Up: Energy Communities in the European Union*. <https://www.catf.us/resource/clean-energy-ground-up-energy-communities-european-union/>.

lost as heat through electrical resistance, known as transmission and distribution losses. To compensate, utilities may be forced to over-generate capacity and use more conductive material in grid infrastructure.²²⁶

A centralized virtual power plant treats large numbers of consumers as a single undifferentiated load. An energy-community-driven virtual power plant, by contrast, can operate closer to the principle of subsidiarity, aligning consumption patterns with the specific generation mix of each municipality or local area. By embedding virtual power plant algorithms at the community level, local appliances can be coordinated to follow local generation patterns. Water heaters, electric vehicle charging stations, or municipal water pumps, for example, can be scheduled to operate when neighbourhood solar or wind generation is highest.²²⁷

A persistent concern with large-scale virtual power plants is their potential reliance on centralized battery energy storage systems, which can intensify demand for lithium and cobalt.²²⁸ Energy communities offer a more resource-efficient alternative when they combine demand flexibility with thermal storage and behavioural adaptation. Rather than storing excess midday electricity only in mineral-intensive chemical batteries for evening use, a localized community can redirect surplus solar generation into district heating networks or communal water tanks, storing energy thermally instead.

Crucially, because community members hold direct democratic stakes and economic interests in their local cooperative, they may exhibit higher social acceptance and greater behavioural flexibility. This can make members more willing to shift flexible electricity demand towards periods of peak local generation than in systems managed by a large, impersonal utility provider.²²⁹

These examples show how sufficiency can become a practical policy approach rather than a call for individual sacrifice. In both cases, the objective is not to reduce welfare, but to deliver the same or better social outcomes with lower material and energy requirements.

²²⁶Clean Air Task Force, see n. 225.

²²⁷Arkadiusz Przychodzień. *Virtual Power Plants - Types and Development Opportunities*. In: *E3S Web of Conferences* 137, 01044 (2019).

²²⁸Przychodzień, see n. 227.

²²⁹Clean Air Task Force, see n. 225.

6. CONCLUSION AND POLICY RECOMMENDATIONS

6.1 Conclusion

The EU's energy transition is not only a question of replacing fossil fuels with renewable technologies. It is also a material, industrial, geopolitical, and social challenge. Electrification, renewable deployment, batteries, hydrogen technologies, digital infrastructure, and electricity grids all depend on specialized raw materials whose supply chains are complex, concentrated, and slow to expand. As this report has shown, critical raw material dependence has become part of energy security, industrial competitiveness, and strategic autonomy.

The central finding of this report is that Europe cannot secure its energy transition through additional supply agreements and isolated Strategic Projects alone. The Critical Raw Materials Act is a necessary first step because it recognizes the need to strengthen extraction, processing, recycling, and supply diversification. However, its benchmarks and Strategic Projects will not by themselves create resilient European value chains. Projects must be connected to reliable material inputs, downstream manufacturers, infrastructure, skilled workers, long-term demand, and end-of-life recovery systems.

China's position illustrates the nature of the challenge. Its leverage is strongest not only in mining, but in refining, processing, and downstream manufacturing, where scale, technical know-how and industrial coordination create bottlenecks that Europe cannot quickly replace. At the same time, domestic European projects face long development timelines, financing barriers, public legitimacy challenges, and social opposition. External partnerships are therefore unavoidable, but they must avoid reproducing extractive dependencies in producer countries.

To build a resilient supply chain strategy, Europe must combine supply- and demand-side measures. The EU needs stronger domestic and partner-country capacity across extraction, processing, manufacturing, and recycling. It also needs to reduce avoidable material demand through efficiency and sufficiency, and material-aware infrastructure planning. The aim of the bloc should not be self-sufficiency, which is neither realistic nor desirable, but the development of diversified, transparent, and mutually beneficial value chains aligned with climate neutrality, industrial competitiveness, and democratic legitimacy.

6.2 Policy recommendations

The findings of this report point to six interdependent priorities for EU action. These recommendations should not be treated as isolated measures but as parts of a single broader resilience building strategy. Securing strategic reserves without building industrial capacity would only buy time. Attempting to rebuild the European critical raw material industrial ecosystem without public legitimacy would only face political and public blockage. The objective of these policy priorities is to combine short-term resilience with long-term supply-chain development.

The recommendations below build on the analysis developed throughout the report and translate it into practical policy priorities. They focus on coordination, industrial capacity, demand management, circularity, public legitimacy, and international partnerships. Taken together, they aim to move EU action from fragmented and reactive supply-risk management towards a coordinated model of critical raw material security aligned with climate neutrality, industrial competitiveness, and democratic legitimacy.

Table 4: Summary of policy recommendations

Recommendation	Main objective
<i>Coordinate EU critical raw material strategic security</i>	Coordinate foresight, risk monitoring, strategic reserves, and crisis response across EU and Member States strategies
<i>Rebuild the European critical raw material industrial ecosystem</i>	Strengthen mining, refining and processing, manufacturing, recycling, research, and skills capacity inside Europe
<i>Put demand management at the centre of the transition</i>	Reduce avoidable material demand through sufficiency, efficient mobility, and material-aware infrastructure planning
<i>Strengthen circularity, traceability, and material efficiency</i>	Create demand for responsibly sourced, traceable, recyclable, and material-efficient products
<i>Build public legitimacy and local benefits</i>	Link strategic projects to transparent participation, local value sharing, and credible environmental safeguards
<i>Develop strategic partnerships for responsible value creation</i>	Diversify imports while supporting local processing, skills, infrastructure, and responsible sourcing in producer countries

1

Coordinate EU critical raw material strategic security

Proposal

The EU should develop a stronger coordination mechanism for critical raw material security, treating it as a cross-cutting energy, industrial, and geopolitical issue. Critical raw material exposure should not be monitored only through combined CRMA benchmarks, but by material, value-chain stage, and strategic use. This would allow the EU to clearly identify where risks are more urgent, and act accordingly.

Key actions

1. Coordinate EU and national demand projections across energy, grids, transport, defence, and digital infrastructure.
2. Map material-specific exposure across extraction, processing, manufacturing, and recycling, rather than relying only on aggregate CRMA benchmarks.
3. Create a limited strategic reserve for the most vulnerable materials, especially where import concentration is high and substitution potential is low.
4. Use long-term purchase agreements and offtake contracts to de-risk new European and partner-country supply chains.

Implementation

The Commission, relevant Directorates-General, and Member State authorities should jointly maintain critical raw material risk assessments linked to national energy and industrial plans. The European Parliament could request annual reporting on reserve coverage, import concentration, and CRMA progress by material, not only in aggregate.

Risks and safeguards

A strategic reserve should remain targeted and transparent, with clear release rules and regular stress tests. If stockpiling is too broad, it could become expensive or distort markets; it should therefore focus on high-risk, low-substitutability materials where temporary disruptions could seriously affect clean technology deployment or industrial resilience.

2

Rebuild the European critical raw material industrial ecosystem

Proposal

The EU should move from a project-based approach towards coordinated value-chain strategies for critical raw materials. Strategic Projects are necessary, but individual mines, refineries, or recycling facilities will not create supply-chain resilience if they remain disconnected from downstream manufacturing, infrastructure, skilled workers, and long-term demand. The EU should therefore treat extraction, refining and processing, component manufacturing, recycling, research, and skills as connected parts of the same industrial ecosystem.

Key actions

1. Prioritize the most severe material-specific bottlenecks, particularly in refining and processing, where European dependence is often strongest.
2. Ensure that new extraction, processing, and recycling projects are connected to downstream manufacturers and long-term buyers.
3. Use public-private financing, European Investment Bank support, and risk-sharing instruments to de-risk strategic processing facilities and component manufacturing.
4. Develop European apprenticeship, vocational, and dual-study pathways in geology, mining engineering, metallurgy, materials chemistry, industrial maintenance, and recycling technologies.
5. Embed innovation ecosystems within industrial ecosystems, so that substitution, sodium-ion batteries, magnet recycling, and low-material designs can scale in Europe rather than leave at pilot stage.

Implementation

This should combine EU funds, national industrial strategies, universities, research institutes, and private firms. Strategic Projects should be assessed not only by the capacity they add individually, but also by how they connect with other stages of the European value chain.

Risks and safeguards

Public support may be wasted if projects are developed without reliable material inputs, downstream buyers, sufficient skilled workers or long-term demand. There is also a risk that Europe builds isolated capacity at one stage of the value chain without solving the wider bottleneck. To avoid this, funding should prioritize projects that demonstrate credible links across the value chain and respond to clearly identified material-specific gaps. Industrial support should also remain conditional on strong environmental and social standards, so that rebuilding European capacity does not come at the cost of public legitimacy or environmental protection.

3

Put demand management at the centre of the transition

Proposal

The EU should integrate material efficiency and sufficiency into energy, mobility, and infrastructure policy, so that the energy transition reduces avoidable critical raw material demand instead of relying only on expanding clean technology supply. This does not mean slowing down decarbonization. Rather, it means designing the transition in a way that delivers the same or better social outcomes with lower material intensity. Critical raw materials should therefore be treated as a planning constraint in major energy, grid, transport, and industrial decisions.

Key actions

1. Prioritize public transport, rail, cycling infrastructure, shared mobility, and smaller, efficient electric vehicles where these reduce battery material demand per passenger-kilometre.
2. Require major grid, renewable, and storage plans to include critical raw material exposure and material-efficiency assessments.
3. Support energy communities, demand-side flexibility, and thermal storage where they reduce avoidable grid reinforcement and battery deployment needs.
4. Strengthen repairability and durability requirements for electronics, batteries, vehicles, and renewable-energy equipment.
5. Use public procurement and EU funding criteria to reward projects that minimize material intensity where technically and economically feasible.

Implementation

Demand management should be integrated into existing EU planning and funding instruments, including national energy and climate plans, TEN-E, TEN-T, public procurement rules and EU infrastructure funding. Projects should not be rejected simply because they require critical raw materials. However, project developers and public authorities should be required to show that material demand has been assessed and reduced where feasible. This would make material efficiency a normal part of infrastructure and industrial planning, rather than an afterthought.

Risks and safeguards

Material efficiency should not become a hidden obstacle to urgent decarbonization. If applied too rigidly, it could delay necessary renewable, grid, or mobility infrastructure. The safeguard is to treat demand management as a design and prioritization criterion, not as a blanket cap on clean technology deployment. The objective should be to avoid unnecessary material demand, not to restrict essential investment.

4

Strengthen circularity, traceability, and material efficiency

Proposal

The EU should strengthen circularity, traceability, and material efficiency for products containing high-value critical raw materials. End-of-life products should be treated as a strategic resource, not only as waste. This requires improving collection, repairability, reuse, product design, and recycling capacity, while ensuring that critical raw materials can be traced across the value chain. A European framework for material-efficient and traceable products could help create demand for responsibly sourced, repairable, recyclable, and high-recovery products.

Key actions

1. Use public procurement to create demand for traceable, repairable, and high-recovery products.
2. Introduce product-level traceability for batteries, electronics, permanent magnets, solar panels, and industrial equipment containing high-value critical raw materials.
3. Support dedicated recycling capacity for materials with low current recovery rates, including rare earth elements from permanent magnets, and high-purity silicon from solar photovoltaics.
4. Strengthen collection and return schemes so that e-waste and end-of-life products become a reliable source of secondary materials.

Implementation

This framework should build on existing EU rules on batteries, ecodesign, due diligence and the circular economy, rather than creating a disconnected reporting burden. Digital product passports could help identify where valuable materials are located, how they were sourced, and whether they can be repaired, reused, or recycled. Public procurement should be used to create early demand for products that meet higher standards of traceability, durability, repairability, and recovery.

Risks and safeguards

Circularity policies can become symbolic if standards are too weak, but they can also become excessively burdensome if reporting requirements are too complex. To avoid this, the EU should use a tiered system that distinguishes minimum compliance from best-in-class performance. The framework should also include clear rules on impact allocation across the supply chain. Otherwise, there is a risk that the environmental and social impacts of extraction and processing are attributed mainly to supplier countries, while the EU benefits from final products and reports progress towards its own climate targets.

5

Build public legitimacy and local benefits

Proposal

The EU and Member States should make public legitimacy and local benefits central conditions for strategic critical raw material projects. Domestic extraction and processing will not advance if affected communities perceive projects as imposed, environmentally risky or disconnected from local needs. Accelerated permitting for Strategic Projects should therefore be matched with early participation, transparent information, credible environmental safeguards, and visible local returns. Where projects affect Indigenous communities, their rights, livelihoods, cultural heritage, and knowledge systems should receive specific protection and meaningful representation in decision-making.

Key actions

1. Launch EU-wide public communication explaining why critical raw materials matter for energy security, climate neutrality, and everyday technologies, while also showing how consumption, mobility, and energy choices influence material demand.
2. Require early, transparent, and accessible consultation for Strategic Projects, including clear information on environmental impacts, risks, and mitigation measures.
3. Use community benefit agreements, local employment targets, training programmes, and infrastructure co-benefits to ensure that host communities share project value.
4. Protect Indigenous rights where relevant, including meaningful participation and respect for Free, Prior, and Informed Consent.
5. Avoid presenting mining and refining as impact-free; credibility depends on acknowledging trade-offs while demonstrating strong standards, monitoring, and local benefits.

Implementation

The Commission and Member States could develop a model local benefit and participation framework for Strategic Projects under the CRMA. This framework should define minimum expectations for consultation quality, public reporting, local benefit sharing, and environmental monitoring. The European Parliament could scrutinize whether accelerated permitting for Strategic Projects is being matched by stronger democratic safeguards, rather than simply shortening procedures without improving trust.

Risks and safeguards

If participation is superficial, public trust will deteriorate and projects may face stronger opposition, even when they are strategically important. Local benefit mechanisms should therefore be concrete, transparent, and enforceable. At the same time, public legitimacy should not be reduced to communication campaigns. Communities need procedural influence, access to environmental information, and visible benefits.

6

Develop strategic partnerships for responsible value creation

Proposal

The EU should develop long-term strategic partnerships that diversify critical raw material supply while supporting responsible value creation in producer countries. Full self-sufficiency is neither realistic nor desirable for Europe, meaning that external partnerships will remain essential. However, these partnerships should move beyond transactional sourcing. They should support local processing, workforce development, infrastructure investment, technology transfer, and responsible sourcing, so that producer countries can capture more value from their own resources and avoid remaining locked into raw material export dependency.

Key actions

1. Move from transactional sourcing to partnerships that support local value creation and reduce the risk of green extractivism.
2. Use EU environmental, social, and governance standards as a competitive advantage, while avoiding one-sided conditionality that makes Europe an unattractive partner.
3. Diversify across multiple supplier countries, regional partnerships, and value-chain stages, including extraction, processing, refining, and component production.
4. Where individual countries lack the scale to develop complete industrial ecosystems alone, support regional strategies that build shared processing capacity, infrastructure, and skilled labour.
5. Where strategically useful, explore controlled knowledge-transfer arrangements with external firms, including Chinese companies, in exchange for European assembly, component sourcing, and industrial learning, while protecting security-sensitive sectors.

Implementation

The EU should align trade policy, Global Gateway, development finance, industrial policy, and raw material partnerships around the objective of responsible value creation. Partnership evaluation should include not only the volume of materials secured, but also local jobs, labour-union, and worker perspectives, infrastructure benefits, human rights protections, environmental safeguards, and supply diversification outcomes.

Risks and safeguards

Strategic partnerships can reproduce dependency if Europe imports raw materials while externalizing environmental and social costs to producer countries. They can also become unattractive if EU standards are perceived as one-sided conditionality rather than as part of a mutually beneficial industrial strategy. To avoid this, local value creation and due diligence conditions should be embedded from the beginning.



Report on Critical Raw Materials in Europe's Energy Transition
VOYCE — Voice Of Youth for Change in Europe
Energy Commission

2026