STUDY

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Strengthening the security of supply of products containing Critical Raw Materials for the green transition and decarbonisation

Policy Department for Economic, Scientific and Quality of Life Policies
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Strengthening the security of supply of products containing Critical Raw Materials for the green transition and decarbonisation

Abstract

This study assesses the needs and vulnerabilities of the EU in accessing products containing Critical Raw Materials (CRM) needed for the green and digital transitions in a changing geopolitical context. It provides an overview on the wider situation, as well as a policy context. The study sets out to identify at which stage of the supply chain, ranging from raw materials to final products, the European industrial eco-system is dependent on CRM imports. It reviews the CRM methodology designed by the JRC to identify which materials are critical and require special attention. The current methodology could benefit from an extension of scope, including an assessment of product groups and sectors. A study finds that setting up of EU stockpiling facilities could mitigate supply disruptions of raw materials and components. However, setting up stockpiling facilities would require an effective public-private management.

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LIST OF ABBREVIATIONS AND GLOSSARY

CAGR	Compound Annual Growth Rate, the annual growth rate that is needed to reach a certain total (for instance annual mining production) in a certain horizon year (for instance 2030)
Capital stock	Stock of tangible, durable fixed assets owned or used by resident enterprises for more than one year. This includes plant, machinery, vehicles and equipment, installations and physical infrastructures, the value of land improvements, and buildings
CBA	Cost Benefit Analysis, a systematic method for quantifying and then comparing the total costs to the total expected rewards
Consumption in all applications	Consumption in all applications or total use of raw materials in all stages of the supply chain: in the shape of raw materials, intermediates and final products
CPA	Classification of Products by Activity, a statistical nomenclature for product groups, directly linked to sector classifications
CRM	Critical Raw Materials, the raw materials that are critical to present society
CRM assessment	Critical Raw Material assessment, the analysis of the role of many chemical elements, in the shape of minerals or processed material
DPA	The Defence Production Act of the USA
EVs	Electric Vehicles
Extraction, processing, manufacturing	The subsequent process in the supply chain, of taking raw materials from the planet, purifying/processing them into intermediate products and finally manufacturing them into a final product ready for household or professional use
EU	European Union
FTA	Free Trade Agreement
First-tier supplier	Entity in the chain that directly supplies an enterprise, including contracted manufacturing facilities or production partners. In cascade, second tier suppliers supply a first-tier suppliers, and so on
FONES	Federal Office for National Economic Supply, of Switzerland
GDP	Gross Domestic Product
HHI	Herfindahl-Hirschman Index, a measure in economic research describing the concentration of suppliers in the market

HS/CN	Harmonized System/Combined Nomenclature, a statistical nomenclature for product groups, adopted by customs throughout the world. It is not directly linked to sector classifications and often includes the label "not elsewhere specified (n.e.s.)"
Human capital	Quality and quantity of the labour force in society. It can also be regarded as a type of stock
Industrial eco-system	Industrial ecosystems encompass all players operating in a value chain: from the smallest start-ups to the largest companies, from academia to research, service providers to suppliers
Industrial policy	Government policies directed at affecting the economic structure of the economy
IEA	International Energy Agency
IPCEI	Important Project of Common European Interest
JRC	Joint Research Centre of the European Union
MAV	Maximum Annual Volatility. This metric for price volatility is calculated as the maximum deviation from the 11 previous monthly averages
MFN	Most Favoured Nations, a group related to a tariff that applies to all members of the World Trade Organisation and to which the EU has committed itself
REE	Rare Earth Elements
(R)MSA	(Raw) Material System Analysis, an extensive analysis of raw material flows through all of the stages of their lifetime, including the end-of-life stage
NACE	Nomenclature statistique des Activités économiques dans la Communauté Européenne, the statistical classification of sectors in the EU
OECD	Organisation for Economic Co-operation and Development, since 1961
Product group	Statistical unit describing a set of heterogeneous products. Depending on the detail level of the data, it can include tens, hundreds or thousands of product groups. In turn, each product group can consist of many actual individual products
PV	Photovoltaic panels
REEs	Rare Earth Elements
Resilience	Capacity of an economy to resist a particular shock and to recover rapidly to the previous level of growth or better

RMIS	Raw Material Intelligence System, the data platform of the European Commission, dedicated to raw materials
RPA	The Risk & Policy Analysts, a limited company located in the UK
RRF	Recovery and Resilience Facility
SCM	Supply Chain Management, the management of the flow of goods and services and includes all processes that transform raw materials into final products
SDS/STEPS	Sustainable Development Scenario and Stated Policies Scenario. The two scenarios identified by the International Energy Agency, widely used in climate change modelling, that respectively describe a desired and a stated policy set
SMEs	Small and medium-sized enterprises
Stock draw	Instance where stocks are used to mitigate a supply shock
Strategic stockpile	A stockpile aimed to fulfil a public responsibility: national security, emergency, pandemic etc. It is different from an economic stockpile that is aimed to support the private sector and its responsibilities: manufacturing industry, wholesale etc.
Third countries	All countries not included in the EU and EFTA (Iceland, Norway, Switzerland, Lichtenstein) organisations
Timescale	Indicative (unit) of time before you can expect any event or action to have an impact. A timescale differs from timeframe, being a specified period in time
Green and digital transition	Common reference to the green and digital transition, reflecting transformational societal goals for respectively sustainability and digitalisation
US	The United States of America
WGI	World Governance Index, a research dataset of the World Bank summarizing the views on the quality of governance
WTO	World Trade Organisation

EXECUTIVE SUMMARY

Background and aim

This study assesses the needs and vulnerabilities of the EU in accessing products containing Critical Raw Materials (CRM) needed for the ongoing green and digital transitions in a changing geopolitical context. The study sets out to identify at which stage of the supply chain, ranging from raw materials to final products, the European industrial eco-system is dependent on imports. It reviews the criticality assessment methodology to account for the changed geopolitical context and future demand that result from the green and digital transition. Finally, it evaluates the potential of stockpiling to address short-term supply disruptions.

The study provides an overview on the wider situation, as well as a policy context of research initiatives. It summarises recent EU policy documents and resolutions, such as the Updated New Industrial Strategy for Europe and the resolution on a European strategy for critical raw materials, and recent calls for public action to strengthen security of supply to the EU of products containing CRM.

The study provides an overview of the supply chains involved in key green and digital technologies, from raw material needs, components, to final goods. It sets the scene of the EU's need for CRM by mapping the technologies needed to meet the various decarbonisation targets. It distinguishes where the EU makes use of the raw materials directly, and where it makes use of components and products that embed these raw materials. Using trade data pre-dating the COVID-19 pandemic, the study identifies the raw materials for which the EU is sensitive to imports from outside the EU, highlighting the raw materials and components that historically came from Russia and China.

Furthermore, the study discusses the CRM methodology designed by the JRC to identify which materials are critical and require special attention. This methodology rests on two criteria, economic importance and supply risk. The study investigates how the identification of materials as critical responds to changes in this methodology that reflect the new geopolitical context.

This study focusses on stockpiling as a course of action to mitigate supply disruptions of raw materials and components. It investigates the suitability of stockpiling as a solution to alleviate the consequences of supply chain disruptions and of the potential 'weaponisation' of trade vulnerabilities, especially in the specific context of achieving the green transition. It compares the advantages and disadvantages of stockpiling.

Finally, the study discusses the feasibility of using trade policy to increase the diversification of supply of products containing critical raw materials.

Key Findings

Material requirements for the green and digital transition and import patterns

The green and digital transition requires the rapid deployment of green and digital technologies, resulting in significant growth of demand for their embedded raw materials. Timely availability of such materials determines whether climate goals can be reachable.

The EU has a dependency on key components for most green energy and digital technologies, more than on raw materials as such. At present, the EU relies on Russia for a significant share of its imports for three CRMs: platinum, palladium and titanium. These are indispensable materials for the development of hydrogen technology. In addition, the EU highly depends on imports from China for both the production of permanent magnets and the extraction and refining of REEs used in their production and relies on China for imports of batteries used for EVs and energy storage.

Access to critical raw materials will become relevant as the EU develops the industrial capacity to manufacture products from these raw materials in line with the industrial policy objectives of the European Commission. These focus on developing domestic industrial capacity for batteries, electrolysers and fuel cells for renewable hydrogen, and the permanent magnets needed for the electric motors used in e-mobility and wind power industries.

Active risk-monitoring of security of supply can help safeguard the European supply of products shaping the green and digital transition. Supply risk-monitoring can make supply chain management by the private sector more effective. Moreover, it secures and fosters public knowledge within the EU, thereby increasing the scope-of-action to solve disruptions in supply to the EU.

Independent assessment of critical raw materials

The present level of raw material criticality is defined by two key factors: economic importance (EI) and supply risk (SR). The outcomes of the EU CRM assessment methodology remain robust under changed data inputs for the SR calculation, reflecting the changed geopolitical situation.

The CRM methodology might benefit from an extension of scope, including an assessment of product groups and sectors. This might support future policy decisions even more effectively.

An independent assessment in this report confirms that including expected future demand in CRM assessments provides relevant additional insights. Furthermore, better publicly available data are a precondition to accurately support policy options to manage CRM supply and safeguard the industrial capacity of the EU.

Stockpiling policy overview, composition and volumes

The strategic stockpiling of products containing CRM is a common policy in the US, Japan, South Korea and Switzerland. These countries provide relevant examples for possible EU-based stockpiling operations. The invocation of the Defence Protection Act by the US government is a recent example of public action that can be taken in order to secure the supply of strategic products and strengthen industrial capacity in the process.

Principles for European stockpiling can be drawn from these examples. Based on the assumption that a potential stockpile could cover 60 days of imports, estimates of the possible value of CRM stockpile range between EUR 6.45 billion and EUR 25.8 billion (2021 prices). This range depends on the breadth of the products considered. The lower bound focuses on raw materials, the upper bound uses a selection of around 300 traded product groups.

Among the preferred composition of product groups to be stockpiled are those shaping the green and digital transition. This means that a volume of 8.6 million tonnes and a value of EUR 25.8 billion will be assumed as respectively the required size and value of the EU stockpile (acquisition costs of the product groups in the stockpile).

Discussion of potential EU stockpiling facilities

Stockpiling products containing CRM takes weeks and months, whereas a successful green and digital transition requires decades to materialise. Stockpiling action in the EU would mitigate supply shocks for nascent and strong manufacturing industries which are vital for the green and digital transition. If stockpiling is introduced as a policy measure, the associated industry ecosystem should also be put in place. Since 1990 in the EU investments into manufacturing capital stock have been smaller than in Japan, South Korea and Switzerland and comparable to the ones in the US.

Professionals active in a supply chain management consider the stockpiling as their main economic activity. However, if stockpiling is encouraged by public policy, the question of its effective public-private management arises.

1. INTRODUCTION

1.1 Background and policy context

The European Green Deal (EGD) aims to transform the EU into a modern, resource-efficient and competitive economy. It sets ambitious targets for the reduction of greenhouse gas (GHG) emissions: a decrease of 55% compared to the 1990 level in 2030, and to net-zero by 2050. The 'Fit for 55' package, presented in July 2021 by the European Commission, includes far-reaching legislative proposals to align EU energy and climate policies to these targets (European Commission, 2021c). The energy transition will require additional annual investments of EUR 360 billion on average across the EU, which represents around 2% of GDP (Lenaerts et al., 2021).

Reaching these targets will require decarbonising electricity production through the deployment of renewable energy, electrifying carbon-emitting activities such as transport, and greatly improving energy efficiency. The bulk of the reduction in GHG emissions will come from deploying technologies that rely on different raw materials than the technologies they replace. For example, switching from Internal Combustion Engine (ICE) vehicles to Electric Vehicles (EVs) will require large quantities of additional materials such as cobalt and lithium for the batteries, rare earth elements (REEs) for electric motors, and aluminium and molybdenum for the body. The energy transition is a materials transition.

At the same time, the decarbonisation challenge needs to be achieved in a geopolitical context that is rapidly changing. The Russian invasion of Ukraine has highlighted Europe's energy dependencies. The successive packages of energy sanctions imposed on Russia and the retaliatory cuts in deliveries have triggered an accelerated shift away from Russian fossil fuels. To manage this shift, the REPowerEU package, proposed in May 2022 in response to the Russian invasion, further strengthens the provisions of the 'Fit for 55' package (European Commission, 2022a). It sets even more ambitious targets for the deployment of renewable energy and energy saving measures[1], and proposes to allocate unused loans from the Recovery and Resilience Facility (RRF), worth EUR 225 billion, and new RRF grants funded by the auctioning of Emission Trading System (ETS) allowances, worth EUR 20 billion.

In this effort to reach energy independence through the deployment of green technologies, European policymakers are conscious of the vulnerabilities of existing supply chains and wary not to create new dependencies. The COVID-19 pandemic has highlighted the danger of depending on single suppliers for critical goods, such as personnel protective equipment, or semi-conductors. As a result of its central position in many supply chains, including those for green technologies and the raw materials they embed, attention has focused on China as a source of new dependencies.

In recent years, geopolitical struggles between the US and China have become a key concern for global value chains. Although China is a central node of many supply chains, the country relies on the US technology, trade networks and finance. The US has adopted policies that aim to reduce their own dependency on Chinese manufacturing and raw materials, as well as at impeding China's catch-up in semiconductor technology. This includes provisions in the Inflation Reduction Act (IRA), the headline green policy initiative of the US that aims for example to replace Chinese imports with near-shored imports in EV production.

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[1] The 'Fit for 55' package sets a target of 40% of electricity generation coming from renewable sources by 2030, increased to 45% in the REPowerEU package.

In this changing geopolitical context, EU policymakers strive for 'open strategic autonomy'. Strategic autonomy refers to the ability of the EU to act autonomously, namely without being dependent on other countries, in strategically important policy areas (EPRS, 2022a).

As a mature open economy, the EU is reliant on imports of raw materials and of intermediate goods for its manufacturing industry and on access to foreign markets for its exports. This requires articulating the needs of strategic autonomy with the principles of rules-based globalisation and openness to trade and investment.

While the EU has a less confrontational approach towards China framed within the concept of open strategic autonomy, it shares many of the policy concerns of the US. Among them is China's deployment of an industrial policy aimed at gaining dominance in key markets, including materials like steel and aluminium or REEs. Two additional areas of attention are relevant. Firstly, the geopolitical tensions surrounding Taiwan, a leading producer of computer chips that are vital to many modern digital and green technologies. Second, the concerns about forced labour in Xinjiang, the Chinese province that is the world leading provider of solar panels and raw materials used in their production (European Parliament, 2022b). Considerations of resiliency in supply chains in the current context of geopolitical tensions are key in the EU's critical raw materials strategy.

Awareness of the EU's dependency on imports of critical raw materials and components for technologies of the green and digital transition predates the current crises. The Raw Material Initiative was launched in 2008 (European Commission 2008a) with the stated objective of reducing dependencies for non-energy raw materials for industrial value chains and societal well-being. The main pillars of the Initiative were, and remain, the diversification of sources of primary raw materials from third countries, the promotion of domestic sourcing and the development of secondary sources of supply through resource efficiency and circularity.

During the year 2020 the European Commission presented the Action Plan on Critical Raw Materials (European Commission, 2020a), the 2020 List of Critical Raw Materials (European Commission, 2020c), and a foresight study on critical raw materials for strategic technologies and sectors from the 2030 and 2050 perspectives (European Commission, 2020b). The Action Plan looks at existing and future challenges and proposes actions reminiscent of the Raw Material Initiative. The objectives are to reduce Europe's dependency on third countries, to diversify supply from both primary and secondary sources and to improve resource efficiency and circularity, while promoting responsible sourcing worldwide.

As highlighted by the European Parliament in its resolution of 24 November 2021 on a European strategy for critical raw materials[2], the use of strategic reserves to mitigate short-run supply disruptions is absent from the list of policy options regarding CRMs (European Parliament, 2021):

"The EP regrets that the creation of strategic stockpiling is not yet part of the action plan and calls on the Commission to also focus on securing supplies of CRMs in the EU by encouraging Member States to carry out strategic stockpiling as part of a coordinated approach, where analysis deems it appropriate; believes that strategic stockpiling in combination with other strategic measures contributes to reducing CRM dependencies; underlines that increasing availability should go hand in hand with a decrease in demand by looking at the entire value chain-design, operation and end of life."

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[2] European Parliament resolution of 24 November 2021 on a European strategy for critical raw materials (2021/2011(INI)), available at: https://www.europarl.europa.eu/doceo/document/TA-9-2021-0468_EN.html.

The supply disruptions experienced during the COVID-19 pandemic have brought stockpiling to the fore. The Single Market Emergency Instrument (SMEI), proposed by the European Commission in September 2022, aims to introduce measures to reduce the impact of future events that might affect supply chains (European Commission, 2022b). It generalises measures introduced for pandemic-related goods, like joint procurement of personal protective equipment and export authorisation schemes for vaccines. New mechanisms include the build-up of strategic reserves of critical goods in case of the activation by the European Commission of the 'Single Market Vigilance' framework. The importance of strategic reserves is further showcased by developments in the markets for natural gas and other fossil fuels.

Ensuring security of supply of CRMs and avoiding new dependencies was highlighted by Commission's President Von der Leyen as key challenges in her State of the Union Address of September 2022. The main policy tools identified therein are the build-up of strategic reserves to face supply risks, and the development of new partnerships with reliable countries and key growth regions.

The objective of the present report is to assess the needs and vulnerabilities of the EU in terms of access to CRMs, with a special focus on the most important CRMs for the green and digital transitions, and to evaluate the potential of stockpiling to address short-term supply disruptions. The report gives an overview of the supply chains involved in key green technologies, from raw material needs, components, to final goods. The report further identifies the stage in the supply chain where Europe relies on imports to achieve its decarbonisation and industrial development objectives. Next, it reviews the methodology used to determine which raw materials are deemed critical, and tests ways in which this methodology could be adapted to reflect the new geopolitical context and the future needs created by decarbonisation. It examines the necessity and feasibility of building stockpiles of CRMs to mitigate the adverse consequences of potential supply disruptions for these materials. Finally, it discusses the suitability of various trade policy options to diversify sources of supply.

1.2 Outline

In Chapter 2 we set the scene of the EU's need for critical raw materials for the green transition, by mapping the technologies required to meet the various decarbonisation targets and the needs in terms of materials and components. In particular, we identify the position of the EU in the relevant supply chains and whether the EU relies on raw materials directly, or on the import of components and products that embed these raw materials. Using trade data predating the COVID-19 pandemic, we identify the materials for which the EU is sensitive to imports from outside the EU, highlighting materials and components that historically originated from Russia and from China.

Understanding existing and future needs and monitoring market conditions is an important part of ensuring security of supply, by helping to anticipate potential market bottlenecks and points of vulnerability in the supply chain. In Chapter 3, we discuss the CRM methodology designed by the JRC to identify which materials are critical and deserve special attention. This methodology rests on two criteria, economic importance and supply risk. We discuss how the identification of materials as being critical responds to changes in this methodology. We focus on refinements of this methodology that would encompass a new global supply structure for raw materials following the new geopolitical situation, and that would better reflect the future economic importance of materials, for example resulting from the green transition.

In Chapters 4 and 5 we discuss the suitability of stockpiling as a solution to alleviate the consequences of supply chain disruptions and of the potential weaponization of trade vulnerabilities, in the specific context of achieving the green and digital transition. We discuss how stockpiling may offer protection against supply shortages and prices increases, and helps companies absorb short-term demand spikes for specialised materials by buying them time to find alternative supplies. At the same time, we highlight that poorly timed stockpiling activities could contribute to market destabilisation by exacerbating shortages and damaging relations with third countries.

Finally, in Chapter 6 we discuss the feasibility of using trade policy to increase the diversification of supply of CRMs. Given the open and multilateral framework set by the World Trade Organisation (WTO), tariffs on CRMs are already low. Furthermore, targeting 'friendly' countries would require negotiating a full Free-Trade Agreement, applying comprehensively to all product groups, not just raw materials of interest. This implies that non-trade policy tools, such as development assistance and international cooperation, appear as more effective options.

1.3 Scope

Assessing the EU's current needs for CRMs must be understood in the context of the EU's existing industrial landscape, which is reliant on imported inputs to produce high value-added goods for exports. Likewise, stockpiling of goods should be viewed as an element of broader industrial policy (Hassink et al. 2012). As explained in Box 1, the present study adopts this broader perspective and analyses the products groups that embed CRMs, in addition to the EU's needs in terms of CRMs per se.

Box 1: Why research on integrated (critical) raw materials is needed

Studies into integrated CRM materials should look beyond minerals extracted from the earth or urban mines. The role of integrated CRM should comprise the products, including their technical specifications and manufacture as well as the entire supply chain.

Integrated CRM are essential to the functioning and integrity of a wide range of industrial ecosystems (European Commission 2020a), but are significant in a greater industrial eco-system. Therefore, a comprehensive strategy requires integrating raw materials, products, economic activities and the societal aims that rely on them. For this reason, this report does not refers only merely to raw materials, but covers also other aspects.

Source: Authors' own elaboration.

In the future, the EU industrial landscape will change as the twin green and digital transitions materialise. While this change will be driven by market forces, policy priorities will also play an important role in shaping its trajectory.

In line with these objectives, the European Commission has ambitious industrial policy objectives in several key industries for the green transition, as reflected by the introduction of Important Projects of Common European Interest (IPCEI) in the battery and hydrogen industries. IPCEI create a framework to channel public funding and crowd-in private funding towards these projects.

For instance, the European Battery Alliance (EBA) was established in 2017 to create a competitive and sustainable battery cell manufacturing value chain in Europe. This was accompanied by an initial IPCEI of EUR 8.2 billion in 2019, followed by a second IPCEI of EUR 11.9 billion in 2021[3].

Likewise, developing a clean hydrogen industrial sector is high on the industrial policy agenda of the European Commission. The REPowerEU program anticipates a direct investment of EUR 27 billion into hydrogen.

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[3] The first IPCEI approved in 2019 consists in EUR 3.2 billion of public funding that is to be accompanied by EUR 5 billion of private investments. The split between public and private funding of the second IPCEI approved in 2021 is EUR 2.9 billion and EUR 9 billion.

The European Clean Hydrogen Alliance was set up in July 2020 to build-up a robust pipeline of investments projects (European Commission 2020d), with the first IPCEI in the hydrogen sector approved in July 2022. In addition, a total of EUR 86 billion was allocated for solar and wind, through initiatives such as the solar strategy, the solar rooftop initiative, and a potential IPCEI.

In parallel to the green transition, the European Commission also has objectives for the deployment of digital technologies ("Shaping Europe's digital future" European Commission 2020f). Together, the green and digital transitions are referred to as the green and digital transition. The flagship European Chips Act, proposed in February 2022, translates the objective of strengthening the EU positioning in global value chains for microchips into industrial policy. The Chips Act will put forward between EUR 2 and EUR 11 billion of public funding until 2030, to be matched by private sources. These investments will complement existing programmes and actions in research and innovation in semiconductors, such as Horizon Europe and the Digital Europe programmes.

The magnitude of the changes involved in achieving the green and digital transition is reflected in the forecasts of the EU's CRM needs, as shown in Table 1. The demand for the main CRMs needed for the green and digital transition will significantly accelerate[4]. In many cases, demand acceleration exceeds historical growth rates, suggesting potential tension in these markets.

Table 1: Compound Annual Growth Rate – CAGR (%) of raw materials relevant for the green and digital transition, past demand (1996-2020) and estimated future demand until 2030

	World production annual growth 1996-2020 (World Mining Data)	CAGR estimate until 2030 (TNO 2019)	JRC predicted required CAGR, medium demand, until 2030 (EC 2020)	JRC predicted required CAGR, high demand, until 2030 (EC 2020)
Aluminium	13.4%	0.3%	0.2%	0.7%
Borates	0.4%	0.0%	0.0%	0.1%
Chromium	6.6%	0.1%	0.2%	0.8%
Cobalt	2.1%	2.6%	14.9%	28.6%
Copper	4.7%	1.0%	0.4%	1.5%
Dysprosium	2.8%	4.5%	10.2%	23.1%
Gallium	3.7%	0.3%	0.0%	3.8%
Germanium	2.2%	0.3%	0.4%	5.8%
Indium	3.3%	1.3%	0.1%	3.0%
Lithium	2.0%	7.6%	26.0%	38.4%
Manganese	2.6%	0.0%	0.2%	0.6%

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[4] These forecasts reflect the increased use only from batteries, fuel cells, wind turbines and solar photovoltaics. Adding demand growth from sectors such as construction, defence and base industry would amplify these future estimated growth rates.

	World production annual growth 1996-2020 (World Mining Data)	CAGR estimate until 2030 (TNO 2019)	JRC predicted required CAGR, medium demand, until 2030 (EC 2020)	JRC predicted required CAGR, high demand, until 2030 (EC 2020)
Molybdenum	2.9%	0.2%	0.3%	1.1%
Natural graphite	4.1%	0.7%	11.9%	19.4%
Neodymium	4.1%	3.0%	3.5%	11.6%
Nickel	3.6%	1.6%	4.4%	8.1%
Platinum	4.1%	0.0%	0.6%	4.7%
Praseodymium	1.1%	1.8%	3.8%	10.4%
Selenium	5.8%	0.3%	0.1%	1.5%
Tellurium	9.4%	7.9%	0.5%	15.3%
Zinc	0.7%	0.2%	0.3%	1.2%

🟧 Increased future demand estimate in recent years, but lower than historical growth

🟥 Future demand estimate that indicates an unprecedented annual growth rate

Source: World Mining Data; TNO 2019; European Commission 2020b.

2. MATERIAL REQUIREMENTS OF THE GREEN AND DIGITAL TRANSITION AND IMPORT PATTERNS

KEY FINDINGS

The green and digital transition requires the rapid deployment of green and digital technologies, implying significant growth in the demand for raw materials embedded in these technologies. Timely availability of such materials determines whether climate goals may be reachable.

The EU has a dependency on key components for most green energy and digital technologies, more than on raw materials per se. Access to raw materials will become relevant as the EU develops the industrial capacity to manufacture products from these raw materials, in line with the industrial policy objectives of the European Commission. These focus on developing domestic industrial capacity for batteries, electrolysers and fuel cells for renewable hydrogen, and the permanent magnets needed for the electric engines motors used in the e-mobility and wind power industries

At present, the EU relies on Russia for a significant share of its imports for three CRMs. These are platinum, palladium and titanium, which are necessary materials for the development of hydrogen technology. In addition, the EU has a high dependence on imports from China for many product groups necessary for the twin transitions. For example, China concentrates both the production of permanent magnets and of the extraction and refining of REEs. The EU has a high dependency on China for imports of the batteries used for EVs and energy storage. Additionally, the EU has a dependency on all the raw materials going into the production of batteries, with the exception of lithium.

Active publicly executed risk-monitoring can help to safeguard the European supply of products that shape the twin transition. Risk-monitoring can make supply chain management by the private sector more effective. Moreover, it secures and fosters public knowledge within the EU, thereby increasing the scope-of-action to solve disruptions in supply to the EU.

This Chapter provides an overview of the supply chains involved in key green and digital technologies, from raw material needs, components, to final goods. It identifies the stage of the supply chain for which the EU relies on imports to achieve its decarbonisation and industrial development objectives. Finally, it reports the raw materials and components for which the EU has a strong dependence on Russia and China specifically.

2.1 Understanding the material needs of the green and digital transition

This report will focus on the two domains that will attract the bulk of the investments needed for decarbonisation: shifting energy systems towards low-carbon sources and the electrification of transport (Lenaerts et al., 2021). Investments in energy systems will need to double compared to their current level as renewables become the dominant source of energy. This will require installing renewable energy capacity, especially from wind and solar photovoltaic (PV), energy storage solutions such as batteries, the development of a hydrogen infrastructure, and upgrading electricity grids. In the transport sector, the main objective is the replacement of the vehicle fleet with electric vehicles, which will absorb around a third of the investments needed for the EGD.

The infrastructures needed for these low-carbon activities require a very different set of materials than for carbon-intensive activities.

Moreover, decarbonisation strategies result in a higher overall use of materials (IEA, 2021). This Section will present the material needs for the main technologies of the green and digital transition.

The technologies covered for renewable electricity generation are solar PV and wind turbines. For e-mobility, the focus is on electric motors and batteries. We also briefly mention the other material needs of electric vehicles (EVs) that differ from internal combustion vehicles. The nascent hydrogen industry relies on electrolysers for the production of green hydrogen from electricity, and on fuel cells for the deployment of hydrogen mostly in the transport sector. Finally, we highlight the increase in demand of four base metals (aluminium, copper, nickel and zinc) that cut across all green applications, including expanding electricity grids[5].

For each technology, we discuss (i) the deployment targets; (ii) the main raw materials involved in production, distinguishing between those deemed critical or not; (iii) a brief overview of the key sources of supply and where potential bottlenecks might lie; and (iv) examples of alternative technologies that use different material compositions. Table 11 in Section 2.1.7 provides a summary of the main materials and their uses, along with estimates of current and projected future demand in the EU. These numbers reflect the required increase in the global supply of materials necessary to achieve Europe's climate objectives. This does not reflect the actual domestic needs for raw materials within Europe, since much of the industrial infrastructure required for green transition technologies is not (or only partly) located in Europe.

2.1.1 Renewable electricity generation

Achieving the renewable energy targets set in the REPowerEU package[6] implies installing 1,236 GW of renewable energy generation capacity by 2030. This is 2.5 times the current installed capacity of 511 GW (IRENA, 2020). The main technologies to achieve this are solar PV, and wind energy, both onshore and offshore[7].

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[5] The list of product groups that are in scope for the analysis in this Chapter is shown in Annex 1. The other goods underlying the green transition (such as heat pumps, biofuels, heat storage, e-fuels) are out of scope of the present report because of the limited amount of critical raw materials going into their composition.

[6] The REPowerEU package included a proposal for an amendment of the renewable energy sources directive, which defines the new proposed EU RES target. Available at: https://emeeting.europarl.europa.eu/emeeting/committee/en/agenda/202211/ITRE?meeting=ITRE-2022-1128_1&session=11-28-15-00.

[7] In some countries, nuclear energy is considered an important part of the energy mix. The material needs for this technology consist mostly in uranium, and will not be presented in detail in this section. Nuclear technology and uranium will be included in the analysis of Sections 2.2 and 2.3. Other low-carbon source of energy, such as hydropower or biomass will not be discussed in this report. They are already well developed in Europe and therefore offer limited expansion potential (Gregoir and van Acker, 2022). They also have comparatively low mineral requirements (IEA 2021a).

a. Solar photovoltaic power

Table 1: Targets for solar power

Capacity installed in 2021[8]	Target for 2025[9]	Target for 2030[10]
160 GW	320 GW	600 GW

Source: European Commission, 2022.

Main materials used in solar photovoltaic supply chain

There are roughly two types of PV panels commercially used today: 'crystalline silicon' (c-Si) PV panels and 'thin film' panels. c-Si PV panels are the more mature technology[11] and dominate the market: they represent over 95% of installed capacity (European Commission, 2020b). This technology is based on **crystalline silicon metalloid**, which is included in the 4th CRM list.

Table 2: Main materials solar power

Main material of focus	Silicon metal
Other materials in JRC's 4th of list of CRMs	Boron, germanium, gallium, indium, tellurium
Other materials	Molybdenum, selenium, cadmium, silver
Base metals	Aluminium, iron, lead, nickel, zinc, copper, tin

Source: Authors' own elaboration.

Overview of sources of supply

At the stage of crystalline silicon metal China covers about 70% of global production capacity, with an annual production of 388 thousand tonnes. The availability of silicon metalloid does not depend on deposits of raw materials but on the presence of an industrial infrastructure for processing oxides into pure silicon metalloid, that is currently dominated by Asian producers.

The most vulnerable step of its supply chain is at the component level: China dominates 89% of global supply of PV panel manufacturing. The EU's share of global production of crystalline silicon cells is only 0.3%, and its share of assembled solar modules is 1.5%.

Potential for reducing material use from alternative technological solutions

Innovation in this field focuses mostly on increasing material efficiency (European Commission, 2020b). In the last ten years, resource efficiency has been improved for the dominant crystalline silicon panels. The amount of silicon in both mono and poly crystalline PV cells has dropped from 16 gram to 4 gram per Watt peak (Wp).

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[8] IRENA, 2020, Renewable Capacity Statistics 2022, available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Apr/IRENA_RE_Capacity_Statistics_2022.pdf.

[9] European Commission, 2022, REPowerEU Plan, SWD(2022) 230 final, https://eur-lex.europa.eu/resource.html?uri=cellar:fc930f14-d7ae-11ec-a95f-01aa75ed71a1.0001.02/DOC_1&format=PDF.

[10] Ibid.

[11] The main advantages of c-Si PV panels over thin film technology are their higher efficiency, longer lifespan, lower power losses and higher robustness, https://coastalsolar.com/photovoltaic-cells-pros-cons-crystalline-thin-film-solar-panels/.

Alternative technologies and changes in material composition are also being explored. Thin film PV technologies such as CdTe (cadmium-telluride) and CIGS (copper-indium-gallium-selenide) use a different combination of CRMs, notably tellurium, germanium and indium. These materials raise concern as they are likely to witness a high increase in demand that will be difficult to match with an increase in supply (European Commission 2020b). However, the combined market share of these technologies has varied over the last years between 5 and 10%, which dampens the pressure exerted on resource demand. Finally, the possibility of producing organic photovoltaic solutions from carbon, as a replacement of silicon-based solar cell technologies, have been studied for a number of years, but is far from being market-ready.

b. Wind power

Table 3: Targets on wind power

	Capacity installed in 2021[12]	Target for 2030[13]	Target for 2050
Onshore wind	187 GW	430 GW	
Offshore wind	15 GW	60 GW	300 GW

Source: European Commission, 2022.

Main materials used in wind energy supply chain

There are two main technical designs of wind turbines suitable for use in onshore and offshore applications: direct drive and gearbox driven. The two types have significantly different constructions, differing in generator design, drivetrain system and grid connection solutions. As a result, both the mass and the material content differ widely between the two.

Each of these can be equipped with or without permanent magnets (PM), but PM-free solutions are less efficient in offshore conditions partly because of much higher maintenance costs (IRENA, 2021). In 2018, 76% of the world offshore market used PM drives. The 2018 total market share for PM containing wind turbines was 24 % (GWEC 2019; Irena 2019). The share of wind turbines containing PM is expected to grow in the coming years.

Wind turbines containing permanent magnets (PM)[14] use Rare Earth Elements (REEs), and boron. Additionally, the structure of wind turbines also requires significant amounts of base metals, as well as niobium.

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[12] IRENA, 2020, Renewable Capacity Statistics 2022, available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Apr/IRENA_RE_Capacity_Statistics_2022.pdf.

[13] Renewable Energy Directive.

[14] One of the most common types of permanent magnets are NdFeB magnets, which are made from an alloy of neodymium (Nd), iron (Fe), and boron (B).

Table 4: Main materials wind power

Main material of focus	Boron, RREs especially dysprosium, neodymium, praseodymium
Other materials in JRC's 4th list of CRMs	Niobium
Other materials	Molybdenum, chromium, manganese
Base metals	Aluminium, iron, nickel, zinc, copper

Source: Authors' own elaboration.

Overview of sources of supply

The share of the European production in global production increases along the supply chain for wind turbines: it is only 1% at the raw material stage, increases to 12% for processed materials, 18% for components, and 58% for final products.

At present, China has a near monopoly for the production of not only REEs but also for permanent magnets manufacturing (European Commission 2020b). Potential REE mining in Europe could take place in Sweden, Finland, Germany, Spain, Norway and Greenland. However, the downstream processing of ores to pure materials and processed goods such as NdFeB permanent magnets is mostly concentrated in China and Japan.

Potential for reducing material use from alternative technological solutions

As stated above, the share of wind turbines that contain permanent magnets is expected to rise in the coming decade. However, the need for permanent magnet equipped wind turbines is less vulnerable than is often assumed. The conventional, gearbox-driven wind turbines requiring less critical raw materials are at hand, though they come with disadvantages with respect to the costs of electricity production (for instance because of higher maintenance costs). On the other hand, domestic technological capabilities for which the supply situation may be less strained, are still available.

2.1.2 E-mobility

Targets

Currently under discussion in the EU legislative process is the provision to require by 2035 that all cars sold on the European market need to be zero-emission, which is effectively a ban on cars with internal combustion engines (ICE). Up until the COVID-19 pandemic, an average of 12 million new cars were registered each year in the European Union. This number dropped to below 10 million in 2020 and 2021[15].

Electric vehicles (EVs) differ from ICE cars in their need for an electric motor and batteries. These aspects result in a higher demand for several critical raw materials compared to ICE cars. In addition, given the additional weight from the batteries, the introduction of EVs has also stimulated the use of lightweight alloys and aluminium in the body of the car with a corresponding increase in the need for critical materials in the shape of alloying elements.

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[15] European Automobile Manufacturer's Association, May 2022.
Available at: https://www.acea.auto/figure/passenger-car-registrations-in-europe-since-1990-by country/#:~:text=9%2C678%2C749%20passenger%20cars%20were%20registered,EU%20%2B%20EFTA%20%2B%20UK%20region.

The transition to electric mobility is not restricted to cars, with lightweight mobility solutions, such as e-bicycles and e-scooters, or heavyweight vehicles, such as agricultural e-tractors and commercial vehicles, also transitioning to electric power. Most estimates of future material demand rely on assumptions about the evolution of the car market, but these additional mobility solutions should not be overlooked.

c. Electric motors

Main materials used in electric motor supply chain

EVs mostly differ from ICE cars in their use of copper and of NdFeB permanent magnets. A current EV uses around 80 kg of copper, which is about 4 times the volume for ICE cars. The rotor of the motor weighs between 1.7 and 3 kg and mainly consists of neodymium (0.25–0.50 kg/car) and some other REEs (0.06–0.35 kg/car), copper, iron and boron. Although used in small quantities, dysprosium is key for the performance of the magnets at high temperature.

Table 5: Main materials electric motors

Main material of focus	Boron, RREs especially dysprosium, neodymium, praseodymium
Other materials in JRC's 4th list of CRMs	
Other materials	Molybdenum, chromium
Base metals	Aluminium, iron, copper

Source: Authors' own elaboration.

Overview of sources of supply

As with the supply chain for wind energy, the key supply challenge comes from the import of REE containing permanent magnets, whose production is concentrated in China. China accounts for 85-90% of global production of permanent magnets, which Japan accounting for the rest (European Commission, 2020b). The broader industrial demand for electric motors, which encompasses small electronics, e-bikes and even larger electric motors for industrial uses, also makes a significant use of permanent magnets. According to IRENA, in 2030, EVs alone will be responsible for around 25% of permanent magnet consumption.

Potential for reducing material use from alternative technological solutions

Instead of synchronous traction motors that use NdFeB magnets, the main alternative technologies are induction motors or wound rotor motors, which do not use magnets, but instead copious quantities of copper. Renault and Tesla have already employed wound rotor and induction motor technologies, respectively, eliminating rare earth magnets (IRENA, 2021). Despite these examples, current projections forecast that PM based motors will continue to represent between 90 and 100% of EV motors.

Other magnet compositions are being explored: ferrite (iron oxide combined with the metals strontium, barium or cobalt) or aluminium nickel cobalt (AlNiCo), or even samarium cobalt (SmCo) magnets (which have military grade performance but are expensive and have a similar or even worse geopolitical supply dependency). Self-evidently, these alternatives come with different trade-offs of performance and price.

d. Batteries

Target

The European Commission's proposed target for battery production is to cover 90% of European demand with domestic production by 2030. To this end, the European Battery Alliance supports around 70 major projects, including 20 giga-factories, and two IPCEI are set-up with a volume of around EUR 6.1 billion.

Table 6: Main materials used in battery supply chain

Main material of focus	Lithium, cobalt, natural graphite, and manganese
Other materials in JRC's 4th list of CRMs	Silicon, titanium, niobium
Other materials	
Base metals	Aluminium, copper, nickel

Source: Authors' own elaboration.

Overview of sources of supply

Raw materials: The EU produces only 1% of all battery raw materials overall.

Around 90% of global lithium mine output is produced in Chile (40%), Australia (29%) and Argentina (16%). China (45%) hosts most of the world's lithium hard-rock minerals refining facilities. Chile (32%) and Argentina (20%) dominate refined lithium capacity from brine operations (EC, 2019). Despite the recent fears of shortages and price spikes, the supply of lithium could be greatly expanded, easing shortages (European Commission, 2020b). However, as exemplified by the case of Portugal, opening new lithium mines is subject to numerous legal challenges.

54% of global cobalt mine production originated from the Democratic Republic of the Congo, followed by China (8%), Canada (6%), New Caledonia (5%) and Australia (4%). However, the further processing of the metal is concentrated in China, which produces 46% of the world's refined cobalt. The second largest producer of refined cobalt is Finland (13% of global production), followed by Canada and Belgium (both representing 6% of global production). Finally, China is also a major supplier of manganese and graphite. Russia is one of the top three producers of nickel.

Components: China is the main supplier of anode materials, and Japan of cathode materials, both of which the EU imports.

Products: The EU is fully dependent on imports of battery cells. China produces 66% of cells, other suppliers provide around 8%, which limits the scope for diversification.

A critical aspect for the EU is that current production volumes do not satisfy the future European demand for Li-ion batteries. Asia, represented by China, Japan and South Korea, delivers 86% of the processed materials and components for Li-ion batteries globally (European Commission, 2020b). The EU27, with 8%, has a small share of the supply. Other countries deliver only 8%, which gives very little margin for supply diversification.

Potential for reducing critical material use from alternative technological solutions

This is a very innovative space, and there is at present a lot of uncertainty about which specific technology will dominate e-mobility, especially for batteries. There is a lot of exploration of different battery chemistries, both within the lithium-ion technology, but also of fundamentally different types. A driver for these changes is the worry about sufficient and reliable supply of cobalt: technology development aims specifically at reducing the cobalt content of batteries. One example among many, iron-air batteries would really change the raw material demand of batteries.

e. Other

In addition to the materials needed for batteries and electric motors, the needs of e-mobility also require materials such as magnesium, niobium, silicon metal and titanium for the structural parts, especially important for weight reduction. Additionally, as vehicles become increasingly more electronic, they will consume gallium, germanium and indium in for example sensors, displays, circuitry, etc. Finally, other alloying elements like chromium, tungsten and vanadium are in demand by almost all technologies.

2.1.3 Hydrogen: electrolysers and fuel cells

Targets:

In the REPowerEU package, the European Commission sees a key role for renewable hydrogen to replace fossil fuels in hard to decarbonise sectors such as material-handling vehicles, light-duty vehicles, buses, and the aerospace sector. As such, it sets a target of 10 million tonnes of domestic production of renewable hydrogen and 10 million tonnes of renewable hydrogen imports by 2030. The current global hydrogen production (of all types) is around 60 million tonnes. Through the use of two IPCEI approved in July and September 2022, the European Commission aims to support a total of 76 ground-breaking industrial projects in this technology.

Essential for the development of hydrogen are electrolysers to produce green hydrogen and fuel cells for the efficient conversion of hydrogen to electricity.

a. Electrolysers

Target:

There are several electrolyser producers in the EU. In order to scale up the production rate, a declaration (‘REPowerEU’) was signed by EU Internal Market Commissioner Thierry Breton and over 20 industry CEOs to increase the production capacity of electrolysers tenfold by 2030 and meet the estimated demand of green hydrogen of the EU of 10 million tonnes per year (reference: at this moment, less than 1 million tonnes are produced in the EU according to IEA). This production of 10 million tonnes will need a 90-100 GW installed capacity of electrolysers. The REPowerEU plan aims for a production capacity of 17.5 GW annually by 2025.

Main materials in the electrolyser supply chain

There are currently two types of commercially available electrolysers: Polymer electrolyte membrane (PEM) and Alkaline Electrolyser (AEL). The CRMs are mainly used in the part of the electrolyser where water is catalytically split into hydrogen and oxygen, called the ‘electrolyser stack'. The catalysts in these stacks hold the most CRMs of the electrolyser.

The key CRMs in PEM-type electrolysers are Iridium and Platinum whereas the key CRM in AEL-type electrolysers is Platinum. To a lesser extent Cobalt is used in AEL-type electrolysers. Also, nickel is used in AEL-type electrolysers.

Based on the ambitious scenario for the demand of green hydrogen in Europe in 2050, it is expected that the requirement of iridium for electrolysers will surpass 122% of the current annual global production of iridium and 25% of the current annual global production of platinum for electrolysers only, given assumptions (Wieclawska & Gavrilova, 2021).

Table 7: Main materials electrolysers

Main material of focus	Iridium and Platinum
Other materials in JRC's 4th list of CRMs	Cobalt
Base metals	Nickel

Source: Authors' own elaboration.

Overview of sources of supply

Platinum, Iridium and Cobalt are the main issues when it comes to supply of CRMs in electrolysers. Iridium poses the largest issue because it is used most in the current types of electrolysers in terms of weight. Cobalt is less of a concern for electrolysers since it is only used in small quantities.

Iridium is mined as a by-product from platinum mining. South Africa is the main producer (59% of global supply). There is a minor iridium supply within the EU from end-of-life products and manufacturing waste.

Platinum is mined predominantly in South Africa. A very small part of primary production of Platinum takes place in the EU: Finland and Poland produce 0.72% and 0.04% of the global supply respectively.

Supply from secondary materials has risen in the past decade from 7.5% (of the total production of Platinum, Palladium and Rhodium) in 2004 to 29.9% in 2014. The supply-line and infrastructure seem established, and these secondary metals are a major source of supply in Europe. Recycling of (automotive) catalysts is the major contributor. Recycling of jewellery and electronic scrap also adds to the secondary metals market.

Potential for reducing material use from alternative technological solutions

There are multiple technological strategies to reduce Iridium and Platinum from electrolysers. There are three types of categories for the reduction of materials: prevention/reduction of the use of Ir and Pt, efficiency increase of the electrolyser and recycling.

For Iridium in electrolysers, reduction is the most effective strategy. For Platinum, reduction and substitution are the most promising strategies. The strategies in the 'efficiency' category will decrease the amount of Ir and Pt somewhat whilst recycling is only deemed interesting for Platinum. Recycling will also only be effective after a significant end-of-life stream becomes available (Wieclawska & Gavrilova, 2021).

Technological differentiation is an interesting strategy: currently a new type of electrolyser is being researched which uses different and less CRMs: the Solid oxide electrolyser cell (SOEC). Materials such as zircon (Zr), yttrium (Y, a REE), lanthanum, strontium, manganese and scandium are used in SOEC electrolysers.

All these strategies are currently under investigation, but the Technology Readiness Levels[16] are low: these strategies are still in the research phase and will take years, if not decades, to be implemented. Recycling strategies exist, but their potential to diminish the volume of materials needed will materialise as the volumes of embedded materials increase and the efficiency of techniques improve (Gregoir and van Acker, 2022).

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[16] Technology readiness levels (TRLs) are a method for estimating the maturity of technologies during the acquisition phase of a program. TRLs enable consistent and uniform discussions of technical maturity across different types of technology.

It can be concluded that all these strategies must be considered simultaneously in order to decrease the risk of inadequate supplies of CRMs for the ambitious electrolyser goals.

b. Fuel cells

Fuel cells are electrochemical devices that convert hydrogen directly into electricity without combustion. Today, the fuel cells are used in three main areas: stationary power generation (ca. 67% market share), transportation (ca. 32%), and portable power generation (<1%). The fuel cell market for the transport sector is expected to grow significantly in the future.

Main materials used in fuel cell supply chain:

The key material in the production of fuel cells is platinum, which represents about 50% of the cost of a fuel cell stack.

Table 8: Main materials fuel cells

Main material of focus	Platinum
Other materials in JRC's 4th of list of CRMs	Cobalt, magnesium, REEs, palladium, borates, silicon metal, rhodium, ruthenium, graphite, lithium, titanium and vanadium
Other materials	
Base metals	Copper, nickel

Source: Authors' own elaboration.

Overview of sources of supply

The main vulnerability in the fuel cell supply chain concerns the platinum group metals (PGMs). Platinum is mined predominantly in South Africa (64% of global production) and in Russia (15% of global production). Lesser players are Zimbabwe, Canada and the USA. The other platinum group metals (PGMs), namely palladium, rhodium and ruthenium are also supplied predominantly by three key suppliers: Russia, South Africa and Zimbabwe.

Beyond raw materials, European companies supply around 40% of processed materials and 25% of fuel cell components.

The major producers of assembled fuel cells are in Asia (mainly Japan and South Korea) and North America (Canada and USA).

Potential for reducing material use from alternative technological solutions

Current research focuses on reducing or eliminating the expensive platinum-group metals from catalysts, and on increased activity and durability.

2.1.4 Energy storage and networks

a. Batteries for energy storage

The main elements needed in batteries for utility scale storage and the supply chain vulnerabilities are like those mentioned in the Section on e-mobility.

Potential for reducing material use from alternative technological solutions

This is also an area with much experimentation. Solutions to the energy storage needs arising from the large-scale deployment of renewable energy include non-battery based storage, such as pumped hydro, heat storage, gravity storage. In terms of battery-based solutions, the utility-scale storage needs do not have the same constraints in terms of weight and density as energy storage for mobility, and hence there is more scope for using more abundant and cheaper, but heavier, elements, such as sodium. The vast majority of R&D investments is driven by the needs of the automobile industry and therefore skewed towards lithium batteries.

2.1.5 Base metals

In addition to the specific uses described above, the energy transition will require large amounts of base metals, especially aluminium, copper, zinc, and nickel.

In particular, the need for copper and aluminium, used for in electricity networks, will grow significantly with the deployment of renewable energy. For example, by 2040, Europe's energy transition will require almost 5 million tonnes of aluminium (equivalent to 30% of Europe's current aluminium consumption), 1.5 million tonnes of copper (35% of current consumption), 300 million tonnes of zinc (10% of current consumption) and 300 thousand tonnes of nickel (110% of current consumption) (Gregoir and van Acker, 2022).

Overview of sources of supply

The markets for these base metals are mature and highly globalised, and the demand covers many fields of application. It is expected that current (and historic) growth rates of supply will be enough to accommodate the needs of the green transition (Gregoir and van Acker, 2022).

2.1.6 Digital transition

The digital transition requires a wide range of product groups. In general, they can be classified as electronics and telecommunication products, but they also comprise products used for edge and cloud computing, photonics, wireless applications (5g/6g) and quantum computing. They contain components such as integrated circuits ("microchips"), optical fibres, displays, motherboards, memory, high speed hard drives, routers, lasers, ferrules, amplifiers, transceivers, detectors, modulators splitters, connectors and LEDs. The range of components used in quantum computing research will present even greater challenges. Most component requires a package or casing when placed in the final product.

All these components have one thing in common: they contain several CRMs and almost all of them in quantities measured in grams or (much) less. Some components have a slight overlap with green transition, such as battery storage units, although these batteries are normally of another make than the ones used in for electric vehicles.

The use of these product groups has been ramped up in the past decades, where electrical devices can be found in multiple sectors. Yet an accelerated use is still foreseen. The link between product groups and raw materials is studied (Marscheider-Weidemann 2021; Aguilar-Hernandez 2022). These studies provide estimates of the material intensity so that we can determine how the growth in demand for ICT hardware translates in increased raw material demand. Quantum computing is an example of a technology that, even though currently at lower technology readiness levels, adopts tools to secure supply chains (Quantum Delta 2022).

A possible bottleneck for products in the digital transition, arising from the war in the Ukraine, is the supply of Neon to the world. Neon and Helium are essential to a range of lasers.

They are widely used for industrial purposes given their cost/quality ratio. The Neon price increased ten-fold or more in 2022[17]. Neon will not be part of the overview table given its limited use for green technologies.

Arguably one of the most iconic cases of disrupted supply in recent years was that of the integrated circuit or microchip. The "chip" is an assembly of electronic components (e.g., transistors, diodes, capacitors and resistors), connected on a base, often a wafer of semiconducting material (typically silicon). The evolution of the chip over recent decades is also an iconic example of both innovation, miniaturisation and complex supply-chains. The digital transition should not be constrained by shortcomings in the supply to the EU industrial eco-system.

Potential for reducing material use from alternative technological solutions

There is an interesting nexus between the digital transition and the green transition. Innovation in the ICT sectors, with their corresponding use of electronics and other hardware, is seen as an enabler and driver for the energy and circular transitions. It is therefore not so much the availability of raw materials but of the entire ICT infrastructure that influences the speed with which a broad array of energy transitions can take place. A striking example is of course the production of advanced EV, which depends strongly on the availability of a digital infrastructure.

2.1.7 Summary: demand of CRM in products shaping the green and digital transition

Table 9 provides a summary of the raw materials needed for the green and digital transition, their main uses, current consumption in the EU, global production, and forecast growth in EU consumption.

Table 9: Summary table of raw materials needed for the green and digital transition

Material	Critical 4th CRM assessment from 2020	Product	Purpose	Current EU consumption in all applications in thousand tonnes	Global production[18], in thousand tonnes metal content (average 2012-2017)	Projected increase in EU annual demand 2030 for green and digital transition, low – high scenarios[19], in thousand tonnes	Projected increase in EU annual demand for digital transition, in thousand tonnes[20]
Aluminium		Base metal	All	12 000	54 628	189 – 770	
Borates	Yes	PV cells, Magnets	Solar, Wind, EVs	36	163	0.08 – 0.32	
Chromium		Alloys	All	400	6 158	8 – 31	
Cobalt	Yes	Batteries	EVs	30	93	52– 170	
Copper (ore)		Base metal	All	4 000	18 700	141 – 590	
Dysprosium (HREE*)	Yes	Magnets	Wind, EVs	0.2	1.0	0.28 – 1.10	0.5

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[17] For specific CRM analyses in the context of the war in Ukraine, see: https://rmis.jrc.ec.europa.eu/uploads/JRC130349_01_rare_gases.pdf.

[18] Processed metal, unless noted as extracted ore. Source: European Commission 2020c.

[19] The widely referenced JRC study was used for this growth estimate: European Commission 2020b.

[20] The growth of raw material demand for the digital transition is based on Marscheider-Weidemann et al 2021.

Material	Critical 4th CRM assessment from 2020	Product	Purpose	Current EU consumption in all applications in thousand tonnes	Global production[18], in thousand tonnes metal content (average 2012-2017)	Projected increase in EU annual demand 2030 for green and digital transition, low – high scenarios[19], in thousand tonnes	Projected increase in EU annual demand for digital transition, in thousand tonnes[20]
Gallium	Yes	PV cells	Solar, All	0.05	0.2	0 – 0.02	0.2
Germanium	Yes	PV cells	Solar, All	0.03	0.1	0.001 – 0.03	
Indium	Yes	PV cells	Solar, All	0.2	0.8	0.001 – 0.06	1.2
Iridium	Yes	Electrolysers	Hydrogen		0.006		
Lithium	Yes	Batteries	EVs, Storage	6	26.7	42 – 106	12
Magnesium	Yes	Alloys	All		928		
Manganese (ore)		Batteries	EVs, Storage	4 000	17 508	73 – 211	
Molybdenum (ore)		Alloys	All	60.5	274	1.7 – 6.5	
Natural graphite (ore)	Yes	Batteries, Fuel cells	EVs, Storage, Hydrogen	250	1 137	439 – 980	600
Neodymium (LREE**)	Yes	Magnets	Wind, EVs	4	9	1.43 – 6.7	10
Nickel (ore)		Base metal	All	500	2 271	238 – 512	
Niobium	Yes	Alloys	All		42.5		
Palladium	Yes	Fuel cells	Hydrogen	0.01	0.2		
Platinum	Yes	Fuel cells, Electrolysers	Hydrogen	0.039	0.18	0.002 – 0.02	
Praseodymium (LREE**)	Yes	Magnets	Wind, EVs	1		0.4 – 1.44	2.5
Rhodium	Yes	Fuel cells	Hydrogen		0.021		
Ruthenium	Yes	Fuel cells	Hydrogen		0.027		
Selenium		PV cells	Solar	1.0	3.4	0.005 – 0.14	
Silicon metal	Yes	PV cells	Solar, All	400	2 541	51 – 285	
Strontium (ore)	Yes	Fuel cells	Hydrogen		334		
Tantalum (ore)	Yes	Alloys	All	0.1	1.2		0.2
Tellurium		PV cells	Solar	0.1	0.37	0.005 – 0.26	
Titanium	Yes	Batteries, Fuel cells, Alloys	EVs, Hydrogen, All		187		
Tungsten	Yes	Alloys	All		70		

Material	Critical 4th CRM assessment from 2020	Product	Purpose	Current EU consumption in all applications in thousand tonnes	Global production[18], in thousand tonnes metal content (average 2012-2017)	Projected increase in EU annual demand 2030 for green and digital transition, low – high scenarios[19], in thousand tonnes	Projected increase in EU annual demand for digital transition, in thousand tonnes[20]
Uranium		Nuclear	Nuclear				
Vanadium	Yes	Alloys	All		86		
Zinc (ore)		Base metal	All	3 000	13 330	80 – 330	

Note: (*) List of other Heavy Rare Earth Elements (HREE): Erbium, europium, gadolinium, holmium, lutetium, terbium, thulium, ytterbium, yttrium; (**) List of other Light Rare Earth Elements (LREE): Cerium, lanthanum, neodymium, praseodymium, samarium, scandium.

Source: JRC 2020.

2.2 Imports of materials and components in key green industries

As an open and mature economy, dependent on trade for access to inputs and export markets, the EU economy benefits from some degree of international specialisation. This means that it does not, and should not aim at, domestically producing all the technologies identified in Section 2.1. Some dependence on imports, of both materials and manufactured goods, is inevitable. However, the choice of trading partners has strategic implications that should not be ignored. In the absence of a domestic production capacity for some technologies, Europe does not necessarily need a stable supply of all components and materials necessary for the green transition. However, ensuring a secure and affordable supply of materials offers the potential for industrial development and ensures international competitiveness in nascent industries.

The present Section discusses Europe's net trading position along the supply chains for the key technologies identified in Section 2.1, from raw materials to finished products. For each supply chain, the top panel reports the value of trade in million EUR, and the bottom panel reports the EU's share of global trade[21]. Across most supply chains, the value of trade in components and final products is orders of magnitude larger than the value of trade in raw materials, reflecting the added-value of components and final products.

The list of product groups that are in scope for the analysis in this Chapter is shown in Annex 1.

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[21] Methodological note: In the graphs that follow, global trade is calculated as the sum of net exports for countries with positive net exports. This measure reduces the amount of double-counting coming from hub countries that import and re-export goods and reduces the amount of intra-EU trade.

2.2.1 Industries in which Europe is in a strong position

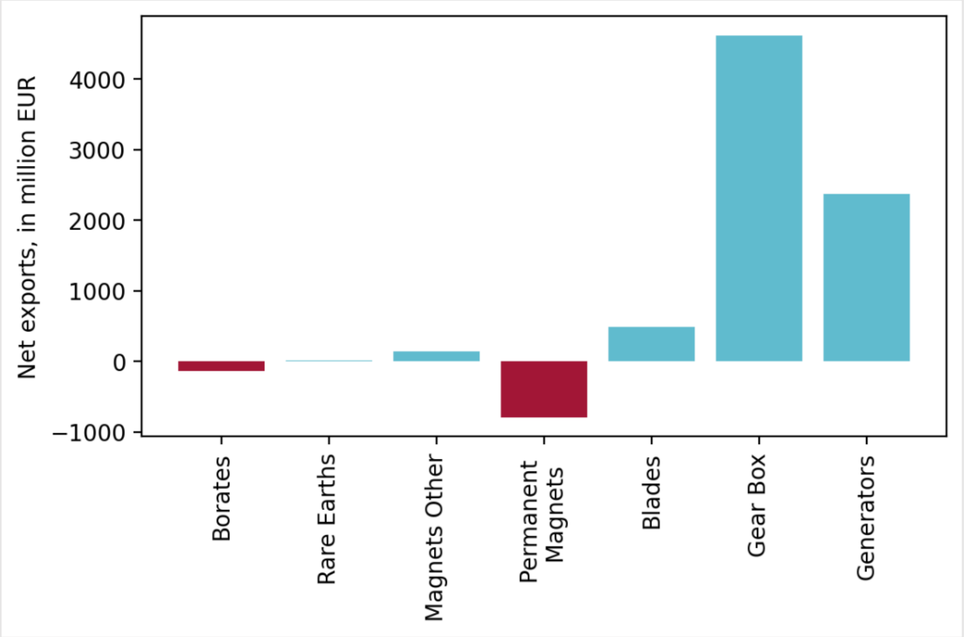
a. Wind energy

<u>EU's trading position in the wind energy supply chain</u>

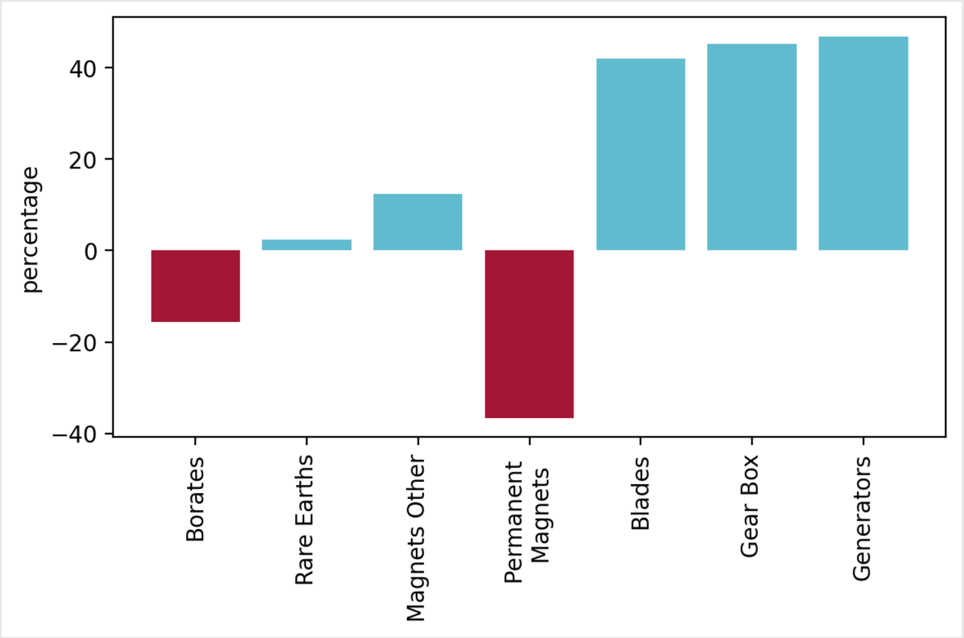
The trade situation with respect to the wind energy supply chain is given by Figure 1.

Figure 1: EU net exports along the supply chain for wind turbines, 2019

Panel A: Value in million EUR



Panel B: As a share of global trade



Source: Bruegel calculations from BACI database, Gaulier and Zignago (2010).

In this supply chain, the EU has a large trade deficit at the stage of permanent magnets, whereas it is a major actor in finished goods.

The EU is a strong net exporter of final goods in the supply chain for wind energy. EU exports of blades, gear boxes and generator represent around 45% of global trade each. In particular, the trade balance for gear boxes stands at EUR 4.6 billion. Hence securing access to permanent magnets is important for the EU's wind industry.

The European Raw Materials Alliance (ERMA) finalised an investment pipeline for supplying 20% of Europe's rare earth elements magnet needs by 2030 in 2021 (concerning all types of permanent magnets, not only for clean energy technologies). Currently, about 1,000 tonnes of permanent magnets are already produced in Europe (Gregoir and van Acker, 2022).

The two main raw materials entering the production of permanent magnets are borates and REEs. The EU is a net importer of borates, importing EUR 133 million, which represents 16% of global trade. It is a net exporter of REEs, exporting EUR 14 million, or 2% of global trade. This small trade surplus in REEs, in the context where almost 70% of global mining (in 2020) takes place in China, suggests that within the EU there is little industrial infrastructure to produce goods from REEs.

b. E-mobility

EU's trading position in the e-mobility supply chain

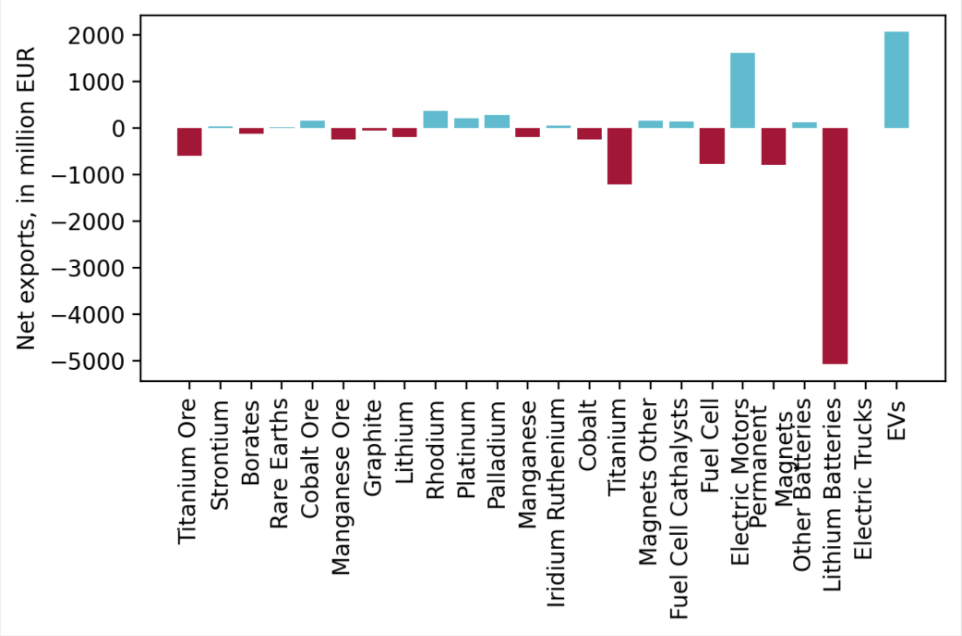
In the supply chain for e-mobility, the EU is a net exporter of EVs. The EU exports EUR 2 billion, or 19% of global trade of electric vehicles (EVs), and EUR 1.6 billion, or 9% of global trade, of electric motors. Hence, a steady supply of components entering the production of EVs is important for Europe's competitiveness in this growing industry.

Strengthening the EU's domestic production of these three components has been established as a priority and will be discussed in detail below.

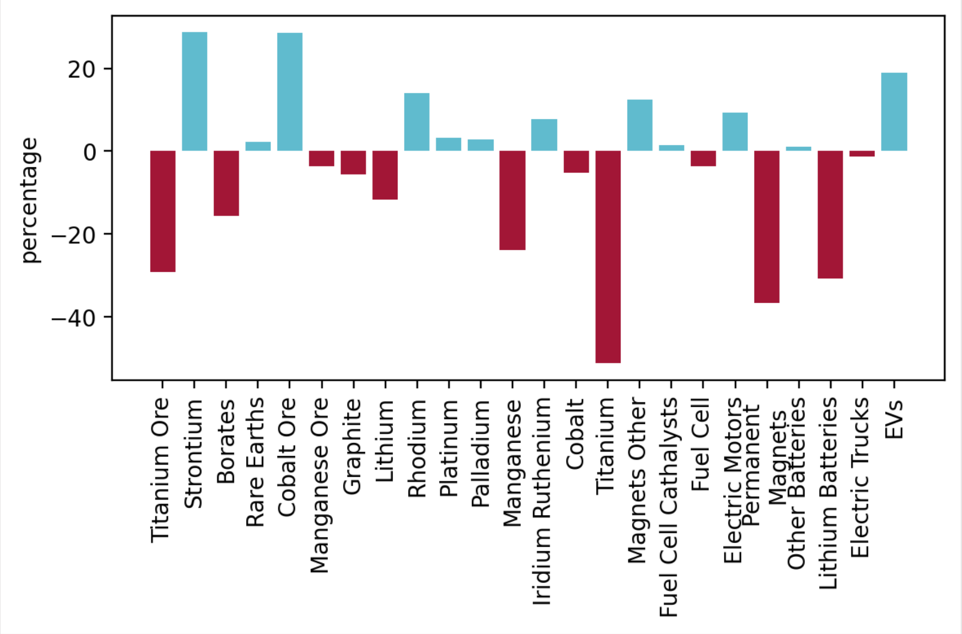
The EU is a net importer of some key components entering the production of EVs, in particular of batteries, permanent magnets, and fuel cells.

Figure 2: EU net exports along the supply chain for e-mobility, 2019

Panel A: Value in million EUR



Panel B: As a share of global trade



Source: Bruegel calculations from BACI database, Gaulier and Zignago (2010).

2.2.2 Developing nascent industries

a. Batteries

As a result of the increasing introduction of EVs (EV), mobile electrical appliances (3C) and stationary decentralised energy storage systems (ESS), demand for lithium-ion batteries is expected to skyrocket yearly (> 30%) for the next 10 years. Various estimates suggest that the industry in the EU requires up to 30% of battery cells produced worldwide. In case the EU aims to reduce dependency on the Asian market, cell production capacity will need to be built up in the EU. Analyses of the consumer market show that the expected consumer demand in the EU cannot be serviced in the coming years even by combining the existing capacities of Asian and European cell manufacturers (European Commission, 2020b).

In 2018, global battery production stood at 150 GWh, with 3 GWh in Europe. However, the European Commission aims to fully cover Europe's battery needs through domestic production from 2025. Significant actions have been taken in the last five years, and the European Battery Alliance (EBA) now reports projects amounting to 310 GWh of gigacell production per year. More projects are in the pipeline to grow the capacity to 540 GWh per year. This would provide batteries for 5 million – 9 million vehicles per year (at a 60 kWh average battery size) (Gregoir and van Acker, 2022).

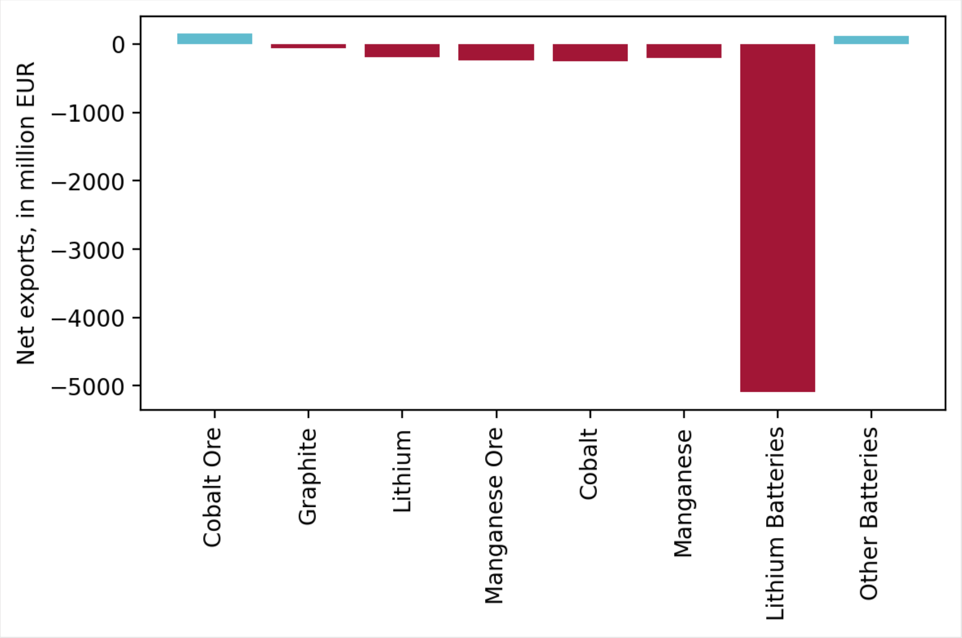
EU's trading position in the battery supply chain

The main supply vulnerability in the battery supply chain remains at the battery stage. In 2019, the EU imported EUR 5 billion of lithium batteries, representing 30% of world trade in batteries. The EU had a small net positive trading position for non-lithium based batteries, exporting EUR 113 million, or 1% of global trade.

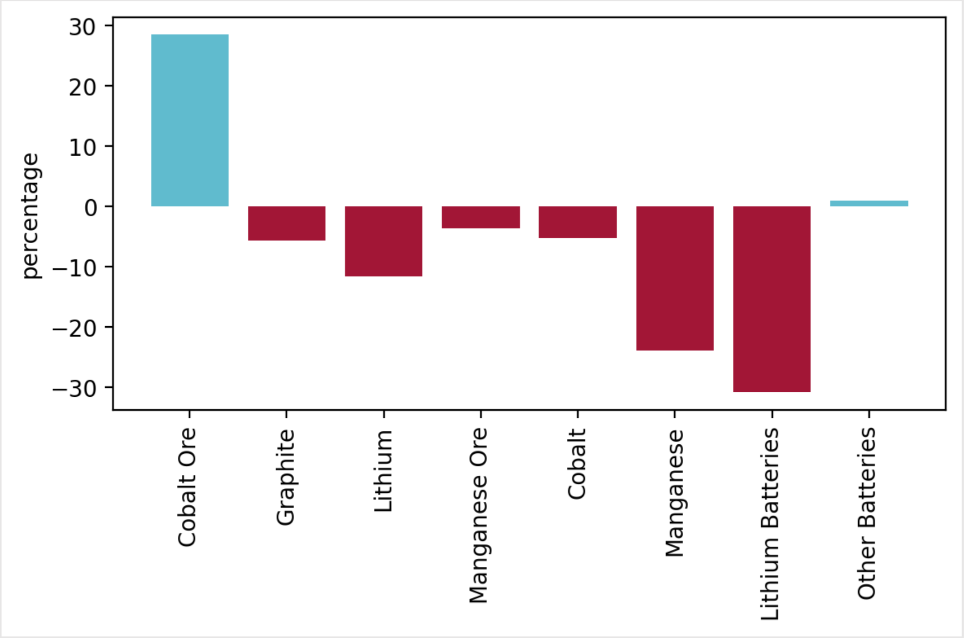
At the material stage, the EU is also a net importer of all elements entering the production of batteries, importing between EUR 200 million and EUR 250 million of lithium, manganese ore and manganese metal and cobalt. As a share of global trade, this represents 24% for manganese, 12% for lithium, and around 5% for the other elements. The EU is a net exporter of cobalt ore.

Figure 3: Value of EU net exports along the supply chain for batteries, 2019

Panel A: Value in million EUR



Panel B: As a share of global trade



Source: Bruegel calculations from BACI database, Gaulier and Zignago (2010).

b. Renewable Hydrogen: electrolysers and fuel cells

EU's trading position in the hydrogen supply chain

In the supply chain for electrolysers, the EU is a net exporter of the final good, but also of the main raw material, iridium. The EU exports EUR 60 million (12% of global trade) of electrolysers, and EUR 40 million (8% of global trade) of the product category "iridium and ruthenium".

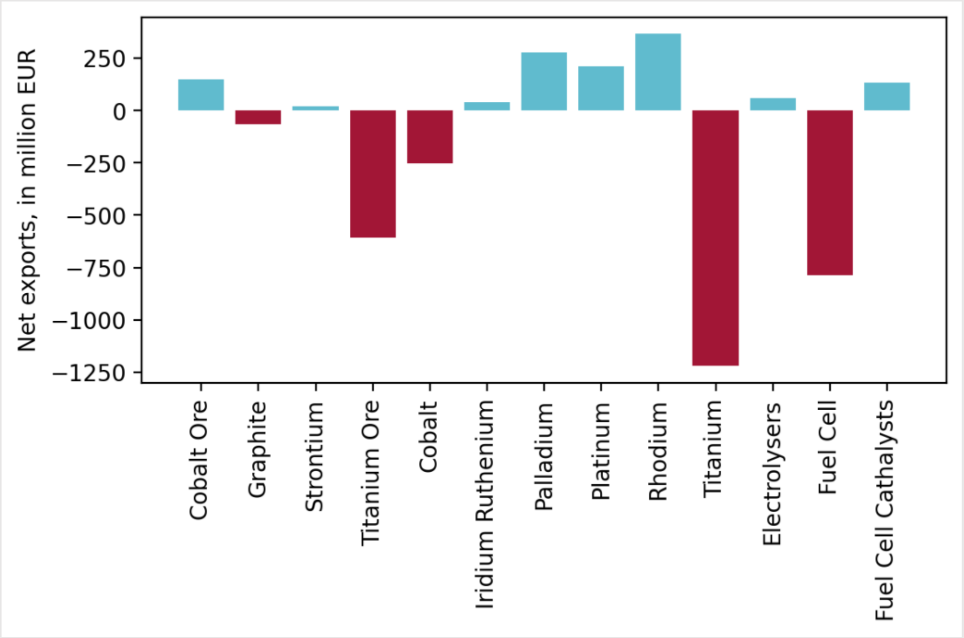
In the supply chain for fuel cells, the EU is a large net importer of the final goods, the fuel cells, but also of titanium, both as an ore and as a processed metal.

The EU imports EUR 785 million of fuel cells, which is less than 4% of world trade. However, the EU imports EUR 608 million of titanium ore and EUR 1.2 billion of titanium, which represent 30% and 50% of world trade, respectively.

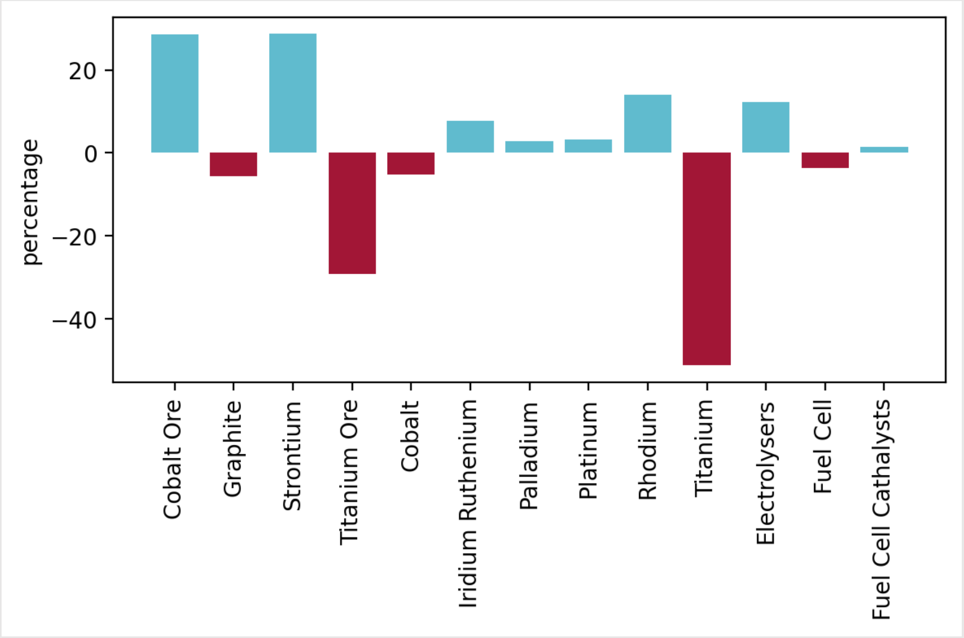
The EU is also a net importer of cobalt and graphite, while it is a net exporter of the other raw materials of the fuel cell supply chain, strontium, iridium, ruthenium, palladium, platinum, and rhodium.

Figure 4: EU net exports along the supply chain for hydrogen production, as a share of global trade, 2019

Panel A: Value in million EUR



Panel B: As a share of global trade



Source: Bruegel calculations from BACI database, Gaulier and Zignago (2010).

2.2.3 Restoring lost industries

a. Solar PV

China is the leader in the supply in all four steps of the supply chain of solar PV technology. The maximum share estimated for the EU is 6% for raw materials and 5% for the processed materials step, while it lacks almost completely of production for solar cells and modules.

Europe has a small and incomplete solar PV production chain. Historically, there was a full production chain that became economically unviable for European producers due to competition conditions with imports of low-cost Chinese products. Europe currently has 26 GW capacity of polysilicon production. This key material is exported to China for further processing, rather than staying in Europe (Gregoir and van Acker, 2022).

The European Solar Initiative was issued in 2021 with backing from the European Commission to redevelop a complete domestic solar PV production chain. It aims at restoring and scaling up the solar PV industrial ecosystem in Europe to 20 GW per year (2025). Because there are options for restarting brownfield facilities, the scale-up could be efficient (Gregoir and van Acker, 2022).

Considering the EU's limited current production of solar cells, reaching the European Commission objectives will be challenging, especially given the cost competitiveness of Chinese panels. The EU has capacity to produce solar grade silicon. However, there is no sufficient manufacturing capacity of solar cells, which appears to be the weakest link of the solar PV value chain in the EU. Entering to the market with EU cells and modules is difficult due to lower production cost in Asia. In this regard, there is potential to expand the market segment of tailored PV products because of relatively good market prospects compared to competing world regions and customer proximity (European Commission, 2020b).

EU's trading position in the solar PV supply chain

In the supply chain for PV panels, the EU has a large trade deficit at the stage of the panels themselves.

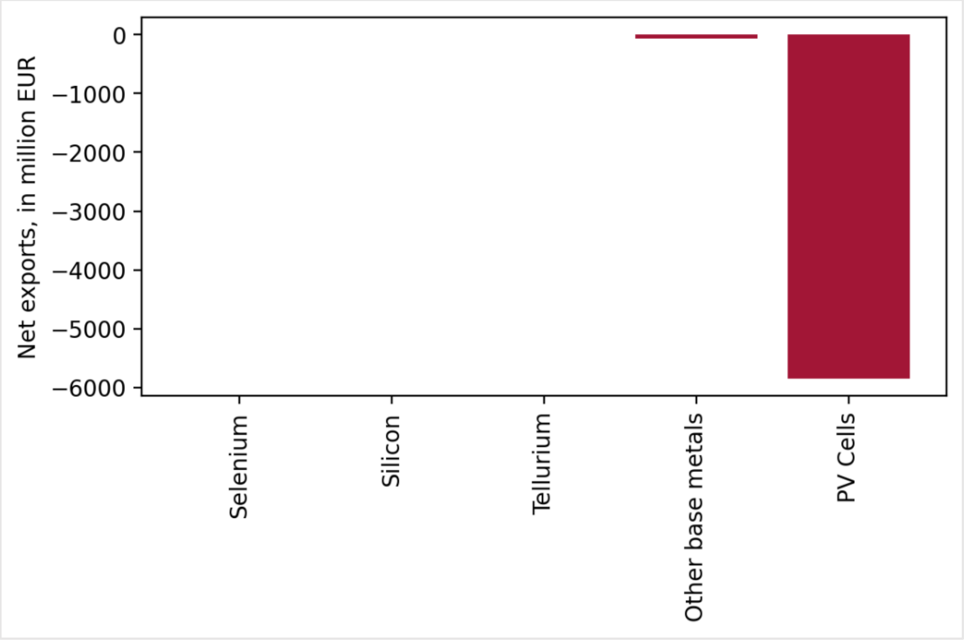
The EU is a net importer of PV cells, importing EUR 5.8 billion in 2019, which represents 24% the solar PV cells being traded worldwide.

In terms of the raw elements needed for the production of PV panels, the EU imports and exports around EUR 780 million of silicon (around 40% of world trade in silicon), with a net trade balance of EUR – 1.2 million (-0.1% of world trade). It is a net importer of tellurium (EUR 3.8 million, or 5% of world trade) and of metals of the group gallium, germanium, hafnium, indium, niobium and rhenium (EUR 63 million, or 14% of world trade).

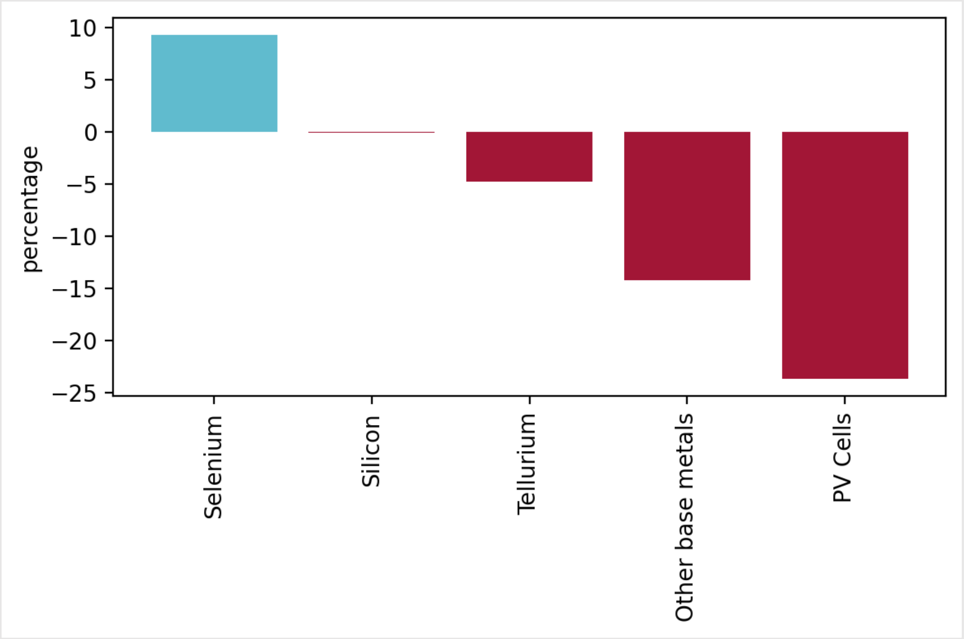
Finally, the EU is a net exporter of selenium (EUR 5.5 million, or 9% of world trade).

Figure 5: EU net exports along the supply chain for solar PV panels, 2019

Panel A: Value in million EUR



Panel B: As a share of global trade



Source: Bruegel calculations from BACI database, Gaulier and Zignago (2010).

2.3 Mapping the country of origin of the relevant imports

2.3.1 Country distribution for raw material production and known raw material reserves

It is generally acknowledged that the geological (and thus country) distribution of many raw materials can be rather concentrated. High concentration of raw materials can lead to quasi-monopolies and thus can be considered a supply risk. This is why country concentration is used as a dominant indicator in most criticality assessments worldwide, among which the EC CRM assessment which will be discussed in detail in Chapter 3.

Here we will discuss some of the geographical characteristics of materials that are of prime importance for the energy transition: rare earth oxides (REO), lithium (Li), cobalt (Co), Platinum Group Metals (PGM), nickel (Ni), graphite. In the graphs we show the current distribution of raw material producing (mining) countries, as well as the distribution of known and recognized reserves. A mineral reserve is defined as the economically mineable part of a measured and/or indicated mineral resource.

Figure 6: Origins of production

Source: Author's own elaboration.

Data concerning reserves are generally not used in assessing material criticality, mostly because of the volatile nature of the reserve data. Reserves can vary depending on the economic circumstances or the development of exploitation technology. However, the side-by-side comparison between production and reserve data provides insight in both the current dominant mining countries as well as in the potential shift in country distribution. Such shifts in potential mining production may lead to awareness about future international relations.

The graphic representation of producing countries and countries in which reserves are concentrated (Figure 6) leads to the following observations:

- For the five materials shown the distribution of production and of reserves are indeed highly concentrated in a few countries, with nickel being the least concentrated;
- Significant shifts between current product concentration and potential future production (i.e. published reserves) may occur for lithium (shift from Australia to Chile); and
- Shifts towards more potentially producing countries may occur for rare earth oxides though the dominant position of China remains.

The country concentration is generally defined by an analysis using the Herfindahl-Hirschmann-Index (HHI), which is calculated by taking the sum of the squared production shares of each country. An HHI of more than 2,500 is considered to be an indicator for a highly concentrated market and a risk for market stability. In Table 10, the HHI for energy transition materials is given for both the current production as well as the reserves.

Table 10: Concentration of source countries for CRM

Mineral	HHI for production	HHI for reserves
Lithium	3,300	2,247
Rare Earth Oxides	4,928	2,138
Cobalt	4,713	2,998
Platinum Group Metals	5,377	8,167
Nickel	1,522	1,547
Graphite	4,760	1,896

Source: Authors' own elaboration.

From Table 10 it can be concluded that the concentration of reserves is generally smaller than the concentration of current production. For lithium, rare earth oxides and graphite (and to a lesser extent for cobalt) the HHI for reserves drops below 2,500. Of course, in order to make the transition from publishing reserves to actual exploitation of these reserves takes time and above all investments. Taking notice of project pipelines and additional investor relevant information may provide intelligence about the likelihood of these reserves coming into production and about the raw material production becoming less quasi-monopolistic. Of course, this only concerns the first step in the material supply chain: taking notice of additional downstream technologies and the potential monopolies in those steps of the supply chain requires attention as well.

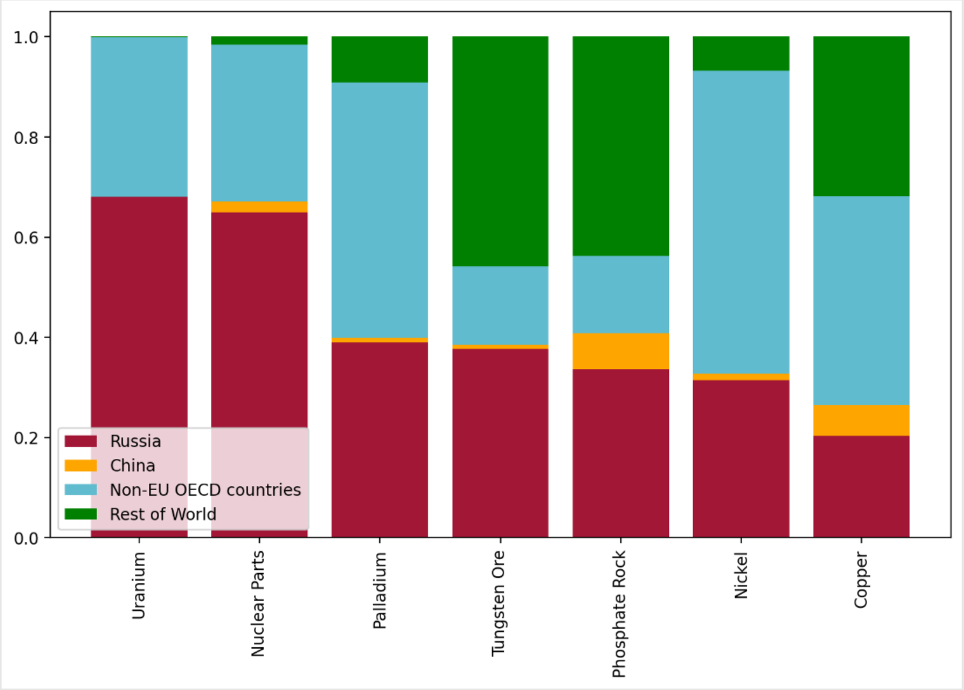
2.3.2 Highlight imports from Russia

The Russian invasion of Ukraine has made Europe's dependence on Russian fossil fuels, especially of natural gas, very clear and forced a thorough reconsideration of Europe's energy dependencies. The desired accelerated deployment of renewable energy begs the question of whether new dependencies will be created in general, and with respect to Russia in particular.

Nickel, cobalt and platinum are elements of particular interest because Russia in one of the top three global producers for these metals (IEA, 2021).

Figure 8 shows the list of materials for which Russia represents at least 20% of EU imports, along with other areas of origin (China, non-EU OECD countries, and rest of the world). This shows a dependence on Russia for nuclear technology and uranium. In terms of raw materials, the EU sources between 30% to 40% of its palladium, tungsten ore, phosphate rock[22] and nickel from Russia. Unreported in Figure 8, the EU imports 17% of its titanium and REEs from Russia.

Figure 7: Origin countries of European imports for materials where Russia represents at least 20% of imports, 2019



Source: Bruegel calculations from BACI database, Gaulier and Zignago (2010).

We also looked at whether the EU was importing significant amounts of materials goods needed for the green transition from Ukraine but found that Ukraine plays no significant role in this domain.

2.3.3 Highlight imports from China

In terms of import dependency, the main country from which Europe imports its materials and components for the green transition is China. Figure 9 shows the list of elements for which China represents at least 20% of EU imports. This list includes many of the components and (raw) materials discussed in the previous Section, highlighting the EU's dependence on Chinese manufacturing besides the dependence on the materials used in them.

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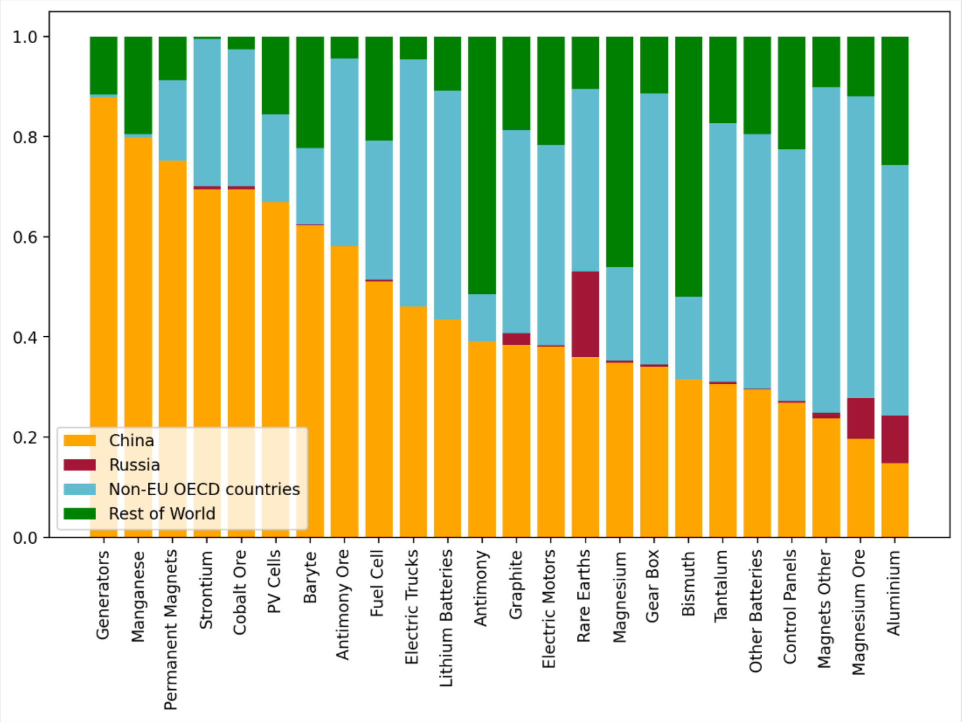
[22] This is a raw material considered critical, but its applications for the green and digital transition remain limited.

The EU imports 88% of its generators, 75% of its permanent magnets, 67% of its PV cells, 50% of its fuel cells, and 44% of its lithium batteries from China.

In terms of raw materials for the green transition, there is a strong dependency on China for manganese (80% of imports), cobalt ore (69%), graphite (38% of imports), REEs (35% of imports), and magnesium (35% of imports). Regarding some of the other flagship materials, the EU imports 16% of its silicon from China, and only 2% of its lithium.

Figure 8: Origin countries of European imports for materials where China represents at least 20% of imports, 2019



Source: Bruegel calculations from BACI database, Gaulier and Zignago (2010).

2.4 Conclusions

The EU is not dependent on raw materials per se, but on components, intermediate products and final products. The EU experiences significant trade deficits along the entire supply chain of technologies relevant for decarbonisation, either at the stages of (raw) materials, components or final goods. Important examples are the trade deficits for permanent magnets, lithium batteries and fuel cells. However, it is a net exporter of finished products in a few key industries, notably wind turbines, electrolysers and EVs.

Reliable and affordable access to components for wind turbines, electrolysers and EV are all the more vital as the EU is a strong exporter of the finished goods in these supply chains.

Access to the raw and transformed materials will become relevant as the EU develops production capacity in certain target industries. This is especially the case for batteries, where the EU is a net importer of all raw material (namely, graphite, raw and processed manganese, and processed cobalt), with the potential exception of cobalt ore.

Another raw material that warrants attention is titanium, as the EU has a strong overall trade deficit in this element, which is needed for fuel cells. **Russia** is in the top three global producers of titanium, and the EU imports 17% if its titanium from this country. Furthermore, the EU imports 15% of its platinum, needed for electrolysers, from Russia.

Overall, the main country of dependence for imports of product groups, raw materials and components, necessary for the green and digital transition is China. The production of permanent magnets, for use in the wind energy and e-mobility sectors, requires REEs. China is a dominant player in the entire value chain from extraction and refining of REEs to the production of permanent magnets using these refined REEs.

Active publicly executed risk-monitoring can help to safeguard the European supply of products shaping the green and digital transition. Risk-monitoring can make supply chain management by the private sector more effective. Moreover, it secures and fosters public knowledge within the EU, thereby increasing the scope-of-action to solve disruptions in supply to the EU.

3. INDEPENDENT ASSESSMENT OF CRITICAL RAW MATERIALS

KEY FINDINGS

The current level of raw material criticality is determined by two key factors: economic importance (EI) and supply risk (SR). The outcomes of the EU CRM assessment methodology remains robust under changed data inputs for the supply risk calculation, reflecting the changed geopolitical situation.

The CRM methodology might benefit from an extension of scope, including an assessment of product groups and sectors. This might support future policy decisions even more effectively.

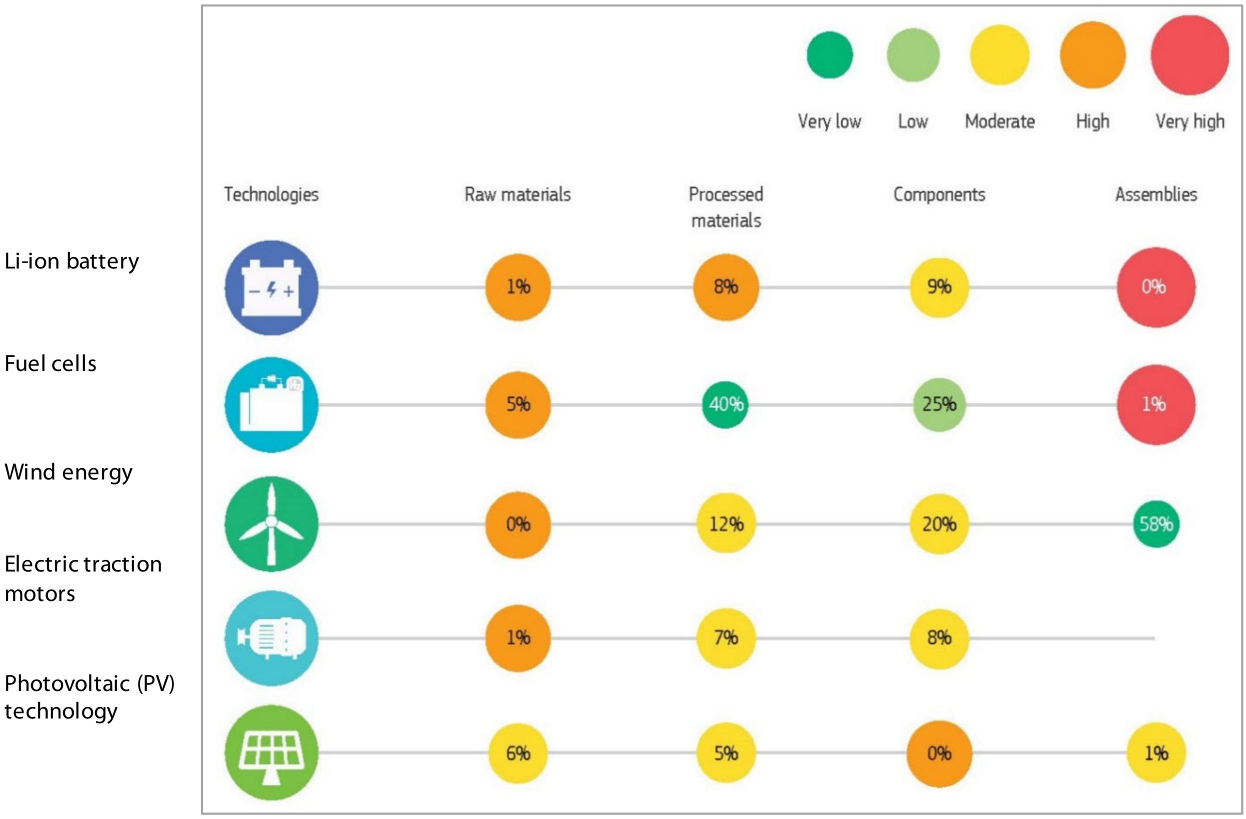
An independent assessment in this report demonstrates that including expected future demand in CRM assessments provides relevant additional insights. Furthermore, better publicly available data are a precondition to accurately manage CRM supply and safeguard the industrial capacity of the EU.

Chapter 2 showed the relevance of assessing international trade products containing CRM to estimate EU dependencies vis-à-vis the green and digital transition. This Chapter discusses the current CRM assessment methodology and performs a sensitivity analysis of its outcomes in light of the new geopolitical context. Furthermore, it discusses possible additional aspects of the CRM assessment that are not part of the existing methodology.

The approach adopted by the European Commission in the assessment of strategic dependencies is based on product groups (European Commission 2021b). However, the foresight study of the European Commission (European Commission 2020b) illustrates that vulnerabilities along the supply chain can exist at the level of raw materials, components and (complex) assemblies. Figure 9 identified existing SR for the EU. It displays the shares of EU production for each supply chain stage (raw and processed materials, components and assemblies) by technology, using green, orange and red indicators to demonstrate their estimated their respective low-, medium- or high- SR.

Despite the fact that such results show vulnerabilities along the entire supply chain, Figure 9 justifies the relevance of assessing raw material supply, especially for batteries since the EU has set out to create a domestic capacity in this area.

Figure 9: Identified SR for the EU



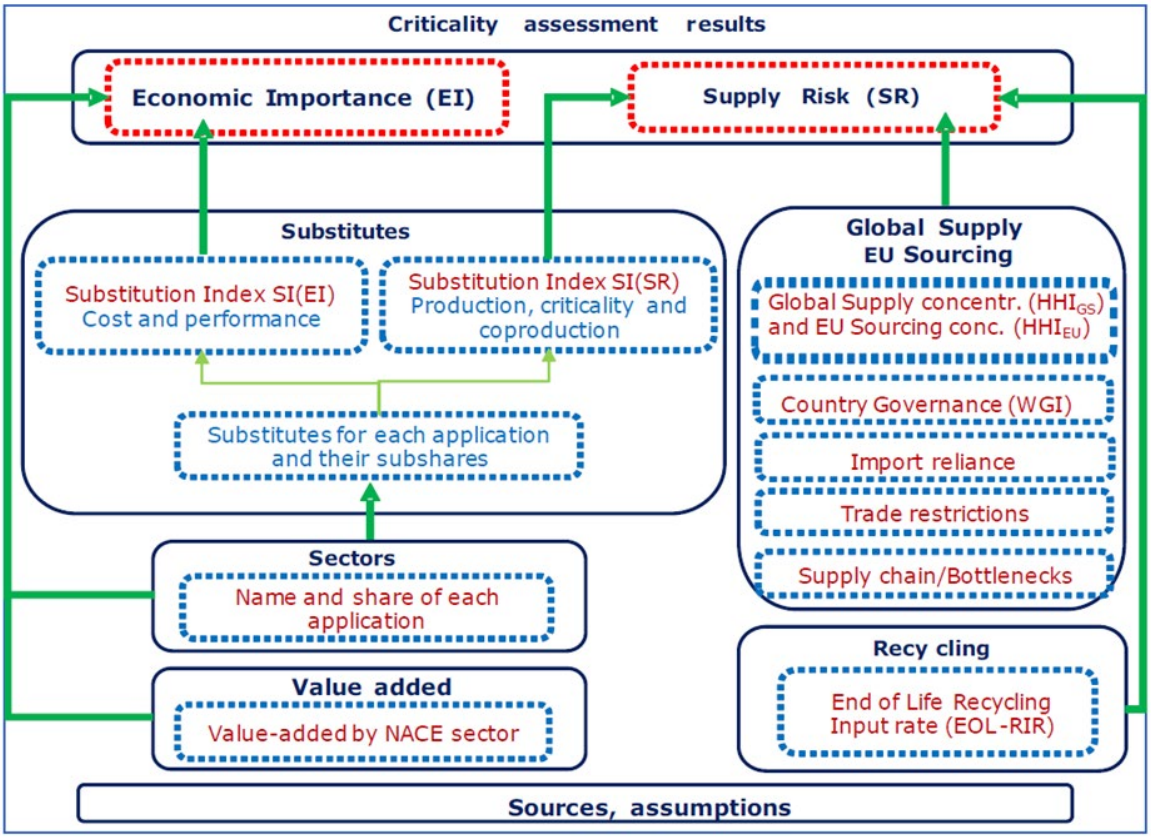
Note: the percentages show the share of EU production for a certain stage in the supply chain.

Source: European Commission 2020b.

3.1 Current CRM assessment methodology

The European Commission committed to an acknowledged methodology (Blengini 2017a) to assess the criticality of raw materials. It investigates the characteristics of supply to the EU of over eighty raw materials. The assessment whether a material is critical or not depends on the two main parameters: Economic Importance (EI) and Supply Risk (SR). The criticality assessment is based on data about the use of raw materials in economic sectors, the concentration and political stability of source countries and the current insights in substitutability and recycling. Figure 10 provides an overview of the most important indicators composing the assessment methodology.

Figure 10: Overview of CRM assessment methodology of the European Commission



Source: European Commission, 2020c.

The two red-dotted rectangles in Figure 10 show the two key parameters of the CRM assessment. Most raw materials are assessed at both extraction and processing stage: the stage with the highest criticality score determines their criticality status.

The value of EI of a raw material is calculated for each sector, by multiplying its application share in the EU with the gross value added (GVA) of that sector. An economic substitution index can reduce the economic importance, in case a raw material can be economically substituted on a short term.

The value of SR of a raw material is calculated based on an increased number of indicators than EI. These indicators are:

- **Global supply concentration:** using the Herfindahl Hirschman Index (HHI) that describes the concentration for source countries;
- **Country governance:** using the World Governance Index (WGI) determined by the World Bank to express governmental stability;
- **Import reliance**: expressing the extent to which the EU is reliant on imports of a raw or processed material from non-EU countries;
- **Trade restrictions**: barriers to international trade as documented by the OECD;
- **Recycling rate:** the flow of secondary material that actually replaces primary materials (expressed in the so-called End-of-Life Recycling Input Rate); and
- **Technical substitution**: indicating the possibility, or impossibility, to replace a raw material by another readily available raw material, with a subsequent acceptable technical performance.

A material is considered to be critical when both EI and SR indicators result in a score that exceeds a certain numerical threshold. The threshold value is set at 2.7 for EI and 1.0 for SR. These values have no intrinsic significance, but they are a mere consequence of the formula used to calculate EI and SR. The examples provided below illustrates the way this methodology is applied in practice for aluminium, sapele wood and tungsten.

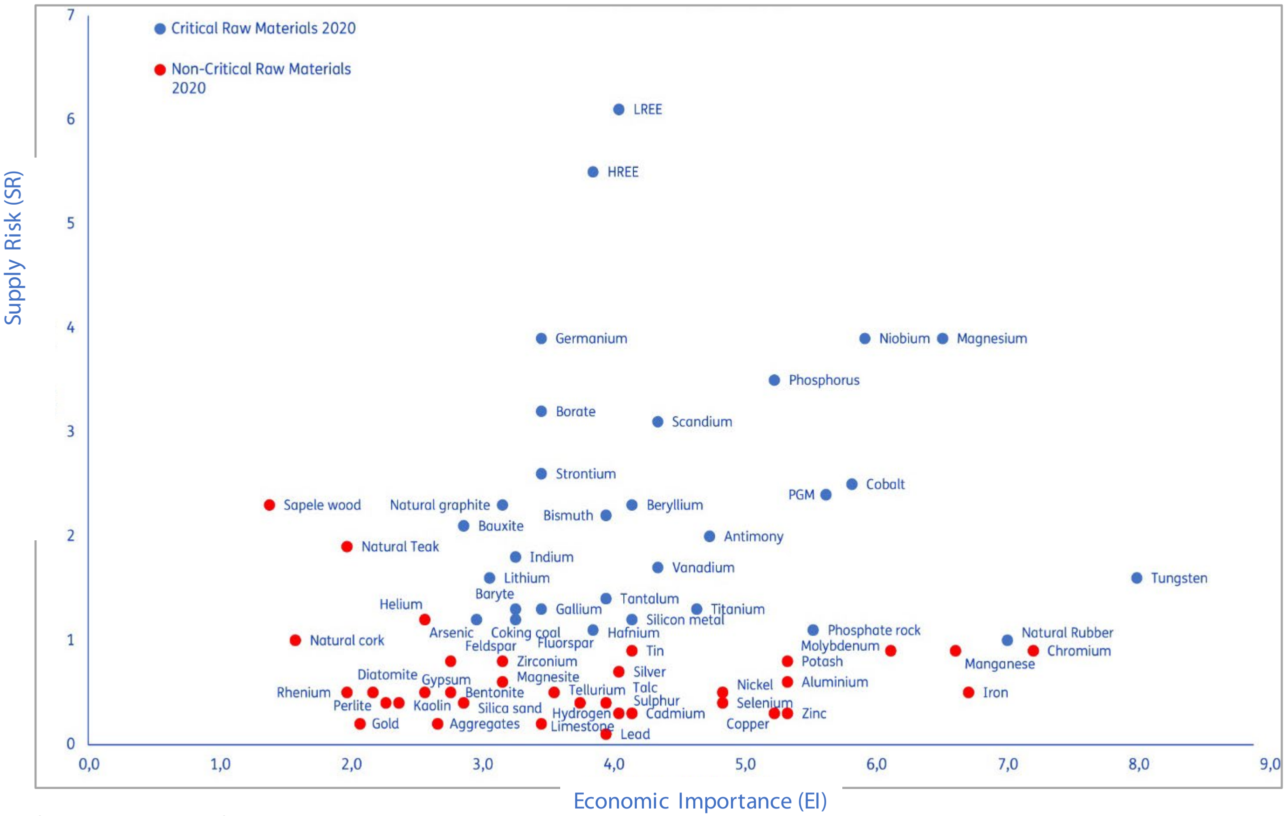
A metal like aluminium is widely used in the automotive industry (21% of aluminium production), in other transport equipment manufacturing (e.g. aerospace, 21% of aluminium production) and in the construction industry (23% of aluminium production). Given its wide sectoral application, aluminium scores of 5.6 in EI. With regard to SR, aluminium scores relatively low at 0.6, as the metal is sourced from more than seven different countries, including Iceland and Norway. Due to this low SR, aluminium is not considered critical.

Regarding sapele wood, it is mostly used in the construction sector (80% of production). Hence, in terms of EI, it receives a relatively low score when compared to the threshold value for EI. However, SR for sapele wood is relatively high at 2.3, given its manufacturing characteristics. The production of sapele wood is highly concentrated in five countries, four of which are located in Central Africa. With only one threshold value exceeded, sapele wood is not assessed as critical.

Finally, a metal like tungsten is used for industrial mill and cutting tools, construction tools and other wear resistant tools (33%, 23% and 18% respectively). Hence, it receives a relatively high EI score of 8.1. In terms of tungsten supply, the EU is heavily relying on its import from China (90%). Therefore, in terms of SR, tungsten also scores relatively high at 1.6. Given that both threshold values for tungsten are exceeded, this metal is assessed as critical.

Figure 11 below shows the results of the 4th CRM assessment, in the shape of a scatterplot diagram presenting the EI and SR of all the raw materials.

Figure 11: Overview of 4th CRM assessment by the EC



Source: European Commission 2020c.

3.2 Customizing indicators from the current CRM methodology

The war in Ukraine challenged the adequacy of the existing CRM definition. In this Section we perform an independent CRM assessment with the aim to understand the impact of the new geopolitical context on the 4th CRM list established in 2020 (European Commission 2020c).

The assessment is carried out by setting up scenarios that reflect various geopolitical changes and analysing the impact these would have on SR scores (note EI scores are left unchanged in this case). The assessment of scenarios uses the CRMs methodology as published by the European Commission for establishing the EU list of CRM (European Commission 2020c). In this independent assessment, only certain data points (i.e. numerical values) are changed. Consequently, the assessment resembles to a sensitivity analysis of the data used in the 4th CRM assessment.

Given the changing geopolitical context, indicators that represent governance or geopolitics seem most suitable for modification in this independent assessment. Five scenarios are defined to explore the impact of modified data for these indicators on the SR score.

- **First Scenario:** A country decides to severely ban exports to the rest of the world, as witnessed in several trade restrictions in recent years[23]. Examples of such a ban include China's 2010 export quota on REEs. In this scenario, the supply of a certain country to the rest of the world is suppressed (e.g. Russia);

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[23] Trade restrictions are documented by the OECD and available online: https://qdd.oecd.org/subject.aspx?Subject=ExportRestrictions_IndustrialRawMaterials.

- **Second Scenario:** Country of destination (trade) decides not to source goods from a certain country. This scenario simulates a cessation of raw materials supply from a certain country to the EU (e.g. Platinum Group Metals (PGM) from Russia to the EU);
- **Third Scenario:** A decision is made to diversify source countries. This scenario simulates the impact of supplying raw materials from as many destinations as possible (e.g. neodymium being supplied from possible trading partners);
- **Fourth Scenario:** This scenario assesses the impact of the war in the Ukraine. In this scenario, the World Governance Index (WGI) of both the Ukraine and Russia are considered as "unfavourably as possible". This exercise investigates whether certain raw materials could be reassessed as critical in this context; and
- **Fifth Scenario:** This scenario assesses the impact of possible conflicts affecting trade with China. The scenario assigns an unfavourable WGI value to supply from China, following the same logic and methodology as in scenario four.

The original calculations are based on the 4th CRM assessment (European Commission 2020c).

3.2.1 First Scenario: A country decision to severely ban exports to the rest of the world

The first scenario aims to investigate a situation where a certain country would ban exporting their mined or stocked materials to the rest of the world. The aim is to analyse the effect of a severe reduction in the supply (or production capacity) of a certain country.

Given the 4th CRM estimates the total world supply by summing up the overall production capacity, the removal of supply from one country implies a lower world availability for that material. In the CRM methodology, this implies that demand will fall proportionately. However, the latter assumption seems rather unlikely. Instead, it would be reasonable to expect adjustments in the market, for example by following the Armington elasticities[24]. This shows a potential limitation of the CRM assessment methodology.

The first scenario does not provide significant outcomes. It demonstrates that no realistic price-demand relation results from the CRM assessment methodology as a result of changing demand. Hence, the CRM assessment methodology is unlikely to effectively model a country's decision to ban on exports to the rest of the world.

3.2.2 Second Scenario: A country of destination (trade) decides not to source goods from a certain country

The second scenario aims to investigate a situation where the EU decides to no longer source raw materials from a certain country (e.g. the supply crisis of gas to the EU). The reason is twofold:

- A certain country stops supplying their mined or processed materials to Europe, and Europe *reactively* satisfies its demand from other producing countries; and
- Europe *proactively* decides to reduce its SR by opting for a different country for import of materials.

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[24] Armington elasticities, used in the in the Global Trade Analysis Project (GTAP) computable general equilibrium model of world economy, are defined as the elasticities of substitution between imported and domestically produced goods. For a basic explanation on how demand and supply totals are expressed in macroeconomic trade models, see (Delahaye E. and C. Milot 2020).

In the second scenario, the supply to the EU from certain countries ended (e.g. China, Democratic Republic of Congo, Argentina, South Africa) and has been replaced by the supply of a different country or combination of countries (e.g. respectively Australia, Canada and Australia, USA, Canada).

The results in changing the supply of materials to the EU are demonstrated in Table 11 for an illustrative sample of the following raw materials: neodymium, dysprosium, praseodymium, cobalt, lithium and nickel. The global SR and the EU SR trends are compared with the new trends based on the action described in the right-hand column (action).

Table 11: Change in total and EU supply risk for ores and concentrates when EU supply from a certain country is replaced by other country

	Supply Risk (Ores and Concentrates)				
	Global Supply Risk	New global Supply Risk	EU Supply Risk	New EU Supply Risk	Action
Nd	5.93	4.35	5.52	2.24	China = 0; replaced by Australia
Dy	4.95	4.19	3.12	1.33	China = 0; replaced by Australia
Pr	5.36	3.84	5.52	2.24	China = 0; replaced by Australia
Co	2.54	1.19	3.97	0.68	DR Congo = 0; replaced by 50% Canada and 50% Australia (*)
Li	1.33	1.33	1.84	1.84	Argentina= 0; replaced by USA
Ni	0.49	0.48	0.67	0.66	South Africa = 0; replaced by Canada

Note: (*) neither country has sufficient production capacity to replace DR Congo supply by themselves.

Source: Authors' own elaboration.

3.2.3 Third Scenario: A decision is made to diversify source countries

The third scenario aims to investigate the perspective of supply diversification at a country level. In this scenario, SR is reduced by a country by diversifying source countries. That is what the EU aims to ensure with its numerous trade agreements and multilateral partnerships.

In the third scenario, the supply of the following three highly critical raw materials is assessed: neodymium, dysprosium and magnesium. For these three materials, China has a majority of the world's production capacity, accounting for over 85% (2019). Table 12 below summarises the results of the third scenario by comparing the official global and EU SR trends with the new ones.

Table 12: Change in supply risk for selected materials when EU supply from a certain country is diversified, sourcing from as many countries as possible

Supply Risk (SR)					
	Total SR official	Total SR new	EU SR official	EU SR new	Action
Nd	5.93	2.04	5.52	0.56	Supply from China removed by setting it to zero and equally divided over Australia, USA, India, Thailand, Brazil and Malaysia.
Dy	4.95	3.63	3.12	0.48	Supply from China removed by setting it to zero and equally divided over Australia, USA, India, Thailand, Brazil and Malaysia.
Mg	3.91	2.37	5.01	1.24	Supply from China reduced to 40%. The maximum production capacity from the USA and Brazil is assumed to replace Chinese supply.

Source: Authors' own elaboration.

The assessment in Table 12 shows interesting results. Firstly, the data for neodymium and dysprosium is peculiar. The EU SR scores less than "1" for both, meaning that neodymium and dysprosium (both REE) would be no longer critical. However, the solution for diversification of sources is to some extent misleading, as the proposed countries (e.g. India, Thailand and Brazil) are not producers themselves but traders of these REE. The traded materials originate from China. Secondly, the data on magnesium shows a strong dependency of the EU's economy from Chinese supply as China has a majority of the world's production capacity, accounting for over 88%. In this case, the diversification of sourcing is impossible and the EU is dependent on China for 40% of its magnesium demand. In turn, magnesium retains it "critical" SR status.

3.2.4 Fourth Scenario: Increased of WGI of Ukraine and Russia

The fourth scenario perform the sensitivity analysis for supply from Ukraine and Russia. The exercise focus on "almost critical" raw materials, which had SR value (just) below the critical threshold of "1". In this scenario the supply of the feldspar, tellurium, zirconium, magnesite, silver, tin, nickel, aluminium, potash, manganese, molybdenum, iron ore and chromium are investigated. Initially, these raw materials were not deemed "critical" in the 4th CMR assessment. However, they might become critical when their producing countries receive an unfavourable WGI score.

The outcome of this assessment is presented in Table 13. First, the status of titanium and tungsten will remain unchanged despite their SR increased as these materials such were initially assessed as "critical". Secondly, although tellurium notes the highest increase of SR, it still remains below critical threshold of "1". Thirdly, the supply of iron ore has insignificantly impacted by changes in WGI. Finally, steel cannot be assessed as 'critical' given it is not listed on the 4th CRM list. It shows that in the fifth fourth scenario no material will exceed the SR threshold.

Table 13: New supply risk for materials sourced from Russia or Ukraine into the EU

Material	Official supply risk	New supply risk
Feldspar	0.78	0.92
Tellurium	0.51	0.79
Zirconium	0.83	0.84
Magnesite (ore)	0.65	0.65
Silver (ore)	0.68	0.68
Tin	0.90	0.90
Nickel (ore)	0.37	0.45
Aluminium	0.59	0.65
Potash	0.79	0.86
Manganese (ore)	0.93	0.93
Molybdenum (ore)	0.94	0.94
Iron (ore)	0.46	0.48
Chromium	0.86	0.86

Source: Authors' own elaboration.

3.2.5 Fifth Scenario: Increased of WGI of China

In the fifth scenario perform the sensitivity analysis of supply from China on a representative sample of baryte, bismuth, gallium, magnesium, natural graphite, scandium, dysprosium, neodymium.

The outcome of this analysis is shown in Table 14. Given that all selected material were assessed as critical in the 4th CRM assessment, no changes are noted in their respective criticality status. Nonetheless, the selected CRM receive a significantly higher supply-risk value. The fifth scenario imply that SR of EU imports from China pertains rather to intermediate and final products containing CRM, opposed to ores or refined materials.

Table 14: New supply risk for materials sourced from China into the EU

Material	Official supply risk	New supply risk
Baryte (ore)	1.26	1.75
Bismuth	2.22	3.23
Gallium	1.00	1.27
Magnesium	3.91	6.03
Natural graphite (ore)	2.27	3.43
Scandium	3.09	4.54
Vanadium	1.42	1.70
Dysprosium	4.95	7.61
Neodymium	4.35	6.12

Source: Authors' own elaboration.

3.3 Adding new indicators to the current CRM assessment methodology

Another way to create an independent assessment of the CRM is to revise the 4th CRM list from 2020 along with new indicators that take into account the most recent developments in the global supply of raw materials.

Exploring new or newly applied indicators for the EU CRM assessment methodology can be necessary due to changing global context. For instance (Blengini et al. 2017a) already stated that "*some … improvements of the existing EU criticality methodology are required, taking into account the most recent methodological developments*". Dependent on technological, market, regional or geopolitical developments, criticality aspects might change in the eye of the beholder (Eggert 2011). The upheaval of markets since the COVID-19 pandemic, the war in Ukraine and the green and digital transition might make it even more relevant to develop additional views on indicators that are not yet part of the current EU methodology.

Therefore, it is suggested to make an independent assessment of (or parts of) the CRM list by looking at the impact of the following four newly defined indicators:

- **Price volatility (SR)**: a newly introduced factor represents the effect of price volatility on SR scores. It paves the way towards discussing conventional raw material stockpiling ambitions discussed in Chapter 4, given the potential of stockpiles to mitigate price-shocks;
- **Geopolitical affinity (SR):** a new interpretation of WGI that uses the average governance quality of EU source countries and compares it to the average governance score of global production countries. This new interpretation indicates to what extent sourcing from mindlike governmental institutions is possible. It paves the way towards a discussion on friend-shoring, a course of action that is part of the recent policies securing supply of critical raw materials;
- **Publicly Reported Reserves (SR)**: a new interpretation of the country concentration, that considers publicly reported geological reserves (instead of reported annual mining/refining production) to determine a new source country concentration. It is marginally relevant to stockpiling, as inactive but operational mining facilities can be considered as potential raw material stockpiles; and
- **Future demand (EI):** a newly introduced factor represents the effects of raw material demand forecasts on Economic Importance (EI) scores. The indicator is predicated on both the principle of public reason and the evidence that global supply-chains are slow to respond to increased demand, as in the green and digital transition.

3.3.1 A new price volatility indicator

Since some raw materials have seen turbulent price developments in recent years, the first analysis will investigate the potential introduction of a new indicator associated with price volatility of raw materials. Though the reasons for price developments and price volatilities can be manifold, one could argue that price volatilities are signs of strained and untransparent markets. Price volatility can therefore signal increased supply risks[25]. However, price information of any kind is not used in the current CRM assessment methodology.

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[25] See Annex 3 for an elaboration of this argument.

The inclusion of price volatility effects in the SR indicator is in this independent assessment obtained by using the Maximum Annual Volatility (MAV) of prices of a certain (critical) raw material. The MAV is used to assign a factor to the total SR[26]. A MAV of 50% indicates that a price on a certain day in a year had a maximum deviation of 50% from the average annual price. It should be noted that price volatility can be independent from price increases. A combination of volatility and a sustained price increase can happen at the same time, but a price increase and price volatility are not always strongly correlated, especially over longer periods.

The MAV values of used in this supply risk extension have been derived from the ROSYS database[27]. The specific MAV values used in this exercise are given in Table 15.

Table 15: The use of Maximum Annual Volatility to include price volatility in supply risk

Raw Material	Maximum Annual Volatility (MAV) between 2015 and 2020	MAV value normalized to 25	Original supply risk score
Cobalt	50.0	2	2.5
Nickel	30.0	1.2	0.5
PGM	29.0	1.16	2.4
Zinc	24.1	0.96	0.3
Tin	20.8	0.83	0.9
Copper	20.2	0.81	0.3
Aluminium	17.6	0.70	0.6
Gold	14.4	0.58	0.2

Source: Authors' own elaboration.

Operationally, each original SR score is scaled by a factor obtained as a ratio of the raw material specific MAV value and the average volatility in the MAV dataset for all raw materials (25). For example, in case of cobalt, its original supply risk of 2.5 is multiplied by 2 (Maximum Annual Volatility for cobalt (50) / average MAV for all elements (25) = 2), doubling its supply risk (SR) of 2.5 to 5.0. For a non-critical raw material such as gold, its original SR of 0.2 would be multiplied by a factor of 0.58, resulting in a new SR value of 0.12. The results of this procedure for all raw materials are shown in Figure 12.

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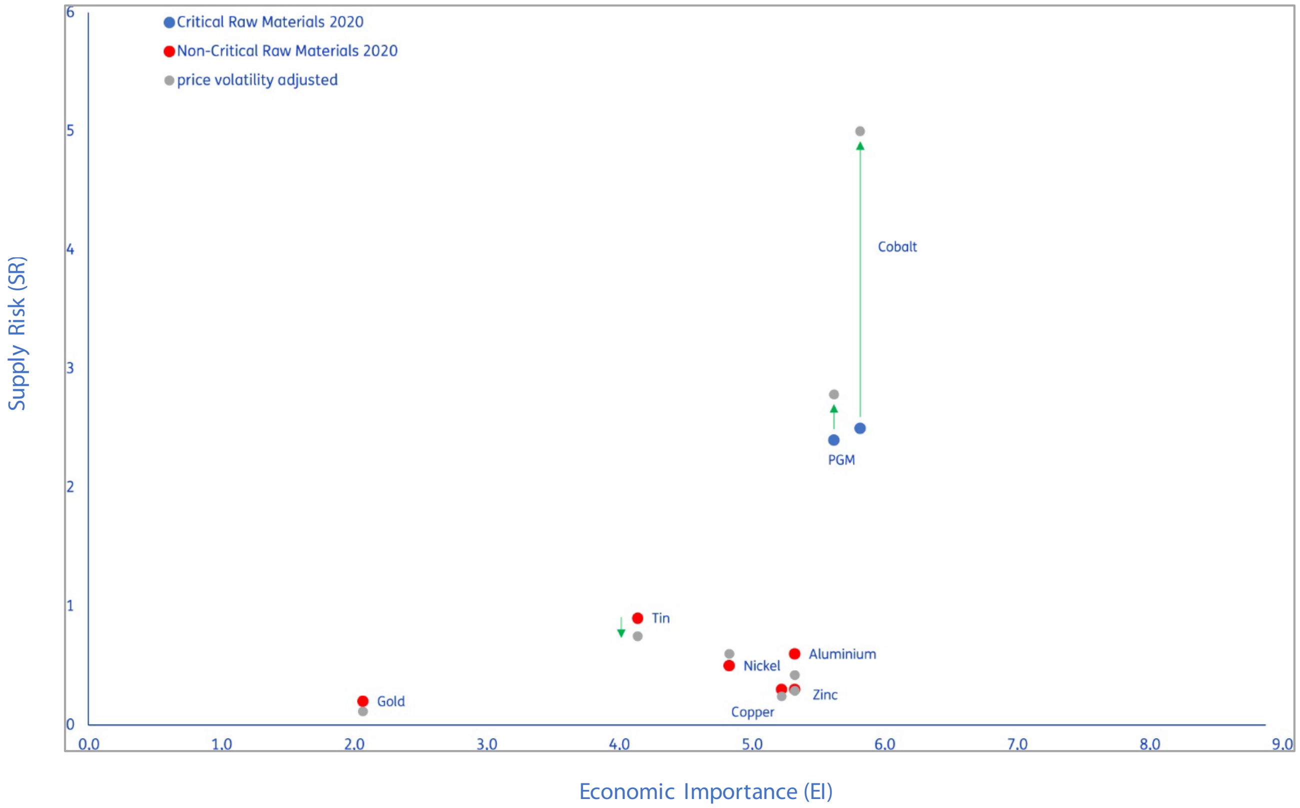
[26] Note that as this independent assessment is for illustration purposes, the use of the factor for price volatility was based on in a simplified way. Factoring price volatility as a separate argument in supply risk formula's might bring more balanced results.

[27] Price information from the German Mineral Resources Agency (DERA) can be found on their ROSYS system: https://rosys.dera.bgr.de/mapapps49prev/resources/apps/rosys2/index.html?lang=en.

Figure 12: Price volatility as new indicator



Source: Authors' own elaboration.

From the analysis of the results, it is concluded that, when considering price volatility for these specific raw materials, the original SR are increased. The adjustment of SR by introducing price volatility is performed in a simplified, but justifiable manner. The rescaling of SR by using the MAV value roughly resembles the way indicators such as country concentration, import dependency and substitution options are factored in the total supply risk by the current CRM assessment methodology. The unsuccessful fate of investments in REE mining after 2012 can partly be explained by the unpredictable price movements. New REE mining production, that could have lowered the supply risk, did not materialise as a result.

For the abovementioned metals, price data is available at an acceptable quality level. Precise price data for other metals with intense price spikes have not yet been available, making this type of price volatility exercise impossible.

3.3.2 A new interpretation of geopolitical affinity

This analysis aims to investigate the way WGI is used in the current CRM assessment methodology.

The WGI aims to capture the quality of governance of a country, consisting of the traditions and institutions by which authority in a country is exercised. It is already part of the current EU methodology for CRM assessment. The WGI score will be low if a country has good governance standards. In this sense, WGI is measured based on good accountability, political stability, government effectiveness, regulatory quality, respect the rule of law and control of corruption indicators. Imports from countries with an unfavourable WGI are consequently assumed to have a higher SR[28].

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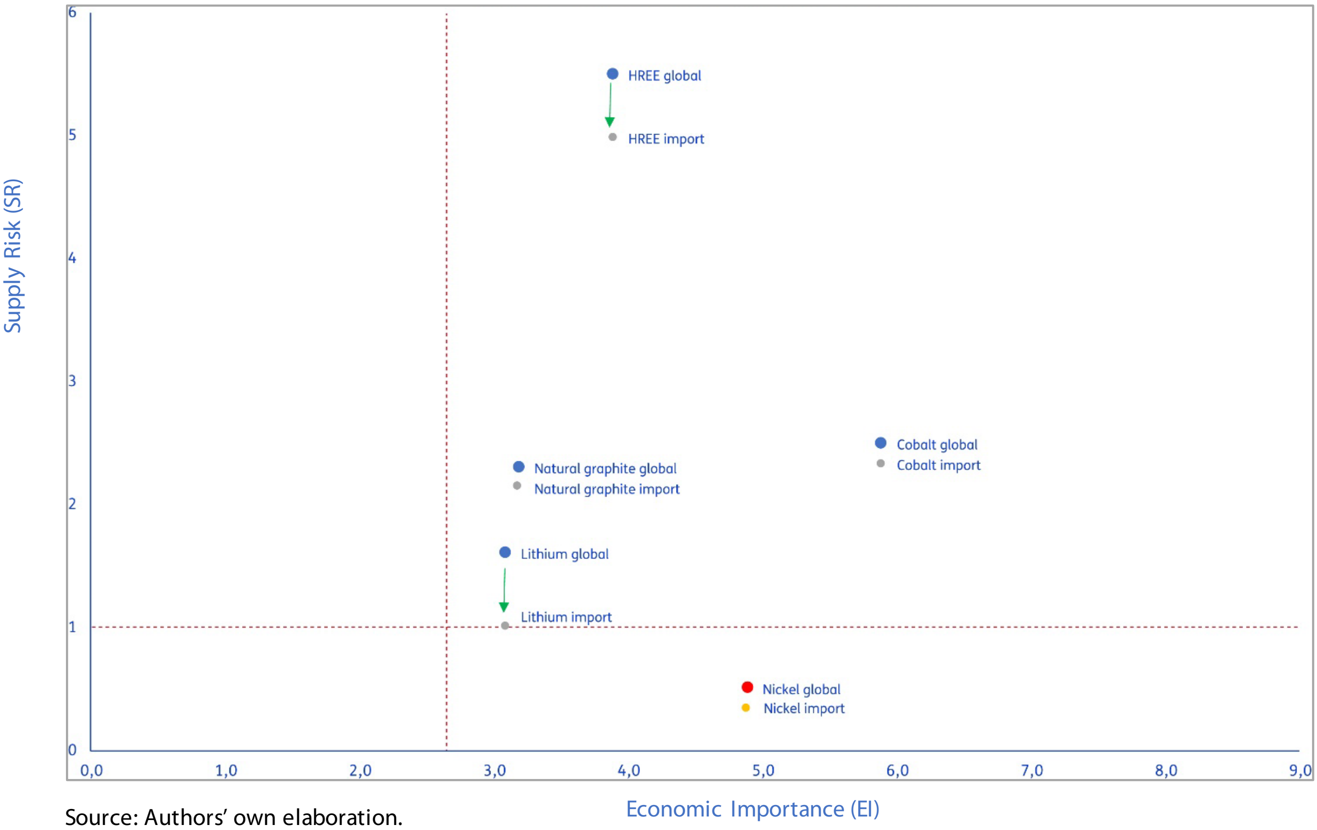
[28] Canada, China, Russia and Venezuela were assigned a WGI value of 2.26, 5.83, 6.20 and 7.30 respectively.

In the current calculation of SR, the WGI for a country is multiplied by the global or EU import share of that country and raw materials, based on the import reliance of the EU for that particular raw material. It can be argued that the vulnerability of supply relations based on the quality of governance, underestimates supply risks in the current CRM assessment methodology. The analysis in Section 3.2.4 showed that even highly unfavourable WGI scores for Russia did not result in a change of the criticality status of raw materials with meaningful trade from Russia to the EU. A new interpretation of the quality of governance of countries exporting raw materials to the EU might more accurately identify the option, or the necessity, to consider "friend-shoring" to a country with a favourable WGI score. Instead of multiplying the WGI score with the country concentration of mining or refining, one can compare the average WGI score for all EU trade partners with the average WGI score of all countries producing a certain raw material.

The results of using the average WGI of EU source countries, rather than multiplying the WGI with the concentration of global production, are shown in Figure 13.

Figure 13: Impact using average WGI of EU imports vs average WGI of global production



Source: Authors' own elaboration.

The y-axis shows SR for the both the original situation (based on global source country concentration multiplied by WGI scores) and the adapted SR score. In all cases in this graph, the average WGI-score for EU imports is more favourable than the global average of production countries. Especially for lithium and for nickel, the weighted average WGI of the source countries for EU imports, including domestic production, is different from the average obtained by global production. In the case of lithium, given that the share of EU import from Australia is significantly higher than the share of Australia's global production, the criticality of lithium would be lower. In this example, lithium is almost assessed as non-critical. Indonesia, a source of lithium, does not appear to play a role in direct imports to the EU and therefore has no impact on the supply risk of EU in the new interpretation.

In some situations, the export of a certain raw material is strongly concentrated in one country, such as China (e.g. natural graphite). In these cases, the distribution of EU import is quite similar to global production distribution. The conclusion of this analysis is that using the WGI in an alternative way results in different supply risk scores for certain raw materials. This might provide new insights in the relevance of trade policy making.

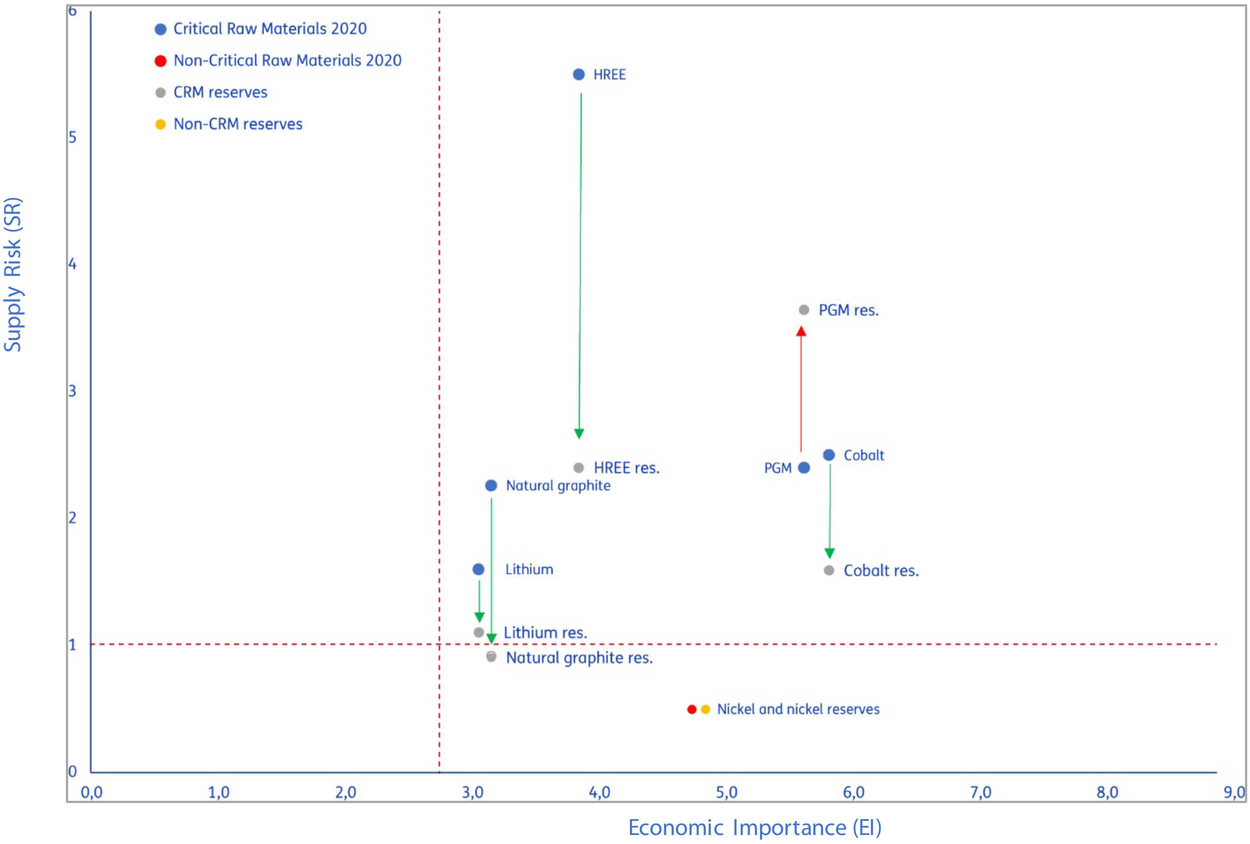
3.3.3 A new interpretation of country concentration

This analysis takes reported geological reserves as a basis to reinterpret the concentration of raw material source country.

The geographical distribution of current mining or refining production is an important indicator of the current CRM assessment methodology. Although this distribution in sourcing is highly relevant for giving insight in e.g. mining monopolies, it does not reflect mining development perspectives.

In Figure 14, the supply risk of several materials according to the EC CRM assessment framework is plotted, and the changes that would occur if the country distribution (symbolized by the HHI factor that represents the level of concentration of EU source countries) for the known reserves would be used[29].

Figure 14: Using geographical distribution of reported reserves instead of production



Source: Authors' own elaboration.

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[29] Data given in section 2.3.1. For this independent assessment, we multiplied the Supply Risk by the Herfindahl Hirschman Index. This created a HHI(reserves)/HHI(production)) ratio.

Some of the materials display a lower SR when the distribution of geological reported reserves is taken into account, indicating a potential future market for mining that is less concentrated and critical than current global supply. In this example, natural graphite would not be considered a CRM and lithium would be close to the criticality threshold. The drop in SR for Heavy Rare Earth Elements (HREE) is very noticeable as Brazil and Vietnam report considerable reserves compared to very small current production. However, it is questionable whether these reserves will be exploited.

3.3.4 A new future demand indicator

This analysis anticipates the future relevance of raw materials based on foresight studies.

The first three independent assessments have suggested additional indicators that give another perspective on SR of raw materials. In all the above-mentioned cases, the original EI definition from the 4th CRM assessment was used. An alternative way of assessing the criticality of a raw material would consist of maintaining SR constant, and account for additional societal importance demonstrated by a demand increase following from essential transitions. Several studies mentioned in Chapter 2 have acknowledged that the need for raw materials will increase significantly if the EU achieves its ambitions in the green and digital transition[30].

A possible approach to this problem would be to account for the future required annual growth for a raw material in its economic importance. The future growth is usually expressed by the Compound Annual Growth Rate (CAGR). The CAGR can be compared to the historic CAGR of that same commodity, as is shown in Chapter 1. If the projected CAGR for future demand exceeds the historical CAGR of that commodity, EI of a raw material is expected to significantly increase. It can be argued that EI needs to be recognised quickly, given the timeframes for action that arise from the increase in EI.

The result of changing EI-axis to an axis based on estimated future demand is shown in Figure 15. The y-axis represents the current assessment of SR. The x-axis represents the ratio between required demand and historic growth. A ratio of "1" means that the historic CAGR matches the growth required for the green and digital transition. A ratio greater than "1" indicates that speeding up of mining is required. Figure 15 shows that several materials require an unprecedented growth in extracting. Some of these materials have already been identified as critical (e.g. germanium, indium and lithium), while others have yet to be assessed as critical (e.g. cadmium, silver, tin and nickel). These raw materials require unprecedented accelerated extraction growth.

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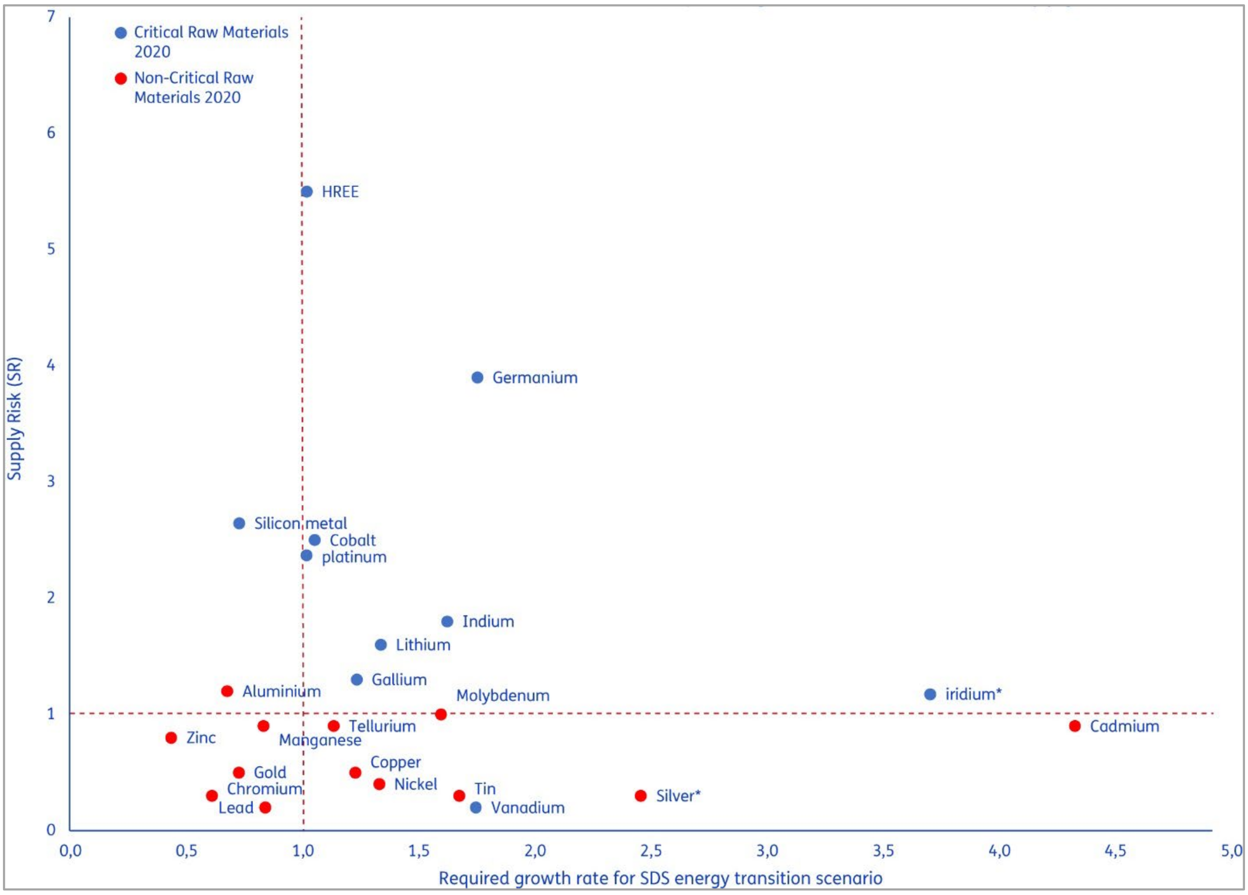
[30] An obvious question could be: why not assessing future demand of all global economic/societal activities? Such scenarios are available, from quantitative models using narratives such as the Shared Socioeconomic Pathways (SSPs) used in the context of the Intergovernmental Panel on Climate Change. We leave these scenarios out of this study since the future demand for the green and digital transition already sends a clear message, and want to avoid downsides resulting from widening the scope of the analyses in this report.

Figure 15: Changing economic importance based on future growth



Note: (*): A required growth rate of 1,0 equals a historic mining production growth. As Iridium and silver had a negative growth rate in 2021, historic growth rates have been assumed.

Source: Authors' own elaboration.

An interesting aspect of the analysis of future demand is that of future supply (partly also discussed in Gregoir et al. 2022). The contributions of planned primary mining projects, or the development of recycling as a potential future domestic source, can be used in future reassessments of required growth. This would help to judge the adequacy of existing and planned investment in (urban) mining.

Future demand estimates lead to rethinking EI. Adopting a different view on EI based on future demand (based on societal transitions) can be incorporated in criticality assessments methodologies.

3.4 Conclusions

The outcomes of the CRM methodology of the EU appear robust. An independent assessment of the current CRM methodology demonstrated that its results are rather robust and insensitive to modifications of the parameters describing EU source countries. No change in criticality assessments were observed in the simulation of import disruptions from Russia and Ukraine to the EU. However, when EU source countries were hypothetically redistributed for cobalt (redistributing the supply Democratic Republic of Congo to Canada and Australia), cobalt lost its criticality status. As a result, it is possible to change the outcome of a criticality assessment using hypothetical scenarios, but the cobalt example seems to be the exception that confirms the rule. The outcomes of the 4th CRM assessment appear to be quite stable.

Four additional indicators are suggested to enrich the current CRM methodology. The European Commission already considered these indicators in 2016 when the methodology was finalised. However, they were put aside in the official JRC methodology. The three additional indicators for supply risk (price volatility, a new interpretation of the WGI and using the concentration of geological reserves instead of mining operations) lead to modest but meaningful changes in assessing criticality based on supply risk. In addition, adjusting economic importance based on expected future demand for decarbonisation technologies results in several raw materials being assessed as critical after the adjustment.

Future demand forecasting could be part of the CRM methodology. A periodic and formalised forecast of demand for raw materials, intermediates and final products, with timescales ranging from 5 to 25 years requires an extension to the CRM assessment methodology. Given the rapid development of new technologies, any future demand scenario for raw materials and underpinning estimates have to be regularly updated. Since forecasts are inherently uncertain, a clear and transparent communication about their role in the assessment will be essential. Demand forecasts will prove useful, if the results of this new assessment will result in policies having long-term impact.

No good decision making without accurate data and information is possible. A final conclusion about CRM assessment pertains to data availability. The independent assessment in this report served as another example of the importance for adequate data and reliable information. Information on estimates of future raw material demand from study reports are available on the RMIS website. Extending this data resource will likely be important in creating accurate policy responses to a probable accelerated growth in demand. For example, the data availability of price levels and especially of raw material reserves and resources deserves further investment. Another example is the Minerals4EU project, providing data about (potential) mining operations. Lastly, academic efforts could be supported to create highly detailed input-output (or supply-use) databases. The availability of such data will greatly increase insights in supply-chain dependencies. Efforts in this direction have already started[31]. Supply chains are notoriously complex. They are formed by many stages and different levels of interest and insights, making data gathering and data exchange a complicated activity. Guiding and stimulating data exchange over supply chains using state-of-the-art ICT data spaces for digital product passports might be useful to improve existing raw material supply chain databased and statistics.

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[31] An example of recent developments in public data that describe supply-use relations between sectors can be found here: https://www.en.plan.aau.dk/getting-the-data-right/about-the-project/.

4. STOCKPILING POLICY OVERVIEW, COMPOSITION AND VOLUMES

KEY FINDINGS

The strategic stockpiling of products containing CRM is a common policy in the US, Japan, South Korea and Switzerland, which provide relevant examples for possible EU-based stockpiling operations. The invocation of the Defence Protection Act by the US government is a recent example of public action that undertaken to secure the supply of strategic products and strengthen industrial capacity in the process.

Principles for European stockpiling can be drawn from these examples. Based on the assumption that a potential stockpile could cover 60 days of imports, estimates of the possible value of CRM stockpile range between EUR 6.45 billion and EUR 25.8 billion (2021 prices). This estimate depends on the breadth of the products considered. The lower bound focuses on raw materials, the upper bound uses a selection of around 300 traded product groups.

The preferred composition of product groups to be stockpiled are those product groups shaping the green and digital transition. This means that a volume of 8.6 million tonnes and a value of EUR 25.8 billion will be assumed as respectively the required size and value of the EU stockpile.

In this Chapter, stockpiling is discussed as a course of action to mitigate supply disruptions of products containing CRM. In Section 4.1, the state of conventional, physical stockpiling in EU Member States is addressed. In Section 4.2, the state of stockpiling is reviewed in a selection of relevant third countries. In Section 4.3, the volumes of possible stockpiling options are quantified.

Box 2: The policy that coined the label "critical"

The term "critical materials" was first used the US Strategic and Critical Materials Stock Piling Act in 1939. This act established material supply reserves for industrial ramp-up of production for military, industrial and essential civilian needs. The act facilitated the acquisition of raw materials stocks for inventory disposition, rotation and storage within the US. This stockpile was created in preparation for a likely war based on lessons learnt from WWI (Eckes 1979; Peck 2019). The US stockpile was amended and maintained through WWII and most of the Cold War.

Source: Authors' own elaboration.

4.1 State-of-play of stockpiling in the EU

4.1.1 Recent developments of the stockpiling debate within the EU

The use of emergency stockpiles has gained importance as a course of action to ensure the security of supply of the EU's economy. Calls for state supported stockpiling are made in 2022 by manufacturing companies[32]. The EU has long been aware of its dependency on imports of CRMs and components for technologies of the green and digital transition (European Commission 2008a).

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[32] A plea for publicly supported stockpiles from the Airbus company can be found here: https://www.argusmedia.com/en/news/2334654-airbus-calls-for-a-metals-stockpile-policy-in-eu.

Stockpiling of goods is viewed as an element of broader industrial policy (Hassink et al. 2012). Implicitly, the attention for stockpiling action by public government indicates that market failures need to be solved. Economic literature usually identifies the following types of market failure: market power, public goods, externalities, imperfect information and coordination failure. It seems plausible that these failures are prominent in global supply-chain management in recent years. For example, the COVID-19 crisis and Ukraine invasion revealed many situations where contracts were not be executed as expected.

Before the recent resurgence of interest in stockpiling, following the outbreak of the COVID-19 pandemic and the war in Ukraine, stockpiling was discussed as a response to the commodity crunch between 2004 and 2013. Several policy actions were instigated by the Raw Material Initiative (European Commission 2008a). The epitome of this period was probably an incident involving fishing boats from Japan and China, against the backdrop of a dispute over the Senkaku islands, which led to the "The Rare Earths hype" period[33]. As a result, a report on stockpiling options for the EU was commissioned, which is accurate to date (see textbox below).

Box 3: Summary of the last EU's report on stockpiling

In 2011, the subject of stockpiling was addressed by the European Parliament, calling on the European Commission to assess the need for setting up a stockpiling mechanism for CRM. Following this request, the European Commission executed a study that analysed different stockpiling practices: Stockpiling of Non-energy Raw Materials (RPA, 2012). In this study, information on past and current experiences with CRM stockpiling was collected, and the desirability, feasibility and added value of CRM stockpiling within the EU was assessed.

The results of this study were discussed with the Commission's Raw Materials Supply Group in November 2012. This led to negative reactions on a potential stockpiling programme in the EU, as the European Commission stated that no Member State would support a mandatory CRM stockpiling scheme as a policy option. To date, the 2012 study on stockpiling is the most comprehensive research conducted on the subject.

The main findings of Chapter 4 are based on its results. Despite the study being ten years old and the unprecedented disruptions to global supply chains caused by the COVID-19 pandemic and war in Ukraine, the findings of the 2012 study appear as relevant as ever. In the current study, all figures used in the 2012 study have been updated for inflation, current commodity prices and current EU demand.

Source: Authors' own elaboration.

The resolution of the European Parliament (European Parliament (2021) quoted in Chapter 1 unequivocally calls for considering stockpiling as part of a coordinated approach to secure the supply of CRM containing products. The intuitive response to consider stockpiling as a strategy is illustrated by the price developments of certain metals, shown in Figure 16. Reliable publicly available raw material price information can be obtained from the German Mineral Resource Agency[34]. Looking at time series from 2010 to April 2022, both the commodity crunch until 2013 and the recent geopolitical events can be observed.

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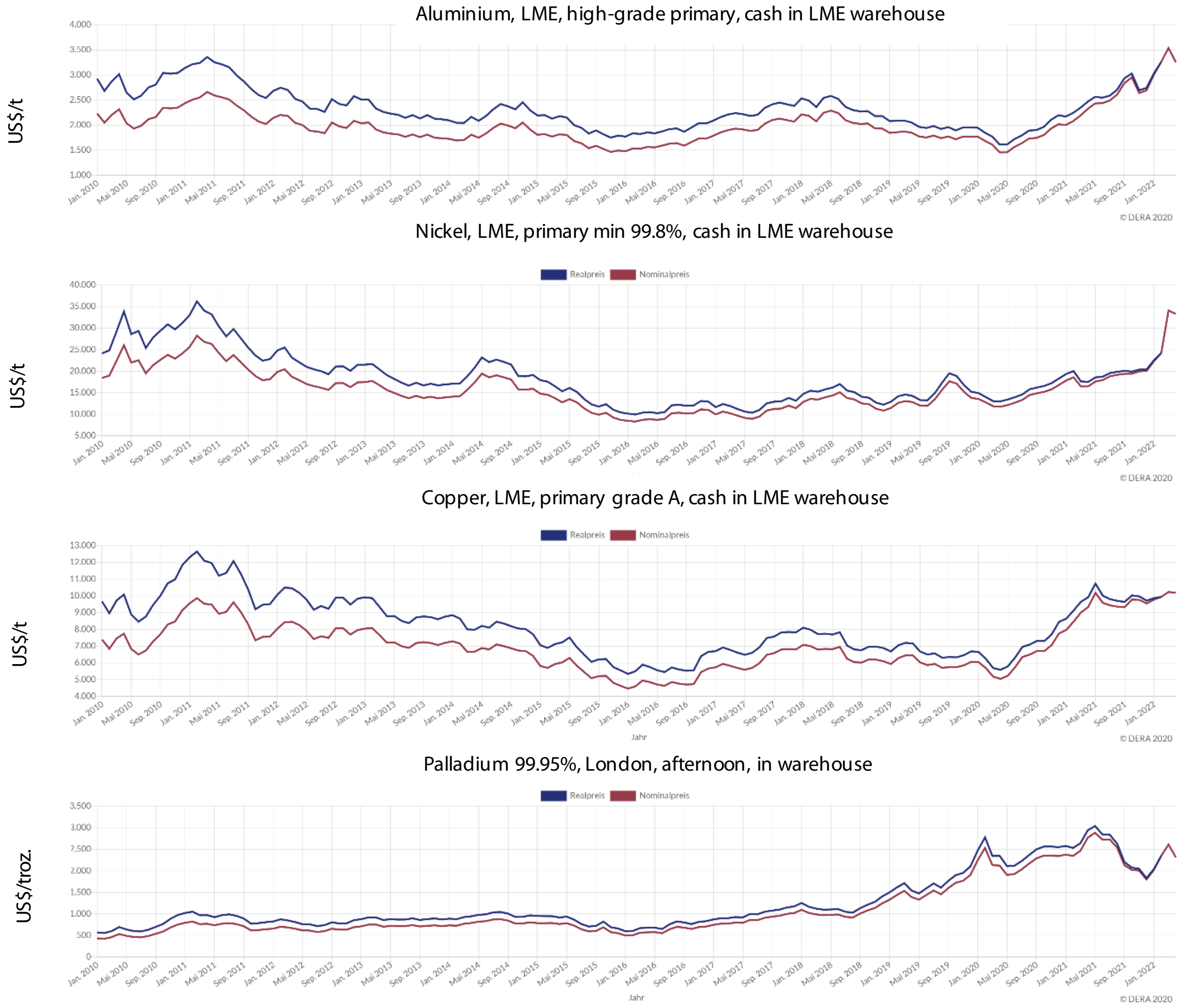
[33] Between 2011 and 2013, certain rare earth elements increased and subsequently decreased in value by over 700%.

[34] Price information from the German Mineral Resources Agency (DERA) can be found on their ROSYS system. See https://rosys.dera.bgr.de/mapapps49prev/resources/apps/rosys2/index.html?lang=en.

Figure 16: Price series of raw materials in the period 2010-2022



Aluminium, LME, high-grade primary, cash in LME warehouse

Nickel, LME, primary min 99.8%, cash in LME warehouse

Copper, LME, primary grade A, cash in LME warehouse

Palladium 99.95%, London, afternoon, in warehouse

Note: (*) Blue graph represent real prices (inflation corrected) and red graph represents nominal price.

Source: German Mineral Resource Agency.

Arguably, the best example of a neatly controlled system of stockpiling and stock draw can be observed for fossil energy carriers. In the aftermath of the Oil Producing and Exporting Countries (OPEC) oil embargo (1970s), the possibility of stockpiling at the European Economic Community level was assessed. Discussions, however, did not progress and such a coordinated stockpiling program did not materialise. Despite this, each International Energy Agency (IEA) member country has an obligation to hold oil stocks at levels that equate to no less than 90 days of net imports. Much research exists on the impact, costs and benefits of the current oil stockpiling program. Because of many existing similarities between the stockpiling of oil and of products containing CRM, such as a high EU import dependency, possibility of supply disruptions, few alternatives for substitution, the rationale of oil stockpiling could serve as an inspiration for a stockpiling scheme for products containing CRM.

There are obviously some crucial differences between energy and non-energy products, such as possible impacts on the economy, the speed of adverse impacts on the economy (a supply disruption of oil will hurt the economy faster than a supply disruption of metal), storage arrangements, homogeneity of the commodities in stock, demand predictability, etc. This is why approaches from oil stockpiling cannot be directly applied to products containing CRM without adaptation of specific characteristics.

The most recent example of the relevance of stockpiling pertains to fossil fuels, and comes from the attempts by EU Member States in 2022 to manage the natural gas market. This Chapter is based on the question if CRM supply management can be compared to the management of natural gas supply.

4.1.2 Current and past stockpiling activities in the EU

Based on the absence of evidence in the shape of public documentation, it is expected that in 2022 the EU lacks a non-energy raw material stockpile. In the past, only a few Member States such as France, Slovakia, Sweden and the UK had stockpiling programs for certain specific raw materials, operated by their governments. These national stockpiles included a range of materials, of which only three are currently on the EU critical raw material list: cobalt (France), magnesium (Slovakia) and platinum (France). The oldest of these stockpiling policies is the Swedish scheme, which was developed during the Cold War and was of a strategic nature. The (mostly economic) stockpiling schemes in France and the UK were developed to secure supply chains as a response to political instability in key mineral producing regions in the 1970s. The stockpiles in these four countries were discontinued (UK's stockpile most early in 1984, and Sweden most recent in 2002) for various reasons: some countries felt that stockpiling was no longer needed, as sources of raw materials became sufficiently diverse or, specifically for Slovakia, risks were reduced due to accession to EU and NATO. Such a development could be considered an effect of friend-shoring through embeddedness in a bloc. Stockpiling costs in all of these examples were borne by public budgets.

The stockpiling examples given above do not cover so called “war reserve stocks”, which can include materials, components, equipment and munitions. During the Cold War, European NATO countries maintained war reserve stocks of typically 30 days for a full-scale war with the Warsaw Pact. Over the decades, since the end of the Cold War, stocks were reduced to very low levels. This has raised concerns, given the war in Ukraine and Russia's threat to the availability of European security equipment[35]. Various other Member States have considered the option of stockpiling in the past (e.g. Finland, West Germany, Italy and Spain), but decided against it. This was due to budgetary reasons or concerns from both the private and public sector about who should control the largest part the stockpile.

4.2 State-of-play stockpiling around the world

Stockpiling is maintained by the heavily industrialised economies outside the EU. This Section provides an overview of the most important stockpiling policies in the US, Japan, Switzerland, South Korea and China. These five countries provide useful examples based on their practice of stockpiling products containing CRM, either primarily for military or for industrial production.

4.2.1 The United States of America

As already discussed in text Box 2, the US has a long-standing history of holding and maintaining critical material stockpiles both for defence, industrial production purposes and even for climate transition technologies (IDA 2010). In response to the concerns raised by REE supplies arising from tensions between China and Japan, the US decided by 2013 to reinvest in their critical materials stockpile. Although REE were at the core of the renewed stockpiling operation, the scope of raw materials stockpiling was expanded to a range of CRMs.

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[35] The recent political deliberation about stockpiling costs in light of conflict, see: https://www.lemonde.fr/en/international/article/2022/06/14/france-considers-requisitioning-civilian-sector-to-replenish-weapons-stocks_5986759_4.html.

The National Defence Stockpile (NDS) Program provides the context of stockpiling in the US. It aims to decrease the risk of dependence on foreign or monopolistic suppliers of strategic and critical materials used in defence, essential civilian, and essential industry applications. The program reports to the US Congress bi-annually. In 2014, the Defence Logistics Agency Strategic Materials used the National Defence Authorization Act (NDAA) to stockpile a list of six materials to mitigate their supply chain risk. By 2015 this list expanded to 12 materials.

By 2021, the list contained 17 materials for stockpiling, most defined as "critical materials". The US list of critical materials for the stockpile is expected to expand further in light of global events. Apart from stockpiling, any criticality status for a raw material aims to identify supply chain challenges, communicate specific concerns to industry, and mitigate risks as appropriate (Department of Defense 2022).

In May 2022, the EU and the US Trade and Technology Council made a common statement. The two parties "*resolved to collaborate to reduce dependencies on unreliable sources of strategic supply, promote reliable sources in our supply chain cooperation, and engage with trusted partners. We share a desire to mitigate jointly the negative effects of sudden supply chain ruptures, such as those created by Russia's aggression, for example in the area of critical materials*."

Whilst stockpiling was not specifically mentioned in this statement, the USA and the EU further sought to facilitate trade through increased cooperation in the area of government procurement. The statement referred to ensure high-tech supplies "shock-proof" by upgrading capacities through government procurement, potentially imply stockpiling agreements to mitigate the supply shocks.

A month later, the White House invoked the Defence Production Act (DPA) to boost the manufacturing of clean energy technologies[36]. This action was highly significant, because it is predicated explicitly to not only stockpile raw materials and other products, but also to safeguard production capacity relevant for the energy transition on USA territory.

4.2.2 Japan

The Japanese stockpile provides an example of a well-documented stockpiling policy. Since 1983, the Japanese government has maintained a stockpile of raw materials. By 2008, seven raw materials were stockpiled in Japan. An explicit component of Japanese stockpiling policy is the support of private companies to maintain stockpiles. It is important to note that the decision to stockpile remains a voluntary act by the companies.

The agency in charge of the stockpile is called the Japan Oil, Gas, and Metals National Corporation (JOGMEC) with a parent agency, the Ministry of Economy, Trade and Industry (METI). In the mid-2000s Japan has undertaken an explicit and increasingly robust strategy for designating critical minerals, and addressing supply risks by emphasising overseas projects, advanced recycling, substitution and stockpiling (DeWit 2021).

By 2020 Japan had 34 materials on the stockpile list, mostly critical materials, holding up to 60 days of production volumes. The stockpiling is part of a wider strategy to reduce Japan's critical materials dependency.

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[36] The US Government has published the DPA invocation. Shoring up existing stockpiling and reinforcing the industrial capacity are represented in different parts/tiers of the initiative, see (Department of Defense 2022).

4.2.3 Switzerland

The Swiss approach towards organising stockpiling is highly relevant to the EU given its proximity and interacting regulatory frameworks. The Federal Office for National Economic Supply (FONES) is the institute coordinating stockpiling at federal level. The FONES is mandated to safeguard supplies of essential goods and services in Switzerland. The stockpile composition is therefore heterogeneous, containing food, energy, therapeutic products and industrial goods. The Swiss approach aims also to secure manpower and includes measures to protect the digital and physical infrastructure. Particularly relevant to the stockpiling facilities discussed in Chapter 5 are its stockpiling tools. For both compulsory and voluntary stockpiling, the Swiss government provides companies with the opportunity to draw on loan guarantees and tax write-offs.

4.2.4 South Korea

South Korea offers a recent example of a stockpiling policy. In 2021, South Korea decided to increase its strategic stockpiles of critical metals for key technologies such as electric vehicle batteries and renewable energy[37]. South Korea holds stockpiles of 35 metals to cover 100 days of supply operated by the publicly-owned Korea Resources Corporation. A policy package announced in 2021 aims to select around a hundred enterprises in the base metals sector, to provide them with various benefits and to support private investment into mineral exploration and staking public money in mining corporations. The South Korean Ministry of Trade, Industry and Energy manages a stockpile of major strategic industrial goods, containing processed materials, components and equipment. It is planning to set up a real-time monitoring system for public and private procurement along the entire value chain[38]. The private sector inventories in South Korea are also relevant. Being a major manufacturer of certain industrial products, publicly reports of its inventory of unsold products affects global markets. A recent example is the growth of domestic stockpiles of microchips, driven by the production of companies such as Samsung Electronics. Changes in these stock sizes are expected to affect global price levels.

4.2.5 China

Information about China's strategic commodities stockpiles is scant. Available policy documents on stockpiling are far less transparent than those published by open democracies (the US, Switzerland, Japan and South Korea). There is evidence of public-private stockpile in the inner-Mongolia province (Wübbeke 2013).

Analysts believe China has significant stockpiles of critical materials and that China's stockpile is growing to secure reserves in event of a conflict. According to Mancheri et al. 2019, "*the Chinese State Reserve Bureau (SRB) began a rare earth stockpiling program in late-2014 and the government had built storage for more than 40 thousand tonnes of REOs. The SRB may purchase up to 100 thousand tonnes, primarily focusing on medium to heavy rare earths* (Brown and Eggert 2017 in Mancheri et al. 2019).

4.3 Stockpiling: composition and quantities

This Section discuss the question of the size and composition of a stockpiling operation in the EU.

Before estimating the desired size of stockpiles, a stock drawdown period must be determined. Supply disruptions, and the incidents causing them may last for days or weeks.

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[37] Several sites aimed at supply chain management covered the decision of the South Korean authorities in 2021, see for instance https://www.argusmedia.com/en/news/2241424-south-korea-to-increase-stockpiles-of-rare-metals.

[38] See the MOTIE website for further details: https://english.motie.go.kr/www/main.do.

However, supply disruptions may persist for much longer, especially in case of a supply chain that is dominated by a few companies or countries. The Republic of Korea and Japan have stockpiling of between 18 and 60 days of domestic consumption of imports. The International Energy Agency (IEA) obliges its members to hold oil stocks corresponding to at least 90 days of net imports. In April 2011, the emergency stock held by EU Member States was equivalent to 121 days of EU consumption. Calls for stock draw timeframes that can last up to two years have been made by industrial stakeholders.

Based on the timeframe used in the aforementioned Risk & Policy Analysts report (RPA 2012), this study finds a period of 60-day of domestic industrial consumption as a reasonable reference period for the size of the stock. Although the decision to adopt a 60-day duration is significant in terms of the size and associated costs of the stockpile, it is irrelevant to the discussion of the viability of stockpiling as a policy option. The outcomes of stockpile size and costs would scale linearly with the assumed period of a stockpile.

In the Sections below, we will determine several stockpile compositions. Firstly, we will investigate a stockpile of critical and non-critical Raw Materials required for the energy transition. Secondly, we will use a set of 137 product groups designated by the European Commission as strategically important is to estimate stockpiling size. Thirdly, we will examine a set of product groups (raw materials, intermediates and final products) shaping the green and digital transition to estimate quantification of volumes and values.

4.3.1 Stockpiling volumes of critical raw materials for green and digital transition

Using the 60-day timeframe, an estimate of the quantity of stockpiles of products containing CRM can be obtained by dividing the annual EU import by six (365 days / 60 days ≈ 6). To discern between the volume of products containing critical raw materials on the one hand, and the actual CRMs on the other, the analysis starts with the assessment of the amount of actual raw materials.

In the analysis, we estimate the required size of raw material stocks only, and we do not focus on product groups containing CRMs. Hence, we take the imported volume of raw materials as a reference for estimating the required volumes of 60-day stocks. The EU consumption provided in the second column of Table 16 is used as reference. However, one needs to keep in mind that these totals include raw materials that are embedded in components or final products.

Table 16: Estimate stockpiling volumes of CRMs based on EU imports of CRM

Raw material	Current annual EU consumption in all applications, in thousand tonnes	Annual EU import of raw materials from non-EU countries (average 2012-2016) thousand tonnes	Estimate of needed stockpile volume (annual import in thousand tonnes, divided by 6)	Average price (USD/tonnes) in 2021	Estimated acquisition cost (million EUR) [39,40]
Non-CRM					
Aluminium	12 000	3 176	529.33	3 537	1 872.25
Chromium	400	96	16.00	7 930	126.88
Copper (ore)	4 000	765	127.50	9 200	1 173.00
Manganese (ore)	4 000	324.3	54.05	5 200	281.06
Molybdenum (ore)	60.5	29.6	4.93	19 900	98.17
Nickel (ore)	500	56	9.33	18 100	168.93
Selenium	1	0.54	0.09	16 000	1.44
Uranium	2.6	2.6	0.43	130 000	0.05
Zinc (ore)	3 000	213	35.50	3100	110.05
CRM					
Borates	36	22.4	3.73	400	1.49
Cobalt	30	14	2.33	62 000	144.67
Dysprosium (HREE)	0.2	0.015	0.00	400 000	1.00
Gallium	0.05	0.03	0.01	570 000	2.85
Germanium	0.03	0.012	0.002	1 200 000	2.40
Indium	0.2	0.035	0.01	158 000	0.92
Iridium	Very small	0.001	0.00017	29 190 000	4.87

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[39] Prices and the average price level of 2021 are taken from USGS and ROSYS. See https://rosys.dera.bgr.de/mapapps49prev/resources/apps/rosys2/index.html?lang=en.

[40] Prices and the average price level of 2021 are taken from USGS and ROSYS: https://www.usgs.gov/centers/national-minerals-information-center/mineral-commodity-summaries.

Raw material	Current annual EU consumption in all applications, in thousand tonnes	Annual EU import of raw materials from non-EU countries (average 2012-2016) thousand tonnes	Estimate of needed stockpile volume (annual import in thousand tonnes, divided by 6)	Average price (USD/tonnes) in 2021	Estimated acquisition cost (million EUR) [39,40]
Lithium	6	0.87	0.15	17 000	2.47
Magnesium	113.0	124	20.67	2 149	44.41
Natural graphite (ore)	250	88.6	14.77	1 540	22.74
Neodymium (LREE)	4	0.44	0.07	49 140	3.60
Niobium	12.2	13.9	2.32	44 000	101.93
Palladium	0.01	0.062	0.01	70 892 000	732.55
Platinum	0.039	0.093	0.02	30 575 000	473.91
Praseodymium (LREE)	1	0.015	0.0025	60 000	0.15
Rhodium	Very small	0.005	0.00083	35 751 000	29.79
Ruthenium	Very small	0.006	0.001	2 443 000	2.44
Silicon metal	400	344	57.33	4 000	229.33
Strontium (ore)	103.3	0.44	0.07	90 000	0.01
Tantalum (ore)	0.1	0.4	0.07	158 000	10.53
Tellurium	0.1	0.26	0.04	68 000	2.95
Titanium	1 509.3	1 519	253.17	2 900	734.18
Tungsten	0.8	0.3	0.05	270 000	13.50
Vanadium	12.7	12.7	2.12	24 000	50.80
Totals					
Total non-CRM		**776.86**			**3 834.74**
Total CRM		**356.81**			**2 610.55**
Total		**1 133.67**			**6 445.29**

Source: Authors' own elaboration.

The size of non-critical metals to be stockpiled resulting from the annual critical raw material demand is 777 thousand tonnes. The volume of embedded CRMs in a 60-day stockpile amounts to 357 thousand tonnes. If we exclude titanium, magnesium, silicon metal and graphite (given their dominant share in the estimated volumes), the volume of embedded CRMs would amount to exactly 11 thousand tonnes. However, it should be observed that many reported metal supply-chain problems in the EU concerned[41] types of major (non-critical) metals like copper and aluminium.

The total size of raw materials to be stockpiled for 60-day is about 1.13 million tonnes. The value of these materials based on average 2021 price levels would be EUR 6.45 billion. For comparison, it is interesting to note that the size of the EU oil stocks in June 2021 was equal to 112.5 mega tonnes[42]. The EU has the capacity to store over 117 billion cubic meters (bcm) of natural gas, which represents roughly a fifth of its annual consumption. This equals just under 89 million tonnes. The estimated value of the Swiss Federal Office for National Economic Supply (FONES), the compulsory surplus stock that is kept by enterprises in Switzerland, is estimated at EUR 7.6 billion in 2021.

4.3.2 Stockpiling volumes of all imported products for strategic autonomy or green and digital transition

The trade analysis presented in Section 2.2 makes it clear the EU industrial ecosystem aims to ensure a first-rate supply of CRM-containing products from non-EU countries. The analysis continue with the assessment of product groups containing CRMs.

To explore the size of a stock composed of product groups, we refer to the 137 product groups recently identified, for which the EU was most dependent on imports from third countries (European Commission 2021b). This dependence is based, as in Chapter 3, on the concentration of source countries of the imported product groups (see Table 17).

Table 17: Imports from non-EU countries of 137 strategically relevant product groups

Imports of 137 product groups (HS/CN 6-digit)	2019	2020	2021
Total annual value (million EUR)	94 579.7	119 731.9	142 132.8
Total annual volume (thousand tonnes)	35 008.0	31 141.2	33 355.1

Source: Eurostat Comext, 2022.

Applying the 60-day stock assumption and dividing the total annual volumes of imports from third countries for the 137 product groups by six, the estimated volume of EU stockpiling is between 5.19 (2020) and 5.83 (2019) million tonnes. The value associated with a 60-day stock for these 137 product groups is between EUR 15.8 billion (2019) and EUR 23.7 billion (2021).

However, we suggest to use an alternative set of product groups to estimate the required size of an EU stockpile. This set consists of the list of product groups shaping the green and digital transition and corresponds to the same product group selection that was used to estimate future demand in Chapter 2, see Table 18.

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[41] For an important news item on expressed supply chain problems for metals, See: https://www.bloomberg.com/news/articles/2022-07-06/white-hot-metal-market-cools-in-warning-for-global-economy.

[42] The stock of oil, managed by EU Member States, is reported on Eurostat. See: https://ec.europa.eu/eurostat/web/products-datasets/-/nrg_143m.

Table 18: Imports from non-EU countries of green and digital transition product groups

Imports of green and digital product groups (HS/CN 6-digit)	2019	2020	2021
Total annual value (million EUR)	115 134.7	114 500.8	154 512.4
Total annual volume (thousand tonnes)	51 130.2	50 055.6	51 431.8

Source: Eurostat Comext, 2022.

If the total annual volume of imports from non-EU countries is determined by the product groups shaping the green and digital transition, the estimated 60-day stockpile volume will range between 8.3 (2020) to 8.6 (2021) million tonnes, with an associated stock value between EUR 19.1 billion (2020) and EUR 25.8 billion (2021). These estimated totals represent roughly 10% of total imports (mineral fuels excluded) from non-EU countries.

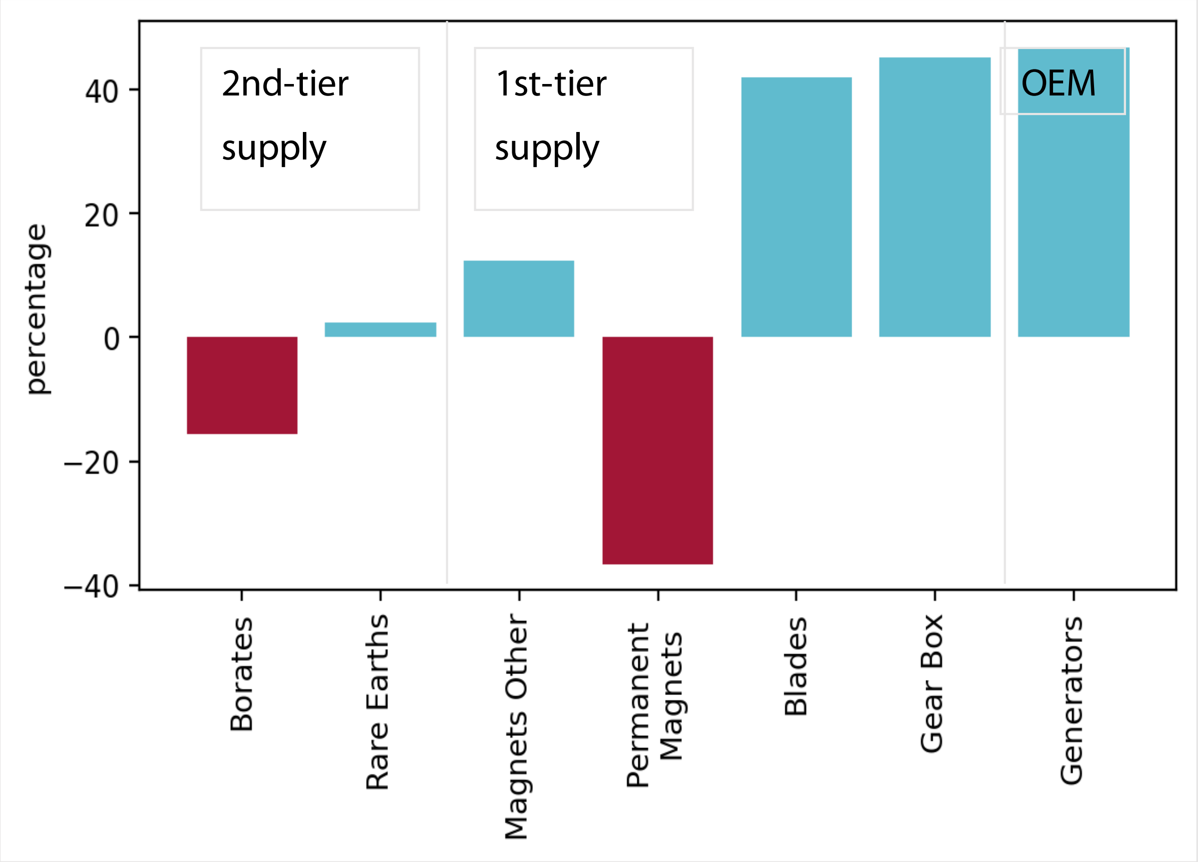
It is essential to bear in mind that all these volumes are expected to grow in line with the factors discussed in Chapter 1, driven by economic growth and the demands of the green and digital transitions.

4.4 Conclusions

Major industrialised economies outside the EU offer useful experience on stockpiling. The strategic stockpiling of products containing CRM is a common policy in the US, Japan, South Korea and Switzerland. These countries provide useful examples, such as stockpile compositions and the governance of stockpile operations. The invocation of the Defence Protection Act by the US government is a recent example of public action that can be taken in order to secure the supply of strategic products and strengthen industrial capacity in the process.

Drawing conclusions from existing global stockpiling models, the likely future product stock in the EU could cover the 60-day period. Assuming a stockpile is designed for a 60-day period, it is easy to determine the EU demand of strategically important products. The composition of the proposed EU stockpile of CRM is based on product groups shaping the green and digital transition. Since the exact need of future markets is difficult to predict, a heterogeneous composition of stockpiling is preferable. Stockpiling imported product groups containing CRM follows the logic that trade patterns automatically can highlight the first-tier supply from non-EU countries (See Figure 17).

Figure 17: Further developed figure 10, signifying the relevance of first-tier supply



Source: Bruegel calculations from BACI database, Gaulier and Zignago (2010).

The fact that part of the EU imports are re-exported to non-EU countries, such as Switzerland, does not significantly change the overall composition of the stock. The distinction between use by industries on the one hand and final consumption by households and governments on the other is difficult to make based on available public data. Better data would allow the stock to prioritise the inclusion of final products used by industry.

If the EU would create a stockpile to supply the EU market for 60-day with imports from non-EU countries, the following stockpile sizes would be determined (see Table 19).

The acquisition costs of stockpiling raw materials or product groups are estimated to range between EUR 6.45 billion and EUR 25.8 billion, depending on the composition of commodities in the stockpile.

The size of a stock of products containing CRMs is determined. The preferred combination of product groups to be stored is composed of those that contribute to the green and digital transition. This means that a volume of 8.6 million tonnes and a value of EUR 25.8 billion will be considered necessary.

Table 19: Stockpile sizes based on three different estimates

Composition of stockpile	Value (billion EUR)			Volume (million tonnes)		
	2019	2020	2021	2019	2020	2021
Critical and non-critical Raw Materials needed for the energy transition	6.45			1.13		
Set of 137 product groups designated by the EC as strategically important	15.7	20.0	23.7	5.83	5.19	5.55
Product groups, (raw materials, intermediates and final products) shaping the green and digital transition	**19.1**	**19.2**	**25.8**	**8.5**	**8.3**	**8.6**

Source: Authors' own elaboration.

5. DISCUSSION OF POTENTIAL EU STOCKPILING FACILITIES

KEY FINDINGS

Stockpiling products containing CRM takes weeks and months, whereas a successful green and digital transition requires decades to materialise. Stockpiling action in the EU would mitigate supply shocks for nascent and strong manufacturing industries, which are vital for the green and digital transition. If stockpiling is introduced as a policy measure, the associated industry ecosystem should also be put in place. Since 1990 in the EU investments into manufacturing capital stock have been smaller than in Japan, South Korea and Switzerland and comparable to the ones in the US. Stockpiling costs are determined by the acquisition costs of the products to be stocked. These are comparable to (planned) public expenditures in (renewable) energy markets.

Stockpiling operations are best managed by the private sector, supported by incentives from Member States and EU designated agencies. Professionals active in supply chain management consider stockpiling as their main economic activity. However, if storage is encouraged by public policy, the question of effective public-private management arises.

Following the analyses in Chapters 2, 3 and 4, where respectively trade, CRM assessment, stock composition and volumes were discussed. Chapter 5 provides an in-depth discussion on the aspect of potential EU storage facilities.

5.1 Including industrial capacity in potential stockpiling policies

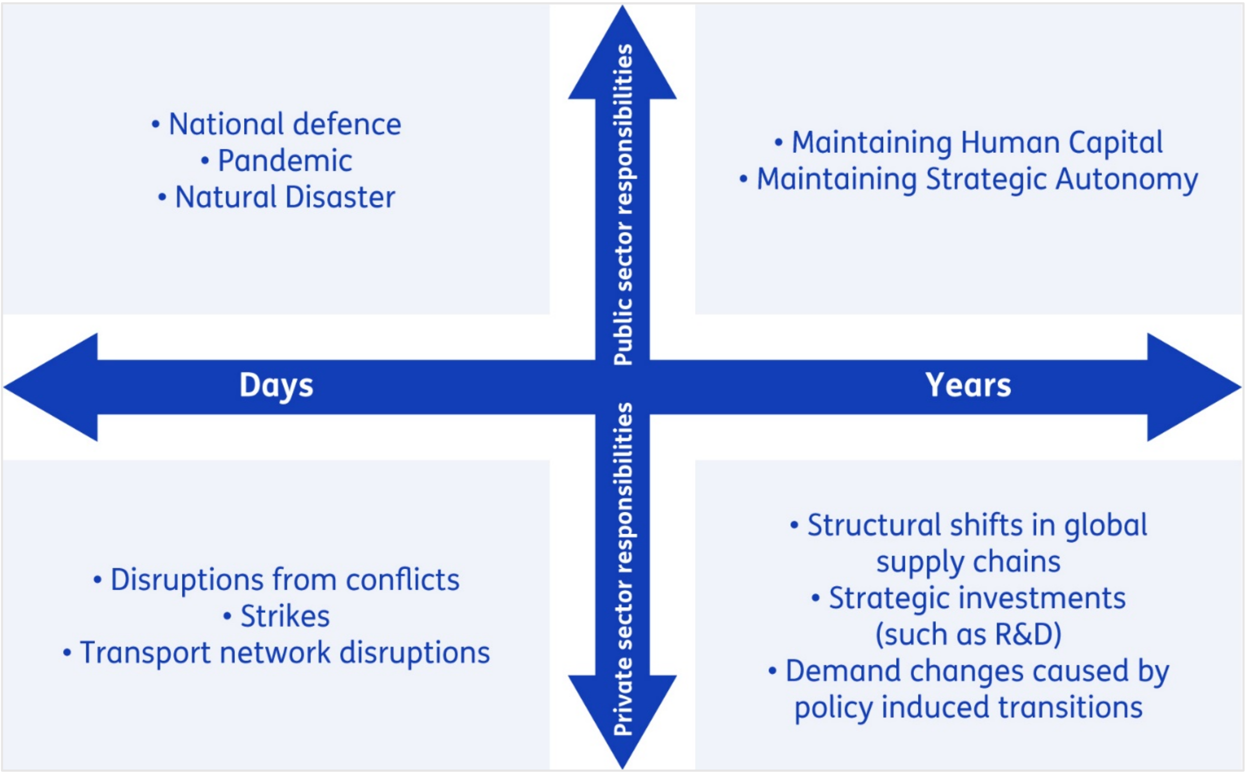
Although stockpiling can be a solution to enhance security of supply, there is a potential discrepancy between safeguarding the long-term requirements of a green and digital transition and engaging in short-term supply chain management. The objective of stockpiling (products containing CRM) takes weeks and months, whereas a successful green and digital transition requires decades to materialise.

The characteristics of stockpiling can be defined by the timescale of disruptions, and the public or private sector responsibilities (Ayres 2019) related to the demand for certain products. An illustration of timescales and responsibilities is shown in Figure 18. Chapter 4 implicitly focused on supporting private sector responsibilities on a time scale of days and weeks (the bottom-left quadrant).

The adoption of 60-day stockpiling contributes to more resilient supply chains in the EU, as it helps manufacturing sectors to overcome supply problems. The responsibilities of the private sector over the years (bottom right quadrant) are better met when it comes to mitigating short-term supply shocks. EU industries that are key to green and digital transition can gain a competitive advantage through the availability of public storage, which are in line with existing global trade rules.

The idea of public participation needs to be validated by a possible stakeholder consultation. Justification could come from the societal importance of transitions or changes in a global geopolitical context that go beyond the normal responsibilities of private sector companies. Public policy support to the private sector would therefore have impacts on policy areas of strategic importance (upper right quadrant) (European Parliament 2022a).

Figure 18: Characterisation of backgrounds to consider stockpiling operations



Source: Authors' own elaboration.

While it is possible to forecast demand in an economy over several months, it is hard to forecast it over several years. Long-term demand depends on technical innovation, changes in demand, policies and other unpredictable conditions. The desired effect of storage can only be achieved if the industrial ecosystem is present in the EU. It is therefore essential to investigate the evolution of investment in industrial capacity beyond the EU. We begin the assessment by comparing investments in the US, Japan, Switzerland, South Korea and China, countries that have already put in place strategic storage policies.

An indicator for the investment level of an industry is Gross Fixed Capital Formation (GFCF), normalised by the Gross Domestic Product (GDP). The GFCF statistic is defined as the acquisition of produced assets excluding the fixed capital that was disposed, i.e. considered to be removed due to elements such as wear and obsolescence. In Figure 19 below, the capital deepening, the ratio of GFCF to GDP, is shown as a measure of an economic investment effort. Figure 19 emphasises that in the last 30 years, investment in European economies has been relatively stable, at around 20% of GDP.[43] In this regards, the Asian economies, Japan, South Korea and most notable China, have higher investment rates than the EU. Switzerland has a consistent GFCF/GDP percentage of (mostly) above 25%. Especially, the case of China demonstrates country's development of a strong manufacturing base over the last three decades. The data shows that European manufacturing investment is similar to the US. In addition, when income of different countries is taken into account, the difference in investment rates can be clearly observed (as prosperous low-income countries have rather high investment rates) (EIB 2016).

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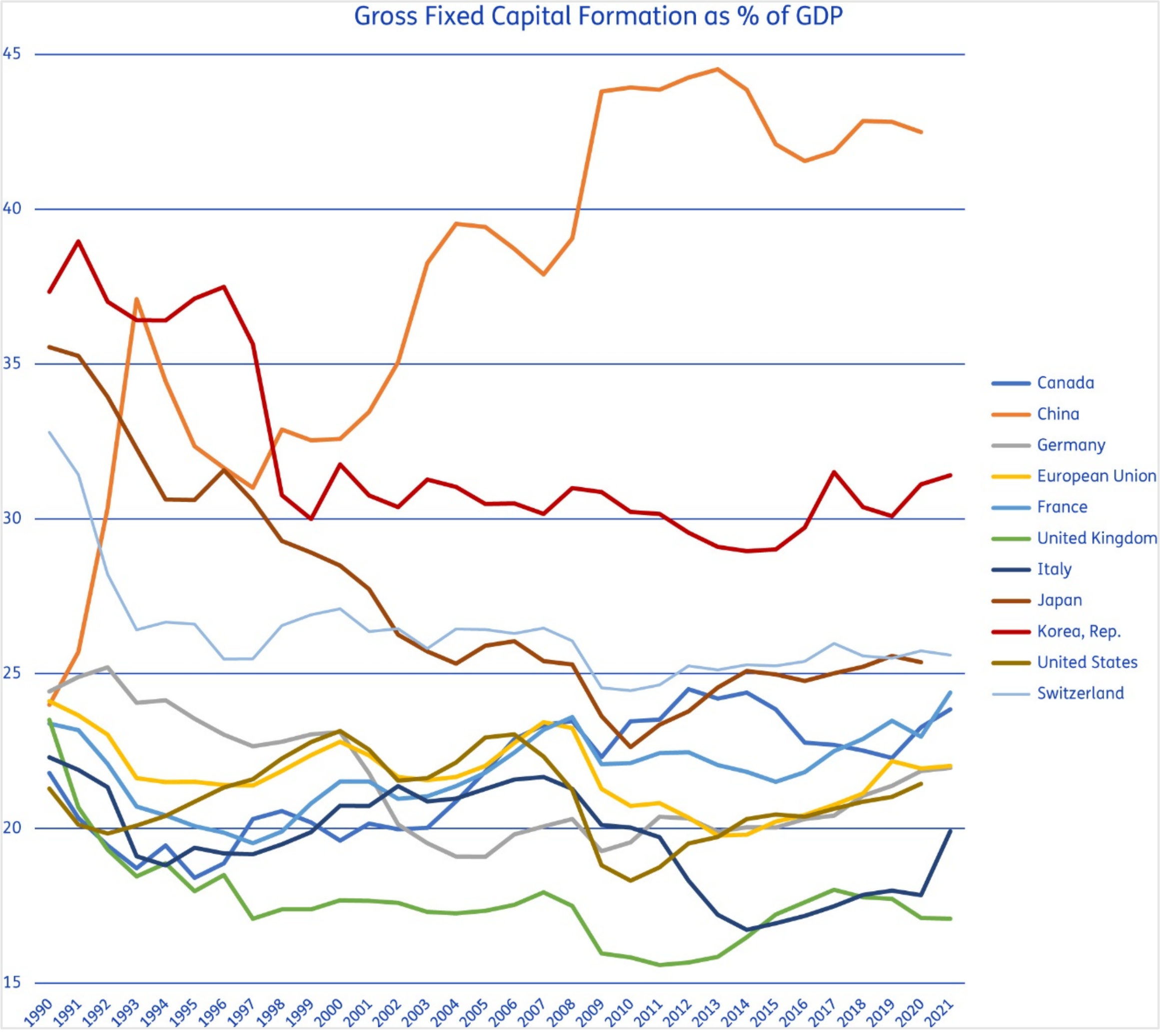
[43] Ranging from around 20% in Italy to a higher value of 21-24% in France.

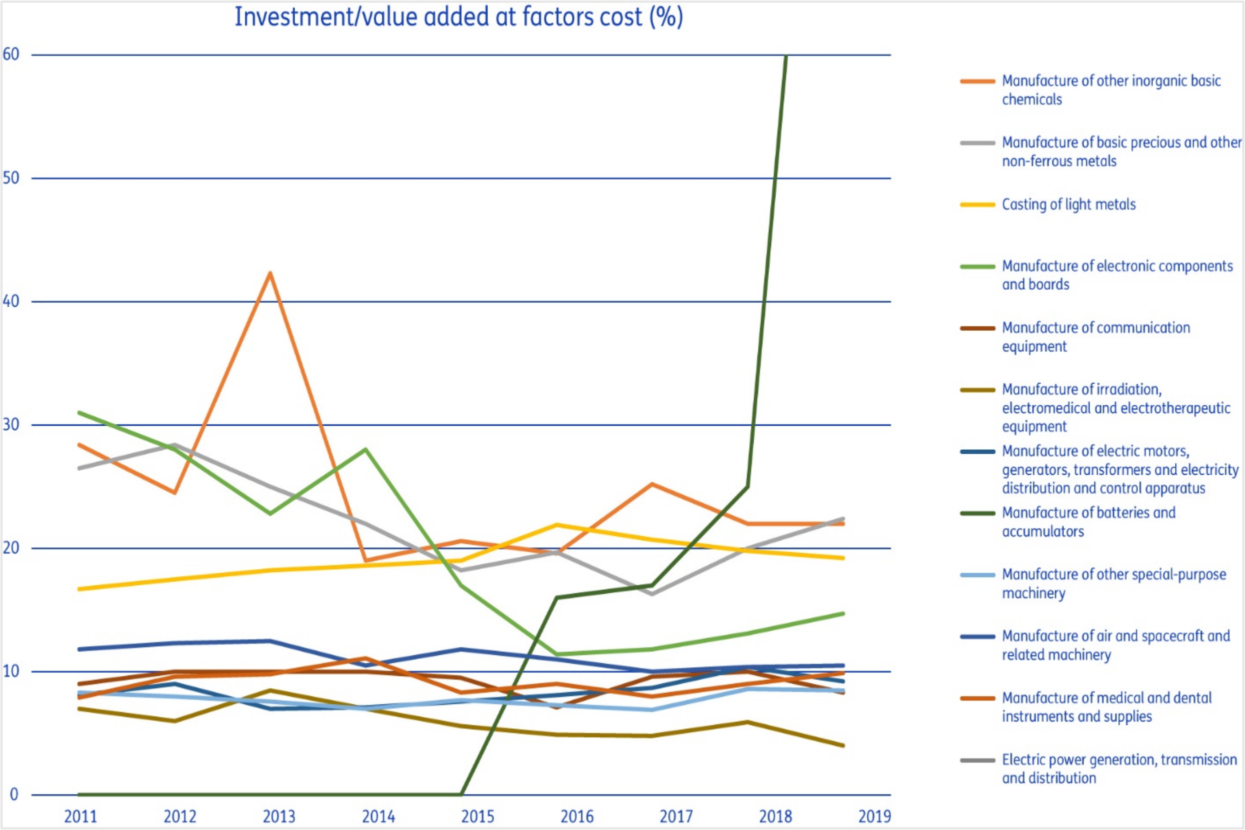
Figure 19: Gross Fixed Capital Formation as share of Gross Domestic Product of major economies and the EU-27



Source: Worldbank.

The investment into the industrial capacity can be further illustrated by the share of (mostly physical) investment of specific EU manufacturing sectors in Figure 20. These investments includes, for instance, to the total value of buildings, machinery, vehicles, ICT infrastructure, land, intellectual property etc. The ratio of investment in tangible assets and value added at factor cost is similar to the GFCF/GDP ratio (Eurostat Structural Business Statistics 2022), the indicator that was used in Figure 19.

Figure 20: Gross Fixed Capital, industry sectors, in Member States



Source: Eurostat Structural Business Statistics.

Figure 21 shows that investment rates in the EU in manufacturing sectors (associated to the products in Annex 1) for the green and digital transition are below the EU-average of 22% except for the manufacturing of batteries and accumulators. The latter sector is "off the charts" for 2019[44], with an investment to added-value ratio of 122%. The absolute value of the associated investment is EUR 2 845 million.

The example of battery manufacturing shows the level of investment associated with the development of a nascent EU industry. Similar growth in investment should be observed in any manufacturing sector the EU want or need to increase.

We find that if stockpiling is adopted as a policy, considering investments into associated capital stock is advised. Monitoring investments into EU manufacturing sectors is relevant, as these investments strongly influence costs and compositions of public stockpiling operations. Influencing the decision-making process around investments in capital stock and business operations will require careful consideration. But these considerations are worth the effort: over the years, a resilient industrial capacity in the EU is the most important form of stock.

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[44] More recent data is not available, once more indicating the need to invest in better public data.

Box 4: Capital stock in the energy generating sector: a new characteristic

The share of renewables increased from a few percentages at the turn of the century, to over 22% in 2020 (EU-27 average). The character of energy generation capital stock is changing. Rather than tailored to dissipative consumption (gas, coal, oil etc.), the capital stock is increasingly characterized by regeneration.

The embedded raw materials seem of less importance than its ability to generate energy with near zero marginal costs. The renewable energy stockpile increases resilience and strategic autonomy. The build-up of the renewable capital stock(pile) could therefore be deemed worthy to be safeguarded from supply disruptions.

Source: Authors' own elaboration.

A final consideration pertains to human capital. The labour force and innovative power of the economy are arguably the most important characteristic and competitive aspect of any industrial eco-system. As several sectors and regions in the EU experience, labour shortages can be a clear barrier to enhance production patterns. Furthermore, the EU is facing a shortage of science, technology, engineering and mathematics (STEM) graduates (Eurofound 2019) and this deficit is expected to increase in the coming years. This trend is also present in the manufacturing industry where the vacancy rate has increased from 0.9% in 2011 to 1.8% in 2021, indicating a steady increase in unfilled vacancies. Hence, investing in raw material supply through stockpiling can only be effective if investments in labour and capital follow suit and result in an actual increase of the capacity of the EU industrial eco-system.

5.2 Towards a cost-benefit analysis of stockpiling

Different options for stockpiling operations will yield different societal benefits over time. These options will be subject to an economic appraisal, which includes a mandatory cost–benefit analysis (CBA) required for all major publicly funded projects, in line with the methodology described in the Commission Implementing Regulation (EU) No 207/2015.

Conventional CBA used for economic appraisal of projects and policies is based on a welfare-economics framework. CBA methods use consumption or production value as key-factors, that are assumed to grow at a certain rate in the future. In case of stockpiling, however, unpredictable geopolitical events could substantially impact consumption and production growth.

There are at least two more problematic things when aspiring to apply CBA techniques to stockpiling. First of all, the acquisition costs of raw materials or other products are made in the first year of the stockpile creation, whereas future benefits must be discounted into the present. The uncertainty, and lack of stock draw precedent, makes these future benefits uncertain. Furthermore, the optimum design of the type and quantity of materials in the stockpile is equally uncertain and requires skills, knowledge and experience. The stockpiling composition needs to account for political, economic and technological developments. This makes even the easiest part of a CBA, the estimation of costs, difficult to quantify, let alone the estimation of benefits.

There is experience in European project/policy appraisal where cost and benefits quantification has proven to be particularly challenging, namely in the absence of statistical data or research studies to provide values for the benefits to be quantified. In these cases, cost effectiveness or cost–utility analysis is the methodology of choice (European Commission 2021d).

This Section presents information about costs and benefits of stockpiling, so that product stockpiling can join other industrial policies in the process of economic appraisal.

5.2.1 Structure of a stockpiling CBA

Costs and benefits of a stockpiling policy can be categorized based on a description of common costs and benefits of stockpiling of the US (US Congress 1976, see Table 20).

Table 20: Common costs and benefits of stockpiling

	Example of costs	Benefits
Direct investment	Acquisition cost of products, transport costs, land acquisition, building costs.	At least, equal to the supply-chain disruption cost and/or price increase in case during a stock draw period. See also Subsection 5.2.4.
Operation costs	Administration, maintenance of facility, material deterioration, interest.	
Indirect impacts	Prices increases as a result of shocks in demand increase, declining price level during stockpiling of a product.	

Source: Authors' own elaboration.

5.2.2 Costs of stockpiling

Costs for raw material stockpiling include direct investments (acquiring products), operational costs (administration, storage, material deterioration, etc.) and disposal costs (administration, physical releases, transport, etc.).

Direct investments

The dominant factor is the acquisition of raw materials. From Section 4.3.2, we learned that the acquisition costs of product groups shaping the green and digital transition are estimated at EUR 25.8 billion. These acquisition cost are subject to price volatility. As substantial price differences within relatively short timespans often occur for some of the product groups, the timing of material acquisition for stockpiling has a large influence on the acquisition costs.

The other factor is an aggregated cost for land acquisition, building facilities and transport cost. Given that around 15% of the land in the EU is unused and abandoned[45], notably around manufacturing locations, finding relatively cheap land (when necessary) should not represent a barrier.

Operational costs

Operational costs include storage costs, material deterioration costs, possible loan interest and administrative costs.

Table 21 shows the estimated costs based on the (RPA 2012) study. It discerns two alternatives: one where a dedicated body in the EU is operating the stockpile or the private sector has to maintain a mandatory stockpile and one where (financial) incentives are in place to delegate the stockpiling operations to the private sector.

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[45] For EU land-use, see the LUCAS database: https://ec.europa.eu/eurostat/databrowser/view/LAN_USE_OVW__custom_3474873/default/table?lang=en.

Table 21: Estimated cost of stockpiling operation

Main type of expenditures	Costs per main type of expenditure	EU dedicated body or mandatory stockpiling by private sector (EUR million)	Stockpiling by private sector based on (financial) incentives (EUR million)
Direct investment	Product group acquisition	28 613	25 752
	Storage (land, transport, building)	14	11
Operation cost	Material deterioration	9	6
	Administrative	3	0
	Loan interest (for stock acquisition)	66	132
Indirect impacts	Not quantified		
Total costs		28 705	25 901

Note: (*) The estimated cost of stockpiling operation is based on required quantities of product groups for the green and digital transition and cost estimates from 2021 price levels.

Source: RPA 2012.

The total costs of the stockpiling operation appear to be a mere 1% higher than the raw material acquisition costs (EUR 25 901 / EUR 25 752). Total costs as mark-up compared to acquisition costs, namely 1% in Table 21, appear small. Indeed, these are smaller than the average mark-ups for trade and transport margins in macroeconomic accounts (Eurostat 2008), but are in the order of magnitude of average mark-ups in international trade (OECD 2016).

The existing study (RPA 2012) expected the acquisition costs for the same stockpiling volumes to differ depending on a public or private stockpiling alternative. The acquisition costs of a centralised or mandatory stockpiling were assumed to be 11.1% higher than the alternative where the private sector would implement the stockpiling policy. The assumption underlying the 11.1% difference is taken from Table 5.10 of the RPA report and is based on information on operating costs in the US and South Korea.

5.2.3 Recent examples of public expenditures into energy or digital markets

Chapter 1 indicates that European stockpiling can be seen as a static part of the new industrial EU response mechanism. As such, the investment costs of stockpiling can be compared to examples of public investment or expenditure in energy or digital markets. This comparison put the estimated costs of storage into perspective. These public expenditures reflect the willingness to intervene and/or invest in markets relevant for the double transition (EPRS 2022b).

The following examples of public investments are briefly discussed in this Section: investment into renewable energy capital based on the REPowerEU plan, investments in chips manufacturing capabilities through the Chips Act and the public expenditures to support public utilities in the current energy market crisis.

Renewable energy

Public investments into the build-up of renewable energy generating capital are extensive, and recently centred around the REPowerEU plan. To allocate financial support for the first REPowerEU investment needs, the European Commission proposed an amendment of the Recovery and Resilience Facility (RRF), anticipating loans and grants resulting in a total funding close to EUR 300 billion. A part of that sum will be allocated to renewable technologies such as solar and wind, batteries and hydrogen.

Solar and Wind

The build-up of solar and wind projects represents a core part of REPowerEU plan. This is done through policy tools such as a Power Purchase Agreement (PPA) guidance, solar strategy, solar roof top initiative involving an amended Renewable Energy Directive (RED), RRF Chapter, solar alliance and potential Important Projects of Common European Interest (IPCEI) focused on breakthrough technologies and innovation. A total of EUR 86 billion is allocated for renewable generation such as solar and wind.

Batteries

Investments in battery production facilities will continue to be supported by governmental expenditures. The main investment channel is the European Battery Alliance (EBA). It was established to channel public support for battery development in the EU. It aims to create a competitive and sustainable battery cell manufacturing value chain in Europe. In 2021, the Commission approved the second battery-related Important Project of Common European Interest (IPCEI), jointly notified by 12 Member States , with a total value of EUR 2.9 billion. It complements the first battery-related IPCEI with a total value of EUR 3.2 billion, which was adopted in 2019[46].

Hydrogen

Hydrogen is a widely anticipated part on the renewable energy investment agenda of the EU. The appointed European Clean Hydrogen Alliance to concert the efforts and help build-up a robust pipeline of investments (European Commission 2020d). The REPowerEU program reserves EUR 27 billion for hydrogen, as a direct investment in domestic electrolysers and distribution of hydrogen in the EU. For instance, the REPowerEU Europe plan indicates that the EU will top-up Horizon Europe investments on the Hydrogen Joint Undertaking (EUR 200 million) to double the number of Hydrogen Valleys (European Commission 2022). Furthermore, two IPCEI projects on hydrogen Hy2Tech and Hy2Use are planned, whose investments range around EUR 5.2 billion[47].

In addition, the ETS Innovation Fund[48] puts together around EUR 10 billion for low-carbon technologies over the period 2020-2030. It has the potential to facilitate first-of-a-kind demonstration of innovative hydrogen-based technologies. The European Commission has launched the funding for the 2022 Large Scale Call of the Innovation Fund in the autumn of 2022 to around EUR 3 billion (European Commission 2022f).

Microchips

The European Chips Act, proposed in February 2022, has the objective to strengthen the European Union's place in global value chains for microchips. The Chips Act plans to combine public and private investments until 2030, whereby the policy driven expenditures should be broadly matched by long-

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[46] Information about the battery IPCEI funding is available: https://ec.europa.eu/commission/presscorner/detail/en/ip_19_6705.

[47] Information about the IPCEI hydrogen is available: https://ec.europa.eu/commission/presscorner/detail/en/ip_22_5676.

[48l] It support innovation in low-carbon technologies and processes in Member States.

term private investment. The public investment will be between EUR 2 and EUR 11 billion, where the EUR 11 billion is expected to be raised by Member States and underlying organisations.

These investments will complement existing R&D&I programmes for semiconductors such as Horizon Europe and the Digital Europe programmes, as well as announced ancillary support by Member States. It should be noted that the investments in the context of the Chips Act remain subject to uncertainty.

Support of energy suppliers

The allocation of governments' financial support to utilities is tracked by Bruegel[49]. This support has the purpose of meeting the liquidity needs of the utility organisations, through loans, bailouts and fully-fledged nationalisations. Between September 2021 and September 2022, the total support amounted to EUR 133.9 billion in Sweden, Finland, Germany, Czech Republic, Austria, Croatia and France. The total investment in utilities is lower than governmental expenditures aimed to shield household consumers from energy price spikes. Yet, the expenditures are significant because they aim to secure the supply to the economy of a generic commodity and is therefore relevant in the discussion of stockpiling policies.

Table 22 provides an overview of examples of public investments into (renewable) energy or digital markets. The last column contains the ratio of EU major societal investments (in wind, solar, batteries, hydrogen, semiconductors and energy) and the stockpiling operation costs.

Table 22: Overview of major EU investment schemes for energy and digital markets

Public investments	Duration	Size (billion EUR)	% of stockpiling cost (stockpile of CRM containing products shaping the green and digital transition, EUR 25.9 billion = 100%)
Wind and solar	2022-2027	86 billion	332%
Batteries	2019-2021	6.1 billion	24%
Hydrogen REPowerEU	2022-2027	35.4 billion	137%
Hydrogen ETS investment fund	2020-2030	13 billion	50%
Chips Act fund	2021-2030	2 – 11 billion	8 - 42%
Governmental support for utility sector in Member States	2021-2022	133.9 billion	517%

Source: Authors' own elaboration.

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[49] For data on governmental support for utility companies, see: https://www.bruegel.org/dataset/national-policies-shield-consumers-rising-energy-prices.

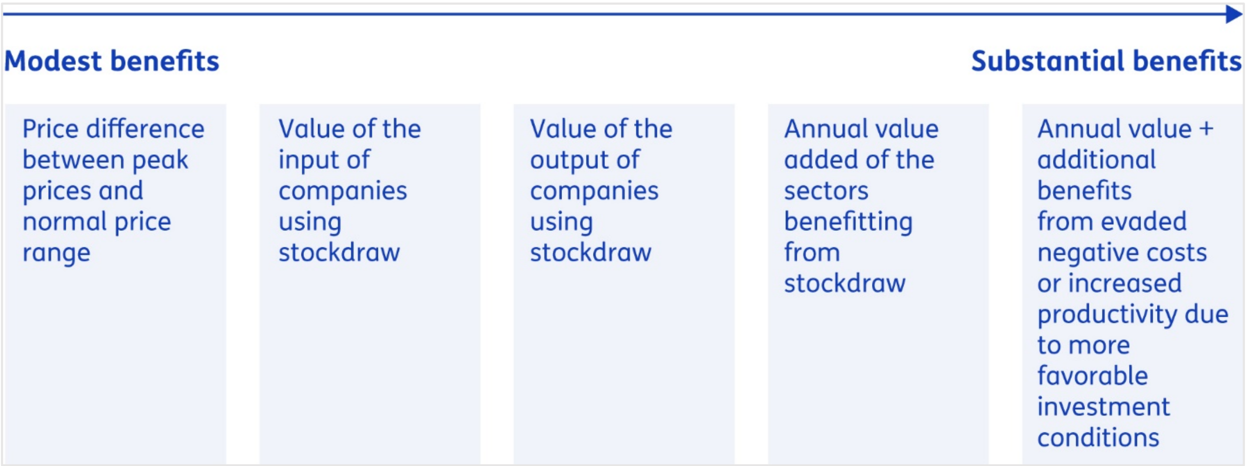
We can conclude that the investment costs of a 60-day stockpile are comparable to relevant examples of public investments in (renewable) energy and digital markets. The expenditures to maintain energy system utility companies are five times higher than the costs of creating a stockpile for the green and digital transition.

5.2.4 Potential benefits of stockpiling

The European Commission observed that the quantification of benefits from stockpiling is highly challenging because the current system has never been put to a real test by a large-scale disruption (European Commission 2008b). Physical shortages have rarely occurred before 2020.

In Figure 21, the range of possible benefits of stockpiling (raw materials, intermediates or final products) are shown. The possible benefits differ in appraising either merely price differences, total input purchasing costs, total output manufactured values, or scaled-up benefits from individual companies to the entire sector. The description of benefits from stockpiling on the right-hand side is based on pages 81 and 82 of (European Commission 2021d).

Figure 21: Range of possible benefits from stockpiling



Source: Authors' own elaboration.

It can be argued that stockpiling solves market failures. These market failures were introduced in an era where stocks were considered a cost and a sign of inefficiency in a supply chain (Srinidhi & Tayi 2004). The paradigm in many logistical operations was to minimize and to provide just-in-time delivery.

Box 5: From Just-In-Time to Just-In-Case

The Just-in-Case (JIC) principle in supply-chain management and operation produces and stocks goods in greater quantities than expected demand. The alternative to it, having been in use for decades, is the Just-in-Time (JIT) principle, which aims instead to minimize stocks and their costs. The JIT principle was introduced in the 1960s by Japanese carmaker Toyota, which considered it more efficient and profitable than the traditional JIC model.

In the past decades, highly competitive markets caused JIT to become the standard manufacturing model for most production facilities around the world (sometimes referred to as "lean production"). In addition, to keeping minimum inventories, companies following this model consolidated orders to reduce shipping costs and started using flexible short-term contracts (Masters & Edgecliffe-Johnson 2021).

However, recent events causing global supply chain disruptions have caused many businesses to rethink the JIT model. Because of this paradigm shift, businesses (not least Toyota) are now increasingly applying strategies to build additional resilience in their supply chains. Examples of these strategies are increasing the size of their inventory or entering long-term contracts with suppliers, but also diversifying manufacturing suppliers or investing in technology that can provide timely warnings for potential bottlenecks.

Source: Authors' own elaboration.

A renewed interest and investment in stockpiling internalises in a way recently reencountered externalities: unpriced costs incurred by supply-chain risks that were irrelevant until recently. It seems that the systemic supply risks in the new geopolitical context have not yet required to be accounted for in the last decades. The new paradigm is illustrated by a statement of EU Commissioner Thierry Breton[50]:

I also believe that we are seeing the end of an economic era dominated by a long-standing belief in just-on-time logistics, geographical specialisation and elongated supply chains. We have ample experience now of global supply chains being disrupted by the Chinese hard lockdown policy, the war in Ukraine and our international partners' export restrictions.

5.3 Exploring stockpiling approaches in the near future

A practical implementation of a stockpiling scheme requires the consideration of a few intuitive aspects: given how much and what is to be stockpiled, where will stockpiles be located? Who should be responsible for the operation?

In the aforementioned study (RPA 2012), different stockpiling alternatives for (economic) EU stockpiling were considered. These were based on real-world examples, such as the EU stockpiling programmes for oil and petroleum and the programmes for (products containing) CRM stockpiling outside the EU (focusing on China, Japan, the Republic of Korea, Switzerland and the US). The alternatives varied levels of responsibility for stockpiling (EU, Member States, private companies). Through assessing these alternatives, the desirability, feasibility and potential costs and benefits of various stockpiling schemes were identified.

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[50] Address of Commissioner Breton from 5 September 2022: T. Breton, September 2022, See: https://ec.europa.eu/commission/presscorner/detail/en/SPEECH_22_5350.

In general, the (RPA 2012) study found that there were potential advantages to all stockpiling alternatives, such as protection against supply shortages and price increases, hedging companies' short and long-term planning, buying time to find alternative suppliers and possibility to absorb short-term demand spikes for materials. Potential disadvantages of stockpiling include market disruptions following from stockpiles created through poorly timed acquisitions, possibly exacerbating market shortages and even damaging relations with third countries.[51] Furthermore, creating stockpiling policies is expected to create winners (i.e. excessive unevenly distributed gains) among suppliers having stronger institutional foundations. Lastly, ineffectiveness at solving longer-term market issues, costs, administrative burden and practical obstacles in stockpile set-up and management (for instance, guaranteed accumulation of stocks) can be considered disadvantages of stockpiling policies. Specific advantages of private stockpiling as opposed to public stockpiling were found, such as a good understanding by the private sector of the needs of downstream users, efficient use of existing capital stock and deploying human resources effectively. Several disadvantages for a private stockpiling alternative were identified such as negative impact on companies' competitiveness from sinking available capital in the stockpile, increased financial risk, practical obstacles and an expected drive to profit maximisation.

Both the disadvantages of general and private stockpiling seem to have changed in the current geopolitical context.

- Market disruptions stemming from stockpile build-up can be moderated by reserving ample time for stockpile creation (for instance 6 to 18 months);
- Problems with governmental intervention in markets, even if not specifically due to stockpiling policy, remain a threat in the long term. Nevertheless, the will to publicly intervene for the benefit of society seems clearly greater in 2022 than in 2012;
- Clear stock draw criteria and financial schemes can avoid competitiveness issues following from a suboptimal allocation of companies' investment opportunities;
- Practical obstacles, such as deterioration of material and availability of transport capacity or simply raw material supply, are problems that procurement and wholesale managers deal with on a daily basis; and
- Clear (financial) incentives, based on clear terms and conditions, will ensure that stockpiling by the private sector is not in conflict with the need to turn a profit.

The study (RPA 2012) concludes that the most feasible course of action for stockpiling policy in the EU would be an alternative based on stockpiling, operationalised by the private sector. Input from (RPA 2012) and recent validation with several trading companies suggest that an alternative where the private sector is incentivised to maintain surplus stock would be an acceptable option. The risks and corresponding rewards would be incurred by the enterprise undertaking the stockpiling operation.

The study from 2012 (RPA 2012) concludes that a voluntary scheme of stockpiling would be most feasible option. This would require the EU to periodically publish updated stockpiling targets when compared to the situation without stockpiling. Stockpiling operations are in either scenario executed based on the decision-making within a company.

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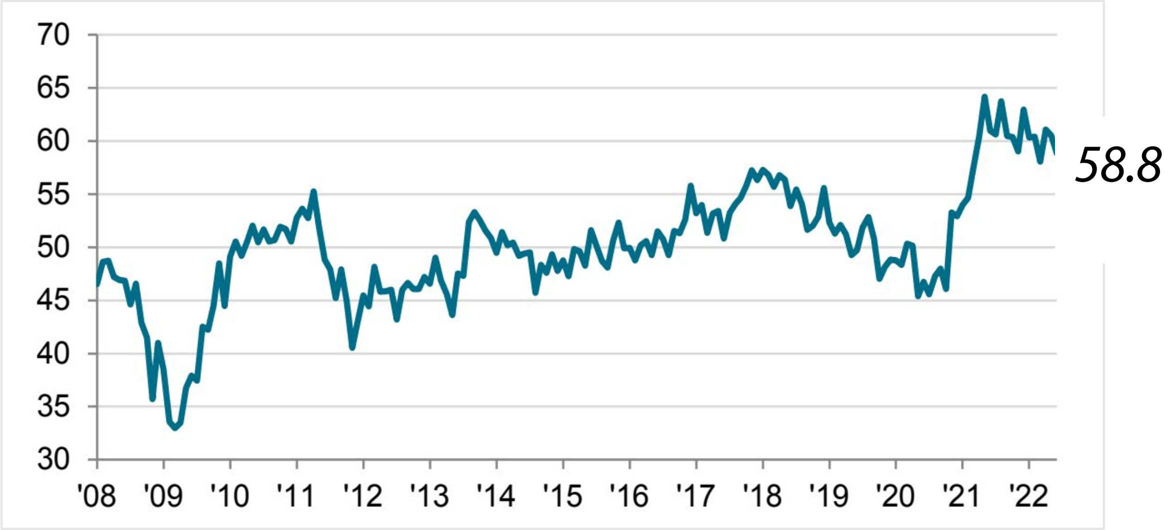
[51] Increased demand could in turn interact with speculative detrimental effects, as happened in the nickel price surge of early 2022. This nickel price increase was not caused by increased demand, but by a Chinese party taking an oversized short position on the commodity. When nickel prices increased as a consequence of Russia-Ukraine war and Russian nickel was subject to the uncertainty of sanctions, the Chinese party became unable to pay its margin calls.

Given urgencies arising from the new geopolitical context and green and digital transition, it is possible that a voluntary alternative without (financial) incentives could be ineffective. We will therefore continue to explore EU stockpiling options supported by public (financial) incentives to enterprises.

It is restated that stockpiling is a core-activity of the wholesale sector. A considerable portion of it consists of affiliates of multinational manufacturers (Broos et al. 2016). Operationalising stockpiling policies via the private sector seems an effective approach since it deploys the professional skills and knowledge of a sizeable (wholesale) sector or corporate units from the manufacturing sector.

A first demonstration of corporate agility comes from professional information systems. The corporate response to the turmoil in international trade since early 2020 is monitored by the IHS Markit Ltd.[52] (Figure 22). A value over 50 represents a growing stockpile compared with the previous month. The graph clearly shows that, once the initial shock of the COVID-19 pandemic receded in Q3 2020, purchases in stocks[53] increased.

Figure 22: Stocks of Purchases Index, in June 2022



Source: IHS Markit.

Figure 22 shows that additional private stockpiling is already taking place in the EU after since summer 2020. One might therefore be tempted to conclude that further state supported action is unnecessary. However, based on the findings of Chapter 2, we have learned that given the significant increase in demand related to the ecological and digital transition, more intervention may be needed.

Public-supported stockpiling policy as an intervention would send a signal to mitigate supply shocks for manufacturing industries in the EU that are vital for the green and digital transition. Based on the tripartite characterization from Section 2.2 (strong position, nascent and restoring) this means that stockpiling policies are aimed at strong and nascent industries in the EU.

Fledging industries needing to restore their industrial base are in a less favourable position to benefit from a stockpiling policy. Their products, such as for instance PV panels, are already imported in significant quantities from foreign markets at competitive prices. Publicly stockpiling these final products would only allow to postpone a supply shock by 60-day, rather than secure a profitable and strategic production, something the private sector can already do.

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[52] The periodic survey, featuring many thousands of procurement managers can be found at: https://ihsmarkit.com/products/pmi.html.

[53] The level of inventory of materials purchased (in units, not money) describes the current inventory compared with the situation one month ago.

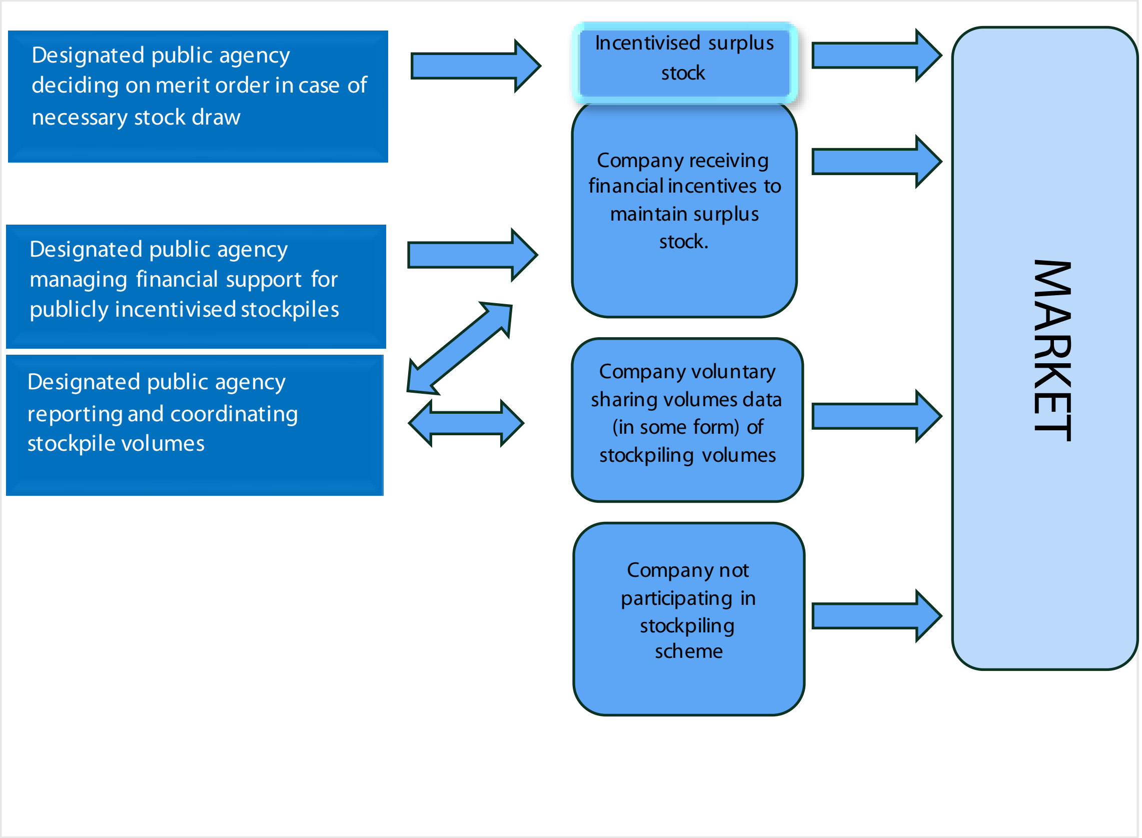
Thus, the implementation of stockpiling by the private sector implies that providing Europe with imports not feeding into the EU industrial eco-system at scale (but imported almost only for final consumption) is an objective that can remain out of scope for public policy.

Incentivising stockpiling in the EU would send a market signal to enhance investment in supply-chain management relevant for green and digital transition in the EU, and to consider its relation with the state of the industrial eco-system in the EU. The need for this market signal is required to achieve politically agreed transition goals.

We therefore converge on a message that an alternative, where stockpiling is coordinated by a dedicated EU body or by national governments of Member States, is desirable. In this alternative, the EU would provide (financial) incentives for companies to acquire materials for their stockpile and collect data on available stockpiles (as reported by EU Member States).

Figure 23 shows simplified arrangements for stockpiling under a private sector-led, supported by the EU. An example of a designated coordinating body can be found in the EU Coordination Group for Oil and Petroleum products[54].

Figure 23: Simplified arrangement of a stockpiling approach based on surplus stockpiling by the private sector, acting on (financial) incentives provided by designated public agencies



Source: Authors' own elaboration.

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[54] The EU Coordination Group for Oil and Petroleum products can serve as an example for EU agencies responsible for stockpiling CRM containing products, see: https://ec.europa.eu/transparency/expert-groups-register/screen/expert-groups/consult?do=groupDetail.groupDetail&groupID=1032.

The possible stockpiling could be mainly maintained by the private sectors, which does not require further policy discussion. Furthermore, SMEs are an important group to consider in a stockpiling, as this group may be most affected by supply disruptions. However, given their resources SMEs may not have the sufficient capacity to identify the best stockpiling practices. Hence, the EU support might be required.

An important detail is the merit order of Incentivised additional stock in case of stock draw. This means that a designated public agency can decide which use should be given priority. It would be desired to separate this competence from the agency that coordinates the stockpiling under normal market conditions and the agency that controls the incentives. The discussion on the supervision of the deployment of goods in the EU has been addressed in the context of the recent work on the Single Market Emergency Instrument to ensure the functioning of the EU single market in case of emergency (European Commission 2022b).

Setting up of stockpiling may encounter many administrative difficulties. In case of stockpiling establishment a thorough analysis of its feasibility and effectiveness should be carried out first. A summary of principles for incentivising stockpiling is provided in Box 6 below).

Box 6: Principles for Incentivised stockpiling

A private stockpiling scheme needs to be attractive enough to make an impact on investments, but robust enough to prevent market distortions or elicit misuse. A limited number of principles might safeguard the stockpiling arrangements of undesirable situations:

Avoiding misuse

- Agree to a fixed share that will fall under the discretion of the EC to be distributed to retai the independent character of enterprises;
- Set an absolute and a relative (to the size of the company) maximum upper bound of tota financial incentives;
- Provide incentives as much as possible in the shape of insurance, certified demand, lending, material leasing, swaps and backing of risks that can't be insured. Only if strictly necessary should payments be made to the private sector; and
- Define clear stock draw criteria and allow governments to distribute the Incentivised stoc after a period of time in case no stock draw situation has occurred.

Ensure impact on investments

- Verify that (financial) incentives make an impact on investment decisions of th manufacturing and wholesale private sector; and
- Prevent excessive administrative burdens when arranging the (financial) incentive particularly for SMEs.

Source: Authors' own elaboration.

5.4 Conclusions

Stockpiles and industrial capacity are firmly linked. Aiming to mitigate supply risk of products shaping the green and digital transition with stockpiling, is trying to mitigate a problem with a timescale of many years by adopting a solution (stockpiling) that is characterized by a timescale of days and weeks.

It is helpful to discuss stockpiling using a quadrant figure categorising the short (days) and long (years) term and public and private sector responsibilities. Considering the time scale of years, this exercise shows that stockpiling of critical raw materials by itself will not provide a resilient industrial eco-system, nor bring open strategic autonomy any closer. Over time, a resilient industrial capacity in the EU is the most important form of stock.

Any investment in stockpiling should at least be mirrored by a commensurate investment in the build-up of the corresponding industrial eco-system. Conversely, any investment into an industrial facility realised within the context of an industrial policy is very likely to manage its newly created supply chain. In the last 10 years, the growth of manufacturing capital stock has been below the EU-average. With the purpose of firmly linking capital stock formation to stockpiling policies, monitoring the state of the industrial capacity in the EU is a necessary part of a stockpiling policy. After all, these capital stock investments strongly influence costs, compositions and benefits of public stockpiling operations.

Stockpiling costs are dominated by the acquisition costs. Given a 60-day reference period and a stockpile composition of products group relevant for the green and digital transition, costs for a EU stockpile are estimated to be up to EUR 25.9 billion, including direct investments and operational costs (transport, buildings, data management etc.). Evidence from stockpiling operations in non-EU countries suggests that product acquisition costs represent around 99% of this cost(RPA, 2012). Operational costs or other one-off direct investment costs contribute marginally to the cost of stockpiling. The costs of stockpiling in general are comparable to major investment schemes for specific renewable green and digital technologies, such as batteries, solar, renewable energies, hydrogen.

A paradigm shift in supply chain management is imminent. Until the disruption of many global supply chains (starting early 2020), the paradigm in many logistical operations was to minimize costs and to provide just-in-time delivery. A renewed interest and investment in stockpiling internalises certain externalities, such as unpriced costs incurred by supply-chain geopolitical risks. These costs were judged irrelevant until recently.

The private sector is the best positioned to operationalise a stockpiling policy. Stockpiling is what professionals active in supply chain management, wholesale and logistics see as their core economic activity. Stockpiling operations is therefore best operationalised by the private sector, supported by incentives from EU designated agencies. In that case, the key challenges of a successful stockpiling policy are effective public-private coordination of the stockpile composition and determination of the characteristics of (financial) incentives. A major point of attention is obviously to prevent their abuse. The designed (financial) incentives provided by the public service should be attractive enough to the private sector to promote actual investment in greater stockpiles.

Providing clarity about the priorities when distributing products in case of a stock draw of publicly incentivised stockpiles is vital. Public authorities grant themselves the right to apply a merit order in case of a supply chain crisis. This right is obtained by the government by providing (financial) incentives that created the surplus stock in the private sector.

Implementation of publicly Incentivised stockpiling by the private sector also implies that support to imports derived from household consumption should remain out of scope of public stockpiling policy.

6. FEASIBILITY OF USING TRADE POLICY TO ENSURE DIVERSIFICATION OF SUPPLY

Different trade policy strategies have been proposed to deal with risks to supply chains arising from the EU's dependence on imports from China and Russia: diversification, re-shoring and friend-shoring.

Diversification refers to increasing the number of suppliers and reducing the reliance on individual countries. The objective of a diversification strategy is to reduce monopolistic power that could be used to exercise economic coercion and to make supply chains less vulnerable to localised shocks (e.g., environmental shocks).

Re-shoring refers to the development of domestic supply chains with the goal of making domestic industries and infrastructure projects independent of global supply chains and therefore reducing the risks coming from outside interference and slowdowns in logistical networks as experienced during the pandemic. Near-shoring is a related concept, which proposes to build supply chains with geographically closer countries and therefore reducing the risk associated with long distance trade.

Friend-shoring on the other hand is the idea of building supply relations with like-minded partners instead of localising supply chains into the domestic economy or prioritising suppliers from nearby countries.

All three concepts have their advantages and disadvantages, both conceptually and with respect to the raw materials used for the green and digital transition of the European economy.

Re-shoring would have the advantage of eliminating risks from outside political interferences, as it would make European industries independent of foreign materials. However, given the complexity of many value chains and the economics of comparative advantage, reshoring entire supply chains is generally not an option. Technologic, demographic and economic forces have led to a continuing structural shift in the EU away from manufacturing towards services[55] (Herrendorf et al., 2014). The remaining manufacturing activities tend to specialise on the parts of the value chain with the highest value-added, which remain viable in a high-wage environment. Re-shoring of just the extraction of critical raw materials will depend on their availability in Europe, as well as on the costs compared to resource extraction in other countries. Some materials may be mined in Europe, but others may not. Furthermore, resource extraction almost always leads to local environmental degradation, which makes such projects politically difficult in many European countries. It would also make the European supply more susceptible to local shocks, which in turn would make it less resilient overall. Completely localised production can be less resilient than open markets[56]. Lastly, re-shoring extractive production can remove levers for cooperation and interaction between geographic parts of the world, especially those where this interaction could lead to socio-economic situations that better adhere to the universal human rights.

Friend-shoring as well as near-shoring would require a lot of effort to revert the economics of comparative advantages and specialisation in supply chains by relying on partner countries.

In this context, near-shoring emphasises geographical distance reducing logistical risks from long distance trade while friend-shoring emphasises like-mindedness and (political) reliability.

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[55] The peak of manufacturing share of GDP for France was around 1920, when it accounted for almost half of the economy compared to just 9% today. In just the last three decades, the manufacturing share of GDP for the EU has declined from 20% in 1991 to 15% in 2021, for all high income countries from 18% in 1997 to 13% in 2020 (sources: World Bank; Herrendorf et al., 2014).

[56] The example of the US baby formula shortage is very illustrative in this regard, see for instance NPR on May 19, 2022 "*How the U.S. got into this baby formula mess*", available at: https://www.npr.org/2022/05/19/1099748064/baby-infant-formula-shortages?t=1659947460545.

Friend-shoring appears as the more relevant concept, as Russia is exemplifying the drawbacks of relying too much on nearby suppliers regardless of their political alignment. Friend-shoring has the advantage over re-shoring that it would allow for international specialisation, but it has drawbacks as well. Geopolitical alliances shift over time and vary by issue, and like-mindedness does not prevent trade conflicts. India, for example, is the world largest democracy and courted as an ally to diversify trade from China by the EU (Poitiers et al., 2021)[57]. While trade conflicts might be less likely with like-minded countries than with 'systemic competitors', they nevertheless happen. For example, such trade conflicts tend to be frequent even among G7 countries.

In either strategy, the ability of European policy makers in setting incentives for companies to reshape their supply chains self-evidently depends on the role of European companies in these supply chains. As long as the EU imports most of its solar PV from China, improving security of supply through stimulating re-shoring or friend-shoring would imply affecting an entire production-ecosystem instead of 'just' supporting security of supply of raw materials. In this case, the reliance so far is more on Chinese manufacturing and less on the materials used in them.

The effect of trade policy instruments available to the EU to shape where its raw materials come from and to enact either re-, near- or friend-shoring strategies is limited. To create economic incentives through trade policy for companies to source their products containing CRM from one country rather than another, there need to be a difference in the tariff rate applied to them. The upper bound for such a differential tariff rate is set by the 'bound' Most Favoured Nation (MFN) tariff rate, which is the tariff that applies to all members of the WTO, including the EU. Free trade agreements (FTAs) allow the EU to set preferential treatment to individual economies and set lower tariff rates than the MFN one. However, the scope for these FTAs to shape where the EU imports from is small. The EU applies 'bound' MFN tariffs that are applied to all countries in the WTO on critical raw materials, which are very low. This leaves only a small scope for further reduction. Figure 25 shows the distribution of the 'bound' MFN tariff rates for critical raw materials. The top panel of Figure 25 shows that almost a third of tariffs on base materials and alloys is zero, with another third having tariffs smaller than 5%. The bottom panel of Figure 25 shows the average 'bound' MFN tariffs. The average 'bound' MFN tariff rate for base materials is 3.66%, and for alloys 3.44%.

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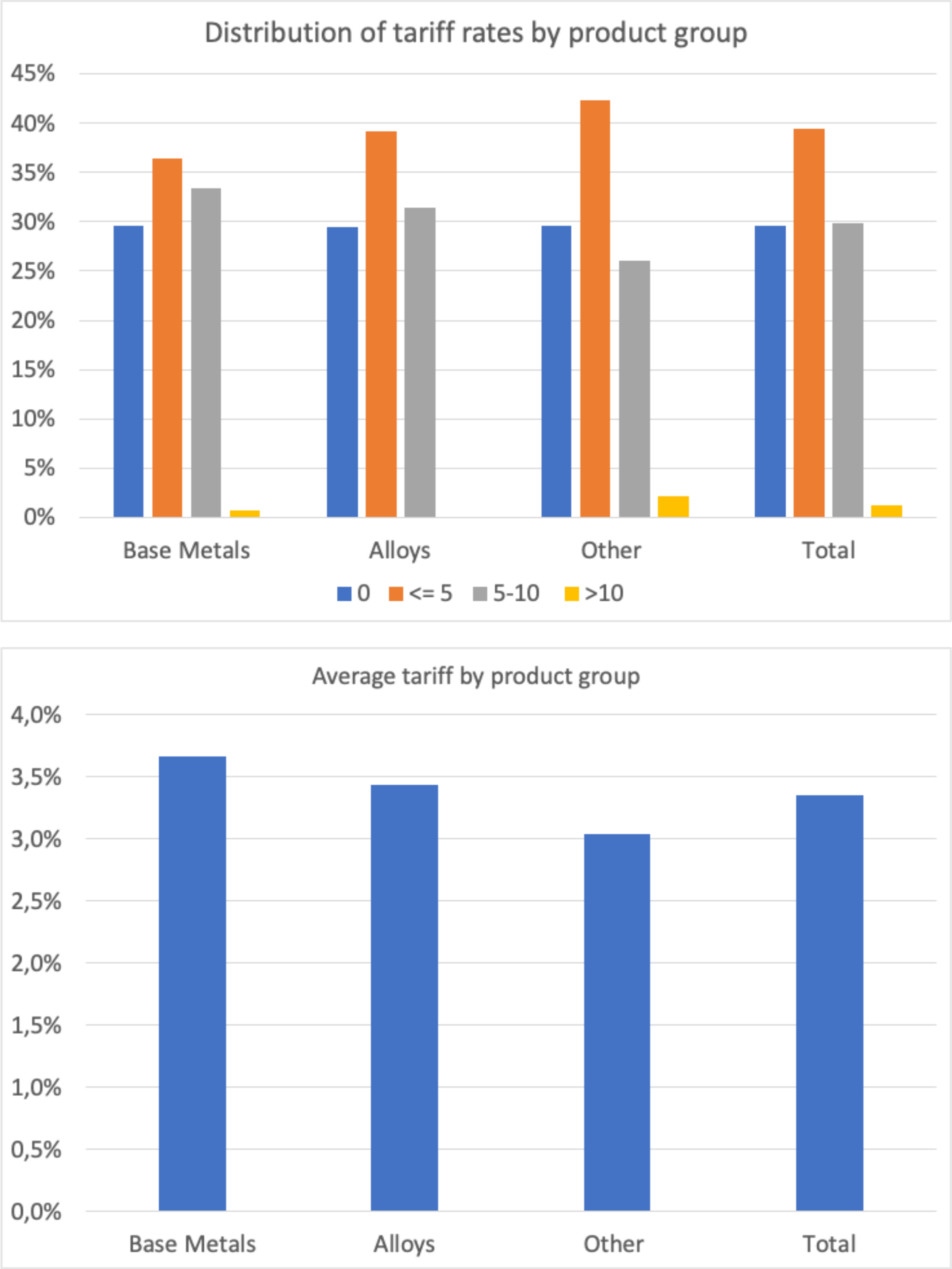
[57] See for instance Reuters on March 29, 2022 'India stands by trade with Russia as Lavrov set to visit', available at: https://www.reuters.com/world/india/india-stands-by-trade-with-russia-lavrov-set-visit-2022-03-29/.

Figure 25: EU MFN Tariffs on Base Materials, Alloys and Components



Source: Bruegel calculations based on data extracted from the TARIC database.[58]

However, this 'bound' MFN tariff is only the upper limit to which the EU has committed itself at the WTO. In practice, the applied MFN tariffs are often lower. For example, in the case of lithium, the 'bound' rate is 5.30%, while the applied tariff is only 2.6%. Other carve-outs also apply: In the case of tungsten in powder form, it has a 'bound' MFN rate of 5%, but tungsten powder destined for aerospace applications is tariff free. Tariff rates are highly specific and there are over 300 different tariffs for the different products containing CRMs and their different forms (ores, refined forms like powders, and different alloys). The overall picture is one of low tariffs, with limited scope for country-specific reductions through FTAs.

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[58] Extracted on 18th of August 2022 from: https://ec.europa.eu/taxation_customs/dds2/taric/taric_consultation.jsp?Lang=en.

Furthermore, FTAs rely on the rigid structure of WTO rules, which makes them a cumbersome policy option. FTAs have to be comprehensive, i.e. they must cover a broad set of sectors and tariffs to comply with international trade rules.[59] It is not possible to sign an FTA that only covers specific tariffs and goods, so they cannot be targeted to specific materials that the EU would consider critical to its green and digital transition. A comprehensive agreement not only involves most sectors, but it also requires making concessions to the partner countries in the negotiations. 'Modern' FTAs not only cover commercial issues but also involve negotiations over non-commercial objectives such as human rights and environmental protection. Disagreement over such issues have halted the ratification process of several important FTAs, such as the Mercosur agreement[60].

There are a number of FTAs of particular interest with regards to products containing CRMs for the green and digital transition. The Mercosur agreement covers important source countries for products containing CRMs like Argentina or Brazil. The CETA agreement with Canada was concluded in 2017 is also currently in the ratification process, but it is already 'provisionally applied'. The EU already has many other FTAs that eliminate tariffs for products containing CRMs, including with important source countries like Chile. It is in the process of negotiating further FTAs with other countries such as Australia or Indonesia. Negotiations on an upgrade of the FTA with Chile have been were concluded in December 2022. In this update, the EU has achieved some liberalisation regarding foreign investment in Chile's raw materials industry[61].

Outside of FTAs, the EU can grant beneficial tariffs and conditions under the GSP+ scheme[62] to selected developing countries, if they fulfil certain conditions on human and labour rights, the environment and governance. However only 8 countries are currently benefitting (Bolivia, Cape Verde, Kyrgyzstan, Mongolia, Pakistan, Philippines and Sri Lanka)[63] and as with FTAs the low MFN tariffs limit the scope for granting preferential tariffs to countries in the GSP+ scheme. Developing countries that do not meet the conditions for GSP+ can still benefit from the normal 'GSP' scheme or 'Everything but Arms' (EBA) preferential tariffs for the least developed economies, which also eliminate many tariffs for products containing CRMs.

For these reasons, supporting diversification of production in raw materials via non-trade policy appears both the most feasible and the most effective solution. Raw materials are commodities that are traded globally, making markets effects very efficient. The EU could provide development assistance through the Global Gateway initiative to projects that are improving the infrastructure in countries that have unexploited deposits, allowing them to develop their industries. This would diversify the supply not only for directly imported raw materials used by the EU industry itself, but also create deeper and more competitive markets for suppliers for EU industries. International cooperation, e.g. through the EU-USA Trade and Technology Council, the G7 or bilateral forums could help coordinate internationally to reduce the costs of supply chain diversification.

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[59] According to Article XXIV §8(b) of the GATT, a FTA needs to eliminate tariffs "on substantially all the trade between the constituent territories in products originating in such territories".

[60] See for instance Borderlex on March 2, 2021 "France pours cold water on idea of swift EU Mercosur pact ratification", available at: https://borderlex.net/2021/03/02/france-pours-cold-water-on-idea-of-swift-eu-mercosur-pact-ratification/.

[61] See Borderlex from December 9, 2022, EU, Chile seal trade deal upgrade', available at: https://borderlex.net/2022/12/09/eu-chile-seal-trade-deal-upgrade/.

[62] The 'enabling clause' of the GATT allows developed economies to provide preferential treatment to developing countries outside of FTAs. GSP+ is an EU program that provides preferential treatment to developing countries that meet certain requirements with regard to human rights, labour rights, environmental protection and governance.

[63] See https://trade.ec.europa.eu/access-to-markets/en/content/generalised-scheme-preferences-plus-gsp (accessed August 8, 2022).

6.1 Conclusion

As argued in Section 2.3, the two supplier countries away from which the EU would like to diversify in priority are China and Russia. The EU's dependence on China covers many CRMs and components necessary for the green and digital transition. In terms of CRMs, the EU has a high import dependence on China mostly for REEs and cobalt. The EU's dependence on Russia concerns mostly platinum group metals and nickel.

The EU is negotiating a FTA with Australia, which has large supplies of lithium, REEs, cobalt and nickel. An upgrade of its FTA with Chile has been agreed, and the EU is in negotiations with Indonesia, which are key suppliers of lithium and nickel, respectively. Finally, the Philippines, a GSP+ country, follows Indonesia as the world's second producer of nickel[64].

Nevertheless, trade policy offers limited scope to increase the diversity of European suppliers, because tariffs on CRMs are already low. This limits the effectiveness of these FTAs in incentivising a diversification of supply. Furthermore, to be compliant with the open multilateral WTO infrastructure, FTAs need to apply comprehensively to all product groups, not just to specific raw materials of interest. Non-trade policy tools, such as development assistance and international cooperation, appear as more effective options.

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[64] See Figure 6 for the main producers of the top 5 CRMs for the green and digital transition.

7. POLICY RECOMMENDATIONS

This study recommends the following five types of policy action:

1. **Trade policy offers limited scope to increase the diversity of European suppliers**

The EU has a dependency on key components for most green energy and digital technologies, more than on raw materials as such. Access to raw materials will become relevant as the EU develops the industrial capacity to manufacture products from these raw materials, in line with the industrial policy objectives of the European Commission.

The EU has a high dependence on imports from China for many product groups necessary for the green and digital transitions. This is especially the case for the extraction and refining of REEs and permanent magnets, and for batteries and all the raw materials going into their production.

Tariffs on CRMs are already low. FTAs, like the update to the EU-Chile agreement and the EU-Australia FTA that is under negotiation therefore only provide limited scope for a targeted diversification of imports. Furthermore, to be compliant with the open multilateral WTO infrastructure, targeting 'friendly' countries would require negotiating a full Free-Trade Agreement, applying comprehensively to all product groups, not just raw materials of interest.

Non-trade policy tools, such as development assistance and international cooperation, appear as more effective options.

2. **The scope for monitoring criticality of products needed for the green and digital transition can be extended**

The current CRM assessment methodology is robust, but the scope should be broadened. Expanding the scope of criticality to traded product groups and sectors, as is anticipated in the Strategic Foresight Report, is feasible. Expected (near) future demand should be added as an important extra indicator for criticality.

Overall, further investments in data and information used in criticality assessment should be made. Additional data on existing stockpiles, for example managed by the wholesale sector, monitoring price developments of materials, and linking supply-use relations along the entire value chain would contribute to filling important gaps in the data infrastructure.

3. **Stockpiling of strategic product groups, and the embedded CRMs, can be boosted by policy incentives for the private sector**

This enables the strong and nascent industrial eco-system in the EU to mitigate the most severe short-term supply shocks in case of trade disruptions. The aim of stockpiling policy should be to ensure supply for 60-day of imports. Based on this assumption, estimates of the possible value of CRM stockpile range between EUR 6.45 billion and EUR 25.8 billion (2021 prices). This range depends on the breadth of the products considered. The lower bound focuses on raw materials, the upper bound uses a selection of around 300 traded product groups.

The preferred composition of product groups to be stockpiled are those product groups shaping the green and digital transition. This means that a volume of 8.6 million tonnes and a value of EUR 25.8 billion will be assumed as respectively the required size and value of the EU stockpile. Total costs, including operational costs and direct investments other than product acquisition are estimated at EUR 25.9 billion, indicating that acquisition costs are dominant in the total costs.

Start designing stockpiling policies using existing knowledge and capital from the private sector, especially manufacturing and wholesale sectors.

Companies could be incentivised to maintain, and be compensated for maintaining, larger stocks. Making use of the private sector intelligence would also guarantee that stockpiles of materials and goods fit with the broader industrial infrastructure (including capital stock and human resources), enabling the effective use of stockpiled materials in production.

4. **Professionals from the private sector are best placed to execute stockpiling operations, supported by financial incentives from public policy**

A designated EU body can monitor the size and shape of the incentivised stockpile and oversee distribution in a situation of stock draw: deploying the stockpile in case of emergency. Financial incentives can predominantly be aimed at covering risks, thereby ensuring a return on investment on additionally stocked products.

5. **Stockpiling policies should be connected to strategic measures that strengthen the resilience of the EU industrial capacity**

Examples of such measures are incentivising the build-up of capital stock, safeguarding tacit knowledge and human capital in manufacturing sectors and further expanding public strategic investments into the industrial eco-system.

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ANNEX 1: PRODUCT GROUPS IN SCOPE OF THIS STUDY

In this annex, a full overview of the statistical product groups from the Harmonised System/Combined Nomenclature are given. This selection of products is used in Chapter 2 to assess the trade position of the EU in the context of the green and digital transition and returns in Chapter 4 when the size of the stockpiles are discussed.

HS/CN code	Label in Harmonised System/Combined Nomenclature (HS/CN) trade classification, grouped per technology	Category reported in Chapter 2
250410	Graphite: natural, in powder or in flakes	graphite
250490	Graphite: natural, in other forms, excluding powder or flakes	graphite
251010	Natural calcium phosphates, natural aluminium calcium phosphates and phosphatic chalk: unground	phosphate_rock
251020	Natural calcium phosphates, natural aluminium calcium phosphates and phosphatic chalk: ground	phosphate_rock
251110	Barium sulphate (barytes): natural	baryte
251910	Magnesium carbonate (magnesite): natural	magnesium_ore
252800	Natural borates and concentrates thereof (whether or not calcined), but not including borates separated from natural brine: natural boric acid containing not more than 85 % of H3BO3 calculated on the dry weight	borates
252921	Fluorspar: containing by weight 97% or less of calcium fluoride	fluorspar
252922	Fluorspar: containing by weight more than 97% of calcium fluoride	fluorspar
260200	Manganese ores and concentrates, including ferruginous manganese ores and concentrates with a manganese content of 20% or more, calculated on the dry weight	manganese_ore
260300	Copper ores and concentrates	copper_ore
260400	Nickel ores and concentrates	nickel_ore
260500	Cobalt ores and concentrates	cobalt_ore
260600	Aluminium ores and concentrates	aluminium_ore
260800	Zinc ores and concentrates	zinc_ore
261000	Chromium ores and concentrates	chromium
261100	Tungsten ores and concentrates	tungsten_ore
261210	Uranium ores and concentrates	uranium_ore
261310	Molybdenum ores and concentrates: roasted	molybdenum_ore
261390	Molybdenum ores and concentrates: other than roasted	molybdenum_ore
261400	Titanium ores and concentrates	titanium_ore
261590	Niobium, tantalum, vanadium ores and concentrates	niobium_tantalum_vanadium
261710	Antimony ores and concentrates	antimony_ore
262011	Slag, ash and residues: (not from the manufacture of iron or steel), containing mainly zinc, hard zinc spelter	zinc_ore

HS/CN code	Label in Harmonised System/Combined Nomenclature (HS/CN) trade classification, grouped per technology	Category reported in Chapter 2
262019	Slag, ash and residues: (not from the manufacture of iron or steel), containing mainly zinc, other than hard zinc spelter	zinc_ore
262030	Slag, ash and residues: (not from the manufacture of iron or steel), containing mainly copper	copper_ore
262040	Slag, ash and residues: (not from the manufacture of iron or steel), containing mainly aluminium	aluminium_ore
262091	Slag, ash and residues: (not from the manufacture of iron or steel), containing antimony, beryllium, cadmium, chromium or their mixtures	chromium
280450	Boron: tellurium	tellurium
280461	Silicon: containing by weight not less than 99.99% of silicon	silicon
280469	Silicon: containing by weight less than 99.99% of silicon	silicon
280470	Phosphorus	phosphorus
280490	Selenium	selenium
280530	Earth-metals, rare: scandium and yttrium, whether or not intermixed or interalloyed	rare_earths
280910	Diphosphorus pentoxide	phosphorus
281212	Phosphorus oxychloride	phosphorus
281213	Phosphorus trichloride	phosphorus
281214	Phosphorus pentachloride	phosphorus
281390	Sulphides of non-metals, (excluding carbon): commercial phosphorus trisulphide	phosphorus
281610	Hydroxide and peroxide of magnesium	magnesium_ore
281640	Oxides, hydroxides and peroxides, of strontium or barium	strontium
281700	Zinc: oxide and peroxide	zinc_ore
281820	Aluminium oxide: other than artificial corundum	aluminium_ore
281830	Aluminium hydroxide	aluminium_ore
281910	Chromium trioxide	chromium
281990	Chromium oxides and hydroxides: excluding chromium trioxide	chromium
282010	Manganese dioxide	manganese_ore
282090	Manganese oxides: excluding manganese dioxide	manganese_ore
282200	Cobalt oxides and hydroxides: commercial cobalt oxides	cobalt_ore
282300	Titanium oxides	titanium_ore
282520	Lithium oxide and hydroxide	lithium
282540	Nickel oxides and hydroxides	nickel_ore
282550	Copper oxides and hydroxides	copper_ore
282570	Molybdenum oxides and hydroxides	molybdenum_ore

HS/CN code	Label in Harmonised System/Combined Nomenclature (HS/CN) trade classification, grouped per technology	Category reported in Chapter 2
282580	Antimony oxides	antimony_ore
282612	Fluorides: of aluminium	aluminium_ore
282731	Chlorides: of magnesium	magnesium_ore
282732	Chlorides: of aluminium	aluminium_ore
282735	Chlorides: of nickel	nickel_ore
282739	Chlorides: other than of ammonium, calcium, magnesium, aluminium and nickel	magnesium_ore
282741	Chloride oxides and chloride hydroxides: of copper	copper_ore
283321	Sulphates: of magnesium	magnesium_ore
283322	Sulphates: of aluminium	aluminium_ore
283324	Sulphates: of nickel	nickel_ore
283325	Sulphates: of copper	copper_ore
283522	Phosphates: of mono- or disodium, whether or not chemically defined	phosphate_rock
283524	Phosphates: of potassium, whether or not chemically defined	phosphate_rock
283525	Phosphates: calcium hydrogenorthophosphate (dicalcium phosphate), whether or not chemically defined	phosphate_rock
283526	Phosphates: of calcium n.e.c. in item no. 2835.25, whether or not chemically defined	phosphate_rock
283529	Phosphates: (other than of mono- or disodium, other than of potassium or of calcium hydrogenorthophosphate (dicalcium phosphate) and excluding other phosphates of calcium), whether or not chemically defined	phosphate_rock
283531	Polyphosphates: sodium triphosphate (sodium tripolyphosphate), whether or not chemically defined	phosphate_rock
283539	Polyphosphates: other than sodium triphosphate (sodium tripolyphosphate), whether or not chemically defined	phosphate_rock
283691	Carbonates: lithium carbonate	lithium
283692	Carbonates: strontium carbonate	strontium
284011	Borates: disodium tetraborate (refined borax), anhydrous	borates
284019	Borates: disodium tetraborate (refined borax), other than anhydrous	borates
284020	Borates: n.e.c. in heading no. 2840	borates
284030	Peroxoborates (perborates)	borates
284410	Uranium: natural uranium and its compounds, alloys, dispersions (including cermets), ceramic products and mixtures containing natural uranium or natural uranium compounds	uranium_ore
284420	Uranium: enriched in U235, plutonium, their compounds, alloys dispersions (including cermets), ceramic products and mixtures containing uranium enriched in U235, plutonium or compounds of these products	uranium

HS/CN code	Label in Harmonised System/Combined Nomenclature (HS/CN) trade classification, grouped per technology	Category reported in Chapter 2
284430	Uranium: depleted in U235, thorium, their compounds, alloys, dispersions (including cermets), ceramic products and mixtures containing uranium depleted in U235, thorium: compounds of these products	uranium
284610	Cerium compounds	rare_earths
284690	Compounds, inorganic or organic (excluding cerium), of rare-earth metals, of yttrium, scandium or of mixtures of these metals	rare_earths
285390	Phosphides, chemically defined or not, not ferrophosphorus: other inorganic compounds n.e.c. (including distilled, conductivity water and water of like purity): liquid air, rare gases removed or not: compressed air: amalgams, not precious metal amalgams	phosphorus
380110	Graphite: artificial	graphite
380120	Graphite: colloidal or semi-colloidal	graphite
380190	Graphite or other carbon based preparations: in the form of pastes, blocks, plates or other semi-manufactures	graphite
381511	Catalysts, supported: reaction initiators, reaction accelerators and catalytic preparations, with nickel or nickel compounds as the active substance, n.e.c. or included	fuel_cell_cath
381512	Catalysts, supported: reaction initiators, reaction accelerators and catalytic preparations, with precious metal or precious metal compounds as the active substance, n.e.c. or included	fuel_cell_cath
381519	Catalysts, supported: reaction initiators, reaction accelerators and catalytic preparations, with an active substance other than nickel or precious metals or their compounds, n.e.c. or included	fuel_cell_cath
381590	Reaction initiators, reaction accelerators and catalytic preparations, unsupported, n.e.c. or included	fuel_cell_cath
711011	Metals: platinum, unwrought or in powder form	platinum
711019	Metals: platinum, semi-manufactured	platinum
711021	Metals: palladium, unwrought or in powder form	palladium
711029	Metals: palladium, semi-manufactured	palladium
711031	Metals: rhodium, unwrought or in powder form	rhodium
711039	Metals: rhodium, semi-manufactured	rhodium
711041	Metals: iridium, osmium, ruthenium, unwrought or in powder form	iridium_ruthenium
711049	Metals: iridium, osmium, ruthenium, semi-manufactured	iridium_ruthenium
740100	Copper mattes: cement copper (precipitated copper)	copper
740200	Copper: unrefined, copper anodes for electrolytic refining	copper
740311	Copper: refined, unwrought, cathodes and Sections of cathodes	copper
740312	Copper: refined, unwrought, wire-bars	copper
740313	Copper: refined, unwrought, billets	copper
740319	Copper: refined, unwrought, n.e.c. in item no. 7403.1	copper
740321	Copper: copper-zinc base alloys (brass) unwrought	copper

HS/CN code	Label in Harmonised System/Combined Nomenclature (HS/CN) trade classification, grouped per technology	Category reported in Chapter 2
740322	Copper: copper-tin base alloys (bronze) unwrought	copper
740329	Copper: copper alloys n.e.c. in heading no. 7403 (other than master alloys of heading no. 7405)	copper
740400	Copper: waste and scrap	copper
740500	Copper: master alloys of copper	copper
740610	Copper: powders of non-lamellar structure	copper
740620	Copper: powders of lamellar structure, flakes	copper
740710	Copper: bars, rods and profiles, of refined copper	copper
740721	Copper: bars, rods and profiles, of copper-zinc base alloys (brass)	copper
740729	Copper: bars, rods and profiles, of copper alloys (other than copper-zinc base alloys)	copper
740811	Copper: wire, of refined copper, of which the maximum cross-Sectional dimension exceeds 6mm	copper
740819	Copper: wire, of refined copper, of which the maximum cross-Sectional dimension is 6mm or less	copper
740821	Copper: wire, of copper-zinc base alloys (brass)	copper
740822	Copper: wire, of copper-nickel base alloys (cupro-nickel) or copper-nickel-zinc base alloys (nickel silver)	copper
740829	Copper: wire, of copper alloys (other than copper-zinc base alloys, copper-nickel base alloys or copper-nickel-zinc base alloys)	copper
740911	Copper: strip, of a thickness exceeding 0.15mm, of refined copper, in coils	copper
740919	Copper: plates and sheets, of a thickness exceeding 0.15mm, of refined copper, not in coils	copper
740921	Copper: strip, of a thickness exceeding 0.15mm, of copper-zinc base alloys (brass), in coils	copper
740929	Copper: plates and sheets, of a thickness exceeding 0.15mm, of copper-zinc base alloys (brass), not in coils	copper
740931	Copper: strip, of a thickness exceeding 0.15mm, of copper-tin base alloys (bronze), in coils	copper
740939	Copper: plates and sheets, of a thickness exceeding 0.15mm, of copper-tin base alloys, not in coils	copper
740940	Copper: plates, sheets and strip, of a thickness exceeding 0.15mm, of copper-nickel base alloys (cupro-nickel) or copper-nickel-zinc base alloys (nickel silver)	copper
740990	Copper: plates, sheets and strip, of a thickness exceeding 0.15mm, of copper alloys (other than copper-zinc base alloys, copper-tin base alloys, copper-nickel base alloys or copper-nickel-zinc base alloys)	copper
741011	Copper: foil, not backed, of a thickness not exceeding 0.15mm, of refined copper	copper
741012	Copper: foil, not backed, of a thickness not exceeding 0.15mm, of copper alloys	copper

HS/CN code	Label in Harmonised System/Combined Nomenclature (HS/CN) trade classification, grouped per technology	Category reported in Chapter 2
741021	Copper: foil, backed with paper, paperboard, plastics or similar backing material, of a thickness (excluding any backing) not exceeding 0.15mm, of refined copper	copper
741022	Copper: foil, backed with paper, paperboard, plastics or similar backing material, of a thickness (excluding any backing) not exceeding 0.15mm, of copper alloys	copper
741110	Copper: tubes and pipes, of refined copper	copper
741121	Copper: tubes and pipes, of copper-zinc base alloys (brass)	copper
741122	Copper: tubes and pipes, of copper-nickel base alloys (cupro-nickel) or copper-nickel-zinc base alloys (nickel silver)	copper
741129	Copper: tubes and pipes, of copper alloys (other than copper-zinc, copper-nickel base alloys (cupro-nickel) or copper-nickel-zinc base alloys (nickel-silver))	copper
741210	Copper: tube or pipe fittings (e.g. couplings, elbows, sleeves) of refined copper	copper
741220	Copper: tube or pipe fittings (e.g. couplings, elbows, sleeves) of copper alloys	copper
741300	Copper: stranded wire, cables, plaited bands and the like, not electrically insulated	copper
741510	Copper: nails and tacks, drawing pins, staples and similar articles of copper, or of iron or steel with copper heads	copper
741521	Copper: washers, (including spring washers), not threaded	copper
741529	Copper: rivets, cotters, cotter-pins and similar articles, not threaded	copper
741533	Copper: screws, bolts and nuts, threaded	copper
741539	Copper: articles n.e.c. in heading no. 7415	copper
741810	Copper: table, kitchen or other household articles and parts thereof: pot scourers and scouring or polishing pads, gloves and the like	copper
741820	Copper: sanitary ware and parts thereof	copper
741910	Copper: chain and parts thereof	copper
741991	Copper: cast, moulded, stamped or forged, but not further worked	copper
741999	Copper: articles n.e.c. in heading no. 7419	copper
750110	Nickel: nickel mattes	nickel
750120	Nickel: oxide sinters and other intermediate products of nickel metallurgy	nickel
750210	Nickel: unwrought, not alloyed	nickel
750220	Nickel: unwrought, alloys	nickel
750300	Nickel: waste and scrap	nickel
750400	Nickel: powders and flakes	nickel
750511	Nickel: bars, rods and profiles, not alloyed	nickel
750512	Nickel: bars, rods and profiles, of nickel alloys	nickel

HS/CN code	Label in Harmonised System/Combined Nomenclature (HS/CN) trade classification, grouped per technology	Category reported in Chapter 2
750521	Nickel: wire, not alloyed	nickel
750522	Nickel: wire, of nickel alloys	nickel
750610	Nickel: plates, sheets, strip and foil, not alloyed	nickel
750620	Nickel: plates, sheets, strip and foil, of nickel alloys	nickel
750711	Nickel: tubes and pipes, not alloyed	nickel
750712	Nickel: tubes and pipes, of nickel alloys	nickel
750720	Nickel: tube and pipe fittings	nickel
750810	Nickel: cloth, grill and netting, of nickel wire	nickel
750890	Nickel: articles thereof n.e.c. in item no. 7508.1	nickel
760110	Aluminium: unwrought, (not alloyed)	aluminium
760120	Aluminium: unwrought, alloys	aluminium
760200	Aluminium: waste and scrap	aluminium
760310	Aluminium: powders of non-lamellar structure	aluminium
760320	Aluminium: powders of lamellar structure, flakes	aluminium
760410	Aluminium: (not alloyed), bars, rods and profiles	aluminium
760421	Aluminium: alloys, hollow profiles	aluminium
760429	Aluminium: alloys, bars, rods and profiles, other than hollow	aluminium
760511	Aluminium: (not alloyed), wire, maximum cross-Sectional dimension exceeds 7mm	aluminium
760519	Aluminium: (not alloyed), wire, maximum cross-Sectional dimension is 7mm or less	aluminium
760521	Aluminium: alloys, wire, maximum cross-Sectional dimension exceeding 7mm	aluminium
760529	Aluminium: alloys, wire, maximum cross-Sectional dimension is 7mm or less	aluminium
760611	Aluminium: plates, sheets and strip, thickness exceeding 0.2mm, (not alloyed), rectangular (including square)	aluminium
760612	Aluminium: plates, sheets and strip, thickness exceeding 0.2mm, alloys, rectangular (including square)	aluminium
760691	Aluminium: plates, sheets and strip, thickness exceeding 0.2mm, not alloyed, (not rectangular or square)	aluminium
760692	Aluminium: plates, sheets and strip, thickness exceeding 0.2mm, alloys, (not rectangular or square)	aluminium
760711	Aluminium: foil, (not backed), rolled (but not further worked), of a thickness not exceeding 0.2mm	aluminium
760719	Aluminium: foil, (not backed), of a thickness not exceeding 0.2mm, not rolled	aluminium
760720	Aluminium: foil, backed with paper, paperboard, plastics or similar backing materials, of a thickness (excluding any backing) not exceeding 0.2mm	aluminium

HS/CN code	Label in Harmonised System/Combined Nomenclature (HS/CN) trade classification, grouped per technology	Category reported in Chapter 2
760810	Aluminium: tubes and pipes, not alloyed	aluminium
760820	Aluminium: tubes and pipes, alloys	aluminium
760900	Aluminium: tube or pipe fittings (e.g. couplings, elbows, sleeves)	aluminium
761010	Aluminium: structures (excluding prefabricated buildings of heading no. 9406) and parts of structures, doors, windows and their frames and thresholds for doors	aluminium
761090	Aluminium: structures (excluding prefabricated buildings of heading no. 9406) and parts of structures, n.e.c. in heading no. 7610, plates, rods, profiles, tubes and the like	aluminium
761100	Aluminium: reservoirs, tanks, vats and similar containers, for material (not compressed or liquefied gas), of a capacity over 300l, whether or not lined, not fitted with mechanical/thermal equipment	aluminium
761210	Aluminium: collapsible tubular containers, for any material, (not compressed or liquefied gas), 300l capacity or less, whether or not lined, not fitted with mechanical/thermal equipment	aluminium
761290	Aluminium: casks, drums, cans, boxes and the like for any material (not compressed or liquefied gas), 300l capacity or less, whether or not lined or heat-insulated, no mechanical or thermal equipment	aluminium
761300	Aluminium: containers for compressed or liquefied gas	aluminium
761410	Aluminium: stranded wire, cables, plaited bands and the like, (not electrically insulated), with steel core	aluminium
761490	Aluminium: stranded wire, cables, plaited bands and the like, (not electrically insulated), other than steel core	aluminium
761510	Aluminium: table, kitchen or other household articles and parts thereof: pot scourers and scouring or polishing pads, gloves and the like	aluminium
761520	Aluminium: sanitary ware and parts thereof	aluminium
761610	Aluminium: nails, tacks, staples (other than those of heading no. 8305), screws, bolts, nuts, screw hooks, rivets, cotters, cotter-pins, washers and similar articles	aluminium
761691	Aluminium: cloth, grill, netting and fencing, of aluminium wire	aluminium
761699	Aluminium: articles n.e.c. in heading 7616	aluminium
790111	Zinc: unwrought, (not alloyed), containing by weight 99.99% or more of zinc	zinc
790112	Zinc: unwrought, (not alloyed), containing by weight less than 99.99% of zinc	zinc
790120	Zinc: unwrought, alloys	zinc
790200	Zinc: waste and scrap	zinc
790310	Zinc dust	zinc
790390	Zinc: powders and flakes	zinc
790400	Zinc: bars, rods, profiles and wire	zinc
790500	Zinc: plates, sheets, strip and foil	zinc
790700	Zinc: articles n.e.c. in Chapter 79	zinc

HS/CN code	Label in Harmonised System/Combined Nomenclature (HS/CN) trade classification, grouped per technology	Category reported in Chapter 2
810110	Tungsten (wolfram): articles thereof, including waste and scrap, powders	tungsten
810194	Tungsten (wolfram): unwrought, including bars and rods obtained simply by sintering	tungsten
810196	Tungsten (wolfram): wire	tungsten
810197	Tungsten (wolfram): waste and scrap	tungsten
810199	Tungsten (wolfram): articles n.e.c. in heading no. 8101	tungsten
810210	Molybdenum: articles thereof, including waste and scrap, powders	molybdenum
810294	Molybdenum: unwrought, including bars and rods obtained simply by sintering	molybdenum
810295	Molybdenum: bars and rods, other than those obtained simply by sintering, profiles, plates, sheets, strip and foil	molybdenum
810296	Molybdenum: wire	molybdenum
810297	Molybdenum: waste and scrap	molybdenum
810299	Molybdenum: articles n.e.c. in heading no. 8102	molybdenum
810320	Tantalum: unwrought, including bars and rods obtained simply by sintering, powders	tantalum
810330	Tantalum: waste and scrap	tantalum
810390	Tantalum: articles n.e.c. in heading no. 8103	tantalum
810411	Magnesium: unwrought, containing at least 99.8% by weight of magnesium	magnesium
810419	Magnesium: unwrought, containing less than 99.8% by weight of magnesium	magnesium
810420	Magnesium: waste and scrap	magnesium
810430	Magnesium: raspings, turnings and granules, graded according to size, powders	magnesium
810490	Magnesium: articles n.e.c. in heading no. 8104	magnesium
810520	Cobalt: mattes and other intermediate products of cobalt metallurgy, unwrought cobalt, powders	cobalt
810530	Cobalt: waste and scrap	cobalt
810590	Cobalt: articles n.e.c. in heading no. 8105	cobalt
810600	Bismuth: articles thereof, including waste and scrap	bismuth
810820	Titanium: unwrought, powders	titanium
810830	Titanium: waste and scrap	titanium
810890	Titanium: other than unwrought, n.e.c. in heading no. 8108	titanium
811010	Antimony and articles thereof: unwrought antimony, powders	antimony
811020	Antimony: waste and scrap	antimony
811090	Antimony and articles thereof: wrought, other than waste and scrap	antimony

HS/CN code	Label in Harmonised System/Combined Nomenclature (HS/CN) trade classification, grouped per technology	Category reported in Chapter 2
811100	Manganese: articles thereof, including waste and scrap	manganese
811212	Beryllium and articles thereof: unwrought beryllium, powders	berryllium
811213	Beryllium: waste and scrap	berryllium
811219	Beryllium and articles thereof: wrought other than waste and scrap	berryllium
811292	Gallium, germanium, hafnium, indium, niobium (columbium), rhenium and vanadium: articles thereof, unwrought, including waste and scrap, powders	gallium_germanium_hafnium_indium_niobium_rhenium_vanadium
811299	Gallium, germanium, hafnium, indium, niobium (columbium), rhenium and vanadium: articles thereof, other than unwrought including waste and scrap and powders	gallium_germanium_hafnium_indium_niobium_rhenium_vanadium
840110	Nuclear reactors	nuclear_reactor
840120	Machinery and apparatus: for isotopic separation, and parts thereof	nuclear_parts
840130	Fuel elements (cartridges): non-irradiated	nuclear_parts
840140	Nuclear reactors: parts thereof	nuclear_parts
840690	Turbines: parts of steam and other vapour turbines	blades
848340	Gears and gearing: (not toothed wheels, chain sprockets and other transmission elements presented separately): ball or roller screws: gear boxes and other speed changers, including torque converters	gear_box
848390	Transmission components: toothed wheels, chain sprockets and other transmission elements presented separately: parts	gear_box
848790	Machinery parts: not containing electrical connectors, insulators, coils, contacts or other electrical features, n.e.c. in Chapter 84, other than ships' or boats' propellers and blades therefor	gear_box
850110	Electric motors: of an output not exceeding 37.5W	elec_motor
850120	Electric motors: universal AC/DC of an output exceeding 37.5W	elec_motor
850131	Electric motors and generators: DC, of an output not exceeding 750W	elec_motor
850132	Electric motors and generators: DC, of an output exceeding 750W but not exceeding 75kW	elec_motor
850133	Electric motors and generators: DC, of an output exceeding 75kW but not exceeding 375kW	elec_motor
850134	Electric motors and generators: DC, of an output exceeding 375kW	elec_motor
850140	Electric motors: AC motors, single-phase	elec_motor
850151	Electric motors: AC motors, multi-phase, of an output not exceeding 750W	elec_motor
850152	Electric motors: AC motors, multi-phase, of an output exceeding 750W but not exceeding 75kW	elec_motor
850153	Electric motors: AC motors, multi-phase, of an output exceeding 75kW	elec_motor
850161	Generators: AC generators, (alternators), of an output not exceeding 75kVA	elec_motor
850162	Electric generators: AC generators, (alternators), of an output exceeding 75kVA but not exceeding 375kVA	elec_motor

HS/CN code	Label in Harmonised System/Combined Nomenclature (HS/CN) trade classification, grouped per technology	Category reported in Chapter 2
850163	Electric generators: AC generators, (alternators), of an output exceeding 375kVA but not exceeding 750kVA	elec_motor
850164	Electric generators: AC generators, (alternators), of an output exceeding 750kVA	elec_motor
850231	Electric generating sets: wind-powered, (excluding those with spark-ignition or compression-ignition internal combustion piston engines)	generators
850440	Electrical static converters	fuel_cell
850511	Magnets: permanent magnets and articles intended to become permanent magnets after magnetisation, of metal	perm_magnets
850519	Magnets: permanent magnets and articles intended to become permanent magnets after magnetisation, other than of metal	perm_magnets
850520	Magnets: electro-magnetic couplings, clutches and brakes	magnets_other
850590	Magnets: electro-magnets, holding devices and parts n.e.c. in heading no. 8505	magnets_other
850610	Cells and batteries: primary, manganese dioxide	batteries_other
850630	Cells and batteries: primary, mercuric oxide	batteries_other
850640	Cells and batteries: primary, silver oxide	batteries_other
850650	Cells and batteries: primary, lithium	batteries_lithium
850660	Cells and batteries: primary, air-zinc	batteries_other
850680	Cells and batteries: primary, (other than manganese dioxide, mercuric oxide, silver oxide, lithium or air-zinc)	batteries_other
850690	Cells and batteries: primary, parts thereof	batteries_other
850710	Electric accumulators: lead-acid, of a kind used for starting piston engines, including separators, whether or not rectangular (including square)	batteries_other
850720	Electric accumulators: lead-acid, (other than for starting piston engines), including separators, whether or not rectangular (including square)	batteries_other
850730	Electric accumulators: nickel-cadmium, including separators, whether or not rectangular (including square)	batteries_other
850740	Electric accumulators: nickel-iron, including separators, whether or not rectangular (including square)	batteries_other
850750	Electric accumulators: nickel-metal hydride, including separators, whether or not rectangular (including square)	batteries_other
850760	Electric accumulators: lithium-ion, including separators, whether or not rectangular (including square)	batteries_lithium
850780	Electric accumulators: other than lead-acid, nickel-cadmium, nickel-iron, nickel-metal hydride and lithium-ion, including separators, whether or not rectangular (including square)	fuel_cell
850790	Electric accumulators: parts n.e.c. in heading no. 8507	batteries_other
853710	Boards, panels, consoles, desks and other bases: for electric control or the distribution of electricity, (other than switching apparatus of heading no. 8517), for a voltage not exceeding 1000 volts	control_panels

HS/CN code	Label in Harmonised System/Combined Nomenclature (HS/CN) trade classification, grouped per technology	Category reported in Chapter 2
853890	Electrical apparatus: parts suitable for use solely or principally with the apparatus of heading no. 8535, 8536 or 8537	control_panels
854140	Electrical apparatus: photosensitive, including photovoltaic cells, whether or not assembled in modules or made up into panels, light-emitting diodes (LED)	pv_cells
854330	Electrical machines and apparatus: for electroplating, electrolysis or electrophoresis	electrolysers
870240	Vehicles: public transport type (carries 10 or more persons, including driver), with only electric motor for propulsion, new or used	e_trucks
870380	Vehicles: with only electric motor for propulsion	EVs
870390	Vehicles: for transport of persons (other than those of heading no. 8702) n.e.c. in heading no. 8703	EVs

ANNEX 2: ADDITIONAL RELEVANT POLICY CONTEXT

The most essential aspects of the policy context are discussed in Section 1.1. There are however many policy documents and fields that are relevant to the scope of this study. These additional context can be found in this annex.

Action plan on Critical raw materials

In 2008, the EU already recognized fundamental changes in global raw material markets, resulting in the first Raw Material Initiative (European Commission 2008a). The latest major policy document that testifies the relevance of managing CRM supply to the EU is the Action Plan on Critical Raw Materials from September 2020 (European Commission 2020a. A Critical Raw Material Act is being prepared, aiming to secure the EU CRM supply for the green and digital transition. The Commission's adoption of the CRM Act is planned for the first quarter of 2023.

The Action Plan on Critical Raw Materials from September 2020 (European Commission 2020a), is the latest major policy document on European strategy for critical raw materials. It concludes that EU institutions, national and sub-national authorities as well as companies should become much more agile and effective in securing a sustainable supply of critical raw materials. The related report from the Joint Research Centre (European Commission 2020b) clearly showed the relation between key-products/key-technology fields and the raw materials that are critical to these technologies.

Another crucial contribution of this report was an estimate of demand for products containing CRM in 2030 and 2050, acknowledging that foresight studies were essential for an effective CRM assessment and needed to be done frequently and periodically (HCSS 2020). Future demand will be implemented in the next version of the Study on the EU's list of Critical Raw Materials (European Commission 2020c). In 2020, the 4th version of the study was published. An important objective of the list is to analyse the production, key trends, trade flows and barriers of the raw materials with the aim to identify potential bottlenecks and supply risks throughout the value chain.

Industrial strategy

Industrial policy is a policy field with a significant historical track record. The objective of Industrial policy aims to secure framework conditions favourable to industrial competitiveness. It interacts with other EU policies such as those relating to trade, the internal market, research and innovation, employment, environmental protection and public health and aims for horizontal (i.e. not sector-specific) structural improvements. Furthermore, the relevance and pertinence of industrial policies are acknowledged by mainstream economists and political leaders from all sides of the ideological spectrum (Stiglitz et al. 2013).

The latest EU industrial strategy was launched in March 2020 and discussed products containing CRM supply in the context of sustainability and strategic goals for 2030 and later. The 2020 strategy was provided with an update (European Commission 2021a) a year later to adapt to a world that had witnessed the effects of a COVID-19 pandemic on global supply chains. The Commission proposed public policy measures that can support industry's efforts to address these dependencies and to develop strategic capacity needs: diversifying supply and demand relying on different trading partners whenever possible. Most significantly, it refers to stockpiling, the dominant policy option researched in this report. The update also referred to identifying measures to reinforce the EU position in global value chains. Lastly, the update featured an analysis of strategic dependency (European Commission 2021b). The analysis was done at a high level of detail (a "granularity" of over 5000 product groups) and identified 137 product groups with a higher risk of supply disruption. It also exemplified the necessary outreach for public decision makers to support supply-chain decisions in a corporate setting.

A final report on the Implementation of the Updated New Industrial Strategy has been adopted by the European Parliament (ITRE 2022), with a focus on aligning spending to policy. Therein it claims that the EU should not be dependent on non-EU countries for products and technologies that are essential to the EU economy of the future. The report stresses that the EU needs to regain a strong position in crucial global value chains and secure the supply of critical materials in times of crisis (ITRE 2022). It states that public procurement is an essential instrument for national and economic security and for supporting the uptake of and demand for clean products. It suggest a legitimate basis for the Commission to review public procurement and competition rules where needed. Interestingly, it suggests adapted public procurement rules- that might be relevant for stockpiling options.

The European Fund for Strategic Investment (EFIS), established under the Investment Plan for Europe enabled additional investment for 315 billion EUR between 2015 and 2017 in digital infrastructure, energy, research, etc. The current ESIF aims to trigger more than €372 billion in additional investment and includes, among others, investment for European regional development and Cohesion funds. Important Projects of Common European Interest (IPCEIs) provide a State Aid compatibility basis under Art. 107(3)(b) TFEU under which Member States can jointly design large cross-border projects to pursue EU strategic goals. The InvestEU Programme, designed to give an additional boost to investment, innovation and job creation in Europe over the period 2021-27, should also be considered. Stemming partly from the sizeable NextGeneration EU economic recovery package to support the EU Member States, it will be added to the EU 2021–2027 long-term multiannual financial framework (MFF) of EUR 1.211 trillion (EUR 1.074 trillion in 2018 prices). The NextGeneration EU package is expected to amount to EUR 806.9 billion (EUR 750 billion in 2018 prices) between 2021 to 2027.

Internal Market and Consumer Protection (IMCO)

The Annual Single Market (ASM) report of 2021 (European Commission 2020g) was among the first evaluations of the turbulent developments of the public response to the outbreak of the COVID-19 pandemic. The report reiterates the importance of measures already identified in the March 2020 Industrial Strategy package. One of the significant findings in the report was that existing EU crisis governance mechanisms are not fully effective at coordinating national responses. The emergency situations proved able to distort trade, innovation, exacerbate product shortages in other Member States , and more generally weaken the collective bargaining power of the EU.

The ASM showed that there are a number of possibilities for Member States to provide equity support under national support schemes to strengthen the solvency and growth of innovative SMEs and mid-caps in line with State Aid rules, including the State Aid Temporary Framework.

One of the lessons learnt from the pandemic as indicated in the report is that: *"…the availability of essential products in the EU and a common approach on stockpiling measures for products that are vital during crises would have helped"*. Also, the risks of uncoordinated stockpiling are referred to in the document: *"Furthermore, the intra-EU export restrictions on products were subject to frequent adjustments exacerbating legal uncertainty and triggering national stockpiling responses with further negative effects."* These quotes indicate that under certain circumstances stock-pilling might be valuable to mitigate risks.

This echoes a quote from the Single Market Emergency Act: *"Commission is identifying public policy measures that can support industry's efforts to address dependencies and to develop strategic capacity needs: diversifying supply and demand relying on different trading partners whenever possible, but also stockpiling and acting autonomously whenever necessary."*

The quotes from these reports indicate that there is an urging question whether stock piling would be relevant in the green and digital transition. Therefore stockpiling is extensively addressed in this report.

Another policy initiative that neatly combines the functioning of the internal market and consumer protection is the proposal for a new regulatory framework on batteries (COM 2020/798). It aims to ensure that there are robust sustainability, safety and performance requirements for all batteries placed on the EU market. Noteworthy, this document demonstrates a traditional focus on safety but not on strategic aspects that will improve the security of supply of all kinds of batteries relevant for the EU green transition.

Safeguarding strategic autonomy

The concept of open strategic autonomy has gained momentum in European politics in the wake of the COVID-19 pandemic. It refers to the EU's ability to chart its own course in line with its interests and values. The most recent example is the Versailles declaration, that states that the EU will secure its supply by means of strategic partnerships, exploring strategic stockpiling[65]. Some argue that being strategically autonomous would enable a region such as the EU to be a global leader in sustainability and to be assertive against unfair and coercive practices (EPRS 2022a). The prefix "open" is intended to point at the will to maintain the principles of globalisation and to remain open to global trade and investment for the EU economy.

An "Observatory of critical technologies" is being prepared by the Commission in line with the Action Plan on synergies. This Action Plan (the 'Three-Point Belt Plan') has three objectives, namely enhancing complementarity between relevant EU programmes, promoting spin-offs from investments in investments in manufacturing space & defence products and promoting "spin-ins" where civil research can infuse defence & space (European Commission 2021e). The Observatory will monitor their potential applications and related value chains that need to be securitized. The Commission, based on data of the Observatory, will present a classified report on critical technologies. It is remarkable as well as logical that such a monitor on risks associated with strategic dependencies affecting security, space and defence will not be available in the public sphere, but it should be available to several decision makers and representatives. The first edition should be ready by the end of 2022, to be continued every two years thereafter.

The latest annual "Strategic foresight report" was presented in 2022 (Muench et al. 2022). It focused on resilience across four dimensions: green, digital, social and economic, and geopolitical. Building on the previous editions, the 2022 report focused on the EU's open strategic autonomy as part of the geopolitical dimension of resilience. Yet, the importance of raw materials have taken a backseat in the most recent edition. The 2021 edition aspired to monitor securing and diversifying supply of critical raw materials. The 2022 edition does not consider raw materials a key requirement for the green and digital transition and trustingly adopts a view that there is "already a clear trend towards less demand for raw materials".

The updated Industrial Strategy also announced a second stage of in-depth review of potential strategic dependencies. A new staff working document (European Commission 2022c) reports on progress made in addressing the strategic dependencies identified in the first round (raw materials, active pharmaceutical ingredients, li-ion batteries, clean hydrogen, semiconductors and cloud and edge computing).

A final example of expressions of strategic autonomy is exemplified by a speech by Vice-President Šefčovič to the European Battery Alliance (23 February 2022).

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[65] The meeting of the heads of state on the 10th and 11th of March can be found here: https://www.consilium.europa.eu/media/54773/20220311-versailles-declaration-en.pdf.

He said "*I am not overstating it when I say that securing supplies of critical raw materials is a strategic security question for Europe. I would say it is now or never. Europe has close to 260 deposits of key battery materials as well as the state-of-the-art technologies and expertise necessary for their responsible and sustainable exploration. It is necessary to urgently: [...] enhance our capacities to monitor global supply chains, helping us anticipate potential crises and to act, for instance through stockpiling*. The statement suggests that strategic autonomy is prioritised over cost-efficiency.

ANNEX 3: BACKGROUND OF INDEPENDENT ASSESSMENT

Further detail on the supply risk indicators of the current assessment

Economic Importance (EI) and Supply Risk (SR) are the two overall factors that determine the criticality status.

Economic importance

For economic importance, the GVA and raw material application share (%) is allocated to all sectors, resulting in a sum of all these multiplications. See Table 23 for a simplified example.

Table 23: Example of the core of the economic importance (EI) calculation

Sector	Sector Gross Value Added (EUR billion)	Share of Raw Material X being applied in sector (%)	Score
Sector 1	50	25	0.25 x 50 = 12.5
Sector 2	150	15	0.15 x 150 = 22.5
Sector 3	180	60	0.6 x 180 = 108
Economic importance Raw Material X (unscaled and without economic substitution coefficient)			143

Source: Authors' own elaboration.

Additionally, for each application a substitution factor is included, based on similarity in price and technological performance. This substitution factor helps to understand whether the impact on the economy of a supply disruption of a material is severe or if there is a comparable substitute in terms of economic qualities, available within a period of a few weeks. The availability of an economically relevant substitute lowers the economic importance of the initial material.

Supply risk

The global supply concentration is determined by using the Herfindahl-Hirschmann index (HHI). It is calculated by squaring the market share (in %) of each producing country and then summing the resulting numbers. It can range from close to zero to 10,000 (one single country producing 100% of a commodity). The HHI indicates how well the supply is distributed over supplying countries. It is considered to be a higher risk when only one or two countries supply to Europe or when the main supply comes from one specific country, even when there are some other smaller suppliers available.

The supply risk is considered greater in case the governance of the country (given by the World Governance Indicator (WGI)) is considered a liability for reliable supply of materials. The indicators take into account factors such as Voice and Accountability, Political Stability and Absence of Violence/Terrorism, Government Effectiveness, Regulatory Quality, Rule of Law and Control of Corruption. The existence of Trade restrictions (such as published by the OECD) are used as an additional factor to assess the 'reliability' of the source country.

The degree to which the demand of the EU is dependent on import from non-EU countries is captured in the import reliance (IR) indicator. This indicates if the EU is able to source the material domestically or not.

If the EU can fulfil a part of the raw material demand by secondary material i.e. recycled materials, this lowers the supply risk of that material. Therefore, the End-of-Life Recycling Input Rate (EOL_{RIR}) is used in the calculation of the SR. It is important to note that the secondary material should be able to replace the demand for the primary material in terms of technical performance i.e. quality.

The availability of material-for-material substitutes is seen to lower the supply risk of a material at EU level. Therefore, an expert judgement is given to the availability of substitutes. To determine whether a material can function as a substitute when assessing supply risk, three factors are considered: whether the substitute material is a critical material itself; the global market size of the substitute material compared to the candidate material and the fact whether a substitute material is a by-product of another metal.

Options for an independent CRM assessment

The unprecedented global and/or geopolitical events of the last 30 months require to examine the EC CRM assessment methodology and to explore whether the methodology is able to address the impact of these recent events. Such a discussion is a necessary prerequisite towards an independent CRM assessment and towards expanding the current methodology to include such aspects.

For the economic importance, we discuss the following aspects:

- Sectors and product allocation requires detailed data about their application in order to assess their economic importance;
- Future economic importance is societal importance; and
- The need to assess the entire value chain.

For the supply risk, we discuss:

- Environmental or societal pressures; and
- Timescales;

Economic Importance: sectors and product allocation requires detailed data about application in order to assess economic importance

As indicated in the paragraph above, the Economic Importance (EI) is based on the allocations of a raw material to certain economic sectors. To be able to assign a certain raw material to the sectors in more detail, the Classification of Products by Activity (CPA) classes are used. These are directly linked to Nomenclature statistique des Activités économiques dans la Communauté Européenne (NACE) sectors. The raw materials are allocated to the NACE 2-digit, assuming the available data does not allow to assess economic sectors in more detail.

The EI assessment is based on the proportion of a raw material used in a specific sector: when a large share of a material is used in a sector with a high GVA, this positively affects the EI of that material. However, the share of the use of a specific material is not related to the importance of that material for the sector in case the data only aggregated sectors at 2-digit level (like “chemical industry” or “other transport equipment”). In the way the current methodology is applied (with aggregated data), the EI is less influenced when only a small share of a material is assigned to a certain sector, than if a large share is used in that sector. Of course, even when a minor share of a raw material is used in a specific sector, it may well be that the material is crucial for the whole sector to operate. However, the data should indicate which specific aspect of that sector and the associated manufactured products are affected. This allocation is difficult to make because detailed (beyond NACE 2-digit level) insights in the application of materials is often not available.

The number of sectors in which the material is used does not significantly influence the economic importance (EI). This is the actual economic contribution of a raw material to the entire 2-digit sector is not considered. The result is a "relative" EI, that takes the view relative to the material instead of the entire economy. When all materials have a total share, which adds up to a 100%, it is of relatively little impact if the shares are allocated to one or many sectors. In case publicly available data would allow to allocate a material to hundreds or thousands of sectors/products, the EI would become more "absolute", since a raw material will no longer be attributed to sectors/products that don't actually use the raw material. Therefore, the insight in EI could be improved by considering explicitly the total amount of detailed product groups in which raw materials are used.

The RMIS agenda (Hamor et al. 2021) anticipates implicitly to assess product group criticality. The product group scoping is present in aspirations to expand the knowledge base of responsible sourcing, criticality and resilience. Specifically, the trade Chapter in raw materials' profile would enable researchers to assess product group criticality.

Economic importance: future economic importance is societal importance

The current methodology is solely focussing on the current economic importance of the European industry and its vulnerability for raw materials availability. Future demand is purposely left out of the methodology, to separate facts from modelling interpretations. However, a consensus is forming in the research community about the relevance of future demand, its potential implications for the economy and society at large and its resulting dynamic impact on CRM criticality (Aguilar et al. 2022).

This way of assessing criticality is most suitable in an environment where the demand for materials is quite stable. However, the current economy is now going through different transitions, notably the digital and energy transition, for which there are clear indications of sharply rising demand of certain raw materials. These transitions do not only require a change towards certain products, but more profound (societal and economic) systemic changes. This increases the importance of properly understanding whether materials needed for these transitions can sustainably be supplied in the future.

The RMIS agenda (Hamor et al. 2021) anticipates continuity in the field of foresight studies an estimating future demand. The experimental data from the International sourcing statistics (ISS) on Eurostat is another example of the direction that the new public data source may take.

Economic importance: the need to assess the entire value chain and refer to "products containing CRM"

As indicated in the previous Chapter, the CRM assessment puts raw materials in focus, whereas the industrial economic processes ultimately result in final products that contain these (critical) raw materials. Based on the current CRM assessment, we can distinguish between ores and concentrates.

It is important to note that the manufacturing steps to get from materials to an assembled process need resources such as capacity and knowledge being present as well. This 'assembly line' often consists of multiple steps across multiple countries. This leads to a particular conundrum with respect to an assessment solely based on critical raw materials for the EU. As concluded in Chapter 2, some products needed for the energy transition are not, or only partially, manufactured in the EU. Focussing solely on the import of materials would be the same as focussing on the import of bricks without having the tools to build a house.

In the current criticality assessment, this leads to the following issue. When looking into a material, it is unclear to what part of the manufacturing process it should be attributed. At this moment, a material (e.g. 'natural rubber') should be attributed to a specific sector (e.g. 'automotive manufacturing' or 'rubber products').

The fact that it is unclear where a specific material should be attributed can lead to overestimating the economic importance and/or overlooking the presence or absence of certain parts of the supply chain or indeed the entire eco-system.

The absence of the availability of worldwide production data of product groups along the value chain is important reason not to assess economic importance of products further down the supply chain.

Supply risk: environmental or societal pressures

The methodology does not consider supply risk factors that are environmental or socially determined. In the past, both the Human Development Index (HDI) and the Environmental Performance Index (EPI) have been considered as factors. The EPI has a regulatory character, and therefore would play a similar and thus overlapping role in the assessment as the World Governance Index WGI. It was therefore omitted from early assessments.

Given the fact that recent events in the global economy are not predominantly environmental or social (rather, economic, technical and most of all political), these factors are not used in the independent assessment.

Recent years have seen policy and business taking an interest in responsible sourcing[66] or the environmental footprint of commodities.[67] Environmental impacts can cause a certain probability of a supply disruption of a raw material from for instance political pushback, transport networks becoming unreliable or operations becoming uneconomical due to environmental pressures. Assessing the renewed impact of social or environmental risks could be part of future studies but are outside the scope of this report.

Supply risk: timescales

Supply risks induce a response that tries to mitigate those risks. However, the time requirement of mitigating supply risk, like upscaling mining operations, is not represented in the calculations. In the long term, it is assumed that raw material prices will rise, which will lower the demand and new supply-demand equilibria will develop. However, evidence (absence of acceleration of mining operations or major supply-chain adjustments) suggests that the long term may indeed be very long. The disastrous implications of delaying reducing greenhouse gas emissions do not allow to disrupt the supply of products shaping the green and digital transition. One method to assess the risks of a distorted supply-demand balance may be to use the proven historic track record of growth in mining production, characterized by the Compound Annual Growth Rate (CAGR). Expected future demand, leading to necessary annual growth rates that (significantly) exceed the historic CAGR of mining production, represent potential future risks.

There are several plans for new mining operations on EU territory or in friendly European countries. The European Commission – alongside France and Germany – entered a Mineral Security Partnership with the U.S., Australia, Japan, South Korea and the United Kingdom to address the growing international demand and meet it with increased supply.[68] Examples of mining opportunities can be found inside[69]

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[66] For the latest policies on conflict minerals, see: https://policy.trade.ec.europa.eu/development-and-sustainability/conflict-minerals-regulation_en.

[67] The environmental impact of mining is captured in data behind this link: https://eplca.jrc.ec.europa.eu/EnvironmentalFootprint.html.

[68] For more details, see: https://www.state.gov/minerals-security-partnership/.

[69] For a discussion on new mines on EU territory, see: https://eurogeologists.eu/european-geologist-journal-42-fostering-mining-potential-european-union/.

and outside[70] the EU. Developing these new primary production locations will take time and should therefore be considered on timescales of many years. Although these primary mining opportunities can be considered a stockpile (just as urban mines), they will remain out of scope of the policy recommendations of this report.

The timescales required for adding mining capacity do not need to apply to all critical raw materials relevant for the green and digital transition: some materials are not mined as the main product of a mine, but are harvested as a by-product during mining or refining of base metals. Examples include germanium (by-product from zinc mining), indium (by-product from zinc and copper mining), tellurium (by-product from copper refining) and cobalt (mined as a by-product from copper and nickel mining). In the case of cobalt, the projected growth rates copper and nickel are 3-4% per year, and slower than required for cobalt, which creates a potential mismatch. However, the growth rate for by-products may also exceed that of its 'host' in case the maximum recovery of by-products has not been reached yet. This is the case for tellurium, which is now only marginally recovered from copper refineries. Since building a recovery factory can be assumed to be much faster than expanding mining capacity, it may also be assumed that the CAGR for tellurium can exceed that of copper significantly. A case-by-case analysis of by-product recovery (and making that part of CRM assessment methodology) is therefore recommendable.

When discussing timescales, the latency in adjusting supply, following as a result of obligations deriving from long-term contracts and price agreements, is a possibly relevant aspect. The current method assumes that producing a certain commodity reduces the supply risk as territorial origins equate a level of control (Leruth et al. 2022). There are corporate reasons to double-check these premises. It is likely that if a commodity is produced in a country with a good WGI score, or even an EU Member State itself, the societal interest of the EU is likely to be served. At the same time, there are examples where long-term contractual obligations can compel a (state-controlled) company to export a product. The fact that a region is producing a commodity is a strong sign (for the potential) of authority, but it is not a guarantee for availability (Nasser et al. 2020).

Customizing indicators from the current CRM methodology (Section 3.2)

It provides insight in the sensitivity of the current CRM assessment method, changing the governmental quality of a source country. It provides this insight by finding a new, and a diversified as possible, distribution of source countries that supply the EU 27. Last but not least, it explores if certain raw materials would now be reassessed, given not a "non-critical" but a "critical" status, as a result of the war in Ukraine or China dependency.

As indicated in the main text in Section 3.2, only certain data points are altered, not the methodology. Indicators that represent governance or geopolitics seem suited to be modified in an independent assessment. This means that the indicator describing the World Government Index (WGI) and the distribution of source countries are the two indicators that will be changed in the independent assessment.

The original calculations from the 4th CRM assessment (2019-2020) are used and, depending on the scenarios, the input parameters will be changed. The countries and materials in scope are listed in the Table 24 below. In the assessment, the imported quantities of these materials will be reduced.

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[70] Among the best examples of new mining operations on friendly shores can be found here: https://www.canada.ca/en/campaign/critical-minerals-in-canada/canada-critical-minerals-strategy-discussion-paper.html.

Table 24: Countries and materials of interest in the independent CRM assessment, scenario 1, 2 and 3 (CRMs), scenario 4 (Non CRMs) and scenario 5 (CRMs)

Countries	CRMs (scenario 1,2,3)	Non CRMS (scenario 4)	CRMs (scenario 5)
China	Nd	Feldspar	Baryte (ore)
Vietnam	Dy	Te	Bismuth
Iran	Pr	Zr	Gallium
Kazakhstan	Co	Magnesite	Magnesium
Japan	Li	Ag	Natural graphite (ore)
All Balkan states	Ni	Sn	Scandium
Azerbaijan	Natural graphite	Ni	Vanadium
Israel	Mn	Al	Dysprosium
Kazakhstan	Mg	Potash	Neodymium
Moldova	Ti	Mn	Baryte (ore)
South Korea	Pt	Mo	Bismuth
Turkey	Pd	Iron ore	Gallium
	Ir	Cr	
	Ru		
	Xe		

Source: Authors' own elaboration.

***Scenario 1**: The decision of a country to severely ban exports to the rest of the world*

Scenario 1 is primarily relevant when a single country supplies a significant share of the global material supply i.e. demand. This concentration or monopoly issue is included in the supply risk calculation, using the Herfindahl-Hirschman-index. This index is a measure of market concentration and used to determine whether the market is dealing with monopolies, oligopolies or a diversified range of suppliers. When only a single or very few countries supply a certain material this directly results in a higher supply risk.

Scenario 1 aims to simulate the situation where a certain country would stop supplying their mined or stocked materials to the rest of the world. The goal of this scenario is to analyse the effect of changing the supply or production capacity of a certain country to zero.

An artificially "lowered" global supply directly affects the supply risk. When the removed supplying country in question has an unfavourable WGI index, the effect will be a lower supply risk since the average WGI of remaining countries is more favourable. However, the production country concentration, which increases, may counteract this effect.

In some cases, a lower global supply will result in an increased supply risk, caused by a more unfavourable WGI-score of the remaining supplying countries in combination with an increased market concentration (given a reduced number of supplying countries).

This makes sense according to the principles of the supply-risk-calculation but, in both cases, trying to reduce supply-risk by removing unfavourable WGI countries does not offers the desired effect.

The economic importance indicator is not affected by this scenario.

***Scenario 2**: A decision by a trade destination to not source from a certain country*

Scenario 2 looks at a change in EU's importing countries.

In this scenario the supplied quantities from a certain country to zero and replace it by a different country. The effect is visible on both the European supply risk and the total supply risk, where the total score of the supply risk is a numerical combination of the global and European supply risk (see also Section 3.1). The countries in Table 24 that are mostly affected by the new geopolitical context are for this scenario removed as an EU supplier. Their removed supply is then substituted by another country, which should meet the following requirements:

- The country is not on the list in Table 24;
- The country has sufficient production capacity to meet the 'replaced' demand;

A peculiar result is sometimes obtained when changing the Herfindahl-Hirschman Index or the World Governance Index. If the number of supplying countries is increased, the supply risk will be reduced even if the WGIs of the new source countries is higher, i.e. more unfavourable, according to western standards. Conversely, even if the number of source countries is reduced and the WGI score of the new supplier is more favourable, the supply risk will be assessed as higher.

In general, we notice that for materials with a higher supply risk, replacing the supply of a country with an unfavourable WGI score to a country with a favourable WGI score, results in a lower supply risk. This is especially true for cobalt: with the redistributed supply the EU supply risk is decreased even below threshold level (0.68), a remarkable result. A higher initial supply risk and larger total share of supply replaced will result in a greater reduction of supply risk.

The economic importance indicator is not affected by this scenario.

***Scenario 3**: To diversify source countries*

The third scenario is set up from a supply chain manager perspective: aiming to reduce the supply risk as much as possible by dividing supply over multiple suppliers. Concluding that most cases show a reduction in supply risk when we steer away from unfavourable WGI countries, it begs the question how low the supply risk can become if we are to divide the removed demand over as many producing countries as possible. With this, we aim to create a hypothetical ideal diversified import situation from a supply risk perspective.

For this assessment three highly critical materials have been selected: neodymium, dysprosium and magnesium. For all three materials the largest supplier to EU will be replaced by as many countries as possible that:

- Are not on the list in Table 24; and
- Have sufficient production capacity to meet a share of the 'removed' demand.

For the material to be 'non-critical' the total supply risk should be below 1. In all cases, we see the European supply risk dropping significantly, but since the global supply risk doesn't change, the effect on the total supply risk (which is a combination of the European and Global supply risk) is less severe. The assessment becomes especially interesting when looking at materials such as magnesium, where one single country (China) possesses over 88% of the global production capacity and it is not possible to redistribute EU import from China (>92%) amongst the other global suppliers. Countries that are not on the list in Table 24 are not able to fully supply our EU demand, which still makes the EU dependent on China for 40% of our Magnesium demand.

There are countries which do not mine or produce materials, but merely trade (and perhaps stockpile) them. These countries are included in this analysis because they appear on the global supply risk. However, they have their own WGI score, which is not directly dependent on the WGI scores of the countries which in their turn, supply them.

This clouds the interpretation of the supply risk parameter: it is unclear to what extent these 'trading only' countries can keep delivering materials when their supply chains are disrupted. It is at this moment unclear what the role of these countries is: they could purely stockpile, speculate and trade materials or also refine the materials to a certain extent. Inquiring more information on this topic has also been suggested in Chapter 3.

In all cases, the economic importance indicator remains unchanged.

Table 25 provides insight which countries supply materials (ores and concentrates) to the EU without having production capacity of their own, the share of the EU import from these 'trading countries' and a short reflection on their refining potential.

Table 25: Overview of countries that trade materials without having national production capacity

Materials	Traders	Share	Notes
Nd	UK	3%	Possible refinery industry - UK also provides refined material to EU (1%)
Dy	UK, Japan	24%	Possible refinery industry - UK also provides refined material to EU (1%). Not for Japan
Pr	UK	3%	Possible refinery industry - UK also provides refined material to EU (1%)
Co	No		All countries that supply to EU are also producing countries.
Li	No		All countries that supply to EU are also producing countries.
Ni	USA, Norway	6%	Possible refinery industry - NOR also provides refined material to EU (12%), USA doesn't
Natural graphite	USA, Belarus	5%	No import data for refined metal

Materials	Traders	Share	Notes
Mn	Argentina, Bulgaria, Hungary, Romania	10%	Possible refinery industry - ROU also provides refined material to EU sourcing (1%), other countries don't
Mg	Serbia, UK	4% (PM)	No datasheet on ores and concentrates, only refined material
Ti	Egypt, Georgia, Turkey	<1%	No import data for refined materials imported to EU
Potash	UK	12%	No import data for refined materials imported to EU

Source: Authors' own elaboration.

***Scenario 4**: Assessing the impact of the war in the Ukraine by maximizing the WGI penalty for the Ukraine and Russia*

For scenario 4, the sensitivity of supply from Russia and Ukraine is investigated. Specifically, materials on the 4th CRM list which got a supply-risk (just) assigned below the threshold value of "1". These raw materials were not deemed "critical" in the 4th assessment, but might be, when the fact that the EU sources from these countries is taken into account. The value of the WGI is assigned to a "9", equating Ukraine and Russia to the countries in the world with the lowest WGI. By artificially changing the WGI value, one can examine if new raw materials would pass the "critical" threshold as a result of changing the WGI. Other countries in Table 24 received a numerical value of 7.

By assigning Russia and Ukraine the absolute highest possible i.e. most unfavourable WGI score, the source are effectively placed outside a range that describes the likelihood of expected changes in data. In simple terms: the WGI score has never had to adjust for one country declaring war to another. This therefore describes an unprecedented effect of the type that signals the need to assess criticality following principles of resilience (Sprecher et al. 2017) instead of (pre-) determined values.

Adding new indicators to the current CRM assessment methodology (Section 3.3)

New indicators might be needed to address novel insights in raw material criticality. These insights might come from sector developments like the EU chemicals strategy[71] that assesses the position of base chemical product groups. New insights can obviously also follow from the major global and geopolitical events witnessed in recent years.

Four newly defined indicators are suggested:

1. A new supply risk indicator: the effect of price volatility;
2. A newly interpreted supply risk indicator: the average governance of EU import countries;
3. A new supply risk indicator: the concentration of publicly reported reserves; and
4. A new economic impact indicator: the future demand of raw materials.

The suggested four new or newly interpreted indicators are not an exhaustive list. Reviews of criticality studies show a variety of possible indicators (Blengini 2017b; Schrijvers et al. 2020), notably on social and environmental impacts.

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[71] The strategy for critical chemicals can be found online at: https://environment.ec.europa.eu/strategy/chemicals-strategy_en.

Supply risk new indicator #1: price volatility

There are some remarks to be made about the clarity of price volatility as an indicator. The relation between security of supply and volatile prices can be of an indirect nature. Price volatility can also be a natural in a market with long time lags on the production side, making it difficult to respond to demand. In a well-functioning market, price volatility could be merely a sign of economic importance and market dynamics (for instance, when increased demand caused by technological needs cannot cope with the self-evident slower increase in mining operations), with price levels aiming to sift out consumer preference. However, for raw material markets it is generally acknowledged that price volatility is a sign of opacity and speculation, with a significant possibility of resulting in a reluctance to structurally increase global supply of raw materials and hence negatively influencing future security of supply, see for instance (Foo et al. 2018; Ma et al. 2021).

Price volatility is briefly discussed in previous criticality assessments, such as in the SCRREEN factsheets in (European Commission 2020c). Despite this, prices or price volatility are currently not part of the CRM methodology.

The time scale of the scope-of-action to mitigate price volatility can be on the short-term (< 1 year), for instance through increasing market control or installing stockpiles that can offset perturbations in price.

Supply risk new indicator #2: alternative use of the World Governance Index WGI

The World Governance Index is part of the current EU methodology for CRM assessment. The idea is that if a country scores poorly on topics like political stability, accountability, regulatory quality etc., the WGI score is unfavourable and subsequently this results in a higher supply risk.

The background is that the supply risk for a given material is considered higher if the source country scores worse on the World Governance Index (the WGI is composed of assessments on voice and accountability, political stability, government effectiveness, regulatory quality, Rule of Law and control of corruption). We can link the WGI to import flows, rather than market concentration through the HHI as is done in the current assessment. This way, one can compare the average WGI "score" of a given raw material based on global mining production figures, with the average WGI for the European imports of these raw materials. In simple terms: have European source countries a higher or similar WGI score than world mining production? The reasoning is: the better the WGI score for EU imports compared to world production, the smaller the supply risk of a raw material (see Table 26).

Table 26: WGI scores associated to either global production or EU imports

Raw material	Weighted average WGI for global production	Weighted average WGI for EU imports
Lithium	0.32	0.2
Rare Earth Oxides	0.53	0.48
Cobalt	0.71	0.66
Platinum Group Metals	0.49	No data
Nickel	0.52	0.35
Graphite	0.56	0.52

Source: Authors' own elaboration.

This analysis is hampered by the fact that imports can come through countries with a high WGI due to logistical considerations, also known as the “Rotterdam-effect”. This could be observed in Section 3.3 where Rare Earth Elements (REE) where imported from Thailand, Brazil or India, where no significant REE mining takes place.

Supply risk new indicator #3: concentration of reported reserves

The current methodology uses the geographical distribution of current mining (or refining) production as an important element of the assessment. Whereas this 'source distribution' is highly relevant as it gives insight in e.g. monopolies, it does not reflect the reality possible reserves that are developed as mining sites in the future.

The data for such reserves (see paragraph 2.3.1 for definitions and data) can be retrieved from geological surveys such as the US Geological Survey (USGS). Criticality metals assessment should be regarded as a result that will evolve over time as new ore deposits are located (Graedel & Reck 2019).

This study assesses the needs and vulnerabilities of the EU in accessing products containing Critical Raw Materials (CRM) needed for the green and digital transitions in a changing geopolitical context. It provides an overview on the wider situation, as well as a policy context The study sets out to identify at which stage of the supply chain, ranging from raw materials to final products, the European industrial eco-system is dependent on CRM imports. It reviews the CRM methodology designed by the JRC to identify which materials are critical and require special attention. The current methodology could benefit from an extension of scope, including an assessment of product groups and sectors. A study finds out that setting up of EU stockpiling facilities could mitigate supply disruptions of raw materials and components. However, setting up stockpiling facilities would require an effective public-private management.

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