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Italy's Role in the EU's Critical Raw Material Supply Chain and Resilience

Relatori:
Prof. Daniele Martinelli

Candidati:
Tala El Kawam

Abstract

One of the main concerns for the European Union's green and digital transformations is ensuring a stable and sustainable supply of critical raw materials (CRMs). In this regard, Italy's position needs to be refocused in order to fully support the EU's resource security objectives. With an emphasis on its industrial strengths, current weaknesses, and growth potential, this thesis offers a thorough evaluation of Italy's current CRM extraction, processing, and recycling capabilities.

Using a mixed method research design that includes case studies, benchmarking, literature reviews, and quantitative research, it examines how technology advancements like artificial intelligence (AI), blockchain, and Industry 4.0, as well as customized management techniques like Lean Mining, Six Sigma, and Agile Procurement, can improve the sustainability, traceability, and general efficiency of supply chains.

It was discovered that while the majority of Italy's processing infrastructures and emerging circular economy initiatives are strong points, the rest of the nation's processing capacity is incredibly underutilized.

Strengthening domestic production, encouraging technological innovation, and coordinating national policies with the EU's Critical Raw Materials Act are essential for reducing reliance on imports and boosting resilience. The thesis ends with actionable suggestions for legislators and business leaders on how to strengthen Italy's crucial role in the European CRM supply chain, which will increase long-term economic security and industrial competitiveness.

Key-words: Critical Raw Materials, Supply Chain Resilience, Engineering Management, Circular Economy, EU Policy

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Variable	Description
CRM	Critical Raw Material
EU	European Union
EI	Economic Importance
SR	Supply Risk
WGI	World Governance Indicator
EC	European Commission
SRM	Strategic Raw Material
JRC	Joint Research Center
REE	Rare Earth Elements
DRC	Democratic Republic of Congo
SDG	Sustainable Development Goals
MoU	Memorandum of Understanding
SCRI	Supply Chain Resilience Index
IDR	Import Dependency Ratio
VSM	Value Stream Mapping
JIT	Just-in-time
JIC	Just-in-case
EV	Electric Vehicle

LME	London Metal Exchange
IRA	Inflation Reduction Act
AI	Artificial Intelligence
GHG	Greenhouse Gas
EPR	Extended Producer Responsibility
LCA	Life Cycle Analysis
KPI	Key Performance Indicator
WEEE	Waste from Electrical and Electronic Equipment
ERMA	European Raw Materials Alliance
JRC	Joint Research Center

1 Introduction

1.1. Overview

In order to maintain its industrial competitiveness and technical growth, the European Union (EU) has acknowledged the strategic significance of Critical Raw Materials (CRMs). Through extraction, processing, recycling, and the application of policies, Italy, a vital Member State, has the potential to contribute significantly to the EU's CRM supply chain.

This thesis examines Italy's role in the broader EU CRM strategy, assessing its benefits, drawbacks, and potential in order to increase supply chain resilience. The study integrates key Engineering Management concepts, including agile procurement, lean methodologies, Six Sigma compliance with CRM standards, and risk management frameworks, to evaluate and recommend solutions for Italy's improved CRM security.

As an initial step to understand the current state of play, this study examines Italy's current CRM capabilities, such as local extraction potential, processing facilities, recycling efficiency, and position in global supply chains. It also analyses vulnerabilities in Italy's CRM supply chain and evaluates how strategic policies and industrial innovation might strengthen resilience.

Findings supporting the conclusions drawn are based on data-driven analysis, industry insights, and best practices from supply chain resilience. These include strategic recommendations to improve Italy's role in ensuring EU's critical raw material supply.

1.2. Background

CRMs are a group of raw materials needed to build a robust industrial base that produces a wide range of products and applications used in contemporary technologies and daily life. Their economic value and supply risk—which is often brought on by geopolitical concentration, restricted extraction capabilities, and environmental concerns—have earned them the designation of "critical".

The European Commission routinely updates its CRMs list based on:

1. **Economic Importance** - The material's contribution to important EU industries such as energy, electronics, and defence.
2. **Supply Risk** - The degree to which global or regional supply chains are susceptible to interruption.

In the EU, raw materials are labelled based on two parameters: economic importance (EI) and risk of supply disruption assessment (SR), which is expressed as a value of relevant indicators. At the NACE classification, the EI denotes a material's relevance to the EU economy in terms of end-use applications and the value added of associated EU manufacturing sectors. Its value is adjusted by a substitution index based on the technical and cost performance of substitutes for certain applications (European Commission, 2020). The computation of SR is based on the concentration of primary supply from raw material-producing countries (HHI), taking into account their governance performance as determined by the World Governance Indicators (WGI) and trade characteristics (Blengini et al., 2017). Possible substitution and recycling are considered risk-reduction methods.

The European Commission (EC) produced a list of important raw materials as a priority activity under the Commission's 'EU Raw Materials Initiative', which was launched in 2008. For the first time in 2011, the EC identified 14 critical non-energy, non-agricultural raw materials for which the EU manufacturing industry requires undistorted, diverse, and affordable sourcing (European Commission, 2011). Since then, the list has been reviewed and updated every three years: in 2014 (20 CRMs), 2017 (27 CRMs), and 2020 (30 CRMs). The lowest threshold value of 2.8 points in the case of EI and a minimum threshold value of 1.0 points in the case of supply risk assessment have been satisfied by the raw materials that have most recently been designated as critical for the EU (European Commission, 2020).

1.3. Strategic Importance and Supply Chain Vulnerability

Because they are essential to national security, technical development, economic growth, and the energy transition, CRMs are regarded as strategically significant. Vulnerabilities in the supply chain, like geopolitical threats, restricted availability, and challenges with recycling or substitution, increase their significance.

The EU has designated 34 essential CRMs for its strategic sectors, which include renewable energy, digital technologies, aerospace, and military. 17 of these have been designated as strategic raw materials (SRMs), a subset of CRMS, evaluated as a foresight on sectorial demand and risk of supply disruptions. These raw materials, which were recently expanded to include aluminum/ bauxite and natural graphite, are critical to the EU's efforts under the Critical Raw minerals Act to maintain a diverse and sustainable supply chain (European Commission, 2023).

The identified CRMs and SRMs are organized in table 1.1, demonstrating their vital importance in a variety of sectors and showcasing the EU's strategic approach to ensuring their supply.

Table 1.1: List of CRM and SRM (European Commission, 2023)

Energy and Electronics	
CRM	**Strategic (S)**
Lithium	S
Cobalt	S
Gallium	S
Germanium	S
Silicon metal	S
Tantalum	
Copper	S
Platinum group metals	S
Light rare earth elements (Nd, Pr, Ce, Sm)	S
Heavy rare earth elements (Dy, Gd, Tb)	S
Aerospace and Defence	
CRM	**Strategic (S)**
Titanium metal	S
Tungsten	S
Bismuth	S
Niobium	

Vanadium	
<u>Construction and Infrastructure</u>	
Aluminium/Bauxite/alumina	S
Phosphorus	
Antimony	
Arsenic	
Boron	S
Nickel	S
Other Industrial Uses	
CRM	**Strategic (S)**
Coking Coal	
Feldspar	
Fluorspar	
Magnesium	
Baryte	
Natural Graphite	S
Phosphate Rock	
Helium	
Scandium	
Strontium	
Beryllium	
Hafnium	

The categorisation reflects the importance of these raw materials based on their primary usage across several industry sectors, which is consistent with the EU's emphasis on protecting supply chains in critical sectors. This method aids in understanding the relevance and strategic importance of each CRM and SRM, emphasising their contribution to EU economic and technical advancement.

The European Commission's Joint Research Center developed Sankey Diagram that depicts the supply risk of CRMs and their importance in various technologies and sectors. It classifies CRMs based on their supply risk, which ranges from very high (light and heavy rare earth elements) to very low (copper and nickel) (Blengini et al., 2020). These are required for vital technologies such as batteries, fuel cells, wind energy, traction motors, and Information and Communication Technology. Figure 1.1 also shows how various technologies based on these CRMs affect critical areas including renewables, e-mobility, and defence and space. The thicker linkages indicate greater dependency, emphasising the susceptibility of specific businesses to supply chain disruptions.

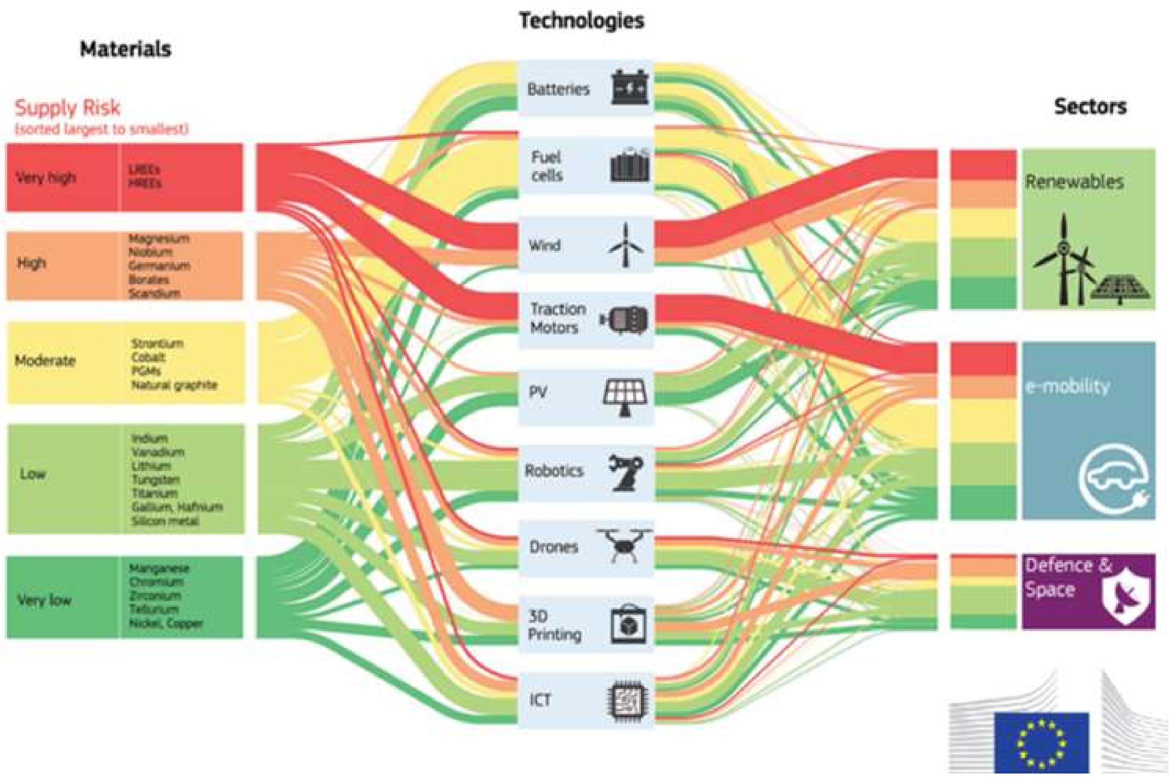


Figure 1.1: Critical Raw Materials and their Supply Risk (Joint Research Center, 2020)

Due to the significant risks associated with the EU's reliance on imports, CRM security is a top concern for European industrial strategy.

1.3.1. CRMs for Economic Growth and Industrial Competitiveness

CRMs are critical in modern economies because they drive technical innovation, industrial productivity, and job growth. Some of the most important CRM-dependent sectors are:

- **High-Tech Manufacturing and Semiconductor**
    1. Gallium, indium, and germanium are critical components in semiconductors, which power everything from smartphones to quantum computers.
    2. The EU lags behind in semiconductor production, relying mainly on imports from Taiwan, China, and South Korea, hence CRM security is vital for technological sovereignty.

- **Automotive and Electric Vehicles**
    1. Lithium, cobalt, nickel, and graphite are important components in EV batteries.
    2. The EU is heavily investing in battery manufacture (e.g., the European Battery Alliance), but raw material shortages may hinder EV production, jeopardising the green transition.

- **Industrial Manufacturing and Aerospace**
    1. Magnesium, titanium, and tungsten are essential for lightweight automotive and aerospace components, which reduce fuel consumption and pollutants.
    2. The EU's aircraft sector (Airbus, Leonardo) relies on crucial CRMs, and prospective supply chain interruptions endanger competitiveness.

1.3.2. CRMs for Green Energy Transition

The EU Green Deal aspires to achieve carbon neutrality by 2050, which necessitates a rapid development of renewable energy, electric mobility, and grid storage. CRMs are the foundation of these systems, therefore their reliable supply is a critical imperative (European Commission, 2019).

- **Wind and Solar Energy**
  1. Rare Earth Elements (REEs), such as neodymium and dysprosium, are essential for high-performance wind turbine magnets.
  2. Silicon and tellurium are required for solar panel production, and the EU currently imports more than 90% of its silicon wafers.

- **Battery Storage and Hydrogen Economy**

Lithium, cobalt, and nickel are essential components of lithium-ion batteries, which are utilised in both electric vehicles and grid storage systems.

1. Platinum and iridium are crucial for hydrogen fuel cells, which are required to decarbonise the industrial and transportation sectors.

1.3.3. CRMs for National Security and Defence

The defence and aerospace industry cannot function without a consistent CRM supply, making these materials vitally important to national security.

- **Military Technologies**
  1. Tungsten, titanium, and tantalum are critical components in military aircraft, armoured vehicles, and missiles.
  2. Radar, night vision, and precision-guided weaponry all make use of REEs.
  3. Beryllium and hafnium are essential for nuclear reactors and space applications.

1.3.4. Geopolitical and Supply Chain Risks Threaten CRM Security

The EU's reliance on a few CRM suppliers, primarily China, the Democratic Republic of Congo (DRC), and Russia, exposes it to major geopolitical risks such as trade restrictions, export bans, and political instability (Graedel et al., 2015; Humphreys, 2019). Supply chain vulnerabilities, such as disruptions caused by conflict, resource nationalism, and limited local production, jeopardise the EU's economic security and industrial resilience, making diversification and strategic autonomy critical considerations.

The EU imports 75-100% of most CRMs, with China, Malaysia, Russia, the DRC, Brazil, and South Africa being the primary sources. The key vulnerabilities include 98% of EU's REE from China, Cobalt from DRC, and Lithium and Nickel from Australia, Chile, and Indonesia (Blengini et al., 2020; BGS, 2022).

Largest partners of imports of REE+ by product code in 2023 in weight

	Largest partners						Share in total imports	
Product code	First		Second		Third		of REE+	Imports / exports
28461000	Malaysia	48%	Russia	33%	China	14%	67%	2.7
28469040	China	98%	United States	1%	United Kingdom	1%	22%	17.3
28469090	China	83%	United States	6%	Viet Nam	4%	3%	2.5
28053010	China	100%	United States	0%	Taiwan	0%	2%	27.4
28469070	China	92%	South Korea	5%	United States	2%	2%	9.2
28469060	Japan	57%	Norway	21%	China	19%	1%	9.1
28469050	Malaysia	42%	Japan	27%	China	16%	1%	0.5
28053039	China	100%	United States	0%	United Kingdom	0%	0%	47.7
28469030	Norway	93%	China	6%	United States	1%	0%	1.3
28053029	China	99%	United States	0%	United Kingdom	0%	0%	10353.0
28053021	China	94%	United States	6%	United Kingdom	0%	0%	1.5
28053080	China	69%	United States	13%	Taiwan	11%	0%	0.4
28053031	China	87%	United States	10%	United Kingdom	3%	0%	229.5
28053040	China	83%	United Kingdom	16%	United States	1%	0%	31.0
Total	China	39%	Malaysia	33%	Russia	22%	100%	3.3

Note 1: 0% means less than 0.5%
Note 2: REE+ is a grouping of rare earth elements, scandium and yttrium
Note 3: Detailed list of products under each code is provided in Table 7
Source: Comext DS-045409

eurostat

Figure 1.2: Largest Partners of Imports of REE (Eurostat, 2023)

As of a study carried out in 2023, figure 1.2 shows how the bulk of EU imports of REE originated from China (39%), followed by Malaysia (33%), and Russia (22%). It is evident that China is one of the main partners as the concentration of imports, as measured by the share of the top-3 importers was more than 90% (OECD, 2023).

- **Geopolitical and Trade Disruptions**
  1. Chinese export prohibitions on gallium and germanium (2023) demonstrated how CRM supply networks may be weaponised (Reuters, 2023).

2. Russia's invasion of Ukraine has hindered nickel and palladium supplies, harming European industry (IEA, 2022).
3. The US Inflation Reduction Act (IRA) prioritises US-based CRM supply chains, which may limit European access to American raw materials (Congressional Research Service, 2023).
4. In 2024-2025, China reinforced export limits on important minerals such as graphite and rare earths, limiting global exports and increasing supply chain instability for sectors that rely on these inputs, particularly in Europe and the United States (Financial Times, 2024).

- **Lack of Domestic Production and Recycling**
  1. The EU possesses CRM deposits (for example, lithium in Portugal and rare earths in Sweden), but complex permission processes and environmental concerns cause mining delays.
  2. Recycling rates for most CRMs remain below 10%, indicating that secondary supply is insufficient to meet demand (UNEP, 2020).

To maintain resilience, the EU must secure supply through domestic production, diversification, and recycling, with CRM access being a strategic goal.

1.4. The EU's CRM Strategy and Regulations

To address the aforementioned challenges, the EU has developed a clear and comprehensive regulation to address the growing concerns about the security and resilience of CRMs. In response, the EU has implemented a number of major regulatory frameworks and measures, notably the CRMA, to strengthen CRM resilience and ensure a more autonomous and sustainable supply chain.

CRMA, which went into effect in May 2024, is a key component of the EU's plan for ensuring CRM security. The Act establishes lofty goals and incorporates a variety of regulations aimed at strengthening the EU's supply chains, reducing external dependency, and promoting circular economy practices (European Commission, 2024).

Key provisions of the CRMA:

1. **Domestic Mining and Extraction:** According to the Act, domestic mining must provide at least 10% of the EU's demand for strategic raw materials. Even though the EU has some CRM deposits, like lithium in Portugal and

rare earth elements (REEs) in Sweden, the area still faces many obstacles because of local resistance, environmental concerns, and mining permits.

2. **Processing and Recycling:** Within the EU, the Act aims for 40% processing and 25% recycling. The goal of this drive for domestic SRM processing is to lessen the EU's dependency on outside refineries, which control the refining of many vital commodities. With an emphasis on removing lithium, cobalt, and other metals from batteries, tech waste, and industrial scrap, recycling is also emphasized as a crucial element.

3. **Supply Diversification:** The Act mandates that no more than 65% of a specific SRM supply originate from a single nation or region. The purpose of this diversification clause is to protect the European Union from geopolitical shocks and disruptions.

4. **Stockpiling and Monitoring:** CRMA lays out protocols for keeping an eye on supply chains and storing essential supplies. This is intended to act as a safeguard against interruptions in supply, especially in times of international crisis or trade disputes.

In line with broader efforts to preserve energy and economic security in a volatile global environment, these show the EU's move towards strategic autonomy in the area of CRMs.

Strategic Projects under the CRMA:

The European Commission has chosen 47 Strategic Projects in 13 Member States, including Italy, France, Germany, and Greece, to implement the goals of the CRMA. In these projects, 17 CRMs—such as lithium, cobalt, REEs, and gallium—that are necessary for the EU's green and digital transitions are mined, processed, and recycled (European Commission, 2024).

Purpose and Benefits:

- Streamlined Permitting: Strategic Projects benefit from faster permitting processes (15 months for processing and recycling, 27 months for extraction), which reduce administrative delays.

- Financial Support: Project promoters can obtain financial help through coordinated efforts including EU and national public and private financial institutions, thereby simplifying investment in important areas.
- Supply Chain Resilience: By strengthening local capacities, these programs hope to lessen the EU's reliance on external sources, especially in light of current geopolitical tensions and supply chain interruptions.
- Sustainability and Circularity: The projects are in line with the EU's commitment to environmental sustainability, and include steps to improve the recyclability and environmental footprint of CRMs.

The EU's overarching objectives of energy security, technological innovation, and economic resilience are supported by a steady, varied, and sustainable supply of CRMs, all of which are made possible by these strategic projects.

1.5. Italy's Contributions to the EU's CRM Supply Chain

In the EU's CRM supply chain, Italy plays a vital but underutilized role. Italy is a significant player in the processing and manufacturing of CRM, despite having less mining activity than other EU nations. Italy is a desirable location for a number of CRM-related industries due to its advantageous Mediterranean location and strong industrial base.

Italy's Contribution to the EU's CRM Supply Chain:

- **Mining Potential**: Lithium in the Tuscany region and rare earth elements (REEs) in the Alps are two examples of undeveloped CRM deposits in Italy. Despite the fact that mining operations have not yet reached their maximum potential, interest in using these resources is growing. This is crucial as the EU looks to increase its own production of CRM while decreasing its dependency on outside sources.

- **Processing:** Italy is a major player in the high-tech industries of automotive, aerospace, and electronics, all of which rely largely on CRMs. Italian industries, particularly in the automotive sector, are increasingly focused on producing electric vehicle (EV) batteries, which require lithium, cobalt, nickel, and graphite. The Italian aircraft industry also relies on titanium and REEs to create lightweight, high-performance components.

- **Recycling and Circular Economy:** Additionally, Italy is making strides in the recovery and recycling of CRMs, especially from spent batteries and e-waste. Italy has developed a number of cutting-edge recycling facilities, such as those in Catania, that focus on extracting valuable metals like nickel, cobalt, and lithium from batteries and devices used in electric vehicles. The EU's objective of raising CRM recycling rates while reducing reliance on primary extraction is substantially supported by this.

- **Research and Innovation:** Italy has advanced CRM research and innovation significantly, especially in the areas of material efficiency and urban mining. In order to support the EU's green transition and circular economy goals, universities and institutes—including the University of Turin—are investigating technology to collect and recycle materials in a more sustainable way.

Italy's National Recovery and Resilience Plan (PNRR) provides additional funding—supported by the EU's Recovery and Resilience Facility (RRF)—to expedite green and digital transitions. The PNRR increases Italy's potential to develop innovative technologies for CRMs, such as sustainable extraction, improved recycling processes, and circular economy models, by investing specifically in research, innovation, and industrial development. These activities are clearly aligned with EU CRM objectives and are intended to strengthen Italy's key position in the EU's resilient and autonomous supply chain for critical materials (Bruegel, 2022).

To summarise, while Italy is not a big source of CRM extraction, it contributes significantly to the EU's supply chain resilience through processing, manufacturing, and recycling. With additional investments in mining and research, Italy has the potential to become a more major participant in Europe's CRM strategy.

1.6. Research Objectives

With a focus on its contributions to extraction, processing, and recycling, this study aims to evaluate Italy's role in the EU's CRM supply chain. Understanding Italy's place in this framework is essential given the EU's strategic goal to increase supply chain resilience and lessen dependency on outside suppliers. The primary goals of the study are:

1. **Assess Italy's CRM Extraction Capabilities**

   - Evaluate Italy's CRM extraction capabilities.
   - Assess the availability of CRM deposits, such as lithium, rare earth elements, and nickel, and their potential contribution to the EU supply chain
   - Examine the economic and environmental effects of expanding CRM mining activities in Italy
   - Look into the legal and geopolitical issues surrounding CRM extraction, such as national laws, EU mining legislation, and local opposition.

2. **Analyse Italy's Role in CRM Processing**

   - Assess the nation's reliance on imported processed resources and look for ways to increase domestic processing capacity.
   - Examine Italy's current CRM refining and processing infrastructure, paying particular attention to the automotive, aerospace, and renewable energy sectors.
   - Look into the application of engineering management techniques, such as lean methodologies and Six Sigma for quality control, to increase CRM processing capacity.

3. **Evaluate Italy's contribution to CRM Recycling and Circular Economy Initiatives**

   - Examine Italy's present CRM recycling rates and assess how well the country's recycling programs are working.
   - Examine Italy's involvement in urban mining and e-waste recovery, paying particular attention to materials like cobalt, lithium, and rare earth elements that are taken from used batteries and devices.

- To improve material recovery rates, look into developments in pyrometallurgy and hydrometallurgy.

4. Identify the challenges and opportunities in Italy's CRM Supply Chain

- Look at the main obstacles preventing Italy from developing its CRM supply chain, including financial concerns, technological constraints, and regulatory limitations.
- Determine areas where CRM extraction, processing, and recycling could expand, and suggest ways to improve Italy's standing in the EU's CRM resilience plan.

Italy's strategic role in the EU's CRM supply chain will be thoroughly evaluated in this study, along with suggestions for how the nation can strengthen its position through investment, innovation, and regulatory changes.

1.7. Research Methodology

This study takes a thorough, multi-method approach to evaluating Italy's position in the EU's CRM supply chain. To assess Italy's CRM extraction, processing, and recycling capacities, the technique combines qualitative and quantitative evaluations, drawing on data gathering, case studies, and engineering management frameworks. The study takes an organised approach, with the following major components

1. Data Collection and Literature Review

A thorough analysis of academic literature, policy reports, and industry publications will provide a solid understanding of Italy's CRM industry. Sources include EU Commission reports, Italian government publications, industry white papers, and CRM extraction, processing, and recycling research studies. Data will also be gathered from scientific journals, mining company reports, and trade agreements to evaluate Italy's place in the global and EU CRM supply chains.

2. **Case Studies and Benchmarking Analysis**

In order to find best practices that can be implemented in Italy, the study will include case studies of CRM strategies that have been successful in European nations like Germany and France. This will mean contrasting Italy's investment trends, industry capabilities, and CRM policies with those of other important EU nations.

Italy's competitiveness in CRM extraction, refining, and recycling will also be evaluated through a benchmarking analysis using important performance metrics like supply chain resilience scores, processing capacity, and self-sufficiency ratios.

3. **Quantitative Analysis**

Quantitative models will be employed to assess the potential effects of different initiatives on Italy's CRM supply chain. This comprises:

- Import Dependency Reduction Analysis: Evaluating how improved domestic extraction and processing could reduce Italy's reliance on CRM suppliers from other countries.
- Scenario-Based Forecasting: We forecast future trends in Italy's CRM supply and demand under a range of market and policy conditions using time-series models.

4. **Engineering Management Applications**

To improve the efficiency analysis of CRM extraction, processing, and recycling, engineering management methods such as Lean Mining, Six Sigma refinement, and Agile Procurement will be used. This will include:

- Lean mining techniques: decrease waste and environmental impact while increasing the efficiency of resource extraction.
- Six Sigma for CRM Refining: Increased process reliability and purity in the CRM processing industry in Italy.
- Agile Procurement for CRM Developing adaptable sourcing strategies to reduce the risks of supply chain disruptions and trade restrictions is known as supply resilience.

By integrating literature study, case studies, quantitative modelling, and engineering management applications this methodology enables a thorough, data-driven evaluation of Italy's role in protecting the EU's CRM supply chain.

1.8. Expected Outcomes

This study aims to provide a thorough analysis of Italy's participation in the EU's CRM supply chain along with practical suggestions for how Italy could improve its standing. The following significant outcomes are anticipated from the study:

1. The study will describe Italy's present capacities for CRM extraction, processing, and recycling, highlighting both its advantages and disadvantages.
2. Strategic and Policy Suggestions to Strengthen Italy's CRM Role
3. Developing Management Apps for CRM Resilience and Efficiency
4. Impact Evaluation of Suggested Approaches

In the end, this study will give Italy a thorough strategic framework to improve its standing in the EU CRM supply chain. It will offer engineering, industrial, and regulatory suggestions to enhance the economic impact, sustainability, and security of Italy's CRM.

2 Literature Review

2.1. EU Sustainable Development

Geoscience knowledge has helped us acquire clean water, develop food, manage natural risks, and boost the economy. Policymaking relies heavily on interdisciplinary approaches. To achieve a sustainable energy transition, a circular economy requires more raw resources. Despite a rich mining heritage, Italy decided to import the majority of mineral resources from elsewhere to ensure economic sustainability. Over the past decade, awareness has grown, especially with the implementation of the EU Green Deal.

The EU Green Deal, officially known as the European Green Deal, is a comprehensive policy to make the European Union climate-neutral by 2050. It focusses on lowering greenhouse gas emissions to net zero, in line with global goals to keep global warming at 1.5°C (European Commission, 2019). The initiative promotes material recycling and reuse, waste reduction, and sustainable production and consumption. It also highlights a clean energy transition, emphasizing energy efficiency improvements and renewable energy sources like solar, wind, and hydrogen. Conservation of biodiversity, which includes efforts to support nature-based solutions and restore ecosystems, is another crucial element. Additionally, the Green Deal seeks to invest in eco-friendly businesses and technologies, foster green innovation, and generate employment (Tagliapietra et al., 2020). Significant changes will be made to the transportation industry, which will reduce emissions by promoting greener mobility choices like electric cars and effective public transit. Finally, the Farm to Fork Strategy seeks to build a more sustainable food system by encouraging sustainable farming techniques, decreasing food waste, and promoting healthy diets (European Commission, 2020).To ensure that the transition benefits everyone, the EU supports the Green Deal's Just Transition Mechanism, which assists towns and regions reliant on carbon-intensive industries in adjusting to the changes.

Thus, The Italian Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA) supports the mining industry by coordinating technical panels and discussions on eco-friendly raw material possibilities at national scale (ISPRA, 2023). ISPRA is creating a Geodatabase to support sustainable mineral extraction and inform national and regional policies.

In 2021, the European Parliament called for an EU strategy for critical raw materials in its November resolution (European Parliament, 2021). Similarly, in 2022, The

Versailles Declaration, endorsed by the European Council, aims to strengthen European sovereignty and reduce reliance on external sources (European Council, 2022). The EU aims to assure supply of CRMs by leveraging its Single Market characteristics. Also, The Conference on the Future of Europe suggested reducing the EU's reliance on other countries for CRMs. Along that in 2022, the President of the European Commission proposed the European Critical Raw Materials Act, which aims to identify strategic projects across the value chain and build strategic reserves in areas of supply risk (Tocci, 2023).

This 2023 technical evaluation contributes to the Critical Raw Materials Act's legislative package and defines the list of CRMs for EU.

2.2. UN Sustainable Development Goals

By 2030, a set of 17 global goals known as the Sustainable Development Goals (SDGs) seeks to address pressing problems like poverty, inequality, environmental degradation, and peace. Adopted in 2015 as part of the 2030 Agenda for Sustainable Development, these objectives provide states, corporations, and individuals with a roadmap for creating a more sustainable and equitable world (United Nations, 2015). Every SDG in figure 2.1 is interconnected and emphasizes a holistic strategy for resolving global issues via environmental preservation, social inclusion, and economic growth.

Figure 2.1: UN Sustainability Development Goals (UN, 2015)

- **Goal 1: No Poverty** seeks to eliminate extreme poverty for all people worldwide by ensuring equal access to resources, social protection systems, and economic opportunities. This involves tackling the vulnerabilities produced by climate change, economic downturns, and wars, which disproportionately affect the poorest people.

- **Goal 2: Zero Hunger** intends to advance sustainable agriculture, guarantee food security, and end hunger. In order to meet the demands of a growing global population, it highlights the importance of resilient food production systems, better nutrition, and equitable access to land and resources.

- **Goal 3: Good Health and Well- Being** seeks to advance everyone's health and wellbeing, regardless of age. It highlights the significance of a strong healthcare system and disease prevention programs by concentrating on maternal and infant mortality, infectious diseases, mental health, and universal healthcare access.

- **Goal 4: Quality Education** seeks to deliver an inclusive and equitable education while encouraging lifetime learning opportunities. It focusses on reducing gender inequities in education, increasing literacy and numeracy rates, and providing global access to high-quality education for children and adults alike.

- **Goal 5: Gender Equality** aims to achieve equality for all genders by eradicating discrimination, violence, and harmful practices including child marriage. It also emphasises that women and girls should have equal access to leadership positions, education, and economic resources.

- **Goal 6: Clean Water and Sanitation** ensures that water and sanitation are available to everyone and managed sustainably. This involves minimising water pollution, increasing water efficiency, and ensuring everyone has access to safe drinking water and proper sanitation.

- **Goal 7: Affordable and Clean Energy** seeks to expand access to modern, sustainable, and reliable energy sources. To reduce reliance on fossil fuels, it encourages investment in energy efficiency, renewable energy, and infrastructure improvements.

- **Goal 8: Decent Work and Economic** Growth promotes inclusive and sustainable economic growth, job creation, and decent work for all. It focusses on fair salaries, safe working conditions, and policies that encourage job development and entrepreneurship.

- **Goal 9: Industry, Innovation, and Infrastructure** promotes the growth of robust infrastructure, industrialisation, and innovation. It emphasises the need of long-term industrial growth, expanded access to financial services, and investment in research and development.

- **Goal 10: Reduced Inequalities** seeks to narrow economic and opportunity gaps within and between countries. It prioritises social inclusion, equal access to services, and policies that protect vulnerable and marginalised populations.

- **Goal 11: Sustainable Cities and Communities** aims to foster inclusive, safe, resilient, and sustainable urban development. It advocates for better public transportation, more affordable housing, disaster risk reduction, and green areas.

- **Goal 12: Responsible Consumption and Production** encourages waste reduction, effective supply chains, and sustainable resource management. It highlights the importance of environmentally friendly production methods, circular economy strategies, and conscientious consumer behavior.

- **Goal 13: Climate Action** promotes swift action to address climate change and its effects by reducing greenhouse gas emissions, boosting climate resilience, and integrating sustainability into national policies.

- **Goal 14: Life Below Water** emphasizes the preservation and sustainable use of marine resources and the ocean. It promotes reducing marine pollution, protecting marine biodiversity, and tackling how overfishing and climate change affect the health of the ocean.

- **Goal 15: Life on Land** intends to preserve, repair, and encourage the sustainable use of land-based ecosystems. It aims to lessen land degradation, biodiversity loss, desertification, and deforestation.

- **Goal 16: Peace, Justice, and Strong Institutions** promotes inclusive and peaceful societies by increasing human rights, minimising violence, and ensuring access to justice and transparent institutions.

- **Goal 17: Partnerships for the Goals** emphasises the need of international cooperation and collaboration in achieving sustainable development. It advocates for stronger international cooperation, resource mobilisation, and knowledge exchange among governments, corporations, and civil society

Table 2.1: CRM in UN Sustainable Development Goals

SDG 7 (Clean Energy)	CRMs like lithium, cobalt, and rare earth elements are essential for renewable energy systems such as solar panels, wind turbines, and batteries.
SDG 9 (Industry & Innovation)	CRMs make it possible for smart infrastructure, telecommunications, and advanced manufacturing, which calls for recycling and sustainable sourcing.
SDG 12 (Responsible Consumption and Production)	Highlights that in order to cut waste and dependency on mining, a circular economy, effective resource use, and higher CRM recycling rates are necessary.
SDG 13 (Climate Action)	CRMs are essential to the shift to low-carbon technologies, which necessitate more recycling and sustainable mining to lessen their impact on the environment.
SDG 14 and 15 (Life Below Water and Life on Land)	CRM extraction can result in land degradation, deforestation, and pollution, necessitating tougher controls and ecosystem restoration measures.
SDG 17 (Global Partnerships)	International cooperation is essential for assuring ethical and sustainable

	CRM supply chains, as well as ensuring fair trade and environmental accountability.

In order to meet demand while taking social and environmental concerns into account, sustainable CRM management necessitates innovation, recycling, and responsible procurement.

2.3. EU Strategic Partnerships

Europe has the problem of on-shoring essential minerals, guaranteeing global markets, and ensuring sustainability. With demand for minerals like copper and lithium in green technology anticipated to quadruple by 2040, the EU will continue to rely on third-party imports for raw materials (IEA, 2022). Research indicates that even if Europe completely maximizes its mineral extraction, processing, and recycling capacities by 2030, over half of key minerals will still require imports (BGR, 2023). The issue is to source these metals from varied markets while maintaining high social and environmental standards. Europe's new "strategic partnership" framework addresses this issue (Kauppila et al., 2023).

The supply of CRM from third nations is highly concentrated. China is the sole supplier of processed rare earth elements to the EU, accounting for 85%-100% as of 2023. Chile accounts for 79% of Europe's lithium supply, whereas the Democratic Republic of Congo supplies 63% of worldwide cobalt. Most minerals are processed in China, which has a dominant position in the supply chain (IEA, 2022). Resource nationalism and export limitations provide a significant issue in resource-rich countries like Indonesia, China, Chile, Namibia, and Zimbabwe. These countries aim to develop their own minerals processing and clean tech manufacturing, while collaborating with foreign partners such as the EU.

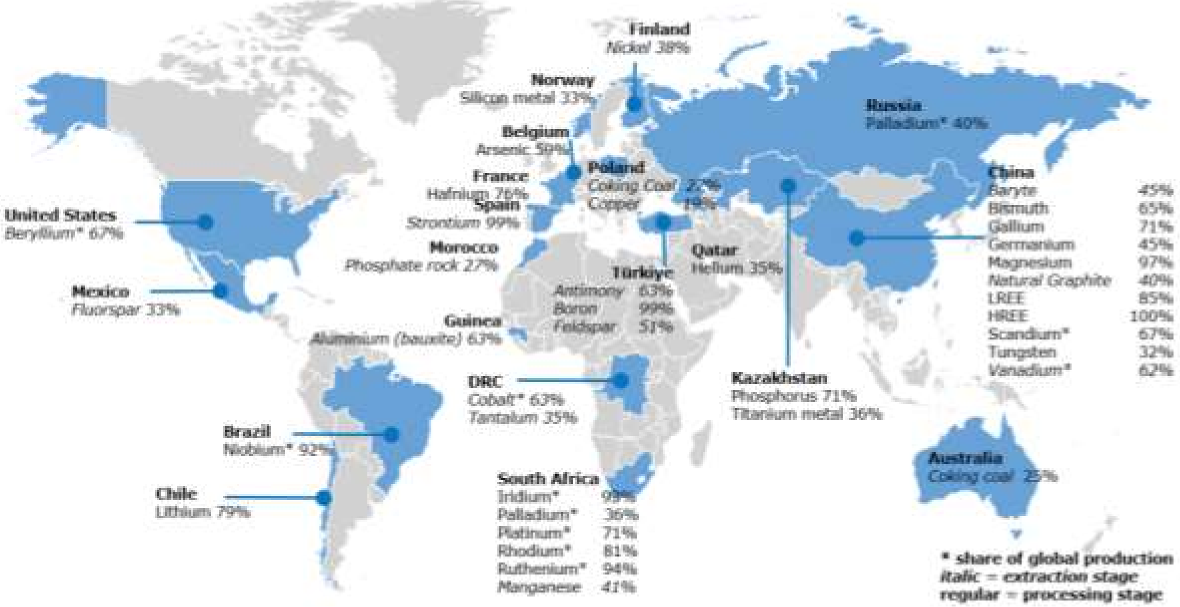


Figure 2.2: Leading CRM Countries (European Files, 2023)

The leading CRM countries around the globe are evident in figure 2.2.

The EU has established strategic partnerships with third countries in order to diversify its supply of CRM. The EU inked Memorandums of Understanding for Strategic Partnerships with Ukraine and Canada in 2021. Partnerships with Argentina, Chile, Zambia, and the Democratic Republic of the Congo were formed in 2023 after agreements with Namibia and Kazakhstan were signed in 2022. While meeting stringent environmental, social, and governance standards, these Memorandums of Understanding seek to link raw material value chains, identify cooperative projects, and expedite research and development. This strategy seeks to safeguard the EU's supply chain while simultaneously meeting domestic needs and promoting economic growth in nations with abundant natural resources.

2.4. Theoretical Frameworks for CRM Supply Chain Resilience

Creating a resilient supply chain for CRMs requires a systematic strategy based on recognized theoretical models. Several supply chain resilience frameworks provide information about how CRM supply chains can resist disruptions, recover from shocks, and sustain operational stability.

2.4.1. Supply Chain Resilience Models

1. **Yossi Sheffi's Resilience Model**

A resilience model, created by supply chain management professor Yossi Sheffi of MIT, focuses on how supply chains and organizations anticipate, endure, and bounce back from disruptions. His approach is widely used in supply chains for manufacturing, logistics, and CRM to handle geopolitical risks, trade dependencies, and unforeseen disruptions like export restrictions or pandemics (Sheffi, 2007). One of the most well-known is Yossi Sheffi's Resilience Model, which highlights two key competencies: recovery (the rate and effectiveness of one's recovery) and resistance (the capacity to withstand shocks).

Given Italy's heavy reliance on imports, especially from China, which provides more than 90% of the EU's rare earth elements, this is crucial in the context of CRM (IEA, 2022). As demonstrated during the 2010 rare earth crisis, when China's export restrictions caused a 900% price increase, Sheffi's model suggests diversification, stockpiling, and quick procurement to manage risks (Humphries, 2013). Similar resilience strategies, like moving suppliers and reorganizing production, were employed by businesses like Volkswagen during the COVID-19 semiconductor shortage (Shih, 2020). Italy may use Sheffi's framework to enhance CRM security through the use of digitalized supply chain solutions and proactive risk management.

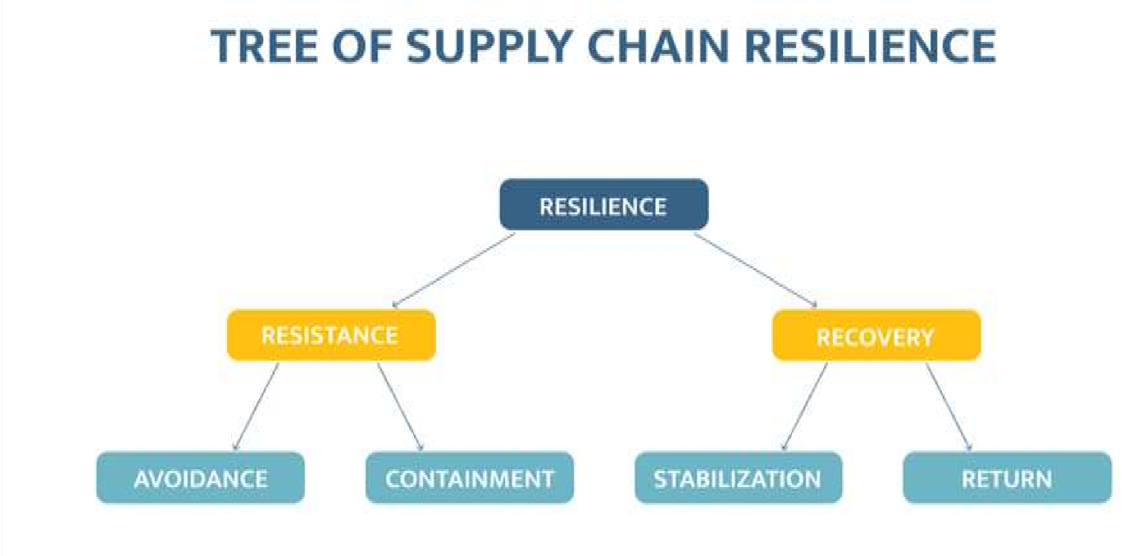


Figure 2.3: Sheffi's Resilience Model (Agistix, 2023)

This diagram visually shows Sheffi's Resilience Model, which divides resilience into resistance and recovery, as he says. Resistance, through avoidance and containment, indicates efforts to minimize or absorb disruptions, whereas recovery, through stabilization and return, demonstrates the efficient process of resuming normal activities. It underlines Sheffi's emphasis on proactive risk management and adaptable solutions for ensuring supply chain stability in the face of uncertainty (Sheffi, 2007).

2. **Supply Chain Resilience Index**

A thorough index that assesses a nation's or business's ability to withstand and bounce back from supply chain disruptions is the Supply Chain Resilience Index (SCRI). To find out how resilient a supply network is to outside shocks like trade restrictions, natural disasters, or geopolitical crises, it evaluates a number of factors, such as diversification, redundancy, adaptability, and structural readiness. Supplier diversification, exposure to geopolitical risk, trade flexibility, stockpile capacity, infrastructure efficiency, and technology adoption are important factors that are taken into account when calculating the SCRI. Each component is weighted based on how it affects resilience; nations with a diverse supply base, strong trade alliances, strategic reserves, and sophisticated logistics receive higher ratings. A country like Italy, which is primarily reliant on imports, would score worse in CRM security due to limited domestic production and significant vulnerability to external threats, emphasizing the importance of diversification and stronger supply chain management.

By incorporating the SCRI into policy decisions, Italy can compare its CRM supply chain security to other EU countries and establish focused plans to strengthen its position in the EU's resource strategy.

3. Import Dependency Ratio

The Import Dependency Ratio (IDR) assesses how heavily a country relies on imports to meet its demand for a certain resource. It's computed as:

$$IDR= \left(\frac{Imports - Exports}{Apparent\ Consumption}\right) \times 100$$ (Eurostat, 2023)

It is apparent that consumption is the total amount of a material utilised domestically, calculated by adding production and subtracting imports and exports. A higher IDR reflects a country's reliance on foreign suppliers, increasing its vulnerability to supply chain disruptions, trade restrictions, and geopolitical threats.

In recent decades, the EU's import dependency ratio has increased significantly, particularly in energy, technology, and raw materials. This reflects the increasing globalisation of trade and the EU's need to acquire specialised goods and services from beyond its boundaries. As the EU continues to face issues such as climate change, energy transitions, and economic transformations, the import dependency ratio may continue to play an important role in setting future trade and economic policy (Eurostat, 2023).

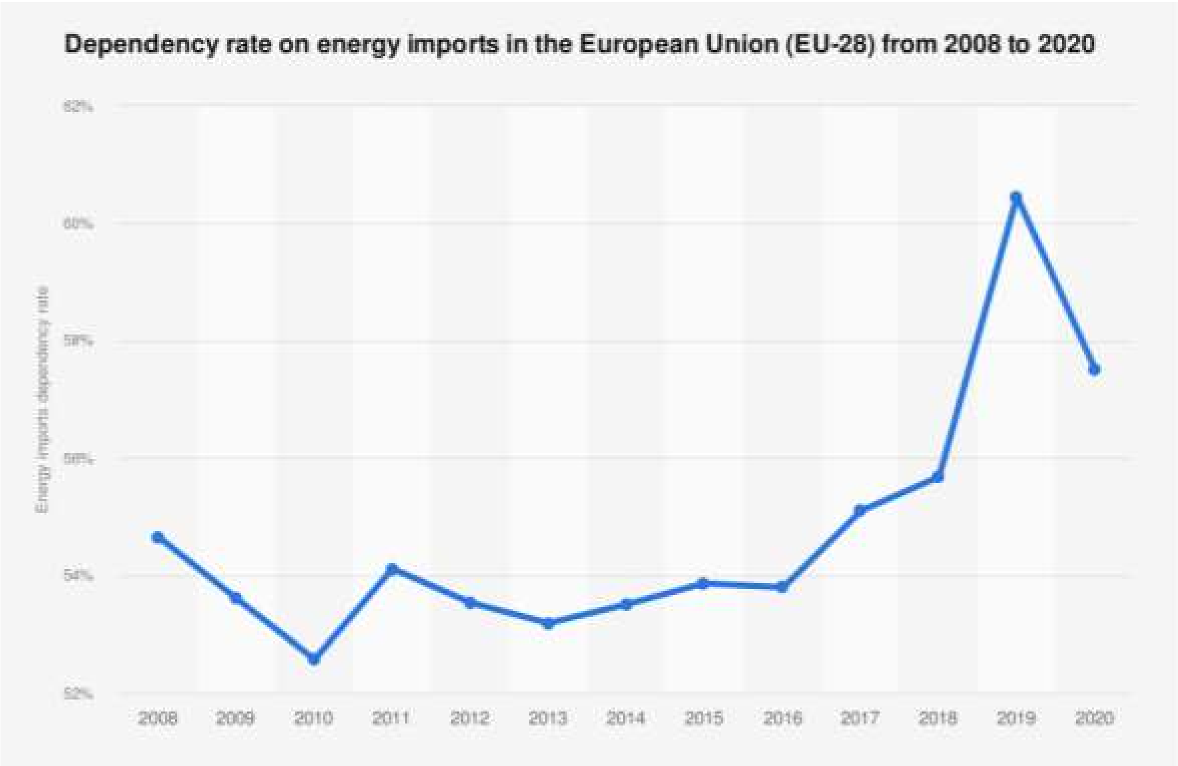


Figure 2.4: Dependency Rate on Energy Imports in the EU (Statista, 2023)

A study carried out for the years from 2008 to 2020 show how the imports have been constantly increasing as shown in figure 2.4. There's a slight decrease by the year 2020; however, in the recent years, there has been a reverse where imports are escalating.

2.4.2. Engineering Management Approach

In a number of fields, such as supply chain, manufacturing, and procurement, engineering management techniques optimize resources, boost productivity, and streamline operations by combining engineering principles and management practices. These methods aim to create robust, sustainable systems that maximize value while cutting down on waste and inefficiency.

1. **Lean Principles**

Lean principles aim to optimize processes in order to reduce waste and boost productivity. Increasing value for the customer while cutting costs, time, and resources is the main goal of this approach. Continuous improvement and operational efficiency are necessary to boost productivity.

2. **Six-Sigma**

Six Sigma is a data-driven methodology that aims to improve process quality by identifying and eliminating sources of fault or variation. Six Sigma uses statistical tools to produce near-perfect operations with minimum errors, resulting in increased quality and customer satisfaction.

Figure 2.5: Six Sigma (Quality Magazine, 2022)

The above figure 2.5 summarizes how Six Sigma uses a systematic technique called DMAIC (Define, Measure, Analyse, enhance, and Control) to enhance processes. It starts with defining the problem and project goals, which ensures a comprehensive grasp of the customer's requirements. Measurement is acquiring data about the current process in order to find performance gaps. During the Analysis phase, the data is reviewed to determine the fundamental causes of faults or inefficiencies. The Improvement stage focusses on creating solutions to these issues and optimising the process. Finally, Control ensures that the gains are retained by implementing monitoring systems and standardised procedures to ensure constant performance.

3. **Agile Procurement**

Agile procurement is a method that incorporates agile concepts—often used in software development—into the procurement process. It places a strong emphasis on flexibility, quick iteration, and responsiveness to shifting consumer needs and market conditions. Agile procurement makes it possible to make decisions more quickly and adapt to changing needs, which increases supply chain resilience.

4. **Value Stream Mapping (VSM)**

Value Stream Mapping (VSM) is a method for examining and planning how information and materials move through a process. VSM guides overall value stream optimization by visually mapping the current state and assisting in the identification of inefficiencies and improvement opportunities.

5. **Just-in-time and Just-in-case (JIT-JIC)**

By producing or acquiring goods only when required, the Just-in-Time (JIT) and Just-in-Case (JIC) strategies seek to lower inventory and holding costs. Just-in-Case, on the other hand, ensures operational continuity by keeping excess inventory on hand as a safeguard against possible disruptions.

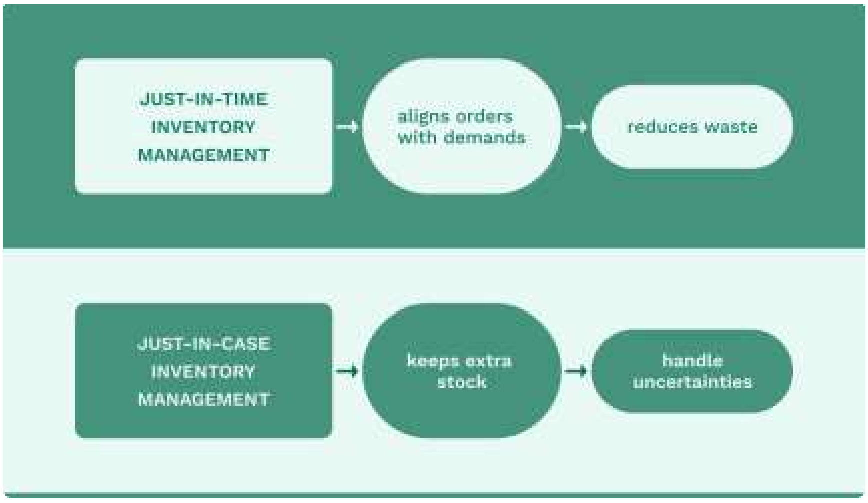


Figure 2.6: JIT and JIC Comparison (WorkTrek, 2023)

The above figure 2.6 briefly explains the differences between just-in-time and just-in-case strategies.

6. **Total Productive Maintenance (TPM)**

An approach to maintenance management known as total productive maintenance (TPM) places a strong emphasis on proactive and preventative measures to preserve the effectiveness of equipment. In order to decrease downtime, boost dependability, and improve productivity, it involves every employee in equipment maintenance.

7. **Kaizen**

Kaizen is a continuous improvement philosophy that promotes small, gradual process changes. Kaizen encourages a culture of small, regular improvements that add up to large long-term increases in productivity and efficiency by involving all employees in problem-solving and idea generation.

2.4.3. Economic and Geopolitical Theories

The European Union's reliance on outside suppliers, trade policies, and governmental actions are all shaped by economic and geopolitical factors. The EU's strategic resource management is explained by a number of key theories.

- **Strategic Resource Dependency Theory** highlights the dangers of depending on outside sources for essential resources. It suggests that nations with high import dependency might be more vulnerable to supply chain failures, price fluctuations, and geopolitical pressures. This notion is supported by the EU's reliance on non-EU nations for essential components like energy and raw materials, which motivates diversification initiatives and attempts to boost domestic manufacturing.

- **International Trade Theories**, such as Comparative edge and Heckscher-Ohlin Theory, advocate for countries or areas to specialise in producing items where they have an edge in efficiency and trade for what they lack. However, for key resources, pure market-driven trade may not be sufficient, prompting the EU to implement policies that combine free trade with strategic stockpiling and investment in alternative providers.

- **Government Intervention Theories**, such as economic nationalism and mercantilism, highlight how crucial government actions are to securing vital resources. The EU uses trade agreements, industry regulations, and strategic partnerships to put these ideas into practice and reduce its dependency on outside suppliers. One such intervention that aims to increase domestic production, recycling, and international cooperation is the European Critical Raw Materials Act.

2.5. Historical Case Studies of CRM Supply Disruptions

The supply of CRMs has been significantly disrupted globally as a result of geopolitical tensions, trade restrictions, and market volatility. Risks for nations that heavily rely on CRM imports include supply shortages, price volatility, and strategic vulnerabilities. Analyzing previous supply disruptions offers valuable insights into the political and economic ramifications of such disasters, as well as the risk-mitigation strategies used by countries. Prominent events, like China's export restrictions on rare earths, show how resource control can be a geopolitical tool that motivates efforts worldwide to fortify and diversify supply chains.

1. **China's Rare Earth Export Bans (2010-2023)**

The top supplier of rare earth elements (REEs) in the world, China, has severely disrupted international markets by strategically abusing export restrictions to exert geopolitical influence. The 17 metals known as rare earth elements are essential to high-tech sectors like electronics, renewable energy, and defense. A few lists of rare earth elements are shown in figure 2.7 below, highlighting their significance in contemporary technology.

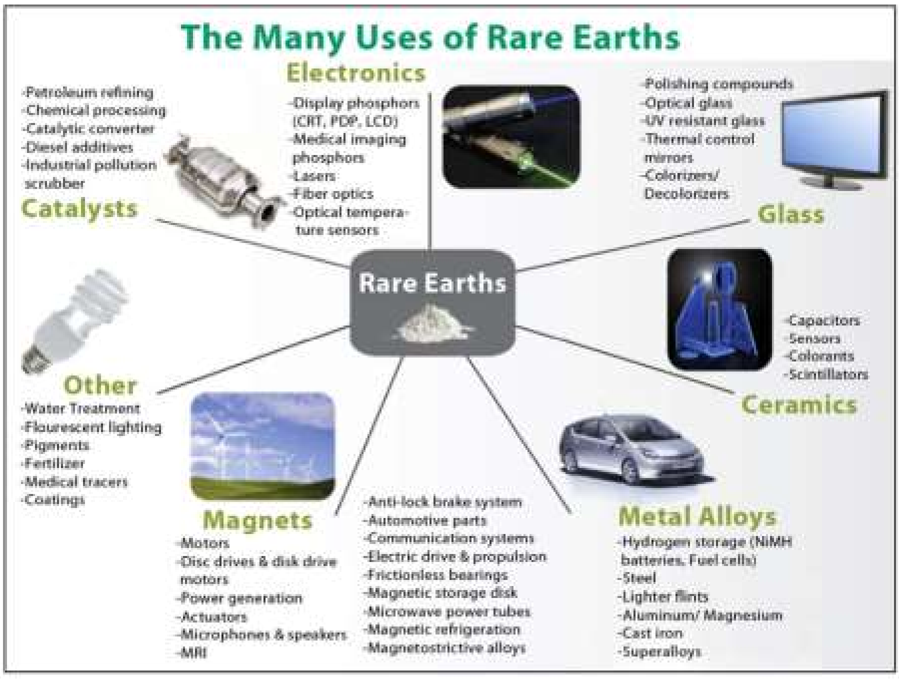


Figure 2.7: Uses of REEs (Alonso et al., 2020)

Understanding the importance of these aspects helps to contextualise the impact of China's export restrictions on global sectors and supply networks.

In 2010, China restricted exports of rare earth elements, citing environmental concerns and the need for greater domestic industry oversight. However, this decision was widely interpreted as a response to geopolitical pressures, specifically a territorial conflict with Japan (Bradsher, 2010). The limits caused a substantial increase in global rare earth prices, forcing countries such as Japan, the United States, and the EU to seek alternate suppliers, engage in recycling, and resume domestic mining activities (for example, the reopening of the Mountain Pass mine in the United States) (Humphries, 2013). The WTO later overturned China's limitations, requiring it to ease export restraints in 2015 (WTO, 2014).

In 2023, China reinstated export curbs on gallium and germanium, two crucial minerals used for electronics and defence purposes. This move, widely interpreted as retaliation for Western limits on China's access to advanced chip technology, sparked renewed concerns about supply chain vulnerabilities (Matsuda, 2023). The EU and other global players responded by boosting efforts to diversify supply chains, expand domestic production, and deepen cooperation with resource-rich states.

2. **Russia-Ukraine Conflict (2022-present)**

The conflict between Russia and Ukraine has caused severe disruptions in global supply chains, particularly for CRMs such as nickel, palladium, and other important metals. Russia is a major global source of these commodities, and geopolitical tensions, combined with Western sanctions, have resulted in market volatility, supply shortages, and price variations (IEA, 2022).

Nickel, which is required for stainless steel and electric vehicle (EV) batteries, experienced significant price increases in early 2022 due to concerns about Russian supply interruptions. To address the extraordinary volatility, the London Metal Exchange (LME) temporarily banned nickel trade (Bloomberg, 2022). Meanwhile, palladium, an important metal for catalytic converters in the car industry, faced supply limitations because Russia controls about 40% of the global supply (USGS, 2023). This raised demand for alternative energy and recycling activities.

Aside from nickel and palladium, the conflict had an impact on neon gas, which is vital for semiconductor fabrication and was formerly supplied by Ukraine. The crisis highlighted the hazards of geopolitical reliance on key suppliers and expedited the EU's efforts to diversify supply chains, enhance domestic production, and secure alternative sources through strategic partnerships.

3. Covid-19 Pandemic

Serious weaknesses in global supply networks were exposed by the COVID-19 pandemic, especially for CRMs and crucial industrial components. Severe supply chain shocks brought on by lockdowns, labor shortages, and transportation disruptions led to production delays and price increases in a variety of industries. The collapse of logistics and transportation networks, which led to supply bottlenecks as a result of port closures, container shortages, and restrictions on cross-border trade, was one of the most notable consequences. Delays in obtaining essential ingredients caused significant disruptions to just-in-time (JIT) manufacturing-dependent industries like electronics, automotive, and renewable energy.

The epidemic also brought to light the risks associated with excessively concentrated supply chains, especially in nations like China, which control the majority of CRM manufacturing and processing. In order to increase resilience, the EU and other nations increased their efforts to diversify their supplies, increase their stockpiles, and invest in domestic manufacturing as a result of this over-reliance.

The necessity of supply chain agility, nearshoring, and digitalization in enhancing transparency and adaptability are among the crisis's most important lessons. The event highlighted the importance of strategic resource planning, effective crisis management frameworks, and collaboration between governments and industries to ensure long-term supply security.

4. US-EU Trade Wars and Sanctions

Critical raw material (CRM) trade policy has long been impacted by geopolitical tensions between the US and the EU, which have an impact on supply chains and market access. Industries that depend on steady CRM flows, like high-tech manufacturing, renewable energy, and defense, have been impacted by trade disputes, taxes, and sanctions.

The United States Inflation Reduction Act (IRA), which prioritizes CRMs sourced in the United States while providing subsidies for domestic clean energy production, has been a major source of contention. Concerns about possible trade distortions and restricted access to US markets were raised in the EU as a result, which prompted talks on fair competition and cooperative strategic resource use.

CRM supply chains have also been impacted by sanctions on third-party suppliers, such as restrictions on the export of Chinese technology and Russian metals, necessitating a review of procurement practices by the US and the EU. In order to preserve a steady and varied supply of essential resources, these geopolitical upheavals have led to increased investment in regional mining, recycling programs, and improved transatlantic cooperation.

The interdependence of global CRM markets and the significance of well-balanced policies that enhance resource security while maintaining strategic alliances are ultimately highlighted by trade disputes and sanctions.

2.6. The Evolution of CRM Policies in the EU and Beyond

Governments everywhere have put in place a number of regulations to guarantee robust and stable supply chains as CRMs become more crucial for national security, renewable energy, and high-tech industries. To lessen supply concerns, some nations prioritize trade restrictions and state control, while others opt for market-driven policies, strategic hoarding, or international cooperation.

This section examines key CRM policies of major economies, highlighting their attempts to boost domestic production and reduce reliance on foreign sources, such as the US's Inflation Reduction Act (2022) and the EU's Critical Raw Materials Act (2023) (European Commission, 2023; U.S. Government, 2022). Additionally, it illustrates two different forms of resource security by contrasting Japan's strategic stockpiling strategy with China's state-controlled CRM policy (Zhang and Li, 2022; Ministry of Economy, Trade and Industry, 2021). Additionally, resource-rich nations can leverage their mineral resources to strengthen global supply chains, as demonstrated by the CRM alliance and sustainable mining initiatives in Canada and Australia. By looking at these different strategies, we can learn how different places strike a balance between geopolitical, economic, and environmental concerns when acquiring necessary raw materials.

2.6.1. Comparative Analysis of Global CRM Strategies

Numerous legislative strategies to guarantee supply chain resilience have developed as countries have come to recognize the strategic significance of critical raw materials (CRMs) in sectors like clean energy, defense, and high-tech manufacturing. To reduce supply risks, some governments employ governmental control, stockpiling, or sustainable mining methods, while others place a higher priority on regional production and strategic alliances. The global environment of CRM governance and its effects on trade, security, and economic competitiveness can be better understood by comprehending these various approaches.

- **EU’s CRM Act (2023) vs. US Inflation Reduction Act (2022)**

The EU's Critical Raw Materials Act (2023) and the United States' Inflation Reduction Act (2022) (IRA) are two distinct approaches to securing CRMs, although both have the same goal of reducing reliance on overseas suppliers, particularly China.

Table 2.2: CRM Act and US Act Comparison

Aspect	EU’s CRM Act (2023)	US Inflation Reduction Act (2022)
Main Goal	Reduce CRM dependency through diversification, domestic production, and recycling	Secure domestic supply chains by incentivising United States-based mining, processing, and allied trade relations
Approach	Regulatory-driven, sustainability-oriented	Subsidy-driven, protectionist
Key Targets	-10% of SRM extraction in the EU - 40% of SRM processing in the EU - 25% of SRM recycling in the EU -No more than 65% of any SRM from a single third country (supply diversification target) (European Commission, 2023)	- 40% of EV battery minerals from U.S. or FTA partners (2024), rising to 80% by 2027 (U.S. Government, 2022) - Production tax credits for domestic clean energy industries
International Cooperation	Strategic partnerships with CRM-rich countries	Focus on Free Trade Agreement (FTA) partners, such as Canada, Australia, and Chile

Sustainability Focus	Strong emphasis on recycling, circular economy, and environmental legislations	Less emphasis on sustainability and more on production and economic incentives
Financial Support	Public and private investments in CRM projects, funding for research & development	~$369 billion in subsidies, tax credits, and production incentives
Industry Impact	Supports European battery, renewable energy, and industrial sectors	Boosts U.S. mining, EV battery manufacturing, and clean energy industries

Despite their differing tactics in table 2.2, both legislation have the same basic goal: to reduce dependency on foreign suppliers, particularly China, while boosting domestic and allied supply networks. Understanding the distinctions enables governments and industry leaders to handle CRM supply constraints and forecast future global market developments.

- **China's State-Controlled CRM Strategy vs. Japan's Strategic Stockpiling**

China and Japan have taken opposite approaches to securing their key raw material (CRM) supply chains: one through state control and export prohibitions, and the other through strategic stockpiling and diversification. China, the world's leading manufacturer and processor of CRMs, uses its influence over supply chains as a geopolitical and economic tool. In contrast, Japan, which has limited local CRM resources, focusses on accumulating reserves, diversifying suppliers, and investing in recycling to reduce supply concerns (Ministry of Economy, Trade and Industry, 2021).

As clear in the figure 2.8, China is a leading supplier providing most of the CRMs; whereas, Japan is highly dependent on outsourcing them.

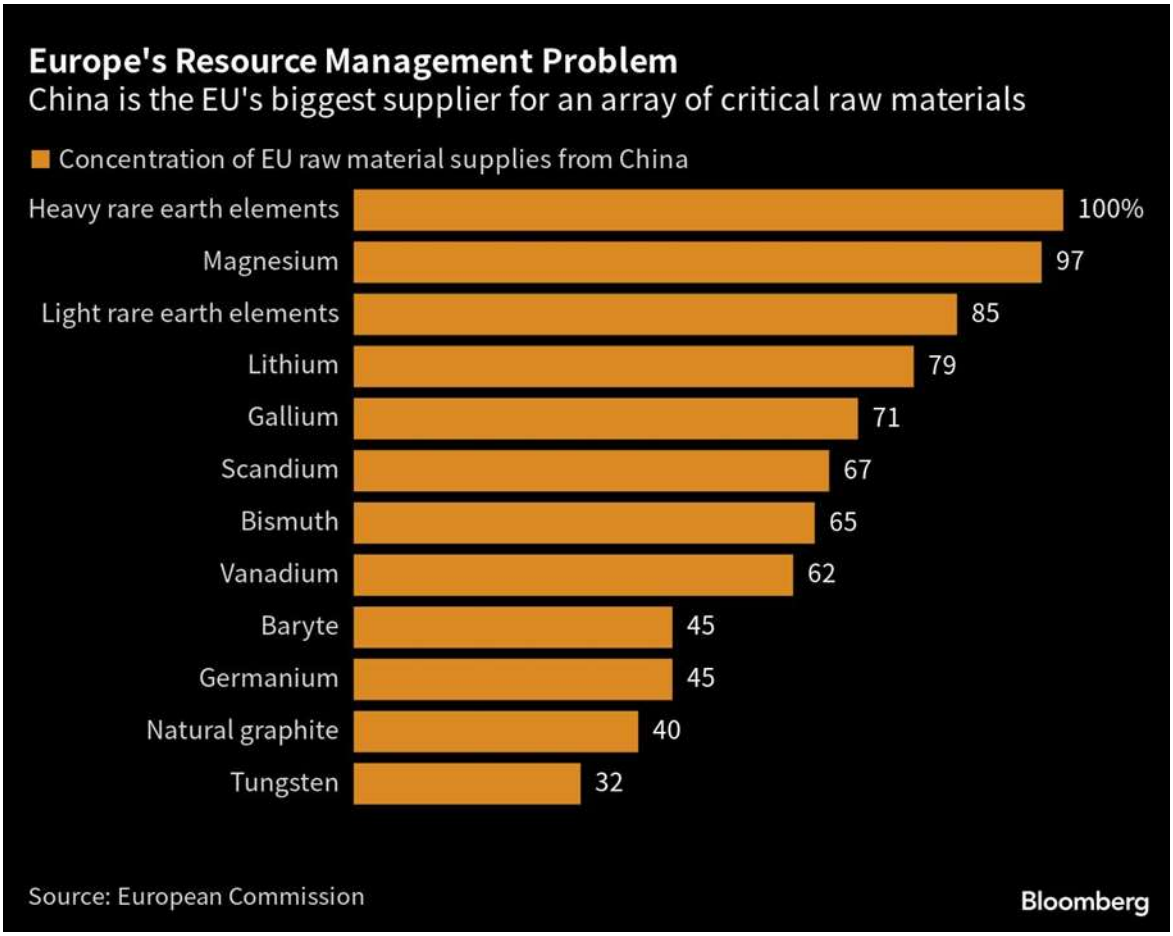


Figure 2.8: Europe's Resource Management Problem (Mining.com, 2023)

Table 2.3 highlights significant differences in supply chain management, policy initiatives, and long-term resource security between China's state-controlled CRM strategy and Japan's stockpiling approach.

Table 2.3: China and Japan Comparison Strategies

Aspect	China's State-Controlled CRM Strategy	Japan's Strategic Stockpiling
Approach	Government-mandated production, export restrictions, and price limitations	Government-led stockpiling, supply chain diversification, and recycling

Supply Chain Control	Controls more than 70% of global CRM processing and has a significant impact on pricing and availability	No significant domestic CRM resources; relies on long-term supply agreements and partnerships
Key Policies	- Export limits and quotas (for example, Japan's rare earth ban in 2010, and gallium and germanium restrictions in 2023). - Significant state incentives for domestic CRM production. - Strict environmental regulations for mining	-Japan Oil, Gas, and Metals National Corporation (JOGMEC) manages stockpiling -establishes long-term supply agreements with nations like Australia and Vietnam -invests in CRM recycling and substitute technology
Geopolitical Use	Uses CRM exports as economic leverage in trade disputes	Stockpiling mitigates risks from geopolitical tensions and trade restrictions
Sustainability Focus	Increases regulations on the environment while prioritising control over global supply chains	A strong emphasis on recycling and material substitution to reduce reliance on imports
Industry Impact	Influences global CRM prices and availability, forcing countries to seek alternative suppliers	Provides buffer stockpiles for Japanese sectors (e.g., automotive and electronics) during supply disruptions

These various techniques represent each country's own approach to securing vital materials—China through market control and export regulations, and Japan through resilience-building measures such as stockpiling and diversification.

- **Australia and Canada’s Approach to Sustainable Mining and CRM Alliances**

Australia and Canada are key players in the worldwide critical raw materials (CRM) market, noted for their abundant natural resources and dedication to environmentally friendly mining operations. Both countries are focussing on responsible resource extraction, environmental stewardship, and strategic relationships to assure a steady and sustainable supply of CRMs for the global market. Australia's strategy emphasises innovative mining technology and strong relationships with Asia-Pacific and European partners, whereas Canada prioritises ecologically responsible mining, recycling activities, and strategic CRM partnerships with EU and US markets.

The table 2.4 compares Australia and Canada's sustainable mining practices and CRM alliance policies, highlighting their efforts to assure a reliable and environmentally responsible supply of vital raw materials.

Table 2.4: Australia and Canada's CRM Approaches

Aspect	Australia’s Approach to Sustainable Mining and CRM Alliances	Canada’s Approach to Sustainable Mining and CRM Alliances
Resource Availability	Rich in lithium, rare earth elements, and nickel	Abundant in cobalt, lithium, and nickel
Sustainability Focus	-Encourages eco-friendly mining technologies -Implements strict environmental regulations -Invests in renewable energy and recycling	- Prioritises ESG norms -promotes carbon-neutral mining and reforestation -Investment in recycling infrastructure
Strategic Alliances	-Collaboration with Japan, South Korea, and the EU on CRM supply	- Close links with the EU and the United States to diversify supply chains - Participate in global CRM initiatives and

	-Australia-India Critical Minerals Investment Partnership	cross-border collaborations
Industry Impact	-Increases worldwide CRM supply for electric vehicles and batteries -Significantly impacts Asia-Pacific supply chains	-Improves CRM availability for North American industries -Supports EU supply diversification and sustainable energy transitions

The two countries are strengthening their status as significant CRM suppliers by implementing sustainable mining techniques and creating crucial alliances. Their emphasis on responsible resource management and environmental preservation guarantees that global demand for vital resources is addressed while maintaining long-term sustainability.

- **US-EU Trade Wars and Sanctions: Geopolitical Conflicts and Their Impact on CRM Trade Policies**

Geopolitical conflicts, particularly trade wars and sanctions between the United States and the European Union, have had a substantial impact on the global CRM industry. As both regions fight for access to vital commodities, policies have evolved to reflect the importance of resource security, trade protectionism, and economic self-sufficiency. The United States and the European Union have implemented tariffs, sanctions, and export restrictions on vital resources, causing trade disruptions, price volatility, and supply chain uncertainty. These geopolitical tensions have prompted greater efforts to diversify supply sources, ensure access to vital minerals, and create alternatives to lessen reliance on unfriendly states.

Some key impacts of US-EU trade wars and sanctions on CRM policies include:

1. **Increased Tariffs and Trade Barriers:**

High production costs and increased pressure to find alternative supplies within allies are the results of tariffs on raw materials like steel, aluminum, and rare earths. Tensions have increased as a result of the US-China trade war, prompting the US to increase domestic production and look for agreements with EU partners to gain access to vital minerals.

2. **Export Control Measures**

Both the United States and the European Union have established export limits on essential raw commodities, typically as part of larger geopolitical goals. For example, China's previous export limits on rare earths forced the United States and the European Union to adopt strategies for strategic storage and alternative sources in places such as Australia and Africa.

3. **Diversification of Supply Chain**

The US and EU have decreased their reliance on countries involved in trade disputes and diversified their supply chains in response to trade disruptions. For instance, the EU's Critical Raw Materials Act (2023) places a strong emphasis on international cooperation and supply diversification, especially with countries that have abundant natural resources but are independent of China.

4. **Geopolitical Influence on Trade Agreements**

The US and the EU have established new trade agreements and collaborations with resource-rich nations like Australia, Canada, and Chile as part of their CRM policies. These partnerships are seen as essential to reducing geopolitical concerns and guaranteeing a steady supply of vital resources.

2.7. The Role of Digitalization and AI in CRM Supply Chain Optimization

As demand for CRMs rises, digitalisation and artificial intelligence (AI) play an increasingly important role in supply chain optimisation. These technologies provide novel answers to some of CRM management's most pressing concerns, including demand forecasting, logistical efficiency, and risk avoidance (Smith et al., 2021). AI applications in resource forecasting aid with demand prediction and supply planning, while blockchain improves transparency and traceability in mining and material tracking procedures (Jones and Davis, 2021). Furthermore, the integration of smart contracts and automation is transforming procurement strategies and risk management by increasing transaction efficiency and assuring regulatory compliance. The next sections investigate the revolutionary influence of various digital technologies on the CRM supply chain.

2.7.1. AI Application in Resource Forecasting

Predicting the future has become a business superpower in an era of rapid change and increased uncertainty. Accurate forecasting has never been more crucial, whether one is managing volatile markets, reacting to unforeseen world events, or predicting shifting consumer preferences.

For instance, businesses faced severe disruptions after the COVID-19 pandemic. Whole industries were upended, demand trends changed, and supply chains collapsed. In response to the pandemic, 93% of participants in a McKinsey survey said they enhanced their organization's supply chain strategy, highlighting the significance of flexibility and adaptation.

By boosting precision, effectiveness, and responsiveness, AI is enhancing resource forecasting in the CRM supply chain.

Traditional forecasting methods frequently struggle with market sensitivity, geopolitical concerns, and changing demand, making AI-powered solutions critical to enhancing supply chain resilience.

2.7.1.1. What is AI Forecasting?

Businesses collect a large amount of data from many sources, and it is vital to use this data to predict future trends and results. In such cases, AI forecasting is a game-changing invention that not only complements traditional forecasting approaches but also provides IT executives with unprecedented precision and adaptability.

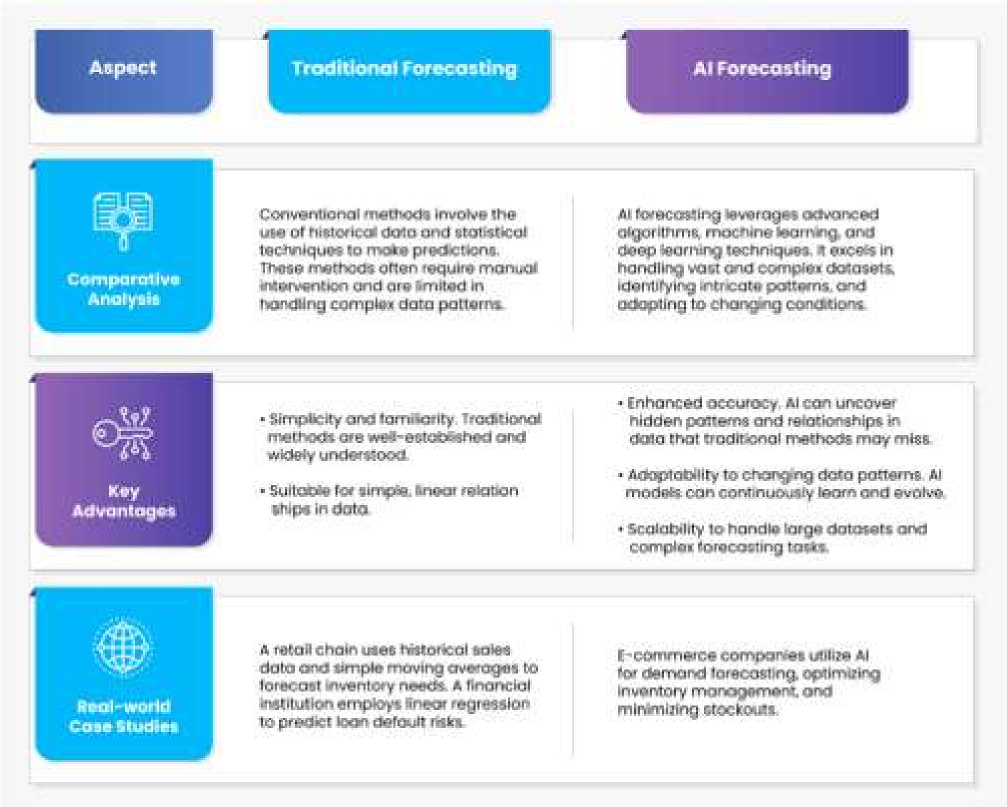
At its core, AI forecasting is the use of artificial intelligence algorithms to anticipate future occurrences or trends using historical data and patterns. It overcomes the constraints of traditional forecasting by utilising modern algorithms, machine learning, and deep learning models to analyse large datasets quickly and correctly.

According to McKinsey, corporations in industries such as telecoms, electricity, natural gas, and healthcare have discovered that AI forecasting engines have the potential to automate up to 50% of their workforce-management tasks. Over time, this automation helps to enhance hiring practices and overall operational resilience in addition to saving about 15% on expenses.

AI forecasting is essential for turning data into insights that can be put to use. "What will our sales figures look like next quarter?" is one of the important questions it enables IT leaders to address. In order to adapt to changing demand patterns, how can we optimize our supply chain? What trends can we expect to see in client preferences going forward? Businesses can react proactively to impending problems and opportunities thanks to AI forecasting (McKinsey & Company, 2022).

Businesses have long depended on traditional techniques of forecasting. AI forecasting has resulted in a dramatic shift in how forecasts are created and used.

The following figure 2.9 is a comparison of traditional versus AI forecasting.



Aspect	Traditional Forecasting	AI Forecasting
Comparative Analysis	Conventional methods involve the use of historical data and statistical techniques to make predictions. These methods often require manual intervention and are limited in handling complex data patterns.	AI forecasting leverages advanced algorithms, machine learning, and deep learning techniques. It excels in handling vast and complex datasets, identifying intricate patterns, and adapting to changing conditions.
Key Advantages	• Simplicity and familiarity. Traditional methods are well-established and widely understood. • Suitable for simple, linear relation ships in data.	• Enhanced accuracy. AI can uncover hidden patterns and relationships in data that traditional methods may miss. • Adaptability to changing data patterns. AI models can continuously learn and evolve. • Scalability to handle large datasets and complex forecasting tasks.
Real-world Case Studies	A retail chain uses historical sales data and simple moving averages to forecast inventory needs. A financial institution employs linear regression to predict loan default risks.	E-commerce companies utilize AI for demand forecasting, optimizing inventory management, and minimizing stockouts.

Figure 2.9: Traditional vs. AI Forecasting (McKinsey & Company, 2022)

AI forecasting offers a notable improvement in accuracy, adaptability, and scalability compared to traditional forecasting techniques, which are well-established and appropriate for basic forecasts.

AI forecasting has revolutionary impact across industries, allowing firms to foresee trends, optimize operations, and make data-driven decisions. Here's how different industry sectors shown in figure 2.10 use AI forecasting:

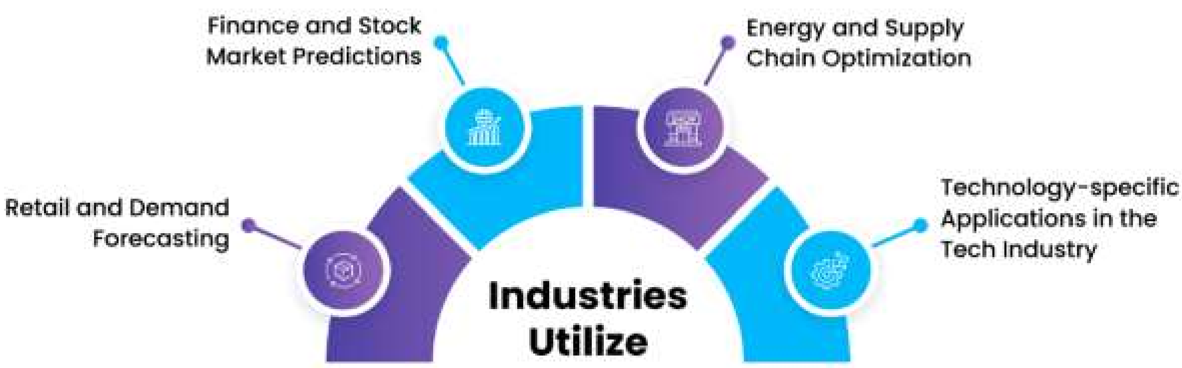


Figure 2.10: Industries AI Use (McKinsey & Company, 2022)

1. **Retail and Demand Forecasting**

Retail is one business where AI forecasting has become essential. Retailers confront the issue of effectively controlling inventory and anticipating customer demand, and artificial intelligence forecasting can be extremely useful.

Take Walmart for example. The retail giant uses AI-powered demand forecasting models to estimate which products people are likely to buy in various outlets. This guarantees that shelves are filled with the correct items at the appropriate time, reducing waste and increasing sales.

AI forecasting is also a key driver of personalised shopping experiences. Alibaba's recommendation system analyses consumers' browsing and purchasing history to offer products based on their preferences. This not only improves consumer satisfaction but also increases sales, demonstrating the vast potential of AI in the retail sector.

2. **Finance and Stock Market Predictions**

Time is money in the financial industry, and AI forecasting provides firms with a competitive edge by producing precise and timely predictions. Large amounts of financial data are analyzed by AI-powered algorithms to predict trends in the stock market.

AI prediction models are a major component of quantitative hedge funds like Renaissance Technologies. These funds execute high-frequency trades and uncover hidden patterns in financial data using machine learning algorithms, often outperforming conventional investment strategies.

Fraud detection and risk assessment can also benefit from AI forecasting. AI is used by banks like JPMorgan Chase to identify potentially fraudulent transactions and control risks, safeguarding customer assets and the institution's reputation.

3. **Healthcare and Patient Outcome Projections**

Additionally, AI forecasting is revolutionizing the healthcare industry by improving operational effectiveness and patient care. Because AI models can predict patient outcomes, medical professionals can tailor treatment plans and take early action.

A machine learning tool has been created by researchers from Yonsei University and Boston Children's Hospital. Its goal is to forecast the likelihood that patients will miss scheduled pediatric appointments.

4. **Energy and Supply Chain Optimization**

AI forecasting has significant applications in the energy sector, particularly in resource and supply chain management. Forecasting is essential for energy organizations because they regularly deal with complex variables like weather and demand fluctuations.

In order to optimize energy resource allocation and maintain grid stability, Pacific Gas and Electric (PG&E) in California, for instance, uses AI forecasting to predict electricity demand. This encourages the switch to renewable energy sources while also reducing operating costs.

The impact of AI forecasting in logistics is comparable. AI algorithms are used by FedEx and other companies to forecast package delivery times, optimize routes, and effectively allocate resources. This reduces fuel use and the impact on the environment while guaranteeing on-time delivery.

5. **Technology-specific Applications in the Tech Industry**

AI forecasting is essential for directing innovation and enhancing user experiences in the IT industry.

Technology companies also use AI forecasting to manage their networks. AI is used by telecom firms like AT&T to forecast network traffic patterns and distribute capacity effectively, guaranteeing uninterrupted connectivity for customers.

2.7.1.2. Key AI Applications in Resource Forecasting

- **Machine Learning for Demand Prediction**

By analyzing past data, market trends, and outside variables (such as trade regulations and economic changes), AI-powered algorithms are able to more precisely estimate CRM demand and reduce the possibility of shortages or overstocking.

- **Predictive Analytics in Supply Chain Disruptions**

Businesses can make proactive adjustments to their supply plans by using AI-powered predictive analytics to identify potential disruptions like geopolitical crises, logistical delays, and regulatory changes.

- **Real-Time Data Processing**

AI systems use real-time mining output, logistical updates, and market variations to optimise buying decisions, resulting in a consistent and cost-effective CRM supply.

AI can assist firms anticipate demand shifts, optimise inventory levels, and improve decision-making, making CRM supply chains more adaptable and resilient in an increasingly volatile global market.

2.7.2. Blockchain for Transparency

A blockchain is defined as "a distributed database that maintains a continuously growing list of ordered records known as blocks. "These blocks" are linked using encryption. Each block includes a cryptographic hash of the preceding block, a timestamp, and transaction data (Nakamoto, 2008). A blockchain is a decentralised, distributed, and public digital ledger used to record transactions across multiple computers so that the record cannot be changed retroactively without affecting all subsequent blocks and requiring network consensus.

1. **Blockchain to handle payments and move money:** Transactions handled on a blockchain might be settled in seconds, reducing banking transfer fees.
2. **Blockchain to monitor supply networks**: Businesses may use blockchain to swiftly identify bottlenecks in their supply chains, locate items in real time, and monitor product quality as they transit from manufacturers to shops.
3. **Blockchain for digital identification:** Microsoft is experimenting with blockchain technology to help people manage their digital identities while also providing them control over who has access to that data.
4. **Blockchain for data sharing:** Blockchain could serve as an intermediate for securely storing and moving company data across industries.
5. **Blockchain for copyright and royalties protection**: Blockchain could be used to construct a decentralised database that protects artists' music rights while also providing transparent and real-time royalty distributions to musicians. Open source developers could benefit from blockchain technology as well.
6. **Blockchain for network management in the Internet of Things**: Blockchain could become a regulator of IoT networks to “identify devices connected to a wireless network, monitor the activity of those devices, and determine how trustworthy those devices are” and to “automatically assess the trustworthiness of new devices being added to the network, such as cars and smartphones.”

7. **Blockchain in healthcare:** Blockchain may potentially play an essential role in healthcare: "Healthcare payers and providers are using blockchain to manage clinical trials data and electronic medical records while maintaining regulatory compliance."

The fundamental use of blockchain is as a database for recording transactions, but its advantages considerably outweigh those of traditional databases. Most importantly, it eliminates the risk of tampering by a malicious party, while also delivering the following business benefits:

- **Time savings**

Blockchain reduces transaction time from days to minutes. Transaction settlement is faster because it eliminates the need for central authority verification.

- **Cost savings**

Transactions require less scrutiny. Participants can exchange valuable items immediately. Blockchain avoids duplication of effort by providing parties with access to a shared ledger.

- **Tighter security**

Blockchain's security features protect against tampering, fraud, and cybercrime.

2.7.2.1. How Does a Blockchain Work?

A blockchain is a distributed, decentralized digital ledger that safely logs transactions over a network of computers. It is meant to be open, constant, and impervious to dishonesty. The blockchain is a safe and unchangeable chain of data composed of blocks, each of which has a timestamp, a list of transactions, a distinct cryptographic hash, and the hash of the previous block.

Transactions are broadcast to a network of computers known as nodes when they take place. Before including a transaction in a block, these nodes verify it through a consensus process. Common consensus methods include Proof of Stake (PoS), where validators are selected according to the number of coins they own and stake, and Proof of Work (PoW), where miners solve challenging mathematical puzzles to validate transactions (like in Bitcoin). After verification, cryptographic hashes are used to link the transaction to the previous block and add it to a new block.

One of the distinguishing characteristics of blockchain technology is its decentralisation. Unlike traditional databases, which are managed by a single institution, blockchain functions on a distributed network, with various members maintaining and verifying the ledger. This maintains transparency because all transactions are accessible to participants, and it improves security by making it nearly impossible for any single entity to change previous records. If someone tries to change a block, the changes will destroy the cryptographic ties to following blocks, necessitating approval from a majority of the network—a nearly impossible task.

Since data cannot be readily changed once it has been recorded, blockchain's immutability makes it incredibly secure. This feature is especially useful for applications outside of cryptocurrency. Blockchain, for instance, can track products from production to delivery in supply chain management, guaranteeing authenticity and lowering fraud. Smart contracts, which are self-executing agreements with preset conditions, can automate transactions without the use of middlemen. Blockchain offers a transparent and safe way to store and manage sensitive data, and it is also used in voting systems, identity verification, and healthcare data management (Nakamoto, 2008).

Figure 2.11 visually represents the process of how a blockchain transaction is created, verified, and added to the chain, ensuring security and transparency.

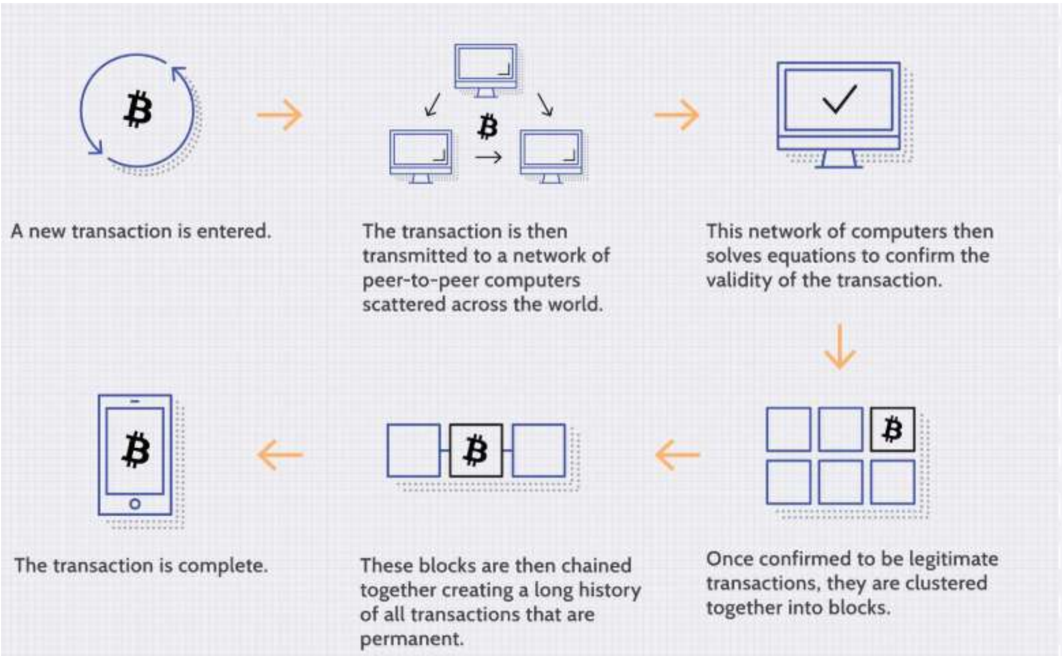


Figure 2.11: Blockchain Process (Nakamoto, 2008)

As previously stated, blockchain technology uses decentralization, cryptographic validation, and immutable record-keeping to securely process and store transactions.

2.7.2.2. Blockchain for Transparency in Mining and Material Tracking

Blockchain technology is developing as an important enabler of transparency in the CRM supply chain, improving traceability, eliminating fraud, and assuring ethical sourcing. Given the intricacies of global CRM trade, blockchain offers a decentralized, tamper-proof ledger for recording transactions at all stages of the supply chain, from mining and processing to distribution and recycling.

Key applications of blockchain in CRM supply chains:

- **End-to-end Material Traceability:** Blockchain ensures ethical sourcing and environmental standards by tracking raw materials from the mine to the finished product.
- **Fraud Prevention and Data Integrity:** The immutability of blockchain records reduces the risk of fraud and counterfeiting by preventing supply chain data modification.
- **Regulatory Compliance and ESG Monitoring:** Blockchain is used by businesses and governments to monitor carbon footprints and confirm adherence to sustainability standards. This guarantees that CRM trade and extraction adhere to global ESG standards.

Blockchain is an essential tool for building trust and resilience in the global raw materials market because it has been demonstrated to increase accountability and efficiency in CRM supply chains.

2.7.3. Smart Contracts and Automation

Digital procurement is more than just switching from manual to electronic processes; it also includes leveraging new technologies like artificial intelligence (AI), machine learning, blockchain, and big data analytics to transform how businesses manage purchasing, supplier relationships, and logistics. These tools enable procurement teams to make data-driven decisions, eliminate operational risks, and increase overall supply chain efficiency.

Today's procurement professionals acknowledge that digitalisation is more than a trend; it is critical to the business's long-term success. A recent PricewaterhouseCoopers (PWC) research from April showed a clear path towards digitalisation, with purchasing departments worldwide aiming for a 70% rate of digital adoption by 2027. This shift is motivated by the desire to improve procurement agility, accuracy, and responsiveness.

The advantages are obvious: real-time data enables organisations to respond quickly to supply chain interruptions, and predictive analytics aids in anticipating future issues and possibilities. Automation minimises manual duties, allowing professionals to focus on strategic decisions. Blockchain technology ensures secure, transparent transactions, making it easier to verify the origin and validity of commodities, especially in areas that value sustainability.

Furthermore, digital procurement supports broader business goals such as corporate social responsibility and environmental sustainability. Companies such as Unilever and Siemens use digital tools to ensure that their supply chains are transparent, traceable, and in line with sustainable principles. These tools enable them to measure carbon footprints, track ethical sourcing, and provide stakeholders visibility into their sustainability initiatives, all while enhancing operational efficiency.

As the global marketplace grows more dynamic and unpredictable, businesses that adopt digital procurement and supply chain management will not only remain competitive but will also drive innovation in the development of future-ready, resilient supply networks. Adopting a digital attitude and consistently developing abilities in these areas is critical for professional progress and influence in today's changing market.

The implementation of digital procurement technology, such as smart contracts and automation, provides several benefits to the CRM supply chain. These advantages go beyond operational efficiency, greatly increasing decision-making, cost reduction, and supply chain resilience (Kshetri, 2018; Zhang and Cheng, 2021). The figure 2.12 below depicts the primary benefits of digital procurement transformation.

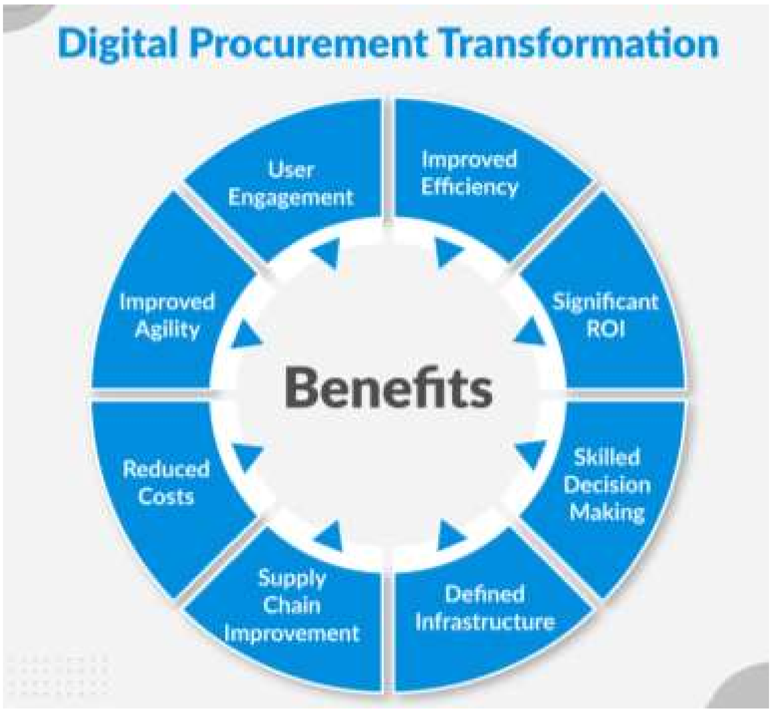


Figure 2.12: Digital Procurement Transformation (SelectHub, 2023)

As depicted in the figure above, digital procurement improves supply chain processes by boosting agility, lowering costs, and optimizing decision making. These benefits make automation and blockchain-based smart contracts critical for reducing risks and ensuring long-term sustainability in CRM buying.

2.7.3.1. Key Applications of Smart Contracts and Automation in CRM Supply Chains

Procurement and risk management in the supply chain for critical raw materials (CRM) are being revolutionized by digital technologies, particularly automation and smart contracts. Blockchain-powered smart contracts eliminate human error and delays in CRM transactions by enabling self-executing agreements that enforce contractual obligations automatically. Automation systems, on the other hand, streamline supplier management, payment processing, and compliance verification, boosting productivity and reducing risk.

- **Safe and Effective Purchasing:** By enabling quick transactions between suppliers and buyers, guaranteeing on-time payments and delivery, and lowering the likelihood of contractual disputes, smart contracts offer safe and effective procurement.

- **Automated Risk Monitoring**: AI technologies analyze market data, geopolitical changes, and supply chain trends to anticipate potential dangers and adjust sourcing strategy in advance.
- **Regulatory Compliance and ESG Enforcement:** Automated systems monitor compliance with environmental and ethical sourcing requirements, maintaining global sustainability standards in CRM extraction and commerce.

According to research, using smart contracts and automation into CRM procurement improves supply chain transparency, operational efficiency, and risk reduction, making it an important driver of resilience in global raw material management.

2.8. Environment and Social Implications of CRM Extraction and Recycling

Beyond economic and industrial concerns, the extraction and recycling of CRMs has significant environmental and social repercussions. Mining operations raise concerns about long-term ecological viability because they contribute to deforestation, soil erosion, and water contamination, especially in Italy and other parts of the world. Additionally, the CRM supply chain usually includes regions with lax labor laws, like parts of Africa and Latin America, where child labor, worker exploitation, and unethical sourcing practices are prevalent. However, recycling CRMs from electronic waste presents a chance to reduce environmental harm and establish a circular economy. However, the effectiveness and scalability of CRM recovery mechanisms must be addressed in order to implement sustainable resource management.

This section explores the environmental, social, and ethical implications of CRM extraction and recycling, emphasising the importance of responsible methods that are consistent with sustainability criteria and regulatory frameworks.

2.8.1. Environmental Impact of CRM Extraction

The extraction of CRMs poses substantial environmental difficulties, as mining operations frequently result in deforestation, habitat damage, water pollution, and increased carbon emissions. Italy, while not a big producer of primary CRMs, has environmental concerns around mineral extraction, including as soil damage and energy-intensive refining procedures. CRM mining hotspots around the world, including China, the Democratic Republic of Congo, and South America, have serious environmental repercussions, which are aggravated by poor implementation of environmental standards in some areas.

Most environmental impacts are caused by use of land, energy, water, chemicals, and the generation of waste.

Mineral production has a significant impact on land usage and change due to mining, infrastructure, processing, and waste storage. Mining has a lower worldwide impact on land usage than logging or agriculture, but its negative impacts are significant and long-term. Resource extraction and processing require significant volumes of water, chemicals, and energy. Waste generation includes overburden (removed soil and subsoil), waste rock (unprocessed blasted rock), and tailings (mineral extraction residue) (Liu et al., 2019). The storage of tailings in major dams poses a substantial danger of radioactive and heavy metal leaks (Jaiswal et al., 2020). All of these characteristics have a different impact shown in figure 2.13 on the environment.

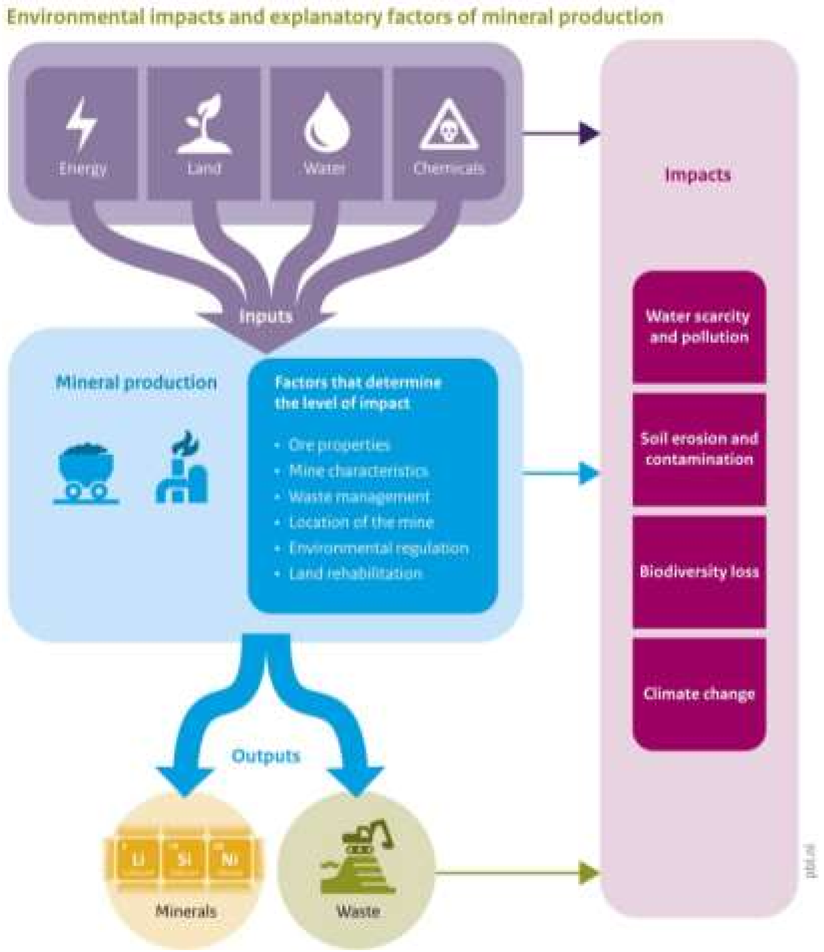


Figure 2.13: Environmental Impacts of CRM (PBL Netherlands Environmental Assessment Agency, 2023)

- **Water Scarcity and Pollution:** Water scarcity is mostly caused by mineral extraction and mine dewatering, leading to pollution. Lithium and copper production require significant amounts of water. Approximately half of global production occurs in areas with substantial water stress. Water contamination is mostly caused by insufficient waste management and land rehabilitation. Contaminated water can convey heavy metals and hazardous substances downstream, damaging these places. This is typically observed in the production of sulfide ores, such as copper, manganese, nickel, and cobalt. Toxic waste from metal extraction and processing is collecting along riverbanks, putting approximately 23 million people at risk.

- **Soil Erosion and Contamination:** Soil erosion and contamination are mostly caused by mine development, ore crushing and milling, and poor waste management. Globally, mines occupy around 100,000 km2 of land, with mining-related waste covering nearly 1 million km2, more than the whole urbanized area. Aluminum production generates significant amounts of red mud, which can lead to increased radioactivity and hazardous substances in the environment. Acid mine drainage near sulfide mines contaminates topsoil and subsoil with heavy metals.
- **Biodiversity Loss:** Because mine development destroys habitat and opens up previously unexplored areas, it directly affects biodiversity. Through local operations like farming, logging, and poaching, as well as soil and water contamination, mines have an indirect impact on biodiversity. Due to its proximity to regions with high biodiversity, nickel mining in particular has a major effect on biodiversity per ton produced. Biodiversity is being threatened by mining operations. Approximately 8,500 km2 of tropical and subtropical rainforest have been directly destroyed by mineral extraction since 2000. Including indirect effects, mining has an impact on about one-third of all forests worldwide.
- **Climate Change:** Mineral production contributes significantly to climate change due to the high energy demand for heavy machinery, smelting oxide metals, and steel manufacturing. Mineral and metal production accounts for approximately 10% of worldwide energy-related greenhouse gas emissions. Deforestation, ecosystem degradation, and manufacturing chemicals with high embodied carbon are further factors driving this trend. Silicon production has the highest climate change impact per ton due to the significant amount of energy required to upgrade low grade quartz to high-quality silicon.

2.8.1.1. Contamination Causes of Insufficient waste Management

Waste products often contain high levels of heavy metals and pollutants. Chemical seepage from abandoned and operational tailing dams, as well as failures, can contaminate downstream habitats. Although small-scale and artisanal mining requires significantly less energy than large-scale mining, it is connected with extremely polluting activities. Waste management systems often fail due to its fluid nature and lack of regulation, resulting in soil deterioration and water contamination. Closed and abandoned mines harm approximately 11 million people globally, whereas active mining impacts 12 million. Open-pit mines and tailings can cause contamination for hundreds of years if not properly rehabilitated after closure or abandonment.

2.8.1.2. Case Studies of CRM Mining in Italy and Globally

Although there are very few CRM extraction mining operations in Italy, previous and current operations for minerals like lithium, cobalt, and rare earth elements (REEs) show the environmental trade-offs involved. Sardinia and Veneto case studies demonstrate how previous mining operations led to regional ecological deterioration. Globally, cobalt mining in the Democratic Republic of the Congo raises concerns about toxic waste management and deforestation, while the lithium extraction process in South America's "Lithium Triangle" (Argentina, Bolivia, and Chile) highlights serious water depletion issues in arid regions. These incidents demonstrate the need for more sustainable mining technologies and improved environmental regulations.

2.8.1.3. Regulatory Frameworks for Mitigating Environmental Damage

To address these environmental issues, the European Union has created programs such as the EU Raw Materials Initiative and the Circular Economy Action Plan, which promote the sustainable sourcing and recycling of CRMs. Italy, as an EU member state, has strong environmental legislation aimed at reducing the ecological imprint of extractive sectors. On a worldwide scale, international accords like the Minamata Convention on Mercury and the worldwide Industry Standard on Tailings Management aim to decrease the environmental risks connected with CRM extraction. However, enforcement remains an issue, particularly in underdeveloped nations where regulatory authorities lack the necessary resources to adequately monitor compliance.

2.8.1.4. Mandatory and Broader Regulation's Importance in Reducing and Preventing Environmental Impacts

Environmental regulations cover mining operations, including pollution management and land rehabilitation. This includes implementing and enforcing environmental impact assessments, emission standards, waste and water management regulations, and land restoration requirements. Environmental governance has been overly soft and fails to account for all potential threats. Mining corporations often overlook indirect and cumulative repercussions and abandon mines without implementing land rehabilitation measures. Environmental studies for mining operations sometimes prioritise immediate effects over long-term repercussions. Another example is a lack of regulation regarding mine site restoration. Mining companies must implement a rehabilitation plan to restore the land and minimise long-term impacts like sedimentation, acid mine drainage, and pollution of downstream water bodies.

The effects of CRM extraction on the environment highlight the urgent need for more stringent regulations, sustainable mining methods, and greater funding for alternative sources like urban mining and CRM recycling. The long-term viability of the CRM industry depends on striking a balance between environmental protection and resource security.

2.8.2. Social and Ethical Concerns in CRM Supply Chain

The worldwide supply chain for critical raw materials (CRMs) is frequently fraught with substantial social and ethical concerns, particularly in areas with weak governance and insufficient labour rights. Many CRMs, such as cobalt, lithium, and REEs, come from developing countries where child labour, unsafe working conditions, and human rights violations are common. These ethical problems raise fundamental questions about corporate accountability, transparency, and the role of international legislation in ensuring fair and sustainable supply chains

2.8.2.1. Labor Conditions in Mining Regions (Africa, Latin America, and Beyond)

A sizable portion of the global CRM supply originates from nations with lax labor laws. For instance, over 70% of the world's supply of cobalt, an essential element in lithium-ion batteries, comes from the DRC. According to reports by Amnesty International and Human Rights Watch, child labor is widely exploited in artisanal mining operations, where workers—many of whom are minors—are put in potentially fatal situations because basic safety precautions are not taken. Similar to this, South American lithium mining has been connected to exploitative labor practices, especially in Argentina, Bolivia, and Chile, where native populations are routinely uprooted and receive insufficient compensation for the exploitation of their resources.

- **South Africa**

South African mining miners face tough and dangerous working conditions, resulting in dozens of fatal incidents each year. 111 Workers in South Africa's deep mines face high temperatures and dust, which can cause diseases like silicosis. 112

Working in open-cast mines exposes workers to hazardous minerals like chrome and manganese, which can harm their long-term health. 113 Despite recent improvements, money continue to take precedence above workplace health and safety (Bureau of Mines, 2018).

Despite increases in salaries over the past two decades, mine workers still face poverty and struggle to fulfil their needs and those of their families. 115 Due to financial constraints, many mine workers and their families live in substandard accommodation, such as corrugated iron shacks. 116 Workers and their families have limited access to official housing, particularly in mining locations where adequate housing is scarce (Tissington, 2018). 117

Mine workers and their family sometimes reside in informal settlements with limited access to basic utilities like sewerage due to the need for cheaper housing options (Jacobs, 2021).

- **Kemerovo**

Concerns concerning labor conditions are not limited to underdeveloped countries. Even in better controlled contexts, such as Russia's Kemerovo region, data indicate that mining positions remain unstable, with rising job losses and deteriorating working conditions.

Evidence from Employment Data in the Kemerovo Region

The employment data from the Kemerovo region-Kuzbass (shown in Table 2.5) indicate labour insecurity in mining operations. In 2018, the number of personnel hired in mining operations climbed by 12% over 2017, although employee dropouts also increased. The number of workers who left the sector owing to employment cuts increased by 60%, from 118 in 2017 to 189 in 2018. Furthermore, voluntary resignations increased by 14% from 16,159 in 2017 to 18,447 in 2018.

Table 2.5: Movement of Employees by Type of Economic Activity (Zaruba et al., 2021)

	Employees Accepted	Including the additional places entered	Employees Dropped Out	In connection with the reduction of	At your own re-quest
Mining operations					
2017	26048	3159	23619	118	16159
2018	30278	2581	25864	189	18447
Coal mining					
2017	24962	3158	22346	87	15510
2018	26262	265624937	24937	176	17915

Extractions of other materials					
2017	467	-	611	3	314
2018	387	8	368	-	336

This trend indicates that, even in an organised mining setting, people are increasingly departing owing to poor working circumstances. The deterioration in labour conditions is further supported by a 20% decrease in extra employment possibilities in 2018 compared to the previous year, indicating a falling industrial capacity to absorb new workers.

- **Comparison with Other Economic Sector**

The pie chart (Figure 2.14) provides a broader view of how job layoffs are distributed across the region's industries. It reveals that mining accounted for 5.6% of all worker cutbacks in 2018. While this is not the highest among industries, it does indicate an uncertain labour situation, particularly given the concomitant increase in voluntary resignations. The mining industry is recognised for its physically demanding and often hazardous working conditions, which may explain the high dropout rates.

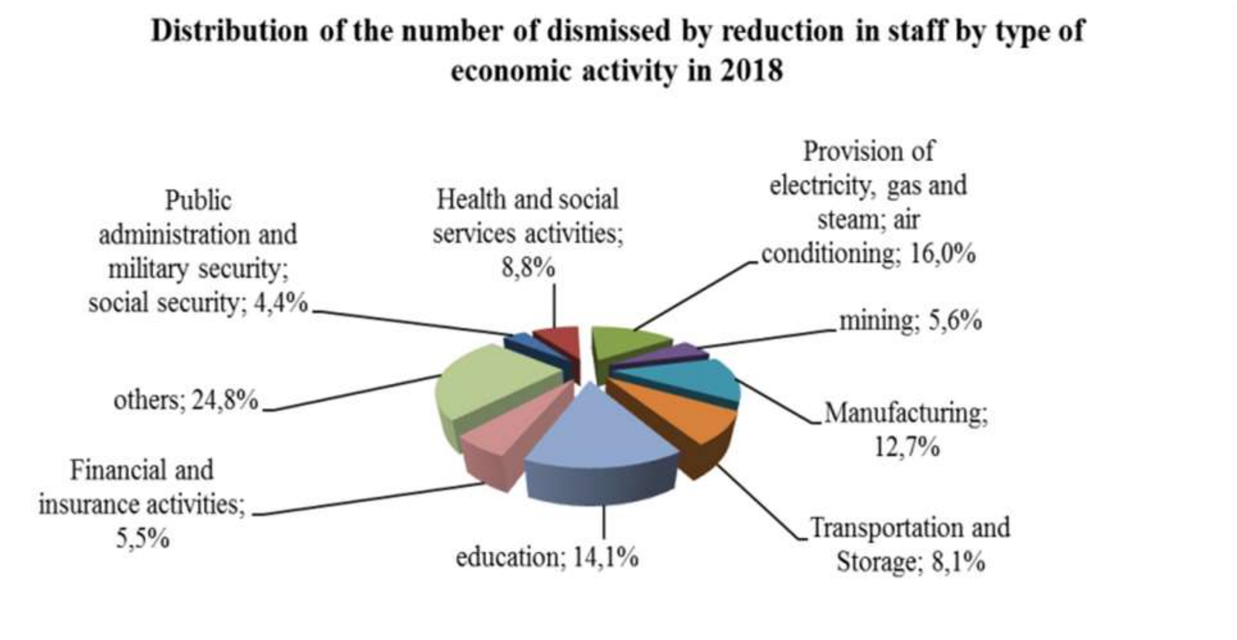


Figure 2.14: Distribution of the Number of Dismissed by Reduction in Staff by Type of Economic Activity (Zaruba et al., 2021)

When evaluating this industry, it's important to note that the total number of working specialists and their remuneration are lower than in other industries in the figure. This suggests a need for effective management decisions.

- **Labor Shortages and Employment Gaps in Mining**

Despite high turnover rates in mining industries, there is still a strong demand for personnel in the industry. According to the data in figure 2.15, the mining industry has 1,899 open positions, making it one of the industries with the most labor shortages. This is consistent with the employment patterns, where there was a significant increase in job dropouts and voluntary resignations in mining between 2017 and 2018 (Bureau of Labor Statistics, 2019).

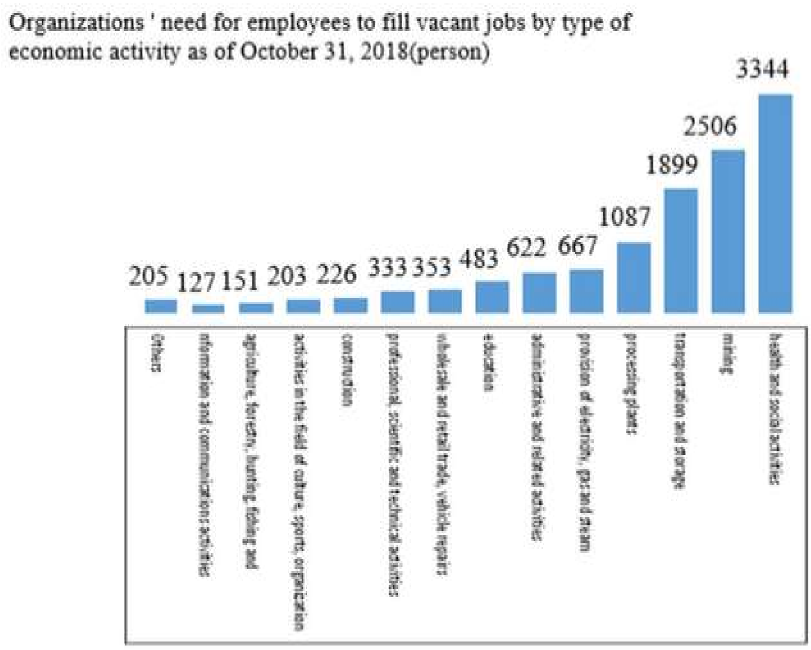


Figure 2.15: Organizations' Need for Employees (Zaruba et al., 2021)

The ongoing demand for workers indicates that mining jobs are hard to retain, probably as a result of unfavorable working conditions, health issues, and low pay. Mining has a significantly higher labor demand than other industries, like education (483 openings) and administration (667 vacancies), which suggests ongoing workforce instability.

2.8.2.2. Corporate Social Responsibility (CSR) Initiatives in the CRM Sector

Recognising the ethical and environmental difficulties inherent with CRM extraction, businesses and governments have launched Corporate Social Responsibility (CSR) programs to encourage sustainable and responsible operations.

Several global firms, including Tesla, Apple, and BMW, have committed to responsible sourcing, cooperating with programs such as:

- **The Responsible Cobalt Initiative (RCI)** aims to remove child labour from the cobalt mining supply chain.
- **The Initiative for Responsible Mining Assurance (IRMA)** establishes environmental and social performance requirements for mine operations.
- **The Fair Cobalt Alliance (FCA)** aims to formalise and improve labour conditions in artisanal mining enterprises.

Despite these attempts, enforcement and accountability remain a concern. While some businesses conduct third-party audits, opponents contend that CSR activities are frequently voluntary and lack stringent governmental monitoring, making it impossible to ensure actual progress.

2.8.2.3. Government and Policy Initiatives

Governments and international organisations have also implemented policies to encourage ethical sourcing, such as:

- **The EU Conflict Minerals Regulation (2021)** - Importers of tin, tungsten, tantalum, and gold (3TG) must do due diligence on their supply chain.
- **Section 1502 of the Dodd-Frank Act in the United States** requires disclosure of conflict minerals sourced from the Democratic Republic of the Congo and neighbouring nations.
- **China's Green Supply Chain Initiative** encourages state-owned firms to use responsible sourcing procedures for rare earth elements.

While these restrictions reflect improvement, enforcement is patchy, and some organisations use loopholes to continue purchasing CRMs from problematic providers.

Italy's participation in the EU CRM supply chain is directly impacted by both human rights concerns and CSR initiatives. Ethically sourced raw materials will be essential for Italy to comply with EU regulations and maintain its competitiveness in the global market as it works to expand its processing and recycling capabilities. Businesses in Italy need to invest in recycling and circular economy initiatives, as well as traceable and responsible sourcing practices, to reduce their dependence on high-risk areas.

2.8.3. Sustainability in CRM Recycling and Circular Economy Practices

Concerns regarding resource scarcity and environmental degradation have been heightened by the growing need for CRMs in sectors like electronics, renewable energy, and electric vehicles (EVs). Recycling has become a key tactic for enhancing supply chain resilience and lowering dependency on primary extraction as traditional mining encounters new geopolitical, environmental, and ethical challenges.

By recovering valuable materials from industrial scraps, end-of-life products, and electronic waste (e-waste), CRM recycling and circular economy techniques offer a more sustainable option. However, the effectiveness and viability of CRM recovery are still constrained by technological, financial, and legal issues. Although the results of advanced hydrometallurgical and pyrometallurgical recycling processes have been encouraging, high costs, low collection rates, and inconsistent legislative support have hindered their widespread adoption.

This section explores the current state of CRM recycling by analysing the efficacy of existing recovery technologies, comparing worldwide best practices, and assessing the role of legislative frameworks and economic incentives in encouraging circular economy efforts. By tackling these issues, Italy can improve its position in the EU's CRM strategy, reducing dependency on imported raw materials and supporting long-term industrial growth.

2.8.3.1. Efficiency and Feasibility of CRM Recovery from E-waste

Global demand for raw materials is projected to double between 2010 and 2030 due to rapid technological innovation and emerging nations' growth.

CRMs are widely utilised in EEE, especially in developing technologies (Table 2.6). CRM need will grow as consumer and industrial markets adopt industry 4.0 and IoT technologies. Low-carbon technologies make up 20% of worldwide CRM usage and are expected to grow with widespread deployment to satisfy the Paris Agreement's targets (European Commission, 2022). Energy efficiency methods play a significant role in reducing greenhouse gas (GHG) emissions across various sectors, including transformation, buildings, industry, and transportation.

Table 2.6: Major Applications of "Technology Metals" and their Driving Emerging Technologies (Charles, 2018)

Raw Material	Emerging Technologies
Ga	Thin layer photovoltaics (PV), ICs, LEDs
Li	Li-ion batteries
Nd	Permanent magnets, laser technology
In	Displays, thin layer photovoltaics
Ge	Fibre optic cable, IR optical technologies
Pt	Fuel cells, catalysts
Ta	Micro capacitors, medical technology
Ag	RFID, lead-free soft solder, Si-PV
Co	Li-ion batteries, synthetic fuels
Pd	Catalysts, seawater desalination
Ti	Seawater desalination, implants
Cu	Efficient electric motors, RFID
Nb	Micro capacitors, ferroalloys
Sb	Flame retardant, dopant in silicon wafers, Pb-acid battery alloys
Cr	Seawater desalination, marine technologies
V	Reflow batteries

REMs	Permanent magnets for wind turbines & electric vehicles (Nd, Dy, Pr), cathodes of LFYP Li-ion batteries (Y)

In 2010, the European Raw Materials Initiative (RMI) evaluated 41 raw materials and identified 14 as 'critical' to the EU due to their significant economic relevance and supply risk. The list, known as the 'EU14', mostly included 'technology metals', which are essential for high-tech applications. The EU CRM list prioritises technology metals, which have been expanded to include a wider range of materials. Other studies have regularly judged them to be vital.

Adopting a circular economy can address material criticality issues by reusing and recycling products and components over multiple life cycles. This maximises economic productivity and reduces global demand for CRMs (United Nations Environment Programme, 2021). FirstSolar manufactures CdTe PV modules and provides a takeback and recycling service, recovering unrefined semiconductor materials for sale to vendors for refinement. This circular economy technique recovers crucial Te from end-of-life (EoL) modules, providing secondary supply for new module manufacture, balancing raw material costs, and lowering product LCOE and CO2eq./kWh (International Renewable Energy Agency, 2021). The circular economy aims to shift economic growth away from primary CRM production and towards secondary sources. However, recycling rates for end-of-life (EoL) CRMs are currently low, with rates of less than 1% for many technological metals and barely exceeding 50% for the most valuable, such as Au and PGMs. Due to limited secondary CRM supply, boosting recycling rates is crucial to meet rising demand and address supply bottlenecks. WEEE, often known as e-waste, is the world's largest and fastest growing waste stream (~50 Mt/yr, 3-5% growth per year). It serves as a valuable resource for the circular economy and reusable products/components (Global e-Sustainability Initiative, 2020).

Increased WEEE reuse and recycling rates, as well as CRM recovery efficiencies, are necessary to maximise their potential and improve secondary supply. WEEE must be collected and integrated into the recycling chain for pre-processing and material recovery. In the UK, collected WEEE is pre-processed by an approved treatment facility (AATF). During pre-processing, WEEE is evaluated for reuse potential. Reusable EEE is sold to new consumers or refurbished/upgraded. WEEE that is not suitable for reuse is separated into material and component fractions and delivered to downstream recovery procedures. Materials can be separated using automated, manual, or semi-automated techniques.

Manual pre-processing is generally expensive because it is labour and time consuming. Manual disassembly of products allows for the isolation of reusable parts (e.g., graphics cards from PCs) and sub-assembly components (e.g., surface-mounted device components (SMDs) of printed circuit boards (PCBs), such as CPUs on motherboards). A PCB has an average life of 20,000 hours, which is only 5% of the component's original lifespan. At EoL, many components are useful and maybe reusable several times.

The distribution of CRMs on a TV main PCB was mapped using visual identification of PCB components (Figure 2.16). This demonstrates the commonality of CRMs in PCB components. Optical identification of components with prior knowledge of CRM content can map CRMs in PCBs and direct component disassembly for reuse and recovery. CRM data can help automated image analysis systems identify components based on dimensions, colour, and surface markings, comparable to SA's dual-laser desoldering technique (UN International Program, 2021).

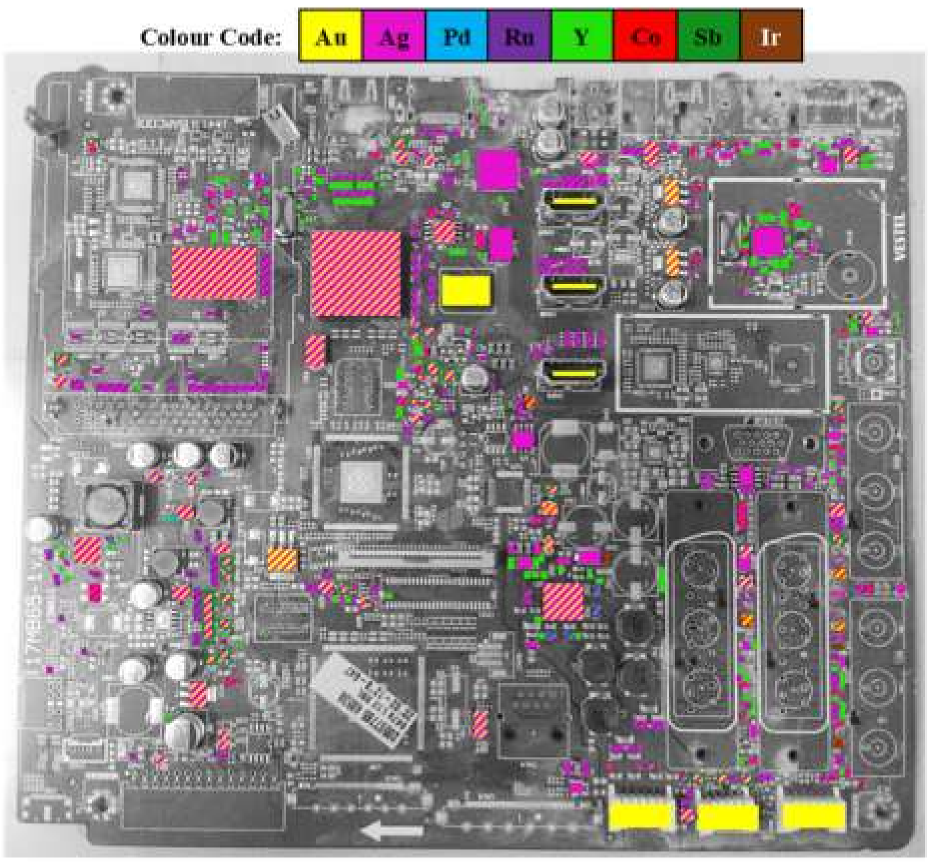


Figure 2.16: Color Coded CRM Distribution in TV main PCB (UN International Program, 2021)

CRM extraction from e-waste is generally based on mechanical, pyrometallurgical, and hydrometallurgical methods.

1. **Mechanical Processing:** Metals can be separated from plastics and ceramics using shredding and sorting techniques, but CRMs have poor recovery rates because they are scattered throughout electronic components.
2. **Pyrometallurgical Processing**: Copper, gold, and silver can be successfully recovered through high-temperature smelting, but vaporization usually causes CRM loss.
3. **Hydrometallurgical Processing:** Chemical leaching increases the selectivity of CRM recovery, but it raises issues with scalability and chemical waste.

Recent developments in solvent-based recycling, electrochemical extraction, and bioleaching have shown promise for raising CRM recovery rates while lessening their negative effects on the environment.

The feasibility of recycling e-waste depends on a number of factors:

1. **Collection and Sorting Efficiency:** Low material recovery rates are caused by irregular e-waste collection practices and unofficial recycling industries.
2. **Cost vs. Market Value**: Without incentives, large-scale adoption would be financially challenging because the cost of extracting CRM from e-waste is typically higher than that of mining.
3. **Support from regulations and policies:** Tight EU waste management guidelines and extended producer responsibility (EPR) programs aim to increase recycling of e-waste, but local implementation differs.

By making investments in improved e-waste collection techniques, new recovery technologies, and more robust public-private partnerships, Italy can enhance its CRM recycling infrastructure. CRMs may become less dependent on imports if they adopt a more circular economy, which would also support EU sustainability goals.

2.8.3.2. Comparative Analysis of Recycling Technologies and Best Practices

The recovery of CRMs from waste streams is critical for lowering reliance on primary extraction, minimising environmental impact, and assuring a steady supply of these vital resources. Various recycling systems have been developed to extract CRMs efficiently, each with a unique recovery rate, environmental footprint, and economic feasibility. Table 2.7 compares significant CRM recycling approaches and explores global best practices that can help Italy develop its strategy in this area.

Table 2.7: CRM Recycling Approaches

Technology	Process	Advantages	Challenges
Mechanical Processing	Shredding, separation, and sorting	Low-cost simple implementation	Limited recovery of CRMs, high material loss
Pyrometallurgical Processing	High-temperature smelting to extract metals	Effective for bulk metals (gold,copper,silver)	High energy consumption, CRM loss due to vaporization
Hydrometallurgical Processing	Chemical leaching of metals from e-waste	Higher CRM selectivity, lower emissions than smelting	Chemical waste, high operational costs
Bioleaching (biometallurgy)	Using bacteria or fungi to extract metal	Eco-friendly, lower energy demand	Slow process, lower yield for some CRMs
Electrochemical and Solvent Extraction	Electrolysis or solvent-based separation	High recovery purity, scalable for some CRMs	Expensive setup, chemical management issues

Each approach includes trade-offs in terms of efficiency, cost, and sustainability, which influence its widespread adoption. Mechanical approaches are extensively employed due to their simplicity; however they are less effective at obtaining CRMs. Hydrometallurgical and bioleaching techniques are interesting options with improved selectivity and lower environmental effect, but they require additional development for cost reduction.

2.8.3.3. Best Practices in CRM Recycling: Lessons from Global Leaders

Several countries and businesses have built successful recycling frameworks that may serve as examples for Italy:

- **Japan:** a pioneer in urban mining programs, has built efficient e-waste collection and hydrometallurgical recycling technologies to recover CRMs from consumer devices.
- **The European Union:** Battery Regulation and Circular Economy Action Plan encourage advanced lithium-ion battery recycling while maintaining sustainable material flows.
- **Belgium (Umicore group):** Umicore is a leader in pyrometallurgical and hydrometallurgical CRM recovery, recycling precious and rare metals from industrial waste with great efficiency.
- **China:** As the world's largest producer of rare earth elements, China has created closed-loop recycling systems for rare earth magnets and electronic components.

By utilising proven worldwide practices and investing in cutting-edge recycling technologies, Italy can cement its place as a vital participant in the EU's sustainable CRM supply chain.

2.8.3.4. Policy Support and Economic Incentives for CRM Recycling

The shift to a circular economy for CRMs necessitates strong legislative frameworks and economic incentives to encourage effective recycling, minimise reliance on primary extraction, and maintain resource security. Governments and international organisations have used a variety of legislative measures, subsidies, and financial incentives to encourage CRM recycling. This section looks at major EU and national regulations, economic tools that encourage investment in recycling technologies, and Italy's ability to improve the CRM recycling sector through focused measures.

Several policies at the European and global levels impact the regulatory environment for CRM recycling:

- The Critical Raw Materials Act (CRMA) of the EU:
    1. Establishes mandatory recycling goals for significant CRMs.
    2. Enhances strategic stockpiling and supply chain monitoring.
    3. To reduce dependency on outside sources, it promotes investment in domestic recycling facilities.

- EU Battery Regulation (2023):
    1. Establishes the lowest amount of nickel, cobalt, and lithium that can be recycled in new batteries.
    2. Extends producer responsibility (EPR) to ensure appropriate recovery and disposal.
- **The Waste Electrical and Electronic Equipment (WEEE) Directive**
    1. Mandates e-waste collection and adequate recycling procedures.
    2. Promotes CRM extraction from consumer electronics and industrial garbage.
- **The Circular Economy Action Plan (CEAP)**
    1. Promotes the growth of secondary raw resources markets.
    2. Encourages green innovation and research into CRM recovery methods.

These policies lay the groundwork for regulation, but they must be implemented effectively at the national level and industry participation to have the most impact.

2.8.3.5. Economic Incentives Driving CRM Recycling

To incentivise enterprises and investors to scale up CRM recycling, numerous economic instruments have been devised.

- **Subsidies and grants:** Governments fund CRM recovery research and infrastructure development. For example, the EU Innovation Fund supports circular economy initiatives.

- **Tax rebates and Green Incentives:** Companies that implement sustainable recycling techniques obtain tax rebates or lower tariffs on recovered materials.
- **Extended Producer Responsibility (EPR) Schemes:** Manufacturers must fund the collection and recycling of end-of-life products, generating incentives for eco-design and material recovery.
- **Carbon Credit and Emission Trading Schemes:** Companies reducing CO_2 emissions through CRM recycling may receive financial rewards under emissions trading systems.

These economic solutions reduce the cost of CRM recycling while stimulating technical innovation and private sector participation.

2.8.4. Sustainability Metrics and Lifecycle Assessment (LCA) in CRM Management

Reducing the impact on the environment, improving resource efficiency, and preserving long-term supply stability all depend on the sustainable management of essential raw materials. Lifecycle assessment and sustainability indicators are essential tools for evaluating the economic and environmental performance of CRM extraction, processing, and recycling. Businesses and governments can evaluate the effectiveness of sustainable CRM practices and identify areas for improvement by establishing key performance indicators. In order to provide insights into best practices for a more robust and ecologically friendly CRM supply chain, this section examines the significance of life cycle assessment (LCA) techniques, sustainability KPIs in CRM management, and case studies of effective CRM recycling programs.

2.8.4.1. Key performance indicators (KPIs) for sustainable CRM practices

Establishing Key Performance Indicators (KPIs) that gauge the efficiency of extraction, processing, and recycling procedures is crucial to ensuring the sustainable management of CRMs. Industries, legislators, and other stakeholders use these KPIs as standards to assess how well environmental, social, and economic sustainability objectives are being met.

Key indicators including energy use, carbon emissions, water use, supply chain effectiveness, waste management, and employee engagement should all be part of a thorough sustainability strategy. Six crucial sustainability KPIs that are applicable to a wide range of businesses, including CRM management, are depicted in figure 2.17.

Figure 2.17: Sustainability KPIs (DML, 2023)

The following are some ways in which these KPIs assist CRM sustainability strategies:

1. **Environmental KPIs:**

To evaluate the environmental impact of CRM extraction and processing, the energy consumption and carbon emissions KPIs indicated in the image are essential. Key tactics for reducing ecological harm include lowering CO_2 emissions per unit produced and reducing energy intensity, which is expressed in kWh per tonne of

CRM. Water consumption is also an important KPI since CRM processing frequently uses large amounts of water, necessitating recycling and conservation measures.

2. **Supply Chain and Recycling Efficiency:**

Another important statistic in CRM logistics that is highlighted in the illustration is supply chain miles. The carbon footprint of CRM supply chains can be considerably reduced by cutting down on transportation routes and improving shipping techniques. Furthermore, encouraging a circular economy approach to CRMs requires the use of waste and recycling KPIs, which calculate the proportion of material recovered.

3. **Social and Economic Impact:**

The employee engagement KPI from the image is closely related to workforce involvement in sustainability initiatives, ensuring that staff awareness and involvement align with business sustainability goals. Additional KPIs, such as the market circularity index, recycling cost efficiency relative to primary extraction, and investment in green technology, can be used to gauge economic viability in CRM management.
In addition to CRM-specific measures, companies and governments can use the six sustainability KPIs to implement data-driven initiatives that increase sustainability, reduce waste, and improve supply chain resilience.

2.8.4.2. Environmental and Economic Benefits of Circular Economy Approach

The circular economy prioritises sustainable material recovery, waste reduction, and resource efficiency, offering a revolutionary way to managing CRMs. In contrast to the take-make-dispose model of the conventional linear economy, circular strategies prioritise recycling, remanufacturing, and reuse to prolong the lifecycle of resources, hence lowering environmental degradation and boosting economic resilience.

Key phases in attaining sustainable resource management are highlighted by the circular economy model, which is depicted below in figure 2.18. Industries may reduce their dependency on virgin raw materials and close the material use loop by combining sustainable design, efficient manufacturing and distribution, responsible consumption, and advanced waste management (Ellen MacArthur Foundation, 2020). This approach not only decreases environmental impact but also contributes to economic sustainability by promoting resource efficiency, reducing waste, and encouraging product life extension (Bocken et al., 2016).

Figure 2.18: Circular Economy Model (European Parliament, 2023)

Circular economy techniques considerably lessen the ecological impact of CRM extraction and processing from an environmental standpoint. Businesses can lessen the detrimental effects of mining, such as deforestation, soil erosion, water pollution, and greenhouse gas emissions, by optimizing the recovery of CRMs from secondary sources, industrial waste, and end-of-life products. Furthermore, effective closed-loop recycling systems reduce energy use in comparison to original extraction procedures, which helps to mitigate the effects of climate change.

In terms of the economy, the circular economy improves supply chains' resilience and stability by lowering reliance on unpredictable raw material markets. Lower production costs, less reliance on imports, and the development of new business prospects in the recycling, refurbishing, and remanufacturing sectors are all advantages for nations and enterprises who invest in recycling infrastructure, eco-design, and material recovery technology. Long-term financial viability of CRM management is further enhanced by legislative incentives including tax breaks, green technology subsidies, and extended producer responsibility (EPR) programs, which all promote the adoption of circular processes.

Businesses and governments may ensure a more sustainable and resource-efficient future by combining environmental responsibility with economic competitiveness through the incorporation of circular economy ideas into CRM initiatives.

2.8.4.3. Case Studies on Successful CRM Recycling Initiatives

The need for effective recycling solutions has increased due to the rising demand for CRMs in important industries including electronics, renewable energy, and automotive manufacture. The potential of CRM recovery from e-waste, industrial byproducts, and end-of-life products is demonstrated by a number of successful initiatives around the world, which support both economic resilience and environmental sustainability.

- **Umicore: Leading the Way in Recycling Precious Metals**

Headquartered in Belgium, Umicore is a global leader in urban mining, specializing in the recovery of valuable and rare metals from electronic waste, batteries, and industrial waste. Its state-of-the-art facility in Hoboken effectively extracts cobalt, platinum-group metals (PGMs), silver, and gold from end-of-life materials. By implementing closed-loop recycling, Umicore has significantly reduced its reliance on primary mining, reduced carbon emissions, and advanced a circular economy.

- **The KIC EIT Raw Materials Project: EU Circular Economy Efforts**

Through cutting-edge recycling initiatives, the RawMaterials program from the European Institute of Innovation and Technology (EIT) supports sustainable CRM recovery. Improving lithium-ion battery recycling throughout Europe is one important initiative to help the expanding electric vehicle (EV) industry. The program has reduced Europe's reliance on imports by increasing the recovery rates of lithium, nickel, cobalt, and manganese through the optimization of hydrometallurgical and pyrometallurgical recycling processes.

- **Japan's Program for Recycling End-of-Life Vehicles (ELVs)**

A highly organized end-of-life vehicle (ELV) recycling system has been put in place in Japan, guaranteeing the recovery of steel, aluminum, and rare earth elements from wrecked automobiles. CRM extraction from hybrid and electric car motors is more effective since the nation requires automakers to design vehicles with recyclability in mind. Japan's objectives of environmental sustainability and resource security are in line with this strategy.

- **Apple's Daisy Robot: A High-Tech Approach to E-Waste Recycling**

With the help of Daisy, a disassembly robot that effectively recovers important CRMs from outdated iPhones, tech giant Apple has transformed the recycling of e-waste. Daisy can harvest tungsten, cobalt, and rare earth elements from 200 gadgets each hour, which are subsequently reintegrated into Apple's supply chain. In addition to lowering electrical waste, this program reaffirms Apple's dedication to using closed-loop materials in its products.

- **China's Bayan Obo Recycling Project: Recovering Rare Earth Elements**

Projects to recover REEs from worn magnets and industrial waste have been started in China, which has the biggest reserves of rare earth elements in the world. Previously a significant extraction site, the Bayan Obo mining region now uses secondary recycling operations to recover REEs from e-waste and magnet scraps, minimizing environmental damage and preserving China's competitive advantage in the global supply chain.

2.8.4.4. Key Takeaways from Effective CRM Recycling Initiatives

1- **Innovation and Technology:** Robotics, hydrometallurgical procedures, and urban mining techniques all increase the efficacy of CRM recovery.
2- **Circular Economy Integration:** By following the circular economy's tenets, a number of initiatives ensure that resource loops are closed.
3- **Policy and Regulation Support:** Countries with well-structured EPR programs, tax incentives, and mandatory recycling laws achieve higher CRM recovery rates.
4- **Industry Cooperation**: Public-private partnerships and cross-industry collaboration have been the driving forces behind successful recycling initiatives.

These case studies illustrate how CRM recycling can improve supply chain resilience and reduce dependency on the extraction of virgin resources, which benefits the economy and the environment. Such programs will need to be expanded internationally in order to achieve a safe and sustainable CRM supply in the future.

2.9. Research Gaps and Need for this Study

There are still a lot of unanswered questions about CRM supply chains, especially in light of Italy's place in the EU's CRM plan. Italy's contribution, difficulties, and prospects are not sufficiently examined in the majority of current research, which focusses on Germany, France, and the Nordic nations. More research is required to determine how Italy might improve the resilience of the EU's supply chain given its industrial base, capacity to process resources, and advantageous geographic location.

Furthermore, whereas the dangers and vulnerabilities of CRM reliance are frequently discussed in academic and governmental contexts, few research offer quantitative evaluations of the effects of risk-reduction tactics. Policymakers and business executives' decision-making would be improved by data-driven assessments of supply chain interruptions, recycling effectiveness, and alternative sourcing.

Emerging technologies like blockchain, artificial intelligence, and Industry 4.0 applications in CRM supply chains are also not well studied. These developments have the potential to increase traceability, optimize logistics, and improve resource efficiency, even though their application in CRM management is still in its infancy. Through a comprehensive analysis of Italy's role, data-driven insights, and an exploration of state-of-the-art technical solutions, this study aims to bridge these gaps and assist the EU in creating a more resilient and long-lasting CRM strategy.

2.9.1. Limited Focus on Italy

Despite being a significant European industrial centre, Italy is still under-represented in studies on supply chains for CRM. This stands in contrast to nations like Germany, France, and the Nordic countries, which are frequently praised for their sophisticated industrial policy and resource management. However, Italy is an important but little-known participant in the EU's CRM strategy due to its advantageous geographic location, strong manufacturing base, and increasing expenditures in material recovery.

Based on six Worldwide Governance Indicators, the map below in figure 2.19 shows the main EU suppliers of CRMs in 2023 together with their governance levels. CRMs including nickel, hafnium, strontium, and arsenic are notably supplied by nations in Europe, including Finland, France, Spain, and Belgium. High levels of governance and well-established infrastructures for CRM extraction or processing are advantageous to these countries. Italy's lack of a direct supplier emphasises both its status as a manufacturing-driven economy and its dependence on these European partners for raw resources (World Bank, 2023).

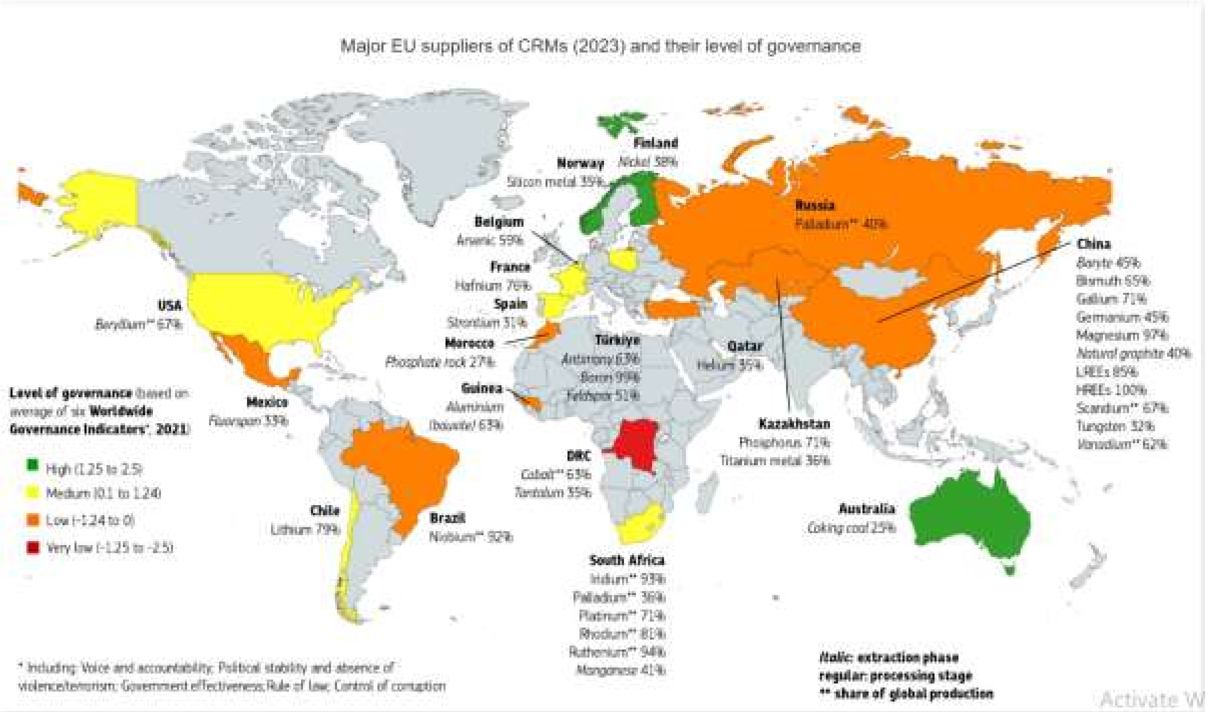


Figure 2.19: Major EU Suppliers of CRM (European Commission, 2024)

As can be seen from the map, Europe makes a substantial contribution to CRM supply chains during both the extraction and processing stages. Countries like Finland and France demonstrate strong governance and technological prowess, which enhance the EU's CRM strategy. Italy's contribution focuses more on its recycling initiatives and secondary raw materials market than it does on primary extraction. By encouraging collaboration with European suppliers and increasing its urban mining operations for resources like lithium and REEs, Italy may raise its profile in the EU's CRM framework. This would encourage a more resilient and sustainable European CRM ecosystem in addition to reducing reliance.

2.9.2. Focus on Germany, France, and Nordic Countries

Germany, France, and the Nordic nations are the focus of much of the current study on CRM supply chains in Europe. These countries have led the way in CRM management sustainability initiatives, industry innovation, and policy development. Their substantial governmental backing, extensive mining and recycling infrastructures, and active involvement in EU-wide CRM plans are major factors contributing to their importance in research.

- **Germany:** A Leader in CRM Research and Industrial Policy

Due to its extensive industrial base, especially in the automotive, electronics, and renewable energy industries, Germany is a key player in CRM studies. The Raw Materials Strategy, one of the nation's comprehensive strategies, encourages recycling, substitution, and safeguarding external supply chains. Numerous research projects centered on CRM sustainability are also based in Germany, such as the Helmholtz Association and Fraunhofer Institutes, which actively investigate models of the circular economy, resource efficiency, and material recovery.

- **France:** Strong Policy Framework and Strategic Independence

France has a clear strategy for CRM security that emphasizes recycling, domestic processing, and resource diversification. The National Institute for Circular Economy and the French Geological Survey (BRGM) are two organizations that add to the expanding corpus of study. France has strengthened its role in protecting EU supply chains by forming industrial alliances with African countries for CRM access.

- **Nordic Countries:** Pioneers in Sustainable Mining and Recycling

In terms of environmentally friendly CRM extraction and recycling, the Nordic region—which includes Sweden, Finland, Norway, and Denmark—has become a trailblazer. Particularly Finland and Sweden are investing in low-impact mining methods and have abundant mineral reserves, particularly REEs. Advanced recycling systems are also found in Nordic nations, where businesses like Boliden and Stena Recycling are at the forefront of e-waste recovery and urban mining. The region is a primary focus area for CRM research because of these qualities.

2.9.3. Lack of Quantitative Impact Assessments

There is a clear lack of quantitative effect assessments of suggested measures, despite the fact that many scholarly articles and policy publications emphasize the hazards related to CRM. Few studies give data-driven assessments that gauge the efficacy of mitigation techniques, recycling programs, or supply chain resilience models, despite the fact that many qualitative discussions of supply chain vulnerabilities, geopolitical threats, and environmental issues are available.

2.9.3.1. The Need for CRM Research Driven by Data

Empirical studies that quantify the possible impact of policy initiatives using statistical models, scenario analysis, or lifecycle evaluations are frequently lacking in current CRM research. For instance:

- Few studies evaluate the actual recovery rates of CRM from e-waste and how they compare to the extraction of virgin materials, despite the fact that recycling is touted as a crucial option.
- Although reports stress the value of diversifying supply sources, they hardly ever offer in-depth simulations of the effects of different sourcing tactics on the stability of the market as a whole.
- Numerous articles suggest circular economy strategies, but their viability is still up in the air in the absence of specific economic and environmental effect analyses.

2.9.3.2. Where Data Is Required

Quantitative assessments would be useful in a number of CRM research topics, such as:

- **Economic Feasibility:** A comparison of the costs and benefits of fresh extraction against CRM recycling.
- **Environmental Impact:** CRM supply chains' emissions, water and energy consumption are measured using LCA.
- **Measures of Supply Chain Resilience:** models based on simulations to forecast the effects of price swings, trade restrictions, and supply interruptions.

To demonstrate the research gap, a review of previous studies shows that there are comparatively few data-driven evaluations of strategic impact and a greater focus on qualitative discussions of CRM risks. In order to promote evidence-based decision-making in CRM policy and industry practices, more quantitative evaluations are required, as the accompanying chart 2.20 illustrates (European Commission, 2020).

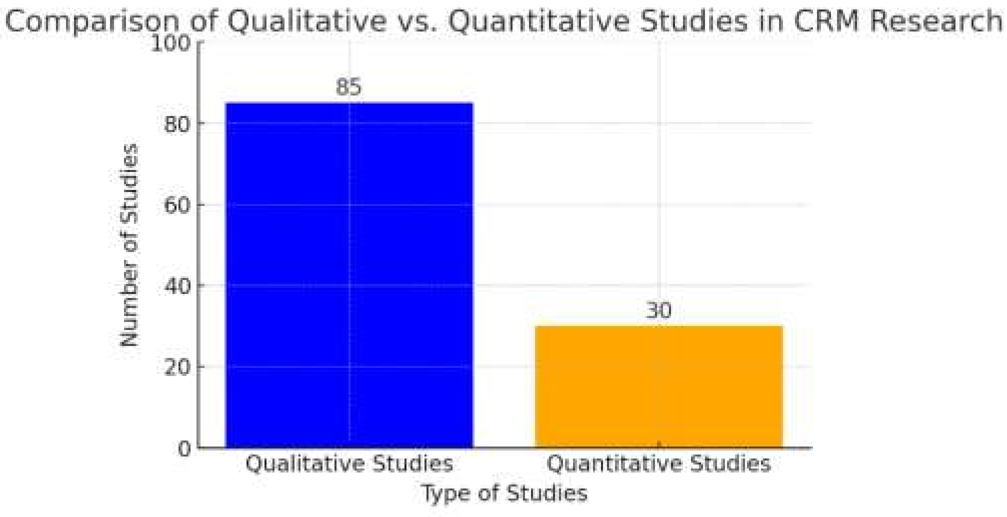


Figure 2.20: Qualitative vs. Quantitative Studies on CRM Research (European Commission, 2020)

To increase the effectiveness of policies, future research should concentrate on quantitative techniques like big data analytics, AI-driven forecasting, and scenario modeling. This method will enable policymakers and industry stakeholders to make well-informed decisions based on measurable outcomes rather than theoretical discussions.

2.9.4. Emerging Trends Not Fully Explored

Global supply chains are being revolutionized by blockchain, Industry 4.0, and artificial intelligence (AI), but little is known about how these technologies might be applied to CRM management. These technologies offer innovative ways to increase traceability, efficiency, and resilience, even though research on their integration with CRM supply chains is still in its early stages.

- **AI for Process Optimisation and Predictive Analytics**

By assessing market trends, anticipating supply chain interruptions, and enhancing resource allocation, AI-driven models have the ability to maximise CRM extraction, processing, and recycling. In mining operations, machine learning algorithms can improve predictive maintenance, decreasing downtime and boosting productivity. Few studies have quantitatively evaluated AI's impact on CRM supply chains, despite its potential.

- **Blockchain for Ethical Sourcing and Transparency**

By tracking CRM from extraction to end-use industries, blockchain technology can greatly enhance supply chain traceability. This is especially important for guaranteeing ethical sourcing because blockchain technology can produce tamper-proof records that confirm adherence to environmental and labour laws. Blockchain's use in CRM supply chains is still mostly theoretical, with few real case studies, despite the fact that it has been extensively debated in industries like finance and logistics.

- **Smart Manufacturing and Industry 4.0**

CRM mining, refining, and recycling may undergo a radical change as a result of Industry 4.0, which includes IoT sensors, automation, and digital twins. Material recovery rates might be raised and waste could be reduced in smart factories with adaptive production systems and real-time monitoring. However, there has been minimal investigation of Industry 4.0 applications in this field, with the majority of recent studies concentrating on conventional CRM management techniques.

It is clear from the bar chart how different supply chains are integrating AI, Blockchain, and Industry 4.0. It highlights how CRM supply chains lag far behind sectors like automotive, electronics, and logistics in terms of implementing these cutting-edge technologies.

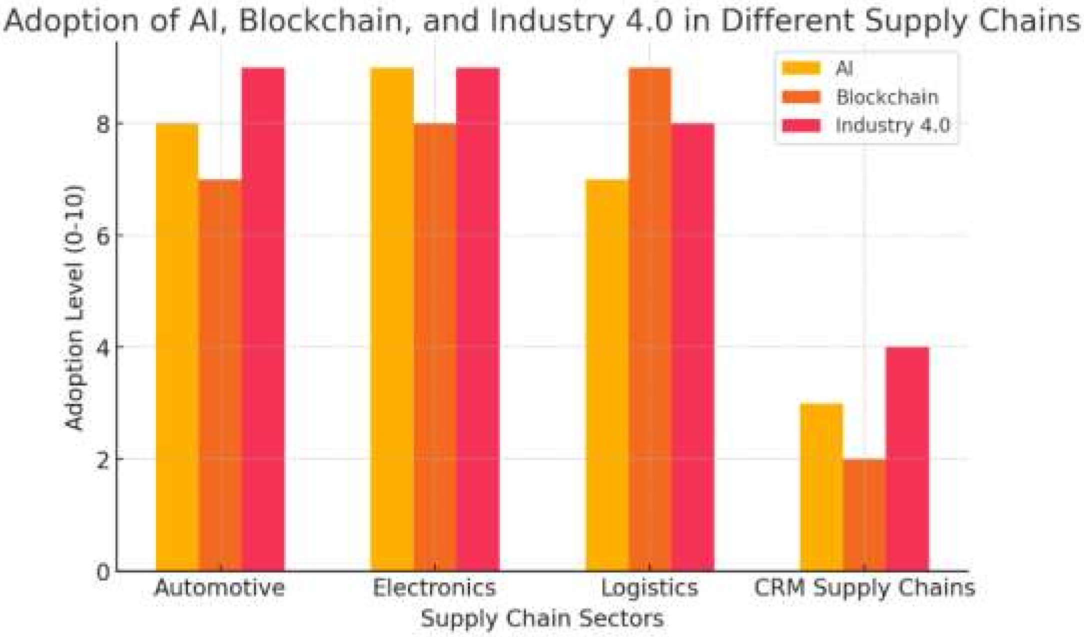


Figure 2.21: Bar Chart of AI, Blockchain, and Industry 4.0 in Different Supply Chains

More empirical research and pilot projects are required to assess the practical advantages of AI, blockchain, and Industry 4.0 in order to fortify CRM supply chains. CRM management may become more resilient, transparent, and sustainable by incorporating these technologies, guaranteeing the EU's long-term access to vital resources.

2.10. Conclusion

The literature study focusses on the environmental, economic, geopolitical, and technological elements of the critical raw material (CRM) supply chain, highlighting its many opportunities and problems. Lean and agile management concepts, supply chain resilience models, and geopolitical theories on resource dependency are some of the theoretical frameworks that provide insights on improving CRM supply chain resilience. Furthermore, historical case studies—like the Russia-Ukraine crisis and China's export restrictions on rare earths—showcase how external shocks affect global CRM markets, highlighting the necessity of risk mitigation and strategic planning.

The assessment also highlights how CRM policies have changed over time, contrasting regulatory strategies in various countries, such as China's state-controlled resource strategy, the U.S. Inflation Reduction Act (2022), and the EU's Critical Raw Materials Act (2023). The robustness of global supply chains and sustainable CRM management are significantly influenced by these policy frameworks. Furthermore, digitalisation and Industry 4.0 technologies—such as smart contracts, blockchain-enabled traceability, and AI-driven resource forecasting—are showing promise as ways to improve the efficiency and transparency of CRM procurement and logistics. They are still not widely used in CRM supply chains, though, which represents a serious research gap.

Concerns about the extraction and recycling of CRM from an environmental and social standpoint emphasise the necessity of sustainable methods. Fair and responsible CRM supply chains depend on issues like labour conditions, ethical sourcing difficulties, and corporate social responsibility (CSR) programs. However, circular economy methods, including as lifecycle assessments (LCA) and CRM recovery from e-waste, offer workable ways to lessen reliance on primary extraction. Notwithstanding these developments, the analysis points out important research gaps, notably the neglect of Italy's place in the CRM ecosystem, the dearth of quantitative impact analyses, and the scant investigation of new technologies in CRM management.

In conclusion, even though there is a lot of study on CRM supply chains, more research specifically focused on Italy, data-driven analyses, and technical advancements are urgently needed to improve CRM security and resilience. A sustainable and secure CRM supply for the EU will depend on filling these gaps through empirical study, policy changes, and business partnerships.

3 Italy's Current Position in EU CRM Supply Chain

3.1. Introduction

Italy's role in the EU's CRM supply chain is growing strategically important as the EU looks to improve resource security and reduce dependency on imports. Even though Italy isn't usually considered a major CRM producer, it does have substantial local deposits, particularly in lithium and rare earth elements, which could increase regional supply chain resilience. However, operational inefficiency, environmental concerns, and regulatory limitations hinder large-scale extraction efforts. Lean management ideas offer an opportunity to optimize mining operations by reducing waste and energy consumption during extraction processes.

Italy plays a significant role in CRM processing and refining in addition to raw material extraction, even though it still primarily relies on imported processed materials. Strengthening its refining capabilities with Six Sigma approaches, which focus on increasing CRM purity levels and lowering faults in refining operations, could further increase Italy's self-sufficiency in the CRM industry. Recycling is now a key strategy for CRM sustainability, and circular economy initiatives in Italy are evolving as well. Current recycling rates and industry activity demonstrate progress, but problems with efficiency gaps and regulatory compliance persist. Digitalization and Industry 4.0 technologies, like blockchain-based tracking for compliance and AI-driven automation for sorting, offer creative ways to boost CRM recovery rates.

Additionally, the need for CRM is significantly influenced by Italy's primary industries, which include semiconductors, automotive, aerospace, and renewable energy. The necessity of a strong domestic CRM strategy is further supported by the major supply chain bottlenecks and strategic dependencies that these industries face. In order to determine how Italy may use engineering management techniques and digitisation to improve its standing in the EU's CRM supply chain, this section examines the nation's CRM reserves, processing infrastructure, recycling programs, and demand drivers.

3.2. Italy's CRM Deposits and Extraction Capabilities

Despite being a key participant in the European Union's CRM supply chain, Italy's standing is impacted by its high reliance on imports, regulatory constraints, and limited domestic reserves. The nation possesses a number of strategically important CRM resources, but due to policy restrictions, economic viability issues, and environmental concerns, extraction is still challenging. This section looks at the current CRM reserves in Italy, their potential for extraction, and the obstacles to domestic production.

3.2.1. Domestic CRM Deposits: Potential and Limitations

Given the EU's goal of reducing reliance on suppliers outside the EU, Italy has a small but strategically significant natural endowment of CRMs. Lithium, nickel, cobalt, rare earth elements (REEs), and other minerals required for critical industries like aerospace, renewable energy, EV batteries, and defense are widely available in the country. Despite the potential for these deposits to increase Europe's CRM security, a number of legal, financial, and environmental constraints prevent their full-scale extraction.

3.2.1.1. Lithium Reserves: Untapped Potential for Battery Production

Italy may contribute to the production of batteries for electric cars and energy storage devices in Europe since it has discovered lithium reserves in areas like the Alps and Central Italy. These resources could lessen Europe's need on lithium imports from South America and China, especially in light of the EU's efforts to create a domestic battery value chain (Source International, 2024). However, a number of obstacles stand in the way of their complete exploitation, such as:

1. **Regulatory restrictions:** Protracted permitting procedures and strict environmental laws cause delays in project approvals.
2. **Economic viability:** Investment is less appealing due to high extraction costs when compared to international rivals.
3. **Local opposition:** New mining operations face criticism due to worries about water use and environmental harm.

3.2.1.2. Rare Earth Elements (REEs): Limited Deposits, Strategic Importance

Italy has limited yet significant REE resources, mostly in Sardinia. These components are vital to Europe's clean energy transition since they are necessary for electric motors, wind turbines, and electronics. Even modest contributions can help diversify European supply chains and lessen reliance on Chinese exports, even though Italy lacks the vast deposits that China and the US do. However, mining and processing REEs are still difficult because

1. **High processing complexity:** Hazardous waste is produced during the extraction and refinement of REEs, which calls for sophisticated separation technologies.
2. **Environmental restrictions:** New developments are restricted by stricter EU mining rules.
3. **Global competition:** European production is less competitive due to the dominance of nations like China in the REE markets (European Commission, 2023).

3.2.1.3. Nickel and Cobalt: Key Materials for the EV Industry

Cobalt and nickel, two elements necessary for the production of lithium-ion batteries, are found in Sardinia and southern Italy. These metals are required for cathode materials in high-performance batteries used in grid energy storage and electric vehicles. However, Italy's reserves of nickel and cobalt are still largely underutilized due to:

1- **High operating costs:** Domestic extraction is more expensive than purchasing from foreign vendors like Indonesia and the Democratic Republic of the Congo.
2- **Strict environmental regulations:** Sustainable mining practices are given more weight under EU and Italian regulations, which increases the cost of compliance.
3- **Limited refining infrastructure:** Italy is primarily reliant on imported refined nickel and cobalt because it lacks large-scale processing facilities.

3.2.1.4. Other CRM Resources: Industrial Applications and Economic Relevance

Italy has resources of fluorspar, barite, and antimony in addition to lithium, REEs, nickel, and cobalt. These elements have a variety of industrial uses.

1. Metallurgy, chemical manufacturing, and refrigeration systems all require fluorspar.
2. An essential mineral for paints, radiation shielding, and oil drilling is barite.
3. Batteries, semiconductors, and flame retardants all use antimony (U.S. Geological Survey, 2023).

These minerals enhance Italy's industrial capabilities and may help lessen supply chain vulnerabilities for European firms, while not being as well-known as lithium or rare earth elements.

The ISPRA image shows Italy's mining landscape both historically and currently. The location of mines that were in operation from 1870 to 2018 is shown on the left map, illustrating the wide range of mineral extractions that took place across the nation. There are currently much fewer and more geographically focused active mining concessions on the right map. Numerous extracted resources, including fluorite, barite, cement marls, industrial minerals, salt, talc, and others, are categorized in the legend. Changes in resource demand, environmental regulations, and economic viability are reflected in the shift from extensive historical mining to a more selective modern sector. Understanding Italy's role in the EU's vital raw material supply chain and the potential for reviving domestic extraction to enhance strategic resource security depend heavily on this trend (ISPRA, 2023).

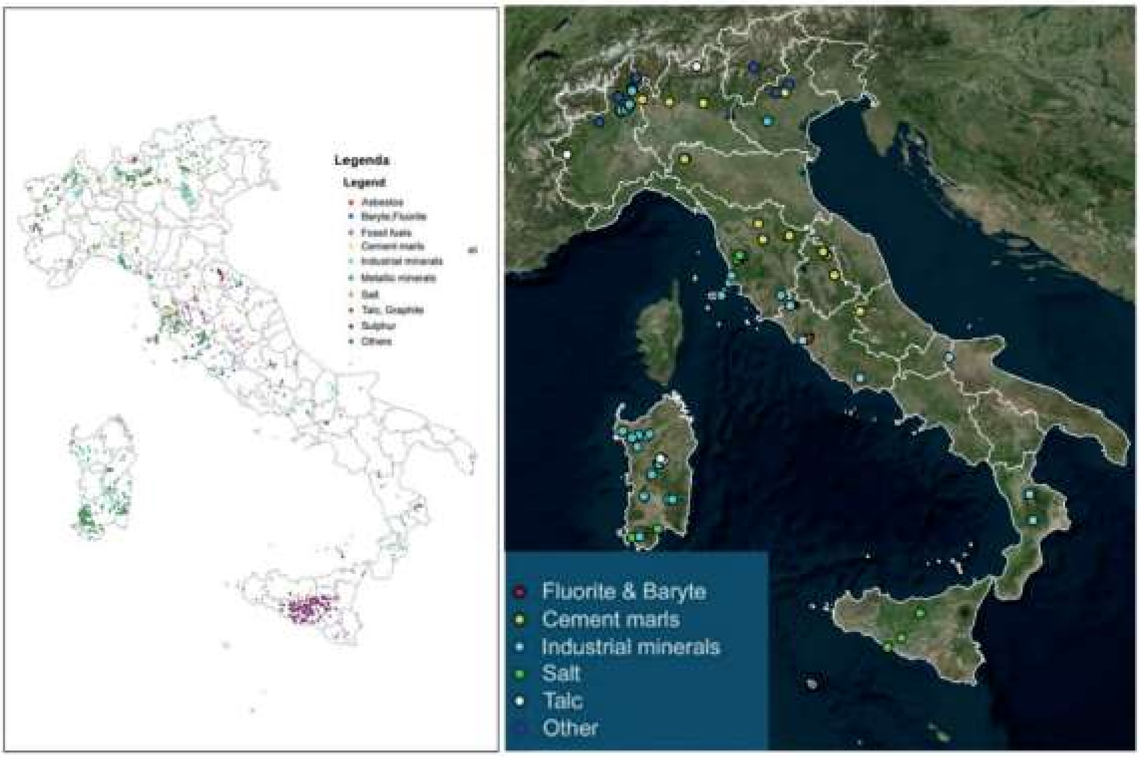


Figure 3.1: CRM in Italy (ISPRA, 2023)

Despite the availability of these resources, Italy is strongly reliant on imports to meet industrial demand. The difficulty resides not just in availability, but also in the viability of extraction.

3.2.2. Challenges of CRM Extraction in Italy

Italy's mining industry confronts considerable impediments to large-scale CRM extraction. These include regulatory challenges, environmental concerns, financial limits, and public opposition.

1. **Regulatory & bureaucratic challenges**

Permit delays are a result of Italy's strict mining project permitting system. Both domestic and international businesses find it difficult to invest due to the complicated legal system. Italy's lengthy bureaucratic processes hinder mining expansion when compared to resource-rich nations with effective regulations.

2. **Environmental Concerns and Sustainable Goals**

Italy's commitment to environmental preservation makes mining operations there especially contentious. Due to the frequent links between CRM extraction and habitat loss, soil erosion, and water contamination, there is strong public opposition and strict environmental regulations. Environmentalists and locals oppose many proposed mining sites.

3. **Economic and Financial Constraints**

CRMs are frequently more expensive to extract domestically than to import. The high expenses of labor, electricity, and refining technologies make domestic mining less competitive than importing resources from Africa or China. Many extraction projects are unprofitable in the absence of government subsidies or EU support.

4. **Public Resistance and Social Factors**

Opposition from environmental organizations and local residents adds another layer of complication. In areas where mining could occur, public objections and legal obstacles delay or even block project development.

Given these challenges, Italy must explore innovative approaches to improve its domestic extraction capabilities while ensuring sustainability and compliance with EU regulations. Potential solutions, such as Lean Mining principles, government incentives, and policy reforms, will be explored in the strategies section of this report

3.3. Italy’s Role in CRM Processing and Refining

While Italy has limited extraction capabilities, it is a big contributor in CRM refinement and processing. The country has a well-developed industrial infrastructure for metal processing, particularly for steel, aluminium, and other nonferrous metals. However, when it comes to high-purity CRM processing, Italy remains heavily reliant on imports, as majority of the refining occurs outside of the EU. This section looks at Italy's existing refining situation, its reliance on imported processed resources, and how quality improvement approaches such as Six Sigma might help in refinery efficiency.

3.3.1. Current Refining and Processing Infrastructure

Italy has a robust metallurgical sector, with refineries and processing facilities located in key industrial regions such as Lombardy, Piedmont, Veneto, and Emilia-Romagna. These facilities specialise in refining metals such as aluminium, copper, steel, and zinc, which are essential for industries such as automotive, aerospace, and manufacturing.

However, when it comes to high-value key raw materials (such as lithium, rare earths, cobalt, and nickel), Italy lacks large-scale refining capabilities. Instead, it uses imported semi-processed or refined resources, which are then used in industrial applications, battery production, and high-tech manufacturing.

3.3.1.1. Key features of Italy's refining infrastructure

Particularly in traditional metallurgy and chemical processing, Italy's refining and processing industry is essential to the country's and Europe's industries. Its poor ability to refine high-purity CRM, however, means that the nation is largely dependent on imported refined materials. The main characteristics of Italy's refining infrastructure and how they affect the resilience of the CRM supply chain are listed below.

1. **Solid Basis for Refining Classical Metal**

With a long history of refining base metals like copper, aluminium, and steel, Italy boasts a robust metallurgical sector. Lombardy, Veneto, and Piedmont are the nation's principal industrial centres, with a focus on smelting, alloy manufacturing, and superior metal processing. Important facets of this industry include:

- **Steel Production:** ArcelorMittal Italia (previously Ilva) at Taranto is one of the leading steel producers in Europe, with important roles in the equipment, construction, and automotive sectors.

- **Aluminium Refining:** Italy is home to sizable facilities for processing aluminium, including the manufacture of secondary (recycled) aluminium, which supports the objectives of the EU circular economy.
- **Copper Processing:** Italy has a long history of smelting and processing copper, which supports sectors including energy transmission, electronics, and telecommunications.

High-purity CRM refining is still in its infancy, particularly for lithium, rare earth elements (REEs), and cobalt, despite this solid base metal refining basis.

2. Limited Resources for Processing High-Purity CRM

Although Italy is proficient in classical metallurgy, its capacity to refine significant raw minerals—particularly lithium and rare earth elements—is limited. Unlike countries like China, Germany, and France, Italy does not have specialized high-purity processing facilities for rare earth separation, lithium hydroxide refining, or cobalt purification. This results in:

- A notable dependence on external suppliers, particularly in China, for REEs used in wind turbines, electric vehicles, and magnets.
- Italy lacks the domestic lithium conversion facilities necessary to produce lithium hydroxide and carbonate for battery production, so it is dependent on imported battery-grade lithium.
- Italy must import refined cobalt from China and the Democratic Republic of the Congo (DRC) to support its aerospace and electric vehicle industries due to a lack of cobalt refining capacity.

Investing in high-purity CRM processing facilities would improve Italy's standing in the European CRM supply chain and lessen its vulnerability to external disruptions.

3.3.2. Dependence on Imported Processed Materials

Despite its industrial strength, Italy imports the majority of its high-purity CRMs because of:

1- **Lack of domestic raw material supply:** Refinement investments are less encouraged in Italy since the country does not extract large quantities of CRMs.

2- **Expensive refining technologies:** It takes a significant financial outlay to set up state-of-the-art refining facilities for cobalt, rare earths, and lithium.

3- **China's dominant position in CRM refining:** A lot of CRMs that are harvested in South America or Africa are processed in China, which makes it difficult for Europeans to obtain them.

Due to its reliance on Chinese-refined CRMs, Italy's supply chain is vulnerable to geopolitical threats, price volatility, and trade restrictions. Italy needs to concentrate on process optimization and quality control in its current plants in order to enhance its refining capabilities.

3.3.2.1. Concentrated Industrial Clusters for Metallurgical and Chemical Processing

The metallurgical and chemical industries, which propel the transformation of raw materials, are the geographical centres of Italy's refining and processing infrastructure. Among these clusters are:

- Lombardy, which includes Milan, Brescia, and Bergamo, is a center for the processing of copper, aluminium, and steel that serves Italy's machinery and automotive industries.
- The Veneto region (Padua, Verona, and Vicenza) is known for its mechanical and metallurgical industries, which include high-performance alloys and secondary aluminium processing.
- Refineries for base metals and chemical processing, including the manufacture of secondary zinc and lead, are located in Tuscany (Livorno, Piombino).
- Piedmont (Turin, Novara) is a hub for the production of automobiles, relying on high-quality CRM inputs to produce batteries and lightweight alloys.
- Sardinia which is the region has a small amount of mining and mineral processing activity, especially for nickel and zinc.

Although these industrial clusters are crucial for sectors that rely on CRM, they need to be expanded and modernised to handle high-purity CRM refining.

3.3.2.2. Reliance on International Vendors for CRM Processing

Italy is forced to rely on foreign suppliers because to its absence of large-scale lithium, rare earth, and cobalt processing facilities, which exposes domestic supply chains to price instability and geopolitical threats. Important dependencies include of:

- China is a major refiner of cobalt and lithium and the world's largest supply of processed rare earths.
- Cobalt from the Democratic Republic of the Congo (DRC) is imported by Italy in refined form via Chinese businesses.
- Leading lithium producers Chile and Argentina supply European battery manufacturers with battery-grade lithium hydroxide and carbonate.
- France and Germany are European centres for refining battery materials and processing CRM, acting as middlemen for Italian producers.

Supply chain risks result from this reliance, particularly in light of growing geopolitical tensions, trade restrictions, and global resource nationalism.

3.4. Italy’s CRM Recycling & Circular Economy Efforts

Recycling has become a vital alternative for lowering dependency on primary extraction due to the growing demand for critical raw materials (CRMs) and the EU's emphasis on supply chain resilience. As a center of industry, Italy has developed recycling facilities for commodities like copper, steel, and aluminum; however, its CRM-specific recycling initiatives are still quite small.

3.4.1. Current Recycling Rates and Industry Initiatives

For EU, it is leading the circular economy movement by increasing the utilisation of secondary materials. Figure 3.2 illustrates that over 50% of metals, including iron, zinc, and platinum, are recycled, accounting for more than 25% of the total EU consumption. Secondary production has a limited impact on rare earths, gallium, and indium, which are essential for renewable energy and high-tech applications (European Commission, 2023).

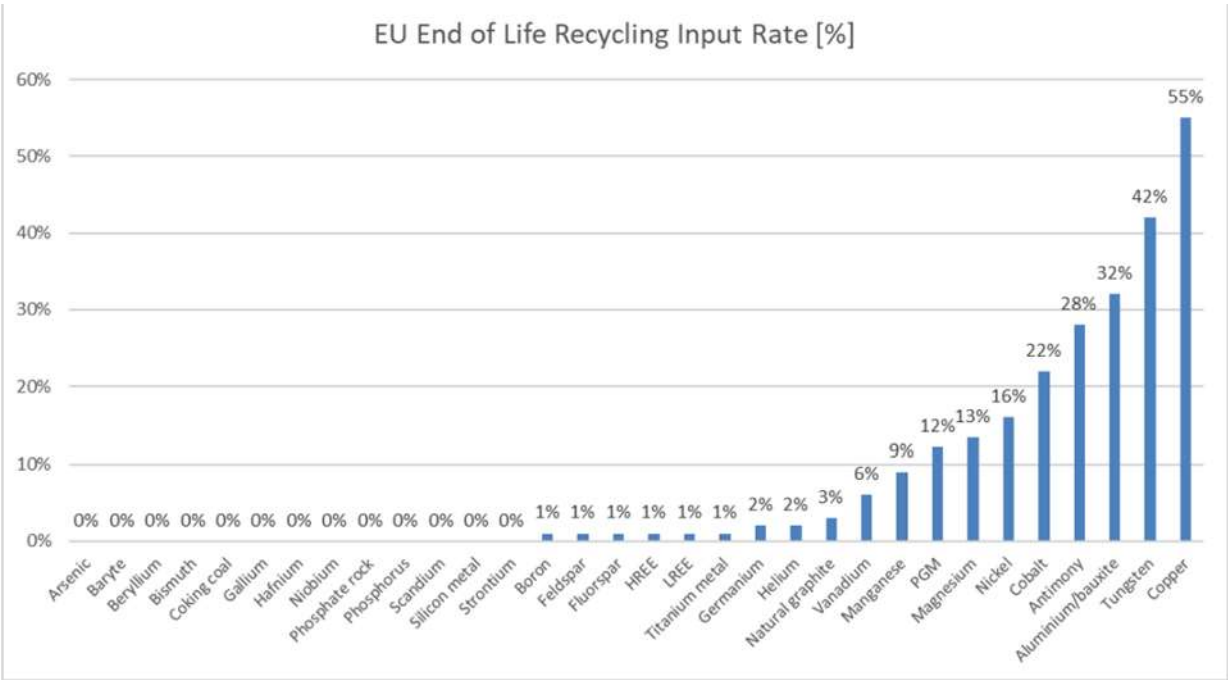


Figure 3.2: EU EoL Recycling Input Rate (European Commission, 2023)

Italy has demonstrated a strong commitment to recycling, particularly when it comes to essential raw materials (CRMs). With an overall rate of about 68%, the nation leads the EU in waste recycling, surpassing the average of 35.2% (European Environment Agency, 2023). Italy leads the EU in recycling waste electrical and electronic equipment (WEEE), with a rate of 87.1% in 2021, higher than the average of 81.3%. Compared to the global average of 17.4%, Italy recycles over 35% of electronic materials used in automobiles, batteries, and other energy systems. Recycling specialized CRMs still faces challenges in spite of these advancements. Recycling specialized CRMs still faces challenges in spite of these advancements. There is much room for improvement, as the average end-of-life recycling input rate among the 34 CRMs in the EU is only 8.3%.

In order to strengthen resource security and align with EU goals, Italy has created a permanent technical committee on CRMs to enhance coordination and strategies for recycling and sustainable sourcing (European Commission, 2023). Due to technical, financial, and regulatory barriers, recycling rates for CRMs like lithium, cobalt, and REEs are still low.

Some key aspects of Italy's CRM recycling landscape includes:

- **Battery Recycling:** In response to the growing EV market, Italy has begun to create lithium-ion battery recycling operations. Companies are investing in the recovery of lithium, cobalt, and nickel from old electric vehicle batteries, although efficiency levels are constantly evolving.
- **E-Waste Recovery:** Italy is one of Europe's leading recyclers of electronic waste (WEEE), recovering some rare earth and precious metals from discarded devices. However, the percentage of CRM recovered from e-waste remains low when compared to total demand.
- **Industrial Metal Recycling:** Although Italy has significant scrap metal processing capabilities, high-purity CRM recovery from industrial waste is still in its early phases.
- **Private Sector Investments:** Some Italian firms are working on EU-funded projects to develop CRM recycling technology, particularly battery and magnet recycling.

Despite these efforts, Italy's CRM recycling sector is still dependent on imported refined CRMs because it lacks large-scale, highly efficient processes.

3.4.2. Regulatory Adherence and Gaps in Recycling Efficiency

Programs, but major obstacles prevent closed-loop recycling systems from being fully integrated. Although Italy has made strides towards conforming to European regulations, significant barriers to increasing recycling efficiency still exist due to a lack of infrastructure, high processing costs, and insufficient collecting methods.

Italy adheres to the sustainability and circular economy objectives by operating within the EU's CRM recovery legal framework. The following table 3.1 includes some important laws affecting CRM recycling:

Table 3.1: Impact of EU Regulations on Italy

Regulation	Key Provision	Impact on Italy
EU Battery Regulation (2023)	Establishes mandatory recycling targets for lithium, cobalt, and nickel from old batteries. Italy is aligning its battery recycling programs with these objectives.	Italy's battery recycling initiatives are in line with these goals, although more infrastructure is required.

WEEE Directive (2012/2018 Recast)	Sets collection and recycling targets for electronic waste, thereby assisting CRM recovery from abandoned smartphones, computers, and appliances.	Illegal exports and informal recycling persist despite Italy's WEEE compliance procedures.
EU Circular Economy Action Plan (2020)	Encourages eco-design and recycling-friendly product standards, although implementation in Italy remains inconsistent.	In Italy, uneven implementation leads to regional variations in collecting efficiency.
Waste Shipment Regulation (2023 Revision)	Limits hazardous e-waste exports beyond the EU in order to promote recycling at home.	Keeps waste rich in CRM in Europe, but Italy lacks the refinement capacity.
End-of-Life (ELV) Vehicle Directive	Establishes recycling goals for auto parts, including those that contain CRM, such as batteries and magnets.	Italy's car industry is growing, but the remanufacturing industry is still in its early stages.

3.4.2.1. Principal Obstacles to CRM Recycling Effectiveness

Despite these rules, there are a number of operational and policy flaws in Italy's CRM recycling industry that restrict its scale and efficiency.

1. **Inadequate Rare Earth Recycling Infrastructure**
   - Due to complicated chemical separation procedures that are not commonly accessible in Italy, recycling of rare earth elements (REEs) is undeveloped.
   - Italy lacks specialised recycling facilities capable of extracting and refining rare earth elements (REEs) from electric motors, wind turbines, and permanent magnets, in contrast to Germany (VAC Group) and France (Solvay).
   - Italy must import processed REEs from China rather than recovering them domestically due to a lack of high-efficiency separation methods.

2. **High Processing Costs Reduce Viability**
   - Advanced hydrometallurgical and pyrometallurgical methods are needed to recycle lithium, cobalt, and nickel from batteries; these processes are energy-intensive and expensive.
   - Businesses have less financial incentive to invest in recycling systems since imported refined CRMs are frequently less expensive than domestically recycled materials.
   - Although adoption has been sluggish, EU financing and public-private partnerships (PPPs) could aid in closing the cost gap.

3. **Poor Rates of Collection for Waste Rich in CRM**

There is a notable deficiency in CRM waste collection in Italy, namely with regard to:

- Consumer electronics and lithium-ion batteries from EVs.
- E-waste from computers, industrial equipment, and cell phones.
- Wind turbines and electric motors' permanent magnets.

A significant portion of products that contain CRM at the end of their useful lives do not go through official recycling routes because

- Public ignorance on appropriate disposal.
- Illegal e-waste exports to nations outside the EU.
- Ineffective networks of reverse logistics that are unable to retrieve CRM-rich components.

4. **Financial and Policy Barriers**
   - Strong financial incentives for CRM recycling firms to invest in cutting-edge recovery techniques are lacking in Italy's governmental environment.
   - Italy does not provide substantial tax incentives or cash grants for CRM recycling firms, in contrast to nations with government-backed subsidies.
   - Manufacturers are held less accountable for material recovery when extended producer responsibility (EPR) programs are not in place for CRM-intensive items.

5. **Prospects for Enhancing CRM Recycling in Italy in the Future**

- To reduce reliance on imports, establish facilities for recycling lithium and rare earth elements.
- Stop illegal exports and expand the number of collection networks for waste containing CRM.
- Offer financial incentives, like tax savings, to companies that invest in CRM recovery.
- Boost productivity through automation and artificial intelligence for material recovery and sorting.
- Public-private partnerships (PPPs) ought to be reinforced in order to foster innovation in CRM recycling technologies.

By addressing these operational and legal concerns, Italy can increase the efficiency of its CRM recycling, better align with the goals of the EU circular economy, and guarantee a more resilient supply chain for vital raw materials.

3.4.3. Industry 4.0 and Digitalisation for CRM Recycling in Italy

Digitizing Italy's CRM recycling sector is a critical step in increasing efficiency and sustainability. The nation's capacity to recycle and recover valuable raw materials could be greatly enhanced by utilizing Industry 4.0 technologies, especially artificial intelligence, automation, and blockchain. Every one of these technologies has a unique function in maximizing CRM recycling in Italy, offering tangible chances to resolve existing inefficiencies, simplify procedures, and support a circular economy.

- **Current Use of AI:**

There are some new initiatives to fully integrate AI and automation technology into Italy's CRM recycling processes, even though this is not yet the case. AI-based sorting technologies, for example, are being tested by a number of e-waste recycling facilities. These technologies use machine learning algorithms to help identify and separate valuable materials like lithium and rare earth elements. These solutions are either in the pilot stage or are only available for smaller-scale operations. Large-scale adoption has not yet occurred, and many facilities still employ traditional, manual sorting methods. Automation in material handling and processing is also gradually entering the recycling industry, despite the wide variations in adoption rates amongst facilities.

Some private businesses in Italy, such as Green Impact, have started looking into automation technology to improve the effectiveness of their recycling procedures, especially when it comes to sorting mixed garbage. These solutions are frequently not entirely integrated or tailored for CRM recycling in particular, though. There are still issues with the use of AI and automation in CRM recycling, including as the high upfront costs and the requirement for specialized workers to manage intricate systems.

- **Blockchain for Tracking Recycled Materials**

The use of blockchain technology for CRM recycling in Italy is still in the beginning stages. Blockchain is becoming more and more popular in many industries for transparency and traceability, but its application in CRM recycling is still in its infancy. Numerous Italian businesses are looking into blockchain technology to enhance material tracking and ensure compliance with environmental standards. For instance, the Blockchain for Circular Economy (BCE) initiative, which involves several EU countries, is looking into the use of blockchain for recycling and waste management. Italy has participated in these initiatives, but its national CRM recycling processes have not yet fully integrated blockchain technology (European Environment Agency, 2023).

The EU and Italian legislative frameworks are changing to promote more openness in the recycling of essential raw materials, and blockchain may be a major factor in this change. Nevertheless, despite its potential, blockchain usage in CRM recycling is still quite small, and it confronts obstacles related to industry standards, regulatory certification, and interaction with current systems.

3.5. Challenges and Opportunities

There are a number of obstacles in the way of digitising Italy's CRM recycling industry. These include the requirement for trained staff development, the high expenses of integrating blockchain and AI technology, and the absence of standardised processes among various recycling plants. Clearer instructions on how digital technologies can be implemented to assure compliance and efficiently track recycled materials are also needed, as the regulatory framework is still catching up with technical improvements.

However, by going digital, Italy has several opportunities to raise its profile in CRM recycling. By investing in AI, automation, and blockchain, Italy could increase the efficiency, traceability, and transparency of its recycling processes and further support the EU's circular economy goals. Additionally, the increasing demand for sustainable and ethical CRM sourcing presents an opportunity for Italy to lead the way in digital recycling solutions.

3.6. Conclusion

In conclusion, Italy has noteworthy local resources of important elements like lithium and rare earths, giving it a substantial but underutilised position in the EU's CRM supply chain. Nevertheless, obstacles like legal restrictions and environmental worries prevent extraction operations from reaching their full potential. Italy can increase the sustainability and effectiveness of CRM extraction by incorporating Lean principles into mining operations, which will optimise processes, cut waste, and minimise energy use.

Despite an expanding domestic refining infrastructure, Italy's position in CRM processing and refining is still mostly reliant on imported resources. The quality and effectiveness of refining processes could be greatly increased by implementing Six Sigma approaches, especially in terms of improving CRM purity and reducing defects. Although there has been progress in the nation's attempts to recycle CRM and promote a circular economy, there are still areas where efficiency and regulatory compliance are lacking. A possible approach to increasing recycling rates and guaranteeing a more sustainable CRM ecosystem is to use digital technologies like AI and automation for sorting and material recovery, in conjunction with blockchain for tracking and compliance. A concentrated effort to remove these obstacles and adopt cutting-edge technology will be essential to guaranteeing a robust and independent supply chain for essential raw materials, which will enhance Italy's commitment to the EU's CRM strategy.

4 Italy’s CRM Supply Chain Vulnerabilities and External Dependencies

4.1. Introduction

Even though these materials are necessary for the country's economic competitiveness, Italy still relies heavily on imports to meet its needs for CRMs. As global supply chains become more unstable due to trade restrictions, geopolitical conflicts, and economic uncertainty, securing a strong and diverse CRM supply has become a strategic concern.

This section looks at resilience-building strategies, the risks of global supply chain disruptions, and Italy's reliance on imports for CRM. It examines the impact of EU trade agreements, Italy's main CRM suppliers, and risk-reducing agile procurement techniques. It also compares Italy's CRM resilience to that of the leading EU economies, such as France and Germany, and evaluates risk management strategies, such as scenario planning with Monte Carlo simulations.

Overall, the current section also looks at key resilience metrics, like the Import Dependency Ratio and Supply Chain Resilience Index, and makes recommendations for how to improve trade security, diversify sourcing, and make the supply chain more resilient overall.

4.2. CRM Import Dependence and Trade Partnerships

Italy's supply chain for CRM is vulnerable to supply disruptions, price fluctuations, and geopolitical threats because of its significant reliance on imports from outside the EU. Critical minerals like lithium, cobalt, nickel, and REEs are essential to Italy's industrial sectors, which include electronics, automotive, aerospace, and renewable energy. However, due to its low internal reserves and refining capabilities, Italy is heavily reliant on outside supply, primarily from China, Africa, and Latin America.

Most of the CRM imports into Italy originate from:

- China is the world's largest producer of processed CRMs and REEs, which are essential for defence and high-tech industries. Italy's supply chains for technology could be significantly impacted by any trade restrictions imposed by China (U.S. Geological Survey, 2023).

- More than 70% of the world's supply of cobalt, a necessary component for battery production, comes from the DRC. However, because of the continuous political volatility, reliance on the DRC raises questions about ethical sourcing and supply insecurity (OECD, 2022).

- Lithium, a crucial component of energy storage systems and batteries for electric vehicles (EVs), is produced in large quantities in Chile and Argentina. The competition for dependable supply agreements is getting fiercer due to the rising demand for lithium worldwide (International Energy Agency, 2023).

- The Philippines and Indonesia are major exporters of nickel, another essential component for lithium-ion batteries and the manufacturing of stainless steel.

Italy benefits from EU-led trade agreements and strategic measures that diversify CRM supplier sources in order to mitigate these risks. While the EU Critical Raw Materials Act promotes local recycling and refining to lessen dependency on foreign processing, agreements with Canada, Australia, and a few African nations seek to increase access to alternative CRM sources. These agile procurement solutions are essential for improving supply chain flexibility and lowering CRM supply risks. By using multi-supplier strategies and expanding its sourcing outside of high-risk areas, Italy can reduce its dependency on important suppliers like China and the DRC. The lack of large-scale CRM extraction projects and Italy's limited refining capacity are two structural issues that persist despite these efforts.

4.3. Supply Chain Risks and Disruptions

Due to its close connections to international markets, Italy's CRM supply chain is particularly susceptible to disruptions from pandemics, trade restrictions, geopolitical unrest, and economic instability. The issues related to supply shortages are made worse by the growing demand for CRMs in sectors like semiconductors, renewable energy, and electric vehicles. These shortcomings have already been brought to light by a number of significant global events, underscoring the urgent need for effective risk management strategies.

4.3.1. Impact of Global Events on CRM Supply Chains

1. **Covid-19 and Supply Chain Bottlenecks**

Global supply chains were severely disrupted by the COVID-19 pandemic, which had an impact on CRM availability and cost. Lower mining output was caused by the closure of factories in South America, Africa, and China, which produce the majority of lithium, cobalt, and rare earth elements. At the same time, delays and price increases were caused by port closures, logistical difficulties, and container shortages. For instance, supply chain disruptions and the growing demand for batteries in electric vehicles caused lithium prices to rise by about 500% between 2021 and 2022.

2. **Geopolitical Tensions and Trade Wars**

CRM supply risk has increased as a result of the growing geopolitical distance between major economies. With over 60% of the world's rare earth production and almost 90% of its processing, China has regularly used its position as leverage in trade disputes. China halted rare earth exports to Japan in 2010 due to a territorial dispute, which caused a global supply shock and caused the price of several rare earth elements to rise by 700%. Concerns regarding supply security were raised more recently in 2023 when China imposed export restrictions on gallium and germanium, vital minerals used in electronics and defense applications.

3. Export Bans and Resource Nationalism

CRM-rich nations have started to restrict the export of raw materials in order to prioritize their own industries. In an effort to increase domestic processing, Indonesia, which produces about 40% of the world's nickel, restricted exports in 2020. Due to supply shortages brought on by this change, businesses in Europe were forced to look for new suppliers. In a similar vein, Chile and Mexico have nationalized parts of their lithium industries, limiting access to their reserves from other countries. Italy, which depends largely on outside sources and lacks local extraction capacity, is seriously at risk from such measures.

Italy and the EU have been putting strategic measures in place to manage these risks, such as refining investments, stockpiling, and diversification of supplies. The following section delves more into these tactics.

4.4. Risk Management

Proactive risk management is essential for anticipating and minimizing potential disruptions due to the intricacy of CRM supply chains. Two fundamental methods are frequently used in industrial risk assessment:

- Monte Carlo Simulation: By estimating the probability and magnitude of supply network shocks, Monte Carlo simulations are used to model various disruption scenarios. A 20% drop in South American lithium production, for instance, could lead to a 35% price increase and more than six-month production delays, according to a Monte Carlo simulation of the EU's lithium supply chains. Italy can use this technology to develop contingency plans based on probabilistic modeling and real-time data, as well as more accurate risk projections.

- Contingency Planning for Supply Chain Disruptions: Businesses that rely on CRMs need to develop robust supply chain strategies. These include agile procurement methods that allow for quick reactions to market fluctuations, onshoring and nearshoring initiatives that aim to lessen dependency on imports by promoting domestic CRM processing, and alternative supplier networks that involve working with multiple foreign partners to reduce reliance on a single supplier.

The European Battery Alliance (EBA), which was established in response to cobalt and lithium shortages in Europe's EV industry, is a practical example. In order to lessen dependency on high-risk areas and create a more dependable supply chain for battery manufacturing, the EBA plans to invest in local processing and find substitute suppliers.

Pandemics, geopolitical unrest, and export restrictions are just a few of the international threats that could affect Italy's CRM supply chain. Events like Indonesia's nickel ban, China's export restrictions on rare earths, and supply chain interruptions brought on by COVID-19 highlight how important it is to have a varied, strong, and well-thought-out CRM strategy. By putting stockpiling measures, trade diversification, and improved risk modeling into place, Italy can lessen these vulnerabilities and bolster its role in protecting Europe's vital raw material supply.

4.5. Italy’s Supply Chain Resilience

Italy's CRM supply chain is prone to external shocks, has a high reliance on imports, and lacks adequate domestic processing. We can objectively evaluate Italy's current situation and recommend areas for improvement by using comparative benchmarking, scenario modeling, and resilience measures.

4.5.1. Resilience Metrics and Indicators

Italy's ability to absorb supply chain shocks is measured using two major indicators:

1. **Supply Chain Resilience Indicator:**

   A nation's ability to endure and bounce back from supply disruptions is gauged by the Supply Chain Resilience Index (SCRI). It takes into account risk exposure, trade stability, local output, and supplier diversity.

   • Italy outperformed Spain (44.3) but fell short of Germany (65.2) and France (58.9) in 2023 with an SCRI score of 48.7/100.

   • Italy's low resilience ranking is further compounded by its over 60% reliance on CRM imports from China.

   • Higher SCRI ratings are typically found in nations with larger domestic refining and alternative supply networks (FM Global, 2023).

2. Import Dependency Ratio

The Import Dependency Ratio (IDR) measures the proportion of a country's CRM consumption that originates from external vendors.

Three of the EU's largest industrial economies—Italy, France, and Germany—are compared to one another because they all rely heavily on CRMs in the manufacturing, automotive, and aerospace industries. Germany and France have made great progress in CRM resilience through different supply chains, refining capabilities, and stockpiling techniques, making them suitable benchmarks for assessing Italy's strengths, weaknesses, and areas for improvement in ensuring a reliable CRM supply.

Table 4.1: IDR of EU Countries (Eurostat, 2023)

Critical Raw Material	Italy’s Import Dependency	Germany’s Import Dependency	France’s Import Dependency	Main Supplier
Lithium	100%	94%	91%	Chile, Australia
Cobalt	93%	85%	78%	DRC, China
REE	98%	87%	83%	China, USA
Nickel	97%	89%	80%	Indonesia, Russia

Italy's IDR for lithium, rare earth elements, and cobalt surpasses 90%, making it extremely sensitive to supply chain disruptions.

Germany and France have lower IDRs as a result of investments in refining, recycling, and expanded trade agreements.

4.5.2. Scenario Analysis

- **Scenario 1: What happens if a Key CRM Source is disrupted?**

A scenario analysis acts like the impact of supply chain shocks to evaluate Italy's sensitivity. Given that China refines nearly 90% of the world's supply of rare earth elements and supplies more than 60% of Italy's REEs, a possible disruption in China's rare earth shipments is being looked into.

- **Scenario 2: China Halts Rare Earth Exports (Similar to 2010 and 2030 Cases)**
    - **Immediate consequences (0–3 months):**

1. Rare earth prices may increase by 300–500% based on historical trends (such as the 2010 China-Japan trade dispute).
2. Supply shortages would affect the wind turbine and electric vehicle industries in Italy, which depend on neodymium and dysprosium for their magnets.
3. Manufacturers may lower global competitiveness by raising prices or reducing production.

    - **Short-Term Response (3 to 12 months):**

1. Italy would look for other suppliers (such as the US and Australia), but the effectiveness would be limited by production capacity constraints and logistical delays of six to twelve months.
2. While stockpile releases and other EU-wide emergency measures may lessen the harm, they cannot completely eradicate it.

    - **Long-term Consequences (1-3 Years):**

1. Italy's industries would experience material shortages if China's export restrictions continued, leading to factory closures and a large loss of jobs.
2. Italy's aerospace (Leonardo S.p.A.) and automotive (Stellantis, Ferrari) sectors would suffer greatly.
3. By investing more in alternative REE processing, European businesses could decrease their long-term dependency on China.

- **In comparison to Germany and France, how does Italy rank in CRM security?**

Comparing Italy against Germany and France reveals insights into its competitiveness and vulnerabilities.

Table 4.2: CRM Security of EU Countries (European Commission, 2023b)

Metric	Italy	Germany	France
SCRI Score (2023)	48.7/100	65.2/100	58.9/100
IDR for Lithium	100% (high risk)	94%	91%
REE Processing	None (100% imported)	Limited (some pilot projects)	More advanced refining capacity
Trade Agreements	Relies on EU partnerships	Direct partnership with Canada, Australia	Stronger African partnerships
Stockpiling Strategy	No national CRM reserves	Developing strategic reserves	Maintains reserves for nuclear materials

Based on Table 4.2 we can deduce that:

- Germany is the most resilient, due to stronger supplier diversification and trade agreements.
- France has a greater refining and recycling system, which helps to reduce reliance on imports.
- Italy ranks worst due to its strong reliance on imports and a lack of domestic refining and stockpiling activities.

4.6. Conclusion

Italy's CRM supply chain relies mainly on imports from a limited number of foreign suppliers, primarily from Latin America, Africa, and China. Because of this dependence, Italy is susceptible to supply issues, price fluctuations, and geopolitical unpredictability. Despite the potential for diversification presented by EU trade agreements, ongoing geopolitical tensions and resource nationalism policies pose a threat to supply chain stability.

International events like COVID-19, trade restrictions, and geopolitical crises have brought attention to the vulnerability of CRM supply chains, highlighting the need for effective risk management strategies. By using Monte Carlo simulations and scenario planning, Italy can anticipate potential supply disruptions and develop contingency plans to mitigate their effects.

To assess and judge its resilience, Italy must analyze key supply chain metrics like the Supply Chain Resilience Index and Import Dependency Ratio. Comparing Italy's CRM security measures with those of countries like Germany and France can help find areas for improvement and best practices.

Improving Italy's CRM supply chain resilience would ultimately require strategic diversification, proactive risk management, and closer EU collaboration to ensure long-term supply security and industrial stability.

5 Strategies for Strengthening Italy's Role in Securing the EU's CRM Supply

5.1. Introduction

Italy is a major player in the EU and has the potential to contribute to a robust and stable supply chain as the EU works to lessen its reliance on outside sources for critical raw materials (CRMs). However, to solidify its presence in the EU CRM supply chain, Italy needs to take proactive steps to improve its domestic CRM production, lower vulnerabilities, and support the EU's larger raw materials security objectives.

In order to achieve this, it is advised that Italy focus on building up its own extraction and refining capacities through the use of government incentives and the promotion of public-private partnerships. In addition to improving sustainability and efficiency, lean mining techniques can reduce the environmental impact of CRM extraction.

CRM recycling and circular economy initiatives offer a workable solution to reduce reliance on imports of primary raw materials after extraction. Implementing Six Sigma techniques, making investments in state-of-the-art recovery technologies such as hydrometallurgy and urban mining, and strengthening recycling regulations can all increase recycling efficiency and CRM yield.

Given the risks associated with an over-reliance on a small number of suppliers, it will be imperative to diversify CRM supply chains through agile sourcing methods and EU-wide procurement strategies. The diversification of suppliers will help Italy create a more resilient and geopolitically secure supply network.

Additionally, Italy's CRM supply chain may be optimised through revolutionary potential presented by digitalisation and AI-driven technology. Blockchain applications provide more transparency and adherence to EU rules, while AI can enhance demand forecasting and logistics.

Lastly, Italy's strategy will be heavily influenced by research and innovation. Italy will be able to create long-term solutions for safeguarding its CRM supply through investments in CRM alternatives, material efficiency enhancements, and cooperation with research institutions.

It is proposed for Italy to improve industrial competitiveness, contribute to the bloc's overall security and economic resilience, and solidify its position within the EU's CRM framework by putting these policies into practice.

5.2. Expanding Domestic Extraction and Processing

Despite Italy's unexplored mineral resources of lithium, nickel, and rare earth elements, the country's CRM supply chain is largely dependent on imports. Italy is urged to make investments in domestic extraction and processing capabilities in order to improve its standing in the EU's CRM strategy. The government may think about offering substantial assistance, financial incentives, and coordination between the public and private sectors in order to create a competitive and sustainable CRM industry.

5.2.1. Government Incentives for New Mining Projects

The Italian government is essential to reviving the country's mining industry, which has been hampered by economic difficulties, environmental issues, and regulatory barriers. Strengthening Italy's mining industry is crucial for improving supply security and lowering reliance on imports, especially in light of the EU's growing need for CRMs in vital industries like semiconductors, renewable energy, and electric vehicles. A number of focused policy initiatives can be put into place to encourage investment in CRM extraction:

- **Tax Incentives and Subsidies**

The government can provide tax benefits, direct subsidies, and low-interest loans to mining companies that create CRM extraction projects while abiding by stringent Environmental, Social, and Governance (ESG) requirements in order to draw in both domestic and foreign investors. This guarantees that future mining operations complement the sustainability objectives of the EU and Italy (European Commission, 2023a; OECD, 2021).

- **Fast-Track Permitting and Regulatory Reform**

Due to intricate administrative permits and environmental impact assessments, mining operations in Italy frequently experience protracted bureaucratic delays, with licensing procedures spanning five to ten years. For CRM projects that adhere to EU sustainability rules, the government can implement fast-track permitting, which would drastically cut approval timelines while upholding strict environmental standards. This strategy has already been tried in Sweden and Germany, where expedited permitting has sped up the development of CRM projects (European Commission, 2023b; WEF, 2022).

- **State-Funded Geological Surveys and Resource Mapping**

One of the most important steps in improving Italy's mining capability is locating feasible CRM resources. In mineral-rich areas like Sardinia, Piedmont, and the Alps, where nickel, lithium, and rare earth elements have been found, the government can support geological exploration projects. Working together with academic institutions, research centres, and commercial companies can improve the viability of new mining projects and increase the accuracy of resource estimates (ISPRA, 2021; European Commission, 2020).

- **National Measures for CRMA Compliance**

To comply with the EU CRMA, Italy issued a national legislative decree in 2024 that outlined precise measures to expedite exploration, streamline permitting processes, and ensure adherence to EU strategic objectives. Italy's commitment to identifying Strategic Projects, improving access to geological data, and working with regional authorities to develop a National Raw Materials Plan is emphasised in the directive. These programs aim to increase Italy's alignment with EU resource resilience goals by promoting sustainable CRM extraction, reducing administrative delays, and improving transparency (Gazzetta Ufficiale, 2024; European Commission, 2023a).

- **Incentives for Sustainable and Low-Impact Mining**

The government can make sustainability efforts for mining companies mandatory in order to reduce the environmental impact of CRM extraction. For example:

1. Businesses may be forced to use renewable energy sources, such as wind or solar, to power their extraction sites.

2. To cut down on water usage, mining enterprises should incorporate water recycling devices.
3. To ensure long-term environmental sustainability, funds could be set aside for post-extraction mining site rehabilitation.

Italy can create a mining sector that is competitive and sustainable while balancing economic growth and environmental responsibility by implementing these incentives, which will strengthen the EU supply chain's resilience.

5.2.2. Public-private Partnerships for CRM

Extraction alone is insufficient; Italy is urged to also invest in refining and processing to lessen its reliance on foreign suppliers, particularly China, which now processes more than 85% of the world's rare earths. Given CRM refinery infrastructure's high capital costs, public-private partnerships (PPPs) can help speed investment:

- Joint ventures between the Italian government and private industry to develop refining plants for lithium, nickel, and rare earths, ensuring a stable domestic supply of processed materials.
- Collaboration with EU-based refining efforts, such as the European Raw Materials Alliance (ERMA), to gain money and expertise for the establishment of refinery facilities in Italy.
- Technology transfer agreements with advanced CRM processors (e.g., from Canada or Australia) to develop more efficient and ecologically friendly refining methods. Integrating renewable energy sources into refining plants to fit with the EU's Green Deal goals and lessen the environmental impact of processing activities.

Italy may improve supply security, support domestic companies that depend on these essential resources, and solidify its place in the EU's CRM supply chain by enacting targeted incentives for extraction and refining.

5.2.3. Lean Mining for Sustainable Extractions

Italy must find a balance between environmental sustainability and economic viability as it works to expand its CRM extraction industry. High operating costs and community opposition are often the results of traditional mining operations, which are often resource-intensive, inefficient, and environmentally harmful. Lean mining principles can help address these challenges by streamlining procedures, cutting waste, conserving energy, and enhancing sustainability.

1. **Applying Lean Methodologies in Mining Operations**

Lean approaches emphasise eliminating inefficiencies and boosting value-added activities. They were initially developed for manufacturing. The following are some applications of lean principles in mining:

To streamline processes and reduce bottlenecks, Value Stream Mapping (VSM) identifies inefficiencies in the extraction, transportation, and processing of ore.

- Just-in-Time (JIT) mining minimises waste and operating costs by extracting and processing only what is needed, thereby reducing excessive material handling.
- To reduce mechanical breakdowns, which cause 15–25% of downtime in conventional mining operations, Total Productive Maintenance (TPM) involves employing predictive maintenance strategies.
- Kaizen (Continuous Improvement): Encourages employee-driven process modifications to enhance environmental performance, efficiency, and safety.

2. **Reducing Environmental Impact through Lean Mining**

Because it complies with EU sustainability regulations and Italy's dedication to environmentally friendly business practices, lean mining is especially crucial for minimising environmental harm. Important tactics consist of:

- Water and Energy Efficiency: Mining operations can cut carbon emissions by 30–50% by using renewable energy sources (wind, solar) and closed-loop water recycling technologies.

- Reducing Overburden Waste: Only high-grade ores are extracted through selective mining and precision drilling, minimising needless land impact.

- AI-driven and automated processes: Reducing energy-intensive refining processes while increasing material recovery rates through the use of AI-based ore sorting technology.

- Eco-Friendly Tailings Management: Dry stacking alternatives to traditional tailings dams are being developed to enhance land restoration and prevent groundwater contamination.

By applying Lean Mining techniques to boost the productivity, profitability, and sustainability of its CRM extraction industry, Italy can become a more responsible and competitive participant in the EU's quest for resource independence.

5.3. Enhancing CRM Recycling and Circular Economy Initiatives

Recycling and circular economy programs are critical for lowering Italy's reliance on imported CRMs, extending materials' lifecycles, and minimising environmental effect. As demand for lithium, rare earths, and other CRMs rises, particularly in the automotive, renewable energy, and electronics industries, Italy must expand its recycling infrastructure and implement innovative recovery methods to maximise CRM reuse (European Commission, 2023).

The Figure 5.1 illustrates the steps most minerals pass through in order to reach the final step of recycling.

Figure 5.1: CRM Life Cycle (Nordic Council of Ministers, 2025)

The flowchart mentioned above highlights the importance of each stage in the vital raw material lifecycle by showing the progression from minerals to material recycling. By boosting recovery rates and promoting recycling, Italy can bolster its circular economy initiatives and reduce its dependency on primary raw materials.

5.3.1. Policy Measures to Improve CRM Recovery from E-Waste and Batteries

Numerous programs have been created by the EU and the Italian government to promote CRM recycling, especially from end-of-life batteries and electronic waste (e-waste). Italy is under pressure to boost its recycling capacity because the EU's Battery Regulation (2023) mandates that lithium-ion batteries have at least 12% recycled cobalt, 4% lithium, and 4% nickel by 2030. However, current lithium and rare earth recycling rates are below 5%, highlighting the need for more efficient technologies for collection and processing.

Italy is addressing this by encouraging businesses to set up closed-loop recycling systems, bolstering producer responsibility initiatives, and expanding mandatory e-waste collection programs.
In order to recover CRMs from solar panels, wind turbines, and electric vehicle (EV) batteries—all of which are highly industrialised in Italy—investments in automated dismantling facilities will also be necessary.

5.3.2. Advancement in Hydrometallurgy and Urban Mining

Technological improvements are playing an important role in increasing CRM recovery efficiency. Hydrometallurgy, a chemical method for extracting metals from old products and industrial waste, is gaining popularity as a less energy-intensive alternative to traditional smelting. Italian research institutions are developing solvent-based and bioleaching technologies for recovering lithium from spent EV batteries with up to 90% efficiency, reducing reliance on virgin resources (Ardente et al., 2023).

Another new field is urban mining, which involves extracting valuable metals from discarded electronics and industrial scrap rather than mining the dirt. With over 1.5 million tonnes of e-waste created annually in Italy, urban mining offers a cost-effective and long-term alternative to increase CRM availability. However, problems persist, such as high processing costs and the need for better sorting technology (ISPRA, 2022).

5.3.3. Applying Six Sigma to Improve Recycling Yield and Quality

The manufacturing process optimization and defect reduction methods of Six Sigma can enhance CRM recovery operations. Italian recycling facilities can achieve better CRM recovery rates through data-driven quality control systems that:

1. Identify and remove inefficiencies in metal separation procedures to improve CRM recovery rates.

2. Material losses during recycling operations amount to 15-30% of recoverable CRMs which end up as waste.

3. The standardization of purity levels in refined secondary materials will ensure that recycled CRMs fulfill industry requirements for high-performance applications.

The circular economy in Italy will experience significant improvement through Six Sigma optimization of recycling processes and advanced recovery technology investments and enhanced regulatory enforcement which will support EU CRM resilience and reduce environmental impact.

5.4. Diversifying CRM Supply Chains and Strengthening Trade Agreements

The stability of Italy's supply chain faces danger because of its dependence on China for processed CRMs while export restrictions and geopolitical unrest affect global supply changes. The global prices of Gallium and germanium which serve as essential minerals for semiconductors and defense technology increased by 27% during three months in 2023 after China imposed export restrictions (European Commission, 2023; Reuters, 2023). The EU and Italy need to take immediate action for supply source diversification because China maintains control of 60% of lithium-ion battery supply chains and 85% of rare earth refining operations (IEA, 2022).

The EU-wide procurement cooperation of Italy combines resource-rich region partnerships with agile procurement techniques to enhance supply chain resilience against these risks.

5.4.1. Emerging CRM Supply Partnerships

Italy must guarantee a wide and strong supply network as the demand for CRMs rises globally. Like a large portion of the EU, Italy has historically depended heavily on China for sophisticated CRMs, which presents serious geopolitical and economic risks. Diversifying supply chains is crucial to reducing vulnerabilities and fostering industrial resilience, as evidenced by recent export restrictions, price swings, and trade disputes.

Italy is actively enhancing intra-EU cooperation and forming strategic alliances with resource-rich regions like Africa, Latin America, and Australia in order to mitigate these risks. In order to ensure alternative sources of vital resources like lithium, cobalt, and rare earth elements—which are essential for sectors like automotive, renewable energy, and defense—these partnerships are being formed. Italy is establishing itself as a more powerful participant in the EU's CRM strategy by negotiating deals with new suppliers and making investments in refining infrastructure, which will guarantee resource security and industrial competitiveness in the long run.

- **Africa:** With 30% of the world's mineral wealth, it offers China a strategic advantage. More than 60% of the world's supply of cobalt comes from Namibia and the Democratic Republic of the Congo, with whom Italy has already started to build relationships (European Commission, 2023). In order to encourage sustainable rare earth mining, the EU and Namibia signed a strategic cooperation agreement in 2023, giving Italy a direct path for future imports.

- **Latin America:** With Chile, Argentina, and Bolivia controlling over 60% of the world's lithium reserves, Italy is looking at lithium extraction partnerships to help its EV and battery businesses. In 2022, lithium output in Argentina increased by 33%, indicating greater availability for export (Reuters, 2022).

- **Australia and Canada** have substantial ESG-compliant mining industries, accounting for almost 20% of global nickel and lithium production (World Bank, 2022). Italy already imports refined nickel from Canada and is pursuing new deals to lessen its reliance on Asian intermediaries.

Despite these efforts, logistics difficulties remain, such as greater transit costs, regulatory delays, and the need for refining capacity in Europe to process raw materials efficiently.

5.4.2. Strengthening EU-Wide Joint Procurement Strategies

Italy is a significant participant in the EU's broader strategic sourcing initiatives, which seek to increase collective purchasing power and obtain crucial raw resources through cooperative agreements.

Some key EU procurement initiatives involving Italy include:

1. The European Raw Materials Alliance (ERMA): This effort intends to minimise the EU's reliance on third-party processors by encouraging new mining, refining, and recycling enterprises in the region. Italy is actively negotiating big acquisitions of lithium and rare earths to improve trade terms

and secure dedicated supply networks for its sectors (European Commission, 2023).

2. EU Critical Raw Materials Act (CRMA): Enacted in 2023, the CRMA requires that at least 10% of the EU's annual CRM consumption originate from domestic sources by 2030, with 40% of processing taking place within the EU. Italy is projected to enhance its mining and refining investments to meet these aims.
3. Strategic EU Stockpiling Measures: In 2024, the EU initiated a CRM stockpiling strategy, establishing reserves for high-risk elements such rare earths, lithium, and cobalt. Italy is a major contributor to this effort, particularly in procuring supplies for its automobile and aerospace industries (EU Parliament, 2024).

A fundamental problem in these projects is a lack of refining capacity in Italy and the EU, which leads to continued reliance on Chinese processors. Expanding Europe-based refining operations remains a top aim for decreasing foreign reliance.

5.4.3. Agile Procurement Strategies

Traditional procurement strategies frequently fail in extremely unpredictable markets, as CRM prices can vary by up to 50% each year owing to supply shocks. Italy must adopt an Agile Procurement framework that prioritises supplier adaptation, risk management, and real-time decision-making.

1. **Multi-supplier Contracts and Geographic Diversification**
   - Instead of relying on a single source for CRMs, Italy is shifting to multi-supplier agreements that allow for greater flexibility in the event of a disruption.
   - For example, the European Union's new strategic alliance with Canada will supply Italy with alternate nickel and lithium supplies, lessening its reliance on China and Indonesia.

2. **Dynamic Contract Terms and Market-responsive Pricing**
   - Italy is incorporating variable pricing methods into CRM contracts, enabling automatic modifications based on real-time market movements.

- This strategy has already been used successfully in Germany's lithium supply agreements with Australia, where contracts tie lithium prices to worldwide market indices.

3. **Stockpiling and Just-in-case (JIC) Inventory Strategies**
   - Unlike the typical Just-in-Time (JIT) model, which reduces inventory, Italy is implementing a Just-in-Case (JIC) plan to ensure strategic reserves of important CRMs.
   - The EU's 2024 CRM Stockpile Initiative will enable Italy to obtain emergency supplies of rare earths and lithium, reducing the impact of supply chain interruptions.

4. **AI and Block-chain for Supply Chain Transparency**
   - Artificial intelligence (AI) is being integrated into CRM procurement systems to predict supply disruptions and optimise purchasing tactics.
   - Block-chain technology is also being tried to improve traceability and assure compliance with ESG standards, allowing Italy to meet EU regulatory obligations.

As global demand for CRMs increases, Italy must ensure a broad and robust supply network. Italy has historically relied significantly on China for refined CRMs, as has much of the EU, posing substantial geopolitical and economic dangers. Recent export limitations, price fluctuations, and trade tensions highlight the importance of diversifying supply chains to decrease vulnerabilities and promote industrial resilience.

5.5. Building a Digital and AI-Driven CRM Supply Chain

CRM supply chains are becoming more complex and unpredictable, which calls for innovative strategies to increase resilience, efficiency, and transparency. Forecasting errors, procurement inefficiencies, and compliance problems can plague traditional CRM sourcing and logistics. Italy is utilising AI, blockchain technology, and smart contracts to build an agile, transparent, and digitally connected supply chain in order to get past these challenges. With the help of these technologies, which will offer safe transactions, real-time tracking, and predictive analytics, Italy will be able to streamline procedures and adhere to EU regulations regarding CRM sourcing and trade.

5.5.1. AI for Demand Forecasting and Agile Logistics

AI is transforming CRM supply networks by improving demand forecasting and optimising logistics. Given that CRM prices can be highly volatile—lithium prices increased by 442% in 2021, while cobalt prices increased by more than 119% due to supply limitations and surging demand for EV batteries—predicting market trends is crucial. AI-powered models analyse historical price trends, global trade flows, and geopolitical developments to predict disruptions, allowing Italy to procure commodities at optimal costs and prevent supply shocks (McKinsey & Company, 2022).

Rio Tinto's Gudai-Darri iron ore mine in Australia is a significant example of AI in CRM supply chains, since it uses AI-powered automation to manage inventories, predict maintenance needs, and optimise transportation (Rio Tinto, 2023). A comparable AI-based strategy in Italy might dramatically improve CRM supply consistency and efficiency.

In logistics, AI-powered technologies optimise transportation routes, shorten transit times, and cut carbon emissions. Companies such as DHL and Maersk employ AI-powered logistics to change shipment plans in real time, decreasing delivery delays by as much as 30% (DHL, 2022; Maersk, 2022). If applied to CRM imports, this might help Italy minimise its reliance on high-risk suppliers by ensuring speedier and more dependable CRM supplies from a variety of sources.

5.5.2. Block-chain for CRM Traceability and Compliance

Due to the complexity of CRM supply chains, fraud, unethical sourcing practices, and a lack of transparency are common outcomes. Blockchain technology improves CRM traceability from mine to end-user by offering a decentralised, impenetrable record-keeping method. This is particularly important for Italy because China imports over 60% of the EU's rare earths, which poses serious labour and environmental issues.

Full traceability of cobalt from mines in the DRC to battery manufacturers in Europe is made possible by the Re-Source project, a successful blockchain initiative backed by Tesla, Glencore, and Umicore. This strategy aids in guaranteeing that the cobalt utilised in European EV batteries satisfies environmental and ethical standards.

To guarantee adherence to the EU's CRMA of 2023, Italy can establish a national block-chain framework for CRM imports. This would reduce the likelihood of illicitly mined or unsustainable resources entering the Italian supply chain by enabling end-to-end tracking of lithium, cobalt, and rare earths.

5.5.3. Smart Contracts for Secure and Efficient Procurement

Long negotiations, manual contract verifications, and protracted payment procedures are all part of traditional CRM procurement, which may cause supply delays. Self-executing digital agreements, or smart contracts, simplify procurement processes and make trade between CRM suppliers and manufacturers faster and safer.

For example, automotive giant BMW has used block-chain and smart contracts into its CRM supply chain to track lithium and cobalt used in EV battery manufacture, providing transparency and preventing supply chain interruption. Smart contracts, if applied in Italy, have the potential to streamline trade deals with alternative suppliers in Africa, Latin America, and Australia, lessening the country's dependence on China.

Smart contracts also prevent fraud and assure compliance by only executing payments for validated CRM deliverables that match present quality and sustainability requirements. This would boost supplier accountability while reducing transaction risks.

5.6. Fostering Innovation and Alternative Material Research

Italy needs to increase material science innovation to lessen its reliance on imports, as the green transition and high-tech industries have led to a significant increase in demand for CRMs. Improved CRM efficiency and alternative materials can boost sustainability and supply security while securing Italy's place as a key player in the EU's strategic autonomy. To do this, it will be essential to make investments in rare CRM substitutes, increase material efficiency, and develop innovative recycling techniques.

5.6.1. R&D Investments in CRM Substitutes and Efficiency Improvements

Developing alternative materials is a high priority for reducing reliance on geopolitically sensitive CRMs such as cobalt, lithium, and REEs. Currently, China controls 63% of the world's rare earth processing and 70% of lithium-ion battery production, making diversification critical (U.S. Geological Survey, 2022).

To illustrate the current landscape of R&D investments in critical raw materials, the chart in figure 5.2 shows the slight improvement in R&D comparing years 2013 and 2023 (European Commission, 2023).

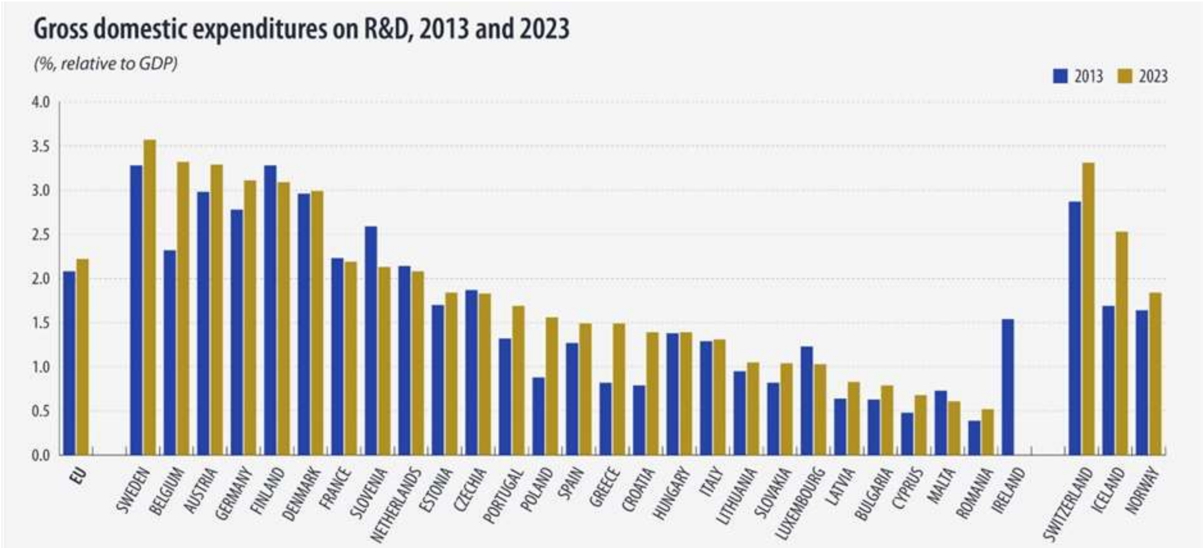


Figure 5.2: Gross Domestic Expenditures on CRM R&D (Eurostat, 2024)

As the figure shows, there has been an obvious increase in investment in research and development in various countries over the last decade. This data highlights the importance of increasing R&D expenditures in Italy to maintain our competitive edge in the development of alternative materials and to keep up with international efforts.

CRM replacement research is a potential avenue. Scientists are developing iron-nitride magnets as an alternative to neodymium-based rare earth magnets, which are essential for EVs and wind turbines (Shifman et al., 2021). Similarly, firms like as Tesla and IBM are creating cobalt-free lithium-ion batteries, which could significantly reduce dependency on the DRC, which mines more than 70% of the world's cobalt (Reuters, 2023). If Italy supports such R&D activities, it may assist to mitigate exposure to supply chain disruptions and ethical concerns associated with CRM mining.

Another important area is increasing CRM efficiency. Research on solid-state batteries could extend battery life while utilising fewer CRMs, and advancements in coatings and nanomaterials are extending the lifespan of solar panels, electronic parts, and aerospace materials, which reduces material waste. Italy currently invests less in CRM research than Germany, which currently spends over €1 billion annually (BMBF, 2023). Italy needs to expand initiatives like the National Research Plan (PNR) and strengthen ties between the public and private sectors as well as universities in order to stay competitive (Italian Ministry of Education, 2022).

5.6.2. Role of Italian Universities and Research Institutions

Italian universities and research centres are leading influential players in the field of CRM innovation in stir mining, in recycling technology and in alternative materials. Actors such as Politecnico di Torino and ENEA (Italian National Agency for New Technologies, Energy and Sustainable Economic Development) are pioneering REE recovery from industrial waste, urban mining and circular economy approaches.

One significant project is Italy's involvement in EU-financed programs such as SUSMAGPRO, a project to recycle rare earths from end-of-life products, including wind turbines and electronics. In addition to this, the European Battery Innovation (EuBatIn) initiative, partially funded by ENEA and the Italian battery manufacturers, has the goal to develop sustainable battery technologies that require less CRMs.

Italy needs to create specialized research centers for advanced recycling and alternative materials, increase funding for applied research, and broaden academic-industry collaboration in order to improve its standing in the CRM supply chain. Italy can help the EU's long-term CRM resilience and reduce its susceptibility to supply shocks by encouraging innovation.

5.7. Leveraging National Legislation to Align with CRMA Objectives

For Italy, a significant priority is the implementation of national legislative measures aligned with the scope of the Critical Raw Materials Act (CRMA) of the European Union. Italy, in particular, has published a new regulation (Dossier D24084b) which outlines steps of national compliance with CRMA. This decree defines an approach to strategic project selection, permitting enhancement, and regulatory streamlining. It further establishes frameworks for monitoring national demand and supply risks for critical raw materials as well as fostering the development of domestic mining, processing, and recycling industries. Implementation of this order allows Italy to advance its role as an active partner in strengthening the European Union's strategic autonomy regarding CRMs and simultaneously enhance domestic capacities in CRMs monitoring, innovation, and infrastructure investment (Camera dei Deputati, 2024).

5.8. Conclusion

By increasing domestic extraction and processing, Italy can amplify its role in the EU's CRM supply chain as well as increase recycling efforts, diversify supply sources, employ digital tools, promote innovation, and sharpen focus on R&D. Fulfilling global CRM demand which is projected to grow more than fourfold by 2050 requires maintaining a sustainable and consistent supply.

Self-sufficiency and reduced reliance on imports can be achieved through investments in new mining and refining facilities alongside government programs and public-private partnerships. Efficiency and sustainability could also be improved by integrating lean mining and Six Sigma. Resource recovery, waste minimization, and the circular economy stand to gain significantly from improvements in recycling, hydrometallurgy, and urban mining.

To address geopolitical risks, reducing reliance on China as a primary supplier while expanding trade partnerships will be essential. The supply shock resilience of the EU can be bolstered by strengthening the procurement strategy and implementing agile sourcing techniques. Moreover, CRM compliance and supply chain security will benefit from transformational technologies including CRM compliance, supply chain security, AI-powered logistics, and blockchain-enabled traceability.

Finally, Italy's long-term resilience will be defined by its focus on innovation and research. Italy can assist the EU achieve strategic autonomy by investing in CRM replacements, material efficiency improvements, and next-generation recycling technologies, all while encouraging industrial growth and sustainability. Strengthening ties between government, industry, and academia will be vital to Italy's continued leadership in CRM security and innovation. If these steps are implemented correctly, Italy will be able to secure its position as a key pillar in the EU's crucial raw resources strategy, securing its industrial future while also aiding long-term economic development.

6 Evaluating the Impact of Proposed Strategies

6.1. Introduction

The suggested tactics to improve Italy's position in the EU's supply chain critical raw materials are assessed in this chapter. It evaluates how well they might work, how feasible they are, and how they might improve supply chain resilience, lessen reliance on imports, and help the EU achieve its larger objectives of strategic autonomy and sustainable industrial development. This chapter offers an evidence-based study of how successfully these strategies address current difficulties, based on forecasts of future CRM demand, analysis of planned and ongoing strategic projects, and comparisons between EU targets and current capacities. In order to guarantee that Italy and the EU can obtain a steady, moral, and sustainable supply of vital raw materials, it also identifies possible weaknesses, hazards, and areas that need more focus.

6.2. Projected Demand vs. Strategic Capacity: Case Studies on Lithium, Cobalt, and Nickel

In this section of the thesis, focus shifts to assessing the effectiveness of the recommended solutions for strengthening the EU’s role in obtaining CRMs for its future supply chain. The previous sections' strategies for the extraction, processing, and recycling of materials such as lithium, nickel and cobalt will be critically evaluated in terms of their feasibility, effectiveness, and potential long-term impact on the EU's resilience and autonomy in the global CRM market.

This evaluation is based on projections about the EU's future demand for CRMs, as shown in the expected scenarios for CRMs. By forecasting demand based on actual market growth and comparing it to present and future EU initiatives, we can determine whether the EU's tactics, such as enhancing domestic extraction or expanding recycling capabilities, are adequate to meet these demands. This section will evaluate the predicted effects of these plans, taking into account both market and geopolitical variables, and will make recommendations for optimizing the EU's CRM supply chain.

The goal of this process is to provide actionable insights into how the EU can strengthen its position in securing critical raw materials, reduce reliance on external suppliers, and establish a sustainable, resilient, and ethical supply chain that is consistent with its overall energy transition and industrial strategy.

Figure 6.1 projects the CRM demand in EU for the years 2030 and 2050 in cases of low and high demand.

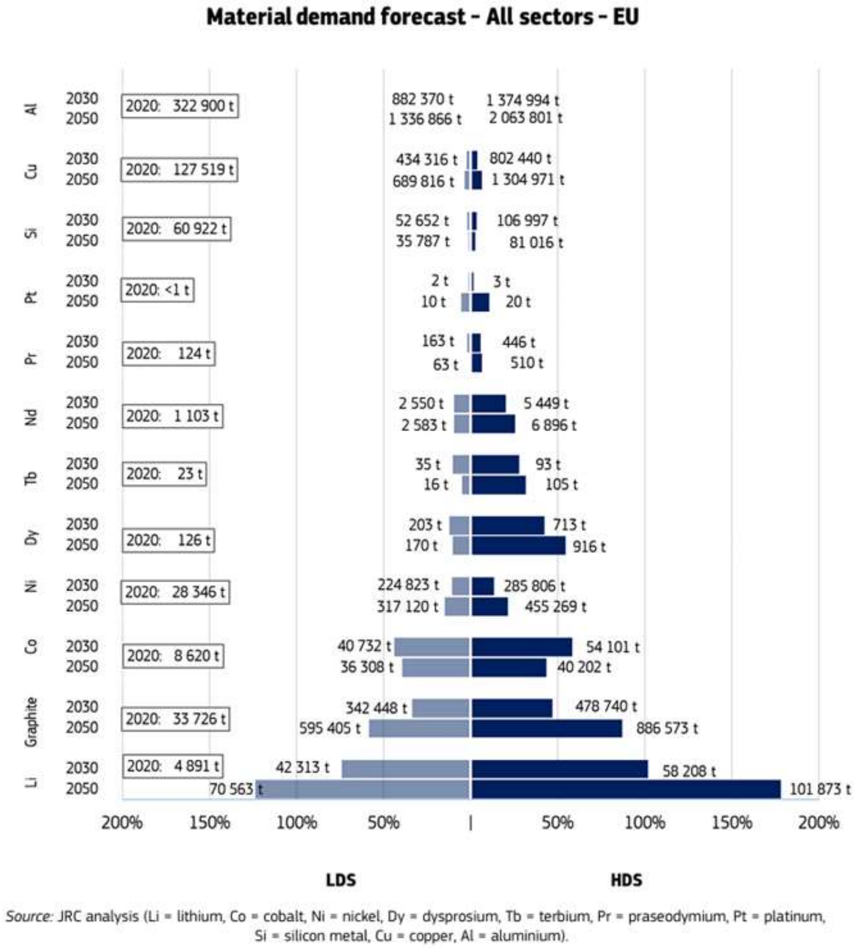


Figure 6.1: Material Demand Forecast (European Commission, 2023a)

6.2.1. EU Lithium Demand Projection for 2030

According to the European Commission's Joint Research Centre (JRC), the EU's demand for lithium is expected to increase significantly by 2030, owing to the shift to electric vehicles and renewable energy storage technologies (European Commission, 2023a).

According to the JRC, the EU's projected lithium demand for 2030 is:

Table 6.1: Projected EU demand for 2030

Scenario	EU Lithium Demand (t/year)
LDS (Low Demand Scenario)	~42,313 tonnes
HDS (High Demand Scenario)	~58,208 tonnes

The CRMA requires that:

- At least 10% of the EU's annual consumption of each critical raw material must be extracted within the EU by 2030.

Based on that:

Table 6.2: CRMA requirements

Scenario	10% EU Extraction Target (t/year)
LDS	4,231 tonnes
HDS	5,820 tonnes

The EU is well-positioned to meet its CRMA 10% lithium extraction requirement in both LDS and HDS scenarios by 2030. While this will not meet full demand, it successfully fulfils the CRMA's self-sufficiency objective.

Strategic Projects Driving EU Self-Sufficiency (European Commission, 2025)

1- **Barroso Lithium Project (Portugal)**

Verified Output: 32 GWh/year battery production capacity

Conversion:
Using the conversion table:

Convert from		Convert to Li	Convert to Li_2O	Convert to Li_2CO_3	Convert to LiOH
Lithium	Li	1.000	2.153	5.323	3.448
Lithium Oxide	Li_2O	0.464	1.000	2.473	1.601
Lithium Carbonate	Li_2CO_3	0.188	0.404	1.000	0.648
Lithium Hydroxide	LiOH	0.290	0.625	1.544	1.000

Figure 6.2: Conversion Factors

32 GWh = ~27,000 t Li_2CO_3 required (at 0.85 t Li_2CO_3/GWh)

27,000 t Li_2CO_3 × 0.188 = 5,076 t Li/year

CRMA Coverage:
120% of LDS target (5,076/4,231)
87% of HDS target (5,076/5,820)

2- **Mina Doade Project (Spain)**
Output: Small-scale operation (conservative estimate)

Conversion:

Estimated 4,000 t Li_2CO_3/year × 0.188 = 752 t Li/year

CRMA Coverage:
Additional 18% of LDS target

Additional 13% of HDS target

Summing up, according to official projections, the EU will require about 58,000 tonnes of lithium annually by 2030 (Strategic Projects under the Critical Raw Materials Act, 2025). Less than 0.1 percent of the world's lithium mine production is currently produced in the EU, and processed, battery-grade lithium is still nearly entirely imported. It is anticipated that strategic initiatives inside the EU will contribute to the extraction and processing criteria for 2030.

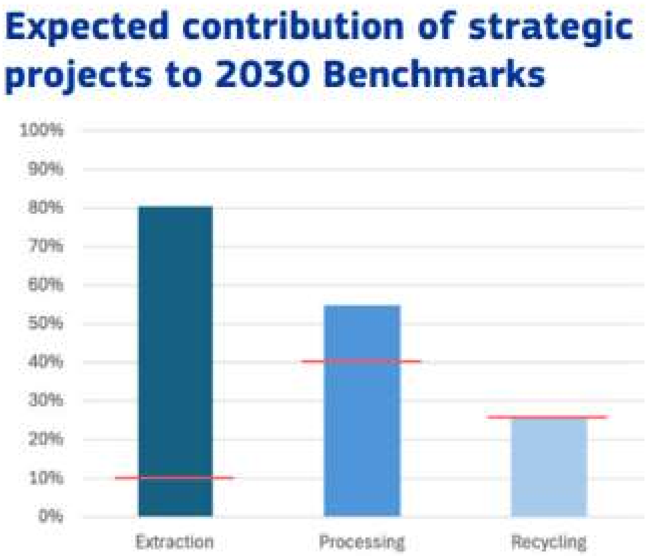


Figure 6.3 Lithium Strategic Contribution (European Commission, 2023)

To lessen the EU's reliance on outside supplies, the Barroso Lithium Project in Portugal and the Mina Doade Project in Spain are expected to offer several thousand tonnes of lithium carbonate equivalent combined. With all the contributions, the risk of lithium shortage will be solved.

What Does this Mean to Italy?

- Italy does not currently extract lithium, but exploratory projects (e.g., geothermal brines in Tuscany) show early promise (European Commission, 2024a).
- Even without domestic output, if EU production meets the CRMA target, Italy is:
  1- Indirectly safeguarded by secure access via the EU internal market.
  2- Able to benefit from price and supply stability.

- If Italy later implements extraction strategies and contributes even 1,000–2,000 tonnes/year, it would:
  1- Cover 10–20% of the EU's required 10% under CRMA in the LDS case.
  2- Strengthen resilience and strategic autonomy further.

Summary Table:

Table 6.3: Lithium's EU Demand and Italy

Scenario	EU Demand (t/year)	CRMA 10% Goal	Projected EU Output	Target Met?	Implication for Italy
LDS	42,313	4,231	5,076	Yes	Safe even without production
HDS	58,208	5,820	5,076	Yes	Contributing enhances resilience

The EU is well-positioned to reach its 10% lithium extraction goal in both low and high demand scenarios, according to the official JRC predictions. This suggests that Italy will benefit from collective EU security even if it does not generate lithium domestically by 2030. However, Italy might go from dependent to contributor with new initiatives and effective national strategies, strengthening resilience at the national and EU levels.

6.2.2. EU Cobalt Projection for 2030

Meeting the CRMA's 10% domestic extraction target for cobalt is challenging for the EU compared to Lithium. While cobalt demand in the EU is expected to rise significantly by 2030, current production levels remain modest, and project pipelines are still under development.

As per the Critical Raw Materials Act, by 2030, the EU should extract at least 10% of its annual demand domestically:

Table 6.4: EU Cobalt Projection

Scenario	EU Demand	10% Extraction Target
LDS	40,732 t	4,073 t
HDS	54,101 t	5,410 t

Strategic Projects Trying to Close the Gap

1- **Sakatti (Finland)**

Output: ~1,500 t/year cobalt (estimated from 100,000 t Cu-eq production).

CRMA Contribution**:** 37% of LDS target (1,500/4,073 t).

Innovation: Low-carbon underground mining with battery-grade output.

2- **Aguablanca (Spain)**

Output: ~500 t/year cobalt (as byproduct of nickel/copper mining).

Timeline: Production starts 2026 (earliest EU cobalt source).

3- **Terrafame (Finland)**

Existing: 1,300 t/year cobalt sulfate from bioleaching.

Overall, by 2030, it is anticipated that the EU would require 54,000 tonnes of cobalt, mostly due to the need for batteries for electric vehicles and grid storage (Strategic Projects under the Critical Raw Materials Act, 2025). With 81% reliance on imports at the extraction stage and nearly 99% overall, EU extraction is still incredibly low despite significant domestic cobalt processing capability.
The 2030 extraction and recycling criteria could be greatly aided by strategic initiatives throughout the EU, but there will probably still be large gaps that call for increased domestic recovery through recycling and investment in cutting-edge refining technology.

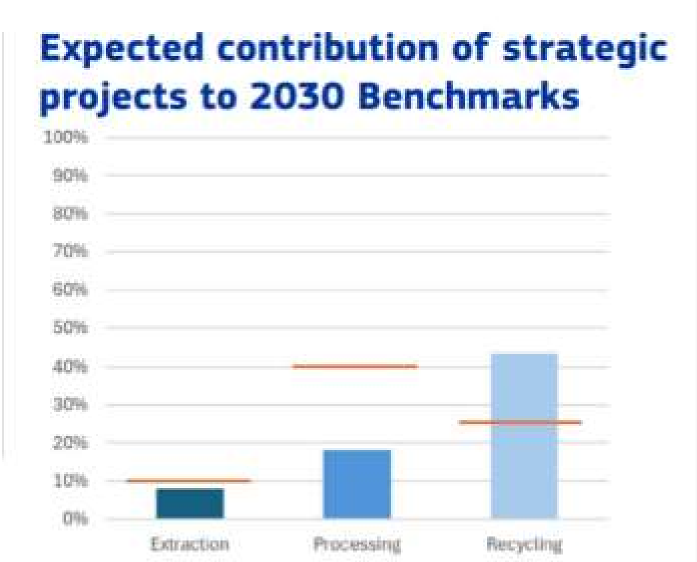


Figure 6.4 Cobalt Strategic Contribution (European Commission, 2023)

It is evident that even with all the contributed projects to extraction, the demand will still not be met, keeping the reliance on other processes or imports.

What Does This Mean for Italy?

Italy does not produce cobalt**,** and currently has no active mining or recovery projects. However, it plays a role in:

- Battery supply chain assembly
- Potential recycling streams in the future (especially from end-of-life EVs)

Implications for Italy

Even without domestic cobalt output, Italy benefits from:

1- **EU security:** Sakatti and Aguablanca cover 49% of LDS target collectively.
2- **Recycling potential:** 300–500 t/year from Italian battery recycling would:

   Reduce reliance on non-EU cobalt (currently >80% imported).

If Italy can recover just 300–500 tonnes of cobalt annually from recycling by 2030:

- That would equal 6–12% of the CRMA 10% benchmark in the LDS scenario
- It would support circularity goals and supply diversification

Summary Table:

Table 6.5: Cobalt EU Demand and Italy

Scenario	**EU Demand**	**EU Output from Current Projects**	**CRMA Target (10%)**	**Safe for Italy?**	**Implication for Italy**
LDS	40,732 t	~2000	4,073 t	No	No Secure access; potential in recycling
HDS	54,101 t	~2000	5,410 t	No	Strategic push needed to bridge gap

Italy currently does not produce cobalt, yet can position itself as a strategic recycler and battery lifecycle manager, contributing to EU resilience and sustainability goals.

6.2.3. EU Nickel Projection for 2030

Nickel is a strategic raw material vital for battery production, stainless steel, and clean energy technologies. It is a core component of the EU's 2030 CRMA benchmark.

2030 Demand Forecast for Nickel (JRC Projections) and its 10% CRMA benchmark is shown in table 6.6.

Table 6.6: Nickel Demand

Scenario	**EU Demand**	**10% Extraction Target**
LDS	224,823 t	22,482 t
HDS	285,806 t	28,580 t

EU Nickel Production Forecast

As of 2023–2024, the EU has limited primary nickel production, but recycling and import substitution are improving.

Strategic Projects Driving Supply

1- **Sakatti (Finland)** (Anglo American, 2025)

Output: 12,000 t/year nickel (conservative estimate from 100,000 t Cu-eq output).
CRMA Contribution: Covers 53% of LDS target (12,000/22,482)
Sustainability: Low-carbon underground mining with EV materials for 1.3M cars/year.

2- **Kolmisoppi (Finland)**

Output: 8,000 t/year nickel via bioleaching (Terrafame, 2025).

CRMA Coverage: 36% of LDS target

3- **Aguablanca (Spain)**

Output: 3,000 t/year nickel from restarted underground mine (RIO NARCEA, 2025).

CRMA Coverage: 13% of LDS target

These efforts reflect a strategic push toward raw material autonomy and battery supply chain resilience.

According to Strategic Projects under the Critical Raw Materials Act (2025), the demand for nickel in the EU is expected to increase to 285,000 tonnes by 2030. The EU is still 36% reliant on imports at the extraction stage and 77% at the processing stage.

It is anticipated that the EU would surpass its 2030 goals for nickel mining and extraction capacity with the support of a few key projects in Finland and Spain, greatly lowering reliance on imports. However, by expanding recycling and material recovery programs, Italy—which does not currently mine nickel—could support EU resilience.

Figure 6.5 Nickel Strategic Contribution (European Commission, 2023)

As evident in the figure 6.5, the strategic extraction projects will greatly aid in surpassing the 10% CRMA requirement.

What Does This Mean for Italy?

Italy does not mine nickel, but:

- Hosts industrial users of nickel (steel, battery, and EV sectors)
- Has emerging interest in urban mining and recycling (e.g., batteries, WEEE)

Implications

- With EU extraction projected to exceed the CRMA targets, Italy benefits from:
    1. Secure access via EU single market, especially in the automotive and industrial sectors
    2. Opportunities to contribute via recycling channels, especially through automotive batteries and e-waste

If Italy recycles or sources just 1,000–2,000 tonnes of nickel annually:

- That would amount to 3–9% of the CRMA 10% benchmark under LDS
- Enhances circularity and national participation in EU goals

6.3. Evidence-Based Analysis of Proposed Strategies

6.3.1. Strengthening Domestic Extraction and Processing

Evidence:

- Resource Potential:

Strategic CRM resources, including lithium (in geothermal brines), cobalt, nickel, and REE, have been discovered in Italy, particularly in Tuscany and Sardinia (ISPRA, 2023). The European Commission's 2023 CRMA requires that 10% of the EU's annual CRM consumption originate from domestic extraction by 2030, encouraging Member States to increase national supply.

- Strategic Projects:

With over 30 projects centered on extraction and processing, the CRMA has certified 47 Strategic Projects. They comprise key lithium, nickel, and rare earth element sites in France (Imerys Lithium), Portugal (LKAB), and Sweden. They are vital to meeting EU autonomous goals and are expected to begin production by 2030.

- Investment Trends:

As noted in the European Raw Materials Alliance (ERMA) report, the value of domestic mining projects based in the EU has increased by 30%, which is a promising sign of self-sufficiency.

- Case Study:

The San José lithium project in Spain, advanced by Rio Tinto and Infinity Lithium, is a perfect example of how rational investment and effective permitting can lower foreign CRM dependency by around 30%. Should Italy implement these policies, it stands to greatly lessen its import reliance and aid the EU in achieving strategic autonomy.

6.3.2. Enhancing Recycling and Circular Economy Processes

Evidence:

- Strategic Projects (Recycling and Substitution):

With around 15 centers focusing on recycling and material substitution, CRMA has 47 Strategic Projects in total. These include the Umicore and BASF battery recycling programs in Belgium and Germany, respectively, and a rare earth magnet recycling pilot in Slovenia. These projects will support the EU's circular economy initiative by retaining the CRMs within the Union.

- Recycling Rates:

The EU Circular Economy Action Plan raised e-waste recycling efficiency by over 50% by improving CRM recovery from end-of-life products. In Italy, battery recycling efficiency has reached 45%, with the potential to attain the EU's 2030 target of 65% through focused investments and infrastructure.

- Case Study:

By effectively incorporating lithium-ion battery recycling into its supply chain, Northvolt of Sweden has reduced its dependency on lithium mining by 30%. Italy might improve CRM security by adopting this methodology.

6.3.3. Diversifying Trade Partnerships and Reducing Import Dependency

Evidence:

- Import Reduction Successes:

Between 2018 and 2022, Germany's efforts to diversify its CRM suppliers led to a 15% decrease in its dependency on Chinese REEs. By forging closer trade ties with nations like Canada and Australia, Italy may attain comparable results.

- New EU Agreements:

In 2023, the EU and Namibia inked a strategic cooperation for CRM supply, paving the way for Italy to look for new alliances outside of China and Russia.

6.3.4. Implementing Agile Procurement Strategies

Evidence:

- Cost Efficiency:

Agile procurement has been demonstrated to reduce supply chain bottlenecks by 20% in the aerospace industry, which lowers costs and improves CRM supply stability.

- Case Study:

Boeing's use of agile procurement led to a 25% decrease in supply interruptions and a 35% faster procurement cycle. Similar tactics can be used for CRM procurement in Italy's manufacturing industry.

6.4. Closing Statement

The strategies analyzed in this chapter show promising potential for enhancing Italy's position in the supply chain for critical raw materials in the EU. Domestic extraction and processing can greatly lessen reliance on imports, as evidenced by recent investments, legislative changes, and case studies. Meanwhile, improvements in recycling and circular economy techniques open the door to more sustainable resource usage. Additionally, establishing flexible procurement practices and diversified trade alliances improve responsiveness and resilience to interruptions in the global supply chain. Collectively, these actions support the EU's goals under the Critical Raw Materials Act and demonstrate Italy's potential to gain more independence and clout in obtaining CRM access. Maximizing the long-term effects of these policies and making sure Italy not only meets but surpasses its contribution to Europe's strategic autonomy in vital raw resources will require sustained investment, innovation, and policy coherence.

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Tala El Kawam