AGEMERA

Critical Raw Materials for a Resilient Europe

TEACHER'S GUIDE

Critical Raw Materials and Smartphone Life Cycle Online Game

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List of Acronyms

AGEMERA	Agile Exploration and Geo-modelling for European Critical Raw Materials
CRM	Critical Raw Material
CRMA	Critical Raw Materials Act
DRC	Democratic Republic of Congo
EU	European Union
EV	Electric Vehicle
GDP	Gross Domestic Product
HREE	Heavy Rare Earth Element
LCA	Life Cycle Assessment
LREE	Light Rare Earth Element
PGM	Platinum Group Metal
REE	Rare Earth Element
SDG	Sustainable Development Goal

1. Introduction

This Teacher's Guide supports the classroom use of the Critical Raw Materials and Smartphone Life Cycle Game – an interactive and thought-provoking learning tool developed as part of the AGEMERA project. The game takes players on a journey through the complex and often hidden life cycle of a smartphone, focusing on the critical raw materials (CRMs) that power the technologies we use every day.

Smartphones are everyday items, yet few people realize the global journey and ethical dilemmas embedded in their production – from mining cobalt in the Democratic Republic of Congo (DRC), refining rare earth elements, to recycling challenges. The game introduces players to real-world issues around sustainability, resource extraction, global supply chains, and technology ethics, making it especially relevant for subjects such as geography, environmental science, civics, technology education, and sustainability studies.

Keywords: *Sustainability, Critical Raw Materials, Smartphones, Circular Economy, Ethics, Technology, Environmental Impact, Responsible Sourcing, Education, Systems Thinking, Supply Chains, Green Transition, Digital Transition, Recycling*

1.1 Why This Game Matters

The green and digital transition depends on access to critical raw materials – but how do we ensure this happens responsibly and sustainably? This game helps students understand the social, environmental, and economic impacts of material sourcing, and encourages reflection on personal consumption habits, ethical trade-offs, and global interdependence. It also helps educators spark interdisciplinary discussions and develop systems thinking among students.

1.2 Educational Package

This guide is part of a broader, which includes:

This guide is part of a comprehensive educational package designed to support educators in teaching about critical raw materials (CRMs) and sustainability through interactive learning. The full educational package includes:

- **Teacher's Guide** – Provides step-by-step instructions for using the game in the classroom, suggested discussion questions, and essential background information.
- **Teacher's Presentation** – An engaging slideshow to introduce students to key themes such as the Life Cycle of a Smartphone, Critical Raw Materials, Rare Earth

Elements, Global Supply Chains & Logistics, Recycling & Sustainability, and Ethical & Environmental Issues.

- **Seminar Recording** – A recorded walkthrough explaining how to effectively facilitate the game in a classroom setting, including a sample presentation and demonstration of gameplay.
- **Online Game** – A browser-based educational game available in multiple languages (English, Estonian, Finnish, German, Portuguese, and Romanian) that takes students on an interactive journey through the smartphone life cycle and the role of CRMs.

Together, these resources offer a flexible and accessible toolkit for integrating CRM and sustainability education into upper secondary school curricula.

1.3 AGEMERA project

The game was created under the AGEMERA project – Agile Exploration and Geo-modelling for European Critical Raw Materials – a Horizon Europe-funded research and innovation initiative that runs from August 2022 to July 2025. Coordinated by the University of Oulu in Finland, AGEMERA brings together 20 partners from 11 countries to explore innovative, transparent, and responsible approaches to sourcing raw materials critical for Europe's future (Figure 1).

Figure 1. The AGEMERA project introduction.

2. The Objectives and Learning Outcomes of the Game

The Critical Raw Materials Smartphone Game is an educational simulation designed to raise awareness and understanding of the role CRMs play in the global supply chain of smartphones – a product familiar to nearly every student. Through interactive gameplay, players explore each phase of a smartphone's life cycle, from the design and development stage through to resource extraction, production, assembly, use, and end-of-life processing such as recycling and reuse. By walking through these interconnected stages, players are introduced to real-world challenges and decisions involving the sourcing and management of critical raw materials.

The broader goal of the game is to foster awareness about the hidden but essential materials that make modern digital devices possible, and to inspire players to think critically about the sustainability of technological development in the context of the European Green Deal, circular economy, and ethical global supply chains.

2.1 Target audience – Who is the game for?

The primary target group of the game is **Upper Secondary School students** (ages ~15–19), particularly those in geography, natural sciences, or interdisciplinary studies.

Secondary audience includes **teachers, policymakers, entrepreneurs, and members of the public** interested in sustainability, technological innovation, raw materials, and resource management.

The game is ideally suited for both classroom use and informal learning settings, including science festivals, awareness campaigns, and professional development workshops.

2.2 Objectives of the Game

The CRM game is designed to achieve the following key objectives:

- **Enhance Awareness**

Increase understanding of how CRMs are used in daily life and the crucial role they play in digital technology, particularly smartphones.

- **Encourage Sustainable Thinking**

Promote the principles of sustainability, circular economy, and responsible sourcing, encouraging students to evaluate the environmental and ethical implications of their consumption habits.

- **Improve Systems Thinking**

Help players connect the dots between raw material extraction, global logistics, product design, consumer behaviour, and end-of-life treatment. Through simulated decision-making, they learn to understand the complexity of global value chains and interdependencies.

- **Support National Educational Curricula**

The game is closely aligned with the curricular goals in countries such as Finland, Germany, and Estonia, especially in subject areas like geography, chemistry, economics, and civic education (see Appendices).

- **Develop Digital Competencies**

By simulating real-world roles and requiring players to make informed choices, the game enhances students' problem-solving, research, argumentation, and collaboration skills – core elements of 21st-century learning.

2.3 Expected Learning Outcomes

By the end of the game, players will be able to:

- Identify what CRMs are and explain their significance in modern technology.
- Describe the life cycle of a smartphone as an example of CRM dependency – from design to disposal.
- Recognize the environmental, economic, and social impacts of critical raw material sourcing.
- Reflect on how personal and collective choices influence global resource use and sustainability.
- Apply critical thinking to challenges in resource management and explore alternative scenarios through simulated decision-making and material flow analysis.

2.4 Competency Focus

The game promotes a broad range of cross-disciplinary competencies, including:

- **Critical thinking** – Evaluating trade-offs and consequences of decisions in resource use and supply chain management.
- **Collaboration** – Encouraging discussion and joint decision-making in team gameplay or classroom dialogue.

- **Ethical reasoning** – Reflecting on fairness, labour conditions, and environmental justice in the sourcing of raw materials.

- **Scientific and digital literacy** – Understanding how materials science, geology, and technology intersect in everyday products.
- **Active citizenship** – Empowering young people to see how their consumption patterns, advocacy, and knowledge can influence policy and sustainability outcomes.

The game is especially effective when accompanied by teacher-led facilitation, using this guide and accompanying resources (including presentations, videos, and discussion prompts) to deepen learning and contextualize gameplay experiences. The overview of curriculum alignment is provided in the appendices.

3. Game Content

The Critical Raw Materials & Smartphone Life Cycle Game is an interactive, browser-based quiz designed to engage players with the critical themes of sustainability, material use, and technology. The game is hosted on the **AGEMERA project website** https://agemera.eu/crm-game and is available in several languages: English, Estonian, German, Finnish, Portuguese, and Romanian. These translations ensure accessibility across the project's partner regions and beyond.

The game consists of **20 multiple-choice questions**, each with four answer options. The questions progressively increase in difficulty and culminate in three "million-dollar" questions that must be answered without hints – mirroring the format of the popular game show Who Wants to Be a Millionaire. To aid comprehension, some questions include supplementary information, such as diagrams, maps, graphs, and short explanations. Players can access this by clicking the ℹ icon or "Additional Info" button beneath the question.

The game uses a point-based **scoring system.** Each standard question is worth 20 points, and the final "million-dollar" questions yield up to 120 points each. This provides players with a sense of progress and achievement and allows for gamified competition or classroom scoring.

The game is designed for both **individual play and teacher-led group sessions**. It typically takes 15–20 minutes to complete individually and 30–40 minutes in a facilitated classroom setting. The game is optimized for smartphones, tablets, and desktop computers.

3.1 Structure of the game

The game mirrors the smartphone's life cycle (Figure 2), divided by the game creators into the following main stages (it should be noted that more subtle parts of the life cycle requiring further dividing are not included in the game). In the following the questions among which the life cycle of the smartphone is divided, together with their correct answers and the additional information are showed. The additional information to each question aims to help the understanding and better processing of the new information, via different forms, e.g. maps, graphs, infographics, tables, articles, etc.

1. **Design and Development**
    - Conceptualisation and Market Research (*Smartphone Components, The Chemical Elements of a Smartphone*)
    - Software and Hardware Development
    - Prototyping and Engineering Validation

- Sourcing Components and Design for Manufacturability (*Source Rocks and Minerals*)

2. **Industrial Production**
    - Raw Materials Extraction
    - Production (*Processing, Smelting, Refining*)
    - Transportation of Raw Materials to Manufacturing
    - Manufacturing Components (Including the Recycling and Reuse of Old Products)
    - Transport and Logistics from the Manufacturing to the Assembly
3. **Assembly and Packaging**
    - Assembly of All the Components
    - Final Testing
    - Product Packaging
    - Transport from the Assembly to Storing
    - Storing of the Product
4. **Usage**
    - Customer Use
    - Services and Support
5. **Post-Usage**
    - End of use
    - Transportation and Storing
    - Dismantling and Recycling
    - Disposal

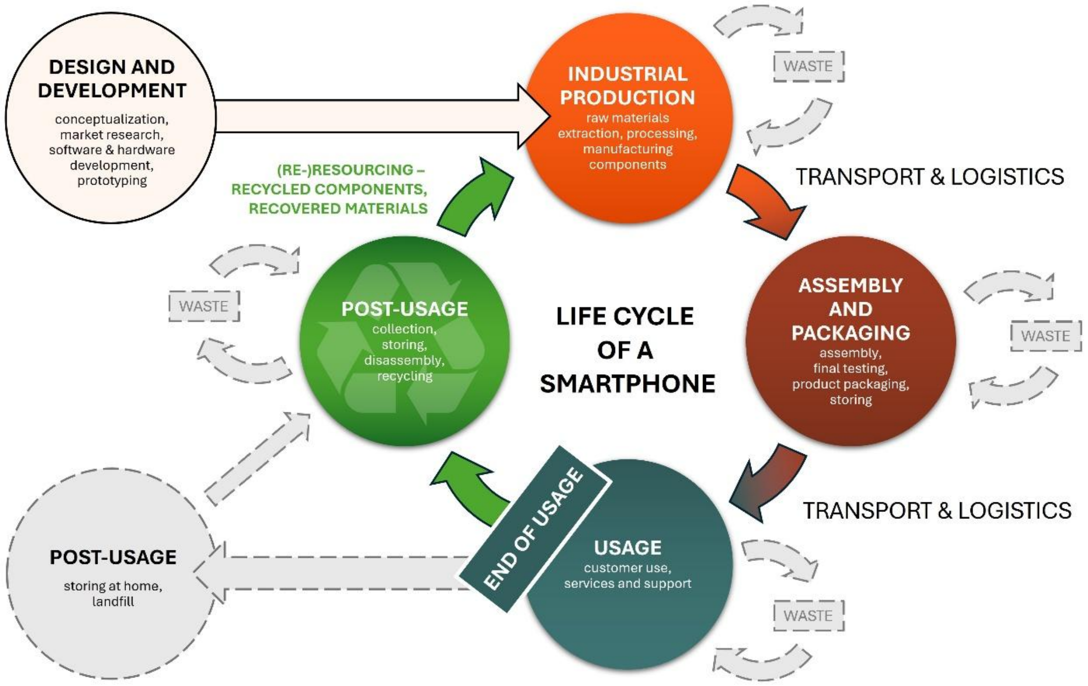

Figure 2. Stages of a smartphone life cycle and the structure of the online game. It is important to note that all these stages are influenced by resource availability, whether derived from primary production (mining) or secondary production (recycling).

3.2 Step-by-Step Guide to Gameplay

To help educators use the game effectively, the following step-by-step teaching plan is proposed:

3.2.1 Before the Game

Start the lesson with an introductory presentation using the slides provided in the AGEMERA educational package. The presentation introduces key themes such as:

- The smartphone's life cycle
- Critical raw materials
- Rare earth elements
- Global logistics and supply chains
- Environmental and ethical challenges in sourcing
- Circular economy principles

🕒 Estimated time: 20–30 minutes, depending on class interaction.

3.2.2 During the Game

Choose one of the following formats depending on class size, available technology, and desired engagement level:

Independent Play

Students play the game at their own pace using phones or computers. This format is suitable for computer labs or regular classrooms using students' smartphones. Encourage them to explore the additional info for each question.

Teacher-Led Group Play

The teacher reads each question aloud, and students respond via:

- Paper ballots
- Digital polling apps (e.g., Mentimeter, Kahoot, Google Forms)
- Show-of-hands voting

After each question, the class discusses the answers, and the teacher reveals the correct one. This format allows deeper exploration of complex questions and group discussion.

3.2.3 After the Game

After completing the game, it is essential to consolidate the learning experience. This can be done through reflection, discussion, creative tasks, and formative assessment. The goal is to ensure that students not only remember the facts but also understand the broader implications of CRMs, sustainability, and the interconnectedness of global supply chains. Use a combination of:

- **Group discussion / reflection**
    - What was the most surprising or unexpected fact you learned from the game?
    - Which stage of the smartphone life cycle do you think has the biggest environmental impact? Why?
    - What are some ethical issues related to mining and using CRMs?
    - How could smartphone producers reduce the environmental footprint of their products?
    - What could you personally do to use technology more sustainably?
    - How are circular economy principles reflected in the smartphone life cycle?
- A quick **post-quiz or anonymous feedback form**

- **Making a poster or presentation** about one stage of the smartphone life cycle / A specific critical raw material (e.g., cobalt, lithium, indium) / The ethical concerns around artisanal mining
- **Mapping the global supply chain of one CRM**
- **Investigating alternatives to specific materials used in electronics**
- Encourage students to explore other everyday objects (e.g., laptops, batteries, or bicycles) and **trace their material journeys** using what they've learned
- Split students into groups representing different stakeholders (e.g., mining companies, environmental NGOs, tech consumers, government regulators) and organise a **debate**.
- **Creative Expression.** Let students choose a creative format to reflect on their learning: comic strip or storyboard explaining the smartphone life cycle; infographic about CRMs used in common electronic devices; diary entry from the point of view of a smartphone or a mining worker.
- **Cross-Subject Connections.** Encourage collaboration between geography, chemistry, technology, and economics teachers to integrate the topic into other lessons. For example: in chemistry: explore the atomic structure and properties of rare elements. In economics: discuss supply and demand or geopolitics of CRM sourcing.

3.3 Game Questions and the Answer Key

In this paragraph the game answers are provided in the order of the game by different phases. Below has been provided a table with correct answers.

Table 1. Questions and Correct answers to the questions.

Question number	Question	Answer letter	Answer	Points
1	What is the first step in designing and developing a new smartphone?	C	Conceptualisation and Market Research ✓	20
2	Which of the following components is not strictly required for a smartphone to function and doesn't impact smartphone's core functionality?	B	Charging port ✓	20
3	Which of the following elements is essential for phone batteries?	B	Cobalt ✓	20
4	Which mineral is the primary source of REEs,	D	Bastnäsite ✓	20

	which are key materials in smartphone components like speakers, vibrators, and display screens?			
5	Which of these countries is NOT a significant exporter of REEs?	D	Brazil ✓	20
6	View the graph in Figure showing the fluctuations in the price of lithium over the past years. Which of the following events led to a sharp increase in its price?	A	Increased demand for EVs ✓	20
7	What is a critical raw material (CRM)?	D	A material that is essential for Europe's economy but has a high supply risk. ✓	20
8	Which of the following raw materials requires the most energy-intensive process for extraction and refining before it can be used in smartphone components?	B	Rare Earth Elements ✓	20
9	Which of the following transportation methods would be the most cost-efficient for transporting smartphones over a long distance (e.g., from Asia to Europe) but also considering environmental impact?	B	Ocean freight ✓	20
10	In the process of manufacturing smartphones, which of the following components is least likely to be reused as a complete part in new devices (assuming all parts are in generally reusable condition)?	D	Cracked smartphone screens ✓	20
11	Which of the following regions would likely have the lowest carbon emissions when transporting CRMs like Lithium and Cobalt for smartphone manufacturing, assuming optimised transportation routes?	B	South America ✓	20
12	Which of the following is the most important	C	Protection from physical damage ✓	20

	consideration when choosing a transportation method for smartphones to ensure they are protected during shipment and storage?			
13	What is one effective way to lower the environmental impact of how much energy your smartphone uses?	A	Adjusting settings like brightness and background apps to reduce energy use ✓	20
14	Which of the following is a chemical process used to recover gold and CRMs like Cobalt, Lithium and Tantalum from old smartphones?	A	Hydrometallurgy ✓	20
15	Based on the global recycling data, which continent recycles the highest percentage of smartphones?	A	Europe ✓	20
16	Recycling raw materials is important to reduce reliance on finite resources and minimise the need for mining new materials. What percentage of smartphones worldwide are currently recycled?	D	Around 20% ✓	20
17	What percentage of REEs are currently being recycled in the EU?	A	Around 1% ✓	20
18	If recycling rates of CRMs from mobile phones increase by 30%, how would this affect the environmental impact, economic savings, and supply chain stability for smartphone manufacturers?	B	Reduced environmental impact, lower costs, and more stable supply chains ✓	120
19	Suppose the demand for REEs for mobile phone production increases significantly while the available supply from mining operations remains the same. Which of the following scenarios is most likely to occur?	A	Increased price volatility, higher environmental degradation, and shift toward alternative technologies ✓	120

20	If global supply chains for REEs become severely disrupted due to geopolitical tensions, what could be the potential economic, technological, social, and environmental consequences for smartphone production?	D	Economic: Price increases due to limited supply, Technological: Slowdown in innovation, Social: Job losses and unemployment in affected industries, Environmental: Increased environmental degradation from illegal mining. ✓	120

4. Background Knowledge on the Game Topics

This section provides additional information to support teaching and discussion around the game topics. The topics have also been covered on slides complimentary to the teaching module of the game.

4.1 Life Cycle of Products

The life cycle of a product refers to the entire journey of a material good – from the extraction of raw materials and production to its use, and ultimately, to its end-of-life management such as disposal or recycling. This concept helps us understand the environmental and social impacts associated with each stage of a product's existence. The typical stages include raw material extraction, manufacturing and processing, transport and distribution, use and maintenance, and end-of-life (reuse, recycling, or disposal). Life cycle thinking is crucial in sustainability because it reveals hidden costs and emissions that might occur outside the visible use phase, such as the energy-intensive production of components or pollution generated during disposal. By analysing and optimising the full life cycle, industries and consumers can make more responsible choices – like designing longer-lasting products, using recycled materials, and supporting circular economy models. Life cycle assessment (LCA) is a scientific method used to quantify environmental impacts across these stages, and is widely used in policymaking, green design, and sustainable development. [1]

The life cycle of a smartphone has been described in paragraph 3.1 Structure of the game.

4.2 Critical Raw Materials

The European economy depends heavily on raw materials, many of which must be imported from outside the EU. When a material plays a vital role in economic development but faces potential supply risks, it is classified as a CRM. CRMs are essential to modern industries, enabling the production of advanced technologies, including renewable energy systems, digital devices, and defence equipment. Their availability directly influences Europe's strategic autonomy, economic stability, and technological leadership.

4.2.1 The EU List of CRMs

The EU maintains a list of CRMs to identify resources that are both economically significant and at risk of supply disruptions. The latest list, published by the European

[1] UNEP (2020). Life Cycle Assessment: A Tool for Policymakers. United Nations Environment Programme. https://www.lifecycleinitiative.org

Commission in 2023, includes 34 essential materials for key industries such as renewable energy, electronics, aerospace, and defence. These materials include metals (e.g., lithium, cobalt, nickel, tungsten), REEs, and industrial minerals (e.g., fluorspar, phosphate rock, natural graphite).

Table 2. The latest list of Critical Raw Materials (created in 2023). 2

2023 CRMs (34)			
Antimony	Copper	LREEs - light rare earth elements	Scandium
Arsenic	Feldspar	Magnesium	Silicon metal
Baryte	Fluorspar	Manganese	Strontium
Bauxite	Gallium	Natural graphite	Tantalum
Beryllium	Germanium	Nickel	Titanium
Bismuth	Hafnium	Niobium	Tungsten
Borate	Helium	PGMs - platinum group metals	Vanadium
Cobalt	HREEs - heavy rare earth elements	Phosphate rock	
Coking coal	Lithium	Phosphorus	

The designation of a material as critical is based on two main criteria: **economic importance** and **supply risk**. The economic importance criterion assesses the significance of a raw material to the EU economy. It considers the material's role in various industrial applications and its contribution to the EU's gross domestic product (GDP). The supply risk criterion evaluates the risk of supply disruptions. It considers factors such as the concentration of production in a few countries, geopolitical stability, trade policies, and the potential for substitution or recycling.

Many of these raw materials are essential for the EU's green and digital transitions, supporting technologies such as coal-free steel production, decarbonising district heating, batteries, wind turbines, semiconductors, and EVs. However, Europe heavily depends on non-EU countries for their supply, particularly China, Russia, and the DRC, raising concerns about geopolitical dependencies, trade restrictions, and market vulnerabilities.

It is important to note that criticality is a regional assessment – a material that is deemed critical for Europe may not necessarily be critical in its country of origin, where it may be more abundant or less economically significant. Furthermore, the CRMs list is not static and evolves over time as new resources are discovered, supply chains shift, or more abundant substitutions emerge to replace a material's function in certain technologies. The EU's first list of CRMs was published in 2011 and included 14 materials.

As an example, some materials currently not classified as critical, such as tellurium, could gain critical status as demand rises due to technological advancements or supply constraints. Similarly, materials once considered critical may lose that designation if

[2] https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en

more efficient recycling methods, alternative materials, or new mining sources reduce their supply risk.

To reduce reliance on external suppliers, the EU is actively working on diversifying sources, increasing domestic extraction, improving recycling, and promoting circular economy solutions. Research into substitution strategies – finding alternative materials with similar properties – also plays a key role in mitigating supply risks. The EU's CRMA was introduced to ensure a secure and sustainable supply of CRMs for Europe.

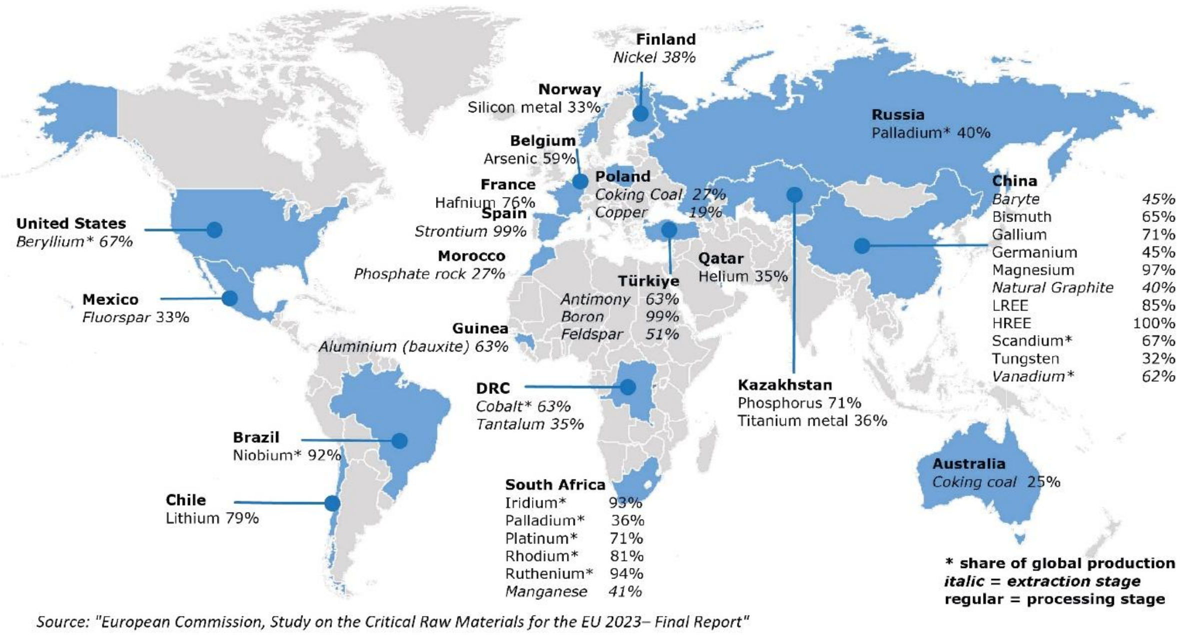

Figure 3. Major suppliers of CRMs to EU. [3]

The CRMs list serves as a strategic tool to help policymakers, industries, and researchers anticipate and address raw material challenges, ensuring a sustainable, resilient, and competitive raw material supply for Europe's technological and economic future. As global demand for CRMs continues to rise, the EU's approach must remain dynamic, adapting to new market conditions, technological advancements, and sustainable and environmental considerations. The demand for raw materials, especially those critical for the energy transition, is accelerating globally. Europe must become more focused and adaptable to compete for such ever-diminishing raw materials.

[3] https://op.europa.eu/en/publication-detail/-/publication/57318397-fdd4-11ed-a05c-01aa75ed71a1

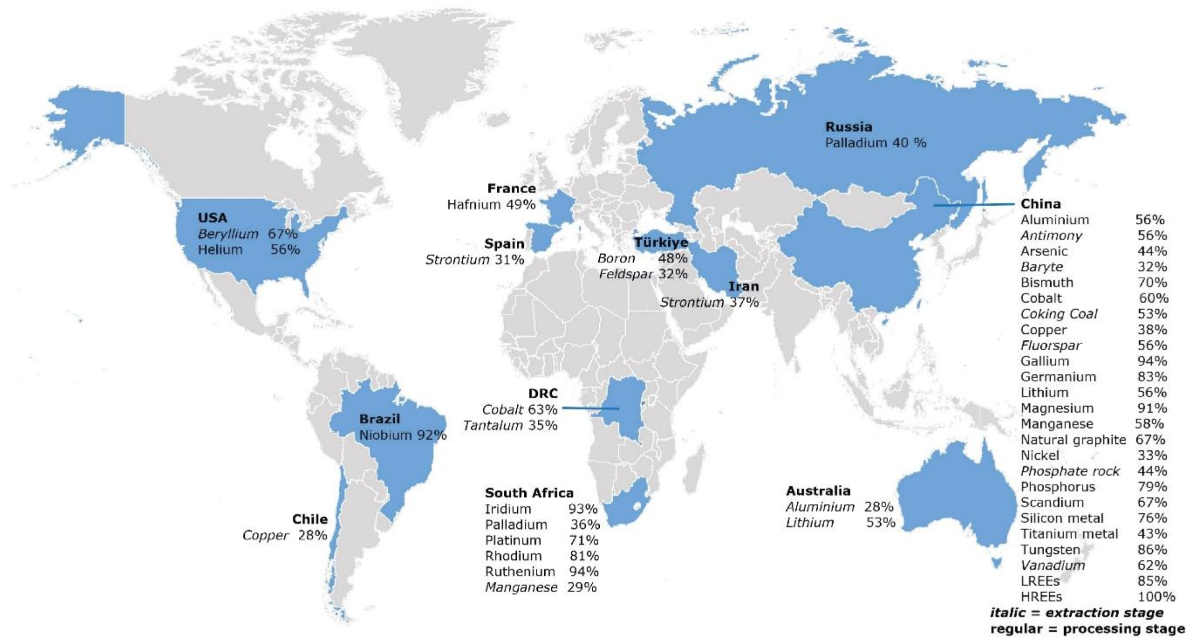

Figure 4. Main Global Suppliers of CRMs. [4]

4.2.2 Applications of CRMs

CRMs are essential components in modern technology, driving innovation across multiple industries, from consumer electronics to renewable energy and aerospace. One of the most notable applications of CRMs is in smartphone production, where elements such as lithium, cobalt, and REEs are used in high-performance batteries, touchscreens, speakers, and vibration motors. These materials enable smartphones to be lighter, faster, and more energy-efficient, making them indispensable to the global digital economy.

Beyond smartphones, CRMs play a vital role in renewable energy, aerospace, defence, and other high-tech industries. In the clean energy sector, CRMs such as lithium, cobalt, and nickel are fundamental for battery storage solutions, particularly in EVs and grid energy storage. REEs are used in the magnets that power wind turbines and electric motors, while tellurium and indium are crucial for high-efficiency solar panels. Without these materials, the transition to low-carbon energy solutions would be severely hindered.

CRMs also drive advancements in automation, AI, and Industry 4.0/5.0, supporting robotics, smart manufacturing, semiconductors, high-performance computing, and telecommunications infrastructure. As industries become increasingly digitised and automated, the demand for these materials continues to grow.

Furthermore, CRMs are strategically important for aerospace and defence. Elements like titanium, tungsten, and REEs are used in jet engines, satellite systems, advanced

[4] https://op.europa.eu/en/publication-detail/-/publication/57318397-fdd4-11ed-a05c-01aa75ed71a1

weaponry, and military communication technologies. Their strength, heat resistance, and unique magnetic properties make them irreplaceable in these applications.

The wide-ranging applications of CRMs highlight their economic and technological significance, making them a cornerstone of industrial innovation and a key enabler of global sustainability efforts. As demand continues to rise, ensuring a stable, ethical, and sustainable supply of these materials remains a top priority for governments, businesses, and researchers worldwide.

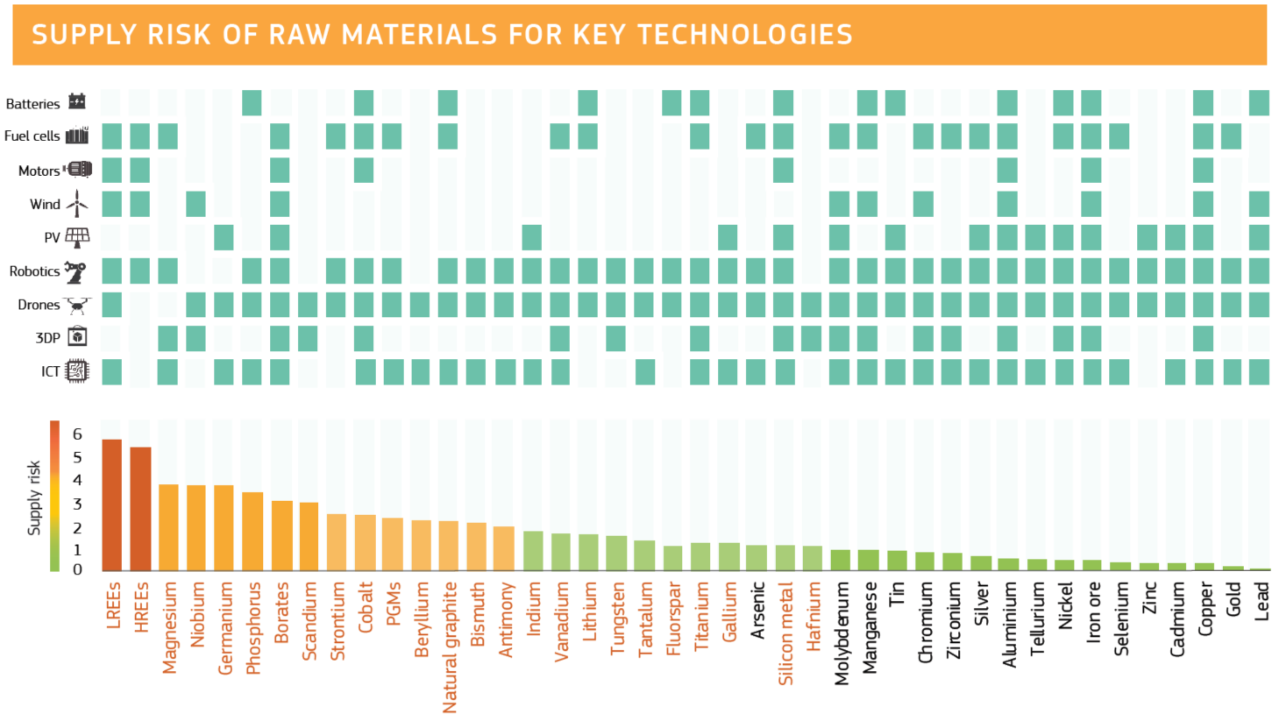

Figure 5. Supply risk of raw materials for key technologies in EU. [5]

4.2.3 Importance of CRMs for Society

The use of natural earth materials has been fundamental to the development and advancement of human civilisation throughout history. Raw materials derived from the Earth's crust have shaped industries, economies, and technological progress. From ancient tools and infrastructure to modern digital innovations, these materials have played an essential role in shaping our way of life.

In the past, basic resources such as coal, petroleum, and uranium have been crucial for energy security, powering industrialisation and global development. Similarly, base metals - common, non-precious metals such as iron, copper, nickel, zinc, tin, and lead - have been the backbone of infrastructure, construction, and manufacturing, enabling advancements in transportation, communication, and urbanisation. Precious metals

[5] https://rmis.jrc.ec.europa.eu/eu-critical-raw-materials

and gemstones, including gold, silver, and diamonds, have historically driven economic expansion, global trade, and the rise of powerful empires.

However, in the modern era, with an expanding global population, the importance of raw materials has evolved, with society becoming increasingly reliant on CRMs that support cutting-edge technologies. Metals such as REEs, indium, tellurium, germanium, and gallium are now essential to produce mobile phones, computers, EVs, and renewable energy technologies such as solar panels and wind turbines. These materials are key enablers of the green transition, helping nations combat climate change and reduce carbon emissions.

4.2.4 CRM Resources and Mining in Europe

With its rich mining heritage, Europe can tackle the challenges of securing raw materials through several strategic approaches. The CRMA aims to ensure a secure and sustainable supply of CRMs for Europe's industries. Europe aims to meet 10% of its annual CRM needs by expanding domestic production by 2030. This involves opening new mines and reviving existing ones.

To mitigate supply risks, Europe is diversifying its sources of raw materials. This involves developing new trade partnerships and securing supply chains through international cooperation.

Significant investments in research and innovation are crucial to further develop the resource and mining potential for Europe. The EU is focusing on developing new sustainable mining, processing, and recycling technologies. This includes exploring substitution strategies to find alternative materials with similar properties.

Establishing strategic stockpiles of CRMs can help Europe withstand supply chain disruptions. This involves coordinated efforts across member states to ensure preparedness and resilience.

Ensuring that mining and processing activities are environmentally sustainable and socially responsible is essential. The EU is committed to high sustainability standards and environmental and ethical sourcing practices.

Despite the EU's heavy reliance on imports for many CRMs, it still boasts substantial domestic resources and actively engages in the extraction and processing of several key materials. Numerous EU countries are involved in ongoing exploration and mining projects, which contribute to the global supply of CRMs and help mitigate dependence on external suppliers.

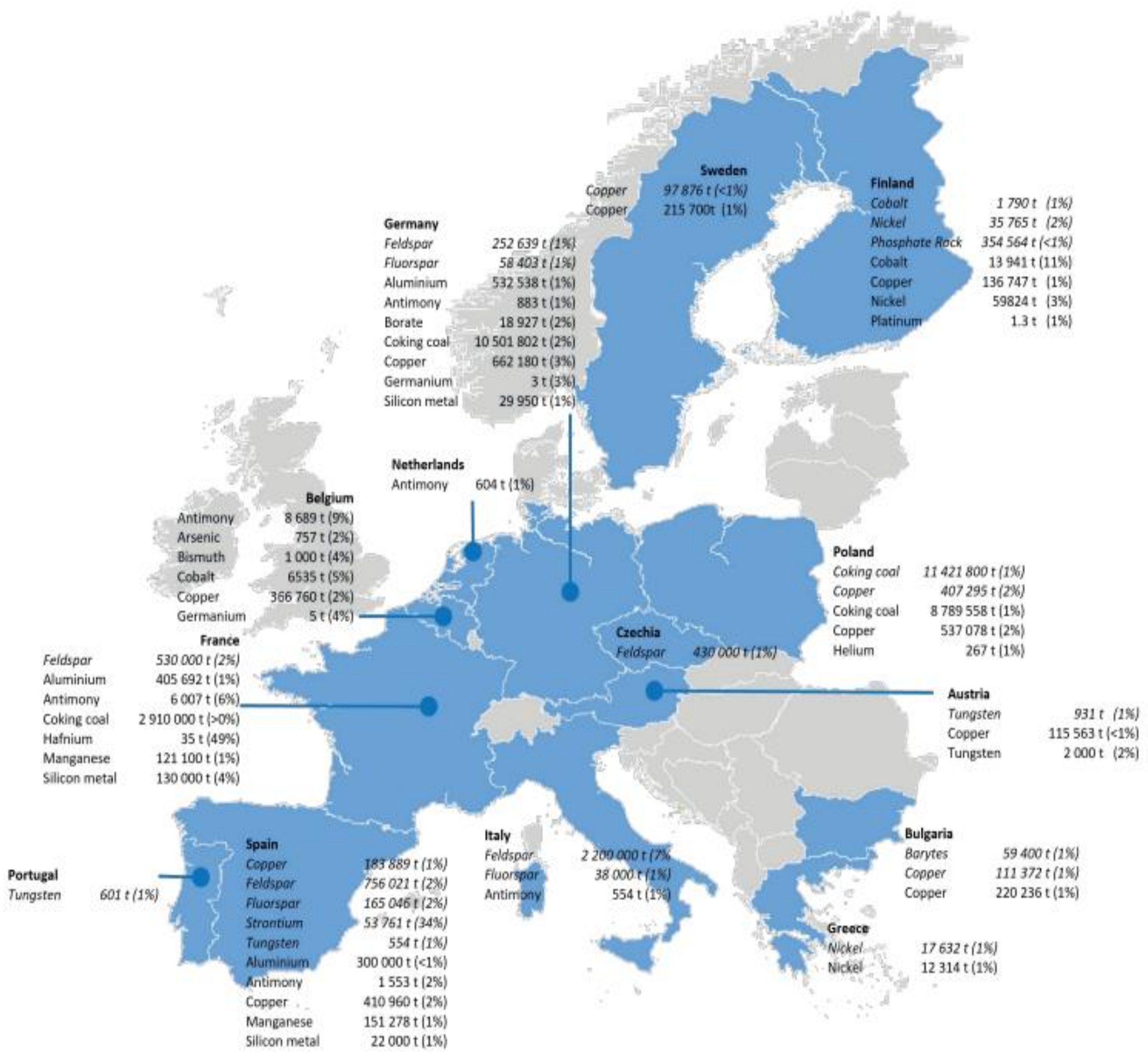

Figure 6. EU producers of CRMs (shares of global supply in brackets). [6]

As already noted, the EU has identified 34 CRMs essential for its economic strength and strategic autonomy. In 2023, the volume of EU imports of CRMs decreased for most materials, except for natural graphite and REEs. Additionally, the EU's domestic mining projects have shown promising results. For example, Sweden's LKAB, a state-owned mining company known for its iron ore production, announced the discovery of over one million tonnes of rare earth oxides. This significant find could greatly reduce Europe's dependency on external suppliers.

Finland and Estonia also have significant potential in producing CRMs[7]. Finland boasts rich deposits of cobalt, lithium, and nickel, and has an advanced mining industry with projects like the Keliber lithium project. With its substantial phosphorite deposits and REEs processing facility in Sillamäe, Estonia is enhancing geological exploration to

[6] https://op.europa.eu/en/publication-detail/-/publication/57318397-fdd4-11ed-a05c-01aa75ed71a1

[7] https://tupa.gtk.fi/kartta/erikoiskartta/ek_102.pdf

assess its resource potential. Both Estonia and Finland are actively contributing to the EU's goal of reducing reliance on external suppliers.

Other European countries are also contributing to the supply of CRMs. Currently, the EU accounts for 34% of the global supply of strontium, with Spain being the primary producer. Additionally, 14% of feldspar is extracted across multiple member states, including Italy, Spain, France, Czechia, and Germany. Europe also contributes 3% of the world's tungsten supply, mainly from Austria, Portugal, and Spain.

The EU is increasingly focusing on developing its own lithium resources to support the growing demand for EVs and renewable energy storage. Currently, Europe relies heavily on imports from countries like Australia, Chile, and China. However, several promising lithium mining projects are underway in countries such as Germany, Portugal, Spain, and Finland. By 2030, Europe aims to produce 25% of the world's batteries, up from just 3% in 2020. This ambitious goal is part of the EU's broader strategy to reduce dependency on external sources and ensure a stable supply of CRMs. Despite the challenges, including environmental concerns and high production costs, the potential for CRM resources in the EU is significant and crucial for the continent's green transition (Table 2).

Table 3. The potential for CRM deposits in EU countries. [8]

Country	Current mine production	Known unexploited resources (tonnage data exists)	Assumed unexploited resources only (no tonnage data)
Austria	Mg, W	Sb, In, Mg, Graphite, P, W	Baryte, Bi, Co, Fluorspar, Ga, Ge, Nb-Ta, Sc, Si, REE
Belgium		Baryte, P	REE
Bulgaria		Sb, Baryte, In, Mg, Nb-Ta, PGM	Bi, Fluorspar, Si, W, V
Croatia			Baryte, P
Cyprus			Co, PGM
Czech Republic		W, REE	Sb, Fluorspar, In, Nb-Ta
Denmark/Greenland		Sb, Co, Fluorspar, Ga, Graphite, Nb, Ta, Hf, REE, PGM, V	Be, Ge, P, W
Estonia		P	V, REE
Finland	Co, Mg, P, PGM	Sb, Be, Co, Nb-Ta, P, Sc, W, V, PGM, REE, Hf	Baryte, Bi, Mg, Graphite, Si,
France		Sb, Baryte, Be, Fluorspar, Ge, Mg, Nb-Ta, P, W, REE, Hf	Bi, Co, Graphite
Germany	Baryte, Fluorspar, In(?)	Baryte, Fluorspar, In, Si	Sb, Be, Bi, Co, P, W, PGM, REE
Greece	Co(?), Mg, PGM(?)	Sb, Co, In, Graphite, P, Sc, W, PGM, REE	Bi, Mg, Si
Greenland		Fluorspar, Ga, Graphite, Nb-Ta, W, V, PGM, REE	Sb, Be, Co, Ge, P
Hungary			Sb, Fluorspar, In, Sc, REE
Ireland		In, Mg, P	Baryte, Fluorspar, W, PGM, REE
Italy		Sb, Baryte, Fluorspar, P	Mg, Graphite, Si, W, REE
Latvia			
Lithuania			
Luxembourg			Sb
Malta			P
Netherlands	Mg		Mg
Norway	Graphite	Be, Co, Nb-Ta, P, Sc, Si, V, PGM, REE, Hf	Bi, Fluorspar, Graphite
Poland	Co(?), He, PGM(?)	Baryte, Co, Fluorspar, Ga, Ge, Mg, Si, V	He, Mg, P, PGM, REE
Portugal	In(?), W	Sb, Be, In, Nb-Ta, W, REE	Si, PGM
Romania		P	Sb, Baryte, Bi, B, Co, Graphite, REE
Slovakia	Mg	Sb, Mg	Co, REE, Nb, Ta
Slovenia			Sb
Spain	Fluorspar, Mg, W, PGM(?)	Baryte, Co, Fluorspar, Mg, Nb-Ta, P, W	Sb, PGM, REE
Sweden		Sb, Co, Fluorspar, Graphite, Nb-Ta, P, Si, W, V, REE, Hf	Be, Bi, Sc, W, PGM
United Kingdom	Baryte, Fluorspar, W	Baryte, Fluorspar, P, W, Hf	PGM, REE

Beyond extraction, the EU is also a significant player in processing and refining CRMs. France refines 49% of the global hafnium supply, while Belgium, France, and Spain contribute to 18% of the world's antimony refining. Cobalt processing, crucial for battery production, is dominated by Finland, Belgium, and France, accounting for 17% of global

[8] https://scrreen.eu/wp-content/uploads/2018/03/SCRREEN-D3.1-Identification-and-quantification-of-primary-CRM-resources-in-Europe.pdf

output. Additionally, Germany and Belgium refine 7% of germanium, an essential material for fibre optics and infrared optics. Other notable contributions include 5% of the world's silicon metal, refined in France, Spain, and Slovakia, and 4% of global nickel production, primarily from Finland, Greece, and France.

Despite these contributions, Europe's CRM supply remains limited, and most materials are produced in smaller quantities, often below 2% of global output. The main challenges for domestic mining include stringent environmental regulations, high operational costs, and social opposition to new mining projects. However, the growing demand for CRMs – driven by the green and digital transitions – presents an opportunity for the EU to boost domestic production, invest in sustainable mining practices, and strengthen strategic autonomy in raw materials supply.

4.3 Rare Earth Elements

Rare earth elements (REEs) are a group of 17 chemically similar metallic elements defined by the International Union of Pure and Applied Chemistry (IUPAC). This group consists of the 15 lanthanides (from lanthanum [La] to lutetium [Lu] in the periodic table), along with yttrium (Y) and scandium (Sc), which, although not lanthanides, exhibit comparable chemical and physical characteristics (Figure 7).[9] [10]

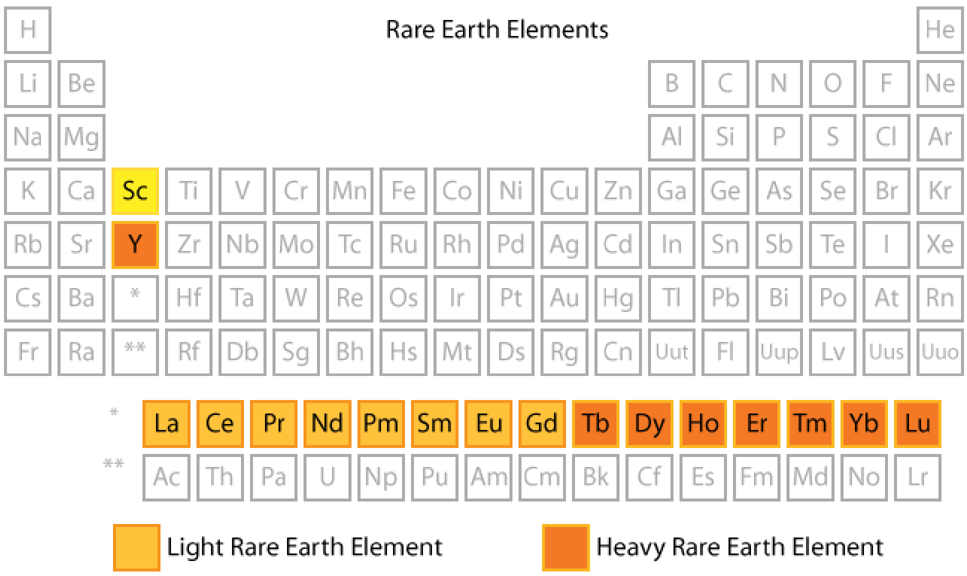

Figure 7. Rare earth element's location in the periodic table. [11]

[9] https://pubs.usgs.gov/publication/pp1802O
[10] https://www.geolsoc.org.uk/media/fv3hk3b0/rare-earth-elements-briefing-note-final-new-format.pdf
[11] https://sciencenotes.org/wp-content/uploads/2015/09/RareEarthElements.png

For classification purposes, REEs are often divided into three sub-groups based on their atomic numbers and geochemical behaviour:

- Light Rare Earth Elements (LREEs): La, Ce, Pr, Nd, Pm
- (Sometimes) Medium Rare Earth Elements (MREEs): Sm, Eu, Gd
- Heavy Rare Earth Elements (HREEs): Tb, Dy, Ho, Er, Tm, Yb, Lu, and Y

Scandium (Sc), while often grouped with REEs, does not fall neatly into any of these subcategories.

Although the term "rare" suggests scarcity, REEs are relatively abundant in the Earth's crust. In fact, cerium, the most common REE, is more abundant than copper (55 ppm) and lead (14 ppm). Average crustal concentrations of REEs range from 150 to 220 parts per million (ppm), placing them above many industrial metals in natural abundance. However, what makes REEs economically and environmentally challenging is that they rarely occur in concentrated deposits. Instead, they are typically dispersed and co-located in complex mineral matrices. [12] [13]

The chemical behaviour of REEs is mostly governed by their trivalent oxidation state (REE^{3+}) and similar ionic radii. Some elements exhibit variable valence states: for example, cerium (Ce) can also appear as Ce^{4+}, and europium (Eu) as Eu^{2+}, influencing how they behave geochemically and how they are separated during processing.

REEs are found in more than 200 known mineral species, though only a few, such as bastnäsite, monazite, and xenotime, have economic significance. These minerals occur in various geological environments, including igneous, sedimentary, and metamorphic rock formations. Despite this widespread distribution, most of the economically viable production has been concentrated in just a few countries. Since the early 2000s, China has dominated global REE production and refining, regularly accounting for over 90% of the world's supply. [14] [15]

REEs are vital to numerous modern technologies due to their unique electronic, magnetic, and optical properties. Applications include:

- Magnets: Neodymium and dysprosium in permanent magnets used in electric motors, wind turbines, and speakers.
- Phosphors: Europium, terbium, and yttrium in displays for TVs, smartphones, and LED lights.

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[12] https://pubs.usgs.gov/publication/pp1802O
[13] https://www.britannica.com/science/rare-earth-element
[14] https://pubs.usgs.gov/publication/pp1802O
[15] https://www.geolsoc.org.uk/media/fv3hk3b0/rare-earth-elements-briefing-note-final-new-format.pdf

- Catalysts: Lanthanum and cerium in catalytic converters and oil refining.
- Alloys: Additives in aerospace and military-grade materials.
- Battery additives: Lanthanum and other REEs in nickel-metal hydride (NiMH) batteries.

In the context of the green transition, REEs are particularly critical. They are essential for the efficient function of low-carbon technologies such as electric vehicles and renewable energy systems, including offshore wind turbines, where their use in lightweight, high-performance magnets is irreplaceable.

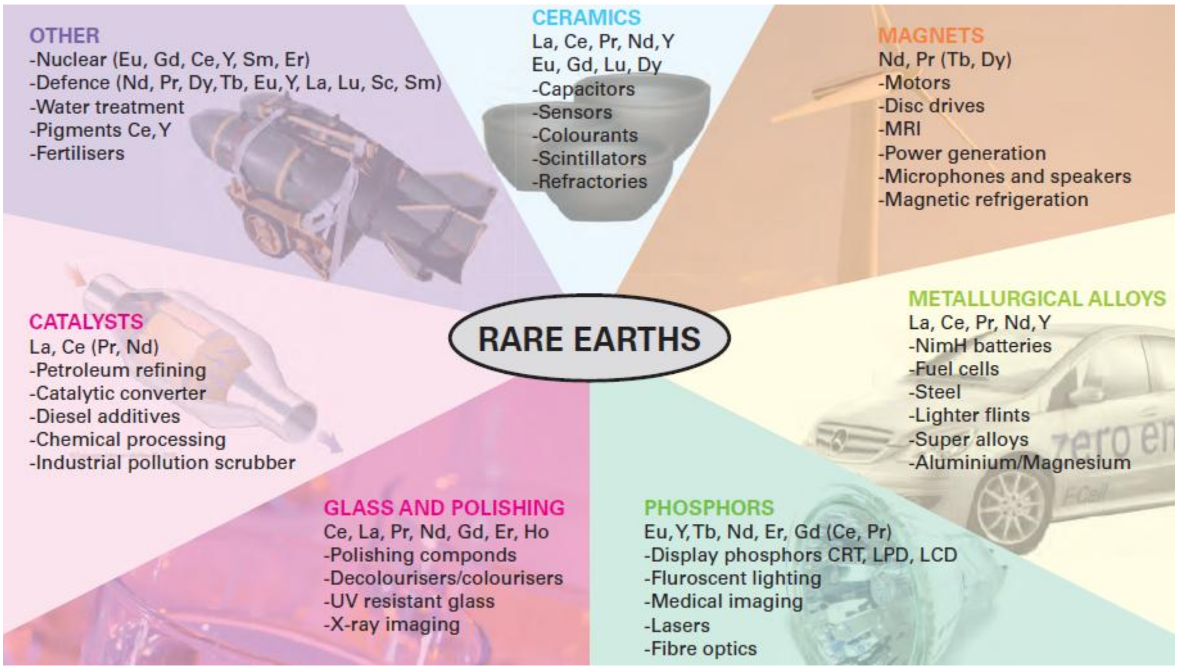

Figure 8. Rare Earth Elements applications.[16]

4.4 Recycling and Sustainability

Recycling and circular economy initiatives play a crucial role in reducing the EU's dependency on imported CRMs by recovering valuable elements from end-of-life products. One key area for CRM recovery is old smartphones, which contain significant amounts of gold, silver, palladium, copper, REEs, indium, and cobalt. These materials are essential for manufacturing new electronics, renewable energy technologies, and other high-tech applications. However, despite the potential, smartphone recycling faces several challenges, including low collection rates, inefficient separation processes, and the complexity of extracting CRMs from miniaturised components.

[16] https://www.researchgate.net/figure/Applications-of-rare-earth-elements-Walters-Lusty-and-Hill-2011_fig5_285538097

Figure 5 illustrates the end-of-life recycling input rate of CRMs in the EU, highlighting the need for improved recovery strategies. Currently, the recycling rate for many CRMs remains low, meaning a significant portion of these valuable materials is lost. To address this, urban mining – the extraction of CRMs from electronic waste and discarded products – has emerged as a sustainable solution. By increasing recycling efficiency and promoting a circular economy, the EU can reduce supply risks, lower environmental impact, and enhance resource security. Investing in better collection systems, advanced recycling technologies, and eco-design principles will be crucial for making urban mining a viable alternative to traditional raw material extraction.

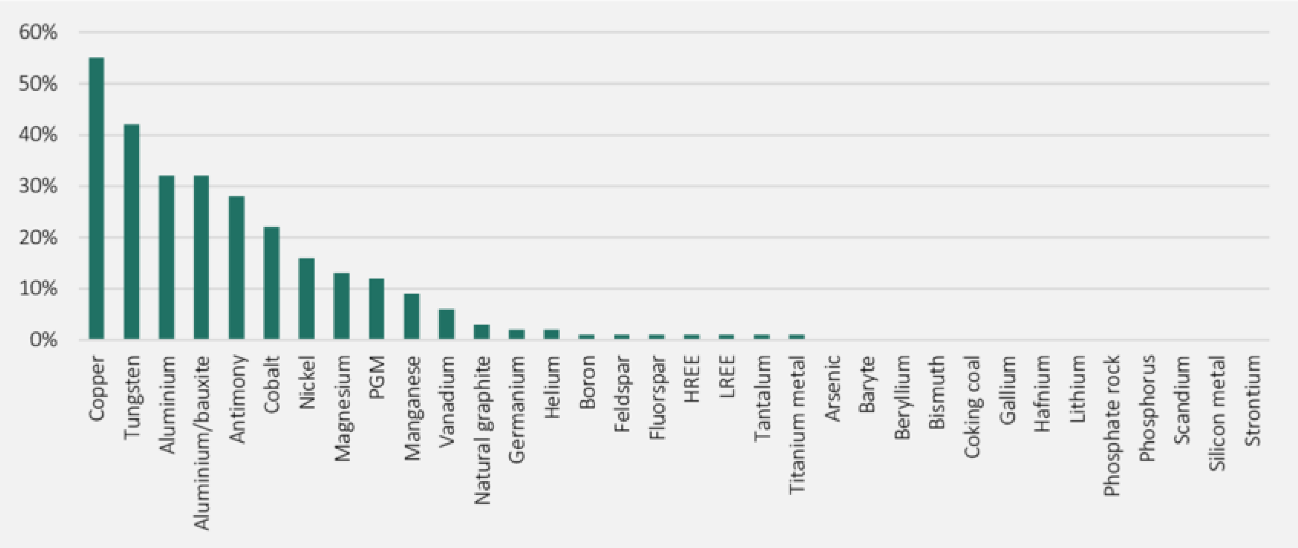

Figure 9. End-of-life recycling input rate of CRMs in the EU. [17]

4.4.1 E-Waste Management

The global generation of electronic waste (e-waste) has been on a consistent upward trajectory, driven by rapid technological advancements and increased consumer demand for electronic devices. In 2022, the world produced approximately 60 million metric tons of e-waste, and this figure is projected to reach 82 million metric tons by 2030, marking a 33% increase. Despite the growing volume, only about 17.4% of e-waste is formally collected and recycled. Europe leads in recycling efforts with a collection rate of 42.5%, while Asia and Africa lag at 11.7% and 0.9%, respectively. Most of the e-waste ends up in landfills or is exported illegally to countries with inadequate recycling infrastructure. Improper disposal of e-waste poses significant environmental and health risks. Landfilling e-waste can lead to the leaching of hazardous substances, such as lead and mercury, contaminating soil and groundwater.[18]

[17] https://circulareconomy.europa.eu/platform/sites/default/files/2024-01/CEPS-InDepthAnalysis-2024-01_Reducing-supply-risks-for-critical-raw-materials.pdf
[18] https://ewastemonitor.info/wp-content/uploads/2024/12/GEM_2024_EN_11_NOV-web.pdf

Addressing these challenges requires comprehensive strategies, including strengthening international regulations, improving domestic recycling capabilities, and raising public awareness about the importance of proper e-waste management.

4.4.2 Sustainable Development Goals

The United Nations Sustainable Development Goals (SDGs) are a set of 17 global objectives adopted in 2015 to promote sustainable development and address global challenges by 2030. The European mining sector plays a crucial role in advancing several of these goals by integrating digitalisation, automation, and sustainability-focused strategies. The EU has been actively promoting digital technologies in mining to enhance efficiency, improve safety, and minimise environmental impact. Aligning mining operations with the SDGs provides a structured framework to balance economic growth with environmental and social responsibility.

Figure 10. The United Nations Sustainable Development Goals. [19]

Mining can impact all 17 SDGs to a lesser or greater extent.[20] Some key examples are

- No Poverty (SDG 1): Mining can create jobs and stimulate economic growth, helping to reduce poverty.
- Affordable and Clean Energy (SDG 7): Supporting the use of renewable energy sources in mining operations, reducing reliance on fossil fuels.

[19] https://sdgs.un.org/goals
[20] Mining contribution to the SDG | MDNP (mineralplatform.eu)

- Decent Work and Economic Growth (SDG 8): The industry provides employment opportunities and can drive economic development.
- Industry, Innovation, and Infrastructure (SDG 9): Mining activities often lead to infrastructure development and technological advancements.
- Responsible Consumption and Production (SDG 12): Sustainable mining practices can promote efficient use of resources and reduce environmental impact.
- Climate Action (SDG 13): Mining operations must address their carbon footprint and contribute to climate change mitigation efforts.
- Life on Land (SDG 15): Mining can significantly impact terrestrial ecosystems, requiring careful management to protect biodiversity and local and wider communities.

Beyond mining, the SDGs also support sustainable resource management, influencing key sectors dependent on CRMs, such as renewable energy, digital infrastructure, and high-tech industries. By integrating these goals, the EU can strengthen its supply chain resilience, promote green technologies, and drive innovation, ensuring a sustainable and responsible raw materials sector for the future.

4.5 Global Supply Chains

The global supply chain for raw materials, particularly critical raw materials, encompasses a complex pathway often described as the journey "from mine to market." This includes exploration, extraction, processing, refining, transportation, manufacturing, and ultimately, end-use in consumer products. Each stage of this value chain adds complexity and potential points of vulnerability. Mining – the starting point of the supply chain – involves locating mineral deposits, extracting ores, and separating valuable materials, which are then processed and refined into usable forms. However, this chain is far from linear or secure.

A major issue lies in the geographical concentration of supply: a few countries, most notably China, dominate mining and refining capacities for many CRMs. This concentration creates geopolitical vulnerabilities, as trade restrictions, export controls, or diplomatic tensions can cause severe supply disruptions. Environmental and social concerns also affect the stability of supply chains, as mining operations can result in pollution, deforestation, water usage conflicts, and community displacement, leading to public opposition and delayed projects.

Moreover, supply chain concentration increases the risks of bottlenecks, as global industries remain dependent on a small number of suppliers. Trade barriers, regulatory hurdles, and infrastructure limitations – especially in resource-rich but economically developing nations – can further destabilize material flows. The COVID-19 pandemic highlighted the fragility of global supply networks, as lockdowns disrupted mining, transportation, and labour availability across continents.

To build resilient and sustainable supply chains, there is a growing need for technological innovation in extraction and processing, increased investment in infrastructure, and more transparent and traceable value chains. Diversifying supply sources, advancing circular economy models (e.g., urban mining and recycling), and fostering international cooperation are essential steps in mitigating these vulnerabilities and ensuring a stable flow of materials necessary for the green and digital transitions. [21]

4.6 Ethical & Environmental Issues

The sourcing of raw materials, particularly those considered critical to modern technologies, presents a range of ethical and environmental challenges. A notable example is cobalt mining in the Democratic Republic of Congo, where reports have documented widespread use of child labour, unsafe working conditions, and human rights violations. These practices raise serious ethical concerns around the exploitation of vulnerable populations and the lack of oversight in artisanal and small-scale mining operations. Such issues highlight the urgent need for responsible sourcing policies, supply chain transparency, and corporate accountability.

On the positive side, some mining initiatives are increasingly adopting socially responsible practices, including the enforcement of fair wages, worker safety, and the exclusion of child labour. Additionally, mining companies are beginning to contribute to local community development by investing in education, healthcare, and infrastructure, thereby creating long-term social benefits in mining regions.

From an environmental perspective, unregulated mining can cause severe ecological damage, including the contamination of water and soil, deforestation, and the loss of biodiversity. Heavy metal pollution and tailings mismanagement remain significant threats to both ecosystems and human health. However, advances in environmental management have brought about promising developments. These include the rehabilitation of mine sites through reforestation and land reclamation, recycling of process water, and the adoption of cleaner, energy-efficient technologies. Moreover, waste reduction strategies and the reuse of mining byproducts are helping to minimize environmental footprints.

In sum, while mining continues to raise ethical and environmental concerns, particularly in regions lacking regulatory enforcement, progress is being made through sustainable practices, technological innovation, and international pressure for accountability. These efforts are essential to ensure that the raw materials critical to the green and digital transitions are sourced in a way that respects both people and the planet. [22]

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[21] European Commission (2023). Critical Raw Materials Act: Securing a sustainable supply of critical raw materials for EU industry.
https://ec.europa.eu/commission/presscorner/detail/en/ip_23_1661
[22] https://www.oecd.org/en/publications/2016/04/oecd-due-diligence-guidance-for-responsible-supply-chains-of-minerals-from-conflict-affected-and-high-risk-areas_g1g65996.html

Appendices

Appendix 1. Alignment to Finnish National School Curriculum

The CRM Smartphone Game is thoughtfully designed to align with the objectives of the 2019 Finnish National Core Curriculum for General Upper Secondary Education (*Lukion opetussuunnitelman perusteet 2019*)[23], thereby enhancing the educational experience for students across various competencies. The game aligns with multiple subjects and cross-curricular themes, particularly in geography, chemistry, physics, sustainability education, and digital competence. By offering an interactive approach to CRMs, sustainability, and global resource management, the game helps students develop scientific literacy, critical thinking, and problem-solving skills, which are central to Finland's educational goals. Below is an overview of how the game supports key curriculum goals:

Alignment with Subject-Specific Goals

1. **Geography (GE1, GE2, GE3)**

- GE1: Maailma muutoksessa (The Changing World)

The game fosters an understanding of natural resources, sustainability, and global interdependencies, which are core themes in upper secondary geography.

- GE2: Yhteinen maailma (A Shared World)

The game helps students explore CRMs, their role in global trade, and environmental impacts, supporting themes of sustainable development and resource management.

- GE3: Riskien maailma (The World of Risks)

By simulating real-world challenges in resource extraction and supply chains, the game aligns with learning objectives related to environmental risks, geopolitical dependencies, and sustainable resource use.

2. **Chemistry (KE1, KE2, KE5)**

- KE1: Ihmisen ja elinympäristön kemiaa (Chemistry of Humans and the Environment)

The game demonstrates the role of CRMs in technology and their chemical properties, connecting chemistry to real-world applications.

[23] Lukion opetussuunnitelman perusteet 2019 https://www.oph.fi/fi/koulutus-ja-tutkinnot/lukion-opetussuunnitelmien-perusteet

- KE2: Kemian mikromaailma (The Microscopic World of Chemistry)

Students can learn about elements used in CRMs, their atomic structures, and chemical properties.

- KE5: Materiaalit ja teknologia (Materials and Technology)

The game highlights the significance of materials science and the role of chemistry in developing new materials.

3. **Physics (FY2, FY3, FY4)**

- FY2: Lämpö, energia ja elämän edellytykset (Heat, Energy, and Conditions for Life)

The game illustrates energy resources, renewable energy technologies, and raw materials used in energy production.

- FY3: Sähkö (Electricity)

The game helps students understand the importance of CRMs in electrical components, semiconductors, and battery technology.

- FY4: Aallot ja optiikka (Waves and Optics)

Topics such as solar panels and fibre optics, which rely on CRMs, can be explored through the game.

Support for Cross-Curricular Themes

4. **Sustainability and Responsibility**

The game promotes sustainable resource management and circular economy principles, directly supporting Finland’s sustainability education goals.

5. **Multiliteracy and Critical Thinking**

The game encourages students to analyse and interpret geopolitical, economic, and environmental data related to CRMs.

6. **Technology and Society**

The game provides insights into Industry 4.0, digitalisation, and automation in mining, aligning with Finland’s emphasis on technological literacy.

7. **Globalisation and Economy**

The game demonstrates how raw materials are linked to international trade, supply chains, and economic dependencies.

8. Connection to Digital and Inquiry-Based Learning

The game-based format aligns with Finland's digital learning strategies, providing an interactive, problem-solving environment. It supports inquiry-based learning (*tutkiva oppiminen*), allowing students to explore real-world CRM challenges and develop solutions.

Table 4 and Table 5 highlight how the CRM game aligns with Finland's upper secondary education goals, particularly in science, sustainability, digital competence, and global awareness. It reinforces critical thinking, problem-solving, and interdisciplinary connections essential for modern education.

Table 4. Alignment of Curriculum Areas in the "Finnish National Core Curriculum" with the CRM Game's Educational Goals.

Curriculum Area	Relevant Courses & Themes	Connections to the CRM Game
Geography	GE1: Maailma muutoksessa (The Changing World)	Explores global resource distribution and environmental impacts of mining.
	GE2: Yhteinen maailma (A Shared World)	Highlights global CRM supply chains, trade dependencies, and geopolitical risks.
	GE3: Riskien maailma (The World of Risks)	Discusses environmental and economic risks related to raw material extraction.
Chemistry	KE1: Ihmisen ja elinympäristön kemiaa (Chemistry of Humans & Environment)	Demonstrates how CRMs are used in everyday technologies and materials.
	KE2: Kemian mikromaailma (The Microscopic World of Chemistry)	Explains the properties of CRMs and their industrial uses.
	KE5: Materiaalit ja teknologia (Materials and Technology)	Covers how CRMs contribute to new materials, semiconductors, and energy storage.
Physics	FY2: Lämpö, energia ja elämän edellytykset (Heat, Energy & Conditions for Life)	Shows how CRMs are essential in energy storage (batteries) and renewable energy (solar, wind).
	FY3: Sähkö (Electricity)	Covers how CRMs are crucial for electronics, power grids, and semiconductors.
	FY4: Aallot ja optiikka (Waves and Optics)	Explains the use of CRMs in fiber optics, lasers, and solar panels.

Sustainability & Circular Economy	Kestävä kehitys ja vastuullisuus (Sustainable Development & Responsibility)	Promotes sustainable mining, recycling (urban mining), and responsible sourcing.
Technology & Society	Teknologia ja yhteiskunta (Technology & Society)	Demonstrates how CRMs support digitalisation, Industry 4.0, and automation.
Multiliteracy & Critical Thinking	Monilukutaito ja kriittinen ajattelu (Multiliteracy & Critical Thinking)	Encourages decision-making based on real-world CRM data and economic scenarios.
Globalisation & Economy	Globalisaatio ja talous (Globalisation & Economy)	Highlights CRM trade, supply chain disruptions, and economic dependencies.
Digital & Inquiry-Based Learning	Digitaalisuus ja tutkiva oppiminen (Digital & Inquiry-Based Learning)	The game provides an interactive, research-based learning environment.

Table 5. Alignment of Key Themes in the" Finnish National Core Curriculum" with the CRM Game's Educational Goals.

Key Curriculum Themes	Description from Finnish Curriculum	How the Game Addresses This Need
Phenomenon-Based Learning	Encourages interdisciplinary and real-world problem-solving.	The game integrates geology, chemistry, physics, economy, and sustainability in a real-world context.
Sustainability & Circular Economy	Focuses on responsible resource use, environmental protection, and long-term sustainability.	The game highlights sustainable mining, CRM recycling, urban mining, and resource efficiency.
Scientific Literacy	Develops understanding of scientific methods, data analysis, and critical evaluation of information.	Players use real-world CRM data and case studies to make informed decisions in the game.
Globalisation & Economic Structures	Examines international trade, resource dependencies, and geopolitical risks.	The game explores CRM supply chains, international trade, and the impact of shortages.
Technology & Society	Investigates how technology shapes societies and economies.	Demonstrates the role of CRMs in digitalisation, AI, automation, and Industry 4.0. and 5.0.

Digital Competence	Strengthens students' ability to use digital tools for learning and problem-solving.	As an interactive online platform, the game enhances digital learning and data interpretation skills.
Inquiry-Based & Experimental Learning	Encourages students to engage in hands-on problem-solving and exploration.	The game simulates real-life decision-making scenarios related to CRM management and sustainability.
Energy & Environment	Covers energy resources, renewable energy, and climate impacts.	Highlights the role of CRMs in energy transition, battery technologies, and green energy.
Entrepreneurship & Innovation	Encourages creativity, problem-solving, and understanding economic processes.	Challenges players to find innovative solutions for CRM shortages, recycling, and sustainable sourcing.
Multidisciplinary Thinking	Encourages connecting knowledge from multiple subjects to understand complex issues.	The game combines physics, chemistry, geography, and economics to show the bigger picture of resource management.

The interactive nature of the game ensures active student engagement, allowing them to apply theoretical knowledge to practical scenarios. This hands-on approach reinforces learning outcomes and makes abstract concepts tangible.

Appendix 2. Alignment to German National School Curriculum

The CRM Smartphone Game also aligns with educational objectives outlined in the 2019 Geography curriculum for high schools in Saxony, Germany.[24] Saxony is a federal state (Bundesland) in eastern Germany, known for its rich cultural heritage, historical significance and economic strength. Saxony and the Erzgebirge region could become critical to Europe's strategy for securing access to CRMs. This alignment ensures that the game not only serves as an engaging educational tool but also reinforces key competencies and knowledge areas emphasised in the curriculum.

1. Alignment with Educational Objectives:

    - Spatial Orientation and Competence: The curriculum emphasises the development of spatial orientation skills, enabling students to understand and interpret geographical data. The game supports this by allowing players to explore global supply chains of CRMs, tracing their origins from extraction sites to manufacturing hubs and end-users. This interactive mapping fosters a deeper understanding of global interconnections and spatial distributions.

    - Human-Environment Interaction: Understanding the dynamic relationship between human activities and the environment is a core aspect of the curriculum. The game immerses students in scenarios where they must make decisions about resource extraction, considering environmental impacts and sustainability. This experiential learning approach highlights the consequences of human actions on ecological systems.

    - Sustainable Development: The curriculum underscores the importance of sustainable practices. Through the game, students engage with concepts of resource management, recycling, and the circular economy, promoting awareness of sustainable development goals and the necessity of responsible consumption.

2. Support for Competency Development:

    - Systemic Thinking: The game encourages students to think systemically by presenting complex supply chains and the interconnectedness of global economies. Players must consider various factors, such as economic viability, environmental sustainability, and social implications, fostering holistic thinking.

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[24] Lehrplan Gymnasium. Geographie.
https://fbgeo-leipzig.de/onewebmedia/1425_lp_gy_geographie_2019.pdf

- Decision-Making Skills: By simulating real-world scenarios, the game enhances students' decision-making abilities. They are tasked with making choices that balance different interests, reflecting the multifaceted considerations present in geographical and environmental issues.

- Media Literacy: The integration of digital tools in the game aligns with the curriculum's emphasis on media literacy. Students interact with digital simulations, enhancing their ability to navigate and critically assess information in a technologically advanced context.

3. Facilitation of Interdisciplinary Learning:

The curriculum advocates for interdisciplinary approaches, recognising that complex topics often span multiple fields. The CRM Smartphone Game serves as a platform for such learning by integrating aspects of geography, economics, environmental science, and technology. This fusion provides students with a comprehensive understanding of CRMs' roles in society.

4. Promotion of Values and Attitudes:

- Responsibility and Ethical Awareness: The game includes a sense of responsibility by highlighting the ethical considerations of resource extraction and consumption. Students confront the moral implications of their decisions, promoting ethical awareness.

- Global Citizenship: By exploring international supply chains and their impacts, the game fosters a sense of global citizenship. Students gain insight into global dependencies and the importance of international cooperation in addressing environmental challenges.

5. Practical Application and Engagement:

The interactive nature of the game ensures that students are actively engaged, applying theoretical knowledge to practical scenarios. This hands-on approach reinforces learning outcomes and makes abstract concepts tangible.

Table 6 highlights how the CRM game aligns with key educational goals in German upper secondary geography education, reinforcing real-world applications of resource management, sustainability, and global economic interdependencies.

Table 6. Alignment of Key Themes in "Geography Curriculum for High Schools in Saxony, Germany" with the CRM Game's Educational Goals.

Key Curriculum Themes	Description from German Curriculum	How the Game Addresses the Theme

Natural Resources and Sustainability	Understanding the availability, extraction, and use of natural resources with a focus on sustainability.	The game introduces players to CRMs, their significance, extraction challenges, and sustainable resource management.
Global Economic and Resource Interdependencies	Examining global trade, supply chains, and economic dependencies on raw materials.	Players experience the impact of CRM supply chains, global market fluctuations, and geopolitical factors affecting resource access.
Environmental Impacts of Resource Extraction	Evaluating the ecological consequences of mining and raw material use.	The game highlights environmental risks of mining, waste management, and the importance of responsible sourcing and recycling.
Circular Economy and Recycling	Understanding strategies for resource efficiency, waste reduction, and urban mining.	The game promotes circular economy principles, allowing players to explore recycling strategies and alternative raw material sourcing.
Technological and Industrial Development	Exploring how industries rely on key raw materials, particularly for green technologies.	Players see the role of CRMs in renewable energy, digital technologies, and innovations like batteries, wind turbines, and semiconductors.
Decision-Making and Sustainability Strategies	Analysing case studies and real-world examples of sustainable resource management.	The game presents scenarios where players must make strategic decisions balancing economic, environmental, and social factors.
Geopolitics of Resources	Understanding regional resource distributions, trade policies, and the role of key producing countries.	The game provides insights into geopolitical dependencies, supply risks, and international cooperation in CRM management.

Appendix 3. Alignment to Estonian National School Curriculum

The CRM Smartphone Game supports the objectives of Estonia's National Curriculum for Upper Secondary Schools (Gümnaasiumi riiklik õppekava[25]) by enhancing students' understanding of CRMs and their role in technological and environmental systems. The game integrates multiple subject areas, fosters key competencies, and encourages active, inquiry-based learning.

1. Alignment with Core Competencies

According to the Estonian national curriculum, high school education must equip students with general competencies, including:

- Technology and Digital Competence → The game introduces students to the global supply chain of CRMs used in digital devices and encourages critical evaluation of technological innovations.
- Entrepreneurial Competence → The game challenges students to consider the economic aspects of CRM use, supply chain logistics, and resource management.
- Environmental and Sustainability Awareness → By exploring resource extraction, production, and recycling, students develop a deeper understanding of sustainable development and circular economy principles.
- Critical Thinking and Problem-Solving → Decision-making in the game (e.g., balancing economic, environmental, and ethical factors) enhances students' ability to analyse complex global issues.

2. Support for Natural Science Education

The subject field "Loodusained" (Natural Sciences), which is presented in Annex 4 of Estonia's National Curriculum for Upper Secondary Schools[26], includes topics directly relevant to the CRM Smartphone Game, particularly the section "Loodusvarade majandamine ja keskkonnaprobleemid" (Natural Resource Management and Environmental Issues):

- Raw Material Extraction and Resource Use → The game simulates the mining and processing of CRMs, helping students understand resource availability, extraction methods, and environmental consequences.

[25] Gümnaasiumi riiklik õppekava. https://www.riigiteataja.ee/akt/108032023006
[26] Gümnaasiumi riiklik õppekava. Lisa 4. Ainevaldkond "Loodusained". https://www.riigiteataja.ee/aktilisa/1080/3202/3006/18m_gym_lisa4.pdf

- Climate Change and Energy → By examining the impact of CRMs on renewable energy solutions (e.g., lithium for batteries in EVs), the game strengthens students' knowledge of energy transitions.
- Circular Economy and Recycling → The game challenges players to optimise smartphone recycling, highlighting Estonia's national goals for sustainable resource use.

3. Integration into Geography, Economics, and Civics

The game aligns with the curriculum in several other subject areas:

- Geography (Geopolitical issues of resource extraction, environmental impacts, and global supply chains)
- Economics (CRM price volatility, global trade dependencies, and sustainable business models)
- Civics and Society (Ethical aspects of mining, working conditions in resource-rich countries, and policy decisions affecting the CRM industry)

4. Inquiry-Based Learning and Digital Innovation

Estonian high schools emphasise research and inquiry-based learning, which the CRM Smartphone Game supports by:

- Encouraging students to simulate different scenarios (e.g., what happens when a key supplier limits CRM exports).
- Providing interactive challenges that require critical decision-making and analysis.
- Allowing students to explore real-world data (maps, graphs, and case studies) to understand economic and environmental trends.

Table 7 and Table 8 demonstrate how the CRM game supports key learning objectives in Estonian upper secondary education, particularly in sustainability, resource management, technology, and environmental awareness.

Table 7. Alignment of the "Estonian National Curriculum for Upper Secondary Schools" with the CRM Game's Learning Objectives.

Key Curriculum Themes	Description from Estonian Curriculum	How the CRM Game Addresses the Theme
Sustainability and Responsible Resource Use	Emphasises the importance of sustainable development, environmental	The game introduces players to CRMs, their sustainable use, and the circular economy, encouraging responsible resource management.

	responsibility, and efficient use of natural resources.	
Natural Sciences and Technology	Encourages an understanding of natural processes, technological developments, and their applications in daily life.	Players explore how CRMs are essential in technology (e.g., renewable energy, digital devices) and their impact on modern industries.
Global Economy and Resource Dependency	Highlights the interconnections of economies and the role of natural resources in economic development.	The game presents CRM supply chains, international trade, and economic dependencies on critical materials.
Environmental Impact of Resource Extraction	Students analyse the effects of human activity on the environment, focusing on pollution, biodiversity loss, and resource depletion.	The game incorporates mining-related environmental impacts, waste management challenges, and the need for sustainable practices.
Circular Economy and Recycling	Promotes understanding of waste reduction, material reuse, and sustainable consumption.	The game teaches urban mining, CRM recycling, and circular economy principles as solutions for resource efficiency.
Geopolitical and Strategic Importance of Raw Materials	Focuses on the global distribution of resources, geopolitical conflicts, and economic dependencies.	Players navigate global CRM markets, supply risks, and international resource politics.
Decision-Making and Problem-Solving in Sustainability	Encourages critical thinking and informed decision-making regarding environmental and economic sustainability.	Players make strategic choices balancing economic growth, environmental protection, and technological development.
Scientific Literacy and Inquiry-Based Learning	Develops analytical skills through real-world problem-solving and interdisciplinary learning.	The game presents interactive scenarios requiring scientific reasoning and strategic decision-making.
STEM Education and Innovation	Supports interest in science, technology, engineering, and mathematics (STEM) fields.	The game provides insights into resource extraction, green technologies, and industry innovations, fostering interest in STEM careers.

Table 8. Alignment of the "Estonian National Curriculum for Upper Secondary Schools" Areas with the CRM Game's Learning Objectives.

Curriculum Area	Description from Estonian Curriculum	How the Game Addresses the Theme
Geography	In the geography curriculum, students are expected to understand the distribution and use of natural resources, the impact of human activities on the environment, and global economic processes.	The CRM game helps students explore the geographical distribution of CRMs, their uses in various industries, and their importance in the global economy and environmental sustainability.
Physics	The physics curriculum includes understanding energy and its transformation, the role of natural resources in energy production, and the relationship between energy, technology, and sustainability.	The game connects physical principles with the extraction and use of CRMs in energy production, especially in the context of renewable energy technologies like wind turbines and EVs.
Chemistry	Students focus on the chemical properties of elements, materials, and the processes involved in the extraction and processing of raw materials, as well as the impact of these processes on the environment.	The CRM game highlights the chemistry behind resource extraction, including the processes involved in refining and recycling critical materials such as lithium, cobalt, and REEs.
Economics	The economics curriculum emphasises understanding market dynamics, the role of natural resources in economic development, and the impact of resource availability on trade, growth, and sustainability.	The game teaches students about the economic importance of CRMs, their role in global supply chains, and their influence on technological advancements, economic development, and trade.

Environmental Science	Students are taught about the importance of sustainable development, resource management, and the environmental impact of human activities, including the extraction and use of raw materials.	The CRM game promotes sustainability by showing how resource extraction, recycling, and the circular economy can mitigate environmental impacts and support sustainable development goals.
Technology	Focus on the role of technology in resource management, energy production, and the development of innovative solutions to address environmental challenges related to natural resources.	The game illustrates how technology is used to manage CRMs more efficiently, including innovations in mining, recycling, and sustainable resource usage in technologies like smartphones and renewable energy.
Mathematics	In mathematics, students are encouraged to develop skills in analysing data, modelling systems, and using mathematical methods to understand and solve real-world problems, including resource management.	The game involves quantitative analysis, where students model resource use, understand supply chain dynamics, and explore sustainability through data-driven decision-making.
Environmental Studies	Focus on understanding the global and local environmental challenges, climate change, and the role of resource use and management in mitigating these challenges.	The game addresses environmental studies by showing how the extraction and efficient use of CRMs contribute to addressing climate change, especially through green technologies and sustainable practices.
Sociology	In sociology, students examine the social impact of resource extraction, the role of industries in society, and how sustainable practices can be implemented in different social contexts.	The game emphasises the social responsibility of resource management, showing the importance of ethical sourcing, the consequences of resource depletion, and the impact on local communities and industries.