Securing strategic raw materials supply Horizon 2024-2030		Sustainable and circular critical raw materials value chains Horizon 2024-2030	
Resources & Materials	**Processes & technologies**	**Circularity**	**Sustainability approach**
Improved recycling of SRM-containing EoL products such as WEEE, PV panels, LIBs, magnets, and electrolysers. *Near-zero waste resource recovery from production waste (slags, sludges, ashes, mine tailings, waste waters).* *Enabling Flemish industry (incl. SMEs) to play an active role in the (future) European low-grade ore responsible mining activities.*	*Develop processes and technologies for a more resilient, flexible and sustainable local SRM production through improved sorting, disassembly, physicochemical pre-processing and improved (more efficient and selective) metallurgical extraction and recovery systems. Developed processes and technologies are required to be cost effective, safe and green.*	*Maintain the functionality of CRM-containing products through re-use, repair, refurbish, and repurpose strategies and through direct recycling (regeneration) processes for EoL products, their components and materials (e.g. battery active materials, alloys, etc.).*	*Processes and technologies allowing for decarbonization (e.g. electrification, substitution of fossil fuel based reagents, hydrogen as fuel/reagent), process intensification.* *Processes and technologies allowing for increased sustainability, i.e. "greening", (e.g. green solvents, production waste reduction, etc.) of the recycling and CRM production industry.*

ENABLERS	
Tools and models	*Development and refinement of tools and models evaluating material stocks and flows, and the sustainability/circularity of the CRM value chain.*
Digitalization	*Several digital solutions (e.g. material passports, robotization, IoT, AI applications, Industry 5.0 and digital twins) will also make their way into the recycling and CRM production industry and should be further developed, improved, validated and implemented to support the overall sustainability goals.*
Regulation	*Focus on adopting to European and International legislations and frameworks such as the European Green Deal, the Critical Raw Material Act, the EU Battery Regulation and the Waste Shipment Regulation; and taking into account the Circular Economy Action Plan.*

Figure 1 Diagram Roadmap Strategic and Critical Raw Materials

Application domain	Focus domain	Main research topics	References and targets			Funding instr. 2024-2027		Funding instr. 2028-2030	
			Ref 2023	Target 2027	Target 2030	SBO	ICON	SBO	ICON
Securing strategic raw materias supply	To unlock as many sources of SRM as possible and develop the necessary recycling and production processes to deal with the increased complexity of working with low-grade and/or highly complex input streams	Improved recycling of SRM- containing EoL products such as WEEE, PV panels, batteries, magnets, and electrolysers.	Actual SotA	contribute to the overall aim of 10% of all SRM from recycling (CRMA). For batteries: see specific data from Battery Regulation (targets 2027 on recycling efficiency and % recovery of specific elements such as Co, Ni, Li, Cu, Pb)	contribute to the overall aim of 15% of all SRM from recycling (CRMA). For batteries: see specific data from Battery Regulation (targets 2031 on recycling efficiency and % recovery of specific elements such as Co, Ni, Li, Cu, Pb)				
		Near-zero waste resource recovery from production waste (slags, sludges, ashes, mine tailings, waste waters).	Actual SotA	contribute to the overall aim of 10% of all SRM from recycling (CRMA)	contribute to the overall aim of 15% of all SRM from recycling (CRMA)				
		Enabling Flemish industry (incl. SMEs) to play an active role in the (future) European low-grade ore responsible mining activities.	Actual SotA	contribute to the overall aim of 7% of all SRM from responsible mining (CRMA)	contribute to the overall aim of 10% of all SRM from responsible mining (CRMA)				
		Develop processes and technologies for a more resilient, flexible and sustainable local SRM production through improved sorting, disassembly, physicochemical pre-processing and improved (more efficient and selective) metallurgical extraction and recovery systems. Developed processes and technologies are required to be cost effective, safe and green.	Actual SotA	contribute to the overall aim of 10% of all SRM from recycling (CRMA). For batteries: see specific data from Battery Regulation (targets 2027 on recycling efficiency and % recovery of specific elements such as Co, Ni, Li, Cu, Pb)	contribute to the overall aim of 15% of all SRM from recycling (CRMA). For batteries: see specific data from Battery Regulation (targets 2031 on recycling efficiency and % recovery of specific elements such as Co, Ni, Li, Cu, Pb)				
Sustainable and circular critical raw materials value chains	To decrease the overall environmental and climate footprint of the recycling and production processes of CRM	Maintain the functionality of CRM-containing products through re-use, repair, refurbish, and repurpose strategies and through direct recycling (regeneration) processes for EoL products, their components and materials (e.g. battery active materials, alloys, etc.).	Actual SotA	Reduction in CRM use of at least 10% (in a value chain) resulting in equivalent or improved environmental impact and/or circularity and with equivalent or improved technical performance of a specific application.	Reduction in CRM use of at least 20% (in a value chain) resulting in equivalent or improved environmental impact and/or circularity and with equivalent or improved technical performance of a specific application.				
		Processes and technologies allowing for decarbonization (e.g. electrification, substitution of fossil fuel based reagents, hydrogen as fuel/reagent), process intensification (e.g. digitalization).	Actual SotA	10% reduction in climate change impact (kg CO_2 eq. per kg) during production with equivalent production efficiency.	20% reduction in climate change impact (kg CO_2 eq. per kg) during production with equivalent production efficiency.				
		Processes and technologies allowing for increased sustainability, i.e. "greening", (e.g. green solvents, production waste reduction, etc.) of the recycling and CRM production industry.	Actual SotA	10% reduction in waste generation during CRM recycling and production with equivalent overall process performance	20% reduction in waste generation during CRM recycling and production with equivalent overall process performance				

Figure 2 Detailed Diagram Securing strategic raw materials supply & Sustainable and circular critical raw materials value chains

Enablers	Aim	Main research topics	References and targets			Funding instr. 2024-2027		Funding instr. 2028-2030	
						SBO	ICON	SBO	ICON
Tools	A more competitive, efficient and resilient CRM ecosystem that is better able to face challenges such as sustainability and productivity, by the implementation of (1) novel tools, (2) digital technologies, and (3) a supportive and well-aligned regulation	Development and refinement of tools and models evaluating material stocks and flows, and the sustainability/circularity of the CRM value chain.	**Ref 2023**	**Solutions supporting the achievement of the targets mentioned above**	**Solutions supporting the achievement of the targets mentioned above**				
Digitalisation		Several digital solutions (e.g. material passports, robotization, IoT, AI applications, Industry 5.0 and digital twins) will also make their way into the recycling and CRM production industry and should be further developed, improved, validated and implemented to support the overall sustainability goals.							
Regulation		Focus on adopting to European and International legislations and frameworks such as the European Green Deal, the Critical Raw Material Act, the EU Battery Regulation and the Waste Shipment Regulation; and taking into account the Circular Economy Action Plan.							

Figuur 3 Detailed Diagram Enablers Sustainable Raw Materials

	Too early, insuficient industrial interest
	Relevant instrument
	Relevant instrument but timing is becoming critical
	Too late to start development

1. What is the importance of the roadmap?

MateriNex's main objective is to support Flemish companies active in materials research, taking into account the **EU research agenda** and **the Flemish government's policy priorities**. A survey has shown that these **needs** are situated in the area of **high-risk long-term research**.

For each MateriNex **innovation theme**, a roadmap with horizon 2030 has been drawn up that establishes the priorities related to basic and applied research for the coming years and the funding instruments to be considered such as strategic basic research (SBO) and/or interdisciplinary cooperative research (ICON). This roadmap covers the innovation theme of Strategic and Critical Resources.

The roadmap will be used to organize calls for project proposals and to evaluate the submitted project proposals. However, it is a dynamic tool and will be adjusted as needed based on consultation with a broad group of stakeholders **(Common Interest Group (CIG))**.

2. What is this roadmap based on?

Initially, this roadmap for the innovation theme of Strategic and Critical Raw Materials was underpinned by recent national and international reports, roadmaps and action plans. For example, a study was commissioned by the Flemish Government that inventories **Flanders' role in the European Critical Raw Materials value chain**[1]. Relevant studies that mapped the need for critical raw materials for the energy transition are, for Europe, the **Eurometaux** study (by KU Leuven)[2] and, worldwide, the study conducted by the **International Energy Agency**[3]. **ERMA** (European Raw Materials Alliance)[4] has also defined an action plan to this end.

This roadmap was fine-tuned in consultation with members of **Flanders Metals Valley**, a bottom-up initiative launched by companies active in the metallurgical sector in Flanders. The organization consists of a mix of companies, active in the metallurgical industry, combined with universities and knowledge centers, which are often at the basis of fundamental research for the future, but also want to be relevant to today's challenges. Currently, the organization has 38 members.

Ultimately, this roadmap was aligned with European directives. In particular, the **Critical Raw Material Act (CRMA)** which includes a series of measures to ensure access to and supply of critical raw materials. These measures aim at reliability, diversification, affordability and sustainability. One relies on the strengths and opportunities of the EU's single market and external partnerships to diversify and make the EU's critical raw materials supply chains more resilient. It further aims to improve EU capacity across the entire value chain, diversify raw material imports to the EU, improve monitoring and risk management capacity, as well as circularity and sustainability. Additional European legislation and directives in which critical raw materials play an important role include the **Battery Regulation**[5], the **European Green Deal**[6] and the **Circular Economy Action Plan**[7].

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[1] Vlaams Planbureau voor Omgeving, De rol van metalen en 'kritieke grondstoffen' in Vlaanderen - Analyse vanuit een omgevingsperspectief, 2024, in press.
[2] L. Gregoir, K. van Acker, S. Beretta, C. Heron, Metals for Clean Energy: Pathways to solving Europe's raw materials challenge, 2022.
[3] International Energy Agency, The Role of Critical Minerals in Clean Energy Transitions, 2021.
[4] F. Pegorin et al., Materials for Energy Storage and Conversion: A European Call for Action. A report by the Materials for Energy Storage and Conversion Cluster of the European Raw Materials Alliance. Berlin 2023.
[5] Regulation (EU) 2023/1542 of the European Parliament and of the Council of 12 July 2023 concerning batteries and waste batteries, amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and repealing Directive 2006/66/EC (Text with EEA relevance)
[6] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en
[7] https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en

3. What does this roadmap focus on?

The diagram of the Strategic and Critical Raw Materials roadmap is presented in Figure 1 and starts from two main application domains, on the one hand, research to help **secure the supply of strategic raw materials** and on the other hand, research to improve the **circularity and sustainability of critical raw materials**.

In addition, the roadmap has a third horizontal part that can be described as **enablers**. These are important cross-cutting challenges namely (i) **tools and models**, (ii) **digitalization** and (iii) **regulation**. Some of these challenges can be the subject of projects e.g. because they are very specific to the priority theme for which the roadmap has been drawn up and in Flanders a substantial number of companies are active in this field and play a pioneering role. On the other hand, these cross-cutting challenges will factor into the evaluation of project proposals in the application domains.
See also part 5 “Which enablers should be considered?”

In the more detailed diagrams of Figure 2 and Figure 3, an estimate of the supporting grant instruments, considered necessary to achieve the objectives within the time frame, has been made for each research domain. This uses a simple color code where green represents the relevant instruments. Blue, too early and currently limited industrial interest, and orange, relevant but critical with respect to timing, can also be funded in principle provided a good argument is made. A red color indicates that the instrument is too late to start up.

4. What core activities are included in this roadmap?

4.1 Introduction

The dual green and digital transition, **the twin transition**, and the further anchoring and strengthening of defense and space are accompanied by the emergence and further expansion of the so-called strategic technologies. The expansion of these technologies creates an increasing demand for resources, largely the critical raw materials. For example, a renewable energy system is much more dependent on minerals and metals than an energy system based on fossil resources. Here it is important to distinguish between strategic and critical raw materials. Strategic raw materials are those that score highest in terms of strategic importance, estimated increase in demand and difficulty of increasing production. The list of critical commodities includes all these strategic commodities, as well as other commodities that meet or exceed the thresholds for economic importance and supply risk.

From the twin transition, the following EU acts, among others, were developed: **Net Zero Industry act (NZI act)** and the **Critical Raw Materials act (CRM act)**. The first includes the measures necessary to initiate the transition towards a climate neutral industry. The second deals with securing the supply of raw materials needed for the transition to a green and digital economy (Figure 4). Several of these raw materials are "critical" because of fragile supply channels and their importance to local economies. For example, currently Flanders, like the EU, is largely dependent on critical raw materials from a limited number of supply sources from countries with not always stable economic or political situations. On top of this, based on current projections, global demand for a number of metals and critical raw materials such as rare earths and lithium will soon exceed global supply.

For Figure 4, it should be noted that (i) Coking coal, although a critical raw material, was not included in the table in the underlying study[12], (ii) Bauxite/Alumina/Aluminum is listed here as a critical material, while it is labeled strategic in the CRM act.
For legend to the technologies on the horizontal axis, please refer to the original study[12].

The current European list includes **34 critical raw materials** (CRMs), of which **17** have been labeled **strategic raw materials (SRMs)** because they are indispensable in technologies that enable a green and digital transition as well as in defense and space applications[8]. It is important to emphasize that several critical raw materials are mined from base **metal ores such as copper, lead, zinc,** etc., or **recycled from waste streams** containing a mix of base metals and critical raw materials.

By introducing the Critical Raw Materials act, the EU aims to secure the supply of critical, and in particular strategic raw materials by strengthening domestic supply chains on the one hand and by establishing international partnerships with third countries on the other[9]. Hereby, by 2030, the EU aims to obtain 10% of strategic raw materials from EU mining, 40% of SRMs should be processed in the EU and 25% of SRMs should be obtained from recycling. In addition, no more than 65% of an SRM should come from a single third country. Europe aims to achieve this objective by (i) strengthening the entire raw material value chain in the EU, (ii) improving the resilience of the supply chain, (iii) **investing in research, innovation and expertise/skills**, (iv) **promoting and supporting a more sustainable and circular critical raw material economy**.

In addition, the EU's ambition to move to net-zero carbon emissions by 2050 requires a radical transformation of society in a very short time frame. Here, on the one hand, there is a huge need for green energy technologies (such as electric vehicles, batteries, solar panels, wind turbines, and hydrogen technology) that will lead to a sharp increase in the demand for (critical) raw materials, and on the other hand, the production of many of these raw materials is energy-intensive, where it becomes essential to avoid that an increase in raw material production leads to an increase in emissions.

Flanders is rich in metallurgical companies with a significant share in the production of base metals and critical raw materials in Europe[1]. Many of these companies have an important focus on recycling. The European metals industry is also well positioned to meet the challenges related to the transition to a climate-neutral society. For example, a 2018 Eurometaux study conducted by the VUB shows that the European non-ferrous industry already has a strong lead in electrification of production processes, reduction of emissions and recycling of base metals compared to the rest of the World[10]. Maintaining this trend toward greening and expanding and applying it to other (critical) raw materials is necessary. Flanders can play an important role here with the expertise available in, among others, recycling and metallurgy. The Flemish metal industry is aware of the pioneering role it can play in the transition to climate-neutral, circular metal production. To this end, it has organized itself into Flanders Metals Valley[11] , in which it networks and collaborates with research institutes and universities on the themes of innovation, communication and education, which should lead to joint research projects.

The main priorities for the Flemish players active in the entire value chain of strategic and critical raw materials highlighted in the following sections are:

- **Securing the supply of strategic raw materials**, with a focus on “raw materials and materials” and "processes and technologies.
- **More sustainable and circular value chains of critical raw materials**, with a focus on “circularity” and “sustainability”;

[8] https://single-market-economy.ec.europa.eu/publications/european-critical-raw-materials-act_en

[9] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/green-deal-industrial-plan/european-critical-raw-materials-act_en

[10] T. Wyns, G. Khandekar, Metals for a Climate Neutral Europe: A 2050 Blueprint, 2019. https://eurometaux.eu/media/2005/full-report-8-56-17.pdf

[11] https://flandersmetalsvalley.be/

- The necessary **enablers** (cross-cutting research topics) that will be supportive in strengthening the value chains of strategic and critical raw materials, namely (i) the development of specific tools (instruments) and models, (ii) the move towards more digitalization and (iii) the translation and implementation of European and international regulations into Flemish legislation.

Supply Risk	Raw material															
4.8	Gallium						•			•	•	•		•	•	•
4.1	Magnesium			•							•	•	•	•	•	•
4.0	REE (magnets)		•	•	•	•		•		•	•	•		•	•	•
3.8	Boron		•	•	•	•	•	•		•	•	•		•	•	•
2.7	PGM		•	•						•	•	•		•	•	•
1.9	Lithium	•								•		•		•	•	•
1.9	Bismuth									•	•	•				•
1.8	Germanium						•			•	•	•				•
1.8	Natural graphite	•	•	•					•	•		•		•	•	
1.7	Cobalt	•	•	•						•		•	•	•	•	•
1.6	Titanium metal											•	•	•	•	•
1.4	Silicon metal		•	•	•	•	•	•	•	•	•	•	•	•	•	•
1.2	Tungsten			•								•	•		•	•
1.2	Manganese	•	•	•	•			•	•	•	•	•	•	•	•	•
0.5	Nickel	•	•	•	•		•	•	•	•	•	•	•	•	•	•
0.1	Copper	•	•	•	•	•	•	•		•	•	•	•	•	•	•
5.3	HREE (rest)		•	•						•	•	•	•	•	•	•
4.4	Niobium			•	•					•			•		•	•
3.5	LREE (rest)		•	•						•		•		•	•	•
3.3	Phosphorus	•					•		•		•	•				•
2.6	Strontium		•	•						•		•				
2.4	Scandium			•							•		•			•
2.3	Vanadium		•	•					•	•			•	•	•	•
1.8	Antimony						•			•	•	•		•	•	•
1.8	Beryllium										•	•				•
1.6	Arsenic						•			•	•	•				•
1.5	Feldspar		•												•	
1.5	Hafnium										•		•		•	•
1.3	Baryte		•	•						•	•	•				•
1.3	Tantalum			•						•		•			•	•
1.2	Aluminium	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
1.2	Helium										•					•
1.1	Fluorspar	•					•	•		•		•		•	•	•
1.0	Phosphate rock									•						

Figure 4 List of strategic (dark red) and critical (dark- and light red) raw materials in the de EU-27 (source: JRC (2023), Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU - A foresight study)[12].

4.2 Securing supply of strategic raw materials

Goal

Securing the availability of SRMs for Flanders and Europe by:

(1) maximizing efforts to unlock as many potential sources of SRMs locally present in Europe as possible, and

(2) developing the necessary recycling and production processes that can deal with the increased complexity associated with low-grade and/or highly complex input streams.

[12] https://op.europa.eu/en/publication-detail/-/publication/9e17a3c2-c48f-11ed-a05c-01aa75ed71a1/language-en/format-PDF

Raw materials

Strategic raw materials can be extracted from different sources through different techniques and business models. We consider (i) **recycling of end of life** (EoL) **products**, (ii) **processing or reprocessing of industrial waste streams or secondary raw materials**, and (iii) mining and processing of **primary ores**.

The extraction of SRMs, which are needed in the energy transition (copper, lithium, nickel, cobalt, etc.), will have to be done mainly from primary raw materials until the end of the next decades.
Especially since there is currently insufficient volume of EoL products and/or industrial waste streams from which the necessary SRMs can already be recycled. Yet it is important to make sufficient efforts to recycle now, because the more CRMs that can be locally recovered through recycling, the more the pressure on supply can be eased. With a view to the future, a well-developed and state-of-the-art recycling sector is crucial to effectively convert future flows into new raw materials.

Flanders is currently known as one of the forerunners in recycling. Since Flanders, and by extension the entire EU, has limited availability of primary raw materials, recycling will become a crucial factor in securing the supply of strategic (and critical) raw materials. Especially when large volumes of EoL products (intended for, among others, the new energy and digitalization technologies) will become available for recycling in 2040. 2040 is advanced in several scenarios as the date when the supply from primary raw materials of strategic materials for the energy transition will peak[2,13]. If the rollout of renewable energy technologies slows, which is predicted by 2050, 45-65% of Europe's demand for these metals will be obtainable through recycling[2]. Recycling of materials from Europe's own internal market will then become more important for the supply of SRMs than primary extraction from other regions.
To illustrate the point: Europe currently accounts for only 1% of global extraction through mining for the production of base metals while it accounts for 6% of global primary smelting and refining and even 24% of global recycling volume (treatment and refining of secondary materials such as scrap and EoL products)[4]. This also shows how important recycling is for Europe and will have to remain.

In addition to the recovery of SRMs from EoL products (e.g. batteries, solar panels, printed circuit boards, etc.), Flemish companies also produce and process important industrial residues/waste streams (e.g.: metal slag, industrial sludges, bottom ashes, mining waste, shredder residues, etc.) that contain SRMs in low concentrations. Primary ores (e.g., zinc (incl. indium, germanium, silver), cobalt, copper (incl. nickel, gold, cobalt, etc.) are also processed in Flanders and the geological, metallurgical and recycling expertise present in Flanders can be deployed to, on the one hand, enable diversification of primary ores in current or new production processes and, on the other hand, to make the processes of (European) mining activities and processing of primary ores more efficient and less environmentally damaging. With its crucial expertise in recycling, both in the field of pre-treatment and metallurgical treatment, as well as its strong logistics network in Europe, **Flanders can become an important hub for the European recycling industry focused on SRMs**.

Processes and technologies

In the past, the composition of raw materials added during the production process was relatively stable. These raw materials were either mined locally or they came from known global sources (concentrates of ores for the ferrous and nonferrous industry). But this is no longer the case. Concentrates of ores are currently typically purchased from multiple sources, are increasingly low grade and are also becoming increasingly complex in composition. Furthermore, the use of secondary

[13] International Energy Agency. The Role of Critical Minerals in Clean Energy Transitions; International Energy Agency, 2021

raw materials and the increasing recycling of EoL products to replace primary raw materials has also led to increasingly complex and variable input streams for the production of metals and other raw materials.

To enable the diversification of raw materials for the production of SRMs (and CRMs), as described above, current production processes need to be adapted and/or new processes and technologies need to be developed over the entire production chain from raw material/waste to final product. These processes and technologies should on the one hand be flexible to process different raw materials and on the other hand offer increased selectivity and efficiency for the recovery and reprocessing of CRMs from complex and low-value raw materials. In addition, the energy and material consumption of the processes should be minimized. Digitalization and automation can contribute significantly to this.

To meet this challenge, detailed and rapid (in-line) characterization of these complex streams is essential. This will provide a better grip on the composition of input streams through the targeted creation of specific blending streams or enabling better separation during pre-treatment of the raw materials and/or materials. In addition, the (production) processes must also be increasingly flexible in order to deal efficiently with the increasing variety of input steams. For this, in-line and non-destructive process measurements are crucial. Such in-line monitoring can lead to increased flexibility in process operations (cfr. Industry 5.0)[14.]

Another way to reduce complexity is to dismantle EoL products, automatically or otherwise. Consider the recycling of solar panels and electric vehicle (EV) batteries. Currently, the battery recycling value chain is still evolving, particularly this one for rechargeable batteries such as lithium-ion batteries (LIBs). It includes collection, discharge, dismantling (including automatic dismantling), sorting into different chemical classes, further pre-treatment (e.g. pyrolysis, shredding, recovery of electrolyte, etc.), separation of components and materials and finally recycling of the CRM-containing battery materials by metallurgical recovery of the SRMs or regeneration of the battery materials. Research is definitely still needed at many of these steps to finally arrive at a recycling process that can maximally recover and recycle all SRMs.

Improving metallurgical processes will have to focus on sustainability (see next section) on the one hand, and on the other hand on producing (extracting and recovering) strategic and critical materials from low-grade and complex primary and secondary raw materials, including waste streams. By addressing new types of raw materials, there is also a need to develop completely new metallurgical processes, e.g. the extraction and recovery of metals from oxidic ores instead of the typical sulfide ores (e.g. copper), the addressing of very low-grade mining-waste streams such as tailings, or the recycling of Li-ion batteries or new-generation batteries (cf. MateriNex Battery roadmap). Metallurgical processes that will be developed for such streams can, for example, make use of intensifying extraction by chemical activation (through the selective delivery of energy: microwaves, sonication, mechanochemical activation, etc.), increasing selectivity by employing, for example, solvometallurgy or electrochemistry, reducing costs by employing slower and passive reaction processes (e.g. heap leaching, bioleaching).

Entirely different ways that can also contribute to securing the supply of SRMs are just the replacement (substitution) of these materials with materials that are not or less critical (research into alternatives) or avoiding/reducing the use of SRMs in existing applications (including through 3D printing, lean manufacturing). Although both routes are very important and can contribute significantly in terms of reducing the demand for SRM, they are not further elaborated in this roadmap.

[14] https://research-and-innovation.ec.europa.eu/research-area/industrial-research-and-innovation/industry-50_en#what-is-industry-50

Main research topics

1. Improved recycling of EoL products containing SRMs such as electronic waste (WEEE), solar panels, batteries (both portable batteries and car batteries), magnets and electrolysers, among others.
2. Recovery of SRM from residual streams and production waste (metal slag, sludges, bottom ashes, mining waste, waste waters) according to the near-zero waste principle.
3. Research to help enable Flemish industry (incl. SMEs) to play an active role in (future) European "responsible mining" activities for low-grade ores.
4. The development of processes and technologies for more resilient, flexible and sustainable local SRM production through improved sorting, (automatic) dismantling, physicochemical pretreatment and improved (more efficient and selective) metallurgical extraction and recovery systems. The processes and technologies developed should be cost-effective, safe and environmentally friendly.

4.3 More sustainable and circular value chains of critical raw materials

Goal
To reduce the overall environmental and climate footprint of CRM recycling and manufacturing processes.

Circularity

Circularity is an important topic that applies to an entire ecosystem and/or product, with repercussions on the use of and thus demand for CRMs. Hence, this theme is widely supported and is also addressed within the programs of the spearhead clusters and on specific applications (such as wind turbines at the Blue Cluster, second life applications of batteries at Flux 50, (regeneration of) catalysts at Catalisti). Other MateriNex roadmaps (cfr. Materials for battery technology) also address the circularity theme.

However, in this roadmap, it is important to emphasize the **preservation of the functionality** of SRMs/CRMs **through advanced recycling processes**. Today, many CRMs are still lost due to inefficient recycling processes, where the CRMs are either not recovered because of non-economically viable recycling processes, or by diluting the CRMs in recycled products thus losing their functionality. Two pronounced examples are battery materials with low intrinsic value (e.g., graphite, lithium iron phosphate, certain Na-ion battery cathode materials, lithium sulfur, etc.) and alloys (e.g., copper alloys, aluminum alloys).

In the **first example, direct recycling** is gaining interest, where the recovered materials are not downcycled into new precursor materials through usual metallurgical processes. This approach has the advantage that valuable materials retain their functionality (and value) and do not require extensive processes to first arrive at pure precursor materials and then reapply these materials to produce new (battery) materials. This approach short-circuits recycling chains, but many research challenges remain to achieve direct recycling of materials.

A **second example** concerns the challenge that currently exists in **recycling scrap metal**. In existing recycling processes, scrap typically undergoes a down-grade (non-optimal recycling) because the different metal alloys found in the various EoL products cannot be distinguished in the heterogeneous input streams (scrap). As a result, alloying elements are diluted, lose their functionality and are lost forever in the metal matrix. Direct, in-line sensor-based **characterization technologies** could be applied to recognize different alloys of the same metal category in a mixed scrap stream to separate high-value alloy classes and prepare scrap blends with the ideal composition required by a particular industry for a specific application. These specific blends can then be recycled or used directly as high-grade alloy materials to produce certain alloys resulting from the proper mixture of different scrap materials. This specific recycling can significantly increase raw material efficiency in metal recycling and minimize operating costs.

Sustainability

EU climate ambitions require an almost instantaneous change in the raw materials industry, with a strong focus on **decarbonization of the entire sector**. Five years ago, the topic of decarbonization was discussed only to a limited extent in the R&D activities of the raw materials industry. However, this has changed with legislation currently giving the biggest push for companies to make changes, in the very short term, to their production process and their products themselves. As a result, research on decarbonization has become one of the most important aspects in terms of innovation in the energy-intensive resource industry.

For decarbonization, **electrification of the process industry** is clearly on the agenda. A recent McKinsey study showed that up to 50% of the fossil fuel used by the process industry (mainly for heating) can already be replaced by electricity using existing technology[15]. European objectives even aim to replace chemicals with electricity. This can be achieved, for example, by using microwaves to efficiently and selectively heat solid and liquid reaction systems to improve, for example, the leachability of elements. Also, electrochemical processes can be used to generate protons to replace mineral acids in aqueous solutions, or electrons to change the oxidation state of elements in solutions. Such chemical processes are employed in metallurgical processes, typically using reagents that can thus be replaced by electricity. The use of alternative reduction reagents, such as hydrogen, for example, to replace coke can also contribute to decarbonization.

Besides decarbonization, sustainability can also be achieved through **reuse/recycling of reagents and solvents, process intensification**, avoidance of energy and material losses through **process optimization**, and **avoidance of waste production through conversion into by-products** (cfr. symbiosis).

Main research themes.

1. Preserving the functionality of CRMs in a material through direct recycling and enhanced recycling (specificity recycling) of end-of-life materials.
2. Development of decarbonized processes and technologies for recovering CRMs (e.g., electrification, alternative green energy sources) and process intensification.
3. Sustainability (greening) of processes and technologies for recovering CRMs (e.g., use of green solvents, reduction of production waste).

[15] https://www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/plugging-in-what-electrification-can-do-for-industry

5. What cross cutting challenges should be considered (enablers)?

This roadmap identified three types of **enablers** to respond to cross-cutting challenges. Examples of these concrete transversal challenges are:

- How to identify sub-processes in a process or the value chain in order to intervene at the right place, with the greatest impact
- How to make trade-offs between different solutions taking into account the impact on climate, environment, economy, etc.
- How to monitor the impact of different actors, in order to later direct them at the level of processes, products and sectors

5.1 Goal

A more competitive, more efficient and more resilient materials ecosystem better able to address challenges such as sustainability and productivity, through the implementation of:

(1) new tools and models,
(2) digital technologies and
(3) a regulatory framework in line with European and Flemish goals

5.2 Tools and models

Securing the supply of strategic raw materials is inherently linked to the integrated value chain of these strategic metals and materials, where actions or improvements can be implemented in each part of this value chain (Figure 5). Understanding, mapping, and monitoring such value chains are important enablers to improve their resilience. Also, with the energy transition in full swing and the rollout of necessary legislation encouraging companies to reduce their carbon emissions and implement circular economy, it is essential to quantify this effort. Such insights help the industry measure the impact of implemented measures, prioritize them, as well as demonstrate and certify the impact achieved. It is also important to know how our society deals with and adopts circularity.

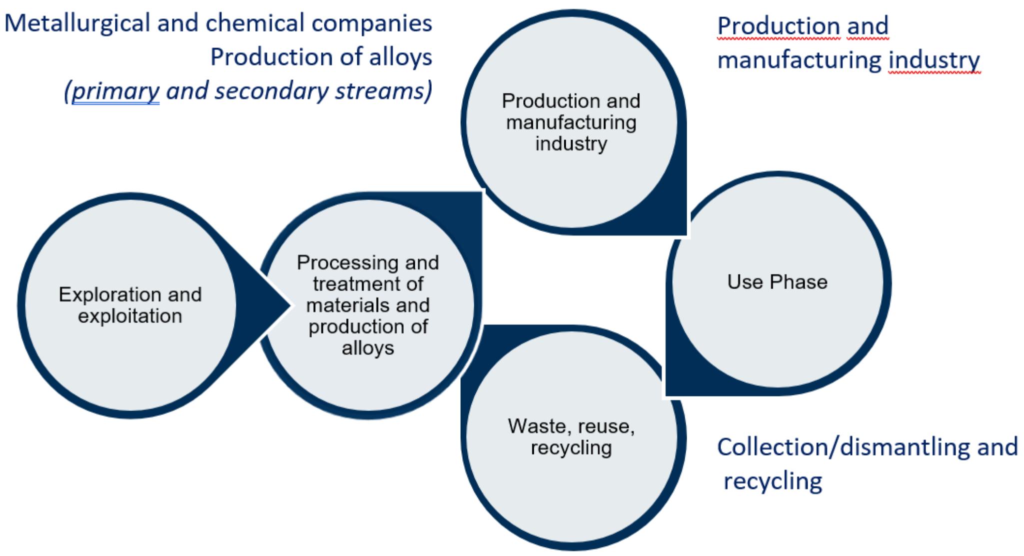


Figure 5 The different parts of an integrated value chain (after ref.1)

Methods and models that map **material flows in the value chain** include, among others, material flow analysis, flowsheet modeling, stock-flow models, urban-industrial symbiosis. Current methodologies and tools that focus on **sustainability, circularity and measuring the impact** of (critical) raw materials value chains include lifecycle assessment (LCA), lifecycle cost assessment (LCC), multi-criteria analyses but also social impact LCA, calculating circular economy indicator or using UNFC methodology for evaluating projects. At the product level, **ecodesign** and methods to predict the **lifetime** of materials and products, as well as **business and revenue models** are important. These methods and models will need continuous improvement to effectively integrate the innovative solutions, which are being developed.

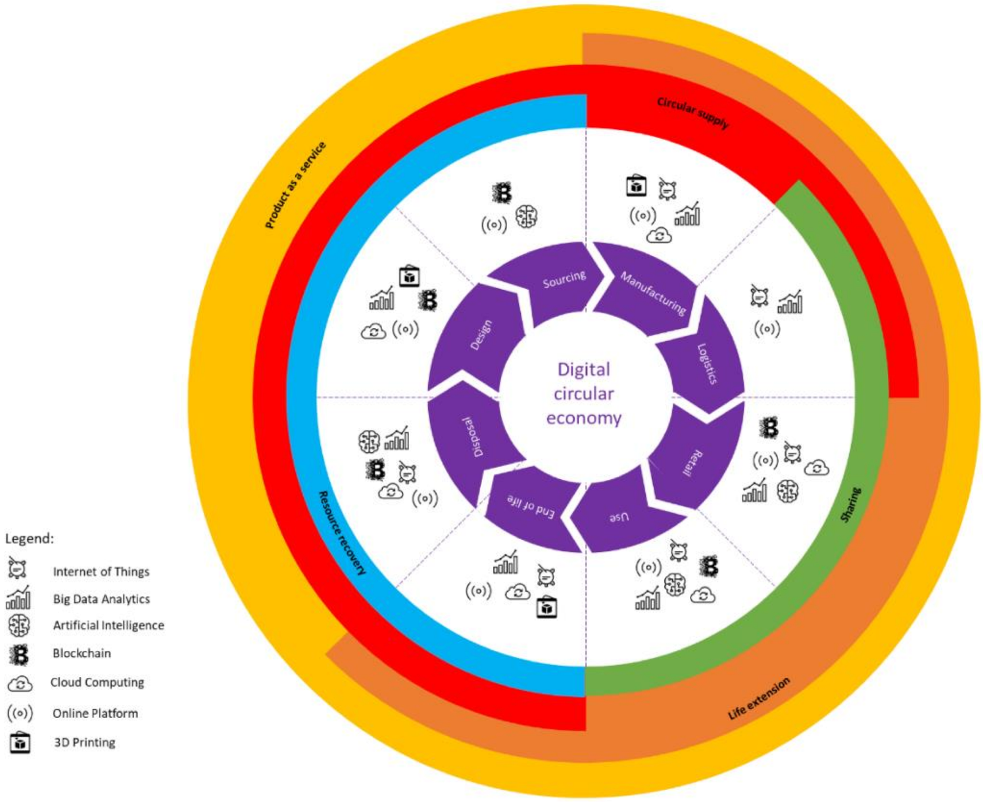
5.3 Digitalization

"The digitization of the (critical) raw materials sector across the entire value chain is vital to achieve the ambitious [EU Green Deal] goals and offers smart solutions that benefit us all".[16]

Central to digital transformation is the collection and analysis of vast amounts of data at different scales and timeframes across the entire (critical) commodities value chain and related sectors. The **availability and flow of data** within and across value chains is essential for the realization of a circular economy[17]. Figure 6 shows digital technologies that facilitate the scale-up of individual circular business models by connecting them to the individual parts of the value chain. Moreover, **digitized technologies** such as 3D printing, in-line characterization, robotization and smart materials offer innovative solutions to engineering problems and new pathways to a circular product lifecycle from the early design phase.

[16] EIT RawMaterials white paper "Digitalisation in the Raw Materials Sector", 2020. https://eitrawmaterials.eu/wp-content/uploads/2020/03/2020-03-12_EIT-RawMaterials_Digitalisation-RM-Sector.pdf

[17] E. Barteková, P. Börkey, Digitalisation for the transition to a resource efficient and circular economy. OECD Environment Working Papers No. 192, 2022. https://www.oecd.org/publications/digitalisation-for-the-transition-to-a-resource-efficient-and-circular-economy-6f6d18e7-en.htm



Note: Most of the time it is the combinatorial power of individual technologies that facilitates the scale-up of circular business models. It is not possible to single out / quantify the magnitude of their individual contribution.

Figure 6 Digital technologies enabling scaling up circular business models (ref 16)

The specific challenges in digitalization and automation in Flanders, that this roadmap aims to highlight, are the development and application of digital product/material passports, introduction of Internet of Things (IoT), development of AI applications, further implementation of Industry 5.0 and creation of digital twins in recycling and CRM production.

5.4 Regulations

The purpose of regulation is to support the decisions made. As described above, in the twin transition it was decided to aim for a climate-neutral Europe by 2050 and to go fully digital. As part of this transition, there is a need to convert from a carbon-based industry to a carbon-free industry (NZI act). This change is linked to the deployment of renewable energy, which requires certain raw materials. In addition, the EU also wants to deploy its own microchip production, among other things, which also leads to increased demand for CRMs. To ensure supply of these raw materials, the CRM act was developed, with the targets described above.

To support the targets from the CRM act and from other European policies, other regulations were worked out. These include the:

- Chips act (2023):
  The European Chips act will strengthen the EU semiconductor ecosystem, ensure the resilience of supply chains and reduce external dependencies. It is an important step for EU

technological sovereignty, and it will ensure that Europe meets its digital decade goal of doubling its global semiconductor market share to 20%.[18]

- Battery regulation (2023):
  The regulation will regulate the entire life cycle of batteries - from production to reuse and recycling - and ensure that they are safe, sustainable and competitive. Batteries are essential to the decarbonization process and the EU transition to zero-emission transport. Also, end-of-life batteries contain many critical substances that we can reuse instead of sourcing them from third countries. The new rules will promote the competitiveness of European industry and ensure that new batteries are sustainable and contribute to the green transition.[19]

- Waste shipment regulation (2023):
  Using waste as a valuable resource rather than dumping it is fundamental to moving to a circular economy. This agreement provides us with the necessary framework to better recover waste and reuse it as a secondary material. It also helps us ensure that the waste we export is not harmful to the environment and human health. The agreement puts us well on the way to the zero pollution and climate neutrality the EU aspires to.[20]

- Circulair economy action plan (2015):
  Aims to make products sustainable, support sellers and public buyers in this, focus on the sectors with the highest potential: electronic and electrical appliances, batteries, vehicles etc.; prevent waste, create jobs and create global impact.

The different objectives (towards mining, extraction, recycling) written down in the CRM act help drive the need for research and developments as they are written down above in the MateriNex roadmap.

5.5 Main research topics

1. Evaluation tools and models for sustainability/circularity/environmental impact assessment including business models.
2. Monitoring tools for tracking material use efficiency across the value chain.
3. Digital solutions for material tracking (material passports).

6. Complementarity in the Flemish innovation landscape for S&CRM

Several Flemish companies are active in research and development regarding strategic and critical raw materials. Some of them have already endorsed this roadmap. In the Flemish academic community, almost all universities and the SOCs (Strategic Research Centers) including VITO are active in this field.

Notwithstanding MateriNex focus on high-risk long-term research, the bridge will also be made to higher TRL (Technology Readiness Level) and production.

[18] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/europe-fit-digital-age/european-chips-act_en#investments-to-support-the-chips-act

[19] https://www.consilium.europa.eu/nl/press/press-releases/2023/07/10/council-adopts-new-regulation-on-batteries-and-waste-batteries/

[20] https://www.consilium.europa.eu/nl/press/press-releases/2023/11/17/waste-shipments-council-and-parliament-reach-agreement-on-more-efficient-and-updated-rules/

Alignment regarding complementarity (of research) with other funding organizations such as the spearhead clusters and the SOCs (as far as their ICON program is concerned) will have an important place in the operation of MateriNex. For strategic and critical materials, we are thinking primarily of Flux 50, Catalisti and the Blue Cluster as far as the spearhead clusters are concerned.

7. Dissemination

Dissemination will be a mandatory part of any project that is approved. The rules of VLAIO will be followed.

Initially, the Common Interest Group "Materials for Strategic and Critical Raw Materials" will focus on sharing (public) research results. In terms of "next step" dissemination or dissemination across the value chain, there will be collaboration with spearhead clusters and SOCs that have complementary roadmaps.

In addition, for broad dissemination regarding the thematic priority, the VLAIO network will be used and MateriNex will provide support. In particular, there will be collaboration with the relevant collective research centers in this area.

8. Which project types and how to submit a project proposal?

With financial support from the department of EWI and commissioned by EWI and VLAIO, **VITO,** as an **independent strategic research center**, makes a team available to facilitate the management of the earmarked resources of the Fund for Innovation and Entrepreneurship to support materials research in Flanders. This is done under the name **MateriNex**.

Every year, MateriNex launches a **call** mentioning the date and modalities of the mandatory **pre-application** (for SBO and ICON) as well as the modalities and timeline to submit a full project proposal. Only project proposals that receive a GO from an **independent expert group (composed by the MateriNex team in consultation with VLAIO)** may develop and submit a full project proposal to VLAIO. This GO has a validity of max 1 year. For ICON projects, a request for partners facilitated by MateriNex can be used. Feasibility studies can be submitted at any time and have a shorter processing time. **VLAIO is responsible for the evaluation of full proposals for cSBO, ICON and feasibility studies**.

The **modalities for cSBO and ICON** projects as well as feasibility studies are defined in the respective manuals on the VLAIO website. We mention in particular:

> A **cSBO** project proposal is submitted by **at least two research groups of at least one Flemish research center** (according to art. II.2 and II.3 of the Codex Higher Education). A Flemish research center is hereby defined as an organization established in the Flemish Region for research and knowledge dissemination (university, university college ("Hogeschool"), (strategic) research center. **Imec, VITO, VIB, Flanders Make, VLIZ and the Flemish scientific institutions with an endowment from the Flemish government**, can only submit a cSBO project proposal in collaboration with at least one other Flemish research center. A **Flemish university college** ("Hogeschool") always submits a cSBO project proposal in collaboration with or at least after advice from the university within the association with which it is affiliated. Flemish university colleges can only submit a project proposal in cooperation with at least one other Flemish research center.

ICON (Interdisciplinary Cooperative Research) is a project type in which an ad hoc and balanced **consortium of one or more research centers and at least three unrelated companies** develop new knowledge, which can be practically applied and thus contribute to economic and possibly broader social added value in Flanders. An ICON project consists of a business part and a research part. The Flemish industrial partners can appeal for support from the Fund for Innovation and Entrepreneurship.

Feasibility studies are studies at the beginning of an innovation trajectory, where the overall feasibility and relevance of further investments in research, development and innovation must be checked. **Applicants are companies** that have a legal personality (at the latest at the time of signing the agreement). Furthermore, the applicant company must be able to sufficiently (but not exclusively) exploit the results in Flanders. The implementation of the project may also involve cooperation with other companies and with research institutions as subcontractors.