

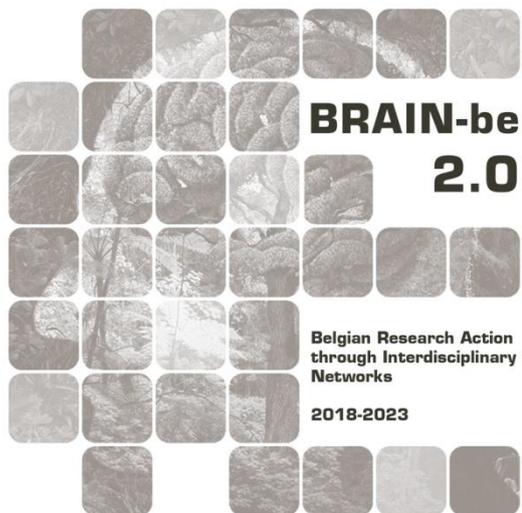
CAMBIUM

Circular Material flows in Belgium

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Pillar 3: Federal societal challenges



NETWORK PROJECT

CAMBIUM

Circular Material flows in Belgium

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FINAL REPORT

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2 **ABSTRACT**

The '*Circular Material Flows in Belgium*' (CAMBIUM) project develops a holistic framework and assessment of material flows and footprints in Belgium, providing a comprehensive overview of the country's progress toward circularity, self-sufficiency, and resilience. Through an extensive review of indicator systems, policy contexts, and statistical sources, the project identifies key data gaps and proposes methodological pathways to strengthen short- and long-term monitoring of material use.

Complementing this system-level analysis, the project delivers an in-depth identification of the critical materials flows for the Belgian economy, using a nationalised adaptation of the EU criticality methodology and informed by Belgium's industrial structure. This effort includes the development of a methodology to systematically identify the product and waste streams that act as major carriers of critical raw materials, and to assess potential supply-chain vulnerabilities by tracing global extraction, processing, and trade pathways. The resulting methodological framework provides Belgian authorities with a consistent and evidence-based approach to evaluate material dependencies, strengthen circularity strategies, and anticipate strategic risks in the context of the European Critical Raw Materials Act.

3 EXECUTIVE SUMMARY - ENGLISH

Belgium, like many European countries, faces increasing challenges related to the sustainable management of materials and the resilience of its supply chains. As the transition to a climate-neutral and digital economy accelerates, the demand for strategic materials embedded in technologies such as batteries, photovoltaic systems, wind turbines, electronics, and electric mobility continues to grow. At the same time, global supply chains are becoming more volatile due to geopolitical tensions, market concentrations, environmental constraints and rapidly shifting technological demand. This combination of rising material needs and diminishing supply security has led European and Belgian policymakers to call for more robust monitoring, improved data infrastructures and a deeper understanding of material flows, resource footprints and critical raw material dependencies. The CAMBIUM project was developed in response to these challenges. Its overarching ambition was to design and test a set of methodological tools that enable Belgium to better monitor and understand its material system, with a particular emphasis on the circularity and criticality dimensions. The CAMBIUM project concentrates on developing methodologies that can support long-term monitoring, guide future research and contribute to evidence-based policymaking.

The project pursued two complementary goals. The first was to develop a holistic methodological framework for analysing material flows and material footprints in Belgium. This required mapping and evaluating existing international indicator frameworks, identifying gaps in Belgian data structures, and designing methodological pathways tailored to Belgium's federal and regional governance systems. The second goal was to develop a criticality methodology for identifying materials and product streams that are important to the Belgian economy. This involved adapting European criticality approaches to the Belgian context, improving the capacity to identify materials embedded in imported products and waste streams, and mapping supply-chain vulnerabilities for both materials and technologies of strategic importance.

Methodologically, the project adopted an integrated approach combining economy-wide material flow analysis, life cycle thinking, environmentally extended input-output modelling, multi-criteria criticality assessment and multilayer material system analysis. Extensive reviews were conducted to identify strengths and weaknesses of existing frameworks and to understand how these could be translated into an approach suitable for the Belgian context. In parallel, detailed analyses were carried out for selected materials and technologies to test and refine the proposed methodologies. The multilayer material system analysis of the Belgian wind turbine fleet, for example, provided a detailed case study that illustrated how material stocks, flows and end-of-life potentials evolve as technologies change over time.

The project produced a range of scientific, methodological and policy-relevant results. It developed a structured analytical framework that allows Belgium to assess material flows and material footprints using consistent and transparent procedures. This framework integrates macro-level indicators aligned with Eurostat's circular economy monitoring systems and micro-level pointers designed to detect short-term changes in critical product flows and supply-chain exposures. The analysis revealed

several hotspots in Belgian material use, including high dependency on imports of specific materials that play a central role in renewable energy technologies, electrification and digitalisation, making them increasingly crucial for both industrial competitiveness and the energy transition. The study also identified gaps and inconsistencies in existing data sources, particularly in combining product flow data and waste statistics and composition data for critical raw material rich products, which need to be addressed to strengthen national monitoring capacities.

The methodology for identifying critical raw materials provided Belgium with its first systematic, nationalised approach to assessing material supply risks. By combining Belgian-specific sectoral data, trade data and technological relevance, the project demonstrated that Belgium's risk exposure sometimes deviates from EU averages. For many critical materials, Belgium's dependence on concentrated and geopolitically sensitive supply chains is substantial, but as is its role in producing some of the critical raw materials. The findings support more targeted policy interventions aimed at improving recycling, enhancing recovery infrastructure and diversifying supply chains.

The multilayer material system analysis demonstrated how these methodological advances can be applied to a real-world technology. By analysing Belgium's wind energy installations between 1996 and 2021, the project showed that material stocks continue to accumulate and will generate substantial end-of-life flows in the coming decades. Copper and steel dominate in terms of mass, but rare earth elements and other speciality materials become increasingly important as offshore and direct-drive technologies proliferate. The multilayer material system analysis also identified potential bottlenecks in recycling pathways and highlighted the importance of improving collection, dismantling and recovery practices to maximise the circularity benefits of renewable energy systems.

Together, these scientific results form a robust base for decision support. The developed or improved methodologies offer Belgian authorities the means to evaluate material dependencies, identify emerging risks, and anticipate future material needs. They can also strengthen Belgium's contribution to European processes under the Critical Raw Materials Act and Circular Economy Action Plan. The project recommends that Belgium periodically monitors material flows and critical material dependencies and risks; improve data integration across federal and regional authorities; and promote transparency in supply chains. Strengthening analytical capacity within public administrations and fostering collaboration across regions, agencies and research institutions will be essential to sustain and expand the methodological advances made by the project.

The CAMBIUM project thus delivers not only scientific insights but also a methodological architecture with long-term value. By enabling a deeper and more systematic understanding of Belgium's material system, it provides the foundation for more resilient, circular and strategically informed resource governance.

3.1 KEYWORDS

material flows

critical raw materials

circular economy

supply-chain resilience

4 INTRODUCTION

4.1 PROJECT CONTEXT

Across Europe, the transition to a climate-neutral and resource-efficient economy has placed material use and circularity at the centre of policy attention. The European Green Deal, the Circular Economy Action Plan (CEAP 2020), and the recently adopted Critical Raw Materials Act (CRMA, 2024) all recognise that sustainable resource management is essential to reducing environmental pressures, strengthening strategic autonomy, and safeguarding industrial competitiveness. These frameworks call for improved monitoring of material flows, increased recycling and reuse, and a better understanding of supply risks linked to (critical) raw materials.

Belgium faces similar challenges. As an open, trade-intensive economy with a strong chemical, refining and high-value manufacturing sector, Belgium depends heavily on imported raw materials and semi-finished products. National and regional circular economy strategies—such as the Belgian Federal Circular Economy roadmap, Vlaanderen Circulair, the Walloon Circular Economy Strategy, and the Brussels Regional Circular Economy Programme—emphasise the need for better data, more consistent monitoring tools, and stronger analytical capacity to support policy development. However, data fragmentation across federal and regional levels, together with limited methodological guidance on how to measure circularity and material dependencies, makes it more difficult to evaluate Belgium’s overall material performance.

4.2 OBJECTIVES

The CAMBIUM project responds directly to these needs by focusing on the development of methodologies that enable Belgium to better understand and assess its material system. More specifically, the project pursues two complementary ambitions:

- To develop a holistic framework and assessment of material flows and footprints in Belgium, including methodological pathways for circularity monitoring, indicators for self-sufficiency and resilience, and improved alignment of national and regional data sources.
- To support the identification of the critical materials and tracking of resource flows for the Belgian economy, through a nationally adapted methodology that builds on European approaches to criticality assessment and is tailored to Belgium’s industrial structure and policy context.

4.3 METHODOLOGICAL FOCUS

A core contribution of CAMBIUM is the creation of new methodological tools that enable consistent, scalable, and policy-relevant assessments. These include:

- A structured framework for analysing Belgian material flows and footprints, aligned with EU indicators but adapted to national data availability.
- A systematic approach for identifying gaps and inconsistencies in Belgian material statistics, strengthening the foundation for future monitoring.
- A nationalised approach to assessing criticality—based on, but not limited to, the EC criticality methodology—reflecting Belgian economic specificities.
- The development of analytical methods to identify key product and waste streams that act as carriers of critical raw materials.

By developing these methodologies rather than merely replicating existing assessments, CAMBIUM enhances Belgium's capacity to evaluate material sustainability, anticipate supply-chain vulnerabilities and dependencies, and support evidence-based policymaking in line with EU ambitions.

5 STATE OF THE ART AND OBJECTIVES

5.1 CONTEXT AND RATIONALE

The transition to a climate-neutral, resource-efficient, and circular European economy has placed material use at the centre of political and scientific attention. Policies such as the European Green Deal, the Circular Economy Action Plan (CEAP 2020), the EU Industrial Strategy, and more recently the Critical Raw Materials Act (2024) stress that sustainable and circular material management is essential for reducing environmental pressure, improving competitiveness, reducing dependencies and strengthening the resilience of European value chains. These policies collectively call for better monitoring frameworks, improved data availability, and robust methodologies capable of describing how materials circulate through economies.

Belgium, as a small but highly industrialised and trade-intensive economy, is deeply integrated into global value chains. Its chemical and refining sectors, high-value manufacturing industries, and central logistical position in Europe make the country an important processing and distribution hub. At the same time, Belgium has limited domestic extraction capacity and therefore relies heavily on imports of raw materials, intermediates, and products containing critical raw materials. Consequently, disruptions in international supply chains, shifts in geopolitical conditions, and the rapidly growing demand for materials required for the green and digital transitions and the strengthening of defence and aerospace can have an outsized impact.

These characteristics create a strong need for tools that allow Belgium to better understand the scale, direction, and composition of material flows, the degree to which the national economy depends on foreign supply chains, and the potential vulnerabilities tied to critical materials. Yet the current monitoring landscape is fragmented. Differences in competences between federal and regional authorities, limited harmonisation of data, variation in methodologies, and gaps in national statistics collectively hinder a consolidated view of Belgium's material system. The existing indicators developed at EU or global levels are often not directly applicable, or insufficiently granular for the Belgian context.

The CAMBIUM project was conceived to respond to these challenges through the development of methodologies enabling a holistic, consistent and policy-relevant monitoring of material flows and critical materials in Belgium. CAMBIUM seeks to establish methodological foundations that public administrations can use, adapt, and extend.

5.2 POSITIONING WITHIN THE INTERNATIONAL STATE OF THE ART

The international scientific field of material flow analysis, resource-use accounting, circularity measurement, and criticality assessment has matured significantly in the past decade. Key frameworks include:

- Eurostat’s economy-wide MFA and circularity indicators
- UNEP International Resource Panel analyses on global material flows
- OECD material productivity and resource efficiency metrics
- EU Raw Materials Scoreboard and CRM methodologies
- Academic approaches to stock–flow modelling, waste system analysis, and supply-chain risk assessment

While these frameworks provide valuable conceptual and analytical foundations, several limitations emerge when they are applied at the national scale, particularly in Belgium:

- **Insufficient granularity:** Many international indicators operate at a high level of aggregation and are not sensitive to sector-specific or material-specific dynamics.
- **Limited applicability to complex governance structures:** Belgium’s layered governance system produces datasets that differ in scope, frequency, and definitions across federal and regional levels.
- **Lack of methodologies for combining circularity and criticality perspectives:** Circularity indicators often focus on material recovery and waste, while criticality assessments focus on supply risks. Few approaches integrate both dimensions in a coherent national framework.
- **Inadequacy of supranational criticality results for national decision-making:** EU-level CRM assessments reflect averages that do not capture national industrial specificities. For Belgium, certain materials are more (or less) strategically relevant compared to the EU average.

At the same time, academic literature has explored the development of more advanced methodologies, such as dynamic stock-flow models, or hybrid MFA-LCA approaches. Studies have also addressed global supply-chain risks, the geopolitical dimension of material provision, and structural vulnerabilities related to the energy transition. Nevertheless, a methodological gap remains between high-level international frameworks and the concrete analytical tools needed by Belgian administrations.

CAMBIUM positions itself within this gap by developing nationally adapted, policy-aligned, and scientifically robust methodologies.

5.3 SOCIETAL AND POLICY RELEVANCE

The work undertaken in CAMBIUM addresses several societal and policy needs:

- Many of the federal and regional government responsibilities relate to material availability. Methodological tools that support monitoring and risk assessment can strengthen these responsibilities.
- Monitoring obligations: Belgium must report progress toward EU circular economy objectives, climate goals, and environmental indicators. Reliable and transparent methodologies are needed to meet these obligations.
- Societal expectations: Citizens and businesses increasingly depend on stable access to materials for renewable energy, mobility, digital infrastructure, and consumer goods. Understanding material dependencies is a prerequisite for safeguarding economic and social resilience.

CAMBIUM contributes by designing methodologies that allow Belgian authorities to monitor material flows, evaluate circularity, and anticipate risks linked to critical materials in a consistent and evidence-based manner.

5.4 SCIENTIFIC OBJECTIVES

CAMBIUM has two overarching scientific objectives, each corresponding to a major methodological development effort:

Objective 1 — Development of a holistic framework and assessment on material flows and footprints in Belgium

This objective aims to build a methodological foundation for understanding Belgium's material system. It includes:

- Developing a structured and harmonised framework for mapping material flows and material footprints
- Reviewing and assessing the applicability of international indicator frameworks to the Belgian context
- Identifying gaps, inconsistencies, and opportunities within federal and regional datasets
- Proposing methodological pathways for circularity, self-sufficiency, and resilience indicators
- Designing micro-level pointers that allow high-frequency monitoring of strategic materials
- Preparing the methodological groundwork for national material accounts, including waste supply-use tables
- Integrating environmental and social considerations relevant to Belgian policy priorities

The aim is not merely to catalogue indicators, but to establish a methodology that can evolve into a comprehensive monitoring architecture for Belgium.

Objective 2 — Identification of the critical materials and resource flows for the Belgian economy

This objective focuses on developing methodologies that enable Belgium to understand its exposure to materials essential for strategic sectors. It includes:

- Adapting and refining the EU criticality methodology for Belgian needs.
- Accounting for Belgium's specific industrial structure, trade composition, and sectoral dependencies.
- Developing procedures to identify products and waste streams that act as carriers of critical raw materials.
- Creating analytical tools to trace global supply-chain pathways and link them to Belgian consumption and production.
- Establishing methodological approaches to evaluate vulnerabilities and resilience.
- Supporting future national risk assessments and strategic planning under the Critical Raw Material Act.

Again, CAMBIUM focuses on methodology development, not only on producing a one-off list of critical materials.

5.5 STRATEGIC APPROACH AND METHODOLOGICAL CHOICES

To achieve these objectives, CAMBIUM adopted several strategic methodological choices:

- Integration of international frameworks with Belgian data structures, ensuring coherence with European methodologies while addressing domestic data gaps.
- Use of structured evaluation matrices and standardised assessment sheets to compare indicator frameworks and assess applicability.
- Focus on interoperability, enabling federal and regional datasets to connect within a consistent analytical approach.
- Alignment with policy needs, ensuring that methodological outputs directly support monitoring, and reporting.

Through this strategic and methodological design, CAMBIUM provides Belgian authorities with tools that can underpin long-term monitoring of material flows, circularity, and critical materials

6 METHODOLOGY

6.1 OVERVIEW OF THE METHODOLOGICAL APPROACH

The CAMBIUM project was designed primarily as a methodology-development project. Its purpose was to establish a durable and adaptable methodological foundation enabling Belgium to monitor (1) its material flows and material footprints and (2) its critical material dependencies. To achieve this, the project brought together analytical practices from material flow analysis, criticality assessment, circularity monitoring frameworks, trade analysis, and supply-chain mapping. The core challenge was to translate and integrate these diverse methodological approaches into a form compatible with the heterogeneous and sometimes fragmented data landscape.

The methodological approach was therefore iterative, combining desk research, data harmonisation, methodological comparison, indicator mapping, expert consultation, and conceptual framework development. Each methodological choice was assessed for feasibility, policy relevance, reproducibility, and compatibility with existing statistical systems.

6.2 METHODOLOGICAL ACTIVITIES FOR THE HOLISTIC FRAMEWORK ON MATERIAL FLOWS AND FOOTPRINTS

6.2.1 Mapping and evaluation of existing indicator frameworks

A first major methodological activity involved an extensive literature review of material flow, footprint, and circularity methodologies from international organisations (Eurostat, OECD, UNEP), academic research, and national initiatives. Each methodology was evaluated using a standardised assessment sheet, capturing:

- scope and system boundaries
- temporal and spatial resolution
- data requirements
- applicability to Belgium
- added value and limitations
- level of alignment with EU policy frameworks
- degree of methodological transparency and reproducibility

6.2.2 Identification of data gaps and inconsistencies

Using the methodological mapping, CAMBIUM systematically compared the requirements of leading indicator systems with Belgian data availability. Special attention was given to:

- inconsistencies between datasets (e.g., nomenclature, values)
- gaps in waste statistics (e.g., reuse, secondary material output)
- incomplete trade datasets for subcomponents containing critical materials
- missing or outdated material composition datasets
- limitations in national material footprint data

This analysis helped define the methodological pathways needed to fill these gaps.

A recurring debate concerned the extent to which existing EU indicators should be adopted versus the need to develop new Belgium-specific indicators. The project ultimately chose a hybrid approach: retain EU-aligned macro-indicators for comparability but complement them with Belgian micro-level pointers.

6.2.3 Development of methodological pathways and micro-level pointers

One of the key methodological contributions of CAMBIUM is the definition of micro-level pointers, i.e., short-term indicators that capture early trends in material use, critical material inflows, and circularity developments. Examples include:

- trends in imports of critical raw material rich subcomponents
- evolution of secondary material output from Belgian recyclers
- shifts in trade partners for critical raw material intensive goods
- market penetration of products containing high-value materials

These pointers complement the slower-reacting macro-indicators provided by Eurostat.

This dual-indicator framework, combining micro- and macro-level indicators, addresses a well-known gap in circularity research by enabling both strategic and operational monitoring.

6.3 3.3. METHODOLOGICAL ACTIVITIES FOR THE IDENTIFICATION OF CRITICAL MATERIALS AND RESOURCE FLOWS

6.3.1 Adaptation of the EU Criticality Methodology for Belgium

The project applied the structure of the EU criticality methodology (supply risk × economic importance) but adapted it to reflect Belgium's industrial structure, trade patterns, and consumption profiles. Key modifications included:

- recalculation of exposure parameters using Belgian data
- incorporation of Belgian import dependency into supply-risk indicators
- adaptation of economic importance indicators to Belgian industrial capabilities

A central methodological debate concerned whether Belgium should apply the same threshold values as the EU when determining criticality considering the structural differences between Belgium and the total EU economy.

6.3.2 Development of a methodology to identify product and waste streams as CRM carriers

A second major methodological component involved designing an approach to identify the key product categories that contain substantial shares of Belgium's critical material stocks. This required:

- collection of composition data for batteries, PV panels, wind turbines, permanent magnets, and other CRM-rich products
- statistical linkage of product codes (CN/PRODCOM) with material content
- construction of a methodology to translate trade volumes into material flows
- integration of lifetime models to estimate in-use stocks and future waste streams

The combination of composition data, product-level trade statistics, and lifetime modelling to identify CRM flows is rarely available at national level and represents a methodological innovation tailored to Belgian data capabilities.

6.3.3 Supply-chain mapping methodology

To assess vulnerabilities, the project developed a structured procedure to map supply chains of selected CRM-rich products:

- Identify global extraction and processing nodes
- Evaluate supply concentration using HHI indicators
- Map dominant trade routes relevant to Belgium
- Identify Belgian industrial users and downstream sectors
- Assess geopolitical, environmental, and logistical risks

All steps used publicly available international datasets (USGS, OECD, COMTRADE) combined with Belgian sector-level information.

A key methodological question was the level of granularity feasible within the limits of available data. Discussions centred on the trade-off between detail (e.g., component-level mapping) and feasibility (data scarcity, confidentiality). The final method balances these constraints while remaining expandable in future work.

6.4 INFORMATION SOURCES AND DATA INFRASTRUCTURE

The methodologies developed rely on a broad set of data sources, including:

- Eurostat MFA, waste statistics, and trade data
- Statbel (federal) datasets on production, trade, and waste
- Regional datasets from OVAM, SPW, and Brussels Environment
- Industry data from manufacturers and recyclers
- International datasets from OECD, UNEP IRP, USGS, and the European Commission
- Scientific literature on MFA, circularity, CRM criticality, and supply chains

Some datasets—particularly product composition data—were incomplete or inconsistent. The methodology therefore includes provisions for updating inputs as new data become available.

6.5 METHODOLOGICAL ORIGINALITY AND ADDED VALUE

Across all components, CAMBIUM contributes original methodological advances:

- A harmonised framework for Belgium that integrates circularity, self-sufficiency, and resilience
- A dual-layer monitoring approach combining macro-indicators and micro-level pointers
- A nationally adapted criticality methodology aligned with Belgian industrial structures
- A novel methodology linking trade statistics with material composition to identify CRM carriers
- An extendable supply-chain mapping tool tailored to Belgian policy needs

Together, these contributions constitute the project's core scientific output: a methodological architecture enabling Belgium to monitor and understand its material system in a coherent and policy-relevant manner.

7 SCIENTIFIC RESULTS AND RECOMMENDATIONS

7.1 OVERVIEW OF THE SCIENTIFIC RESULTS

The CAMBIUM project produced a set of scientific and methodological results that advance Belgium's ability to monitor material flows, assess material footprints, and identify critical material dependencies. These results take the form of methodologies, analytical frameworks, datasets, indicator proposals, supply-chain analyses, and policy-relevant recommendations. Each result contributes to a coherent analytical architecture designed to support federal and regional policy needs.

The results can be grouped into two interconnected clusters:

- A holistic framework and assessment for analysing material flows and material footprints in Belgium, including indicator mapping, methodologies for circularity and resilience, guidance for waste accounts, and micro-level monitoring tools.
- A methodology for identifying critical materials and associated resource flows, including adapted criticality assessment tools, CRM-carrier product mapping, supply-chain vulnerability assessment methods, and structured analyses of Belgium-specific material dependencies.

Together, these outputs form a methodological basis that Belgian authorities can use to build long-term monitoring systems, strengthen strategic resilience, and inform policy development across federal and regional competences.

The project delivered a coherent and methodologically robust body of scientific results that advance the understanding of material flows, resource dependencies, and critical materials challenges for Belgium. The outputs cover both the development of an integrated methodological framework and its application to the Belgian context. Across the work, particular emphasis was placed on establishing transparent procedures, replicable data pipelines, and analytical instruments that can be used beyond this project by Belgian authorities, research institutes, and other stakeholders.

The combined methodological architecture—consisting of the holistic framework for material-flow assessment and footprinting, and the multilayer system analysis for critical materials—allowed the project to quantify material stocks, flows, and vulnerabilities across the Belgian economy in a systematic and comparable manner. Importantly, the methodologies were designed not as static assessments but as tools that can support recurrent monitoring, help evaluate the effects of policy interventions, and inform future scenario development.

7.1.1 Material-flow and footprint analysis for Belgium

The first component of the work centred on constructing a harmonised approach for quantifying Belgian material flows, including product streams, waste pathways, and trade-related linkages. Building on the principles of economy-wide material flow analysis, life-cycle assessment, and

consumption-based accounting, the project produced a comprehensive representation of how materials circulate through the Belgian economy and how these flows contribute to domestic and external environmental pressures.

Through integration of Eurostat data, waste statistics, environmentally extended input-output tables, and sector-specific datasets, the analysis provided a detailed picture of supply-chain dependencies and environmental burdens associated with Belgian consumption. The methodological novelty lies in the combined use of territorial and footprint indicators, allowing the assessment to reflect both domestic pressures and pressures embodied in imports. This dual accounting is particularly relevant in a small, open economy such as Belgium, where many resource-intensive processes occur abroad while consumption occurs domestically.

The results reveal clear hotspots of resource use in construction materials, metals, and fossil-derived products. They also highlight the increasing significance of technology-related materials—particularly metals used in renewable energy systems, batteries, electronics, and electrification technologies. Uncertainties mainly arise from incomplete detail in trade classifications, variability in waste-treatment data, and assumptions necessary to allocate mixed product flows to specific material categories. These uncertainties were made explicit in the methodological documentation to ensure that further refinement is possible in future updates.

7.1.2 Methodological advances in identifying critical materials and resource risks

The second methodological pillar focused on identifying critical materials and mapping systemic vulnerabilities in material supply chains relevant to Belgium. Rather than reproducing existing EU studies, the project adapted a multi-criteria risk approach to the Belgian economic structure. This method combines criteria on supply concentration, geopolitical exposure, technological importance, substitution potential, recycling performance, and strategic significance for Belgian industrial sectors.

A major outcome of this work is the identification of critical materials that matter most for Belgium's industrial and societal priorities—particularly those relevant for the energy transition, digital infrastructure, manufacturing competitiveness, and federal environmental mandates. The adopted risk indicators were tailored to the Belgian context, enabling the ranking of materials not only according to global or European importance but also according to Belgium's specific demand patterns, trade dependencies, and sectoral profiles.

Across the assessment, metals such as copper, nickel, aluminium and rare earth elements, as well as several speciality materials, emerged as high-risk categories. For many of these materials, Belgium is heavily import dependent, often from supply chains subject to geopolitical instability or high environmental and social risks. The analysis also highlighted the potential for cascading vulnerabilities: disruptions in one stage of a global supply chain can affect multiple downstream industries simultaneously. This systemic perspective offers actionable insights for federal authorities involved in resource policy, industrial strategy, and environmental regulation.

7.1.3 Multilayer Material System Analysis (MMSA) applied to wind-energy technologies

A central scientific contribution of the project lies in the application and extension of the multilayer Material System Analysis (MMSA) to a Belgian case study. Building on recent methodological developments, the project applied the MMSA to wind turbine technologies installed in Belgium between 1996 and 2021. This approach provides a technology-specific and material-specific view of stock accumulation, replacement needs, trade linkages, and end-of-life potentials.

By distinguishing between drivetrain technologies (gearbox vs. direct-drive) and between individual materials (Al, Cu, Fe, Mn, Ni, Nd), the MMSA captures the dynamics of how material demand evolves as wind technology changes. The analysis showed that direct-drive technologies, which have become increasingly prevalent in the offshore segment, require significantly higher copper and rare earth elements due to generator design. Gearbox-based systems, by contrast, show higher aluminium and steel intensities.

The MMSA reveals several important findings. First, material stocks in the Belgian wind fleet have grown rapidly and are expected to continue increasing as the offshore sector expands. Second, although end-of-life volumes remain modest today, they will rise substantially in the coming decade, especially for copper, steel, and cast iron. Third, recycling potential is high for many materials, but recovery depends on improving disassembly practices, increasing the functional recycling rates of metals, and ensuring appropriate collection and dismantling pathways for offshore components.

The MMSA also uncovered important uncertainties. These relate mainly to incomplete technical data on turbine components, varying failure rates of drivetrain parts, limited transparency in international turbine trade, and gaps in recycling efficiency values. However, the methodological structure makes these uncertainties explicit and allows future assessments to reduce them as better data becomes available.

7.1.4 Integration of results across methods

By bringing together the material-flow analysis, the criticality assessment, and the multilayer system analysis, the project demonstrates how different methodological lenses can be combined to produce a comprehensive view of material-related risks and opportunities. Technologies identified as growing material hotspots in the footprint analysis correspond closely to those identified as risk-intensive in the criticality assessment. The MMSA shows how these risks manifest physically in infrastructure deployed inside Belgium, thereby creating a direct link between national policy goals—such as expanding renewable energy—and the material dependencies that accompany them.

7.2 BROADER SCIENTIFIC, SOCIETAL, AND POLICY RELEVANCE

The scientific relevance of the results lies in their methodological rigor, transparency, and replicability. The project contributes to the scientific literature on circular economy monitoring, critical-material risk assessment, and technology-specific material modelling. It also expands the empirical knowledge base of Belgian material flows and resource dependencies, an area for which high-resolution data have historically been limited.

From a societal perspective, the findings are directly relevant to the energy transition, industrial competitiveness, waste management, and environmental protection. The data and models developed in the project support informed debate on how Belgium can balance the demand for strategic technologies with the need to reduce environmental pressures and improve circularity.

The project also delivers clear added value for federal decision-making. The methods and results can support national and regional administrations in preparing and implementing policies related to the Belgian Circular Economy Roadmap, the federal Circular Economy Programme, the national raw materials strategy under development, and federal reporting obligations under the EU Critical Raw Materials Act. The MMSA in particular offers a tool for evaluating how technology deployment targets influence future material needs and recycling potential—information essential for long-term infrastructure and industrial-policy planning.

7.2.1 Scientific contribution

CAMBIUM contributes to scientific research by:

- bridging the gap between international MFA/CRM methodologies and national policy needs
- creating a hybrid indicator framework combining material flows, footprints, circularity, and criticality
- providing new methods for analysing CRM flows in products and supply chains
- demonstrating how data from federal and regional authorities can be integrated into a unified analytical architecture

These contributions can be reused in scientific work on MFA, criticality, and resource governance.

7.2.2 Societal relevance

The project responds directly to societal needs linked to:

- energy transition (batteries, renewable technologies)
- digitalisation (electronics, semiconductors)
- stable access to essential materials and technologies
- waste reduction and improved recycling pathways
- informed public debate on resource use and environmental impacts

The methodologies support a future transition toward more resilient and sustainable material systems.

7.2.3 Policy relevance and positioning in Belgian decision-making

The results strengthen Belgium's capacity to support policy development in:

- federal product and resource policy
- national implementation of the Critical Raw Materials Act
- circular economy strategies at federal and regional levels
- waste and recycling regulation
- trade and industrial policy
- environmental health and sustainability monitoring
- climate and energy planning

The methodologies allow authorities to:

- detect supply-chain risks early
- prioritise recycling and recovery investments
- evaluate strategic dependencies
- strengthen federal–regional coordination
- report more consistently to EU institutions

7.3 CO-BENEFITS AND ADDITIONAL OUTCOMES

Beyond the scientific findings, the project generated several important additional outcomes. The interdisciplinary collaboration fostered capacity building within the partner institutions and strengthened connections between researchers, policymakers, and technical experts. Project activities also advanced methodological competencies, particularly in advanced MFA modelling, multilayer system analysis, and criticality assessment. These skills now form a basis for future Belgian research and policy-support projects.

The project stimulated the creation of data infrastructures, coding routines, and analytical templates that can be reused in future assessments. In addition, team members acquired expertise in processing heterogeneous datasets, aligning statistical sources, and designing transparent documentation—all valuable competences for federal research support.

Finally, the project has contributed to the development of a longer-term scientific and policy network. This network connects federal services, regional authorities, European institutions, and Belgian research centres, improving the knowledge base available for future decision-making on materials, circularity, and strategic dependencies.

7.3.1 Side-Results and Added Value Beyond the Primary Objectives

The project generated significant additional value, including:

- **Capacity building**
 - Training of junior researchers in MFA, criticality assessment, and supply-chain analysis
 - Development of analytical skills related to trade data, composition datasets, and modelling
- **Acquisition of new techniques and tools**
 - Techniques for linking product trade codes with CRM content
 - Methods for deriving micro-level pointers
 - Framework for nationalised criticality assessments
- **Strengthening cooperation networks**
 - Interaction with FPS Health, FPS Economy, and other federal actors
 - Collaboration with regional authorities
 - Engagement with EU-level initiatives (CRMA implementation)
 - Creation of a methodology platform reusable for future research projects
- **Dissemination and public outreach**
 - Media coverage increasing public awareness (e.g., De Tijd article and interactive module)
 - Contributions to stakeholder workshops and follow-up committee meetings

7.3.2 Contribution to Scientific Support for Federal Authorities

CAMBIUM contributes to federal decision-making by providing:

- **Tools for strategic monitoring**
 - Methods to evaluate Belgium's dependency on critical materials
 - Frameworks to monitor circularity and material footprints
 - Indicators to track early signals of supply-chain stress
- **Evidence for policy development under federal competences**
 - Product policy and eco-design
 - Trade and import diversification
 - Waste shipment regulation
 - Environmental health assessments related to material use
 - Reporting obligations under EU legislation
- **Input for Belgium's role in EU policy processes**
 - CAMBIUM strengthens Belgium's analytical capacity for participation in:
 - CRMA expert groups
 - CEAP monitoring
 - EU industrial strategy dialogues
 - International resource governance initiatives

7.4 RECOMMENDATIONS FOR DECISION SUPPORT

The methodological and empirical work culminates in several recommendations for Belgian federal authorities. These recommendations aim to strengthen evidence-based policymaking in line with the objectives of the Critical Raw Materials Act, the EU Circular Economy Action Plan, and Belgian federal circular-economy strategies.

First, Belgium should institutionalise periodic monitoring of material flows and critical-material risks using the methodological frameworks developed in this project. Embedding these methods in federal and interregional monitoring systems would ensure continuity and comparability across years. Second, federal authorities could use the MMSA and criticality assessment to anticipate future material needs associated with energy and industrial transitions. This would support proactive policy design, including measures for supply diversification, strategic stock management, and sustainable sourcing.

Third, investment in high-quality recycling and dismantling infrastructure is essential, particularly for technology-specific materials such as those embedded in wind turbines, batteries, and electronics. Improving the recovery of copper, rare earths, and other metals will reduce Belgium's dependence on international supply chains and strengthen domestic circularity. Fourth, policy efforts should prioritise transparent supply-chain data, including trade statistics, end-of-life reporting, and technology-specific material intensity values. Such improvements would enhance the reliability of future assessments and reduce uncertainties.

Finally, federal authorities should continue fostering collaboration across ministries, regional governments, research institutions, and industry. Material challenges are inherently cross-sectoral; effective governance requires coordinated action that combines environmental, industrial, energy, and foreign-policy perspectives. The interdisciplinary approach developed in this project provides a strong foundation for such integrated decision-making.

Based on the scientific results, the following recommendations are proposed:

- **Strengthen national data integration**
 - Improve harmonisation between federal and regional material statistics
 - Develop a national material accounts infrastructure (including waste accounts)
 - Establish a long-term data-sharing protocol across administrations
- **Expand critical material monitoring**
 - Create a Federal Critical Materials Dashboard using CAMBIUM methodologies
 - Update CRM assessments biennially using the nationalised method
 - Monitor CRM-rich product flows via micro-level pointers
- **Enhance circularity and secondary resource use**
 - Prioritise recovery pathways for high-impact CRM-carrier waste streams
 - Support industrial investment in domestic processing and recycling
 - Encourage eco-design aligned with Belgium's strategic vulnerabilities

- **Strengthen supply-chain resilience**
 - Diversify import sources for critical materials and components
 - Identify opportunities for strategic stockpiling
 - Improve transparency in supply-chain mapping for key sectors
- **Improve strategic foresight capacity**
 - Integrate methodologies into federal foresight exercises
 - Develop early-warning systems for material disruptions
 - Align national monitoring with CRMA reporting obligations

8 DISSIMINATION AND VALORISATION

The dissemination and valorisation activities conducted throughout the project were designed to ensure that the scientific results, methodological innovations, and policy-relevant insights reached a broad and diverse set of stakeholders. The objective was not only to communicate findings, but also to embed the developed methodologies within the Belgian policy landscape, strengthen the scientific community working on materials and criticality issues, and generate societal awareness about the challenges and opportunities associated with sustainable resource use.

From the outset, dissemination was approached as an integral part of the project's scientific and policy mission. Because the project focused on the development of new methodologies that could support long-term monitoring and decision-making, the communication strategy prioritised clarity, transparency, and accessibility. This ensured that the tools and approaches developed by the project could be effectively taken up by federal and regional authorities, industry stakeholders, and other research institutions.

A central channel for dissemination was the project's engagement with the Follow-up Committee. Regular meetings with representatives of federal and regional administrations, academic experts, and relevant societal actors enabled the exchange of feedback during the development of the methodologies. These meetings played an important role in validating assumptions, aligning analytical choices with policy needs, and ensuring that the project outputs would be directly relevant for Belgium's multi-level governance structure. This iterative exchange also acted as a mechanism of valorisation: policy stakeholders became familiar with the methodologies early on, increasing the likelihood that the tools developed will be used in ongoing and future policy processes.

At the scientific level, dissemination centred on the publication of research results in peer-reviewed outlets and the presentation of findings at academic conferences and expert workshops. The methodological work on the multilayer material system analysis (MMSA) applied to the Belgian wind energy sector, for instance, resulted in the preparation of a scientific paper that contributes to the international literature on technology-specific material modelling. This work highlights Belgium's role in European energy transition dynamics and positions the country within broader debates on critical materials and renewable infrastructure. The scientific publication not only strengthens the academic visibility of the Belgian research community but also ensures that the methods developed under the project benefit international researchers and practitioners.

Beyond the academic domain, dissemination targeted a broader societal audience. Media engagement proved particularly successful in raising public awareness about material dependencies and the importance of circularity. The project's findings were featured in *De Tijd*, accompanied by an online interactive module that visualised key results. This media presence helped communicate complex scientific insights in an accessible way to policymakers, journalists, civil society, and the general public. Such public-facing dissemination is important not only for transparency, but also for strengthening societal understanding of the material challenges underlying the green and digital transitions.

Valorisation also took place through extensive collaboration with government services. Federal and regional authorities received detailed briefings on the project results, enabling direct use of the methodologies in ongoing processes. For example, the insights on critical materials and supply-chain vulnerabilities provide useful input for the implementation of the European Critical Raw Materials Act, while the methodological framework for material flows contributes to a more harmonised approach to circularity monitoring. These exchanges ensure that the project outcomes have immediate relevance for Belgian policy development and facilitate their integration into long-term strategic planning.

Finally, the project generated significant internal valorisation. Through interdisciplinary collaboration, team members acquired expertise in advanced material flow modelling, criticality assessment, trade data analysis, and multilayer system modelling. These new capacities strengthen Belgium's research infrastructure and enhance the ability of institutions to engage in complex material systems research. Moreover, the project fostered new and durable networks between research partners, public administrations, and European experts. These networks form an essential basis for future collaborations, particularly in areas related to resource governance, circular economy policies, and environmental monitoring.

In sum, dissemination and valorisation were key components of the project's impact. By engaging scientific, policy, and societal communities simultaneously, the project ensured that its methodological contributions are not only widely understood but also positioned for long-term uptake. The sustained interest from stakeholders and the successful transfer of knowledge to policy processes demonstrate the strong added value of the project beyond its scientific achievements.

9 PUBLICATIONS

The list of publications resulting from CAMBIUM:

- Louise Noël, Alizé Carême, Marco Orsini (ICEDD), Maarten Christis, Jana Deckers (VITO) ***State of the art of methodology and results for Belgium***. Final Report. Brussels: Belgian Science Policy Office 2023 – 124 p. (BRAIN-be 2.0 - (Belgian Research Action through Interdisciplinary Networks))
- Christis M., Deckers J., Nelen D., Vercalsteren A., Braconnier O., Noel L., Carême A. ***Identification of the critical materials for Belgium - Criticality assessment***. Final Report. Brussels: Belgian Science Policy Office 2023 (BRAIN-be 2.0 - (Belgian Research Action through Interdisciplinary Networks))
- Deckers, J. Christis, M., Sangers, D., Braconnier, O., Noel L., Carême, A. (VITO & ICEDD). ***Material flow framework and data architecture, identifying inconsistencies and data gaps***. Final Report. Brussels: Belgian Science Policy Office 2023 (BRAIN-be 2.0 - (Belgian Research Action through Interdisciplinary Networks))
- Deckers, J., Coppens M. (VITO). ***Case studies on critical material flows - Mapping critical material flows in Belgium: a multilayer material system analysis***. Final Report. Brussels: Belgian Science Policy Office 2023 (BRAIN-be 2.0 - (Belgian Research Action through Interdisciplinary Networks))
- Nelen, D. (VITO). ***Case studies on critical raw material flows – Mapping critical material flows in Belgium: Case study on Platinum Group Metals and Nickel***. Draft Report. Brussels: Belgian Science Policy Office 2023 (BRAIN-be 2.0 - (Belgian Research Action through Interdisciplinary Networks))
- Coppens, Margot and Rommens, Tom and Van Opstal, Wim and Nelen, Dirk, ***A Pragmatic Methodology to Prioritize Critical Raw Material Recovery*** (January 27, 2025). Available at SSRN: <https://ssrn.com/abstract=5113249> or <http://dx.doi.org/10.2139/ssrn.5113249>
- Christis M., Van den Abeele L., Deckers J. (2024). ***De rol van metalen en 'kritieke grondstoffen' in Vlaanderen - Analyse vanuit een omgevingsperspectief***, uitgevoerd door VITO in opdracht van het Departement Omgeving.
- Online article in De Tijd: <https://www.tijd.be/ondernemen/zware-industrie/chinees-gepoker-met-grondstoffen-kan-europa-zuur-opbreken/10574904.html>. Linked to this article is an interactive module which will be re-used in further publications around this topic: <https://multimedia.tijd.be/kritieke-grondstoffen/>. Both links refer to the CAMBIUM-project, and show an easy accessible information and illustrations of this topic.

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