FutuRaM

Future availability of secondary raw materials

Project Final Report

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Abbreviations

Abbreviation	Description
BATT	Waste batteries
BAU	Business-as-usual (used to indicate scenarios)
CDW	Construction and demolition waste from buildings
CF	Controlling Factor (UNFC)
CIR	Circularity (used to indicate scenarios)
CRMs	Critical Raw Materials
EEE	Electrical and Electronic Equipment
EF	Environmental Footprint
ELV	End-of-life vehicles
EU27	27 Member States of the European Union
EU27+4	27 Member States of the European Union plus Iceland, Norway, Switzerland and United Kingdom
EV	Electric vehicle (battery)
kg	Kilogram
kt	Kilotonne (1,000 tonnes)
LFP	Lithium-iron-phosphate (battery)
LCO	Lithium-cobalt-oxide (battery)
LMO	Lithium-manganese-oxide (battery)
LMT	Light means of transport (battery)
MINW	Mining waste
Mt	Million tonnes (1,000,000 tonnes)
NCA	Nickel-cobalt-aluminium (battery)
NMC	Nickel-manganese-cobalt (battery)
OBS	Observed past stocks and flows
REC	Recovery (used to indicate scenarios)
SLASH	Slags and ashes
SLI	Starting, lighting and ignition (battery)
t	Tonne (1,000 kilograms)
TRL	Technology Readiness Level
WEEE	Waste Electrical and Electronic Equipment
WTB	Dismantled wind turbines

Glossary

Term	Definition	Reference
Components	Uniquely identifiable parts or subunits of products. Components are usually mechanically removable in one piece and are considered indivisible for a particular function or use. A component can consist of other subcomponents, e.g. a printed circuit board may contain a capacitor which is also a component. Some products may contain other products as components, for instance, a car has a battery.	Based on ProSUM Harmonisation paper for external feedback and consultation Annex 1 (Huisman et al., 2016)
Critical raw material (CRM)	'Critical raw materials' are defined as a set of non-energy, non-agricultural raw materials that are considered to be critical due to their high economic importance and their exposure to high supply risk, often caused by a high concentration of supply from a few third countries. The raw materials, including in unprocessed form, at any stage of processing and when occurring as a by-product of other extraction, processing or recycling processes, listed in Annex II, Section 1, shall be considered to be critical raw materials. By 24 May 2027 and at least every three years thereafter, the Commission shall review and, if necessary, update the list of critical raw materials in accordance with paragraph 2.	(CRM Act – Regulation (EU) 2024/1252)
CRM recoverability	'CRM recoverability' describes the ability of CRMs present in products and waste to be recovered through recycling processes under consideration of technical, economic, environmental, and legal factors.	Based on EN 45555:2019 and developed in the FutuRaM project (refer to FutuRaM's Deliverable D3.1 'Extended waste stream composition assessment to enable secondary raw materials assessment', chapter 4.2)

Term	Definition	Reference
Functional Recycling	Functional recycling is that portion of end-of-life recycling in which the metal in a discarded product is separated and sorted to obtain recyclates that are returned to raw material production processes that generate a metal or metal alloy. Often it is not the specific alloy that is remelted to make the same alloy, but rather, any alloys within a certain class of alloys that are remelted to make one or more specific alloys. For example, a mixture of austenitic stainless-steel alloys might be remelted and the resulting composition adjusted by addition of reagents or virgin metal to make a specific stainless-steel grade. Recyclates obtained by functional recycling are used for the same functions and applications as materials obtained from primary sources—as opposed to recyclates generated from non-functional recycling which substitute other raw materials and therefore do not contribute directly to the total supply of the initial raw material.	(UNEP 2011, Talens Peiró et al., 2018)
Mass	The mass of an entire component or product (subscript c or p, respectively), kg or also kg/unit, kg/piece.	Based on ProSUM Harmonisation paper for external feedback and consultation Annex 1 (Huisman et al., 2016)
Mass fraction	The mass fraction of an element, material, component or product in a material, component, product or stock/flow (subscript e.g. e-m, e-c, e-p, m-c, m-p, or c-p), kg/kg, mg/kg (ppm), wt%.	Based on ProSUM Harmonisation paper for external feedback and consultation Annex 1 (Huisman et al., 2016)
Materials	Refers to 'engineered materials' that are composed, manufactured, and processed to achieve intended properties.	Based on ProSUM Harmonisation paper for external feedback and consultation Annex 1 (Huisman et al., 2016)
Minerals	A valuable or useful chemical substance that is formed naturally in the ground.	Based on Cambridge Dictionary: https://dictionary.cambridge.org/dictionary/english/mineral
Open-loop recycling / downcycling	In open-loop recycling, the inherent properties of the recycled material differ from those of the virgin material in a way that it is only usable for other product applications, mostly substituting other materials.	(Huysman et al., 2015)
Placed on the market	Placed on the market (also commonly referred to as 'put on the market') refers to the first time a product is sold on the market within the territory of a country on a professional basis.	(WEEE Directive – Directive 2012/19/EU)
Post-consumer material	Material generated by households or by commercial, industrial, or institutional facilities in their role as end-users of the product which can no longer be used for its intended purpose. This includes returns of material from the distribution chain.	ISO 14021:2016 EN 45557:2019 (which uses ISO 14021:2016 definition)

Term	Definition	Reference
Pre-consumer material	Material diverted from the waste stream during a manufacturing process. Excluded is reutilisation of materials such as rework, regrind, or scrap generated in a process and capable of being reclaimed within the same process that generated it.	ISO 14021:2016 EN 45557:2019 (which uses ISO 14021:2016 definition)
Products	Usually refers to anything that is made to be sold, including components and materials. Here, it refers only to items consisting of parts made from materials (e.g. batteries, vehicles, EEE, buildings).	Based on Cambridge Dictionary: https://dictionary.cambridge.org/dictionary/english/product
Recovery	Any operation, the principal result of which is waste serving a useful purpose by replacing other materials that would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy. In this report, 'critical raw materials recovery' refers to the separation and refining of critical raw materials from waste, where part is functionally recycled or made available for further processing, while another part is dissipated into residues. The term also includes recovery of critical raw materials as part of materials and components classified as secondary raw materials, which are subsequently sent for further recycling, processing, or recovery.	Integrated from (Directive 2008/98/EC) and developed in the FutuRaM project (refer to FutuRaM's Deliverable D3.1 'Extended waste stream composition assessment to enable secondary raw materials assessment', chapter 4.1)
Recycling	'Recycling' means any recovery operation by which waste materials are reprocessed into products, materials, or substances, whether for the original or other purposes. It includes reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations.	(Waste Framework Directive - Directive 2008/98/EC, ELV Directive - Directive 2000/53/EC, ISO 22628:2002 (ELV))
Secondary raw material	'Secondary raw materials' are raw materials recovered from a secondary source, i.e. waste, instead of being obtained from a primary source, i.e. an ore, and have undergone all necessary treatment steps to substitute primary raw materials.	Based on • European Parliament (2019) • Regulation (EU) 2025/40 on packaging and packaging waste • UNECE (2022)
Stocks and flows	'Stocks' refer to accumulated materials that remain within a system over time. 'Flows' refer to the movement of materials into, through, and out of a system over a specific period. For the purpose of this report, stocks and flows are measured annually in terms of mass. Additionally, the geographical boundaries are the national territories of the EU27+4.	(European Commission, 2001)

Term	Definition	Reference
Strategic raw material	Materials essential for key strategic technologies related to the green and digital transitions that have high projected demand growth and that face significant challenges in scaling up supply. The raw materials, including in unprocessed form, at any stage of processing and when occurring as a by-product of other extraction, processing or recycling processes, listed in Annex I, Section 1, of the CRM Act shall be considered to be strategic raw materials. The Commission shall review and, if necessary, update the list of strategic raw materials by 24 May 2027, and every three years thereafter.	(CRM Act – Regulation (EU) 2024/1252)
Volume	The volume of an entire component or product (subscript c or p, respectively), m^3 or also m^3/unit, m^3/piece.	Based on ProSUM Harmonisation paper for external feedback and consultation Annex 1 (Huisman et al., 2016)
Waste	'Waste' means any substance or object that the holder discards or intends or is required to discard.	(Waste Framework Directive – Directive 2008/98/EC)
Waste collected	Household and similar waste, selectively collected in homogeneous parts by public services, non-profit organisations, and private enterprises acting in the field of organised waste collection.	(Regulation (EC) 2150/2002)
Waste collection	The gathering of waste, including the preliminary sorting and preliminary storage of waste for the purposes of transport.	(Directive 2008/98/EC, n.d.) (UNECE, 2022a)
Waste generated	Waste generated refers to the total weight of waste resulting at the end-of-life of products (post-consumer material), from manufacturing processes (pre-consumer material), from waste treatment facilities, or from the prospecting, extraction, treatment, and/or storage of mineral resources and the working of quarries.	• Regulation (EU) 2017/699 for EEE placed on the market and WEEE generated calculation (https://eur-lex.europa.eu/eli/reg_impl/2017/699/oj/eng) • Directive 2006/21/EC on the management of waste from extractive industries (https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32006L0021)

Executive Summary

The FutuRaM project was developed in a context characterised by increasing geopolitical uncertainty, accelerating energy and digital transitions, and growing concerns regarding the security of supply of critical raw materials (CRMs). These developments have reinforced the need for robust, harmonised, and transparent information on the availability of secondary raw materials and recoverability of CRMs from Europe's waste streams, or 'urban mine'. FutuRaM has addressed this need by developing datasets, methods, and tools to improve the assessment of the potential of this urban mine and to support policy implementation, strategic planning, and long-term monitoring.

Building on the foundations laid by previous initiatives, notably Prospecting Secondary raw materials in the Urban mine and Mining waste (ProSUM, 2017) and Raw Materials Information System (RMIS, European Commission, n.d.), FutuRaM substantially expanded the scope and depth of the knowledge on the European urban mine for seven waste streams – i.e. waste batteries, construction and demolition waste from buildings, end-of-life vehicles, mining waste, slags and ashes, waste electrical and electronic equipment, and dismantled wind turbines. Existing datasets for waste batteries, end-of-life vehicles, mining waste and waste electrical and electronic equipment (WEEE) were updated, while construction and demolition waste from buildings, dismantled wind turbines, and slags and ashes were assessed and integrated for the first time within the same analytical framework. All waste streams had a harmonised and hierarchical composition data structure, enabling a coherent description of flows/stocks, products, components, materials, and elements across highly heterogeneous waste streams.
A novel methodological development of FutuRaM was the implementation of a recovery model that translates waste generated and end-of-life flows into estimates of secondary raw materials after treatment. This allowed a clear distinction between CRMs embedded in waste generated and CRMs embedded in secondary raw materials after waste treatment, addressing a key limitation of previous assessments. The recovery model was complemented by a recoverability assessment, which provided additional insight into the barriers and enabling conditions for CRM recoverability based on how these CRMs are present in a waste stream. Additionally, three long-term scenarios up to 2050 – business-as-usual (BAU), recovery (REC), and circularity (CIR) – as well as a life cycle assessment (LCA) were developed to explore the implications of different assumptions on product consumption, waste generated, and recovery. This enables the exploration of how today's policy and investment choices may affect future environmental impact and critical and secondary raw material availability.

The 42 CRMs analysed in the FutuRaM project are presented in the most comprehensive database of CRMs to date, covering the 27 Member States of the European Union (EU27) plus Iceland, Norway, Switzerland and the United Kingdom (EU27+4), which the FutuRaM project has made available via the Urban Mine Platform. The Urban Mine Platform offers a new way to explore the availability of secondary raw materials and CRMs in the EU27+4. Covering the seven key waste streams noted earlier, the platform provides clear, structured data and projections out to 2050. All datasets and documentation can be accessed via the FutuRaM's repository on Zenodo.

VISIT THE URBAN MINE PLATFORM

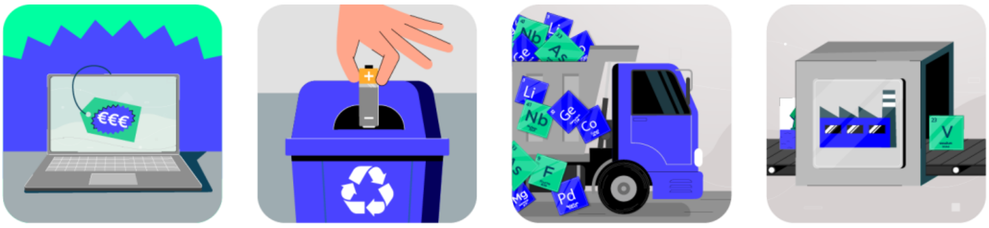
In parallel, FutuRaM has adapted the United Nations Framework Classification (UNFC), originally developed for fossil energy and primary mineral residues, to enable its application to secondary raw materials from anthropogenic resources. This adaptation provides a harmonised and holistic framework to assess and transparently communicate the potential of recovery projects to project developers, authorities, and policymakers. As part of this work, the assessment criteria were extended to better capture the specific characteristics of secondary resource projects, resulting in a more comprehensive evaluation of their technical feasibility, socio-economic, and environmental viability. To operationalise the approach, the SARA4UNFC digital tool was developed, offering UNFC practitioners a clear, structured, and replicable way of undertaking a workflow for UNFC-based classification. The adaptation of the UNFC principles in a structured procedure supports transparency and consistency across different waste streams and project development stages. Twenty UNFC case studies across all waste streams – covering site-specific recovery projects and national-level scenarios – were used to test and refine the methodology, identify areas requiring further adaptation, and demonstrate its applicability across diverse contexts. Furthermore, a reporting standard was drafted to explain how the viability of secondary raw materials recovery projects should be documented in line with the UNFC, and it is to be submitted for attention to the United Nations Economic Commission for Europe (UNECE).

Headline results from FutuRaM presented below provide an overview of the aggregated results of the project to show the extent of the potential of the urban mine in the EU27+4 for providing a supply of CRMs.

The first figure shows the quantity of CRMs (Mt/year) for the EU27+4 at different stages of their life cycle for the baseline year (2022) and three different scenarios for 2050, for waste batteries, construction and demolition waste from buildings, end-of-life vehicles, waste electrical and electronic equipment, and dismantled wind turbines.

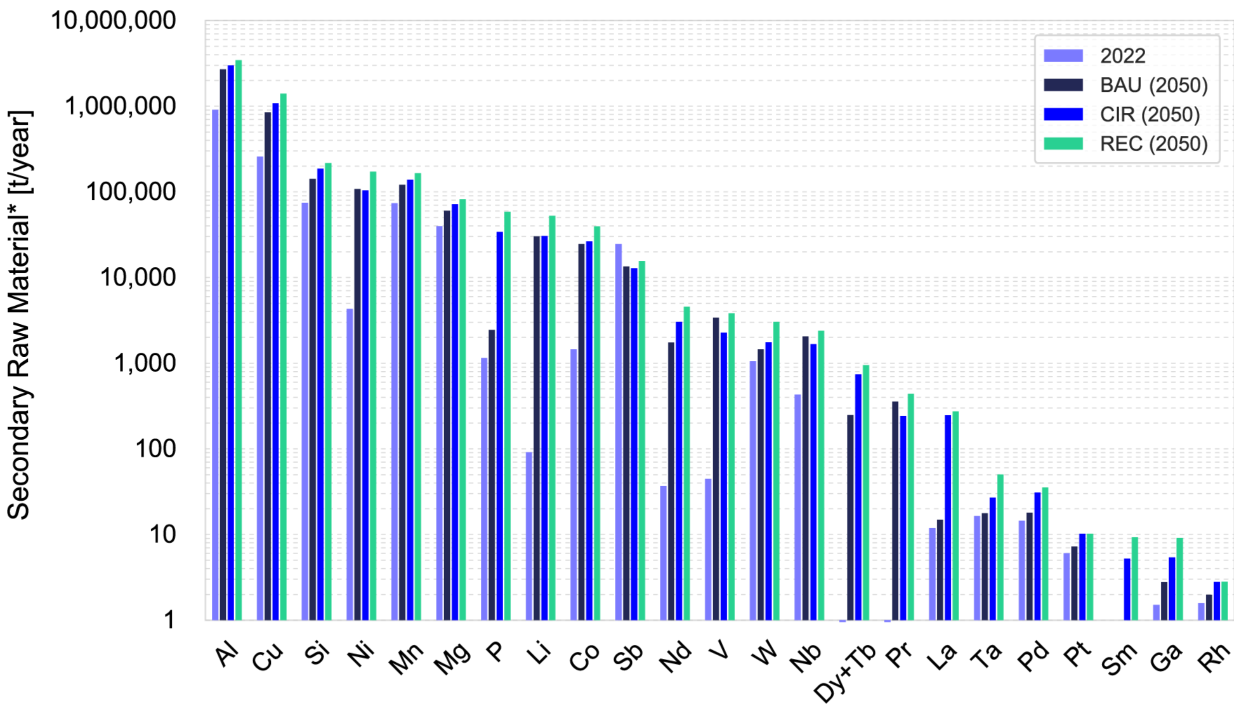
The second figure shows the quantities of the most prominent CRMs that are recovered (2022) and could potentially be recovered in 2050 under the three different scenarios. In this figure, values below one tonne/year for CRMs in secondary raw materials in any of the years or scenarios represented are not shown in the chart.

It should be noted that datasets for slags and ashes, as well as mining waste, are not comparable with the other waste streams at these aggregated levels and thus are not included in these figures. Also, the data presented excludes Iceland, Norway, Switzerland, and the United Kingdom for construction and demolition waste from buildings and dismantled wind turbines.



	Placed on the market	Waste Generated	Not collected or recovered	Secondary raw materials*
2022	5.2	2.1	0.7	1.4
2050 CIR	8.4	5.2	0.5	4.7
2050 BAU	12.2	6.4	2.3	4.1
2050 REC	12.2	6.4	0.7	5.7

*Waste treatment can happen outside of the EU27+4



*Waste treatment can happen outside of the EU27+4

The LCA work undertaken in the project enables data to be provided regarding the impact that the recovery of secondary raw materials has in terms of greenhouse gas emissions for the EU27+4. As well as the processes included in the system boundary to calculate CRM recovery, the LCA also models the remelting of waste output fractions in marketable metals and alloys (fuller information on this process is available in chapter 3). Data is not included here for dismantled wind turbines or mining waste.

	Reference year*	2050		
	OBS	BAU	REC	CIR
Net CO_2-eq:	-39 Mt	-81 Mt	-273 Mt	-263 Mt
Direct CO_2-eq:	38 Mt	71 Mt	80 Mt	74 Mt
Avoided CO_2-eq:	-77 Mt	-152 Mt	-353 Mt	-338 Mt

*The reference year is 2019 for construction and demolition waste from buildings and from slags and ashes. The reference year is 2020 for waste batteries, end-of-life vehicles, and WEEE.

FutuRaM results show that improved waste collection and recovery processes could increase the substitution of primary CRMs with secondary CRMs to 56% under the CIR scenario for waste batteries, construction and demolition waste from buildings, end-of-life vehicles, waste electrical and electronic equipment, and dismantled wind turbines in the EU27+4. These findings underpin FutuRaM's recommendations for establishing, in the EU27+4, more consistent reporting, stronger data infrastructures such as the Urban Mine Platform, and better integration of circularity principles into industrial policy. FutuRaM recommends that the following actions be taken:

- Create a harmonised framework for classification, reporting, and life cycle tracking of secondary raw materials, including standardised methodologies, improved statistics, and consistent composition data systems.
- Institutionalise the Urban Mine Platform as a permanent European digital infrastructure with stable governance, interoperability, and integration of multiple data sources and reporting tools.
- Mandate common European treatment standards and apply UNFC-based frameworks and reporting standards to improve transparency, comparability, and investment readiness of projects.
- Require all actors across the value chain to register, report, and contribute data, strengthening shared responsibility and improving monitoring systems.
- Invest in awareness, education, skills, and recycling capacity to drive behavioural change, improve collection and recovery rates, and support circular economy goals.
- Leverage digital tools and industry reporting systems to enhance data transparency, interoperability, and evidence-based decision-making while ensuring data accessibility and confidentiality.

Overall, FutuRaM provides a harmonised analytical framework and an integrated knowledge base for the assessment in Europe of secondary raw materials availability, with a focus on CRMs. The datasets, methods, and tools developed in the project form a basis for future updates, policy monitoring, and continued development of the European knowledge base on secondary raw materials.

1 Introduction

Effective raw materials management is essential to Europe's green and digital transitions. As part of its raw materials strategy, the European Union, in 2011, identified numerous raw materials as 'critical', which have both economic importance and a high risk of supply disruption, since they are largely sourced from outside of its borders. Since then, this CRMs List has been updated four times, most recently in 2023, so that it remains relevant and current. The United Kingdom takes a similar approach, having introduced the UK Critical Minerals Strategy in 2022. Norway addresses CRMs specifically as part of its wider minerals strategy, and Iceland and Switzerland manage these resources through more general policies. The EU and these four nations are the focus of this research.

The EU recognises that secondary sources of CRMs play a key role in its raw materials strategy and that there is an opportunity to bolster its raw materials resilience by identifying and accessing these materials from within its waste streams.

To help secure a sustainable and resilient supply of CRMs, the EU has introduced the CRM Act (Regulation (EU) 2024/1252). Adopted in 2024, the CRM Act was developed to enable a supply of CRMs from primary and secondary sources in Europe. Part of the aims with the CRM Act are for it to enable EU-wide harmonised monitoring of the quantity of CRMs in waste streams, and the Member States will be required to report such quantities beginning in 2027.

The CRM Act and the CRMs List of 2023 (European Commission, 2023) introduce a subset of CRMs denoted as 'strategic', these being essential for strategic technologies but with supply risks that are anticipated rather than currently occurring. As these strategic raw materials are a subset of CRMs, in this report, the term 'CRMs' covers both critical and strategic raw materials.

Figure 1 below shows the EU CRMs list of 2023, set out in the periodic table. It indicates those that are also considered to be strategic.

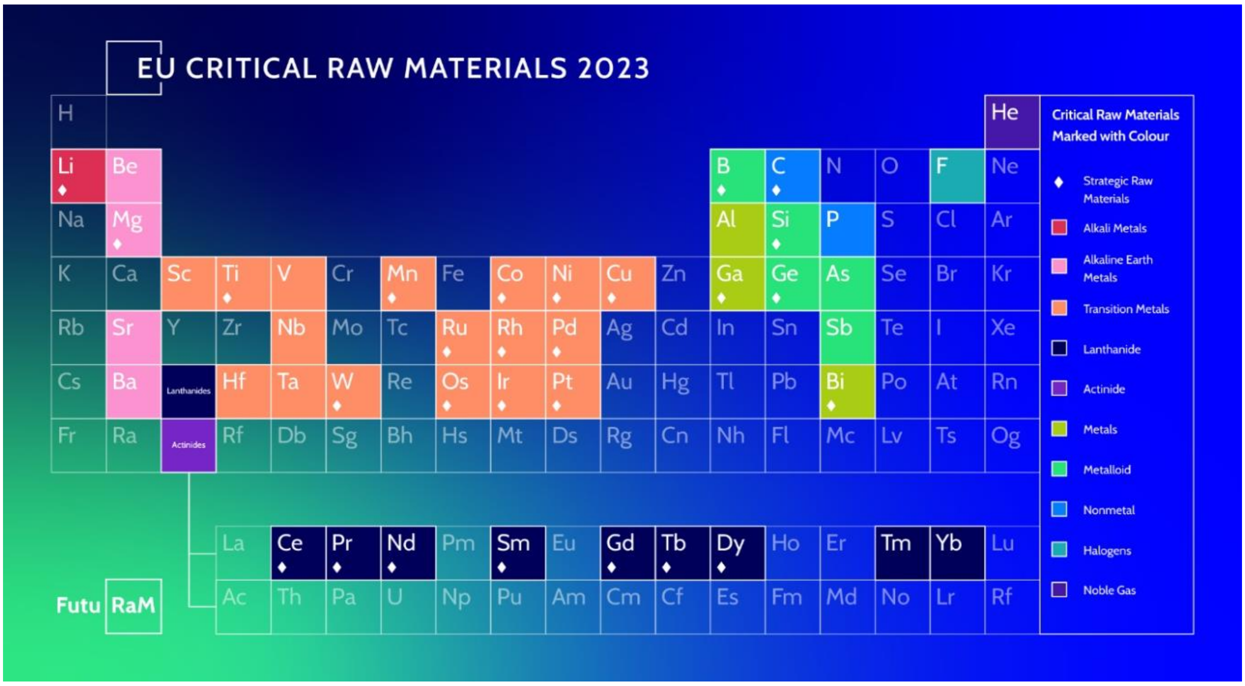


Figure 1: EU list of Critical Raw Materials 2023, set out in the periodic table.

Whilst recycling itself is not new, the explicit recognition of raw materials extraction from waste and the emphasis on CRMs introduce a shift in priorities and requirements, particularly in terms of identifying, classifying, and quantifying secondary sources of CRMs. This shift entails increasing the emphasis on CRMs in current recycling and material recovery pathways. To encourage this increase, the CRM Act designates as 'strategic' new projects that are considered crucial for securing the EU's supply of CRMs, and these projects are eligible to receive regulatory support. As part of this initiative, the Act calls for greater transparency and comparability across raw materials-focused projects and for reporting on secondary raw material infrastructure projects to be aligned with the United Nations Framework Classification (UNFC) for resources. The UNFC is a harmonised, global, principle-based classification system which is valuable for decision-making and responsible resource management and essential to evaluate if a project can be classified as strategic.

In support of these endeavours, the Horizon Europe-funded FutuRaM project has produced two major outputs. The first of these is harmonised datasets on the availability of secondary raw materials and CRMs from seven key waste streams in the EU27+4. These waste streams are:

- Waste batteries
- Construction and demolition waste from buildings
- End-of-life vehicles
- Mining waste
- Slags and ashes
- WEEE
- Dismantled wind turbines

The resulting dataset gives detailed insight into the availability of secondary raw materials and CRMs from these waste streams, with projections along different scenarios out to 2050. This dataset feeds into the Urban Mine Platform (www.urbanmineplatform.eu), a web portal enabling in-depth data analysis, visualisation, and download, that has been developed in FutuRaM. It is important to note that the quantitative analyses conducted by FutuRaM are based on the CRMs List of 2023. For the forward-looking assessment out to 2050, it is assumed that this list remains unchanged, notwithstanding the fact that it is subject to periodic revision and will undoubtedly evolve over time.

The second output of FutuRaM is a concept for the application of the UNFC to secondary raw materials recovery projects that provides a clear framework for obtaining a holistic overview of their viability. This concept encompasses technical, economic, social, environmental, and regulatory dimensions, enabling clear communication of project status and consistent comparison and aggregation across such projects. Documenting the assessment underlying the classification helps decision-makers understand the enabling conditions required to implement projects to recover secondary raw materials and also supports informed, fact-based decision-making.

In contrast to conventional practice, where recovery projects are assessed through isolated evaluations focusing on individual aspects such as technical feasibility, economic performance, or environmental sustainability, the UNFC provides a unified, principle-based framework applicable across different types of waste streams, treatment methods, and project development phases. The application of the UNFC to secondary raw materials has been tested by FutuRaM in 20 case studies covering the focused waste streams noted above.

The intelligence generated by FutuRaM has already supported fact-based decision-making for the sustainable exploitation of CRMs and will continue to do so. For example, Article 26 of the CRMs Act requires EU Member States to adopt national measures to improve the circularity and recovery of CRMs. Through work conducted in collaboration with the Joint Research Centre (JRC), the FutuRaM project has developed and applied a transparent methodology that identifies waste streams, products, and components with significant CRM contents or recovery potential. This has provided the data needed by the European Commission to define a list of priority products and waste streams in line with the requirements put forward in Article 26.

This report summarises the main work conducted and results obtained in the project, and the project's role in decision-making. It presents the methodologies developed to harmonise concepts and models across the focused waste streams, the results of the assessment of CRMs in these waste streams, an assessment of their recoverability potential, and LCA of their treatment. It also documents the development and functionalities of the Urban Mine Platform. Furthermore, it covers the dissemination and policy impacts derived from the project, including a basis for reporting under the UNFC standard, a proposal for secondary raw materials statistics, recommendations for composition data reporting, and optimisation of a reporting tool. These outputs are intended to support harmonised, comparable, and policy-relevant secondary raw materials statistics at national and EU levels.

Overall, this report represents the culmination of the FutuRaM project, integrating scientific analysis, data, tools, and practical guidance to support decision-making and policy development for the sustainable management of secondary raw materials and critical raw materials in Europe.

2 Methodology

This chapter provides an overview of the concepts, methods, models, and procedures developed within the FutuRaM project. Its purpose is to present the FutuRaM framework in a coherent and structured manner, showing how the different elements developed across the project are connected and aligned.

2.1 Overview of the FutuRaM framework

Figure 2 provides an overview of the FutuRaM framework and its main conceptual and methodological building blocks. The individual components, as well as the methods used to implement and connect them, are described below.

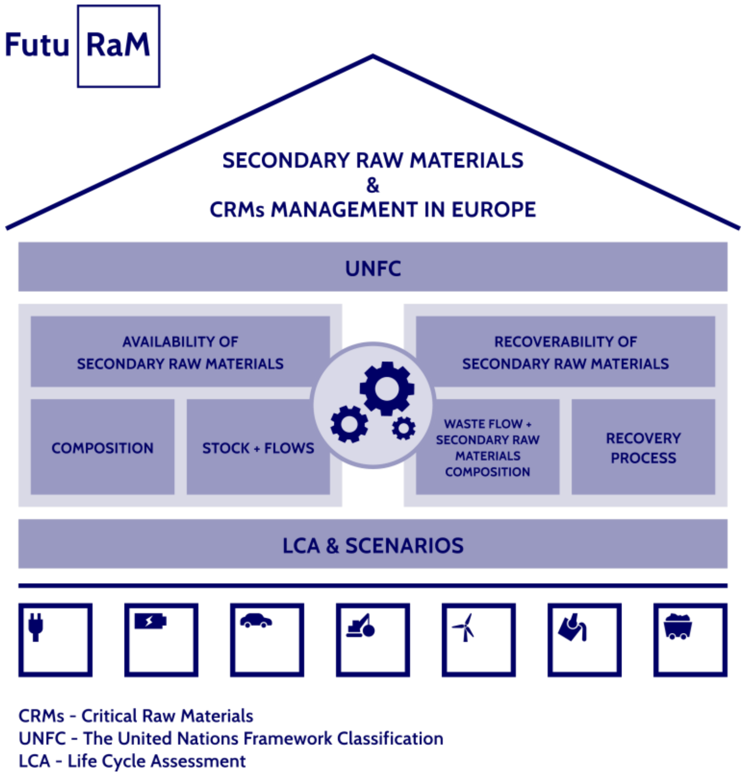


Figure 2: Overview of the FutuRaM framework and its main conceptual and methodological building blocks.

Building on the ProSUM project (2017), which focused solely on assessing availability of CRMs within four waste streams (i.e. waste batteries, end-of-life vehicles, mining waste, and WEEE), FutuRaM expands on this framework by introducing recoverability assessments and scenario modelling out to 2050 as well as adding three new waste streams, namely construction and demolition waste from buildings, slags and ashes, and dismantled wind turbines. These additions required both conceptual and methodological adjustments, which resulted in updated procedures applied for each of the waste streams studied. These new developments were harmonised across all waste streams while allowing sufficient flexibility for waste stream-specific adaptations. Figure 3 provides an overview of the applied methodological steps.

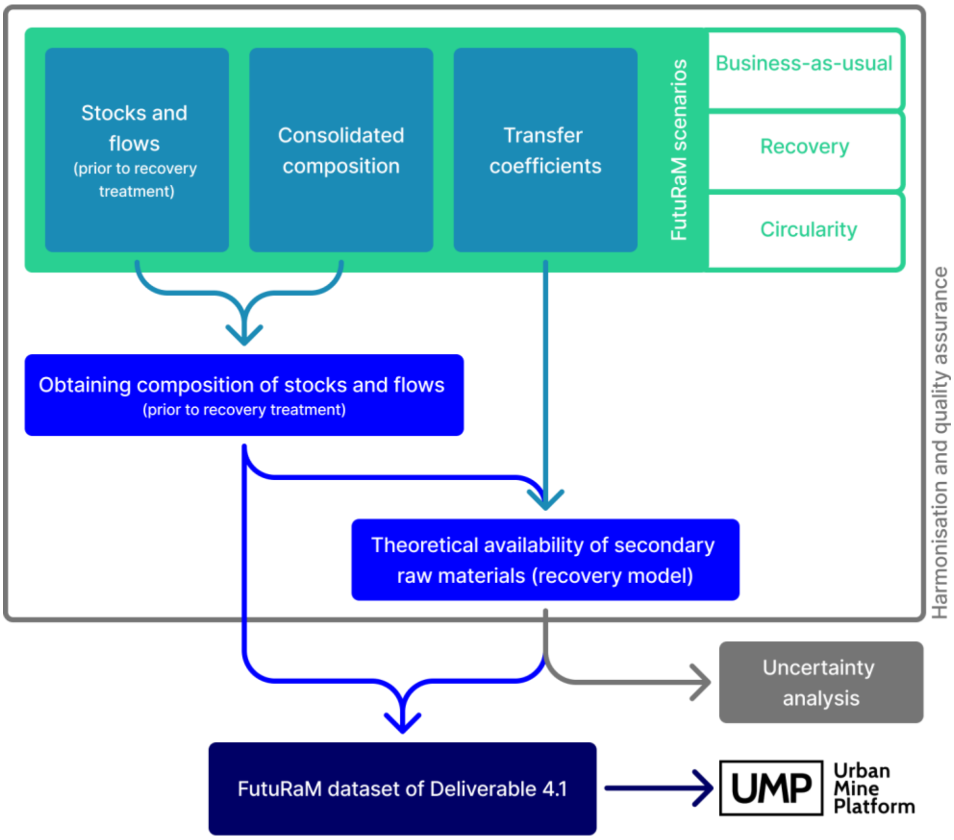


Figure 3: Workflow applied to provide data for the Urban Mine Platform.

The overall FutuRaM scope is depicted in Figure 4. FutuRaM focuses on quantifying composition as well as stocks and flows of end-of-life products and waste streams, thereby establishing a clear picture of how much material, related to the waste streams studied, is present within the urban mine in the EU27+4[1]. FutuRaM expands on the four waste streams studied in ProSUM by adding construction and demolition waste from buildings, slags and ashes, and dismantled wind turbines, meaning that it covers seven waste streams. Dismantled wind turbines were initially considered and integrated within construction and demolition waste, but in terms of the final result on the Urban Mine Platform, dismantled wind turbines are presented as an individual waste stream.

[1] Transboundary movement, such as used EEE exports, as well as imports and exports of used vehicles and their embedded batteries, were included in FutuRaM. Transboundary movement of waste for (or during) treatment is not included in the scope.

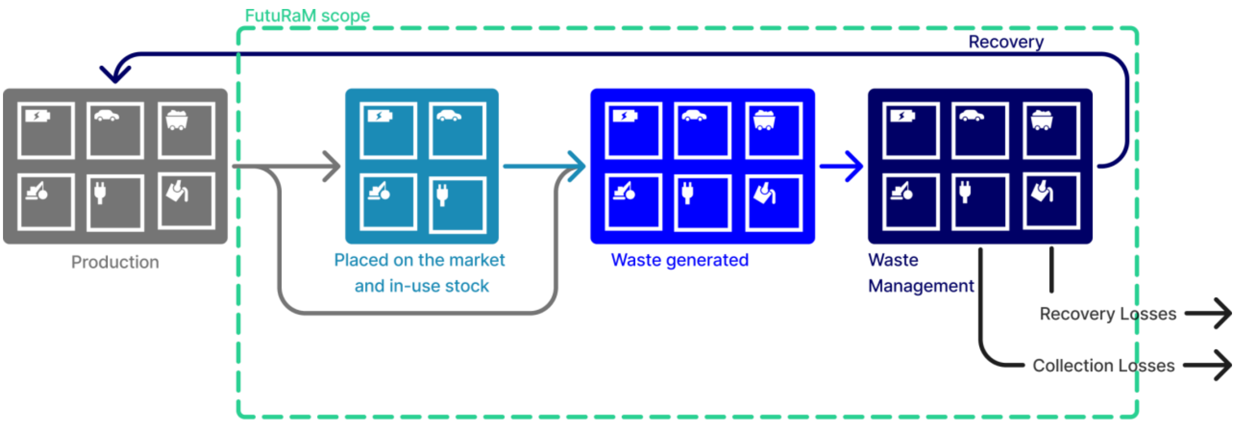


Figure 4: FutuRaM scope.

A key aspect in the extension of the framework is the assessment of recoverability of secondary raw materials. Here, emphasis is placed on linking material composition and waste flows with recovery processes. This ensures that the technical feasibility of extracting CRMs is assessed alongside their physical presence within the waste stream. This required a thorough update of the composition data concept used in ProSUM, which then later impacted the applied procedures within FutuRaM. The established composition data framework ensures consistent interlinkages across elements, materials, components, and product types. The level of detail is crucial: the more granular the data, the more robust the analysis. However, more granular level data often results in a loss of practicability. Furthermore, this data structure allows interoperability. For this reason, harmonised code lists have been developed for each waste stream. Figure 5 gives an example of the hierarchical structure followed (see FutuRaM's Deliverable D3.1 and Milestone M23).

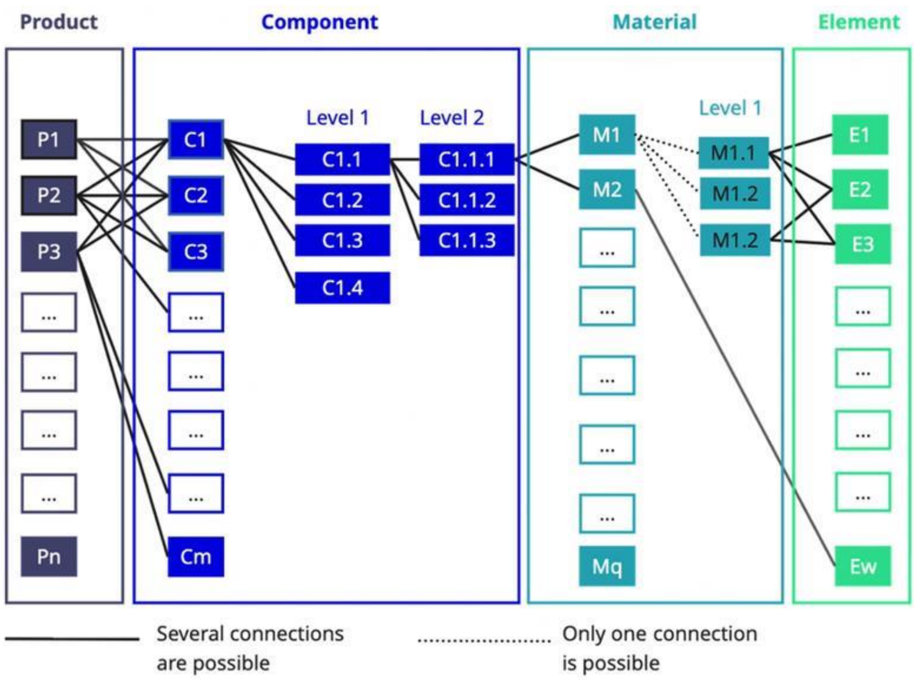


Figure 5: Hierarchical structure of the FutuRaM composition framework. The dotted line indicates that only one connection is possible; the solid line indicates that several connections can occur simultaneously.

An additional feature compared to the ProSUM framework in FutuRaM is the development of scenarios, which provide forward-looking insights into how material availability and recovery may evolve under varying future technological and policy conditions. Where possible, scenarios are applied consistently across the targeted waste streams, allowing harmonised yet adaptable analysis for each sector. The narratives developed for the scenarios can be applied either to composition data or to stock and flow models of products prior to their end-of-life phase as well as during the recovery phase. For mining waste, where the essential work was to assess legacy and historical mining waste stocks, with a high degree of site-specific aspects, the scenario approach was not considered appropriate.

Lastly, the project applied the UNFC, which is a global, project-based and principle-based classification system used to categorise resource projects according to their maturity and viability. The framework serves the overarching goal of supporting secondary raw materials and CRMs management in the EU27+4. This integrated approach ensures that data, processes, and classifications converge into a coherent system to support evidence-based resource strategies and policy development (see FutuRaM's Deliverable D5.1)

2.2 Implementation of Methods and Procedures

Developing a comprehensive stock and flow model for different waste streams is inherently complex. One main challenge lies in defining the system boundaries and aligning them with the available data. System boundaries can vary significantly, not only between different waste streams but also within a single waste stream, depending on how data is collected and structured. Establishing a framework that is both flexible enough to accommodate these differences and sufficiently strict to allow comparability, consistency, and long-term usability is therefore essential. Finding every detail will rarely be possible. Instead, the focus must be on building a robust and transparent structure that can evolve as new data becomes available.

The process begins with the availability and quality of data. Challenges start as early as the data collection phase, where composition data and stock and flow data often originate from entirely different sources. It is crucial that these two data types align in terms of system boundaries and granularity. For instance, if flow data exist for a specific battery chemistry such as Nickel-Manganese-Cobalt (NMC) 111 (with a 1:1:1 ratio of nickel, manganese, and cobalt), the composition data should ideally match that level of detail. This is rarely the case, and aggregation must be carried out to ensure compatibility. Achieving this requires a thorough understanding of both the system and the data sources involved.

Stock and flow data is often derived from official statistics such as Eurostat, which provides a valuable macro-level overview but is frequently incomplete or too aggregated to represent actual product or material flows. These statistics also tend to use classifications that do not fully reflect technical realities. For this reason, FutuRaM complemented statistical data with branch-specific reports, stakeholder knowledge, and expert validation, ensuring that the model reflects realistic system conditions and industry practices (see FutuRaM's Deliverable D4.1).

Composition data, on the other hand, tends to be scattered and fragmented across publications, industry reports, and confidential datasets. Such data is often not machine-readable and rarely follows a consistent hierarchical structure from product to component, material, and element layer (see Figure 5). In FutuRaM, this challenge was addressed through a harmonised data collection template supported by common code lists (Kippert, et al., 2024a and Kippert, et al., 2024b). This template allowed data entries at various hierarchical levels, while the code lists provided clear definitions for products, components, materials, and elements. Data quality was assessed by an agreed-upon data quality framework, which allows the rating of the data sources according to their reliability. Each waste stream defined the ranges individually. These measures ensured traceability, interoperability, and compatibility across data types and sources.

The extension to the recovery model (Yamamoto et al., 2026) was an additional challenge. Data on the recovery potential for materials as well as elements is highly scattered and is often region- or product-specific. FutuRaM addressed this discrepancy by maintaining the hierarchical data structure, linking recovery information directly to the relevant component or material level, and engaging stakeholders in validating realistic recovery pathways (see FutuRaM's Deliverable D4.1).

Besides the quantitative estimation of secondary raw materials with the recovery model, the recoverability of CRMs in the different waste streams was further assessed (FutuRaM's Deliverable D3.1). For this, a set of criteria/factors was developed based on a barrier analysis in the UPgrade project (Rotter et al., 2016) and in line with the framework structure for recoverability assessment presented by van Nielen et al. (2022). Subsequently, the recoverability of the most relevant CRM-application combinations in waste batteries, construction, and demolition waste from buildings, end-of-life vehicles, WEEE, and dismantled wind turbines was qualitatively evaluated according to the abovementioned criteria. A CRM application refers to the sector-specific or product-specific use of a CRM, where it plays an essential technical or functional role (SCRREEN2 Project, 2023). This concept can be connected to the FutuRaM composition data model, which links CRMs and elements not only to entire products but also to specific materials and components. The recoverability of CRMs is specific for the application in which they are used and for the corresponding end-of-life treatment scenario. The concept could be also transferred to slags and ashes and mining waste. Here, the recoverability of the most relevant CRM-waste flow combinations was evaluated. In the FutuRaM project, 'CRM recoverability' describes the ability of CRMs present in products and waste to be recovered through recycling processes under consideration of technical, economic, environmental, and legal factors and considering functional recycling (UNEP, 2011).

A harmonised scenario framework was established, allowing the same conceptual structure to be applied for each waste stream while using its specific parameters and drivers. This ensured both consistency and flexibility, enabling comparable projections across sectors (FutuRaM's Deliverable D2.1).

Using the scenario-based projections for material recovery, an LCA was conducted to estimate environmental impacts of material recovery (see FutuRaM's Deliverable D2.1). LCA provides a systematic framework for assessing the potential environmental impacts associated with a product system across its life cycle, from raw material extraction through processing, use, and end-of-life management. The LCA methodology consists of four main phases: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation.

- **Goal and scope definition:** The conducted LCA focuses on the end-of-life stage of products and waste streams, including in the system boundary the collection, pre-treatment, recycling, and recovery processes. The functional unit is defined according to the waste stream or process assessed, typically as the treatment of the end-of-life waste going into the recycling system. To properly account for material recovery and provide insight into the way secondary materials mitigate impacts by replacing primary materials, we use a substitution approach: taking on the assumption that secondary materials can be used in place of primary materials on the market, we credit the recycling system with 'avoided' environmental impacts that could have occurred if the same material or product would need to be sourced from the market.
- **Life cycle inventory analysis:** Inventory data is obtained from the material flow projections modelled in the project and is supplemented by literature review and assumptions where necessary.

- **Life cycle impact assessment:** In this phase, inventory flows are translated into environmental impact indicators using the Environmental Footprint (EF 3.1) midpoint method, which includes 16 impact categories. These categories reflect the main environmental issues associated with waste treatment and material recovery, such as climate change, human health impacts, ecosystem impacts, and resource use.
- **Interpretation:** In this phase, impact assessment results are analysed and interpreted to provide policy recommendations. This includes estimating impacts attributed to different products and recycling routes as well as to specific materials or product stages, allowing identification of hotspots for environmental impacts.

2.2.1 Data collection and processing

Once collected, the data had to be consolidated into a coherent and internally consistent structure. This process required a balance between strictness and flexibility. The consolidation methodology used in FutuRaM was designed to be strict enough to preserve hierarchical consistency but flexible enough to capture the specific characteristics of each waste stream (see FutuRaM's Deliverable D3.1 and Milestone M23). The hierarchical structure, linking products, components, materials, and elements was crucial for ensuring that the data could later be used in the recovery model and for recoverability assessments. Understanding where a material or element is located within a product determines whether and how it can be recovered, while knowing only the total amount of an element in a product is insufficient.

To manage the diversity of data sources, FutuRaM developed a consolidation approach that combines uniform methodological guidance with waste-stream-specific flexibility. Each stream applied tailored consolidation procedures, but all adhered to a shared data model and coding framework, ensuring compatibility and comparability across sectors (see FutuRaM's Deliverable D3.1 and Milestone M23).

Filling data gaps required the use of estimation methods, expert input, and stakeholder engagement. These inputs were carefully documented to maintain transparency and allow future revisions as more accurate data becomes available. The data quality framework was used to assess the data sources in terms of reliability (see FutuRaM's Deliverable D1.1). As well, where relevant, assumptions were cross-checked against literature. This approach ensured that even incomplete datasets could be integrated into the broader model while retaining transparency and traceability (see FutuRaM's Milestone M23).

Misalignment between the defined system and the underlying data can lead to inconsistencies and misinterpretations. Therefore, clear system boundaries and common terminology were indispensable. FutuRaM defined these through shared flow charts and harmonised vocabulary, ensuring that terms such as 'secondary raw materials,' 'waste flow,' and 'recovery process' were interpreted consistently across partners and work packages (see FutuRaM's Deliverable D1.1). Code lists were developed to define each product, component, and material (Kippert et al., 2026).

Beyond technical modelling, accessibility and governance of the developed data is key to ensuring transparency and long-term usability. FutuRaM made all non-confidential datasets openly available[2] via Zenodo and/or the Urban Mine Platform, providing persistent identifiers and metadata that allow datasets to be cited and reused.

The project also conducted a FAIR data assessment to evaluate the findability, accessibility, interoperability, and reusability of its datasets (see FutuRaM's Deliverable D1.1). This assessment not only benchmarked the current status but also provided recommendations for future improvements in

[2] Some datasets will be made available after an embargo.

data management. It helped to identify where interoperability could be enhanced, where metadata needed to be enriched, and where long-term accessibility should be strengthened. While striving for openness, the project also had to balance this with confidentiality requirements, particularly for industrial data. Therefore, FutuRaM adopted a sequenced openness approach, allowing sensitive data to be aggregated or anonymised while still contributing to the overall analysis.

2.2.2 Data limitation and uncertainty

A comprehensive assessment of data quality is essential for ensuring that the conclusions and recommendations developed in FutuRaM are scientifically sound and fit for policymaking. The project relies on data originating from a wide range of sources, including literature, industrial reports, monitoring systems, expert input, and model-based estimates. These sources vary considerably in methodological rigor, geographic and temporal relevance, and degree of verification. Therefore, it is not sufficient to report numerical values alone; we also need to evaluate how reliable these values are. Only by integrating data quality into our analyses can we provide transparent, well-grounded evidence to support decisions on secondary raw materials availability and resource management across Europe.

To ensure a comprehensive assessment, data quality in FutuRaM is evaluated along six key dimensions (Figure 6):

- Validity – the extent to which the data complies with predefined requirements or expected ranges.
- Accuracy – how closely the data reflects the actual, measurable reality.
- Consistency – the degree of alignment within the dataset and with external datasets measuring the same parameter.
- Integrity – the overall soundness of the data, considering accuracy, consistency, and completeness together.
- Timeliness – the relevance of the data in relation to the period being studied (i.e. whether or not it is up to date).
- Completeness – the extent to which all necessary data is available and no relevant information is missing.

Figure 6: Data Quality Framework.

This framework helps both to make data quality transparent and to assess data uncertainty. Instead of treating all data as equally reliable, the approach enables us to systematically identify where confidence is high and where additional caution or verification is required. This data assessment allows an evaluation in all three data collection activities: composition data, stock and flow data, and data on transfer coefficients.

FutuRaM distinguishes four levels of data quality, aligned with the principles of the UNFC:

1. High-quality, well-documented, reliable, and representative data
2. Good-quality data with some limitations, but still suitable for analytical use
3. Low-quality data with substantial uncertainty or limited documentation
4. No meaningful basis for assessing quality (no reliable information available)

Level 1 represents a situation where data has been collected systematically, is supported by multiple sources or measurements, and can be confidently used for quantitative estimates. At the other end of the scale, Level 4 indicates that the value is essentially unknown or cannot be verified; in such cases, the uncertainty must be clearly acknowledged and handled with caution in modelling or scenario interpretation. Each waste stream team has the flexibility to define how these levels are applied in practice, taking into account the type of data available, the maturity of the sector, and relevant methodological or reporting standards. The application of these scores can be found in more detail in FutuRaM's Deliverable D1.1.

To complement the FutuRaM Recovery Model (Yamamoto et al., 2026) and assess the robustness of recovery estimates, a Monte Carlo simulation was developed. This approach enables the quantification of uncertainty arising from variability in input data, such as inflow quantities, composition shares, and process efficiencies, and provides a distribution of possible recovery outcomes rather than a single deterministic result. More detail can be found in FutuRaM's Deliverable D1.1.

2.3 Summary

In summary, the challenges of building comprehensive composition and stock and flow models result from fragmented data sources, inconsistent system definitions, and varying data granularity. FutuRaM addressed these issues by developing a harmonised but flexible data framework supported by common templates, code lists, and shared terminology. Scattered and non-harmonised data was consolidated through a structured approach; gaps were bridged through expert judgment and stakeholder engagement; and assumptions were transparently documented. System boundaries and scenarios were harmonised across waste streams, and open and FAIR data principles were embedded throughout the project to ensure long-term accessibility and reusability.

This approach has provided a solid foundation for consistent and comparable material flow modelling across diverse waste streams, supporting Europe's transition to a circular and resource-efficient economy. The highlights of the results obtained by the implementation of this framework within FutuRaM are described in more detail beginning in chapter 3.

3 Critical raw materials in the Urban Mine in Europe

This chapter contains the main results on the critical raw materials (CRMs) in the Urban Mine in Europe obtained during the FutuRaM project.

The chapter provides highlights of the results per waste stream of the:

- Future trends of secondary raw materials and critical raw materials
- Recoverability assessment of important critical raw materials
- Environmental and socio-economic impacts of waste treatment and secondary raw materials recovery
- Application of the UNFC (see chapter 5 for further information on UNFC in FutuRaM).

The waste streams results are presented in the following order: Waste batteries, Construction and demolition waste from buildings, End-of-life vehicles, Mining waste, Waste electrical and electronic equipment, and Dismantled wind turbines.

Additionally, chapter 3.8 provides a distribution of the waste streams concerning CRMs in waste generated and in secondary raw materials, and chapter 3.9 dives into the total quantities of CRMs at different stages of life.

3.1 Waste batteries

Selected key results for waste batteries are presented across four infographic pages. The table below summarises the scope, methodology, limitations, and key deliverables for each. For full results, methodological details, and assumptions, readers are invited to read the corresponding project reports and datasets, which are listed below.

Future trends of secondary* and critical raw materials (CRMs) in waste batteries

- **Scope:** The analysis covers eight different battery types (primary lithium, zinc-based, rechargeable lithium (Li-ion), rechargeable sodium, lead-acid, nickel-metal hydride, nickel-cadmium, and other) and includes batteries from end-of-life vehicles and WEEE for the 27 Member States of the European Union (EU27) plus Iceland, Norway, Switzerland and the United Kingdom (EU27+4). Results are presented for the period 2010–2050 under three scenarios: business-as-usual (BAU), recovery (REC), and circularity (CIR).
- **Method:** Trends are derived using a combination of composition information of battery products with stock and flow and recovery models. The presented CRMs combine the most abundant materials with those that have available recoverability data.
- **Disclaimer/limitations:** The analysis is subject to some data limitations. Producer Responsibility Organisations data required the use of extrapolations. Battery-grade quality of recovered secondary raw materials from cathode-active materials was not assessed. Consistent integration of data from multiple sources was not possible and estimates for light means of transport and industrial batteries rely on single sources and related assumptions. Finally, second-life electric vehicle (EV) batteries were excluded from the estimation of waste generated.
- **Data sources:**
  - composition data: ProSUM project, public datasets, manufacturer datasheets, BattPacV5.1 for EV battery packs (Knehr et al., 2022) and scientific literature.
  - stock and flow data: national statistics offices and commercial and public databases.
  - recovery model data: scientific literature and expert assumptions.
- **Further information can be found in:** Milestone M23 'Methodology paper - Composition data collection and consolidation', Deliverable D3.1 'Extended waste stream composition assessment to enable secondary raw materials assessment', Deliverable D4.1 'Future trends of secondary raw materials and critical raw materials'.

Recoverability Assessment of important Critical Raw Materials (CRMs) in waste batteries

- **Scope:** The assessment focuses on CRMs (Al, Cu, Co, Graphite, Li, Mn, Ni, P) contained in batteries and their main applications. The analysis considers present and tested recovery technologies, considering different Technology Readiness Levels (TRLs).
- **Method:** Recoverability is evaluated through a barrier and enabler analysis according to different criteria in five categories: design-specific, waste-flow-specific, technical, economic, and environmental and legal.
- **Disclaimer/limitations:** The assessment is qualitative and had to deal with a lack of sufficient information to evaluate according to certain criteria.
- **Data sources:** The evaluation is based on FutuRaM modelling results, JRC reports, scientific literature, and expert judgment from stakeholders.
- **Further information can be found in:** Deliverable D3.1 'Extended waste stream composition assessment to enable secondary raw materials assessment'.

Environmental and socio-economic impacts of treating waste batteries and secondary raw materials recovery

- **Scope:** The analysis covers eight different battery types: rechargeable Li-ion, primary lithium, zinc-based, lead-acid, nickel-metal hydride, and nickel-cadmium, with the rechargeable Li-ion batteries further separated by cathode chemistry. The geographic scope is EU27+4. Results are presented for the period 2020–2050 under three scenarios: BAU, REC, and CIR. The scope of the assessment includes mechanical and thermal pre-treatment, thermal treatment (pyrometallurgy), chemical treatment (hydrometallurgy), and refurbishing of batteries.
- **Method:** Life Cycle Assessment (LCA) conducted using 1 kilogram of batteries product-treated as functional units, with impact categories selected according to the Environmental Footprint (EF) 3.0 method.
- **Disclaimer/limitations:** By placing our focus on the waste treatment system itself, life cycle stages such as mining, production, and use of batteries are excluded.
- **Data sources:** The assessment builds on the material flows analysis conducted to estimate the future trends of secondary raw materials and CRMs in waste batteries (see first section above), as well as a literature review, expert assessments, and reports by statistical agencies.
- **Further information can be found in:** Deliverable D2.1 'Environmental and socio-economic barriers, trade-offs and benefits to secondary raw materials recovery'.

United Nations Framework Classification (UNFC) of recovery projects

- **Scope:** The case studies examined the recovery of selected CRMs: black mass (Li, Ni, Co, Mn, Cu) in the site-specific case study; Li, Al, and Cu in the national-level case study. It includes one site-specific case study at a recycling plant in Switzerland on Li-ion batteries in end-of-life vehicles and one national-level case study on CRMs recycling from Lithium-Iron-Phosphate (LFP) batteries in Germany. The purpose of the site-specific and national case studies was to analyse the current state of implementation of recycling technologies.
- **Method:** A five-step screening procedure and a seven-stage procedure were applied at the site-specific level. At the national level, material flow analysis was combined with a UNFC-compliant approach using statistics and sectoral data.
- **Disclaimer/limitations:** Results are sensitive to site-specific assumptions, data availability, and current technological configurations.

- **Data sources:** The case studies rely on multiple data sources, including national statistics and reporting systems, operational data from waste treatment operators, project datasets, scientific literature, and expert judgment to support the estimation of material flows and recovery potentials.
- **Further information can be found in:** Deliverable D5.1 'Reports of case studies for secondary raw materials assessment availability assessment in alignment with the UNFC'.

* 'Secondary raw materials' are raw materials recovered from a secondary source, i.e. waste, instead of being obtained from a primary source, i.e. an ore, and have undergone all necessary treatment steps to substitute primary raw materials. However, the CRMs from those secondary raw materials might not necessarily be functionally recycled, i.e. when they have the same functions and applications as materials obtained from primary sources.

Future trends of secondary and critical raw materials (CRMs) in waste batteries

Waste generated

1.8 Mt/year in 2022

In 2022: 106 kt/year of CRMs
In 2050: 1.2 Mt/year
to 1.5 Mt/year of CRMs

Not recovered as secondary raw materials

0.6 Mt/year in 2022
(33% of waste generated)

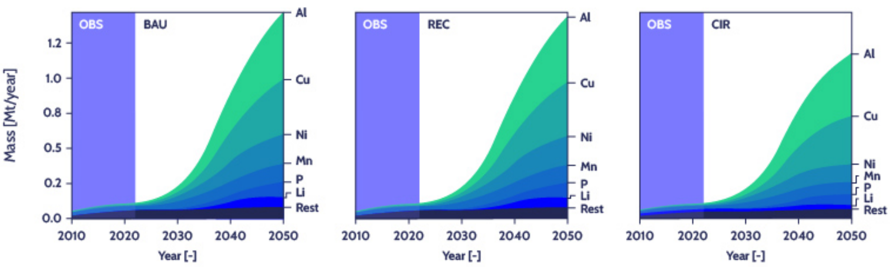
In 2022: 69 kt/year of CRMs
In 2050: 223 kt/year
to 640 kt/year of CRMs

Secondary raw materials

1.2 Mt/year in 2022
(67% of waste generated)

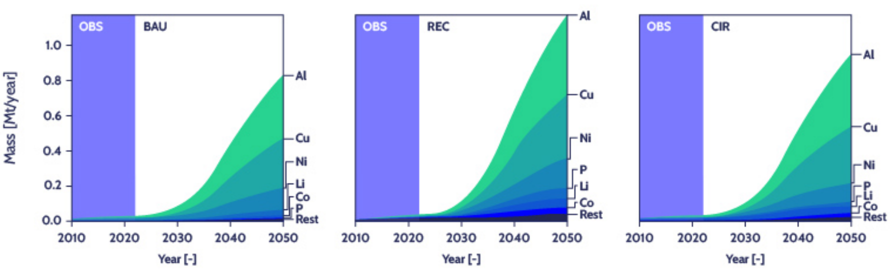
In 2022: 37 kt/year of CRMs
In 2050: 827 kt/year
to 1.2 Mt/year of CRMs

Outlook to 2050 of most significant CRMs in waste generated



The total amount of CRMs embedded in waste generated is dominated in mass by aluminium (450-480 kt/year in 2050) and copper (346–386 kt/year in 2050). Other CRMs with significant mass include nickel, manganese, phosphorus and lithium. CRM quantities embedded in waste generated are the same under BAU and REC scenarios, and in both cases are higher than in the CIR scenario.

Outlook to 2050 of most significant CRMs in secondary raw materials



CRMs in secondary raw materials are dominated by aluminium (360-450 kt/year in 2050) and copper (290–360 kt/year in 2050).
The highest quantities of CRMs are present under the REC scenario. In the CIR scenario, CRM recovery can be equivalent to BAU scenario, albeit with less waste generated.

Al Total in secondary raw materials: 3.4 kt/year in 2022, increasing from 360 kt/year to 420 kt/year in 2050. Mostly from battery pack; cathode current collector and casing are already recovered.

Cu Total in secondary raw materials: 3.9 kt/year in 2022, increasing from 290 kt/year to 360 kt/year in 2050. Most copper from anode current collector and cables already recovered.

Ni Total in secondary raw materials: 4.3 kt/year in 2022, increasing from 105 kt/year to 170 kt/year in 2050. High recoverable potential from cathode active material.

Li Total in secondary raw materials: 90 t/year in 2022, increasing from 30 kt/year to 50 kt/year in 2050. Limited recoverability from cathode active material.

P Total in secondary raw materials: 0.2 t/year in 2022, increasing from 32 kt/year to 56 kt/year in 2050. Low recoverability from cathode active material.

- Already recovered
- High recoverable potential
- Limited recoverability
- Low recoverability

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Recoverability Assessment of important Critical Raw Materials (CRMs) in waste batteries

CRM	Application within the Waste Stream
Li	Cathode active material in Li rechargeable batteries
Co	Cathode active material in Li rechargeable batteries
Graphite	Anode active material in Li rechargeable batteries
Ni	Cathode active material in Li rechargeable batteries
Al	Battery pack parts, cathode current collector and casing in Li rechargeable batteries
Cu	Anode current collector and cables in Li rechargeable batteries
P	Cathode active material in Li rechargeable batteries
Mn	Cathode active material in Li rechargeable batteries

Already recovered
High recoverable potential
Limited recoverability
Low recoverability

Enabling Conditions for improving Recoverability

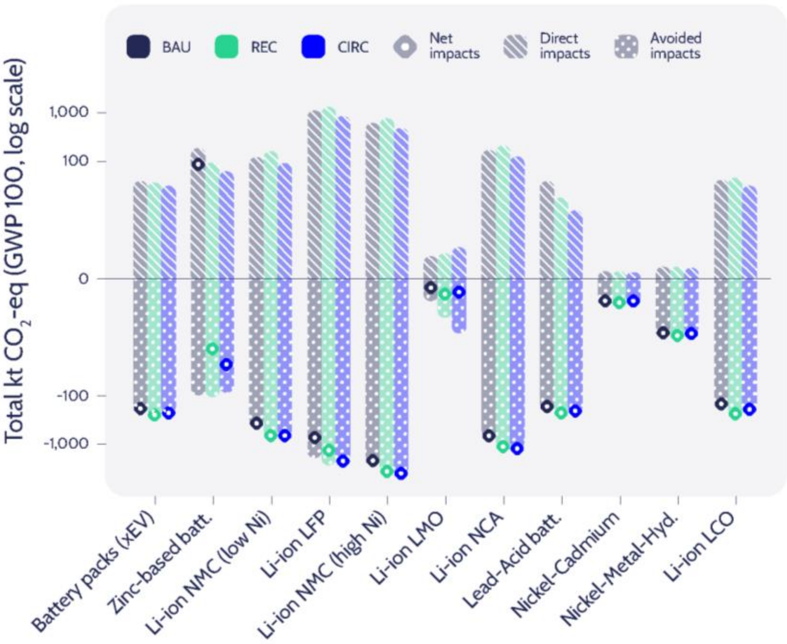
- Standardisation of battery cells, modules and packs, facilitating easy disassembly.
- The Battery Regulation (EU) 2023/1542 as a strong legislative instrument to regulate, among other things, the overall recycling and the recovery of certain elements as well as the incorporation of recyclates in new products increasing future demand (through collection rates, recycling efficiency targets, recycled content requirements, and battery passport).
- More dedicated recycling capacities for CRM recovery.
- Better identification and sorting by Li-ion cathode chemistry improves recovery potential.
- Increased demand of recyclates pushes recycling and recovery activities.

Environmental and socio-economic impacts of treating waste batteries and recovering secondary raw materials

	2020	2050		
	OBS	BAU	REC	CIR
Net CO_2-eq:	-0.70 Mt	-4.38 Mt (-600% vs 2020)	-7.59 Mt (-1100% vs 2020)	-8.83 Mt (-1200% vs 2020)
Direct CO_2-eq:	0.30 Mt	2.29 Mt (+700% vs 2020)	2.62 Mt (+800% vs 2020)	1.64 Mt (+500% vs 2020)
Avoided CO_2-eq:	-1.00 Mt	-6.67 Mt (-600% vs 2020)	-10.21 Mt (-900% vs 2020)	-10.47 Mt (-900% vs 2020)

Direct impacts include impacts of material recovery through recycling, as well as repurposing of batteries, including required reagents, transport, produced wastes, and energy use. Avoided impacts are impacts mitigated by avoiding production of materials by recovering or repurposing materials from batteries, and net impacts are the sum of avoided and direct impacts.

Comparing climate impacts across materials by scenario in 2050

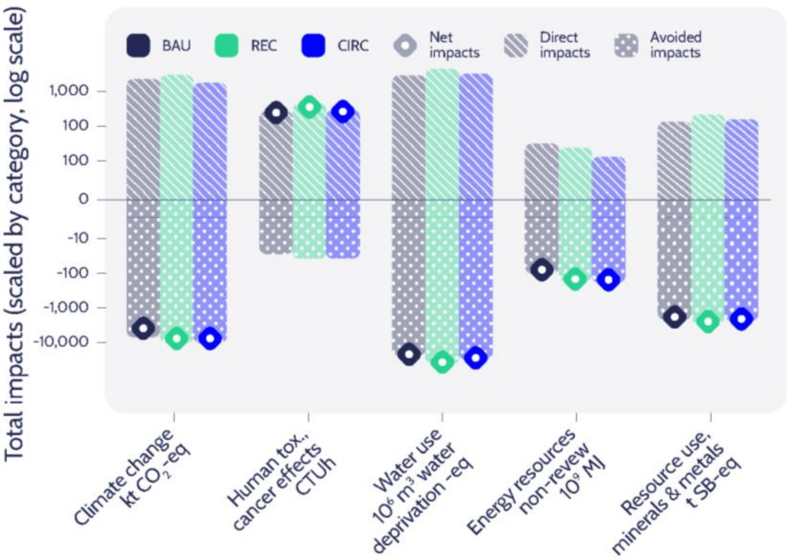


While only contributing a small fraction of impacts in 2020, emissions attributed to Li-ion battery recycling are projected to exceed that of recycling all other battery types combined by 2050.

Greenhouse gas emissions from the recycling of lithium-iron-phosphate (LFP) and nickel-manganese-cobalt (NMC) batteries contribute the most to emissions of recycling as well as to potential mitigated emissions.

Strong contributors to climate impact are the heat and electricity required for recycling, and the strongest contributors for avoided emissions are the recovery of cobalt and nickel, together with the potential reuse of battery cathode and anode materials through direct recycling or refurbishment.

Comparing impacts across selected categories by scenario in 2050



The waste batteries treatment in the REC and CIR scenarios is projected to decrease net impact across all impact categories by 2050 when compared to BAU scenario. The highest potential for impact reduction between scenarios comes from increasing the potential to reuse EV batteries in grid applications, followed by decarbonization of heat and electricity sources used in recycling, and scaling up EU hydrometallurgical and direct recycling capacity for Li-ion batteries.

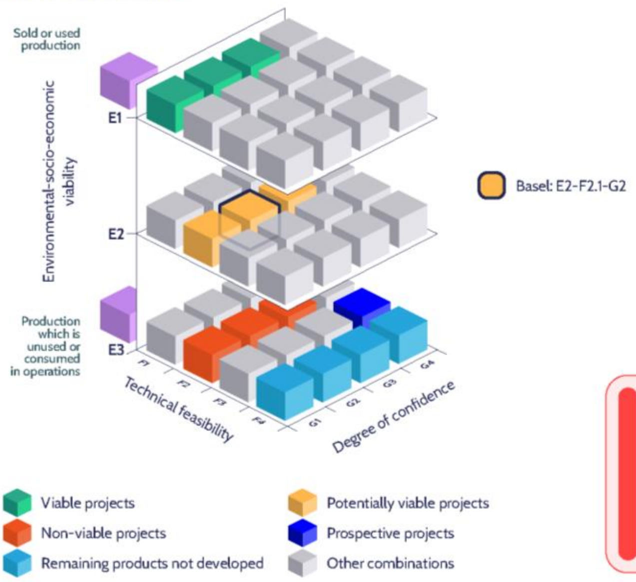
United Nations Framework Classification (UNFC) of recovery projects

UNFC site-specific case studies

Case study	SRMs/CRMs	Waste input	Recoverable Quantity
BEV Li-ion battery recycling, Basel, SWITZERLAND	Black mass (Li, Ni, Co, Mn, Cu)	~ 320 kt	~ 80 kt

This case study evaluates the recovery potential of **black mass** from **end-of-life lithium-ion batteries from battery electric vehicles (BEVs)**.
It focusses on a newly constructed processing facility in Switzerland operated by the Company LIBREC.

UNFC Results:



Key barriers

- Variability in Li-ion battery chemistries and formats
- Limited long-term certainty on feedstock quantities

Key enablers

- Strong regulatory framework
- Stable investment climate
- Growing market demand for recycled black mass
- High technology readiness level

UNFC national-level case study - Germany

Lithium-Iron-Phosphate Batteries in Germany (Li, Al, Cu)

This national-level case study evaluates the **potential recovery of critical raw materials (CRMs) from lithium-ion batteries in Germany** using a **top-down material flow analysis (MFA)** approach, **showing that while recovery of some materials is feasible, limitations remain for critical elements such as lithium, requiring further development of refining capacity and system integration**.

Key findings:

1. **Current recycling infrastructure limits recovery**
   Existing recycling routes are dominated by mechanical treatment processes that produce black mass, with limited refining capacity.
2. **Li recovery remains limited**
   Li is not recovered in the current recycling system. Recovery becomes only feasible with future refining capacities.
3. **Higher recovery for Cu and Al**
   Recovery efficiencies for Cu and Al can reach around 80-90 % in advanced recycling routes. However, losses still occur during mechanical processing and when black mass is exported outside the system.

3.2 Construction and demolition waste from buildings

Selected key results for construction and demolition waste from buildings are presented across four infographic pages. The table below summarises the scope, methodology, limitations and key deliverables for each. For full results, methodological details, and assumptions, readers are invited to read the corresponding project reports and datasets, which are listed below.

Future trends of secondary* and critical raw materials (CRMs) in construction and demolition waste from buildings

- **Scope:** The analysis covers two building types for the 27 Member States of the European Union (EU27): residential and non-residential. Iceland, Norway, Switzerland, and the United Kingdom are not included due to lack of data. Results are presented for the period 2010–2050 under three scenarios: business-as-usual (BAU), recovery (REC) and circularity (CIR).
- **Method:** Trends are derived using the stock and flow approach, where building group-specific data, material intensities, and building classifications are combined with survival functions and data from Eurostat and literature to estimate waste flows and secondary raw materials over time. The presented CRMs combine the most abundant materials with those that have available recoverability data.
- **Disclaimer/limitations:** The model was limited by incomplete, aggregated, and probabilistic data. Material composition was assumed at EU27 averages, ignoring regional or building-type differences. The construction and renovation waste is not fully captured. Moreover, it was assumed that all waste generated is collected. Finally, data was harmonised to the reference year 2022, which was used in the BAU scenario.
- **Data sources:**
  - composition data: scientific database.
  - stock and flow data: scientific and intergovernmental database.
  - recovery model data: national statistics offices and literature review.
- **Further information can be found in:** Milestone M23 'Methodology paper - Composition data collection and consolidation', Deliverable D3.1 'Extended waste stream composition assessment to enable secondary raw materials assessment', Deliverable D4.1 'Future trends of secondary raw materials and critical raw materials'.

Recoverability Assessment of important Critical Raw Materials (CRMs) in construction and demolition waste from buildings

- **Scope:** The assessment focuses on CRMs as Al, Cu, Ni, Sb + B, Li, B / borate, As, REE, alloying elements (Cu, Mg, Mn, Si, Ti) contained in construction and demolition waste and their main applications. The analysis considers present and tested recovery technologies, considering different Technology Readiness Levels (TRLs).
- **Method:** Recoverability is evaluated through a barrier and enabler analysis according to different criteria in five categories: design-specific, waste-flow-specific, technical, economic, and environmental and legal.
- **Disclaimer/limitations:** The assessment is qualitative and had to deal with a lack of sufficient information to evaluate according to certain criteria.
- **Data sources:** The evaluation is based on FutuRaM composition datasets, factsheets from the SCRREEN2 project, and scientific and grey literature.
- **Further information can be found in:** Deliverable D3.1 'Extended waste stream composition assessment to enable secondary raw materials assessment'.

Environmental and socio-economic impacts of treating construction and demolition waste from buildings and secondary raw materials recovery

- **Scope:** The analysis covers several metals (aluminium, copper, steel) and non-metal materials (brick, ceramics, etc.) for EU27. Iceland, Norway, Switzerland, and the United Kingdom are not included due to lack of data. Results are presented for the period 2010–2050 under three scenarios: BAU, REC, and CIR. The assessment focuses on all waste treatment operations.
- **Method:** Life Cycle Assessment (LCA) conducted using 1 kilogram of construction and demolition waste from buildings' materials treated as functional unit expanded to full EU27 waste flows. The impact categories were selected according to the Environmental Footprint (EF) 3.0 method.
- **Disclaimer/limitations:** The LCA was limited by the availability of data on waste treatment processes. The avoided impacts from substitution were estimated, as markets were not modelled and quality specifications were unknown. This may lead to an overestimation of avoided impacts, particularly when high recycling shares are assumed in the REC and CIR scenarios.
- **Data sources:** The assessment builds on the material flows analysis conducted to estimate the future trends of secondary raw materials and CRMs in construction and demolition waste from buildings (see first section above), in combination with commercial LCA data and literature review.
- **Further information can be found in:** Deliverable D2.1 'Environmental and socio-economic barriers, trade-offs and benefits to secondary raw materials recovery'.

United Nations Framework Classification (UNFC) of recovery projects

- **Scope:** The case studies examined the recovery of selected CRMs (Al, Cu, Fe & steel and other metals + secondary brick and aggregate, timber, flat glass, and gypsum). It includes two site-specific case studies in the UK and a site-specific case study in the Netherlands.
- **Method:** The UNFC is applied through a five-step screening procedure and seven-stage procedure for assessing the UNFC class based on project-level data.
- **Disclaimer/limitations:** Results are sensitive to site-specific assumptions, data availability and current technological configurations.
- **Data sources:** The case studies rely on multiple data sources, including national statistics and reporting systems, operational data from waste treatment operators, project datasets, scientific literature, and expert judgment to support the estimation of material flows and recovery potentials.
- **Further information can be found in:** Deliverable D5.1 'Reports of case studies for secondary raw materials assessment availability assessment in alignment with the UNFC'.

* 'Secondary raw materials' are raw materials recovered from a secondary source, i.e. waste, instead of being obtained from a primary source, i.e. an ore, and have undergone all necessary treatment steps to substitute primary raw materials. However, the CRMs from those secondary raw materials might not necessarily be functionally recycled, i.e. when they have the same functions and applications as materials obtained from primary sources.

Future trends of secondary and critical raw materials (CRMs) in construction and demolition waste from buildings

Waste generated

412 Mt/year in 2022

In 2022: 225 kt/year of CRMs
In 2050: 415 kt/year of CRMs

Not recovered as secondary raw materials

132 Mt/year in 2022
(32% of waste generated)

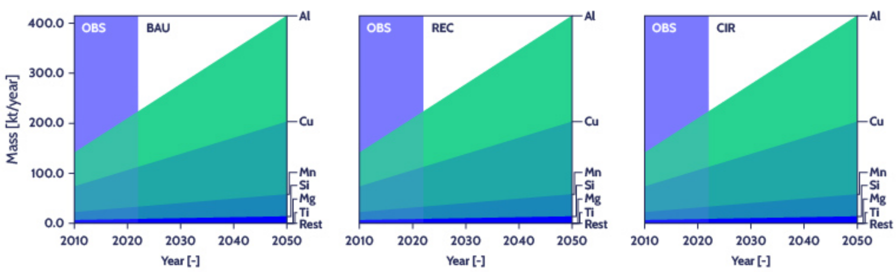
In 2022: 5 kt/year of CRMs
In 2050: 0 kt/year
to 10 kt/year of CRMs

Secondary raw materials

280 Mt/year in 2022
(68% of waste generated)

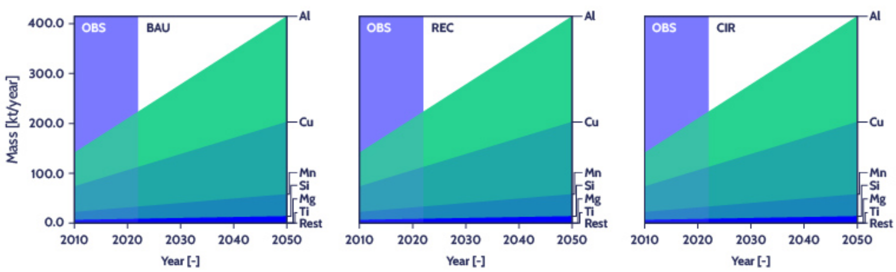
In 2022: 220 kt/year of CRMs
In 2050: 405 kt/year
to 415 kt/year of CRMs

Outlook to 2050 of most significant CRMs in waste generated



The total amount of CRMs embedded in waste generated is dominated in mass by aluminium (~210 kt/year in 2050) and copper (~145 kt/year in 2050). Other CRMs with significant mass include manganese, silicon metal, magnesium, and titanium that are found in metals as alloying elements. CRM quantities embedded in waste generated are the same under BAU and REC scenarios, and in both cases are higher than in the CIR scenario.

Outlook to 2050 of most significant CRMs in secondary raw materials



CRMs in secondary raw materials are dominated by aluminium (~210 kt/year in 2050) and copper (~145 kt/year in 2050). The quantities of CRMs available under the three scenarios are equivalent.

Al Total in secondary raw materials: 110 kt/year in 2022, increasing to ~210 kt/year in 2050. Most Al from alloys in structural components is already recovered.

Cu Total in secondary raw materials: 80 kt/year in 2022, increasing to ~145 kt/year in 2050. Most copper from cables is already recovered. Limited recoverability from other alloys.

Mn Total in secondary raw materials: 25 kt/year in 2022, increasing to ~45 kt/year in 2050. Limited recoverability from alloys in structural components.

Si Total in secondary raw materials: 6 kt/year in 2022, increasing to ~11 kt/year in 2050. Limited recoverability from alloys in structural components.

Mg Total in secondary raw materials: 950 t/year in 2022, increasing to ~2 kt/year in 2050. Limited recoverability from alloys in structural components.

- Already recovered
- High recoverable potential
- Limited recoverability
- Low recoverability

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Recoverability Assessment of important Critical Raw Materials (CRMs) in construction and demolition waste from buildings

CRM	Application within the Waste Stream
Ni (alloying element)	Stainless steel in beams, columns, supports, roof structures, frames, cladding, and roofing in buildings
Al	Aluminium alloys in windows, doors, cladding, roofing, and structural components of buildings
Cu, Mg, Mn, Si, T (alloying elements)	Alloying elements in aluminium alloys in windows, doors, cladding, roofing, and structural components of buildings
Cu	Cables in buildings
Sb + B (zinc borate)	Flame retardant in cable sheathing
Sb + B (zinc borate)	Flame retardant in plastic flooring and roofing membranes
Sb + B (zinc borate)	Flame retardant in EPS insulation (thermoplastic rigid panels)
Sb + B (zinc borate)	Flame retardant in PUR insulation (thermoset rigid panels)
Li	Additive in concrete to prevent alkali-silica-reaction
B (borate salts)	Preservative in wood
Rare Earth Elements	Tiles and ceramics
Li	Tiles and ceramics
B / borate	Tiles and ceramics
B / borate	Glass wool
Rare Earth Elements	Flat glass
Li	Flat glass
As	Flat glass

- Already recovered
- High recoverable potential
- Limited recoverability
- Low recoverability

Enabling Conditions for improving Recoverability

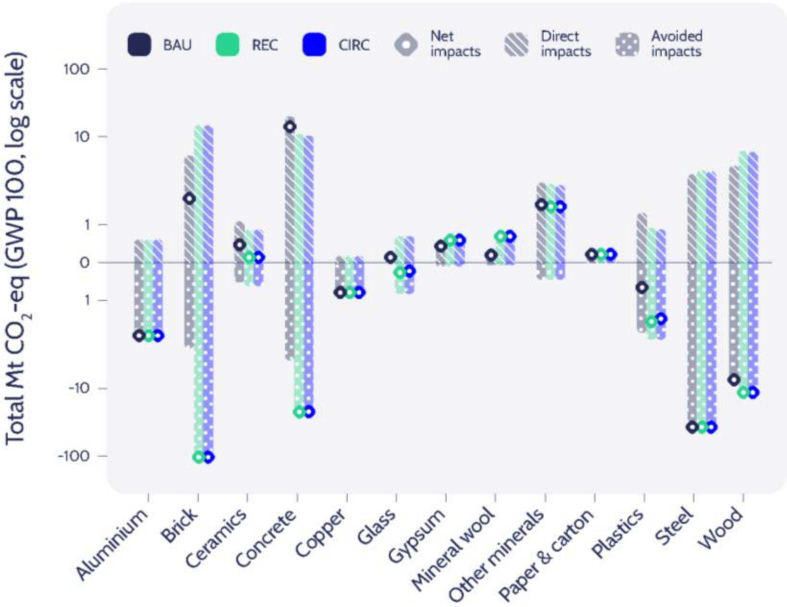
- Separate collection at source with further sorting beyond current practice, including more selective dismantling and advanced sorting technologies to increase high-quality and functional recycling.
- Application of sensor-based or XRF-based sorting technologies to increase high-quality and functional recycling.
- Material- or CRM-specific recovery targets to avoid open-loop/downcycling.

Environmental and socio-economic impacts of treating construction and demolition waste from buildings and recovering secondary raw materials

	2019	2050		
	OBS	**BAU**	**REC**	**CIR**
Net CO_2-eq:	-20 Mt	-40 Mt (-102% vs 2019)	-216 Mt (-994% vs 2019)	-213 Mt (-980% vs 2019)
Direct CO_2-eq:	27 Mt	54 Mt (+101% vs 2019)	58 Mt (+115% vs 2019)	57 Mt (+112% vs 2019)
Avoided CO_2-eq:	-47 Mt	-94 Mt (-101 vs 2019)	-274 Mt (-487% vs 2019)	-271 Mt (-479% vs 2019)

Results include all waste treatment (recycling, downcycling, energy recovery, incineration, landfilling).
Net impacts are broken down into direct impacts (i.e., process impacts from waste treatment itself) and avoided impacts (i.e., assumed substitution/displacement of primary materials reflected in a negative value), with net impacts showing the sum of both.

Comparing climate impacts across materials by scenario in 2050

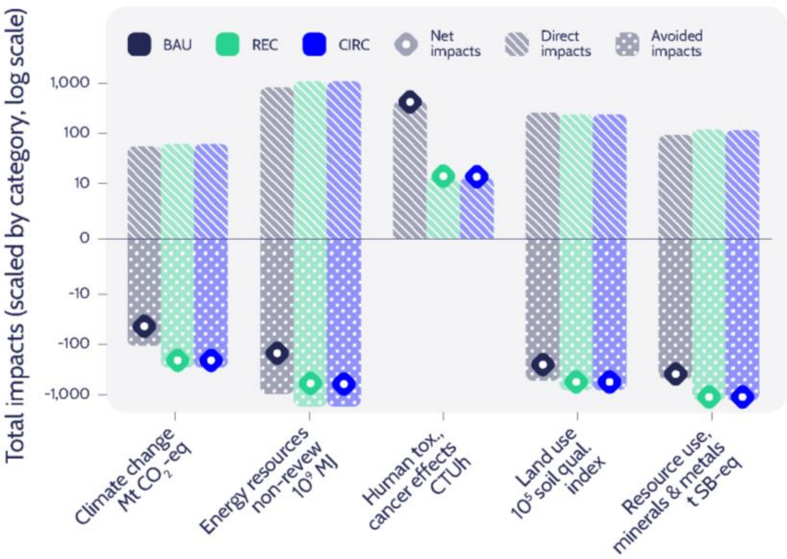


The highest potential for reduction of construction and demolition waste from buildings net climate impacts between the baseline BAU and the REC and CIR scenarios stems from *brick, ceramics* and *concrete*. In REC and CIR scenarios, a shift away from low-quality recycling and landfilling toward higher quality recycling generates substantial avoided impacts mostly through substitution of cementitious material (assuming recycled materials are of sufficient quality).

Metals (*steel, aluminium, copper*), by contrast, already achieve near-complete recovery under BAU, so scenarios converge. Yet metals still deliver among the largest absolute avoided impacts, reflecting the high climate impact of primary metal production.

For remaining materials, net impacts are comparatively small, due to lower volumes in the waste stream, and show limited variation between scenarios, as recycling rates are already relatively high or substitution benefits are limited.

Comparing impacts across selected categories by scenarios in 2050



Four selected impact categories, representative of the full set of 16 evaluated, are shown. REC and CIR scenarios reduce net impacts across all categories compared to BAU.

The reduction is especially prominent for resource use (minerals and metals), driven by higher raw material recovery displacing primary extraction.

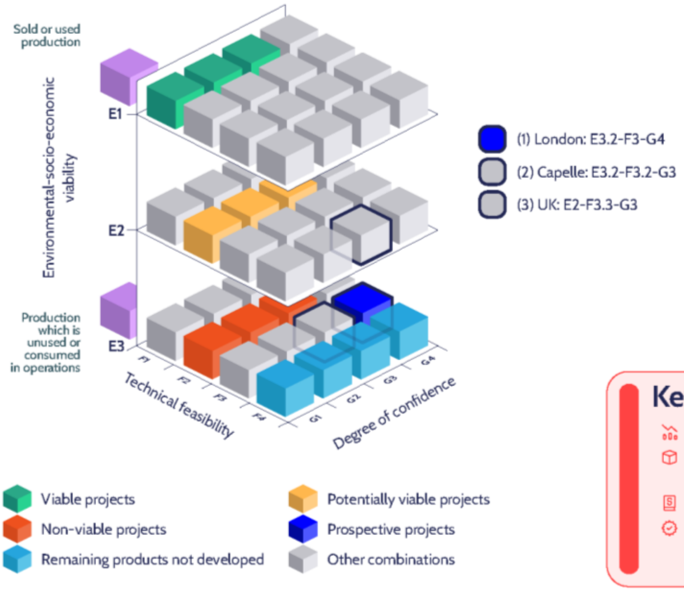
For energy resources, direct impacts are higher in REC and CIR than in BAU, reflecting the additional energy required for recycling processes. However, once avoided impacts from substituting energy-intensive primary production are accounted for, and net impacts are lower.

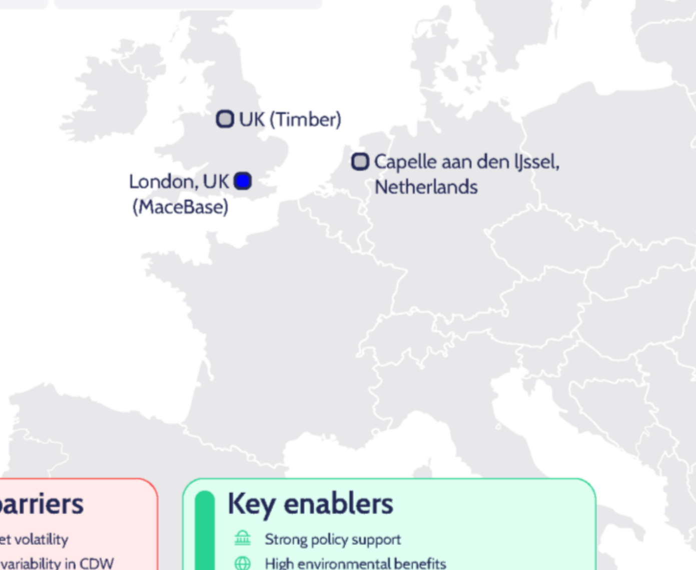
United Nations Framework Classification (UNFC) of recovery projects

UNFC site-specific case studies

Case study	SRMs/CRMs	Waste input	Recoverable Quantity
(1) CDW recovery - MaceBase project, London, UNITED KINGDOM	Bricks, aggregates, metals	~ 1.81 kt	~ 18 t Bricks ~ 1.63 kt Aggregats ~ 105 t Metals
(2) Flat glass and gypsum recycling from CDW - Capelle aan den IJssel, NETHERLANDS	Flat glass, gypsum	~ 1.5 kt/year	~ 48 t/year Flat glass ~ 117 t/year Gypsum
(3) Waste timber recovery - UNITED KINGDOM	Recovered timber	~ 136 kt/year	~ 40 kt/year

UNFC Results:





Key barriers
- Market volatility
- High variability in CDW material quality
- Low data accuracy
- There is no certification pathway (for the reuse of recovered timber)

Key enablers
- Strong policy support
- High environmental benefits
- Using existing recycling infrastructure

UNFC national-level case studies

No national-level case studies were conducted for construction and demolition waste from buildings.

3.3 End-of-life vehicles

Selected key results for the end-of-life vehicles waste stream are presented across four infographic pages. The table below summarises the scope, methodology, limitations, and key deliverables for each. For full results, methodological details and assumptions, readers are invited to read the corresponding project reports and datasets, which are listed below.

Future trends of secondary* and critical raw materials (CRMs) in end-of-life vehicles

- **Scope:** The analysis covers Passenger cars (M1) and light commercial vehicles (N1) ≤ 3.5 tonnes, classified in eight different vehicle types (petrol, diesel, battery electric vehicle, hybrid electric vehicle, plug-in hybrid electric vehicle, liquefied petroleum gas, natural gas, and other), for the 27 Member States of the European Union (EU27) plus Iceland, Norway, Switzerland and the United Kingdom (EU27+4). Results are presented for the period 2010–2050 under three scenarios: business-as-usual (BAU), recovery (REC) and circularity (CIR).
- **Method:** Trends are derived using a combination of composition information of vehicle types with stock and flow and recovery models to estimate waste generation and secondary raw materials flows. The presented CRMs combine the most abundant materials with those that have available recoverability data.
- **Disclaimer/limitations:** Dynamic composition assumptions were adopted with limited recycling data, without any country level differences. Heavy-duty vehicles (e.g. categories N2 and N3) were excluded, while electric vehicles (EV) and starting, lighting, and ignition (SLI) batteries are calculated as components in vehicles but presented in the batteries waste stream. Additionally, the indicator 'not collected or recovered' refers to the vehicle gap, i.e. vehicles that leave the registered stock but do not enter formal treatment or documented export flows.
- **Data sources:**
  - composition data: Løvik, et al., (2021).
  - stock and flow data: national statistics office, non-profit scientific and industrial organisations.
  - recovery model data: literature review.
- **Further information can be found in:** Milestone M23 'Methodology paper - Composition data collection and consolidation', Deliverable D3.1 'Extended waste stream composition assessment to enable secondary raw materials assessment', Deliverable D4.1 'Future trends of secondary raw materials and critical raw materials'.

Recoverability Assessment of important Critical Raw Materials (CRMs) in end-of-life vehicles

- **Scope:** The assessment focuses on CRMs as rare earths elements (Nd, Pr, Dy, Tb), Al, alloying elements (Si, Mn, Al, B, Cu, Nb, V, P, Mg, Ni, Ti, Ga), Mg, Cu, La, Pt, Pd, Rh contained in end-of-life vehicles, and their key applications. The analysis considers present and tested recovery technologies, considering different Technology Readiness Levels (TRLs).
- **Method:** Recoverability is evaluated through a barrier and enabler analysis according to different criteria in five categories: design-specific, waste-flow-specific, technical, economic, and environmental and legal.
- **Disclaimer/limitations:** The assessment is qualitative and had to deal with a lack of sufficient information to evaluate according to certain criteria.
- **Data sources:** The evaluation is based on FutuRaM composition datasets, results of the EVA II project, reports from the automotive industry, scientific literature, factsheets from the SCRREEN2 project, and websites of companies specialised in the recycling of CRMs.

- **Further information can be found in:** Deliverable D3.1 'Extended waste stream composition assessment to enable secondary raw materials assessment'.

Environmental and socio-economic impacts of treating end-of-life vehicle and secondary raw materials recovery

- **Scope:** The analysis covers passenger cars and light commercial vehicles classified in seven different vehicle types for the EU27+4. Results are presented for the period 2010–2050 under three scenarios: BAU, REC, and CIR. The assessment focuses on pre-treatment operations in the formal sector, including dismantling, shredding, and separation.
- **Method:** Life Cycle Assessment (LCA) conducted using 1 kilogram of end-of-life vehicles treated as the functional unit, with impact categories selected according to the Environmental Footprint (EF) 3.0 method.
- **Disclaimer/limitations:** By placing our focus on the waste treatment system itself, life cycle stages such as mining, production, and use of batteries are excluded.
- **Data sources:** The assessment builds on the material flows analysis conducted to estimate the future trends of secondary raw materials and CRMs in end-of-life vehicles (see first section above), as well as a literature review, expert assessments, and reports by statistical agencies.
- **Further information can be found in:** Deliverable D2.1 'Environmental and socio-economic barriers, trade-offs and benefits to secondary raw materials recovery'.

United Nations Framework Classification (UNFC) of recovery projects

- Two site-specific projects were carried out to investigate the recovery of precious metals from waste electrical and electronic equipment (WEEE) and the recycling of lithium-ion batteries in end-of-life vehicles. The results are presented alongside the waste streams of batteries and WEEE.

* 'Secondary raw materials' are raw materials recovered from a secondary source, i.e. waste, instead of being obtained from a primary source, i.e. an ore, and have undergone all necessary treatment steps to substitute primary raw materials. However, the CRMs from those secondary raw materials might not necessarily be functionally recycled, i.e. when they have the same functions and applications as materials obtained from primary sources.

Future trends of secondary and critical raw materials (CRMs) in end-of-life vehicles

Waste generated

8.2 Mt/year in 2022

In 2022: 890 kt/year of CRMs
In 2050: 2.3 Mt/year
to 2.5 Mt/year of CRMs

Not recovered as secondary raw materials

0.7 Mt/year in 2022
(9% of waste generated)

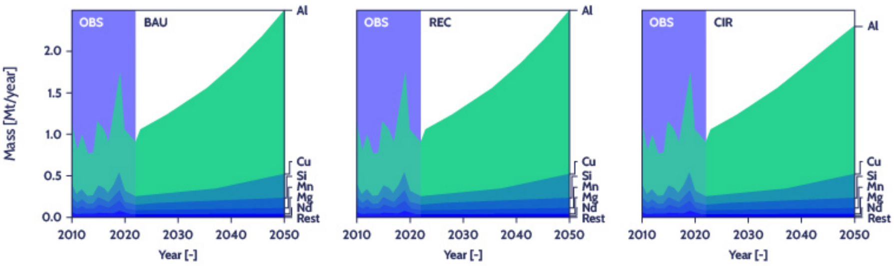
In 2022: 150 kt/year of CRMs
In 2050: 0 kt/year
to 650 kt/year of CRMs*

Secondary raw materials

7.5 Mt/year in 2022
(91% of waste generated)

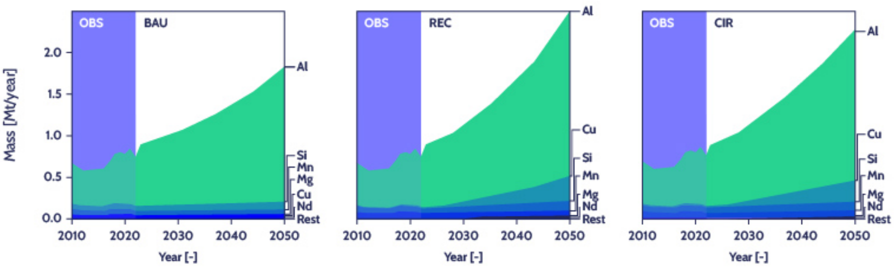
In 2022: 750 kt/year of CRMs
In 2050: 1.9 Mt/year
to 2.5 Mt/year of CRMs

Outlook to 2050 of most significant CRMs in waste generated



The total amount of CRMs embedded in waste generated is dominated in mass by aluminium (~1.8 Mt/year in 2050) and copper (~270 kt/year in 2050). Other CRMs with significant mass include silicon, manganese, magnesium, and neodymium. CRM quantities embedded in waste generated are the same under BAU and REC scenarios, and in both cases are higher than in the CIR scenario.

Outlook to 2050 of most significant CRMs in secondary raw materials



CRMs in secondary raw materials are dominated by aluminium (1.6–2.0 Mt/year in 2050) and copper (20–285 kt/year in 2050). The highest quantities of CRMs are available under the REC scenario, followed by CIR and BAU.

* By 2050, unrecovered CRMs are near zero in CIR/REC due to a largely closed vehicle gap through improved collection, while BAU remains above zero.

Al Total in secondary raw materials: 590 kt/year in 2022, increasing from 1.6 Mt/year to 1.9 Mt/year by 2050. Already recovered from cast aluminium in e.g. motor blocks, limited recoverability as alloying element in high strength steel and as wrought aluminium material.

Cu Total in secondary raw materials: 15 kt/year in 2022, increasing from 20 kt/year to 290 kt/year in 2050, mainly due to electrification (growth of electric traction motors) and embedded electronics from the 2022 baseline. Already recovered from motors, limited recoverability from embedded electronics and cast aluminium.

Mn Total in secondary raw materials: 50 kt/year in 2022, increasing from 60 kt/year to 70 kt/year in 2050. Limited recoverability from most applications.

Mg Total in secondary raw materials: 32 kt/year in 2022, increasing from 35 kt/year to 44 kt/year in 2050. Limited recoverability from magnesium alloys, cast aluminium in wheels and wrought aluminium.

Si Total in secondary raw materials: 56 kt/year in 2022, increasing from 97 kt/year to 120 kt/year in 2050. Limited recoverability from most applications.

- Already recovered
- Limited recoverability
- High recoverable potential
- Low recoverability

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Recoverability Assessment of important Critical Raw Materials (CRMs) in end-of-life vehicles

CRM	Application within the Waste Stream
Rare Earth Elements (Nd, Pr, Dy, Tb)	NdFeB-magnets (in electric and electric traction motors)
Si, Mn, Al, B, Cu, Nb, V, P (alloying elements)	Ultra-high strength steel (UHSS) and Advanced high strength steel (AHSS) in chassis (body-in-white)
Al*	Wrought aluminium (5000x, 6000x, 7000x series) in body-in-white
Si, Cu, Mg, Mn, Ni, Ti, Ga, V (alloying elements)	Wrought aluminium (5000x, 6000x, 7000x series) in body-in-white
Al*	Cast aluminium e.g. in motor blocks
Si, Mn, Ni, Ti, Cu, Mg (alloying elements)	Cast aluminium e.g. in motor blocks
Mg	Magnesium alloys (replacing wrought aluminium alloys)
Cu	Embedded electronics
Cu	Electric and electric traction motors
La	Catalytic converters
Pt, Pd, Rh	Catalytic converters

* Considering functional recycling at the material level.

- Already recovered
- High recoverable potential
- Limited recoverability
- Low recoverability

Enabling conditions for improving recoverability

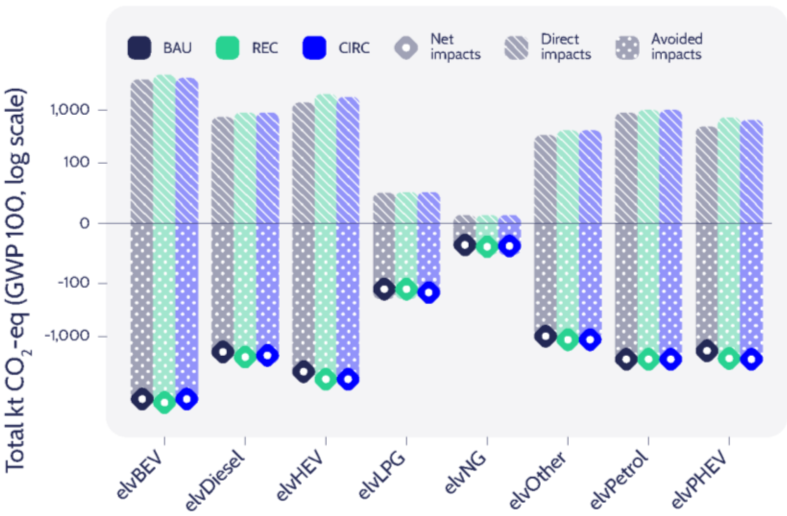
- High collection due to the regulatory aspects (ELV Directive 2000/53/EC).
- Concentration of the CRMs in specific components (e.g., copper and neodymium in electric traction motors).
- Application of sensor-based or XRF-based sorting technologies to increase high-quality and functional recycling, e.g. separation of different aluminium alloys and magnesium alloys.
- Development of logistics and infrastructure in the EU for recovery of specific components in all vehicles (embedded electronics) and in electric vehicles (traction motor, battery and cables).
- Disassembly and removal of electronics before further processing steps, e.g. shredding, to recover copper and other precious elements in printed circuit boards.

Environmental and socio-economic impacts of treating end-of-life vehicles and recovering secondary raw materials

	2020	2050		
	OBS	BAU	REC	CIR
Net CO_2-eq:	-13.1 Mt	-26.4 Mt (-101% vs 2020)	-32.1 Mt (-145% vs 2020)	-29.6 Mt (-126% vs 2020)
Direct CO_2-eq:	7.42 Mt	8.5 Mt (+14% vs 2020)	10.5 Mt (+42% vs 2020)	9.62 Mt (+30% vs 2020)
Avoided CO_2-eq:	-20.5 Mt	-34.9 Mt (-70% vs 2020)	-42.7 Mt (-108% vs 2020)	-39.2 Mt (-91% vs 2020)

Direct impacts include dismantling and shredding of vehicles as well as smelting of scrap into alloys (copper, iron and aluminium). Avoided impacts are impacts mitigated by avoiding production of raw materials by recovery of components and materials. This includes recovered components, after dismantling, as well as avoided impacts from production of copper, steel, and aluminium.

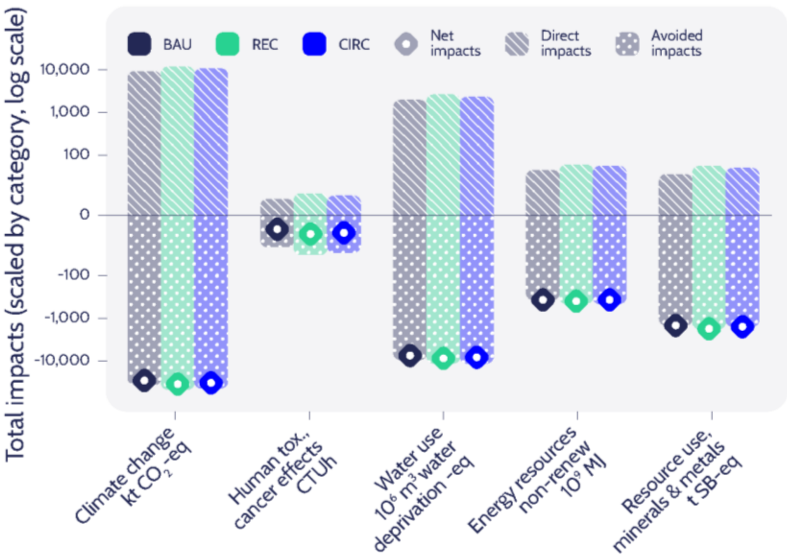
Comparing climate impacts across materials by scenario in 2050



By 2050, recycling of BEV vehicles contributes the highest direct, avoided and net impacts across all scenarios since this drivetrain dominates the end-of-life vehicles recovered. Avoided impacts exceed direct impacts of recycling for all vehicle types, indicating that recycling is more environmentally beneficial than other sources (e.g. mining of primary materials) of the same materials.

Direct impacts of recycling processes are driven by electricity use and heat used in the smelting of scrap. Avoided impacts are largely driven by the recovery of aluminium after dismantling and shredding, which has a relatively high greenhouse impact if it would be sourced as primary material from the market. The second process with a large contribution to avoided burdens is the production of steel from ferrous scrap. Aluminium and ferrous dominate the material composition of end-of-life vehicles.

Comparing impacts across selected categories by scenarios in 2050



Avoided impacts exceed net impacts for all impact categories, with a clear improvement in terms of resource and energy use due to material recovery. The REC scenario has higher direct as well as avoided impacts, driven by higher collection rates of end-of-life vehicles. The CIR scenario includes efforts to shift to smaller and lighter vehicles, which, by reducing the quantity of waste, leads to reduced direct and avoided impacts across all categories.

3.4 Mining waste

Selected key results for mining waste are presented across three infographic pages. The table below summarises the scope, methodology, limitations, and key deliverables for each. For full results, methodological details and assumptions, readers are invited to read the corresponding project reports and datasets, which are listed below.

Future trends of secondary* and critical raw materials (CRMs) in mining waste

- The analysis was not conducted for mining waste. For mining waste, only historical and closed mine waste stocks were considered based on a database compiled by geological services organisations in Europe and enriched during the FutuRaM project (GSEU, n.d.). Freshly generated mining waste is not included in the current database, as ongoing mining operations were not addressed within the scope of FutuRaM.

Recoverability Assessment of important Critical Raw Materials (CRMs) in mining waste

- **Scope:** The assessment focuses on CRMs Ba, Bi, Co, Cu, In, Mn, Phosphate rock, REE, Sb, and Ti; and Ag, Au, Co, Ga, In, Pb/Zn, Sb as by-products + Si from in mining waste sites in Sweden, Germany, Czech Republic, Finland, and Balkan region. The analysis considers present and tested recovery technologies, considering different Technology Readiness Levels (TRLs).
- **Method:** Recoverability is evaluated through a barrier and enabler analysis according to different criteria in five categories: design-specific, waste-flow-specific, technical, economic, and environmental and legal.
- **Disclaimer/limitations:** The assessment is qualitative and had to deal with a lack of sufficient information to evaluate according to certain criteria.
- **Data sources:** The evaluation is based on the MINERALS4EU database, studies from planned recovery projects at mining waste sites, and expert judgment from the involved geological surveys.
- **Further information can be found in:** Deliverable D3.1 'Extended waste stream composition assessment to enable secondary raw materials assessment'.

Environmental and socio-economic impacts of treating mining waste and secondary raw materials recovery

- **Scope:** The analysis focuses on the recovery processes from mining waste within the EU.
- **Method:** Life Cycle Assessment (LCA) was conducted through a literature review, identifying available life cycle inventories for recovery from mining waste and adapting available datasets to the EU context.
- **Disclaimer/limitations:** Available processes are at a low TRL and are in geographies that do not share the same policy and technological framework as the EU. As such, the results focus on highlighting potential hotspots for environmental impacts. Future analyses should incorporate site-specific assumptions to better reflect the diversity of processes.
- **Data sources:** Data regarding the environmental impacts of material recovery from mining waste was obtained from the literature review.
- **Further information can be found in:** Deliverable D2.1 'Environmental and socio-economic barriers, trade-offs and benefits to secondary raw materials recovery'.

United Nations Framework Classification (UNFC) of recovery projects

- **Scope:** The case studies examined the recovery of selected CRMs (Ag, Au, Bi, Co, Cu, Sb, Zn), as well as ilmenite and SiO_2. They include site-specific case studies in France, Finland, Serbia, and Sweden, and a national-level case study in Sweden based on sampling and geological data. The purpose of the national-level case study is to assess the recovery potential and identify opportunities for improving resource recovery from historical tailings and waste rock at the system level.
- **Method:** The UNFC is applied through a bottom–up approach, compiling and aggregating geological data across multiple mining sites into a national overview. As well, a seven-stage procedure was applied at the site-specific level.
- **Disclaimer/limitations:** Results are sensitive to site-specific assumptions, data availability, and current technological configurations. At the national level, variable data quality and recoverability not assessed.
- **Data sources:** The case studies rely on multiple data sources, including reporting systems, operational data from waste treatment operators, project datasets, scientific literature, and expert judgment to support the estimation of material flows and recovery potentials.
- **Further information can be found in:** Deliverable D5.1 'Reports of case studies for secondary raw materials assessment availability assessment in alignment with the UNFC'.

* 'Secondary raw materials' are raw materials recovered from a secondary source, i.e. waste, instead of being obtained from a primary source, i.e. an ore, and have undergone all necessary treatment steps to substitute primary raw materials. However, the CRMs from those secondary raw materials might not necessarily be functionally recycled, i.e. when they have the same functions and applications as materials obtained from primary sources.

Recoverability Assessment of important Critical Raw Materials (CRMs) in mining waste

CRM	Waste flow
Phosphate Rock	Together with REE, different mining waste sites in Sweden, age 400 years
Rare Earth Elements	REE often with phosphate rock, different mining waste sites in Sweden, age 400 years
Cu	Different historical mining waste sites in Sweden
Cu	Mining waste site Håkansboda, Sweden, age 700 years
Bi, Co	Mining waste site Håkansboda, Sweden, age 700 years
Si (Pb/Zn as by-product)	Mining waste site Laisvall, Sweden, deposited between 1940-2002
Cu (Ag and Au as by-product)	Bor (Field 1 and Field 2) tailings in Serbia, deposited between 1933-2003 during operation of old concentration plant at RTB Bor
Sb	Historical tailings in Balkan region (Lojane, Macedonia, possibly Zjača, Serbia and Gornje polje III, Kosovo)
In (as by-product of Au or Pb/Zn)	Historical tailings in Balkan region (Probištip I and Veles, North Macedonia; Lece, Serbia)
Ba (In, Ga, Co, Sb as by-products)	Bollrich tailings in Goslar, Germany, mining of about 1,000 years until 1988, flotation residuals processed between 1936-1988
Mn	Mining waste site Chvaletice, Czech Republic, deposited between 1951-1975 (Euro Manganese Project)
Ti	Mining waste site Otanmäki in Finland, tailings facility, deposited between 1953-1985 (Ilmenite Project)

High recoverable potential

Unclear

Low recoverability

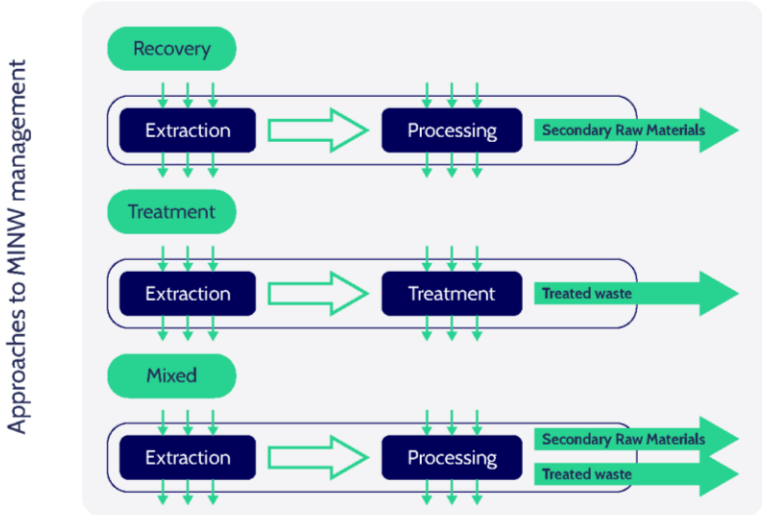
Enabling conditions for improving recoverability

- High grades and tonnage of the target CRM.
- Occurance in combination with other economically interesting raw materials (ranging from Zn, Au, and Ag to the material being used for industrial purposes such as aggregates, gypsum or cement).
- Mineralogy and grain size favouring low-cost liberation of the target CRM.
- Favourable site in terms of infrastructure and logistics, i.e. road or rail access, access to low-cost power/energy, nearby existing recovery plant (from primary mining), short distance from extractive site to recovery plant (cheap transport), and no/little conflict with other land uses.
- Waste management solutions for unrecovered rest fraction are available.
- Status as strategic project under the CRM Act.
- Functioning permitting procedures.

Environmental and socio-economic impacts of treating mining waste and recovering secondary raw materials

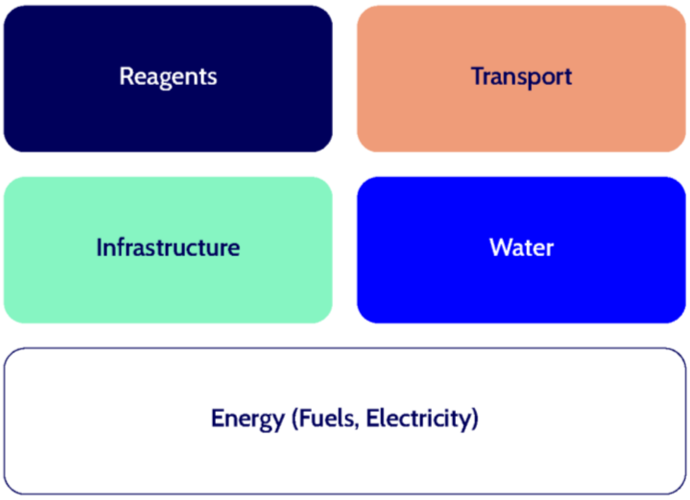
The study of potential environmental impacts of mining waste treatment, can be conducted from a life cycle perspective. Life cycle assessment (LCA) allows for analysing multiple approaches associated to the multiple objectives of mining waste management: raw material recovery, waste treatment, or a mix of both.

The treatment of mining waste from a life cycle perspective



Mining waste sites in Europe are widely diverse, covering multiple critical and non-CRMs. Processes for recovery are considered of low TRL due to the different compositions, relatively low concentrations, and potential high investment required. The development of LCAs of secondary raw materials obtained through mining waste treatment require detailed life cycle inventories that are mostly unavailable in the scientific literature.

Potential contributors to environmental impacts in raw material recovery



The estimation of the impacts of waste treatment and raw material recovery require the development of site-specific life cycle inventories, tailored to the location of the mining site, waste composition, the recovery processes, the targeted material and legislation.

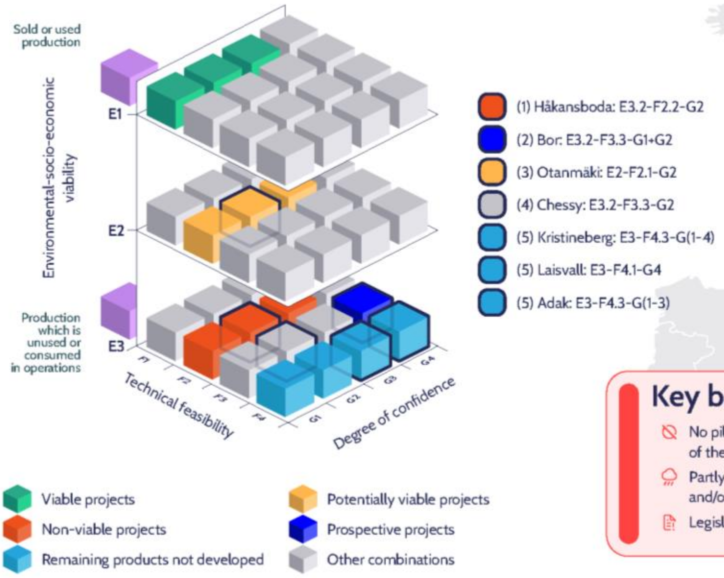
Available studies highlight the need for more transparent and detailed data to identify potential contributors to environmental impacts.

United Nations Framework Classification (UNFC) of recovery projects

UNFC site-specific case studies

Case study	SRMs/CRMs	Recoverable Quantity
(1) Håkansboda mining waste - SWEDEN	Ag, Au, Bi, Co, Cu, Sb	Not quantified
(2) Bor tailings - SERBIA	Ag, Au, Cu	~ 55 kt Cu; ~ 33 t Ag; ~ 9 t Au
(3) Otanmäki ilmenite tailings - FINLAND	Ilmenite (Ti)	~ 753 kt
(4) Chessy mine water liming wastes - FRANCE	Cu, Zn	~ 2 kt Cu; ~ 6.6 kt Zn
(5) Adak, Kristineberg, and Laisvall tailings - SWEDEN	Ag, Au, Cu, Co, Zn	Not quantified

UNFC Results:



Key barriers

- No pilot-scale demonstration of the recovery processes
- Partly uncertain environmental and/or social impacts
- Legislation is often unclear for recovery (1)

Key enablers

- Public and policy support
- Strong geological data
- Existing industrial infrastructure

UNFC national-level case study - Sweden

CRMs recovery from mining waste in Sweden

This national-level case study evaluates the **potential recovery of critical raw materials (CRMs) from mining waste deposits across Sweden,** focusing on both tailings and waste rock from historical mining activities, **indicating that while certain materials show recovery potential, further investigation of recoverability and clearer regulatory and economic conditions are needed to support viable project development.**

Key findings:

1. **Sampling density varies across sites**
   Sampling ranges from dense to sparse, with waste rock often well characterized and tailings showing a wide range of data density.
2. **Recovery potential depends on commodity and grade**
   Phosphate rock and rare earth elements show recovery potential based on grade and tonnage, while many other commodities remain below economic viability without existing plants or higher commodity price.
3. **Recoverability not yet assessed**
   In general, investigations focus on the UNFC G-axis, recoverability in terms of the criteria of the E- and F-axis were roughly estimated or only preliminary.

3.5 Slags and ashes

Selected key results for the slags and ashes waste stream are presented across five infographic pages. The table below summarises the scope, methodology, limitations, and key deliverables for each. For full results, methodological details, and assumptions, readers are invited to read the corresponding project reports and datasets, which are listed below.

Future trends of secondary* and critical raw materials (CRMs) in slags and ashes

- **Scope:** The analysis covers twenty different slags and ashes sub-streams covering metallurgical end-slags, metallurgical sludges, and incineration ashes for the 27 Member States of the European Union (EU27) plus Iceland, Norway, Switzerland and the United Kingdom (EU27+4). Results are presented for the period 2010–2050 under three scenarios: business-as-usual (BAU), recovery (REC) and circularity (CIR).
- **Method:** Trends are derived using stock and flow modelling based on production and waste statistics, combined with literature-based composition data and transfer coefficients to estimate waste generation and secondary raw materials flows. The presented CRMs combine the most abundant materials with those that have available recoverability data.
- **Disclaimer/limitations:** High heterogeneity and site-specific variability of slags and ashes and significant data gaps, with a limited differentiation between slag and ash sub-streams. Additionally, compositions are available at the element level only and recovery efficiencies are based largely on assumptions and expert judgment. Finally, harmonisation to the reference year 2022 was achieved using BAU scenario data.
- **Data sources:**
  - composition data: public databases, literature review.
  - stock and flow data: national statistics offices, public databases, literature review.
  - recovery model data: literature review.
- **Further information can be found in:** Milestone M23 ‘Methodology paper - Composition data collection and consolidation’, Deliverable D3.1 ‘Extended waste stream composition assessment to enable secondary raw materials assessment’, Deliverable D4.1 ‘Future trends of secondary raw materials and critical raw materials’.

Recoverability Assessment of important Critical Raw Materials (CRMs) in slags and ashes

- **Scope:** The assessment focuses on CRMs Al, Mg, Ti, Mn, Ni, Cu, P, PGMs, Co, Ge, Ga, In, V and rare earth elements embedded in their key applications. The analysis considers present and tested recovery technologies, considering different Technology Readiness Levels (TRLs).
- **Method:** Recoverability is evaluated through a waste-flow-specific barrier and enabler analysis according to different criteria in five categories: design-specific, waste-flow-specific, technical, economic, and environmental and legal.
- **Disclaimer/limitations:** The assessment is qualitative and had to deal with a lack of sufficient information to evaluate according to certain criteria.
- **Data sources:** The evaluation is based on FutuRaM modelling results, scientific literature, Best Available Techniques (BAT) reference documents, publications from sector federation and industrial companies, and relevant legislation.
- **Further information can be found in:** Deliverable D3.1 ‘Extended waste stream composition assessment to enable secondary raw materials assessment’.

Environmental and socio-economic impacts of treating sewage sludge and municipal solid waste incineration ashes and secondary raw materials recovery

- **Scope:** The analysis covers municipal solid waste incineration and sewage sludge mono-incineration for the EU27+4. Results are presented for the period 2010–2050 under three scenarios: BAU, REC, and CIR.
- **Method:** Life Cycle Assessment (LCA) conducted using 1 kilogram of waste treated for municipal solid waste incineration and 1 kilogram of phosphorus recovered from dry sewage sludge ashes as functional unit, with impact categories selected according to the Environmental Footprint (EF) 3.0 method.
- **Disclaimer/limitations:** Information on the substitution rates of feedstocks of primary materials with secondary materials produced from ashes is limited. For the sewage sludge, the environmental analysis was limited to the phosphorus recovery process (AshDec technology) and did not quantify systemic differences (governance- or market-related) between the REC and CIR scenarios. Due to the lack of scenario-specific life cycle inventory data to differentiate them, both were modelled with identical impacts; therefore, any distinction between them is conceptual and strategic and is not based on differences in environmental burden metrics.
- **Data sources:** The assessment builds on the material flows analysis conducted to estimate the future trends of secondary raw materials and CRMs in slags and ashes (see first section above), as well as a literature review, expert assessments, and reports by statistical agencies.
- **Further information can be found in:** Deliverable D2.1 'Environmental and socio-economic barriers, trade-offs and benefits to secondary raw materials recovery'.

United Nations Framework Classification (UNFC) of recovery projects

- **Scope:** The case studies examined the recovery of selected CRMs (P, Cr, V). They include three site-specific case studies in Belgium, France, and Germany and one national-level case study on P recovery from sewage sludge ashes in Germany. The purpose of the national-level case study is to assess the recovery potential and identify opportunities for improving P recovery at the system level.
- **Method:** The UNFC is applied and combined with the FutuRaM approach, material flow analysis, and industrial data at the national level, and through a five-step screening and seven-stage procedure at the site-specific level. At the national level, material flow analysis was combined with a UNFC-compliant approach using statistics and sectoral data.
- **Disclaimer/limitations:** Results are sensitive to site-specific assumptions, data availability, and current technological configurations.
- **Data sources:** The case studies rely on multiple data sources, including national statistics and reporting systems, operational data from waste treatment operators, project datasets, scientific literature, and expert judgment to support the estimation of material flows and recovery potentials.
- **Further information can be found in:** Deliverable D5.1 'Reports of case studies for secondary raw materials assessment availability assessment in alignment with the UNFC'.

* 'Secondary raw materials' are raw materials recovered from a secondary source, i.e. waste, instead of being obtained from a primary source, i.e. an ore, and have undergone all necessary treatment steps to substitute primary raw materials. However, the CRMs from those secondary raw materials might not necessarily be functionally recycled, i.e. when they have the same functions and applications as materials obtained from primary sources.

Future trends of secondary and critical raw materials (CRMs) in slags and ashes

Waste generated

69 Mt/year in 2022

In 2022: 5.5 Mt/year of CRMs
In 2050: 5.5 Mt/year to 6.2 Mt/year of CRMs

Not recovered as secondary raw materials

53 Mt/year in 2022
(77% of waste generated)

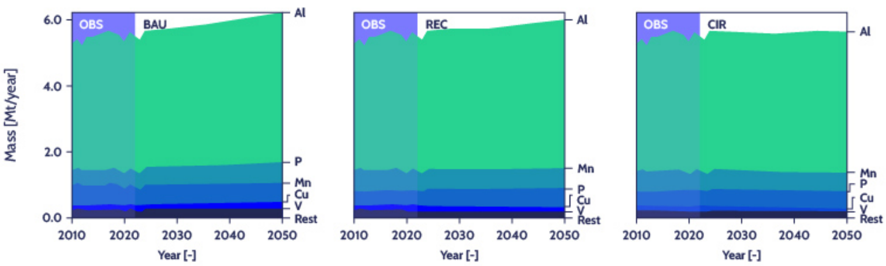
In 2022: 4.2 Mt/year of CRMs
In 2050: 3.5 Mt/year to 4.7 Mt/year of CRMs

Secondary raw materials

16 Mt/year in 2022
(23% of waste generated)

In 2022: 1.3 Mt/year of CRMs
In 2050: 1.5 Mt/year to 2.2 Mt/year of CRMs

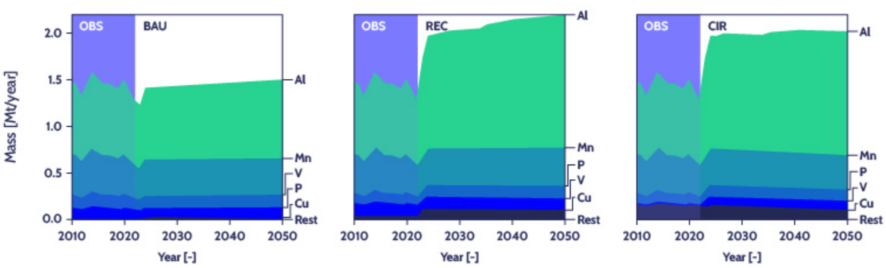
Outlook to 2050 of most significant CRMs in waste generated



The total amount of CRMs embedded in waste generated is dominated in mass by aluminium (~4.3 Mt/year in 2050) and manganese (~560 kt/year in 2050). Other CRMs with significant mass include phosphorus, copper, and vanadium.

Note that aluminium and manganese are very abundant in the earth's crust and certain ores, which explains their presence in slags and ashes. CRM concentrations in slags and ashes generated are kept unchanged in the BAU, REC, and CIR scenarios.

Outlook to 2050 of most significant CRMs in secondary raw materials



CRMs in secondary raw materials are dominated by aluminium (0.8–1.4 Mt/year in 2050) and manganese (380 - 410 kt/year in 2050).

The highest quantities of CRMs are available under the REC scenario, followed by the CIR and BAU scenarios.

Al — Total in secondary raw materials: 690 kt/year in 2022, increasing from 835 kt/year to 1.4 Mt/year in 2050. Already recovered from municipal solid waste incineration bottom ash, low recoverability from aluminium black dross.

P — Total in secondary raw materials: 90 kt/year in 2022, increasing from 100 kt/year to 135 kt/year in 2050. Low recoverability from municipal solid waste incineration bottom ash and other biowaste ashes, high recoverable potential from sewage sludge ashes.

- Already recovered
- High recoverable potential
- Limited recoverability
- Low recoverability

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Recoverability Assessment of important Critical Raw Materials (CRMs) in slags and ashes

CRM	Waste flow
Al	Aluminium scrap in municipal solid waste incineration bottom ash
Mg, Ti (alloying elements in aluminium)	Aluminium scrap in municipal solid waste incineration bottom ash
Ni (alloying element in stainless stell)	Stainless steel scrap in municipal solid waste incineration bottom ash
Cu	Copper scrap in municipal solid waste incineration bottom ash
P	Municipal solid waste incineration bottom ash
Platinum Group Metals	Municipal solid waste incineration bottom ash
Al, Cu, Mg	Aluminium dross
Cu, Co, Ge	Lead slag
Cu, Ga, In	Zinc sludges
Co, Cu, Ni	Copper slags
V	Steel slags from Basic Oxygen Furnace
Rare Earth Elements	Red mud
P	Other biowaste ashes (excluding wood ash and agricultural waste ash, which only have low concentrations of P)
P	Sewage sludge ashes

- Already recovered
- High recoverable potential
- Limited recoverability
- Low recoverability

Enabling conditions for improving recoverability

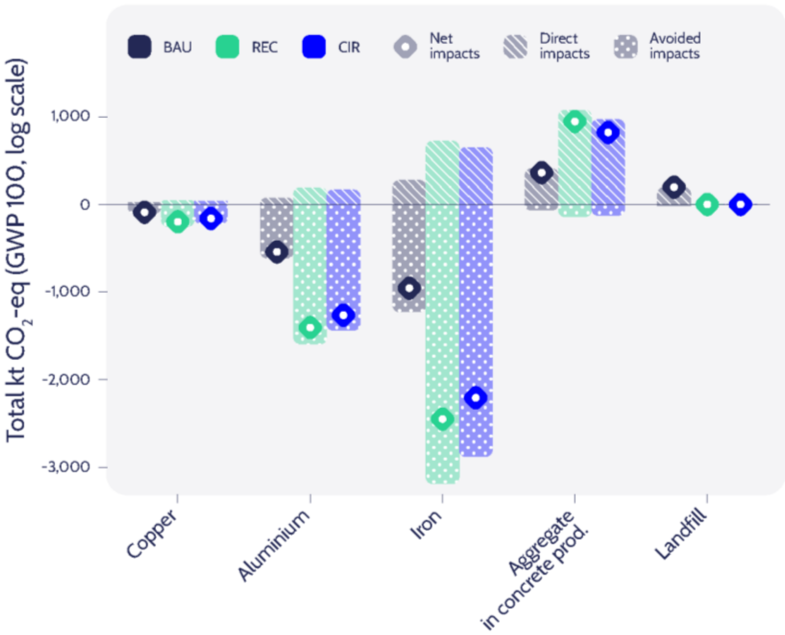
- Availability of reliable and sufficient site-specific data.
- Incentives for recovery in upcoming legislation.
- Ashes: Sufficiently pure streams through low-cost separation methods or application of mono-incineration.
- Slags: Suitable mineralogical state, processing via conventional metallurgical processes possible, advantageous if more than one element can be recovered and the hazard associated with the remaining residue is reduced.

Environmental and socio-economic impacts of treating municipal solid waste incineration ashes and recovering secondary raw materials

	2019	2050		
	OBS	BAU	REC	CIR
Net CO_2-eq:	-0.59 Mt	-0.96 Mt (-62% vs 2019)	-3.0 Mt (-409% vs 2019)	-2.7 Mt (-358% vs 2019)
Direct CO_2-eq:	0.61 Mt	0.99 Mt (+62% vs 2019)	2.05 Mt (+236% vs 2019)	1.84 Mt (+202% vs 2019)
Avoided CO_2-eq:	-1.20 Mt	-1.94 Mt (-62% vs 2019)	-5.05 Mt (-321% vs 2019)	-4.55 Mt (-279% vs 2019)

Results include all waste treatments applied on bottom ashes from MSW incineration (pre-processing, metal recovery, recovery for aggregates for concrete, landfilling). Net impacts include direct impacts from waste treatment and avoided impacts through displacement of primary materials; Direct impacts exclusively include impacts from waste treatment itself; Avoided impacts are the impacts that do not occur due to displacement of primary by recycled materials.

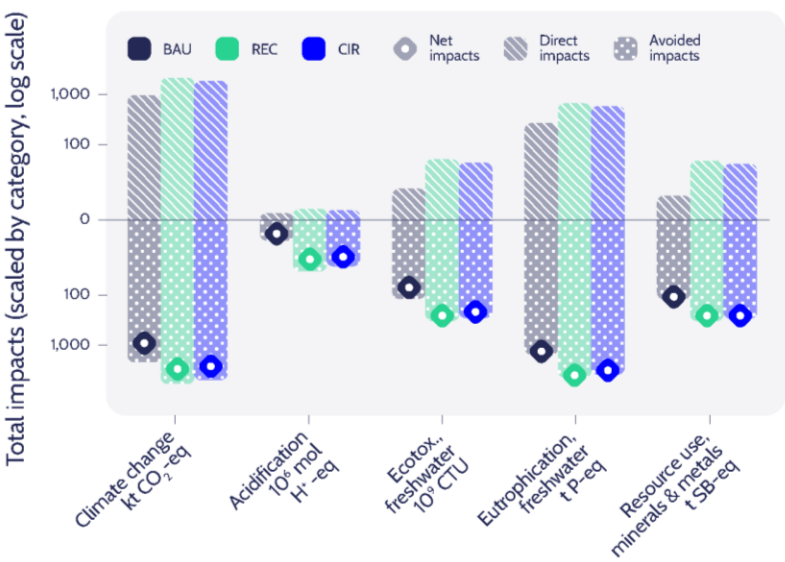
Comparing climate impacts across materials and EOL destination by scenario in 2050



The highest potential for reduction of MSW bottom ash climate impacts stems from metal recovery of *copper*, *aluminium*, and *iron*. This potential stems from increased recovery instead of currently standard landfilling under the assumption that secondary metal substitutes primary metal produced.

By contrast, benefits from replacement of aggregates in concrete are not high enough to result in net climate impact reduction. There is no bottom ash landfilled in the recovery and circularity scenarios.

Comparing impacts across selected categories by scenario in 2050



REC and CIR scenarios can decrease net impacts across all evaluated impact categories in 2050 when compared to BAU scenario.

For all the impacts of the REC and CIR scenarios surpass those of the BAU scenario.

However, the overall net impacts when avoided impacts are included are lower than for BAU.

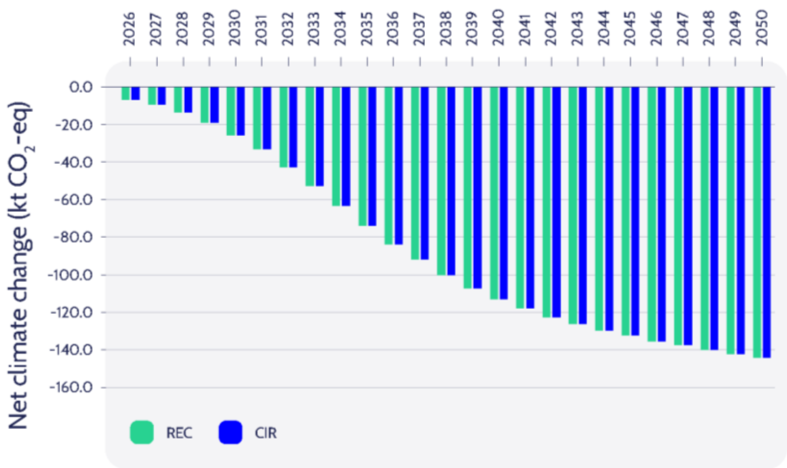
Environmental and socio-economic impacts of treating sewage sludge and recovering secondary raw materials

2019	2050		
OBS	BAU	REC	CIR
Net CO_2-eq: 0.00 Mt	Net CO_2-eq: 0.00 Mt	Net CO_2-eq: -0.14 Mt	Net CO_2-eq: -0.14 Mt

The system boundaries comprise transport of sewage sludge ash from a mono-incineration plant to the Ash-Dec technology facility in Germany, thermo-chemical treatment of ash at high temperature with chemical additives, flue gas treatment of the Ash-Dec process, and management of secondary residues, including potential landfill disposal. Furthermore, the assessment accounts for upstream production of energy carriers and auxiliary materials required for the thermo-chemical treatment, as well as environmental credits from substituting conventional mineral phosphate fertilisers with the recovered phosphorus product (P-Rex Project, 2015).

In the OBS and BAU scenarios, it was assumed that no phosphorus is recovered from sewage sludge ash at the industrial operational level. From now until 2050, the impacts are zero. In the recovery scenario, it was assumed that the Ash-Dec technology would be gradually deployed across EU countries, Norway, and Switzerland, starting in 2026. In the CIR scenario, it is assumed that the same recovery technology as in the REC scenario is deployed.

Comparing climate impacts across materials by scenario in 2050

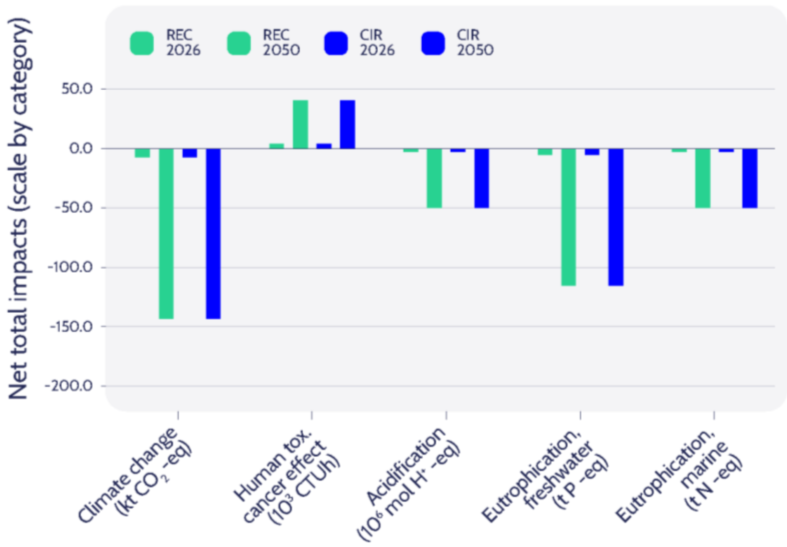


The year-over-year increments are highlighted under the assumption of gradual adoption of Ash-Dec technology.

The total direct and indirect emissions are lower than the avoided emissions from substituting conventional mineral phosphate fertilisers.

When compared across materials and end-of-life destinations, routes that recover phosphorus and produce a marketable fertiliser product (such as Ash-Dec) can show lower, or even negative, net GWP, depending on substitution assumptions.

Comparing impacts across selected categories by scenarios in 2050



Human toxicity is the only burden-dominated category, representing the main trade-off in Ash-Dec technology.

Both acidification and eutrophication categories exhibit net environmental benefits, thanks to substitution credits.

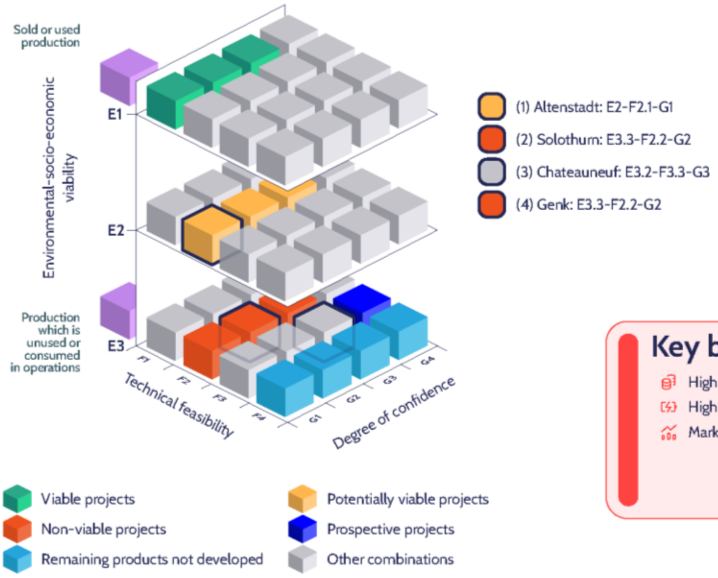
While climate change, as previously mentioned, is also net beneficial, toxicity remains the primary environmental hotspot.

United Nations Framework Classification (UNFC) of recovery projects

UNFC site-specific case studies

Case study	SRMs/CRMs	Waste input	Recoverable Quantity
(1) P recovery from dewatered sewage sludge ashes, Altenstadt, GERMANY	P	~ 150 kt/year	~ 2 kt/year
(2) P recovery from sewage sludge ashes Solothurn, SWITZERLAND	P	~ 40 kt/year	~ 2.8 kt/year
(3) CRMs recovery from steel slags Chateauneuf, FRANCE	Cr, V	~ 56 kt	Not quantified
(4) Cr recovery from steel slags Genk, BELGIUM	Cr	~ 3 Mt	Confidential

UNFC Results:



Key barriers

- High investment cost (2)
- High energy use (2)
- Market uncertainty

Key enablers

- Policy support (for P recovery (1&2))
- High technology readiness level (for P recovery (1&2) and Cr recovery (3)
- Existing industrial infrastructure for several processing steps (for P recovery (1) and Cr recovery (3))

UNFC national-level case study - Germany

P recovery from sewage sludge ashes in Germany and in Bavaria

This national-level case study applies **top-down material flow analysis (MFA) approach** using national waste statistics and regional sludge management data to estimate P flows and recovery potential in Germany and in Bavaria, with the aim of determining the extent to which the legal obligation to recover P can be met. **This shows that, while significant recovery potential exists, its realisation depends on expanding treatment infrastructure and deploying suitable recovery technologies in the regions.**

Key findings:

1. **Recovery depends on treatment infrastructure**
   P recovery potential strongly depends on the share of mono-incineration of sewage sludge and the availability of suitable recovery technologies.
2. **Recovery efficiency varies by technology**
   The amount of P that can be recovered depends on the specific ash treatment technology applied.
3. **Recovery infrastructure remains uneven**
   P recovery capacity is still limited and unevenly distributed across regions.

3.6 Waste electrical and electronic equipment (WEEE)

Selected key results for the WEEE waste stream are presented across four infographic pages. The table below summarises the scope, methodology, limitations, and key deliverables for each. For full results, methodological details and assumptions, readers are invited to read the corresponding project reports and datasets, which are listed below.

Future trends of secondary* and critical raw materials (CRMs) in WEEE

- **Scope:** The analysis covers EU-6 WEEE categories as defined in the WEEE Directive (i.e. temperature exchange equipment, screens and monitors, lamps, large equipment excl. PV panels, PV panels, small equipment, small IT and telecommunication equipment), for the 27 Member States of the European Union (EU27) plus Iceland, Norway, Switzerland and the United Kingdom (EU27+4). Results are presented for the period 2010–2050 under three scenarios: business-as-usual (BAU), recovery (REC) and circularity (CIR).
- **Method:** Trends are derived using stock and flow and recovery modelling, combining composition data of electrical and electronic equipment (EEE) with waste generation and treatment pathways. The presented CRMs combine the most abundant materials with those that have available recoverability data.
- **Disclaimer/limitations:** Material composition is assumed to remain constant over time and across scenarios, and recycling data is partly confidential or incomplete, requiring the use of assumptions. Batteries from WEEE are accounted for within the waste batteries stream.
- **Data sources:**
  - composition data: ProSUM project, contribution from consortium partners, and literature review.
  - stock and flow data: national statistics offices, contribution from consortium partners, and literature review.
  - recovery model data: contribution from consortium partners and confidential industry data, stakeholder consultations, including industry representatives, research centres, and producer responsibility organisations.
- **Further information can be found in:** Milestone M23 ‘Methodology paper - Composition data collection and consolidation’, Deliverable D3.1 ‘Extended waste stream composition assessment to enable secondary raw materials assessment’, Deliverable D4.1 ‘Future trends of secondary raw materials and critical raw materials’.

Recoverability Assessment of important Critical Raw Materials (CRMs) in WEEE

- **Scope:** The assessment focuses on strategic and CRMs (Ag, Al, Au, Ba, Co, Cu, Dy, Eu, Ga, Mg, Nd, Pd, Pr, Sb, Sc, Si, Sm, Sn, Sr, Ta, W and Y) contained in WEEE and their key applications. The analysis considers present and tested recovery technologies, considering different Technology Readiness Levels (TRLs).
- **Method:** Recoverability is evaluated through a barrier and enabler analysis according to different criteria in five categories: design-specific, waste-flow-specific, technical, economic, and environmental and legal.
- **Disclaimer/limitations:** The assessment is qualitative and had to deal with a lack of sufficient information to evaluate according to certain criteria.
- **Data sources:** The evaluation is based on FutuRaM composition datasets and modelling results, JRC reports, SCRREEN2 factsheets, results of the UPgrade project, results of the UNFC case studies, and scientific literature.

- **Further information can be found in:** Deliverable D3.1 'Extended waste stream composition assessment to enable secondary raw materials assessment'.

Environmental and socio-economic impacts of treating WEEE and secondary raw materials recovery

- **Scope:** The analysis covers EU-6 WEEE categories as defined in the WEEE Directive (i.e. temperature exchange equipment, screens and monitors, lamps, large equipment excl. PV panels, PV panels, small equipment, small IT, and telecommunication equipment), for the EU27+4. Results are presented for the period 2010–2050 under three scenarios: BAU, REC, and CIR. The assessment includes waste treatment and material recovery processes: dismantling, shredding, separation, and smelting of scraps into alloys.
- **Method:** Life Cycle Assessment (LCA) conducted using 1 kilogram of WEEE product as the functional unit, with impact categories selected according to the Environmental Footprint (EF) 3.0 method.
- **Disclaimer/limitations:** By placing the focus on waste treatment itself, other parts of the life cycle of electronics such as mining, production, and use are not included in our system boundary.
- **Data sources:** mainly Ecoinvent 3.11 database.
- **Further information can be found in:** Deliverable D2.1 'Environmental and socio-economic barriers, trade-offs and benefits to secondary raw materials recovery'.

United Nations Framework Classification (UNFC) of recovery projects

- **Scope:** The case study examined the recovery of selected strategic and CRMs (Ag, Au, Cu, Dy, Ga, Ge, Nd, Ni, Pd, Pr, Pt, Sn, and Y). It includes one site-specific recycling plant in France, four national-level case studies on CRMs recycling from WEEE in Italy, France, the United Kingdom, and Austria, and a national-level case study of WEEE in end-of-life vehicles in Switzerland. The purpose of these national-level case studies is to assess the recovery potential and identify opportunities to improve material recovery across collection, treatment, and recycling systems.
- **Method:** At the national level, material flow analysis was combined with a UNFC-compliant approach using statistics and sectoral data using industrial data at the national level; additionally, a seven-stage procedure was used at the site-specific level.
- **Disclaimer/limitations:** Results are sensitive to site-specific assumptions, data availability, and current technological configurations.
- **Data sources:** The case studies rely on multiple data sources, including national statistics and reporting systems, operational data from waste treatment operators, project datasets, scientific literature, and expert judgment to support the estimation of material flows and recovery potentials.
- **Further information can be found in:** Deliverable D5.1 'Reports of case studies for secondary raw materials assessment availability assessment in alignment with the UNFC'.

* 'Secondary raw materials' are raw materials recovered from a secondary source, i.e. waste, instead of being obtained from a primary source, i.e. an ore, and have undergone all necessary treatment steps to substitute primary raw materials. However, the CRMs from those secondary raw materials might not necessarily be functionally recycled, i.e. when they have the same functions and applications as materials obtained from primary sources.

Future trends of secondary and critical raw materials (CRMs) in WEEE

Waste generated

10.6 Mt/year in 2022

In 2022: 900 kt/year of CRMs
In 2050: 1,150 kt/year to 1,750 kt/year of CRMs

Not recovered as secondary raw materials

6.5 Mt/year in 2022
(61% of waste generated)

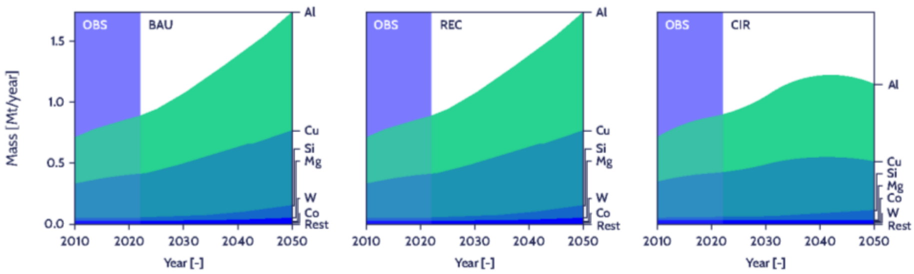
In 2022: 500 kt/year of CRMs
In 2050: 240 kt/year to 850 kt/year of CRMs

Secondary raw materials

4.1 Mt/year in 2022
(39% of waste generated)

In 2022: 400 kt/year of CRMs
In 2050: 860 kt/year to 1,370 kt/year of CRMs

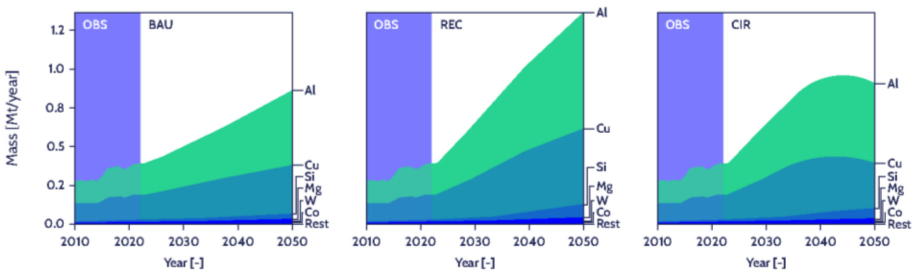
Outlook to 2050 of most significant CRMs in waste generated



The total amount of CRMs embedded in waste generated is dominated in mass by aluminium (650–950 kt/year in 2050) and copper (370–620 kt/year in 2050). Other CRMs with significant mass include silicon metal, magnesium, tungsten, and cobalt.

CRM quantities embedded in waste generated are the same under BAU and REC scenarios, and in both cases are higher than in the CIR scenario. In the REC scenario focus is given to waste management, whereas in the CIR scenario the focus is both on the waste management but also in waste prevention.

Outlook to 2050 of most significant CRMs in secondary raw materials



CRMs in secondary raw materials are dominated by aluminium (490–755 kt/year in 2050) and copper (295–490 kt/year in 2050).

The highest quantities of CRMs are available under the REC scenario. In the CIR scenario, CRM recovery can be equivalent to BAU, albeit with less waste generated.

Al — Total in secondary raw materials: 200 kt/year in 2022, increasing from 485 kt/year to 755 kt/year in 2050. Most from alloys already recovered.

Cu — Total in secondary raw materials: 160 kt/year in 2022, increasing from 295 kt/year to 490 kt/year in 2050. Most copper from PCB, cables, motor already recovered.

Si — Total in secondary raw materials: 12 kt/year in 2022, increasing from 33 kt/year to 80 kt/year in 2050. High recoverable potential from PV cells.

Nd — Total in secondary raw materials: 34 t/year in 2022, increasing from 0.052 kt/year to 1.2 kt/year in 2050. High recoverable potential from permanent magnets.

Co — Total in secondary raw materials: 590 t/year in 2022, increasing from 1 kt/year to 3 kt/year in 2050. Low recoverability in sensors and PCBs.

- Already recovered
- High recoverable potential
- Limited recoverability
- Low recoverability

Recoverability Assessment of important Critical Raw Materials (CRMs) in WEEE

CRM	Application within the Waste Stream
Nd, Pr	NdFeB permanent magnets in speakers
Nd, Pr	NdFeB permanent magnets in motors
Nd, Pr	NdFeB permanent magnets in HDDs
Dy	Additive for heat resistance in NdFeB permanent magnets
Ga	Minor additive in NdFeB permanent magnets
Ba, Sr	Ferrite magnets in speakers
Sm, Co	Samarium cobalt magnets in sensors (rare presence)
Ta	Capacitors on PCBs
Ga	Integrated circuits and semiconductors on PCBs
Sb	Flame retardant in PCB resin
Sb	Solders on PCBs
Sn	Solders on PCBs
Ag, Au, Pd	PCB connectors, contacts, pins, and plating
Co	Integrated circuits and semiconductors on PCBs
Sc	Integrated circuits, semiconductors, and thin film applications on PCBs
W	Electron emitter in integrated circuits on PCBs

CRM	Application within the Waste Stream
Cu	PCB connectors and contacts
Cu	External cables
Cu	Internal cables and wiring
Cu	Coils in motors
Ga	LEDs for general lighting and background illumination
Eu, Y	LEDs for general lighting and background illumination
Eu, Y	Phosphor powder in fluorescent lamps for general lighting and background illumination (CCFLs)
Sc	Arc tube in metal halide lamps in camera or industrial and street lighting
Sb	Flame retardant in plastic casing
Al	Heat sinks in various applications
Al	Aluminium alloys in casing, frame, and chassis
Mg	Alloying element in Al alloys in casing, frame, chassis
Mg	Mg alloys in casing, frame, and chassis
Sb	Glass (e.g., LCD, CRTs, solar)
Si	Silicon PV cells
Ga	Thin layer in CIGS PV cells

Already recovered | High recoverable potential | Limited recoverability | Low recoverability

Enabling conditions for improving recoverability

- High mass fractions and volumes of CRMs in specific components.
- Digital product passports with information regarding content and location of CRMs.
- Existence of dedicated collection streams.
- Identifiability and removability of CRM-containing components.
- Manual and automated dismantling practices.
- Availability of advanced sorting and metallurgical processes (LIBS, XRF, integrated copper smelters, short-loop magnet recycling).
- Maturity of recycling markets and infrastructure.
- Upcoming incentives from the CRM Act and the revision of the WEEE directive (e.g. CRM recovery targets).

Environmental and socio-economic impacts of treating WEEE and recovering secondary raw materials

2020

OBS

Net CO_2-eq: -5.1 Mt
Direct CO_2-eq: 2.3 Mt
Avoided CO_2-eq: -7.4 Mt

2050

BAU

-9.0 Mt (-180% vs 2020)
5.1 Mt (+220% vs 2020)
-14.1 Mt (-190% vs 2020)

REC

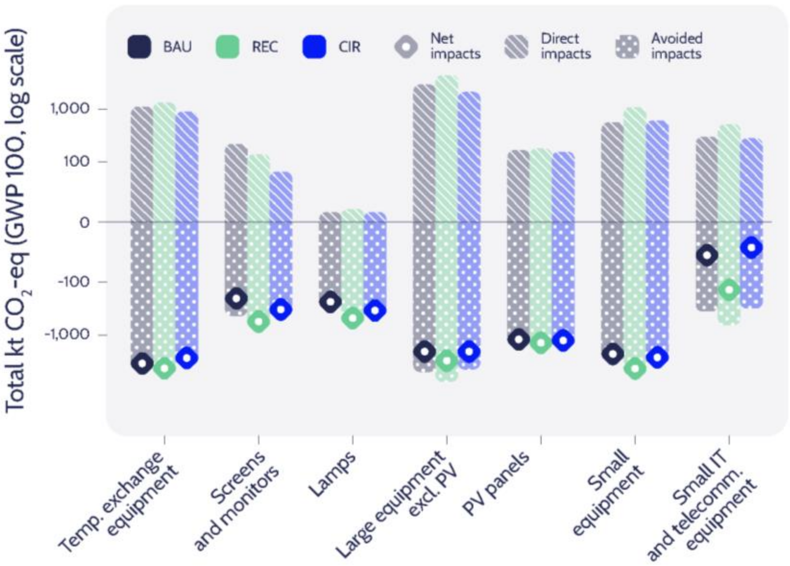
-14.0 Mt (-275% vs 2020)
7.2 Mt (+315% vs 2020)
-21.2 Mt (-290% vs 2020)

CIR

-9.2 Mt (-180% vs 2020)
4.1 Mt (+180% vs 2020)
-13.3 Mt (-180% vs 2020)

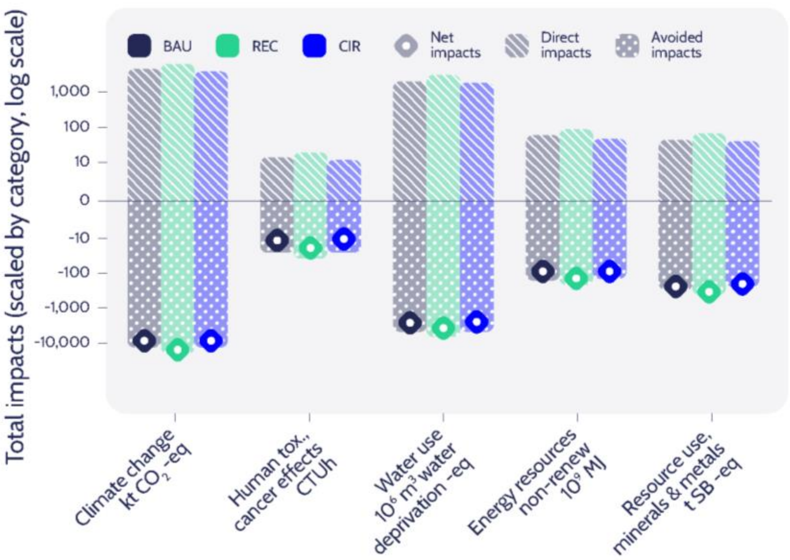
Results include mechanical treatment (dismantling and shredding), energy recovery, incineration, landfilling, and smelting of copper, aluminium, and ferrous scrap). Net impacts include direct impacts from waste treatment and avoided impacts through displacement of primary materials; Direct impacts exclusively include impacts from waste treatment itself; Avoided impacts are the quantity of impacts avoided due to material recovery replacing otherwise needed production of materials, e.g. mining.

Comparing climate impacts across WEEE categories by scenario in 2050



The mechanical treatment of WEEE and smelting of ferrous and non-ferrous scraps (aluminium and copper) are environmentally beneficial from a climate change perspective in all three scenarios in 2050. The highest gains are in the recovery scenario, followed by circularity and business-as-usual. The highest potential for reduction of WEEE climate impacts stems from temperature exchange equipment, large equipment (both including and excluding PV panels), and small equipment. The greatest impact reduction for these WEEE categories is due to increased quantities and recovery of materials, especially ferrous and nonferrous metals. The highest direct impacts stems from depollution and treatment of toner modules.

Comparing impacts across selected impact categories by scenarios in 2050



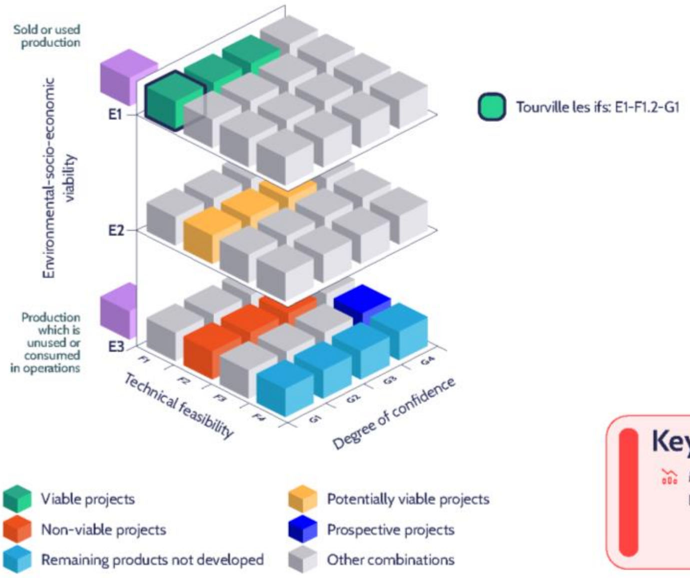
Apart from climate change, the effect of WEEE treatment across four other evaluated impact categories is that of reduced impact. This is also due to recovery of materials, especially ferrous and non-ferrous metals, including copper and aluminium. Overall, the net impact when avoided impacts are included is more pronounced in the recovery scenario, followed by circularity and business-as-usual scenarios. This is also due to higher quantities of recovery of materials.

United Nations Framework Classification (UNFC) of recovery projects

UNFC site-specific case studies

Case study	SRMs/CRMs	Waste input	Recoverable Quantity
CRMs recycling in WEEE – Tourville-les-ifs, FRANCE	Ag, Au, Cu, Dy, Ga, Ge, Nd, Ni, Pd, Pr, Pt, Sn, Y	~ 60 kt/year	~ 22.5 kt/year Ferrous; ~ 12.7 kt/year non-Ferrous; ~20.6 kt/year Plastics

UNFC Results:



Key barriers

- Minor exposure to CRM price volatility

Key enablers

- Full regulatory approval and environmental permitting
- Secure feedstock supply
- High technology readiness level

UNFC national-level case studies – Austria, France, Italy, Switzerland and the United Kingdom

The national-level case study in **Switzerland**, evaluates the **recovery potential of electronic components embedded in ELVs** using a **top-down material flow analysis (MFA)** approach.

Another case study evaluates the **material flows and recovery potential of CRMs from WEEE across multiple countries (France, Italy, and the United Kingdom)**, using a **top-down MFA** approach.

A third case study evaluates the **recovery potential of CRMs from within the Austrian recycling system, focusing on the structure of the national collection and treatment network** using a **bottom-up approach**.

Key findings:

Case study in Switzerland

- Current shredding of end-of-life vehicles leads to losses of embedded CRMs and precious metals.
- Existing pre-processing capacity could enable improved recovery.
- Additional dismantling before shredding could improve CRM recovery.

Case study in France, Italy, and the UK

- Limited traceability of CRMs across the value chain.
- Cross-border recycling plays an important role in the treatment routes.
- The recovery of Ag, Cu, Pd, and Sn from PCBs is currently demonstrated at the laboratory scale and remains prospective.

Case study in Austria

- Very high Cu circularity is achieved with existing plants. Major losses occur before treatment.
- Several CRMs remain unrecovered in the current recycling system.
- Large data gaps limit the assessment of CRM recovery potential.

3.7 Dismantled wind turbines

Selected key results for dismantled wind turbines are presented across three infographic pages. The table below summarises the scope, methodology, limitations, and key deliverables for each. For full results, methodological details, and assumptions, readers are invited to read the corresponding project reports and datasets, which are listed below.

Future trends of secondary* and critical raw materials (CRMs) in dismantled wind turbines

- **Scope:** The analysis covers seven types of wind turbines, classified by generator type: Direct Drive EESG, Direct Drive PMSG, Doubly-Fed Induction, Gearbox + EESG, Gearbox + PMSG, Squirrel Cage Induction, and Wound Rotor Induction for the 27 Member States of the European Union (EU27). Iceland, Norway, Switzerland, and the United Kingdom are not included due to lack of data. Results are presented for the period 2010–2050 under three scenarios: business-as-usual (BAU), recovery (REC) and circularity (CIR).
- **Method:** Trends are derived by combining wind turbine classification by generator type, gearbox, components, and onshore/offshore location, with material intensity, inflow and stock-driven modelling, and recovery model. The presented CRMs combine the most abundant materials with those that have available recoverability data.
- **Disclaimer/limitations:** Transfer coefficients used in the recovery model are not turbine-specific and may overestimate secondary raw materials, except for permanent magnets. Collection and recycling rates were estimated due to limited data on wind turbine waste.
- **Data sources:**
  - composition data: research centre dataset, other projects, and literature review.
  - stock and flow data: private database, research centre dataset and sector specific association
  - recovery model data: other projects and literature review.
- **Further information can be found in:** Milestone M23 'Methodology paper - Composition data collection and consolidation', Deliverable D3.1 'Extended waste stream composition assessment to enable secondary raw materials assessment', Deliverable D4.1 'Future trends of secondary raw materials and critical raw materials'.

Recoverability Assessment of important Critical Raw Materials (CRMs) in dismantled wind turbines

- **Scope:** The assessment focuses on CRMs Al, Cu, rare earth elements (Dy, Nd, Pr, Tb), alloying elements (Cu, Mg, Mn, Si, Ti) embedded in dismantled wind turbines and in their key applications. The analysis considers present and tested recovery technologies, considering different Technology Readiness Levels (TRLs).
- **Method:** Recoverability is evaluated through a barrier and enabler analysis according to different criteria in five categories: design-specific, waste-flow-specific, technical, economic, and environmental and legal.
- **Disclaimer/limitations:** The assessment is qualitative and had to deal with a lack of sufficient information to evaluate according to certain criteria.
- **Data sources:** The evaluation is based on FutuRaM composition datasets, factsheets from the SCRREEN2 project, and scientific and grey literature.
- **Further information can be found in:** Deliverable D3.1 'Extended waste stream composition assessment to enable secondary raw materials assessment'.

Environmental and socio-economic impacts of treating dismantled wind turbines and secondary raw materials recovery

- Analysis was not conducted, as the waste treatment is still emerging and sufficient data is lacking for conducting a Life Cycle Assessment (LCA).

United Nations Framework Classification (UNFC) of recovery projects

- **Scope:** The case study examined the recovery of selected CRMs (Dy and Nd). It includes one national-level case study on permanent magnets in dismantled wind turbines in the EU and evaluates the current recycling technologies. Its purpose is to assess the future recovery potential and identify opportunities to improve the management and recycling of these materials at the system level.
- **Method:** The UNFC is applied and combined with material flow analysis and industrial data at the national level.
- **Disclaimer/limitations:** Results are sensitive to data availability and assumptions, current technological configurations, and the industrial deployment of recycling plants.
- **Data sources:** The case studies rely on multiple data sources, including national statistics and reporting systems, operational data from waste treatment operators, project datasets, scientific literature, and expert judgment to support the estimation of material flows and recovery potentials.
- **Further information can be found in:** Deliverable D5.1 'Reports of case studies for secondary raw materials assessment availability assessment in alignment with the UNFC'.

* 'Secondary raw materials' are raw materials recovered from a secondary source, i.e. waste, instead of being obtained from a primary source, i.e. an ore, and have undergone all necessary treatment steps to substitute primary raw materials. However, the CRMs from those secondary raw materials might not necessarily be functionally recycled, i.e. when they have the same functions and applications as materials obtained from primary sources.

Future trends of secondary and critical raw materials (CRMs) in dismantled wind turbines

Waste generated

250 kt/year in 2022

In 2022: 3 kt/year of CRMs
In 2050: 190 to 320 kt/year of CRMs

Not recovered as secondary raw materials

185 kt/year in 2022
(74% of waste generated)

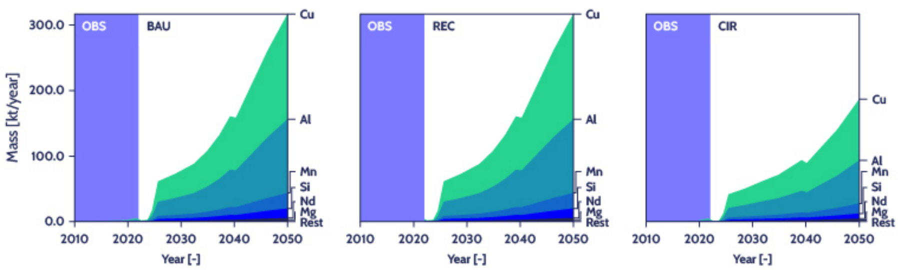
In 2022: 2 kt/year of CRMs
In 2050: 55 to 175 kt/year of CRMs

Secondary raw materials

65 kt/year in 2022
(26% of waste generated)

In 2022: 1 kt/year of CRMs
In 2050: 125 to 225 kt/year of CRMs

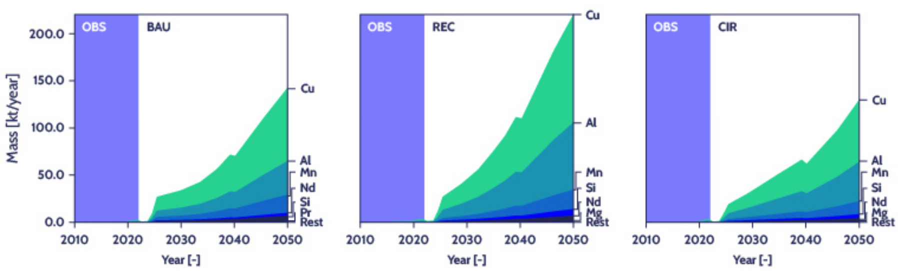
Outlook to 2050 of most significant CRMs in waste generated



The total amount of CRMs embedded in waste generated is dominated in mass by copper (95–160 kt/year in 2050) and aluminium (65–110 kt/year in 2050). Other CRMs with significant mass include manganese, neodymium, silicon metal, and magnesium.

CRM quantities embedded in waste generated are the same under the BAU and REC scenarios, and in both cases are higher than in the CIR scenario. This is because in the CIR scenario the focus is given on reducing waste (e.g. extending lifetime).

Outlook to 2050 of most significant CRMs in secondary raw materials



CRMs in secondary raw materials are dominated by copper (69–116 kt/year in 2050) and aluminium (35–70 kt/year in 2050).

The highest quantities of CRMs are available under the REC scenario. In the CIR scenario, CRM recovery can be equivalent to BAU, albeit with less waste generated, and less placed on the market.

Cu Total in secondary raw materials: 670 t/year in 2022, increasing from 70 kt/year to 115 kt/year in 2050. Only recovered when collected, such as internal cables. Limited recoverability as alloying and external cables not recovered.

Al Total in secondary raw materials: 430 t/year in 2022, increasing from 37 kt/year to 70 kt/year in 2050. Most from alloys in structural components already recovered.

Mn Total in secondary raw materials: 205 t/year in 2022, increasing from 14 kt/year to 23kt/year in 2050. Limited recoverability from alloys in structural components.

Nd Total in secondary raw materials: 2 t/year in 2022, increasing from 1 kt/year to 2 kt/year in 2050. High recoverable potential from magnets in dismantled wind turbines.

Dy Total in secondary raw materials: 0.3 t/year in 2022, increasing from 125 t/year to 225 t/year in 2050. High recoverable potential from NdFeB- magnets.

- Already recovered
- High recoverable potential
- Limited recoverability
- Low recoverability

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Recoverability Assessment of important Critical Raw Materials (CRMs) in dismantled wind turbines

CRM	Application within the Waste Stream
Rare Earth Elements (Nd, Pr, Dy,Tb)	NdFeB-magnets in wind turbines
Ni (alloying element)	Stainless steel in structural components of wind turbines
Al	Aluminium alloys in structural components of wind turbines
Cu, Mg, Mn, Si, T (alloying elements)	Alloying elements in aluminium alloys in structural components of wind turbines
Cu	Wind turbine external cables
Cu	Cables in wind turbines (internal)
Sb + B (zinc borate)	Flame retardant in cable sheathing
Li	Additive in concrete to prevent alkali-silica-reaction

- Already recovered
- High recoverable potential
- Limited recoverability
- Low recoverability

Enabling conditions for recoverability

- Separate collection at source with further sorting beyond current practice including more selective dismantling and advanced sorting technologies to increase high-quality and functional recycling.
- Application of sensor-based or XRF-based sorting technologies to increase high-quality and functional recycling.
- Material- or CRM-specific recovery targets to avoid open-loop/downcycling.

United Nations Framework Classification (UNFC) of recovery projects

UNFC site-specific case studies

No site-specific case studies were conducted for wind turbines.

UNFC national-level case study – Europe Union

Permanent magnets in dismantled wind turbines in EU

This national-level case study evaluates the potential recovery of **rare earth elements (REEs)** contained in permanent magnets used in wind turbines across the European Union.

The assessment applies a **top-down material flow analysis (MFA)** approach to estimate the quantities of **neodymium (Nd) and dysprosium (Dy)** embedded in wind turbine installations and to evaluate their potential as future secondary raw material resources, **indicating that while a significant resource exists in the long term, short-term recovery remains limited due to low waste flows and system uncertainties, requiring integration with other waste streams and improved collection and recycling system coordination**.

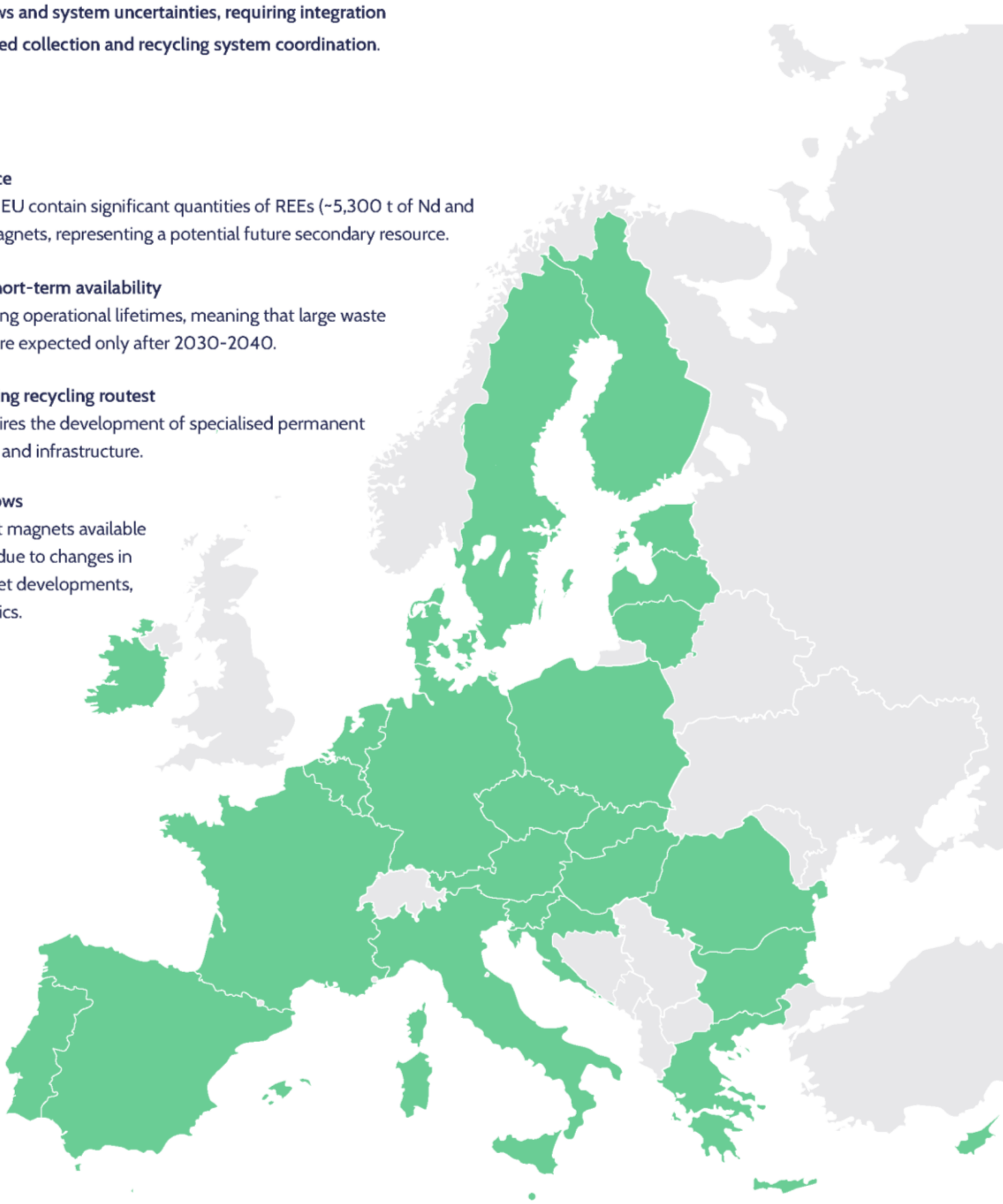
Key findings:

1. **Prospective secondary resource**
Wind turbines operating in the EU contain significant quantities of REEs (~5,300 t of Nd and ~650 t of Dy) in permanent magnets, representing a potential future secondary resource.

2. **Long product lifetime limits short-term availability**
Wind turbines typically have long operational lifetimes, meaning that large waste flows from decommissioning are expected only after 2030-2040.

3. **Recovery depends on dedicating recycling routest**
Efficient recovery of REEs requires the development of specialised permanent magnet recycling technologies and infrastructure.

4. **Uncertainty in future waste flows**
Future quantities of permanent magnets available for recycling remain uncertain due to changes in wind turbine technology, market developments, and geopolitical supply dynamics.



3.8 Distribution of Critical Raw Materials Across the Waste Streams

In the FutuRaM project, waste generated[3] and secondary raw materials[4] were quantified for waste batteries, construction and demolition waste from buildings, end-of-life vehicles, slags and ashes, WEEE, and dismantled wind turbines. Secondary raw materials can be obtained from waste generated when the latter is treated. Both waste generated and secondary raw materials quantities contain critical raw materials (CRMs) and other materials that are not CRMs. These can be functionally recycled[5], i.e. *returned to material streams where their metal properties are utilised* (UNEP, 2011, Talens Peiró et al., 2018), when processing secondary materials. The potential of CRMs to be functionally recycled is not quantitively assessed in the FutuRaM project but is qualitatively done with the recoverability assessment (FutuRaM's Deliverable D3.1). Thus, distribution of CRMs across the waste streams in Table 1 only provides a comparison of CRMs embedded in waste generated and in secondary raw materials between the waste streams, without further information on the quality of the material itself (see Figure 7) and whether or not CRMs are or will be functionally recycled.

The comparison provides annual mass estimates of CRMs embedded in waste and secondary raw materials for the reference year 2022 and for the three scenarios in 2050: business-as-usual, recovery and circularity. Harmonisation across waste stream was carried out for the year 2022 as the present year. For construction and demolition waste from buildings and slags and ashes, the business-as-usual data for 2022 was used for this harmonisation.

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[3] Waste generated refers to the total weight of waste resulting at the end-of-life of products (post-consumer waste), from manufacturing processes (pre-consumer waste), from waste treatment facilities or resulting from the prospecting, extraction, treatment and storage of mineral resources and the working of quarries (extractive waste).

[4] Secondary raw materials are raw materials recovered from a secondary source, i.e. waste, instead of being obtained from a primary source, i.e. an ore, and have undergone all necessary treatment steps to substitute primary raw materials.

[5] Functional recycling is that portion of end-of-life recycling in which the metal in a discarded product is separated and sorted to obtain recyclates that are returned to raw material production processes that generate a metal or metal alloy. Often it is not the specific alloy that is remelted to make the same alloy, but rather, any alloys within a certain class of alloys that are remelted to make one or more specific alloys. For example, a mixture of austenitic stainless-steel alloys might be remelted and the resulting composition adjusted by addition of reagents or virgin metal to make a specific stainless-steel grade. Recyclates obtained by functional recycling are used for the same functions and applications as materials obtained from primary sources—as opposed to recyclates generated from non-functional recycling which substitute other raw materials and therefore do not contribute directly to the total supply of the initial raw material.

Illustration of CRM quantities compared across FutuRaM's waste streams

Figure 7: Illustration of CRM quantities compared across FutuRaM's waste streams within waste generated and secondary raw materials.

In the left-side chart of Figure 7, part of CRMs and other non-CRMs (indicated in the chart as 'other materials') in waste generated are processed into secondary raw materials. These materials in secondary raw materials can be functionally recycled or remain as impurities. In the right-side chart, the distribution of CRMs across the waste streams is represented with the blue box (CRMs embedded in waste generated) and with the green dotted box (CRMs embedded in secondary raw materials). The quality of the secondary raw materials cannot be ascertained.

Disclaimers

1) CRMs being embedded in secondary raw materials do not mean that the CRM is being functionally recycled or that it will be refined. For instance, considerable quantities of arsenic are present in secondary raw materials from slags and ashes, but these are not economically viable as a metal source. Also, aluminium is very abundant in slags and ashes, but most of it is in an unrecoverable oxidic form. The secondary raw materials within and among the different waste streams might differ in quality. In other words, highest quantities do not equal highest quality. The quantitative analysis of the quality of the secondary raw materials is out of the project's scope.
2) Not all elements embedded in waste generated and secondary raw materials are CRMs. The data structure describing the composition of waste and secondary raw materials is used to determine whether or not an element (except for graphite or phosphate rock) is a CRM. For instance, silicon or titanium are only considered CRM in metal form, and nickel is only CRM with a specific grade or if it is present in certain products.
3) Whether or not the CRM in a secondary raw material is exported from the 27 Member States of the European Union (EU27) plus Iceland, Norway, Switzerland and the United Kingdom (EU27+4) is not assessed. Some of intermediate products from waste streams may be

processed as secondary raw materials outside of this geographic location. For instance, Li from batteries' black mass may be exported for recovery.

4) Not all CRMs were analysed in all waste streams (see FutuRaM's Milestone M23). In these cases, the CRM in the secondary raw materials is represented as not available (N.A.) for the respective waste stream.
5) Not all CRMs are equally analysed in all waste streams. Discrepancies such as the degree of coverage or non-harmonised modelling assumptions may occur. When the CRM in the secondary raw material is reported as 0%, it indicates either that the CRM is not present, that there is no evidence of its presence, or that it is present only in very small amounts in secondary raw materials for the applicable waste stream.
6) The indication of possible functional recycling and refinement options is based on present technologies and aided by the recoverability assessment task (see FutuRaM's Deliverable D3.1).
7) Batteries of WEEE products and end-of-life vehicles are quantified in the waste batteries waste stream. Slags generated during battery recovery processes (e.g., lithium and cobalt recovery) are not accounted for within the slags and ashes waste stream and therefore are likely underrepresented. The quantities of battery materials that are currently processed in the EU for lithium and cobalt recovery are currently unreported and therefore remain unknown. For further information on scope context of each waste stream, please refer to the previous sections of chapter 3, FutuRaM's Deliverable D1.1, and Deliverable D4.1.

Table 1: Distribution of critical raw materials (CRMs) across the waste streams embedded in secondary raw materials and in waste generated (indicated in brackets) for the present (2022) and for the business-as-usual, recovery, and circularity scenarios in 2050. Waste streams considered are: waste batteries (BATT), construction and demolition waste from buildings (CDW), end-of-life vehicles (ELV), slags and ashes (SLASH), waste electrical and electronic equipment (WEEE), and dismantled wind turbines (WTB).

CRM	Present 2022	Business-as-usual 2050	Recovery 2050	Circularity 2050	FutuRaM waste streams contribution of CRM in secondary raw materials in the Recovery scenario for year 2050	Further information. When recoverability information is provided, it is based on present recoverability technology.
Mass flow quantities expressed in Mt/year						
Al	1.6 (5.3)	3.5 (8.2)	4.9 (8.1)	4.3 (7.4)	BATT 9% CDW 4% ELV 41% SLASH 29% WEEE 16% WTB 1%	Al is present in metal or alloy form in waste batteries, construction, and demolition waste from buildings, end-of-life vehicles, WEEE and dismantled wind turbines. In slags and ashes, Al can be present in mineral form. Al in metal or alloy form could be functionally recycled when sorted according to alloy type.
Cu	0.3 (0.7)	0.9 (1.8)	1.5 (1.8)	1.2 (1.4)	BATT 24% CDW 10% ELV 19% SLASH 7% WEEE 32% WTB 8%	Cu is present in metal or alloy form in waste batteries, construction, and demolition waste from buildings, end-of-life vehicles, WEEE and dismantled wind turbines. In slags and ashes, Cu can be present in mineral form. Cu in metal or alloy form is functionally recycled in integrated copper smelters.
Mass flow quantities expressed in kt/year						
Mn	419.7 (644.3)	507.2 (857.1)	577.2 (861.2)	508.0 (742.1)	BATT 5% CDW 8% ELV 12% SLASH 71% WEEE N.A. WTB 4%	Mn is present in cathode active material in waste batteries. Mn is present in metal alloys in construction and demolition waste from buildings, end-of-life vehicles, and dismantled wind turbines. Mn is present in steel slags in slags and ashes. Mn could also be present in metal alloys in WEEE, but this has not been quantified. Mn from all waste streams is likely not functionally recycled.
Si	74.6 (92.7)	141.8 (246.1)	216.3 (246.1)	186.6 (209.1)	BATT 0% CDW 5% ELV 55% SLASH 0% WEEE 37% WTB 3%	Si is present in waste batteries. Si is present in metal alloys in construction and demolition waste from buildings, end-of-life vehicles and dismantled wind turbines and likely not functionally recycled. Si is present in semiconductors of photovoltaic panels in WEEE, which might be recovered in a subsequent process. Si in glass and ashes is excluded from the figures since it is not considered a strategic or critical raw material.
P	91.6 (472.8)	104.4 (706.5)	192.3 (642.3)	156.4 (568.7)	BATT 29% CDW 1% ELV 0% SLASH 70% WEEE 0% WTB 0%	P is present in cathode active material and electrolytes in waste batteries. P is present in ferrous metals in construction and demolition waste from buildings. P is present in unprocessed slag from basic oxygen and electric arc furnaces and in sewage sludge incineration ashes in slags and ashes. Only P from sewage sludge incineration ashes might be recovered.

CRM	Present 2022	Business-as-usual 2050	Recovery 2050	Circularity 2050	FutuRaM waste streams contribution of CRM in secondary raw materials in the Recovery scenario for year 2050		Further information. When recoverability information is provided, it is based on present recoverability technology.
Mass flow quantities expressed in kt/year							
Mg	39.8 (52.0)	60.1 (92.3)	81.5 (92.3)	71.5 (79.7)	BATT	0%	Mg is present mainly in metal or alloy form in waste batteries, construction, and demolition waste from buildings, end-of-life vehicles, WEEE, and dismantled wind turbines. Mg in aluminium alloys might be downcycled, and Mg in magnesium alloy scrap is not used for magnesium alloy remelting but for other metallurgical applications.
					CDW	2%	
					ELV	54%	
					SLASH	0%	
					WEEE	43%	
					WTB	1%	
Ni	4.3 (10.3)	108.2 (213.2)	171.9 (204.9)	103.6 (123.6)	BATT	100%	Ni is present in many components in waste batteries and could be destined for refinement into battery-grade precursor material. Ni as an alloy element in steels in construction and demolition waste from buildings, end-of-life vehicles, slags and ashes, WEEE and dismantled wind turbines is excluded from the figures since it is not considered a strategic or critical raw material.
					CDW	0%	
					ELV	0%	
					SLASH	0%	
					WEEE	0%	
					WTB	0%	
V	117.3 (177.1)	134.6 (201.7)	106.9 (157.6)	79.0 (118.5)	BATT	0%	V is present in metal alloys in construction and demolition waste from buildings and dismantled wind turbines and is not functionally recycled. V in slags and ashes can only be recovered from steel slags (approximately 5 kt).
					CDW	0%	
					ELV	0%	
					SLASH	96%	
					WEEE	0%	
					WTB	4%	
Li	2.9 (6.7)	33.5 (65.6)	57.0 (65.3)	35.1 (44.1)	BATT	92%	Li is present in cathode active material and electrolytes in waste batteries and could be destined for refinement into battery-grade precursor material. Li present in slags and ashes is not functionally recycled. Slags produced from Li recycling are likely not covered in slags and ashes.
					CDW	0%	
					ELV	0%	
					SLASH	8%	
					WEEE	0%	
					WTB	0%	
Co	1.4 (15.1)	24.6 (57.7)	41.8 (56.8)	29.2 (39.2)	BATT	88%	Co is present in anode active material and cathode active material in waste batteries and could be destined for refinement into battery-grade precursor material. Co present in slags and ashes is not functionally recycled. Co is present in permanent magnets and printed circuit boards in WEEE and is not functionally recycled. Slags produced from Co recycling are likely not covered in slags and ashes.
					CDW	0%	
					ELV	N.A.	
					SLASH	5%	
					WEEE	7%	
					WTB	N.A.	
Sb	24.6 (45.8)	13.5 (33.1)	15.6 (30.3)	12.9 (26.7)	BATT	97%	Sb is present in current collectors in waste batteries and could be functionally recycled. Sb present in slags and ashes and WEEE is not functionally recycled. Sb could also be present in construction and demolition waste from buildings, end-of-life vehicles and dismantled wind turbines, but this has not been quantified and is potentially underestimated. However, it would likely not be functionally recycled.
					CDW	N.A.	
					ELV	N.A.	
					SLASH	0%	
					WEEE	3%	
					WTB	N.A.	
Nd	0.0 (3.8)	1.7 (6.9)	4.6 (6.8)	3.0 (5.0)	BATT	1%	Nd is present in waste batteries and ends up in slags, where it is not functionally recycled. Nd is present in permanent magnets in end-of-life vehicles, WEEE and dismantled wind turbines and could be functionally recycled.
					CDW	0%	
					ELV	32%	
					SLASH	0%	
					WEEE	26%	
					WTB	41%	

CRM	Present 2022	Business-as-usual 2050	Recovery 2050	Circularity 2050	FutuRaM waste streams contribution of CRM in secondary raw materials in the Recovery scenario for year 2050	Further information. When recoverability information is provided, it is based on present recoverability technology.
Mass flow quantities expressed in kt/year						
W	1.1 (3.4)	1.4 (4.4)	3.0 (4.4)	1.8 (2.7)	BATT 0% CDW 0% ELV 0% SLASH 0% WEEE 100% WTB 0%	W is present in printed circuit boards in WEEE and is not functionally recycled.
Nb	0.4 (0.7)	2.1 (2.7)	2.4 (2.7)	1.7 (1.9)	BATT 0% CDW N.A. ELV 34% SLASH 0% WEEE 0% WTB 66%	Nb is present in steel alloys in end-of-life vehicles and dismantled wind turbines and likely is not functionally recycled. Nb could also be present in construction and demolition waste from buildings, but this has not been quantified and is potentially underestimated. However, it would likely not be functionally recycled.
As	0.0 (7.6)	0.0 (7.1)	0.8 (7.1)	1.1 (6.8)	BATT 0% CDW 0% ELV N.A. SLASH 100% WEEE N.A. WTB 0%	As is present in waste batteries and is not functionally recycled. As is present in slags and ashes, mainly due to its presence in many ores, but not economically viable as a metal source. As could also be present in end-of-life vehicles and WEEE, but this has not been quantified and is potentially underestimated. However, it would likely not be functionally recycled.
Mass flow quantities expressed in t/year						
Dy + Tb	1 (421)	247 (1,209)	949 (1,219)	744 (1009)	BATT 0% CDW 0% ELV 66% SLASH 0% WEEE 6% WTB 29%	Dy and Tb are present in permanent magnets in end-of-life vehicles, WEEE and dismantled wind turbines. For the latter, it can be functionally recycled. Dy and Tb in permanent magnets can substitute each other, but their individual market shares have not been assessed. Tb is also present in very small quantities in LED lamps in WEEE, but this has not been quantified. However, it would likely not be functionally recycled.
La	11 (2,398)	14 (2,443)	273 (2,393)	246 (2,298)	BATT 23% CDW 0% ELV 77% SLASH 0% WEEE 0% WTB 0%	La is present in anode active material in waste batteries. It is assumed that La will be recovered via pyrometallurgical process in the future. La is present in catalytic converters and embedded electronics in end-of-life vehicles and is not functionally recycled.
Pr	1 (415)	356 (765)	436 (785)	241 (585)	BATT 1% CDW 0% ELV N.A. SLASH 0% WEEE 8% WTB 91%	Pr is present in anode active material in waste batteries. It is assumed that Pr will be recovered via pyrometallurgical process in the future. Pr is present in permanent magnets in WEEE and dismantled wind turbines and could be functionally recycled in magnet-to-magnet recycling. Pr could also be present in permanent magnets and catalytic converters in end-of-life vehicles, but this has not been quantified and is potentially underestimated.
Ce	0 (5,260)	0 (5,382)	37 (5,259)	35 (5,141)	BATT 100% CDW N.A. ELV N.A. SLASH 0% WEEE N.A. WTB N.A.	Ce is present in anode active material in waste batteries and could go to pyrometallurgy and is assumed to be functionally recycled in the future. Ce may also be present in other applications and waste streams, but this has not been quantified and is potentially underestimated. However, it would likely not be functionally recycled.

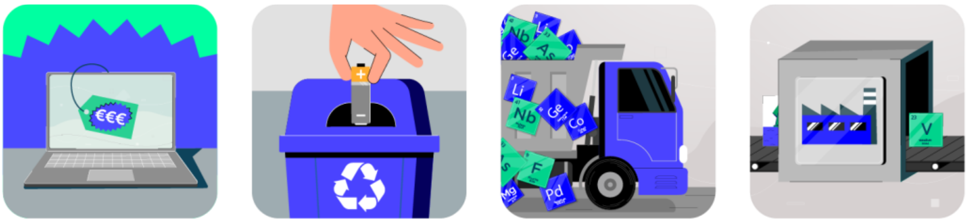
CRM	Present 2022	Business-as-usual 2050	Recovery 2050	Circularity 2050	FutuRaM waste streams contribution of CRM in secondary raw materials in the Recovery scenario for year 2050	Further information. When recoverability information is provided, it is based on present recoverability technology.
Mass flow quantities expressed in t/year						
Pd	14 (25)	17 (37)	35 (37)	30 (31)	BATT 0% CDW 0% ELV 76% SLASH 0% WEEE 24% WTB 0%	Pd is present in catalytic converters in end-of-life vehicles and in printed circuit boards in WEEE.Pd is recovered with other precious metals in integrated copper smelters.
Ta	16 (129)	17 (100)	50 (100)	26 (72)	BATT 0% CDW 0% ELV N.A. SLASH 0% WEEE 100% WTB 0%	Ta is present in printed circuit boards in WEEE but ends up in slags and is not functionally recycled. Ta could also be present in printed circuit boards in end-of-life vehicles, but this has not been quantified and is potentially underestimated. However, it would likely not be functionally recycled. Ta in metal alloys has not been quantified, but quantities are likely low and not functionally recycled.
Ga	1 (1,410)	2 (1,496)	9 (1,381)	5 (1,333)	BATT 0% CDW 0% ELV N.A. SLASH 0% WEEE 93% WTB 7%	Ga is present in printed circuit boards, photovoltaic panels and permanent magnets in WEEE and in aluminium alloys in dismantled wind turbines and is not functionally recycled. Ga could also be present in embedded electronics in end-of-life vehicles, but this has not been quantified and is potentially underestimated. However, it would likely not be functionally recycled.
Pt	6 (7)	7 (10)	10 (10)	10 (10)	BATT 0% CDW 0% ELV 100% SLASH 0% WEEE 0% WTB 0%	Pt is present in catalytic converters in end-of-life vehicles. Pt is recovered with other precious metals in integrated copper smelters.
Sm	0 (273)	0 (244)	9 (257)	5 (251)	BATT 0% CDW 0% ELV N.A. SLASH 0% WEEE 100% WTB N.A.	Sm is present in permanent magnets in WEEE and is not functionally recycled. Sm could also be present in permanent magnets in end-of-life vehicles, but this has not been quantified and is potentially underestimated. Sm could also be present in permanent magnets in dismantled dismantled wind turbines, but quantities are likely low. However, it would likely not be functionally recycled.
Rh	1 (4)	1 (6)	2 (5)	2 (5)	BATT 0% CDW 0% ELV 100% SLASH 0% WEEE 0% WTB 0%	Rh is present in catalytic converters in end-of-life vehicles. Rh is recovered with other precious metals in integrated copper smelters.

Removed
1) Sr, Y, Sc, Gd, Yb, Er, Be, Hf, Eu, Ho, Tm, Lu, Ge. Elements are in the waste streams and may be undercovered. Likely no functional recovery of it.
2) B data quality assessed not to be sufficient for publication.
3) Ti is in metal alloy form in end-of-life vehicles and dismantled wind turbines, but data quality assessed not to be sufficient for publication.
4) Bi can be found in aluminium alloy in the waste streams, but data quality assessed not to be sufficient for publication.

3.9 Critical Raw Material Totals Across Placed on Market, Waste Generation, and Secondary Raw Materials

In total, 42 CRMs were analysed for waste batteries, construction, and demolition waste from buildings, end-of-life vehicles, slags and ashes, WEEE, and dismantled wind turbines. Mining waste was *not* assessed in this overview because its data structure differs from that of the other six waste streams. For more information on mining waste, see chapter 3.4. For the assessment presented in this chapter, the analysis covers the stages from placed on the market, through waste generated, to waste management. Slags and ashes are not included here, as there are no quantities placed on the market for that waste stream, meaning that analysis across placed on the market, waste generation, and waste management would be too complex to represent visually.

The quantities of CRMs (Mt/year) for placed on the market, waste generated, not collected or recovered, and secondary raw materials are shown in Figure 8 for 2022, as well as for BAU, CIR, and REC scenarios for 2050.



	Placed on the market	Waste Generated	Not collected or recovered	Secondary raw materials*
2022	5.2	2.1	0.7	1.4
2050 CIR	8.4	5.2	0.5	4.7
2050 BAU	12.2	6.4	2.3	4.1
2050 REC	12.2	6.4	0.7	5.7

Datasets from slags and ashes and mining waste were not comparable in these aggregates and hence were excluded from the totals. The presented aggregate was determined for the EU27 plus Iceland, Norway, Switzerland and the United Kingdom for the waste batteries, end-of-life vehicles, and WEEE, and for the EU27 for the waste streams construction and demolition waste from buildings and dismantled wind turbines.

* Waste treatment can happen outside of the EU27+4

Figure 8: CRM quantities (Mt/year) at the stages of placed on the market, waste generated, not collected or recovered, and secondary raw materials for the baseline year (2022) and three different scenarios for 2050, for waste batteries, construction and demolition waste from buildings, end-of-life vehicles, WEEE, and dismantled wind turbines.

The total amount of CRMs placed on the market in the five streams is 5.2 Mt/year in 2022 and is projected to increase to between 8.4 Mt/year in the CIR scenario and 12.2 Mt/year in the BAU and REC scenarios. In 2022, the CRM with the largest mass placed on the market is aluminium

(3.4 Mt/year), which is mostly contained in end-of-life vehicles (2.1 Mt/year), followed by content in waste electrical and electronic equipment (WEEE) (0.9 Mt/year), construction and demolition waste from buildings (230 kt/year), waste batteries (79 kt/year), and dismantled wind turbines (33 kt/year). The second largest CRM in mass is copper with 1 Mt/year in 2022 which is present in EEE (492 kt/year), followed by end-of-life vehicles (261 kt/year), construction and demolition waste from buildings (135 kt/year), waste batteries (67 kt/year), and dismantled wind turbines (52 kt/year).

The total amount of CRMs in waste generated in the five waste streams was 2.1 Mt/year in 2022. CRM quantities in waste generated are projected to grow from 2.1 Mt/year in 2022 to between 5.2 and 6.4 Mt/year by 2050, depending on the future scenario considered. Of 2.1 Mt/year of CRMs in waste generated in 2022, 0.7 Mt/year was not collected or collected and was not recovered, while the remaining 1.4 Mt/year of CRMs were recovered as secondary raw materials.[6] If these CRMs in secondary raw materials were functionally recycled, they could substitute up to 27% of the primary CRMs placed on the market. The CRMs in secondary raw materials are projected to grow from 1.4 Mt/year in 2022 to between 4.1 and 5.7 Mt/year. If these CRMs in secondary raw materials were functionally recycled, by 2050 they could substitute up to:

- 33% of the primary CRMs placed on the market in the BAU scenario, which reflects current increasing trends in consumption and waste generated and minor improvements in existing collection and recovery systems.
- 47% of the primary CRMs placed on the market in the REC scenario, which is based on current increasing trends in consumption and waste generated and assumes improvements in collection and recovery systems.
- 56% of the primary CRMs placed on the market in the CIR scenario, where CRM demand for placed on the market and waste generated is lowest and there is improvement in collection and recovery systems.

The Sankey diagram in Figure 9 shows the overall flows of aluminium, copper, silicon, manganese, nickel, and other CRMs for EU27+4 in 2022, from placed on the market to net addition to the stock, waste generated, and waste management, disaggregated by CRM. The CRMs placed on the market are added to the stock and in the same year, 2.1 Mt/year of CRMs were embedded in waste generated, making the net addition to the stock 3.0 Mt/year of CRMs. There are 0.2 Mt/year of CRMs leaving the stock, being exported as second-hand end-of-life vehicles from the EU27+4.

The diagram also shows that from the 2.1 of Mt/year of CRMs in waste generated, 1.6 Mt/year were collected, and 0.6 Mt/year were not collected. From the 1.6 Mt/year of collected CRMs, 1.4 Mt/year of CRMs were found in secondary raw materials, and 0.2 Mt/year were lost during processing and treatment. These losses included, for instance, the CRMs in permanent magnets or copper that are not separately dismantled and hence recovered together with the ferrous output fraction. The 0.6 Mt/year of CRMs in waste generated that were not collected were ending up in non-compliant treatment destinations. These non-compliant destinations include 1. WEEE or waste batteries disposed of as residual solid waste which is then incinerated and/or landfilled, 2. WEEE mixed with metal scrap, where only the ferrous fraction is likely recovered and the CRMs are lost, and 3. leaving the EU27+4 territory through exports of second-hand EEE which has a high chance of being illegally mixed with WEEE. A small amount, 0.01 Mt/year, is contained in exports of used EEE and its embedded batteries.

[6] The above do not resemble functional recycling or losses that may occur during smelting.

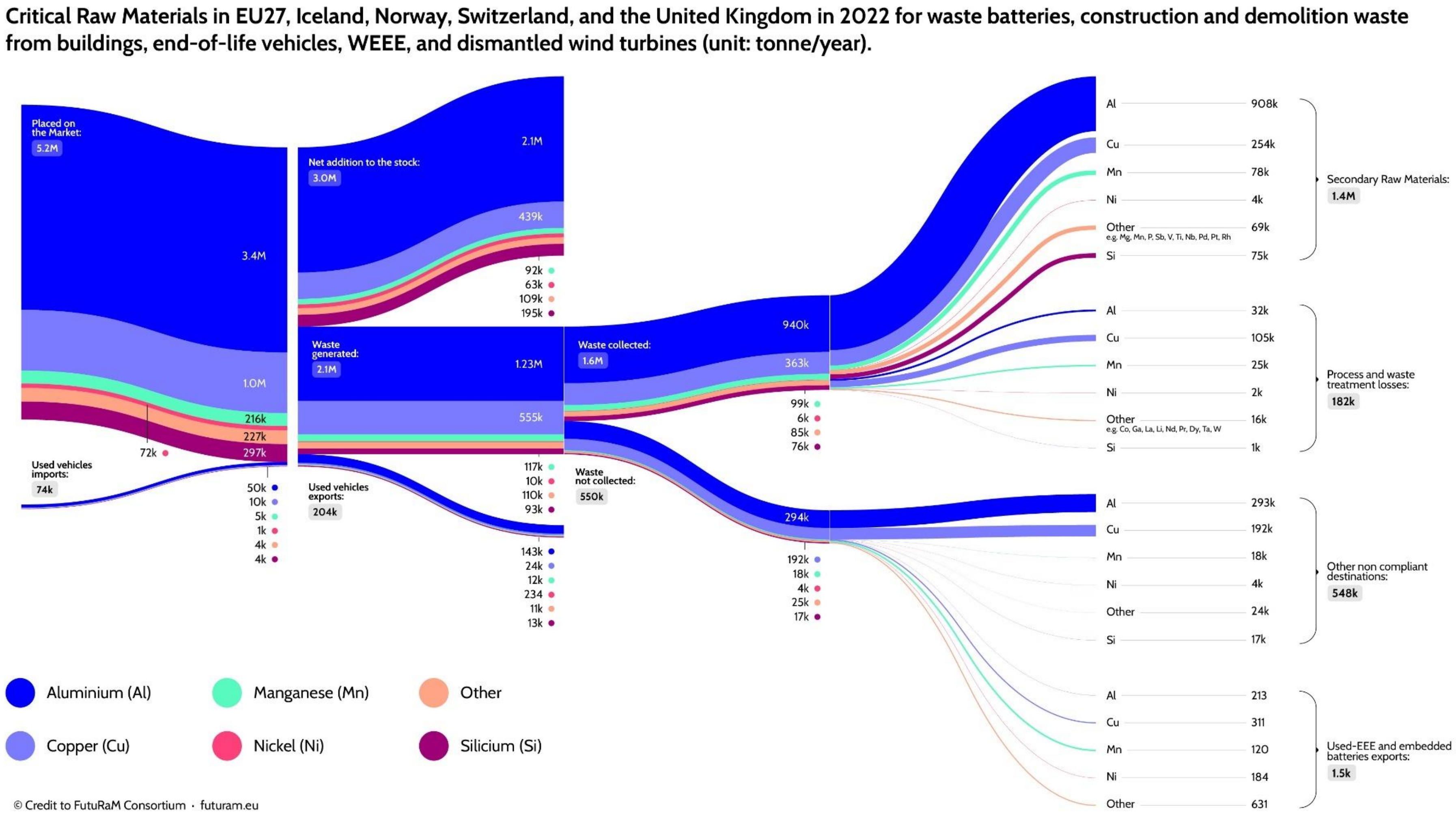


Figure 9: Sankey diagram for CRMs in placed on the market, waste generated, waste collected, and recovery.

The quantities of each CRM contained in secondary raw materials from waste batteries, construction and demolition waste from buildings, end-of-life vehicles, WEEE, and dismantled wind turbines for 2022 are shown in Figure 10. This figure also shows projections for 2050 for the three future scenarios. Not all of the 42 CRMs analysed are shown in the figure because it only displays values greater than 1 t[7]. The quantities of CRMs in secondary raw materials in the EU27+4 are projected to increase for all the analysed CRMs across all scenarios, except for antimony, which is being phased out of use in batteries and EEE. The most abundant CRMs in secondary raw materials are aluminium (0.9 Mt/year in 2022 and between 2.7 and 3.5 Mt/year by 2050) and copper (0.3 Mt/year in 2022 and between 0.8 and 1.4 Mt/year by 2050), both of which are present in all waste streams, followed by silicon (74 kt/year in 2022 and between 141 and 216 kt/year by 2050), mainly found in photovoltaic panels and as an alloying element in stainless steel. Projecting to 2050, the quantities of several CRMs are expected to increase due to a combination of higher waste generated and/or lower losses, whereas for the rest the increase is caused by an increase in the quantity of these CRMs placed on the market. For more information on the origin and recovery potential of CRMs in secondary raw materials, please see section 3.8.

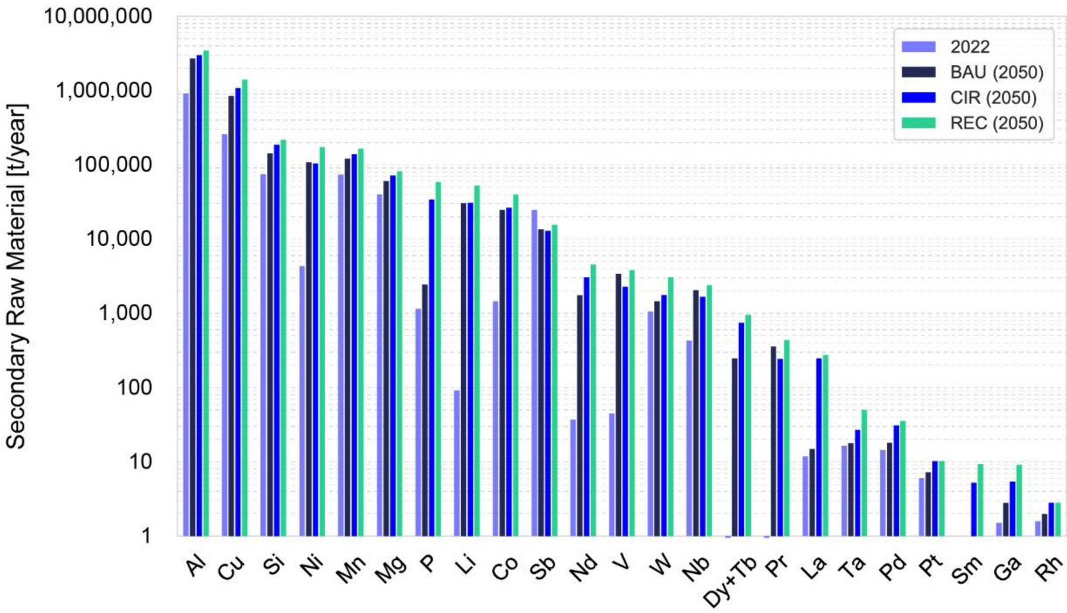


Figure 10: CRMs in secondary raw materials for waste batteries, construction and demolition waste from buildings, end-of-life vehicles, WEEE, and dismantled wind turbines (unit: tonne/year). Values for CRMs in secondary raw materials below 1 tonne/year in a given year are not displayed. Bars are ordered based on the REC scenario in 2050.

Figure 10 shows large proportional increases for lithium (<0.1 kt/year in 2022 increasing to between 30 and 52 kt/year by 2050), cobalt (1 kt/year in 2022, and between 25 and 40 kt/year in 2050), and nickel (4 kt/year in 2022 and between 103 and 171 kt/year by 2050). These increases are primarily driven by the battery waste stream, reflecting the electrification of the passenger vehicle fleet. Lithium in waste batteries is contained in the black mass, and recovery of lithium from black mass is not currently economically viable in Europe. However, there is a substantial body of ongoing research, with EU legislation promoting black mass recycling and upcoming global trade restrictions through the

[7] The CRMs below 1 t in the secondary raw material that are omitted from the figure are arsenic, boron, cerium, bismuth, titanium, beryllium, erbium, europium, gadolinium, germanium, hafnium, holmium, lutetium, scandium, strontium, thulium, yttrium, and ytterbium.

Basel Convention on the control of transboundary movement of hazardous wastes, such that is likely to result in viable black mass recycling in Europe. Therefore, lithium in secondary raw materials is expected to increase by 2050 in the REC and CIR scenarios.

A large proportional increase can be also observed for rare earth elements that are mostly found in permanent magnets from end-of-life vehicles, WEEE, and dismantled wind turbines. These rare earth elements include neodymium, dysprosium, terbium, and praseodymium. While their presence in secondary raw materials is less than 1 t/year in 2022 and they are not currently functionally recycled, this is projected to significantly increase for neodymium, for instance, to between 1.7 and 4.6 kt/year by 2050, and for dysprosium and terbium [8] to between 0.2 and 1 kt/year in 2050. This increase is more pronounced in the CIR and REC scenarios due to improved selective dismantling and potential subsequent refining resulting from legislation, industry response, and research.

Across the CRMs assessed in the five waste streams covered in this section, the average ratio of CRMs from waste generated to secondary raw material was 65% in 2022. This means that, on average, 65% of the mass of CRMs contained in the waste generated was processed into a secondary raw material. Figure 11 shows these ratios for the 42 CRMs analysed in FutuRaM. The periodic table cell is divided diagonally: the upper-left triangle represents 2022 ratio, while the lower-right triangle represents 2050 (recovery scenario) ratio. This ratio has been calculated as the amount of CRM in secondary raw materials divided by the amount of CRM in waste generated.

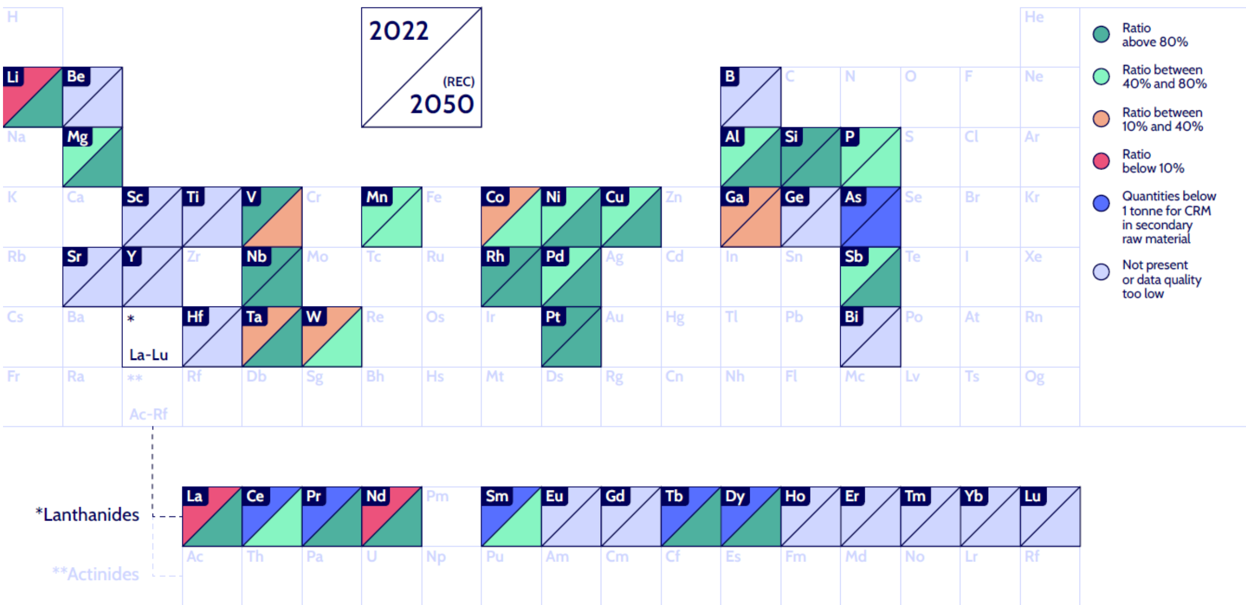


Figure 11: Ratio of CRMs in secondary raw materials versus CRMs in waste generated for waste batteries, construction and demolition waste from buildings, end-of-life vehicles, WEEE, and dismantled wind turbines in 2022 and in 2050 for the recovery scenario.

[8] Dysprosium and terbium are grouped together as they are both used in permanent magnets, and exact splits were not available.

Whilst the ratio is 65% for all CRMs combined, this ratio differs considerably between individual CRMs:

- There are 5 CRMs with ratios higher than 80% in 2022. Vanadium, niobium, and silicium are present in stainless steel alloys from end-of-life vehicles, construction and demolition waste from buildings and dismantled wind turbines. CRMs in stainless-steel alloys end up most likely downcycled with ferrous scrap. Silicon is also found in photovoltaic panels, where it is not currently recycled. Platinum and rhodium are found in automotive catalysts, which are currently recycled. The number of CRMs with ratios higher than 80% increases to 17 in 2050 in the REC scenario.
- There are 8 CRMs with ratios between 40% and 80% in 2022, indicating that collection and recycling technologies are in place, although losses occur in the waste management phase. These include aluminium and copper, which are present across multiple waste streams, nickel and antimony in waste batteries[9], palladium in end-of-life vehicles and WEEE, and magnesium, phosphorous, and manganese in steel alloys. The number of CRMs with ratios between 40% to 80% reduces to 6 in 2050 in the REC scenario.
- There are 4 CRMs with ratios between 10% and 40% in 2022, where collection and recycling take place, but losses are significant. These include cobalt in WEEE and waste batteries, and gallium, tantalum, and tungsten in WEEE. For those present in WEEE, most losses occur due to 44% of WEEE not being collected in the EU27+4. The number of CRMs with ratios between 10% to 40% reduces to 2 in 2050 in the REC scenario.
- There are 3 CRMs with ratios below 10%, including lanthanum in waste batteries and end-of-life vehicles that are not economically viable to recover in Europe. Li in waste batteries is contained in the black mass, and recovery of lithium from black mass is not currently economically viable in Europe. However, as noted earlier, there is substantial research ongoing, plus legislation and regulation to underpin this. Hence, this is expected to increase in 2050 in the REC and CIR scenario. The number of CRMs with ratios below 10% reduces to zero in 2050 in the REC scenario.
- There are 6 CRMs with recovery below 1 tonne, which are hardly present and recycled in 2022, such as arsenic, and rare earth metals, such as neodymium, terbium, samarium, praseodymium, and cerium. In the REC scenario in 2050, this number decreases to 1 CRM (arsenic).
- The remaining 16 CRMs show little or no functional recycling in 2022 and 2050. The exact quantities and ratios could not be assessed with the same accuracy and thus are shown separately.

The equivalent figures per waste stream analysed in Figure 11 as well as slags and ashes are available in Annex I.

[9] Ni in stainless steel was not assessed.

4 Urban Mine Platform

The Urban Mine Platform provides knowledge about the availability of secondary raw materials through giving access to clear and structured data with a focus on the seven waste streams studied in FutuRaM.

As described in detail in chapter 2, the data has been compiled in FutuRaM following extensive research into the material composition and stocks and flows of these waste streams, and by establishing three different future scenarios that influence the arisings and characteristics of the waste streams out to 2050: BAU, REC, and CIR.

By combining these elements, the Urban Mine Platform presents the quantities placed on the market, currently in the stock (where the focus waste stream allows), and arising as waste, providing data on the raw material content and insights into availability of secondary raw materials. In case of mining waste, the data is geographically located. Therefore, the sites are displayed on an interactive map rather than in charts and graphs.

Users of the Urban Mine Platform can explore the data using the interactive parts of the knowledge base to focus on areas of interest, with datasets being available for download for further analysis.

4.1 Background analysis and user requirements

In 2017, the EU-funded project ProSUM (2017) released the first-ever web-based platform offering a public access to statistics data on three waste streams, i.e. end-of-life vehicles, waste batteries, and WEEE. Although mining waste was included in the scope of ProSUM, that first version of Urban Mine Platform did not deliver access to data about mining waste; instead, the corresponding dataset was disseminated via the European Geological Data Infrastructure (EGDI) developed and operated by EuroGeoSurveys (n.d.).

The Urban Mine Platform version 1 has been available online ever since the conclusion of ProSUM. It served as a solid reference in FutuRaM when consulting the stakeholders to design version 2. This reference was twofold: the data model and registries of the Secondary Raw Materials Knowledge Base (SRM-KB), particularly for the new waste streams considered in FutuRaM, as well as the user interface to benefit from the latest design approaches.

The state of the art was established through a benchmark of several well-known data platforms, namely the UN Comtrade (UNSD, n.d.), Resource Trade (Chatham House, n.d.), the Raw Materials Information System (European Commission, n.d.), Panorama (Panorama Project, n.d.), Urban Mine Platform v1.0 (ProSUM, n.d.), Material Flow Accounts (Eurostat, 2025.), and Elementarium (n.d.) The analysis focused on a panel of criteria as follows:

- Choice of dataset from a pool of categories (incl. filtering)
- Data representation using various charts
- Possible downloading of data
- Access to publications, news, and reports in the web tool
- Possible customising of the data representation

A user experience / user interface study (UX/UI) was conducted, and a detailed questionnaire was prepared as a guideline for a series of bilateral interviews between the Urban Mine Platform development team and the waste stream representatives.

During the design stage, it was found logical that the new website to access the FutuRaM datasets would replace the first version Urban Mine Platform produced by the ProSUM project. By essence, it is a standalone data access platform different from the FutuRaM project website. It is named Urban Mine Platform v2 and uses the same web link (https://www.urbanmineplatform.eu/).

4.2 Delivering the Urban Mine Platform v2

A development process was put in place to include stakeholders' requests for bug fixing and suggestions for evolutions.

The main features of the Urban Mine Platform version 2 include (Figure 12):

- One page for each waste stream to display the datasets through several graphics (bar charts, line charts, Sankeys). These are interactive with dynamic filtering. The graphics and selected subsets of data are downloadable.
- One page to compare the waste stream datasets using dynamic filtering.
- One page dedicated to the mining waste with an interactive map to display the datasets capitalised in the European Geological Data Infrastructure (EGDI) platform and accessed using an INSPIRE-compliant webservice.
- One page to download the complete waste stream datasets.
- One page for the acronyms and definitions that explains the terms used on the platform.

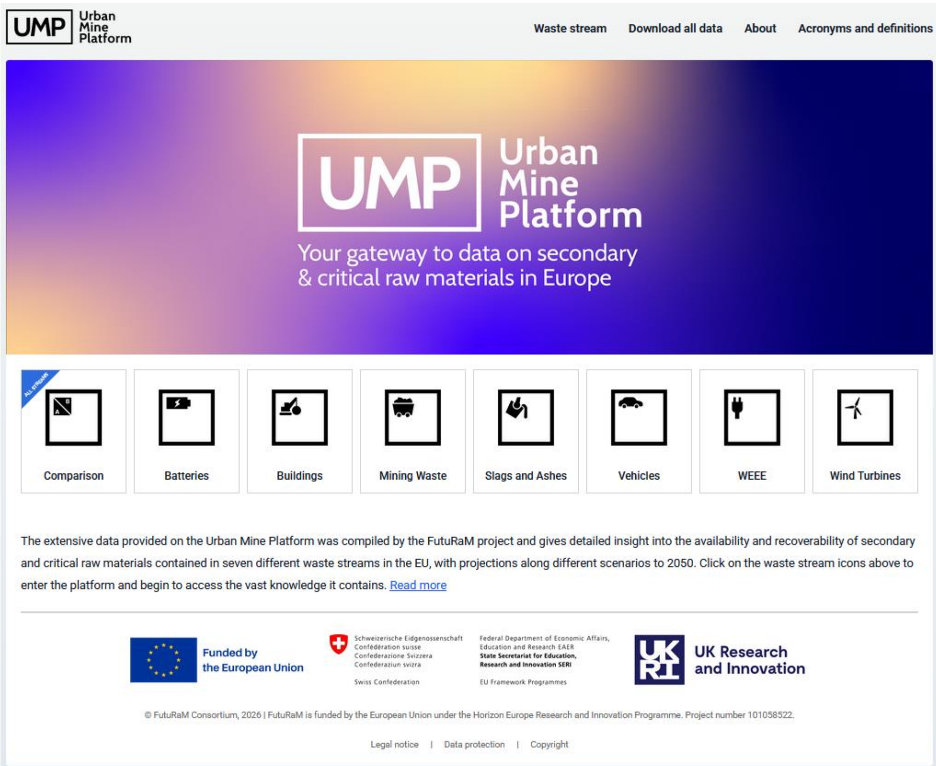


Figure 12: Urban Mine Platform home page – https://www.urbanmineplatform.eu/.

Bar charts (Figure 13) present the quantity from 2010 to 2050 based on the selection of filters. Several interactive widgets are included to allow users to adjust the time display, select products, and download both the selected dataset and the corresponding chart as an image.

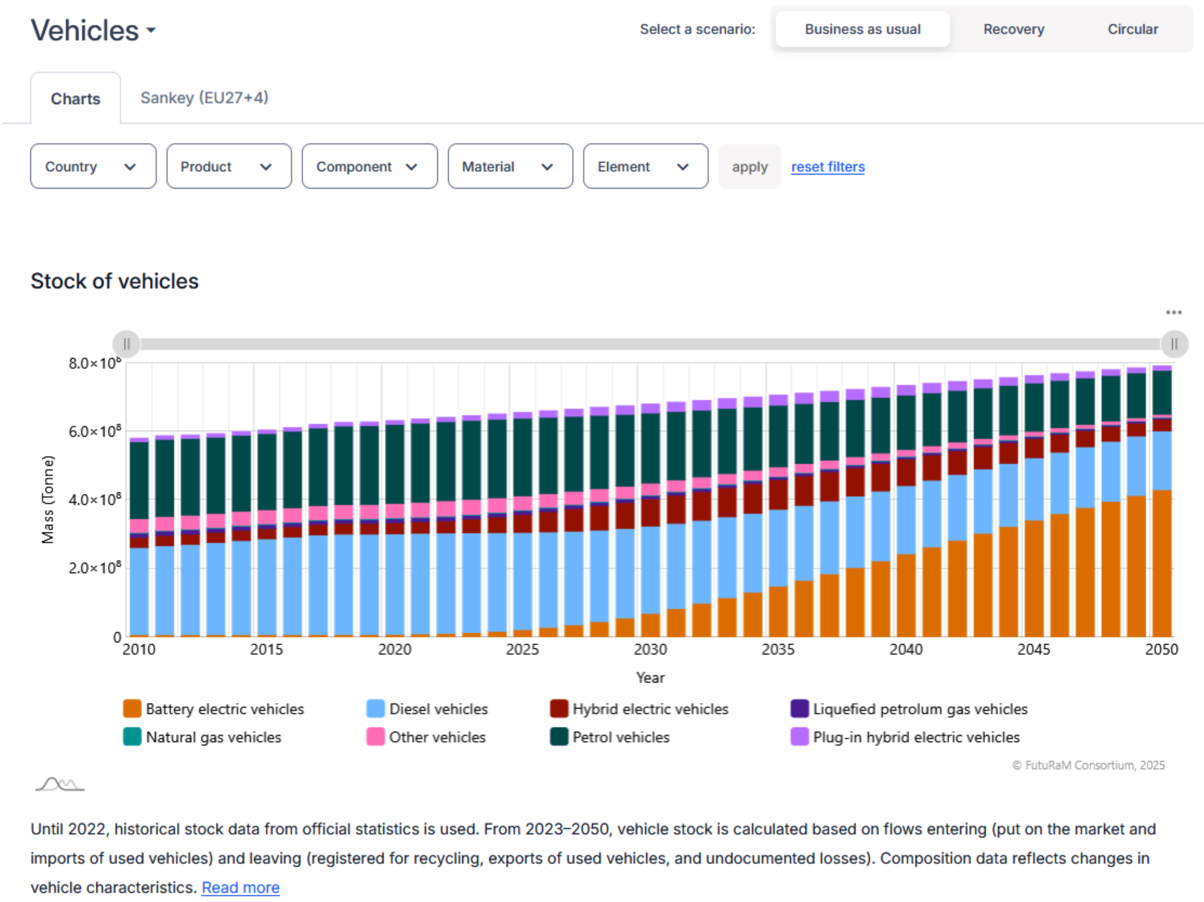


Figure 13: Bar chart from the Urban Mine Platform – example for stock of vehicles.

Line charts (Figure 14) present the quantity of waste generated and collected (according to the waste stream selected) from 2010 to 2050. The two lines (waste generated and waste collected) are displayed in the same graph for the three scenarios (business-as-usual, recovery, circularity). The lines corresponding to the scenario chosen from the selection are highlighted.

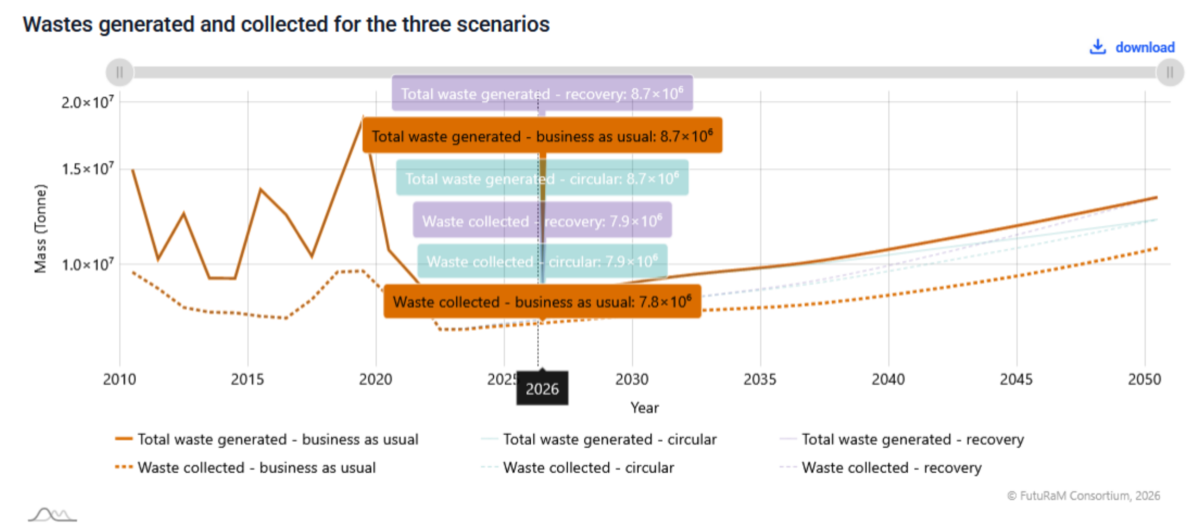


Figure 14: Line chart from the Urban Mine Platform – example of waste generated and collected for end-of-life vehicles.

Sankey diagrams (Figure 15) present data resulting from the recovery model. They can be filtered according to the year and a selection of material and/or element.

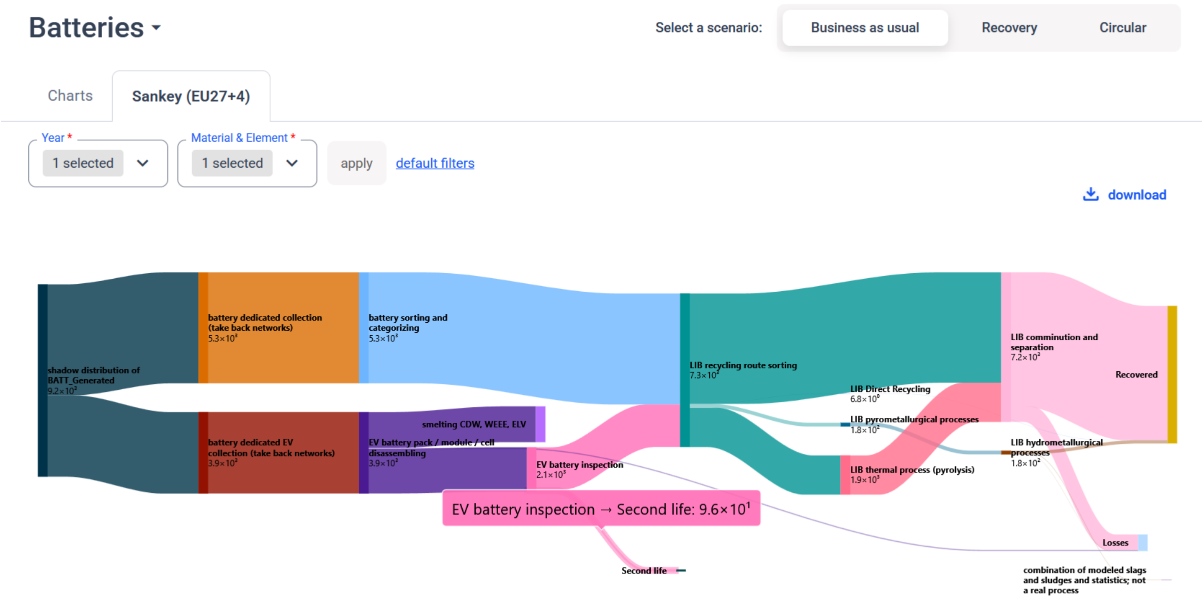


Figure 15: Sankey diagram from the Urban Mine Platform – example for waste batteries.

Factsheets about stock and flow and recovery models for each waste stream, as presented in chapter 3, are implemented and accessible as well in the Urban Mine Platform. This factsheet section in Urban Mine Platform displays data charts and key numbers without any filtering option to the user (see Figure 16).

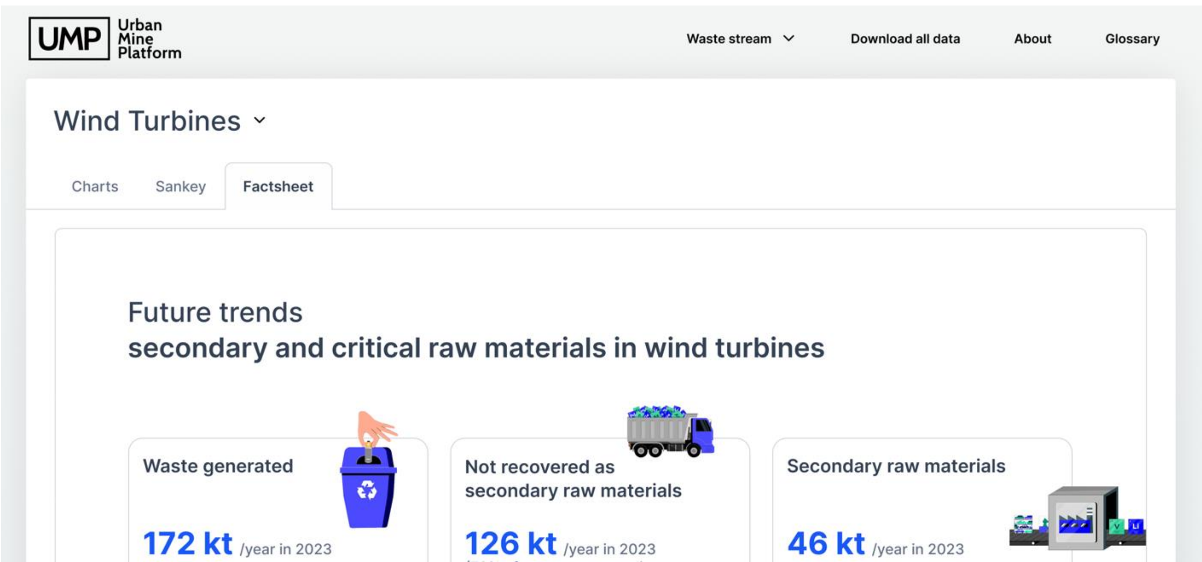


Figure 16: Example of waste stream factsheet integration in the Urban Mine Platform.

The comparison pages have two graphics, comparing the waste generated across waste streams. For all graphs, the user can select the waste stream, year, and set of materials and elements.

The first comparison graph (Figure 17) is showing the distribution and geographical breakdown of waste generated.

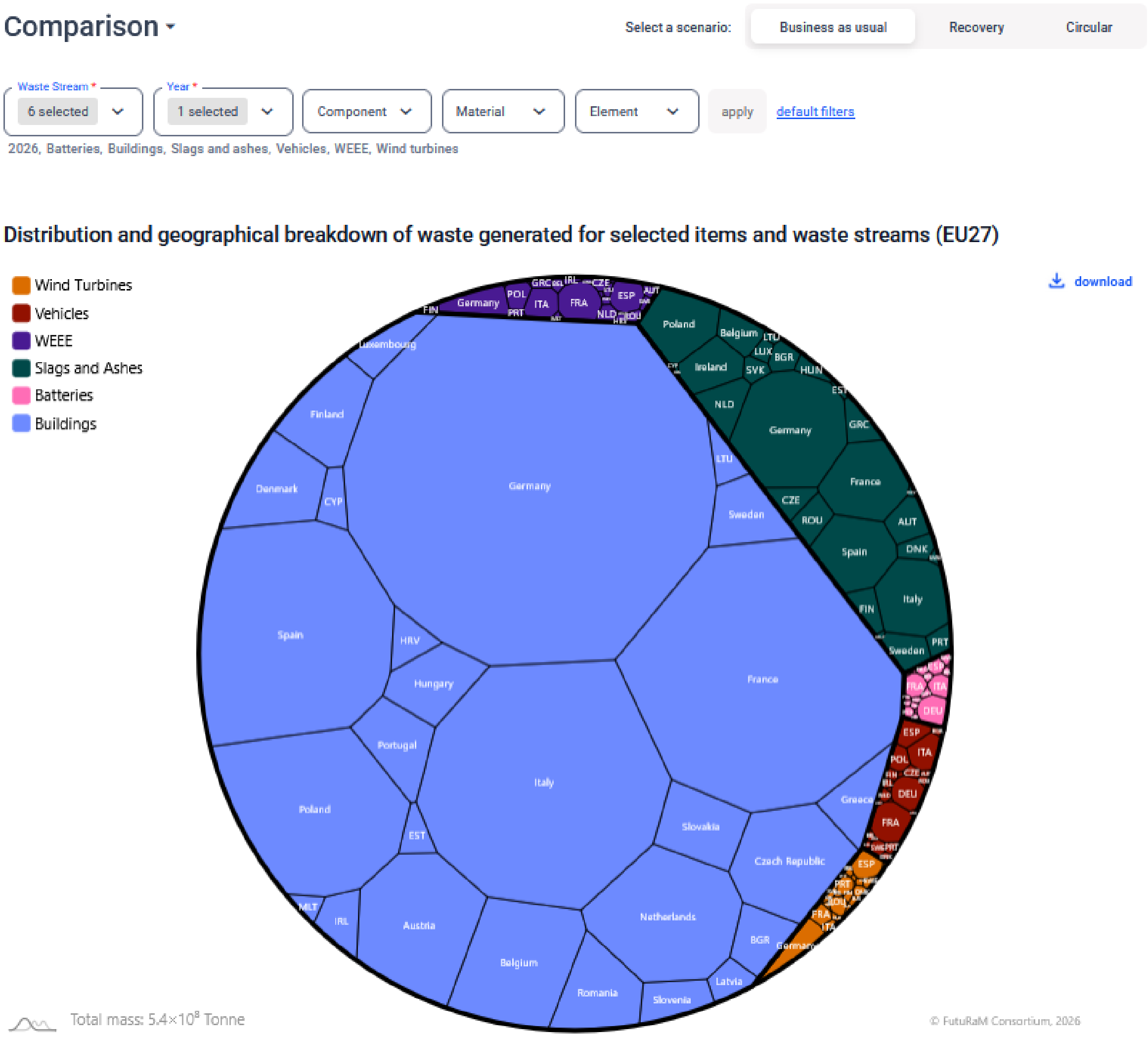


Figure 17: Distribution and geographical breakdown of the waste generated on the Urban Mine Platform – example with all the waste calculated in the FutuRaM project.

The second comparison graph (Figure 18) presents the total mass of waste generated of the selected elements for 2019, 2030, and 2050.

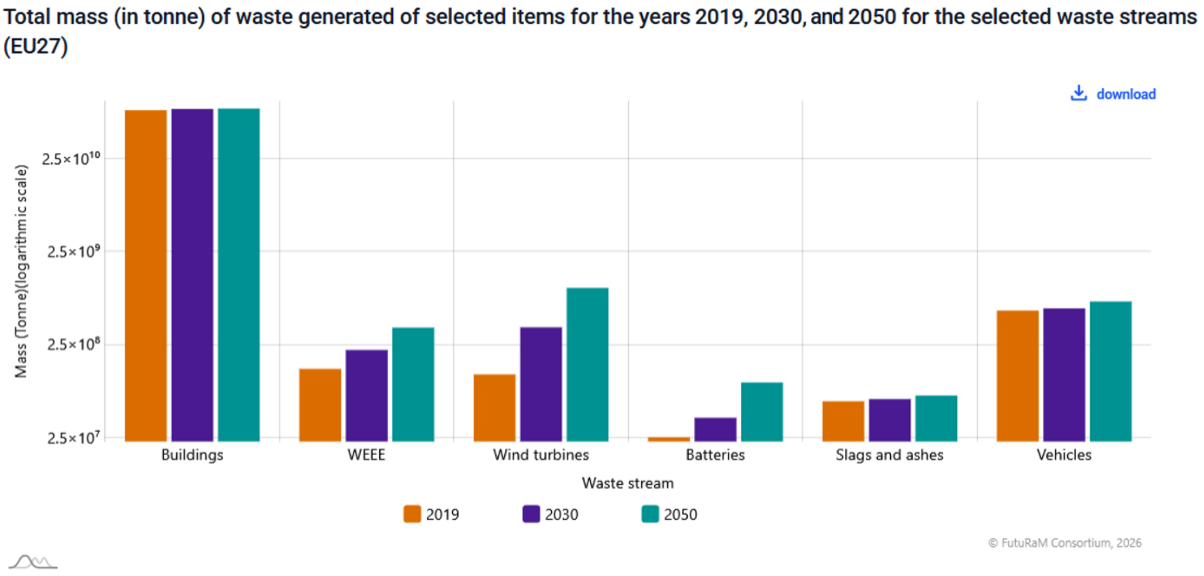


Figure 18: Evolution of waste in 2019, 2030 and 2050 for the different waste streams.

The Urban Mine Platform is continuously being updated. Figures in this report may differ from those displayed online. Moreover, additional features and figures may be added to the Urban Mine Platform.

4.3 Datasets in the Urban Mine Platform

Each waste stream was responsible for data collection (composition, stocks, and flow statistics) and modelling (stock and flow and recovery models). Except for mining waste (see 4.4), all waste stream teams used a single and unique data template for model outputs, with code lists and vocabularies centralised and harmonised within the project. Prior to any data upload in the Secondary Raw Materials Knowledge Base for interactive visualisation on the Urban Mine Platform, a protocol of data control and data accuracy was put in place, with the objective of a consistency check to eliminate the residual errors (e.g., meaningless zeros, mass balance issues, etc.).

The total size of FutuRaM Secondary Raw Materials Knowledge Base (SRM-KB) is 44 GB (Table 2). To optimise the display of charts and minimise the response time on the website, thus improving the user experience, several solutions are combined. These include indexing of Secondary Raw Materials Knowledge Database data tables, specific intermediate data calculations, and dedicated filtering algorithms to eliminate void combination results.

Table 2: Number of records and file size in the Secondary Raw Materials Knowledge Database for charts and Sankey diagrams.

Waste stream	Number of records (x 1,000)		File size (MB)	
	Bar and line charts	Sankey diagrams	Bar and line charts	Sankey diagrams
Waste batteries	7,600	199	965	22.4
Construction and demolition waste from buildings	743	729	68	67.5
End-of-life vehicles	9,747	102	895	10.5
Slags and ashes	831	31	64	2.7

WEEE	17,522	385	2,070	48.1
Dismantled wind turbines	8,564	434	980	53.6

4.4 Particular case of the mining waste data map

Mining waste data is made accessible in the Urban Mine Platform in a completely different way than it is in other waste streams. As mining waste sites are geographically located, the most appropriate manner is to present this dataset on an interactive map (Figure 19). By default, it displays the mining sites classified by waste type. By clicking on a site or a group of sites, the user opens a table below the map showing detailed information about each deposit (e.g., waste type group, waste type, commodities, content measurements, etc.).

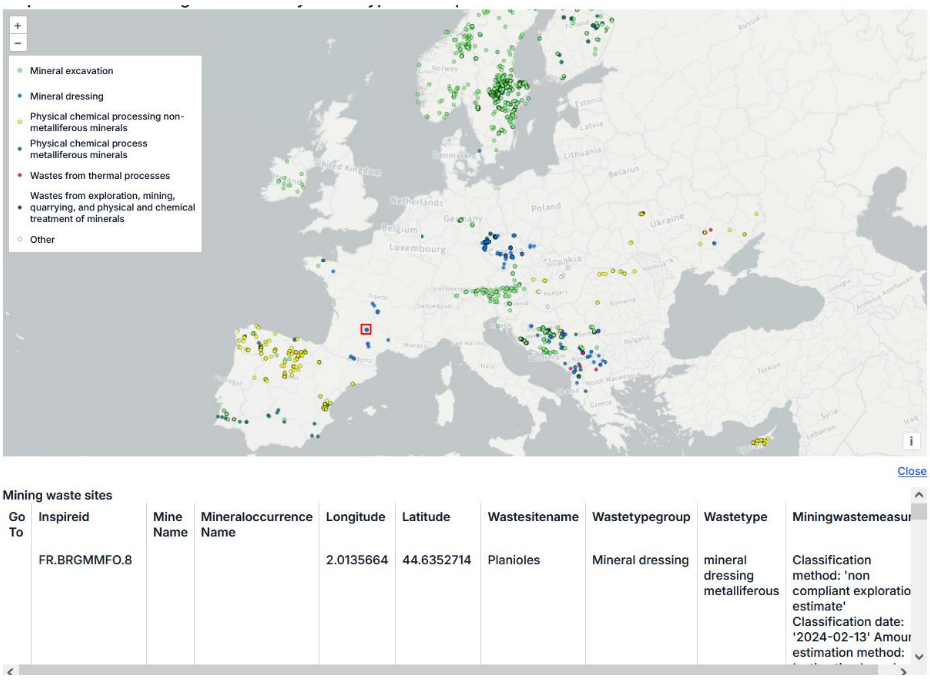


Figure 19: Map of historical mining waste sites

The data collected by the FutuRaM team in charge of the historical mining waste has been first uploaded in the European mineral resources database (MIN4EU – primary and secondary), created and operated by EuroGeoSurveys. This unique data repository is accessible on the EGDI (2022) web portal. Thanks to the collaboration with the HE-funded Geological Service for Europe project (GSEU, n.d.) and the implementation of an interoperable connection, a web service is exposed by EGDI and made accessible on the Urban Mine Platform. This way, any new and/or updates records in the MIN4EU database is immediately accessible on the Urban Mine Platform.

MIN4EU database have a data structure with more than 30 attributes (ore grades, waste dimension, classification and sampling methods, etc), but those attributes are not filled systematically. The filling of the database – with more countries present, more points on the map, and more data entered – is a dynamic process that will take place with the entry into force of article 27 of the CRM Act.

4.5 Data copyright, Intellectual Property

The content, texts, data, graphics, and images published on the Urban Mine Platform are protected by copyright under Creative Commons Attribution 4.0 International Public License CC BY 4.0.

To acknowledge the use of Urban Mine Platform data, the following sentence must be used:

*"This **[study/project/research]** used the FutuRaM produced Urban Mine Platform (https://www.urbanmineplatform.eu) to access the **[dataset/service name][insert relevant DOIs / PIDs]** on **[date]**."*[10]

In documents and scientific articles, the citation would be as follows:

Urban Mine Platform [Insert Waste Stream dataset] [insert version if applicable], provided by FutuRaM project, [insert licence information if applicable], [insert relevant DOIs/PIDs if available]. Accessed on [DD-MM-YYYY] through the www.urbanminepatform.eu.

[10] https://www.urbanmineplatform.eu/copyright

5 Application of the UNFC to the Urban Mine

5.1 Classification of secondary raw materials recovery projects

Existing recycling frameworks for WEEE, batteries, and ELVs are product-, stock-, and flow-based. While they are well suited for setting collection and recycling targets, they cannot determine how much of a waste stream can actually be utilised as a raw material under real-world technological, economic, and regulatory conditions. This question can only be addressed on a project-by-project basis. Project-level classification closes this gap. By classifying recovery projects, waste streams are translated into resource estimates – aligning with the language of investors and regulators, placing primary and secondary resources on an equal footing, and enabling project assessments to be comparable across borders in a consistent format that policymakers, industry, investors, and geological surveys can all understand.

The classification of resource development projects was originally introduced for primary raw materials to communicate project maturity and the level of confidence in the information used to estimate resources and reserves. However, as resource development expanded across different sectors and jurisdictions, a variety of classification approaches emerged, many of which are still in use today, such as the CRIRSCO template for minerals. Despite their continued relevance, comparability across resource types and jurisdictions has remained limited.

The United Nations Framework Classification for Resources (UNFC) is an international classification system developed to provide a consistent and transparent framework for resource data across different sectors. It originated in the 1990s as a tool to compare quantity and quality information from diverse sources for fossil energy and mineral resources. Over time, it evolved into a comprehensive, project-based system that provides a common structure for classifying resource projects, including anthropogenic resources[11] such as secondary raw materials recovery projects.

A key strength of the UNFC lies in its ability to simplify complex information about mineral deposits by organising it into a clear three-dimensional system that reflects the current state of knowledge regarding the deposit, the technical maturity of the project, and the socio-economic and environmental sustainability of its development. According to (UNECE, 2020), 'the products[12] of a mineral resource project are classified on the basis of three fundamental criteria of environmental and socio-economic viability (E), technical feasibility (F), and degree of confidence in estimates (G),

[11] UNFC focuses on resources, and it is on this basis that the term 'anthropogenic resources' was created as a counterpart to 'natural resources' used in primary raw material projects. Essentially, these are the resources contained in the anthroposphere, usually designated as waste, that have the potential to meet the demand for raw materials.

[12] Note that this refers to project products in the UNFC context. Anthropogenic sources provide the feedstock to projects from which products can be developed. Project products may be bought, sold, used, or produced without being sold or used (UNECE, 2025).

using a numerical coding system'. In this context, products refer to the outputs of a defined project – for example, extracted raw materials such as copper, aluminium, or lithium extracted from a source such as waste. Depending on the project's progress, these products may already be on the market, may still be in the pilot phase, or may not yet have been produced.

The numerical coding system is structured along the three criteria (E, F, and G), each of which is subdivided into categories that describe the status of the project. These categories are defined as follows:

- E – Environmental and socio-economic viability:
    - E1: confirmed to be viable
    - E2: expected to become viable in the foreseeable future
    - E3: not expected to become viable
- F - Technical feasibility:
    - F1: feasible
    - F2: subject to further evaluation
    - F3: cannot to be evaluated due to limited data
    - F4: no development identified
- G - Confidence in estimates:
    - G1: high confidence
    - G2: moderate confidence
    - G3: low confidence
    - G4: indirect evidence

In this context, 'UNFC provides a consistent framework to describe the level of confidence of the future quantities produced by the project', while a project is defined as 'a defined development or operation[13] which provides the basis for environmental, social, economic, and technical evaluation and decision-making' (UNECE, 2020). Within this system, the development status or maturity of a project is expressed through its E-F-G class (e.g., E1F1G1, E3F2G2), as shown in Figure 20. In general, projects classified as E1F1G1 to E1F1G3 are considered to be viable, indicating that they are commercially feasible and technically implementable, with varying levels of confidence in the estimates ranging from high (G1) to low (G3). Projects with lower classifications (e.g., E2 or E3, F2–F4, G3–G4) reflect increasing levels of uncertainty, lower technical maturity, or limited viability and typically require further evaluation before implementation. In some cases, intermediate sub-categories (e.g. F1.2 or F2.1) are used to provide a more refined representation of project status, particularly along the E and F axes. These sub-categories allow a more detailed differentiation within a category and reflect incremental progress in project maturity. Furthermore, UNFC emphasises transparency and traceability in reporting, stating that 'estimates shall be documented in sufficient detail that would allow an independent evaluator or auditor to clearly understand the basis of the estimate and their classification.'

[13] A development may refer to planned or proposed activities aimed at establishing or expanding a resource project, such as the design, construction, or modification of facilities and processes. An operation, by contrast, refers to an ongoing activity or functioning system where recovery processes are already being carried out and can be evaluated within the UNFC framework.

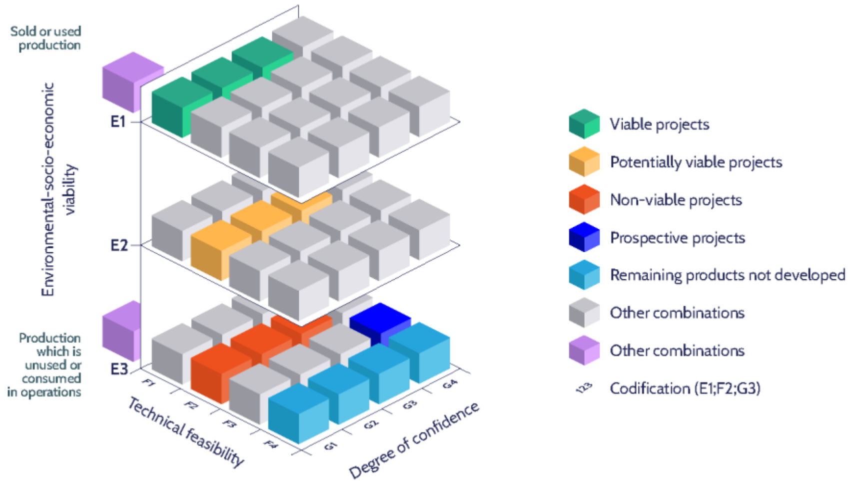


Figure 20: UNFC Categories and Examples of Classes. Source: United Nations Framework Classification for Resources (UNECE, 2020).

In UNFC terminology, waste is treated as an anthropogenic resource, i.e. a resource created by humans. Once recovered, the materials are SRMs, the product of a recovery project. The 'Specification for the Application of UNFC to Anthropogenic Resources' was adopted by the United Nations Economic Commission for Europe (UNECE) Working Group on Anthropogenic Resources (UNECE, 2025). Prior to the introduction of this harmonised framework, recovery projects were assessed using case-specific and often disparate methodologies, which were based on specific requirements that limited comparability across projects.

In the context of the circular economy, with its numerous recovery technologies for processing different waste streams, SARA4UNFC contributes to improved consistency, transparency, and comparability of individual projects. There are two distinct benefits: First, the E-F-G structure provides a structured self-assessment that helps project teams diagnose where their project stands and what still needs to be done to advance it. Second, the resulting classification is an internationally recognised language that supports communication between project developers, authorities, policymakers, investors, and the public, and facilitates comparison across technologies, waste streams, and jurisdictions. The E-F-G class offers a succinct, high-level assessment that can give stakeholders a quick grasp of the status of a project.

However, applying the UNFC to waste as an anthropogenic resource has required methodological adjustments. Unlike primary raw materials, the focus is not on extracting minerals from natural deposits but on implementing new treatment technologies to recover products from heterogeneous waste streams. These projects face additional challenges: complex value chains, diverse regulatory frameworks, and fragmented and often incomplete data.

5.2 Conceptual approach

Within the FutuRaM project, the SARA4UNFC was developed as a conceptual framework to apply the principles of the UNFC to projects for recovering secondary raw materials from different waste streams. While UNFC provides a general framework for classifying project maturity, it does not prescribe a detailed procedural approach for such projects. The FutuRaM framework therefore introduces a structured methodology tailored to recovery projects. The objective was to provide a transparent and consistent method for evaluating and classifying project maturity, while also accounting for the specific characteristics of the recovery project. The framework covers three typical project development phases: screening, pre-feasibility, and feasibility (Figure 21), followed by possible project outcomes such as implementation or discontinuation.

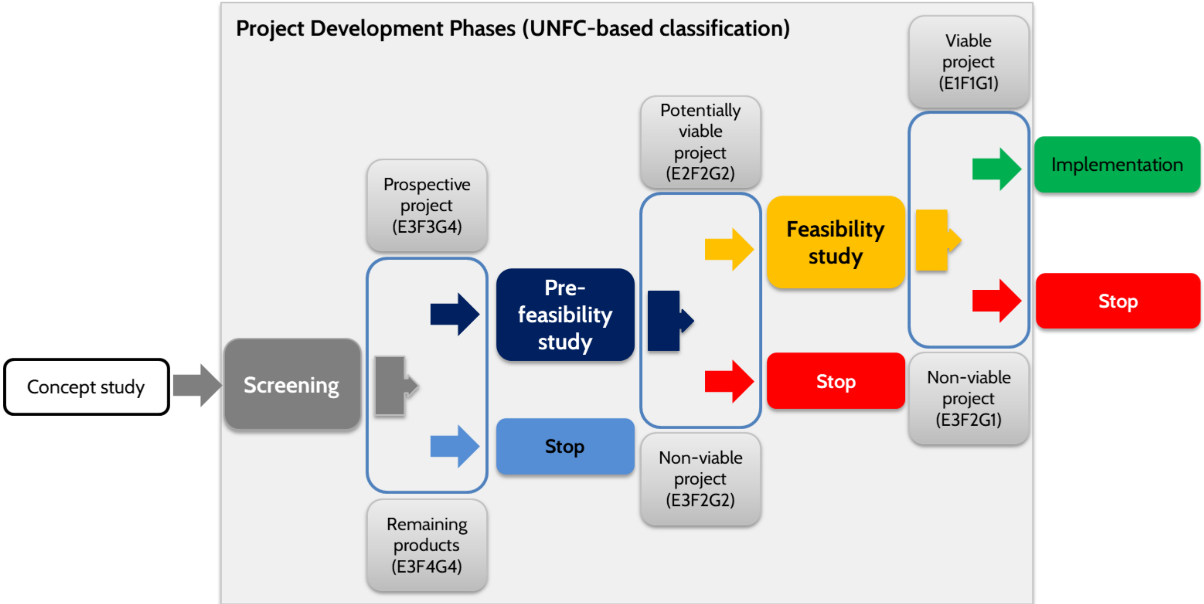


Figure 21: Project development phases with the E-F-G classes, e.g. E2FG2 (potentially viable) or E3F2G2 (non-viable)

The **screening phase** represents an initial evaluation of a project idea. Its objective is to determine whether or not a recovery concept shows sufficient potential to justify further investigation. At this stage, the information is typically qualitative and focuses on the driving forces behind a project, and the general feasibility of the project ideas in a broader economic, environmental, social, and regulatory context. Projects with credible project rationale, such as strategic relevance, regulatory drivers, or an attractive resource base, typically reflected by classification E3F3G4, may be classified as 'prospective projects', justifying further quantitative investigations. The inclusion of a scoping phase is planned to quantify the data. By contrast, projects that fail to demonstrate such a rationale, and are classified as E3F4G4, are designated 'remaining products not developed from prospective projects'. In these cases, project outputs have been identified, but no viable development pathway has been established. Such projects may either be discontinued or reconsidered if circumstances change.

Based on this initial evaluation, decision-makers decide whether the prospective project will proceed to the **pre-feasibility phase.** Once sanctioned, this phase provides a more detailed assessment of technical options, preliminary economic considerations, environmental and social aspects, and a more accurate understanding of material quantities, drawing on both qualitative and quantitative data. Its purpose is to determine whether or not the project could become potentially viable under favourable technical, social, environmental, and economic conditions. However, uncertainties associated with the preliminary results will remain. Projects that demonstrate sufficient technical and economic potential during pre-feasibility – typically classified as E2F2G2 – may advance to the next phase as 'potentially viable projects'.

The **feasibility phase** represents the most advanced stage of project development. It relies on detailed technical design, robust economic assessment, and well-documented consideration of environmental, social, and legal aspects. The focus is on obtaining approval for implementation, including social licence to operate. Projects that meet all criteria are ultimately classified as 'viable projects' (E1F1G(1,2,3)). A project may be downgraded to the category of 'non-viable projects' (E3F2G(1,2,3)) at any point during the project development phase, either because its assessment yields a negative outcome, or due to change in external conditions (e.g. market price changes, regulatory requirements).

In summary, the E-F-G class expresses a project's socio-economic and environmental viability (E), technical feasibility (F), and the level of confidence in the quantities (G), thereby documenting its current maturity against the prevailing technical, economic, environmental, and regulatory conditions. The transition between these phases is not strictly linear. In practice, project development is often iterative, taking changing circumstances into account. Additional investigations, testing, or data collection feeding back into earlier assumptions, a UNFC classification represents a snapshot of the project status at a given point in time that requires periodic re-evaluation.

To operationalise UNFC for anthropogenic resources, that is, for waste stream regarded as a resource, FutuRaM developed the Structured Anthropogenic Resource Assessment for UNFC (SARA4UNFC). SARA4UNFC guides practitioners through the three project development phases described above and provides a consistent framework for documenting project information, evaluating data transparently, and assigning UNFC classes. A detailed description of the procedures and their applications is provided in FutuRaM's Deliverable D5.1; what follows is a summary.

For the screening phase, a 5-step procedure (Figure 22) has been developed to capture key information about the project, including the drivers of the project and the stakeholders directly or indirectly involved:

1. Compilation of basic information, including the waste source and targeted secondary raw materials.
2. Assessment of the preconditions, such as technical feasibility, environmental aspects, socio-economic relevance, and regulatory conditions.
3. Preliminary technical description of the recovery project concept and expected outputs.
4. Identification of stakeholders.
5. UNFC-compliant categorisation to determine whether the project can be considered prospective.

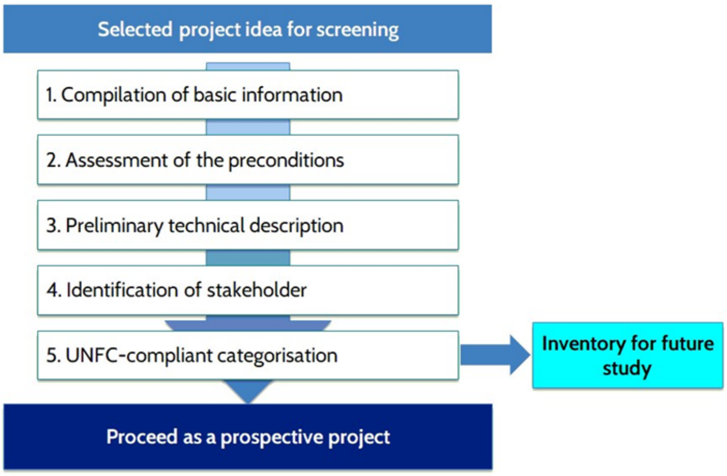


Figure 22: The 5-step procedure to classify a project in the screening phase (FutuRaM's Deliverable D5.1).

For the pre-feasibility and feasibility phases the development of a 7-stage procedure promotes transparency by disclosing the factors used to evaluate the criteria (Figure 23).

1. Definition of the project profile and key project characteristics.
2. Detailed project definition, including scope, process chain, stakeholders, and data sources.
3. Identification of relevant controlling factors (CFs) for UNFC classification.
4. Structured evaluation of the project against the selected CFs.
5. Categorisation of results to visualise strengths, weaknesses, and uncertainties.
6. Assignment of the corresponding UNFC E–F–G classification.
7. Preparation of a structured UNFC report documenting the evaluation and classification results.

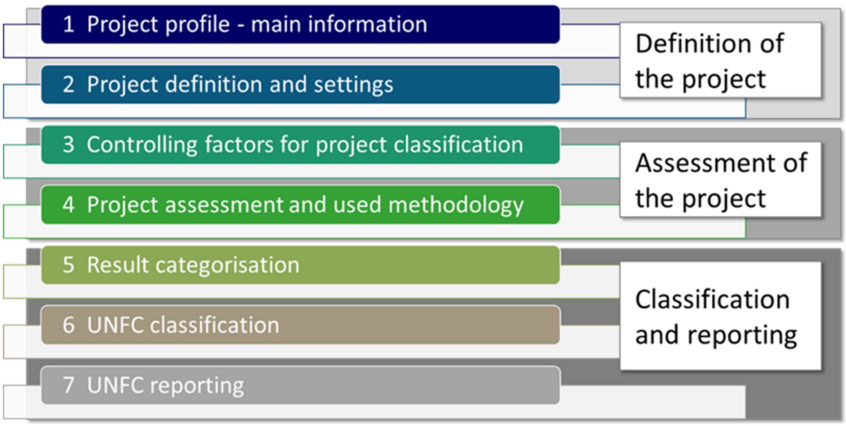


Figure 23: The 7-stage procedure to classify a project in the pre-feasibility and feasibility phases (FutuRaM's Deliverable D5.1).

A key implementation feature of SARA4UNFC is the explicit documentation of **which CFs are assessed and which are excluded** (in stage 3), including justification for exclusions. This functionality directly addresses one of the main sources of variability in UNFC applications by enabling tracing of classification outcomes to differences in factor selection or data availability.

Assessment results (stage 4) are summarised using a qualitative **categorisation scheme** (stage 5) that allows users to visualise strengths, weaknesses, and uncertainties across the assessed CFs. This structured presentation supports internal review and comparison without introducing additional interpretation layers beyond those defined in the methodology. At the end of each assessment phase, SARA4UNFC summarises the categorisation into the E-F-G class (stage 6) and generates a standardised **UNFC report** that compiles the recorded project information, assessment inputs, and classification outcomes in a consistent format (stage 7).

5.3 The digital tool SARA4UNFC

SARA4UNFC is a digital tool (Figure 24) to facilitate practitioners in conducting the UNFC-compliant assessment and classification of a project to recover secondary raw materials. It is designed as a structured workflow that supports consistent application across site-specific projects. Instead of a spreadsheet and lengthy reports, the tool guides users through predefined data-entry and assessment steps and ensures that all required information leading to the classification is collected and documented. Its role is to implement and operationalise the concept described in chapter 5.2. The user can select the development phase of the specific project (Figure 25-a), and the tool ensures that project information, assumptions, and assessment results, including the categorisation of the CFs and classification, are recorded in a consistent, traceable, and reproducible manner (Figure 25-b and c). The key findings of each step are summarised in a document (Figure 25-d).

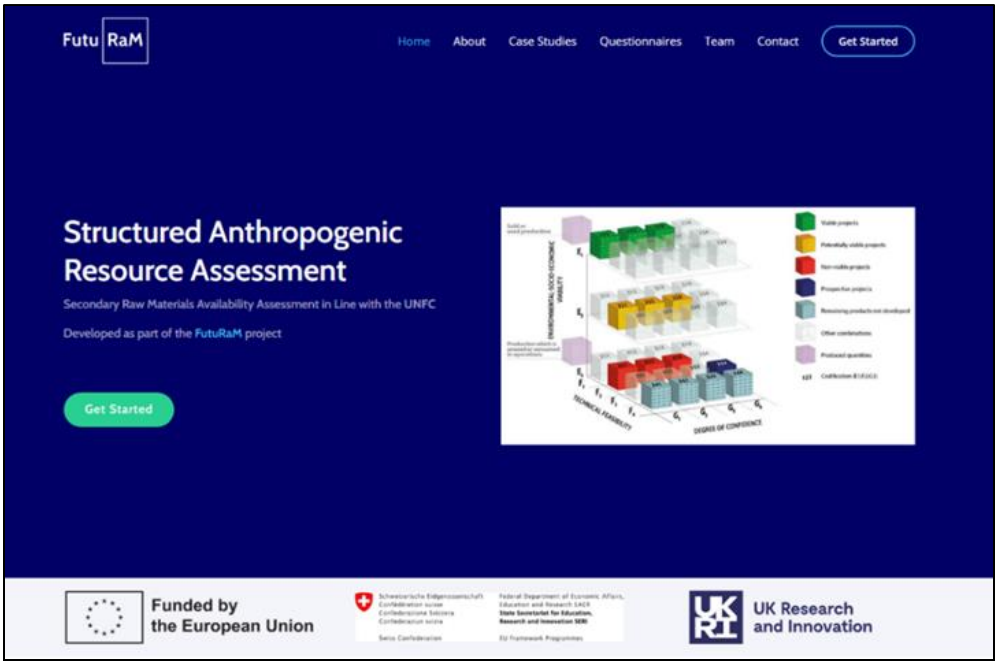


Figure 24: SARA4UNFC web-based tool home page – https://sara.geologie.geowissenschaften.uni-muenchen.de/

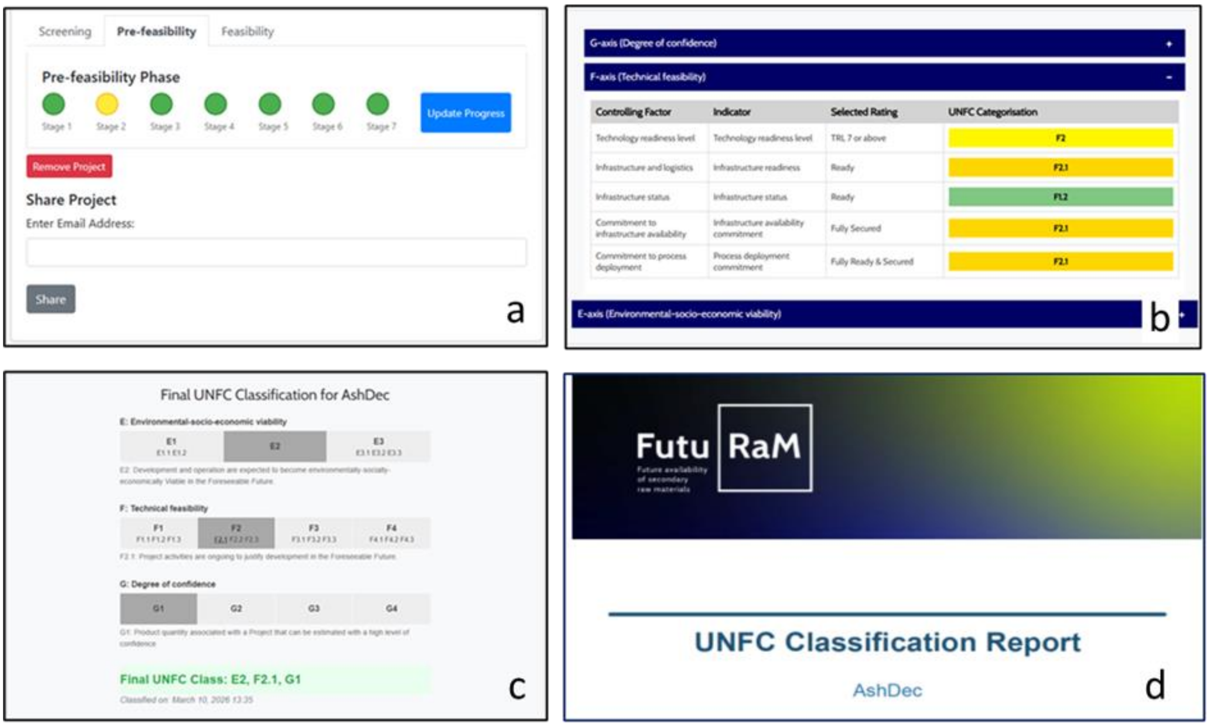


Figure 25: Screenshots of SARA4UNFC (a) user dashboard, (b) result of categorisation, (c) final UNFC classification, and (d) final report.

5.4 Site-specific case studies

The adapted UNFC methodology developed in FutuRaM and the SARA4UNFC tool were tested in 13 site-specific case studies across five waste streams. These case studies represent existing or proposed recovery projects and were evaluated and classified using the conceptual approach described in chapter 5.2 and implemented through SARA4UNFC. Table 3 summarises the UNFC classes achieved for the site-specific case studies, the target elements and the recoverable quantities reported in the case study reports. The classification of the projects conveys two aspects regarding estimated quantities and maturity of the projects. They reflect the full spectrum of maturity.

More detailed descriptions of each case study are provided in FutuRaM's Deliverable D5.1. Most projects started in the screening phase and reached the pre-feasibility phase during the case studies. Only two advanced projects went through the feasibility phase. In summary, these site-specific case studies can be grouped into four broader viability categories (Table 4), which aggregate project outcomes and corresponding secondary raw materials quantities. Although several materials were identified across the case studies, detailed and consistent quantification of CRMs is limited, with Cu and P being the most systematically assessed.

Table 3: Overview of site-specific case studies and their final UNFC classifications. Results are presented using a colour scheme: green indicates viable projects, yellow indicates potentially viable projects, dark blue indicates prospective projects, red indicates non-viable projects, light blue indicates remaining products not developed from prospective projects, and grey indicates other combinations. The colour scheme follows the visual representation used in UNFC (UNFC, 2019) and is applied here for illustrative purposes.

Case Title	Waste Stream	Screening	Pre-feasibility	Feasibility	SRMs/CRMs	Recoverable Quantity	UNFC (E-F-G)
CS01 – Håkansboda mining waste, Sweden	MINW	—	✓	—	Cu, Zn, Pb, Co, Ag	Not quantified	**E3.3-F2.2-G(1,2,3)**
CS02 – Bor tailings, Serbia	MINW	—	✓	—	Cu, Au, Ag	Cu ≈ 55 kt, Au ≈ 9 t, Ag ≈ 33 t	**E3.2-F3.3-G1+G2+G3**
CS03 – Otanmäki, Finland	MINW	—	—	✓	Ti	~753 kt recoverable ilmenite	**E2-F2.1-G2**
CS04 – Chessy mine water liming wastes, France	MINW	—	✓	—	Cu, Zn	Cu ≈ 2 kt, Zn ≈ 6.6 kt	**E3.2-F3.3-G2**
CS06 – Large tailings in Sweden (Adak, Kristineberg, Laisvall)	MINW	—	✓	—	Cu, Co, Zn, Ag, Au	Not quantified	**Kristineberg: E3-F4.3-G(1-4)**
		—	✓	—	Cu,Sb, Zn, Ag, Au	Not quantified	**Adak: E3-F4.3-G(1-3)**
		—	✓	—	Si, F, Zn, Pb, Ag	Not quantified	**Laisvall: E3-F4.1-G4**
	SLASH	✓	✓	—	P	~2 kt/year	**AshDec: E2-F2.1-G1**

Case Title	Waste Stream	Screening	Pre-feasibility	Feasibility	SRMs/CRMs	Recoverable Quantity	UNFC (E-F-G)
CS07 – P recovery from sewage sludge ashes, Germany & Switzerland		✓	✓	—	P	~2.8 kt/year	**Phos4Life: E3.3-F2.2-G2**
CS08 – CRMs in steel slags (HYPASS), France	SLASH	✓	—	—	Metals (Cr, V)	Not quantified	**E3.2-F3.3-G3**
CS10 – CRM in steel slags (CHROMIC), Belgium	SLASH	—	✓	—	Cr	Quantities not explicitly stated due to confidentiality reasons	**E3.3-F2.2-G2**
CS11 – Li-ion batteries, Switzerland	BAT	✓	✓	—	Black mass (Li, Ni, Co, Mn, Cu)	~2 kt/year	**E2-F2.1-G2**
CS14 – CRMs recycling, France	WEEE	—	—	✓	Cu, Au, Ag, Pd etc.	22.5 kt/year of ferrous metals, 12.7 kt/year of non-ferrous metals that contain CRM, 20.6 kt/year of plastics	**E1-F1.2-G1**
CS16 – Mace building site, London, UK	CDW	✓	✓	—	Bricks, aggregates, metals	18 t bricks, 1629 t aggregates, 105 t metals	**E3.2-F3-G4**

Case Title	Waste Stream	Screening	Pre-feasibility	Feasibility	SRMs/CRMs	Recoverable Quantity	UNFC (E-F-G)
CS17 – Milieustraat circularity (Capelle), Netherlands	CDW	✓	—	—	Flat glass, gypsum	48 t/year flat glass, 117 t/year gypsum	**E3.2-F3.2-G3**
CS18 – Timber recovery, UK	CDW	✓	✓	—	Secondary timber	40 kt/year	**E2-F3.3-G3**

Table 4: Secondary raw materials assessed in the site-specific case studies by viability category.

Category	Interpretation	Number of case studies	Total SRMs (kt)	Cu (kt)	Ti (kt	Ag (t)	Au (t)	P (kt)	Zn (kt)	Other
Viable projects	Project ready for implementation	1	~1953	—	n.a.	—	—	n.a.	n.a.	22.5 kt/year of ferrous metals, 12.7 kt/year of non-ferrous metals that contain CRM, and 20.6 kt/year of plastics for 35 years
Potentially viable projects	Promising recovery projects requiring further development	2 (+1 scenario in CS-07)[a]	~908	—	753*	n.a.	n.a.	~50	n.a.	*ilmenite, ~80 kt black mass
Prospective projects[c]	Early-stage recovery concepts requiring further investigation	7[b]	~18313 + (~40 kt/year)	~57	n.a.	~3	~9	n.a.	6.6	18 t bricks, 1629 t aggregates, 105 t metals; 48 t/year flat glass and 117 t/year gypsum for 100 years; 40 kt/year secondary timber and project duration is not defined
Non-viable projects	Projects currently constrained by technical or economic barriers	2 (+1 scenario in CS-07)[a]	~71	—	n.a.	—	n.a.	~71	—	—

[a] Case study 07 has two scenarios: one classified as Potentially Viable and other as Non-viable.

[b] Case study 06 includes three tailings, both classified as Prospective projects.

[c] Classifications of 'remaining products not developed from prospective projects' and 'other combinations' are also considered within 'prospective projects'.

Note: Cu (copper), Ti (titanium), and P (phosphorus) are considered CRMs. Ag (silver), Au (gold), and Zn (zinc) are included as secondary raw materials specifically assessed in the case studies. '–' indicates data not available or not reported. 'n.a.' indicates that the material was not assessed or not within the scope of the respective case study.

Beyond these project-level results, the case studies also served to test the conceptual framework and the SARA4UNFC tool itself. Both proved effective in structuring project evaluation and enabling consistent classification across different waste streams and project types. The approach supported transparency in documenting assumptions as well as comparison between projects at different maturity levels. At the same time, the case studies also highlighted challenges related to data availability and heterogeneity of waste streams, and introduced uncertainties, particularly along the G-axis. The case studies confirmed that the framework itself is robust and transferable, and operates consistently across different data situations. The adaptations that proved necessary lay elsewhere: the terminology was aligned with the context of anthropogenic resources; categories and definitions were re-examined against the specific requirements of recovery projects; the technical handling of the tool was refined for operational use. The use of G-axis is documented in the FutuRaM G-axis report (Kral et al., 2025).

Some case studies have replicated established processes, such as the processing of batteries from end-of-life vehicles to recover black mass (CS-11, Switzerland), or treatment of steel slags (CS-08, France and CS-10, Belgium), while others have assessed and classified the impact of technological change, such as improved sorting of construction and demolition waste from buildings (CS-16, UK). Among these, the project for recycling high-grade WEEE (CS-14, France) represents the only clearly viable project, with permits and financing secured, and construction currently underway (E1–F1.2–G1). The Otanmäki ilmenite tailings project (CS-03, Finland) achieved feasibility with strong technical readiness and well-documented resource data with positive economic indicators (E2–F2.1–G2).

The mining waste case study Lovisagruvan (CS-01, Sweden) confirmed the potential for recovery of Cu, Ag, and associated metals. The principal limitations were associated with the representativeness and completeness of sampling and quantification data. This is due to the inherent heterogeneity of the mining waste, restricted access to the full volume of waste piles, and the inability to sample deeper sections, resulting in uncertainties in estimating the distribution and concentration of the strategic and critical raw materials (Cu, Co) and other metals such as Zn, Pb and Ag, which is reflected in a lower G categorisation. A comparable pattern is evident at the historical tailings deposits at several sites in Sweden, including Adak and Kristineberg (CS-06), where sampling density varies considerably across the sites. At Adak, drilling and sampling allowed the estimation of resource quantities with moderate confidence. In contrast, the Kristineberg site includes both drilled and non-investigated parts of the tailings dam, leading to a wider range of confidence levels (G1–G4) depending on the investigated area.

At the Chessy mine water waste site (CS-04, France), the conceptual framework, operationalised through the web-based tool (SARA4UNFC), proved to be a powerful structuring approach, prompting the project team to identify weaknesses that a purely descriptive project account would have obscured – particularly, shortcomings related to public consultation, the complexity of approval procedures and the environmental impact of the reprocessing plant. The value here lay in the framework itself: the act of classification forced the diagnosis, while the tool provided a consistent format in which to record it.

In the case study on phosphorus recovery from sewage sludge ash (CS-07), the same SARA4UNFC framework was used to evaluate two technology scenarios individually and then to compare them. The first scenario, Rhenania (thermochemical AshDec process, Germany), was classified as potentially viable (E2–F2.1–G1), reflecting high technical maturity and low operating costs. The second case, Phos4Life (wet chemical extraction to phosphoric acid, Switzerland), was classified E3.3–F2.2–G2, where greater technical complexity leads to greater economic uncertainty.

Each project was assessed individually using the framework, and the resulting CFs were used to derive a structured analysis of strengths and weaknesses. This comparison highlights key trade-offs: while AshDec is cost-effective but highly dependent on input material quality, Phos4Life is more flexible in handling contaminated inputs and produces higher-value products, but at the expense of higher costs and technical complexity. Juxtaposing the categorisation of the CFs of the two UNFC class codes made the trade-offs explicit: AshDec is cost-effective but is sensitive to input-material quality, whereas Phos4Life tolerates contaminated inputs and yields a higher-value product at the cost of greater complexity and expense. The framework thus supports technology selection by grounding the comparison in the same set of structured criteria rather than in narrative descriptions alone.

CS17 (Netherlands) differs from the other case studies in the unit of analysis: rather than a specific recovery facility, it examines the organisation of a municipal waste collection point for construction and demolition waste. Applying the SARA4UNFC framework made clear that the binding constraint is not technical feasibility (F) or data availability (G), but the socio-economic configuration on the E-axis – specifically, the collection logic itself. Recyclable output fractions such as gypsum and flat glass are currently diverted into mixed streams and are lost. The assessment identified source separation at the point of collection as the single most effective intervention, raising the E-axis score and enabling higher-purity recyclates at the municipal scale.

CS-18 (United Kingdom) addresses an early-stage recovery concept for producing high-value engineered timber from waste wood. It illustrates how the conceptual framework developed within the FutuRaM project, implemented through the SARA*4*UNFC tool, can accommodate projects whose technical pathway is still being defined. With technology at low maturity and regulatory barriers, notably end-of-waste status and restrictions on the use of recovered wood in load-bearing applications, preventing near-term market entry, the project is classified as a prospective project (E3-F3-G4). The case demonstrates the value of applying UNFC early: it places prospective concepts in the same structured register as operating projects and makes the regulatory rather than technical nature of the bottleneck explicit. They showed how the introduction of new concepts at a very early stage is confronted with regulatory restrictions that can prevent market entry. Using UNFC at the national level

'At a government level, national product estimates may be based on an aggregation of reported or published corporate estimates for individual projects (UNECE, 2020)'. Unlike site-specific applications, national assessments of waste treatment of end-of-life materials address multiple facilities and governance contexts simultaneously and must account for cross-border movements and aggregation effects. Correspondingly, the national-level case studies in FutuRaM extended the UNFC application from individual projects to the scale of **national waste management and recycling systems**, focusing on system-wide flows, treatment pathways, and future recovery pathways.

The national approach assesses how much of a given waste stream is available and recoverable across a country's waste-management and recycling system as a whole. Its methodological value lies in triangulation: project-level data provide site-specific estimates, while system-wide material flow analysis provides the top-down total for the country, derived from reported flows in national and sectoral statistics. The reconciliation of the two data levels, where project data is under- or over-represented, reported flows are incomplete, and system boundaries interrupt material flows. This cross-validation, combined with the enforced mass-balance consistency, increases the reliability of the resulting estimates regarding the G-axis beyond what either project-level assessment or national statistics could achieve on their own.

The starting point of the national studies is the **clear definition of the system boundary**, typically aligned with geographic boundaries, e.g. national borders. Within this boundary, all relevant processes along the value chain are identified, including collection, dismantling, pre-treatment, recycling, export, and disposal.

A **material flow analysis (MFA)** is carried out for waste streams, particularly end-of-life materials, that undergo several processes before final material recovery. It is used to quantify stocks and flows of materials, components, or elements within the system. The mass balance with MFA enables the tracking of target materials or elements, e.g. CRMs, from input (e.g., products placed on the market or waste generated, including imports) through intermediate processes to outputs leaving the system boundary. These outputs may include recovered materials, exported output fractions, residues sent to landfill, or emissions. Consequently, **flows** represent the aggregated inputs and outputs of processes, which can be viewed as the sum of quantities occurring in individual projects.

Two methodological approaches were applied depending on data availability: a bottom-up approach based on project-level information and a top-down approach based on MFA.

The **bottom-up approach** relies on project- and operator-level data, e.g. project reports, feasibility studies, technical documentation, and direct exchange with operators and stakeholders. Each project's reported quantities are aggregated by UNFC class, so that contributions to the national total reflect their respective E-, F- and G-axis maturity rather than being counted on equal terms. This approach was used for mining waste in Sweden (CS-05). When combined with additional system-level information, bottom-up assessments can highlight material yields and losses that may occur at any point along the treatment chain, e.g., during collection and sorting, and, crucially, support a differentiated diagnosis of *why* a route underperforms: technical limitations (F-axis), socio-economic or regulatory conditions (E-axis), or data gaps (G-axis). This was the case for WEEE in Austria (CS-15b).

However, applying the bottom-up approach poses a challenge for many waste streams because the downstream treatment chain is typically fragmented across multiple different operators, and the data for the intermediate steps is often confidential, incomplete, or missing altogether. To address these limitations, a complementary **top-down approach** was developed that uses data from national and sectoral statistics, reports or other sources, e.g. collected by waste streams, and the model used for FutuRaM's Urban Mine Platform. Because the unit of analysis shifts from individual *projects* to *processes,* i.e. aggregated quantities treated by a given type of waste treatment, the project-level detail that underpins conventional UNFC assessments is no longer available. FutuRaM introduced the term 'UNFC-compliant classes', marked with an asterisk (*), to reflect the shift. This means that the unit of analysis is an aggregated material flow and not a specific project with operator, site and system boundaries was introduced by FutuRaM introduced the term 'UNFC-compliant classes', marked with an asterisk (*), to reflect the shift. This means that the unit of analysis is an aggregated material flow and not a specific project with operator, site, and system boundaries. Accordingly, the G-axis of asterisk classes is capped at G2: confidence can be raised through statistical reconciliation and mass-balance closure, but G1 (verified, project-level measurement) is not attainable at aggregated scale.

Table 5 shows the colour code assigned to the flows, reflecting their contribution to the national circular economy. Red (non-viable) marks all losses due to landfilling, recycled as a by-product of treatment or exported. Only quantities recovered within a country's border as a substitute for primary raw materials are marked green (viable). Quantities expected to be produced in the near future (treatment facilities are under construction) are marked in yellow (potentially viable), and those expected to be treated in the mid-term are marked in dark blue (prospective). Flows classified as ‘remaining products not developed from identified projects or prospective projects’ are marked in light blue, representing stocks or flows for which no recovery project has been identified. Figure 26 provides a schematic representation of the recycling value chain, mapping product inflow, building the stock, and recycling processes. The flows leaving the system boundary are rated using the colour code in Table 5.

Table 5: UNFC-compliant descriptions of the flows in MFA.

UNFC- compliant Class*		Definition	Adapted definition
	(E1 F1.1 G(1,2,3))*	Viable	Flows related to **operating plants** that produce the target material, plants under construction, or expected to become operational soon.
	(E2 F2 G(1,2,3))*	Potentially viable	Flows containing target material that are **expected to be developed** in the near future.
	(E3 F2 G(1,2,3))*	Non-viable	b) Flows containing the target material that **leave the system boundary (i.e., are exported)** before the recycling of the target material b) Flows containing the target material from which the target material **cannot be recovered.**
	(E3 F3 G4)*	Prospective	Flows containing the target material that are expected **to be generated through future projects.**
	(E3 F4 G(1,2,3))* (E3 F4 G4)*	Remaining products not developed from identified projects or prospective projects	b) A stock or flow containing the target material for which the quantity and quality of the **target material is known** (E3 F4 G1,2,3), and **no specific project was identified** for its recovery. b) A stock containing the target material, but with **little information about the quantity and quality of the target material** (E3 F4 G4) and **no specific project identified** for its recovery.

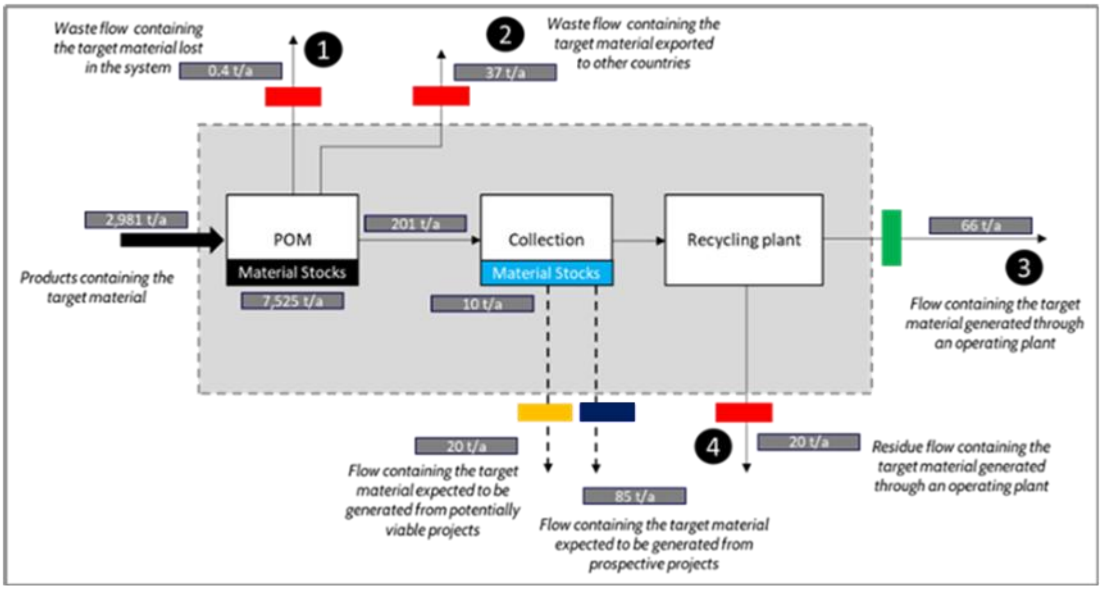


Figure 26: Schematic representation of an MFA using an UNFC top-down approach.

This approach offers several advantages: it builds on clearly defined system boundaries, represents complex treatment chains in a simplified, standardised form, and uses UNFC-compliant codes to make each flow's contribution to the national economy – and its losses – explicit. The resulting material flow diagram also shows how components and elements (notably critical and strategic raw materials) are distributed along the treatment chain, and where and to what extent they are recovered or lost. Where project-level data is incomplete, combining bottom-up detail on key projects with top-down information from statistics and MFA yields robust approximations and, through cross-validation, raises the confidence of the resulting estimates. The same representation supports strategic decision-making: a regulatory change acts on the E-axis, a new technology on the F-axis, and the framework allows their effects to be visualised against the current baseline in a structured, comparable way.

5.5 National-level case studies

Seven national case studies were conducted in FutuRaM, across five waste streams. Table 6 summarises the national-level case studies and the main materials assessed. Two case studies used a **bottom-up approach**: The recovery of CRMs (Co, REE) from mining waste in Sweden (CS-05) determined the quantities of Cu, Co, REEE and other metals at individual sites and these were aggregated at the national level. The WEEE case study in Austria (CS-15b) mapped all WEEE treating facilities in Austria and conducted interviews with plant operators to obtain detailed information on CRM recovery. The rest of the case studies used the top-down approach, described above because the relevant data at the operator-level were limited.

Table 6: Overview of national-level case studies.

Case ID	Case title	Waste stream	Country / Region	Main secondary raw materials / CRMs assessed	Approach
CS-05	CRMs (Co, REE) recovery from mining waste, Sweden	MINW	Sweden	Cu, Co, REEs, other metals	Bottom-up
CS-09	Sewage sludge ashes (P), Bavaria	SLASH	Germany/ Bavaria	P	Top-down
CS-12	WEEE in end-of-life vehicles, Switzerland	WEEE	Switzerland	Precious metals, Cu	Top-down
CS-13	Lithium-iron-phosphate batteries	BATT	Germany	Li, Co, Ni	Top-down
CS-15a	CRM recovery from WEEE	WEEE	France, Italy, United Kingdom	Cu, Au, Ag, Pd and other CRMs	Top-down
CS-15b	CRM recovery from WEEE	WEEE	Austria	Cu and CRMs from WEEE	Bottom-up
CS-19	Permanent magnets in dismantled wind turbines	WTB	Europe	Nd, Dy (rare earth elements)	Top-down

For the study on phosphorus recovery from sewage sludge (CS-09), national and sectoral statistics, together with regional reports were used to create the integrated UNFC-based MFA representations at three spatial scales: Europe, Germany, and Bavaria. Contrary to what might be expected, the resolution of available information increases as the study area becomes more specific. At the European level, data is highly aggregated and associated with significant uncertainties. At the national level, data combines sources such as Destatis with branch-specific reports. At the Bavarian level, plant-level information on sewage-sludge incineration, regional regulatory implementation, and direct access to operators becomes available. In UNFC terms, zooming in raises the G-axis confidence of the input data, while the E-axis context becomes increasingly site-specific. The CS-09 UNFC-MFA representation can then be coupled with the technology-level assessments from CS-07, AshDec (E2-F2.1-G1), and Phos4Life (E3.3-F2.2-G2) to estimate the recovery capacity required at national and regional scales and to construct UNFC-consistent scenarios for phosphorus recovery, including roll-out pathways and technology-mix options.

The battery case study (CS-13, Germany) combined Urban Mine Platform data with a mapping of treatment plants in Germany and interviews with operators. Current material flows were rated using UNFC-compliant codes to estimate the recoverable materials (black mass) and target elements Li, Co, and Cu. This shows where and in which stage material is lost along the chain. Whether material is processed within or outside of Europe matters directly to the colour code used for the UNFC-MFA diagram: exports are coded as non-viable (red) in the national/European circular-economy perspective adopted here. Taking into account treatment capacities currently under construction (potentially viable, E2F2G2*) and further capacities planned by operators (prospective, E3F3G4*), the case study delivers UNFC-consistent projections for 2030 and 2050.

Three different studies focus on WEEE; with one of them (C15b, Austria) applied a bottom-up approach based on operator-level data. The case study on WEEE in end-of-life vehicles (CS-12, Switzerland) provides information on the precious metals lost when vehicles go through the scrapping process. The UNFC-based MFA representation helps to understand cross-border treatment processes. Its central finding is that careful manual dismantling in a high-labour-cost country can be economically sustained only if the clean output fractions it yields are profitably processed further downstream in partner countries; binding cross-border agreements are therefore the precondition for the system to work, not an incidental feature of it. The WEEE studies for France, Italy, and the United Kingdom (CS-15a) used transfer coefficients from the WEEE Forum's RepTool, combined with national material-flow data to estimate the distribution of recovered materials. Copper was the only critical raw material quantified in detail, while additional CRMs were identified but not systematically assessed due to data limitations.

Finally, CS-19 evaluates the potential for recovering REEs, particularly Nd and Dy, from permanent magnets in decommissioned wind turbines across Europe. The MFA-based estimate of REE stocks in operating wind turbines is substantial, while end-of-life flows remain small in the short term because of the long service life of the installed fleet. In UNFC terms, the bulk of the recoverable quantity is therefore prospective (E3F3G4*), with short-term recovery potential limited due to the long lifetime of wind turbines.

Several recurring insights were observed across the national-level case studies, as summarised in Table 7. They concern data collection related to confidence achievable on the G-axis, the role of system boundaries, the regulatory and economic conditions on the E-axis, and the transparency gained and its limits from UNFC–MFA mapping. Taken together, they show that the value of the national approach grows with the analyst's access to the regional and local recycling system: finer spatial resolution improves the G-axis confidence, and only with a sound understanding of local structures can the flow visualisation be interpreted correctly.

Table 7: Key insights from national-level case studies.

Key finding	Explanation
Data harmonisation and granularity are major limitations regarding the G-axis	National statistics can differ across sources in definitions, units, and classification boundaries (harmonisation), and typically lack the resolution needed for robust UNFC classification (granularity). Both restrict the achievable confidence in quantity estimates (G-axis).
Spatial resolution improves the reliability of the G-axis	Narrowing the scope of the study from European to national and then sub-national levels increases the availability of plant-level data and gives operators direct access, leading to more robust estimates despite the reduced geographical scope.
System boundaries affect results	Cross-border flows of waste and intermediate products, and decisions regarding temporal, procedural, and functional boundaries, influence what is considered recoverable in a national assessment.
Regulation drives recovery potential (E-axis)	Clear regulatory frameworks improve the probability that recovery projects cross the threshold from prospective (E3) to potentially viable (E2) and ultimately to viable (E1).
Technical recoverability (F) does not imply economic viability (E)	Many CRMs are technically recoverable, but remain economically non-viable due to low grades, limited downstream markets, or export dependencies. A distinction that UNFC highlights by plotting F and E on independent axes.
UNFC–MFA mapping improves transparency, but is not self-interpreting	Mapping flows along the recycling chain helps to identify where materials are recovered, lost or exported, and assign a UNFC-compliant code to each flow. However, the interpretation of these flows requires detailed knowledge of how the local recycling system is organised.

6 Highlights of dissemination

The relevance of FutuRaM to the current global geopolitical situation, and, in the EU, the implementation of the CRM Act, is clear from the interest the project has received. Project researchers have been offered many opportunities to discuss the project and, consequently, the results have been disseminated to a wide audience. The project's twin outputs of CRMs data and UNFC methods applied to secondary raw materials have been equally relevant and its perspectives and results have been sought by many different stakeholders.

FutuRaM results and methods have been presented at 132 external events and conferences, including many high-level policy and expert forums, such as the annual Raw Materials Week in Brussels and the UNECE Resource Management Week in Geneva. Most of these events have taken place in Europe, but FutuRaM has also been presented in Singapore, Brazil, Thailand, Canada, Japan, Kenya and Panama.

The foundations for these dissemination activities were established at the outset of the project when over 300 stakeholder organisations were identified and grouped into the following main categories: 1) Industry; 2) Investors; 3) EU/MS governments, policymakers and institutions; 4) other projects and initiatives; 5) research peers; 6) general public, and 7) other stakeholders. These stakeholders come from 27 different countries; the three with the most stakeholders being Germany, Belgium, and the UK. Forty relevant projects and initiatives were also identified and included in this exercise.

The project established a formal stakeholder network for those with a specific interest in the project and these individuals registered through the project website. The members of this network received project updates in the form of a newsletter, were notified of events and invited to join consultations. At the time of writing, there are 187 individuals subscribed to this network. On top of that the project has over 1,200 followers on LinkedIn, where it has been active in making over 300 posts to regularly disseminate project results and updates.

FutuRaM stakeholders supported the progress of the project work by participating in:

- 4 annual project events
- 5 co-creation workshops
- 22 business modelling interviews and 2 sessions
- 2 capacity building sessions
- 9 policy working group meetings
- 15 UNFC-focused workshops
- 2 statistics-focused meetings

To date, the project has had 9 scientific articles published in journals (see Table A. 1), all of which are available on FutuRaM's Zenodo page. One of the highlights of the FutuRaM dissemination effort will be the special issue of the Cleaner Engineering and Technology Journal, titled 'Sustainable Recovery and Classification of Anthropogenic Resources' (Stegemann et al., 2025). This special issue is being edited by three senior FutuRaM researchers and will contain around 12 unpublished articles from the project focusing on the work on the UNFC framework and case studies. Articles for the special issue will be submitted before the end of May 2026, with a planned publication date of Autumn 2026.

Another highlight was the production of a report for International E-Waste Day 2025. The report, titled *2050 Critical Raw Materials Outlook for Waste Electrical and Electronic Equipment in the European Union plus Iceland, Norway, Switzerland and United Kingdom* (Iattoni et al., 2025) was used as the central publication for this international awareness-raising campaign , run by the WEEE Forum, that aims to increase WEEE collection, reuse, and recycling rates globally. The accompanying news release[14] was picked up by almost 900 online news outlets across 55 countries and published in 27 different languages, providing FutuRaM with huge exposure across the world.

Significantly, FutuRaM has actively used its research output to aid policy implementation and development. As mentioned previously, the project was timed to input to the implementation of the CRM Act and has, therefore, worked closely with DG GROW to provide data and insights. Specifically, the focus of this work has been Article 26 of the CRM Act and, together with the Joint Research Centre (JRC), FutuRaM has provided data and intelligence to assist Member States in complying with this Article by identifying products, components and waste streams containing relevant CRMs. A paper has been produced resulting from this work: 'National Measures on Circularity' (Lodato et al., 2025).

Additionally, FutuRaM has provided relevant analytical input to support the ongoing impact assessment of the EU WEEE legislation, informing ongoing discussions regarding its potential revision.

[14] https://weee-forum.org/ws_news/critical-raw-materials-are-a-vital-new-currency-europes-e-waste-is-the-vault/

7 Policy recommendations

The FutuRaM project concludes that Europe’s transition toward a resilient, competitive, and climate-neutral economy requires a structural shift in how CRMs from secondary raw materials are managed, recovered, and reused. Building on FutuRaM’s research and analysis in the development of its exploitation plan, the following recommendations aim to support a coherent, enforceable, and investment-ready European framework for circularity. These recommendations are particularly relevant in the context of the EU’s evolving industrial policy framework, including the Clean Industrial Deal and geopolitical pressures affecting CRM supply chains.

Create a harmonised framework for secondary raw materials reporting and classification

Persistent fragmentation of waste classifications, reporting systems and end-of-waste criteria across EU Member States undermines the functioning of the single market for secondary raw materials and limits the effectiveness of policy interventions. A harmonised classification and reporting framework would enable policymakers to track material flows consistently, identify losses in the system, and design targeted interventions to improve recovery rates. It is recommended that the EU27+4 establish a harmonised framework for secondary raw materials data collection, reporting and classification, building on the Urban Mine Platform. This framework should include:

- Strengthened life cycle monitoring of secondary raw materials and CRMs by ensuring systematic tracking from placed on the market, through waste generated and management, to final disposal and the recovery of CRMs from secondary raw materials, including transboundary movements.
- Establish standardised reporting applicable to all actors (e.g. WF-RepTool approach for WEEE in the Netherlands, Belgium, and France).
- Mandatory harmonised standards in Europe for treatment and preparation for reuse can establish a uniform quality and safety baseline across different countries, reduce compliance ambiguity, and facilitate cross-border comparability.
- Europe-wide methodological coordination, including shared terminologies, indicators, reporting formats, and digital exchange protocols, to enhance interoperability between national systems and increase the use of data across governance levels, such as those proposed in the recommendations for EU Secondary Raw Material Statistics in FutuRaM’s Deliverable D1.2.

This approach would improve uniformity and transparency and enable evidence-based policymaking across Europe.

Institutionalise the Urban Mine Platform as a core EU digital infrastructure

FutuRaM's exploitation activities, in particular its workshops and consultation with the potential users of the Urban Mine Platform, emphasised the importance of validated sets of standardised metadata and clear references to support policymaking, scenario development, and investment strategies at both Member State and EU level. Stakeholders also underlined the importance of the Urban Mine Platform having a dynamic and flexible system, capable of evolving with policy needs and technological innovation, to enable, for example, the inclusion of new waste streams, while ensuring that data sources remain fully transparent.

Within the EU, the Urban Mine Platform can support policy harmonisation and compliance, providing a trusted data reference for Member States, European Commission services and national CRM observatories. By offering standardised, transparent, and interoperable datasets, the platform can enhance decision-making under the CRM Act and other relevant legislation.

FutuRaM has demonstrated the strategic value of the Urban Mine Platform as data transparency and harmonisation are seen as critical priorities for stakeholders. The European Commission should embed the Urban Mine Platform as a permanent EU reference platform for urban mining and secondary raw materials, ensuring:

- Long-term governance and funding arrangements; and
- Interoperability with RMIS, EGDI, Digital Product Passports, and EPR reporting systems.

Institutionalisation of the Urban Mine Platform requires the identification of a hosting and governance model. The European Commission should assess options for integrating the Urban Mine Platform within existing EU infrastructures such as the proposed CRM Centre in the European Commission's RESourceEU Action Plan, or partnering with international organisations, such as the IEA, and Member States' CRM observatories and statistical bodies.

The platform should support both policy monitoring and industrial planning, including investment prioritisation and risk assessment.

Managing the updates of data within the Urban Mine Platform should also be a key consideration here. The European Commission should also consider signing a framework agreement with the FutuRaM consortium and associated affiliates to provide services regarding the maintenance of the Urban Mine Platform, data collection and finetuning of methodologies.

Mandate common standards and apply the UNFC framework to anthropogenic resources

Differences in treatment standards and quality criteria reduce trust in secondary raw materials. European treatment standards, notably EN 50625 and EN 50614 for WEEE, should be referenced in the Official Journal of the EU, making them legally binding. Standards are, by nature, flexible and can be updated to include additional requirements to support the recovery of CRMs and regular updates to align with state of the art.

In parallel, the adapted UNFC framework for anthropogenic resources developed in FutuRaM could be made mandatory to secondary raw materials and urban mining projects. FutuRaM's Deliverable 1.3 provide guidance to facilitate this.

This approach would improve transparency, comparability, and investment readiness, while enabling policymakers to distinguish between technically viable, economically feasible and environmentally sound recovery projects.

All actors should contribute to the development and operation of EU Raw Materials Monitoring systems

Monitoring and feeding CRM and secondary raw materials schemes should include all actors with access to relevant waste streams, including logistics operators, refurbishers, dismantlers, brokers, traders and online marketplaces. Broadening accountability improves transparency and reduces leakage into sub-standard, informal or illegal channels. This requires:

- Mandatory registration and reporting by all actors handling the different waste streams;
- EPR Co-ordination Bodies representative of Producer Responsibility Organisations (PROs) as well as all actors that have access to WEEE;
- Stronger enforcement to address free-riding, illegal exports and non-compliant treatment.

This should remain a core policy tool but redesigned as a shared societal responsibility rather than an exclusive producer obligation.

Strengthen enforcement, market surveillance and control of illegal flows

A significant share of CRMs continue to bypass official collection and treatment systems, undermining secondary raw materials supply and distorting markets. Without enhanced enforcement, these flows will persist.

FutuRaM data shows that, within the waste streams it focusses on, 762 kt/year of CRMs continue to bypass official collection and treatment systems in 2022, undermining the supply of secondary raw materials containing CRMs. 531 kt/year takes the route of illegal or sub-standard waste treatment within the EU27+4, which comprises 427 kt/year from WEEE, 64 kt/year from end-of-life vehicles and 38 kt/year from waste batteries. 231 kt/year of CRMs are estimated to be exported as used products, likely to low- and middle-income countries, and may comprise legal and illegal exports. These are mostly from vehicles (200 kt/year), followed by WEEE (25 kt/year), and waste batteries (6 kt/year).

The EU27+4 should substantially improve legislation and enforcement capacity to reduce CRMs handled in sub-optimal (unofficial) and illegal waste management practices by:

- Increasing inspections, prosecution and sentencing related to illegal waste handling within the countries and for exports, namely for WEEE;
- Banning cash transactions for metal scrap dealers at EU level;
- Clarifying and enforcing take-back obligations for actors involved (e.g. online marketplaces), including free take-back of end-of-life items and traceability requirements such as new trade codes for wastes.

Enforcement should cover the entire value chain, from market entry to end-of-life and export activities.

Use long-term scenario modelling to support strategic autonomy and industrial policy

FutuRaM's 2050 scenarios demonstrate that future material security depends on today's waste management and recovery decisions.

EU and Member State authorities should integrate secondary raw materials and CRMs future scenario modelling into:

- Industrial strategies and CRM Act implementation;
- Industrial vision (material needs for EU industry) and not only a vision on end-of-life product waste;
- Infrastructure and investment planning;
- Impact assessments of circular economy policies.

Scenario tools should be used to identify priority waste streams, recovery technologies and opportunities for economies of scale.

Invest in awareness, skills and capacity building

Circularity is ultimately a societal challenge that requires behavioural change, institutional capacity, and skilled labour. FutuRaM findings show that by 2050, the CRMs in secondary raw materials could substitute 56% of primary resources[15] in a CIR scenario. This is attributed to the reduction in consumption-based CRM demand, alongside simultaneous improvements in waste collection and recovery. This is substantially higher than in the BAU scenario (33%), which reflects increasing trends in consumption and waste generation, as well as subpar collection and recovery efficiencies, and in the REC scenario (47%), which also reflects rising consumption and waste generation, but with improved collection and recovery efficiencies.

In order to realise this, the EU and Member States, and other relevant countries, should support:

- Coordinated EU-wide and national awareness campaigns on waste return and circular consumption;
- Integration of circular economy principles into education and training curricula;
- Investment in recycling industry capacity and technology development
- Capacity-building programs for competent authorities, inspectors, and local administrations.

Behavioural research combined with financial support of the recycling industry should be systematically used to design effective awareness and return schemes.

Detailed datasets, methodologies and tools supporting these recommendations are available through the Urban Mine Platform, and associated project deliverables.

[15] when subsequent smelting leads to the right quality to substitute primary

8 Long-term impact through better reporting

This chapter presents the main outputs of the FutuRaM research aimed at achieving long-term impact through improved, harmonised, and policy-relevant reporting of secondary raw materials and CRMs. It addresses complementary dimensions of reporting, ranging from project-level classification to composition data and operational reporting from the recycling industry.

Specifically, the chapter introduces a draft UNFC reporting standard for secondary raw material projects, proposals for secondary raw materials statistics aligned with EU statistical frameworks, and recommendations for harmonised composition data reporting across the waste streams in scope. In addition, it presents the adaptation of the WEEE Forum Reporting Tool (RepTool), which complements scientific analyses with industry data and supports transparent reporting of recycling and recovery performance, including CRMs.

8.1 UNFC reporting standard

Harmonised reporting is essential to ensure transparent communication of project information and support informed decision-making for projects related to secondary raw materials.

Various specifications have been developed by UNECE to apply the UNFC principles to specific resource types such as minerals, energy and anthropogenic resources as presented in UNFC (2020). UNECE (2022b) has also developed the guidance document 'UNFC Guidance Europe: Guidance for the Application of UNFC for Minerals and Anthropogenic Resources', to support the implementation of UNFC. However, there is no guidance or standard on how a project classified under UNFC should be reported. This gap is critical, as a reporting standard is essential for harmonising reporting and ensuring transparent communication of a project and its UNFC classification to various stakeholders, thereby supporting better decision-making.

To address this gap, FutuRaM's Deliverable D1.3, on the reporting standard for projects classified in accordance with UNFC, serves as a working document. It was prepared for the UNECE Expert Group on Resource Management as an initial step toward developing a reporting standard. This document provides suggestions on the structure and content of the reporting standard, the relevant terminology and definitions, as well as minimum requirements for the information that should be provided in a report for project classification. These suggestions are aligned with the Structured Anthropogenic Resource Assessment SARA4UNFC presented in chapter 5.3.

A reporting standard supports EU policy implementation, particularly within the framework of the CRM Act, and facilitates structured data collection.

Specifically, the reporting standard suggested in Deliverable D1.3 can contribute to the CRM Act by addressing the requirements for reporting secondary raw material projects under UNFC - including strategic projects – and for monitoring new projects, including those projects involving the recovery of materials from extractive waste. In addition, it suggests a clear structure for recording key project data and information. Harmonised data collection is crucial for building a database on projects related to secondary raw materials in the EU.

8.2 Statistical proposals for secondary raw materials

The harmonised material flow accounting methods and datasets for secondary raw materials, with a focus on CRMs, that FutuRaM has developed for waste batteries, construction and demolition waste from buildings, end-of-life vehicles, slags and ashes, WEEE, and dismantled wind turbines across the EU27+4, could be relevant for the EU statistics community. This is highlighted below.

The general review of the suitability of FutuRaM methods for official statistics shows that waste batteries, WEEE, and dismantled wind turbines are the most promising for consideration for official statistics.

For waste batteries, a first draft of EU-level methodological guidelines was developed, describing how Member States could compile battery waste statistics from placed on the market to end-of-life management. This is in alignment with the Conference of European Statisticians Waste Statistics Framework (UNECE, 2022a). A key innovation is the "battery-keys" classification, which can link various official statistics classifications to the embedded materials, further enabling the production of statistics on secondary raw materials. For WEEE, methodological insights from FutuRaM have already been incorporated into the latest revision of the UN e-waste statistics guidelines (Lysagth et al., 2026). Methods for end-of-life vehicles, construction and demolition waste from buildings, and slags and ashes are considered suitable in principle but subject to waste-stream-specific limitations that require further research before their systematic use in official statistics. Mining waste data developed in FutuRaM are stock-oriented and conceptually differ from EU waste statistics, although underlying geological databases, such as MIN4EU (EGDI, 2022), may still be relevant for statistical purposes.

Recommendations to adapt the PRODCOM and EU List of Waste codes to improve the capture of data for secondary raw materials include:

- 30 new codes in sections 38.21.2 and 38.21.3 of the PRODCOM classification, and
- 43 new codes for the EU List of Waste.

These focus on components that can be dismantled during waste management, and have a high critical raw material recovery potential and are mentioned in Article 26 of CRM-Act, such as printed circuit boards, permanent magnets, battery black mass, and batteries prepared for reuse.

For more details, readers are invited to consult FutuRaM's Deliverable D1.2.

8.3 Recommendations for composition data reporting

FutuRaM developed harmonised composition datasets for the waste streams in scope using a structured, nested, and hierarchical data model.

The project created consolidated composition datasets for the six different waste streams in scope based on extensive raw data collection and a subsequent consolidation process within a harmonised framework for composition analysis. This resulted in generic product and sub-waste stream compositions. The FutuRaM composition data structure distinguishes between hierarchical layers within a waste stock or flow, where each layer is composed of the entities of the previous one. This hierarchical structure enables a systematic and scalable description of composition across diverse waste streams. To better reflect the varying characteristics of the waste streams, the composition data model employs two distinct approaches. The product-centric approach, in which the waste stream is described as stocks or flows of products composed of components and subsequent materials and elements, was applied to waste batteries, construction and demolition waste from buildings, end-of-life vehicles, WEEE, and dismantled wind turbines. The deposit-centric approach, in which the waste stream is described as stocks and flows composed of minerals or compounds and subsequent elements, was applied to slags and ashes and mining waste.

Data availability and data granularity represent key challenges for composition analysis across all waste streams.

For all waste streams, challenges regarding insufficient availability and insufficient granularity of data were faced during data collection. Insufficient availability of data resulted in data gaps, where broad assumptions often had to be applied. Data gaps included (a) completely absent composition data for a specific product group or a sub-waste stream, (b) missing information on some layers in the composition data model, and (c) individual data gaps in certain references. Insufficient granularity relates to the level of detail of information required to make solid assumptions for secondary raw material and recoverability assessments, and differences in the level of detail across composition data references. The level of detail needed depends on (a) the waste stream, (b) the end-of-life scenario, and (c) the variability within the composition. For example, if a certain alloy type or series is always used for a certain component in a product, even if this is not reported, it can be inferred even if the references only mention the metal type in the composition. Furthermore, introducing threshold values can simplify composition datasets by focusing on the most relevant materials.

Standardised reporting frameworks are essential to ensure comparability and transferability of composition data across waste streams.

Harmonised and standardised reporting is important to address the difficulties mentioned. A standardised classification system and predefined component lists (incl. synonyms and translations) are needed to ensure comparability and interoperability of composition information for waste types which originate from final products and goods manufactured using materials and semi-finished products that are placed on the market, e.g. waste batteries, construction and demolition waste from buildings, end-of-life vehicles, WEEE, and dismantled wind turbines (cf. FutuRaM Code List Repository developed by Kippert et al., 2026).

For waste which stems from industrial activities such as mining, quarrying, manufacturing and energy generation, site-specific compositions are needed. These can only be extrapolated to other sites if sufficiently detailed information on the mineral characteristics, sources, and origins of the materials that are extracted or processed on these sites – and on the corresponding technologies, operating conditions and processes – is available. This also applies to secondary waste from waste management activities, including mining waste and slags and ashes.

As a next step towards fully realising the capabilities envisioned by FutuRaM, adopting a consistent semantic approach is essential to ensure both human and machine readability. This requires the development of a clearly defined ontology capable of structuring and organising compositional knowledge. Such an approach will enhance interoperability between composition datasets and enable their seamless integration, while ensuring consistent and unambiguous interpretation by both humans and machines (Boga, 2026).

Digital reporting tools may significantly improve harmonisation, transparency, and interoperability of composition data.

Different upcoming reporting tools such as the Battery Passport, Digital Product Passports (DPPs), and Digital Building Logbooks (DBLs) might potentially ensure the required harmonisation and standardisation in composition data reporting but testing and research is required. Other composition data reporting such as results of sampling activities, Bills of Materials, or industry reports should follow the same standards where possible. An important requirement for transparency and ensuring the high quality of assessments based on composition data is accessibility. For external documents, such as DPPs or DBLs, easy accessibility to the information should be ensured. Representing composition data in Resource Description Framework (RDF) or other interoperable formats will allow seamless navigation across different layers and levels of the composition data hierarchy and integration with other datasets.

These recommendations support both future updates of the Urban Mine Platform and the implementation of the EU policy objectives.

The proposed recommendations support future updates of the Urban Mine Platform and contribute to the implementation of the CRM Act (Regulation (EU) 2024/1252) by promoting harmonised reporting practices that can significantly reduce long-term data collection efforts. For more details, readers are invited to consult FutuRaM's Deliverable D3.1.

8.4 WEEE Forum Reporting Tool (RepTool)

Complement FutuRaM scientific analyses with industry data to improve the understanding of WEEE recycling processes.

The FutuRaM project identified the need to complement scientific data with industry data. The recycling industry is a source of up-to-date information on waste processing technologies, composition and types of fractions arising from recycling processes, and the efficiency of recycling processes. As part of its activities, the project included the adaptation of the WF-RepTool[16], a tool owned by the WEEE Forum, to allow users to report on the components containing CRMs and CRMs recovered. The features to be added to the tool and the CRMs and components to focus on were discussed and agreed with project partners.

The adapted WF-RepTool functions as a calculator for recycling and recovery rates of WEEE processes and includes CRMs rich components in the scope.

Users enter information about the type and quantities of the input, interim and output material of the process in scope, which is then used for calculating the recycling and recovery rate achieved by the operator for the specific process and input material. Users can create flow charts showing the full processing until end of waste status or final disposal of every fraction. Additional analysis of the data

[16] https://wf-reptool2.org/

entered provides information about the composition of the input material (WEEE) based on the final output fractions obtained.

Aggregated and anonymised results are displayed through a public chart area.

Users of the tool that audit their reports through a third party were invited to contribute their figures to a public chart area. The design of the public chart area was agreed with project partners and is developed on the WF-RepTool website, which comprises four different types of charts that will display, for every WEEE collection category:

- Average recycling and recovery rates achieved;
- Average composition of secondary raw materials;
- Average CRMs recovered; and
- Average components in WEEE (for a selection of components e.g. batteries and printed circuit boards).

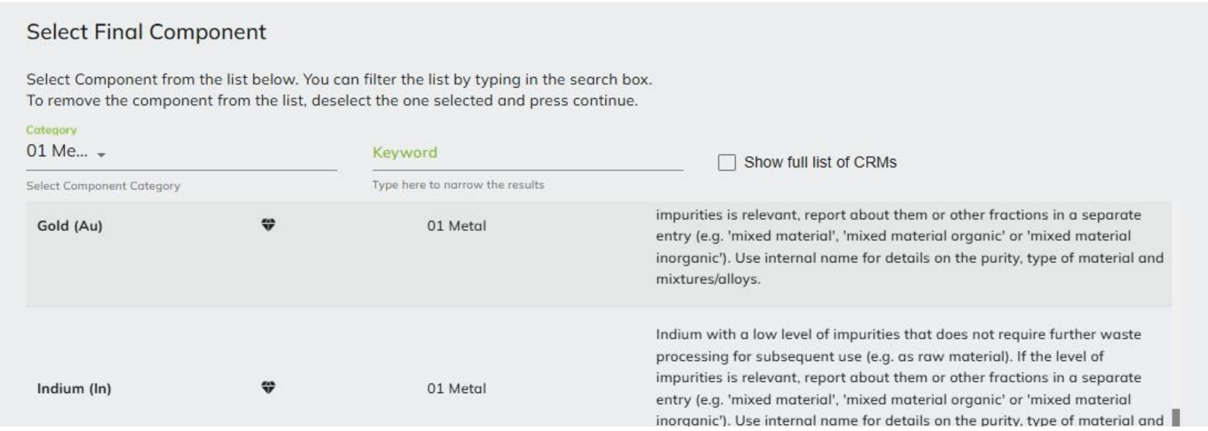


Figure 27: Screenshot of the WF-RepTool showing a part of the system developed in FutuRaM

Commercial sensitivity requires rules and criteria to allow data sharing and visualisation.

Composition of WEEE and recycling processes are commercially highly sensitive for the recycling industry and, therefore, despite the restrictions on displaying confidential information on the charts, a long process to engage with the recycling industry is expected. To avoid data provided by users identifying the owner of the data, charts include rules to aggregate, anonymise and only display data when a sufficient number of datapoints is reached.

Training, dissemination activities, and long-term maintenance by the WEEE Forum will ensure uptake of the WF-RepTool and secure data access.

Six training courses for operators, auditors, and producer responsibility organisations have been held (June, September and December 2025, and January 2026), alongside presentations to strategic partners, such as producer associations, and a Member of the European Parliament. WEEE Forum members were invited to access the tool for one year without cost to familiarize themselves with it and experience the benefits of its use. This arrangement was established because PROs are considered a major vector for dissemination through their recycling services suppliers. After the project closure, the WEEE Forum will maintain the tool and continue dissemination. To secure data confidentiality and the commitment of the tool users, charts will be open to the public only once a sufficient number of datapoints has been reached. Additionally, if such industrial data were made available it could improve the estimations of secondary raw materials. At the time of the writing this report, the new version of the WF-RepTool is being used by PROs in the Netherlands, Norway, Belgium, Sweden, Switzerland and Denmark, and an estimated number of 75 sites from treatment operators based in these countries. Three Italian PROs were preparing to join with some of their respective service suppliers (approximately 40 sites). The streams currently reported include mostly WEEE, but also batteries.

9 Conclusions and next steps

The FutuRaM project represents a substantial step forward in strengthening the knowledge base on secondary raw materials and CRMs within Europe's urban mine. In the face of supply risks, geopolitical uncertainty, and growing demand driven by the green and digital transitions, the project provides a robust, harmonised framework to support evidence-based policymaking and strategic resource management.

By integrating the focused waste streams into a unified analytical structure, FutuRaM expands previous efforts and delivers a more comprehensive, cross-waste stream understanding of material availability. The development of harmonised datasets and a detailed composition framework have enabled consistent modelling of materials across products, components, and waste flows. This is complemented by the recovery models and recoverability assessment, quantifying and assessing secondary raw materials from the waste streams, using numerous influencing factors along the value chain, and in doing so distinguishes between the raw materials embedded in waste and secondary raw materials recovered from waste.

The inclusion of the secondary raw materials quantification alongside scenario modelling to 2050 and recoverability assessment strengthens the project's contribution, offering insights into how technological, economic, and policy developments may shape future material supply. Together with the application of FAIR data principles and uncertainty analysis, these outputs enhance transparency, comparability, and long-term usability. The Urban Mine Platform and the adaptation of the UNFC to anthropogenic resources provide practical tools for data access, project classification, and informed decision-making, with the latter being strengthened through its application in 20 case studies within the project.

FutuRaM has already demonstrated strong policy relevance by supporting the implementation of the CRM Act and contributing to ongoing legislative processes. However, several challenges remain to be addressed, including persistent data gaps, inconsistencies in system boundaries, and limited availability of high-resolution composition and recovery data.

To address these challenges and build on the project's achievements, the following recommendations are proposed:

- Create a harmonised European framework for classification, reporting, and life cycle tracking of secondary raw materials, including standardised methodologies, improved statistics, and consistent composition data systems.
- Institutionalise the Urban Mine Platform as a permanent European digital infrastructure with stable governance, interoperability, and integration of multiple data sources and reporting tools.
- Mandate common European treatment standards and apply UNFC-based frameworks and reporting standards to improve transparency, comparability, and investment readiness of projects.
- Require all actors across the value chain to register, report, and contribute data, strengthening shared responsibility and improving monitoring systems.

- Strengthen enforcement and market surveillance to reduce illegal waste flows, including stricter inspections, traceability measures, and controls on exports and non-compliant activities.

- Integrate long-term scenario modelling into EU and national strategies to guide industrial policy, infrastructure planning, and critical raw material security.

- Invest in awareness, education, skills, and recycling capacity to drive behavioural change, improve collection and recovery rates, and support circular economy goals.

- Leverage digital tools and industry reporting systems to enhance data transparency, interoperability, and evidence-based decision-making while ensuring data accessibility and confidentiality

In conclusion, FutuRaM establishes a coherent and forward-looking foundation for assessing and managing secondary raw materials in Europe. Its integrated approach, combining harmonised data, advanced modelling, and structured classification, provides important support for enhancing resource efficiency, improving supply security, and advancing the transition towards a more circular and resilient economy.

References

Boga, B. (2026). FutuRaM Ontology. GitHub https://github.com/bogabiborka/futuram-ontology

Chatham House. (n.d.). Resource Trade Database. Retrieved February 19, 2026, from https://resourcetrade.earth/

Directive 2000/53/EC. *Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of life vehicles - Statement by the European Parliament, the Council and the Commission.* https://eur-lex.europa.eu/eli/dir/2000/53/oj/eng

Directive 2006/21/EC. *Directive 2006/21/EC of the European Parliament and of the Council of 15 March 2006 on the management of waste from extractive industries and amending Directive 2004/35/EC - Statement by the European Parliament, the Council and the Commission*. https://eur-lex.europa.eu/eli/dir/2006/21/oj/eng

Directive 2008/98/EC. *Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives.* https://eur-lex.europa.eu/eli/dir/2008/98/oj/eng

Directive 2012/19/EU. *Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE).* https://eur-lex.europa.eu/eli/dir/2012/19/oj/eng

EDGI (2022). *MIN4EU - Minerals Intelligence Network for Europe*. https://www.europe-geology.eu/

Elementarium (n.d.). *Elementarium*. https://lelementarium.fr/

EuroGeoSurveys (n.d.). *The Geological Surveys of Europe*. https://eurogeosurveys.org

European Commission. (n.d.). *Raw Materials Information System*. https://rmis.jrc.ec.europa.eu/

European Commission (2001). *Economy-wide material flow accounts and derived indicators : a methodological guide*. Office for Official Publications of the European Communities. https://ec.europa.eu/eurostat/web/products-manuals-and-guidelines/-/ks-34-00-536

European Commission (2023). *Study on the critical raw materials for the EU 2023 – Final report*, Publications Office of the European Union, 2023, https://data.europa.eu/doi/10.2873/725585

European Committee for Standardization (2019). General methods for assessing the recyclability and recoverability of energy related products (European Standard No. 45555:2019).

European Committee for Standardization (2020). General method for assessing the proportion of recycled material content in energy-related products (European Standard No. 45557:2020).

European Parliament (2019). *EU Legislative Train*. https://www.europarl.europa.eu/legislative-train/carriage/strategy-for-secondary-raw-materials/report?sid=6601

Eurostat (2025). *Material flow accounts*. https://doi.org/10.2908/ENV_AC_MFA

GSEU (n.d.). *Geological Service for Europe*. https://www.geologicalservice.eu/

Huisman, J., Habib, H., Brechu, M. G., Downes, S., Leroy, P., Herreras-Martínez, L., Løvik, A. N., Wäger, P., Cassard, D., Tertre, F., Mählitz, P., Rotter, S., Chancerel, P., & Söderman, M. L. Løvik, A., Marmy, C., Ljunggren - Soderman, M., Kushnir, D., Huisman, J., Bobba, S., Maury, T., Ciuta, T., Garbossa, E., Mathieux, F. and Wäger, P., Material composition trends in vehicles: critical raw materials and other relevant metals., EUR 30916 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-45213-3, doi:10.2760/351825, JRC126564. (2016). *ProSUM Harmonisation paper for external feedback and consultation*. https://doi.org/10.5281/zenodo.17047708

Huysman, S., Debaveye, S., Schaubroeck, T., De Meester, S., Ardente, F., Mathieux, F., & Dewulf, J. (2015). The recyclability benefit rate of closed-loop and open-loop systems: A case study on plastic recycling in Flanders. *Resources Conservation and Recycling*, *101*, 53–60. https://doi.org/10.1016/j.resconrec.2015.05.014

Iattoni, G., Bottausci, S., Yamamoto, T., Schubert, M., Forti, V., Kippert, K., Hu, R., Rotter, V.S., Charytanowicz, M., Bizouard, A., de Vries, H., Perello-Y-Bestard, A., Kuehr, R., Baldé, C.P. (2025). *2050 Critical Raw Materials Outlook for Waste Electrical and Electronic Equipment in the European Union plus Iceland, Norway, Switzerland and United Kingdom*. United Nations Institute for Training and Research, Technische Universitaet Berlin, WEEE Forum, Ecosystem. Bonn, Germany. https://doi.org/10.5281/zenodo.17941941

International Organization for Standardization. (2016). Environmental labels and declarations — Self-declared environmental claims (Type II environmental labelling) (ISO Standard No. 14021:2016). https://www.iso.org/standard/66652.html

International Organization for Standardization. (2002). Road vehicles — Recyclability and recoverability — Calculation method (ISO Standard No. 22628:2002). https://www.iso.org/standard/35061.html

Kippert, K., Korf, N., & Remmen, K. (2025a). FutuRaM Composition Data Collection Template – Product-centric Approach. Zenodo. https://doi.org/10.5281/zenodo.17176540

Kippert, K., Korf, N., & Remmen, K. (2025b). FutuRaM Composition Data Collection Template – Deposit-centric Approach. Zenodo. https://doi.org/10.5281/zenodo.17176513

Kippert, K., Hu, H.-. jung ., Korf, N., Rotter, V. S., Yamamoto, T., & Remmen, K. (2026). FutuRaM Code List Repository. Zenodo. https://doi.org/10.5281/zenodo.18697399

Knehr, K. W., Kubal, J. J., Nelson, P.A., Ahmed, S. (2022). *Battery Performance and Cost Modeling for Electric-Drive Vehicles: A Manual for BatPaC v5.0*, DOI: 10.2172/1877590

Kral, U., Heuss-Aßbichler, S., Dorri, I., Nelen, D., Vietinghoff-Scheel, M., Roesslein, M., Wäger, P. A., Arvidsson, R., Monfort, D., & Yamamoto, T. (2025). UNFC G-axis use for recycling projects. Zenodo. https://doi.org/10.5281/zenodo.17992646

Lysaght, O., Forti, V., Garam, B., Bottausci, S., Schubert, M., Yamamoto, T., Shyla, H., Blepp, M., Cenni, F., de Linde, S., Escobar Ocampo, D., Iattoni, G., Khwamsawat, K., Kuehr, R., Korajčević, Š., Ngumba, L., Magpantay, E., Martínez, L. H., Menton, N., … Balde, K. (2026). *E-waste Statistics:*

Guidelines on Classifications, Reporting and Indicators, Third Edition. UNITAR SCYCLE. https://doi.org/10.5281/zenodo.18328494

Lodato, C., Baldé, C.P., Bobba, S., Böcher, C., Bottausci, S. et al. (2025). Support to implementation of 2024/1252 Critical Raw Materials Act Article 26: National Measures on Circularity - Priority list of waste streams, evidence; and methodology, Publications Office of the European Union, Luxembourg [currently unpublished].

Løvik, A., Marmy, C., Ljunggren - Soderman, M., Kushnir, D., Huisman, J., Bobba, S., Maury, T., Ciuta, T., Garbossa, E., Mathieux, F. and Wäger, P., *Material composition trends in vehicles: critical raw materials and other relevant metals*. Publications Office of the European Union, Luxembourg, DOI:10.2760/351825

Panorama Project (n.d.). *Physical accounts of raw material stock and flow information service.* https://www.panoramaproject.eu/

P-Rex project (2015). *Sustainable sewage sludge management fostering phosphorus recovery and energy efficiency. Deliverable D 9.2. Life Cycle Assessment of selected processes for P recovery from sewage sludge, sludge liquor, or ash*. https://kompetenz-wasser.de/en/forschung/publikationen/821

ProSUM Project. (2017). *Prospecting Secondary raw materials in the Urban mine and Mining waste*. DOI: 10.3030/641999

Regulation (EC) 2150/2002. Regulation (EC) 2150/2002 of the European Parliament and of the Council of 25 November 2002 on waste statistics. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32002R2150

Regulation (EU) 2017/699. Commission Implementing Regulation (EU) 2017/699 of 18 April 2017 establishing a common methodology for the calculation of the weight of electrical and electronic equipment (EEE) placed on the market of each Member State and a common methodology for the calculation of the quantity of waste electrical and electronic equipment (WEEE) generated by weight in each Member State. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32017R0699

Regulation (EU) 2023/1542. 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. https://eur-lex.europa.eu/eli/reg/2023/1542/oj/eng

Regulation (EU) 2024/1252. Regulation (EU) 2024/1252 of the European Parliament and of the Council of 11 April 2024 on establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) No 168/2013, (EU) 2018/858, (EU) 2018/1724 and (EU) 2019/1020. https://eur-lex.europa.eu/eli/reg/2025/40/oj/eng

Regulation (EU) 2025/40. Regulation (EU) 2025/40 of the European Parliament and of the Council of 19 December 2024 on packaging and packaging waste, amending Regulation (EU) 2019/1020 and Directive (EU) 2019/904, and repealing Directive 94/62/EC. https://eur-lex.europa.eu/eli/reg/2025/40/oj/eng

Rotter, V. S., Flamme, S., Walter, G., Ueberschaar, M., Geiping, J., Chancerel, P., Marwede, M., Andreae-Jäckering, M., Hypki, T., Palitzsch, W., Jokic, G., Bröhl-Kerner, H., Schlummer, M., Breer, J., & Jantzen, A. (2016). *Abschlussbericht UPgrade Integrierte Ansätze zur Rückgewinnung von Spurenmetallen und zur Verbesserung der Wertschöpfung aus Elektro-und Elektronikaltgeräten*.

SCRREEN2 Project (2023). *Solutions for CRitical Raw materials - a European Expert Network 2*. DOI: 10.3030/958211

Stegemann, J., Leonard, S., Liew, P.Y., Rotter, V.S., Wäger, P. (2025). *Sustainable recovery and classification of anthropogenic resources [Special issue call].* https://www.sciencedirect.com/special-issue/326883/sustainable-recovery-and-classification-of-anthropogenic-resources. Cleaner Engineering and Technology

Talens Peiro, L., Nuss, P., Mathieux, F. and Blengini, G. (2018). *Towards Recycling Indicators based on EU flows and Raw Materials System Analysis data*. Publications Office of the European Union, Luxembourg, doi:10.2760/092885

UNECE (2020). *United Nations Framework Classification for Resources: Update 2019. United Nations Economic Commission for Europe. Geneva, Switzerland.* https://unece.org/sites/default/files/2023-10/UNFC_ES61_Update_2019.pdf

UNECE (2022a). *Conference of European Statisticians Framework on Waste Statistics*. United Nations Economic Commission for Europe. Geneva, Switzerland. https://unece.org/sites/default/files/2022-01/ECECESSTAT20212.pdf

UNECE (2022b). *UNFC Guidance Europe: Guidance for the Application of the United Nations Framework Classification for Resources (UNFC) for Mineral and Anthropogenic Resources in Europe*. United Nations Economic Commission for Europe. Geneva, Switzerland. https://unece.org/sites/default/files/2023-10/UNFC_ES61_Update_2019.pdf

UNECE (2025). *Supplementary Specifications for the Application of the United Nations Framework Classification for Resources to Anthropogenic Resources. United Nations Economic Commission for Europe*. Geneva, Switzerland. https://unece.org/sites/default/files/2025-03/ECE-ENERGY-GE.3-2025-8_UNFCAnthropSpecs.pdf

UNEP (2011). *Recycling Rates of Metals – A Status Report, A Report of the Working Group on the Global Metal Flows to the International Resource Panel*. United Nations Environment Programme. https://www.unep.org/resources/report/recycling-rates-metals-status-report

UNSD (n.d.). *UN Comtrade Database*. https://comtrade.un.org/

van Nielen, S. S., Kleijn, R., Sprecher, B., Miranda Xicotencatl, B., & Tukker, A. (2022). Early-stage assessment of minor metal recyclability. *Resources, Conservation and Recycling*, 176. https://doi.org/10.1016/j.resconrec.2021.105881

Yamamoto, T., De Vries, H., Perello-y-bestard, A., Francisco Morgado, J., Vingerhoets, R., Böcher, C., Boga, B., Bottausci, S., Capelli, M., Das, D., Guth, B., Hu, H.-J., Iattoni, G., Kippert, K., Ljunggren, M., Maisel, F., Marriyapillai Ravisandiran, S., Munizaga-Plaza, J. A., Philippe, A., Remmen, K., Rösslein, M., Tippner, M., van Stee, J., Zhang, C. (2026). FutuRaM Recovery Model - Code and Supporting Documents. Zenodo. https://doi.org/10.5281/zenodo.18612588

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About us

FutuRaM is a collaborative research consortium formed by 28 partners from leading universities, research institutes, industry, and industry associations across 11 countries, working closely with the European Commission and other key policy stakeholders. As part of the Horizon Europe programme, FutuRaM has developed a knowledge base on the present and future availability and recoverability of secondary raw materials within the European Union, with a special focus on CRMs. The project has established robust methodologies, reporting structures and datasets that model current and future stocks and flows of secondary raw materials and CRMs across multiple waste streams to 2050, including waste batteries, construction and demolition waste from buildings, end-of-life vehicles, mining waste, slags and ashes, WEEE, and dismantled wind turbines. By generating harmonised data and analytical tools, FutuRaM supports fact-based decision-making for the recovery of secondary raw materials, enables improved monitoring and statistical frameworks, and supports strategies for resource resilience and a circular economy in the EU and beyond.

A short description of each partner contributing to the FutuRaM project, along with its role and responsibilities, is provided in the following paragraphs.

weeeforum

Coordinator

WEEE Forum

The WEEE Forum is an international not-for-profit association of fifty producer responsibility organisations focused on the management of WEEE. It provides a platform for cooperation, exchange of best practices, and benchmarking to improve the collection, logistics, depollution, processing, reuse and recycling of e-waste. Through its members across Europe and globally, the WEEE Forum advances implementation of extended producer responsibility and contributes to circular economy policy and operations. In FutuRaM, WEEE Forum acts as the administrative coordinator and leads WP8, with input to WP1-4 and WP6-7. https://weee-forum.org/

Scientific Coordinator

United Nations Institute for Training and Research

The United Nations Institute for Training and Research (UNITAR) is a specialised UN institute providing training, capacity development, and research support. It helps governments and stakeholders strengthen decision-making and implement international agendas. The SCYCLE Programme, part of UNITAR's Division for Planet, works with governments, industry, and international partners to promote sustainable resource use and environmentally sound waste management through research, policy development, and capacity building. In FutuRaM, UNITAR is Scientific Coordinator and lead in WP4, and provides input to all other WPs being the waste stream leader for WEEE. https://www.scycle.info/

Eidgenössische Materialprüfungs- und Forschungsanstalt

The Eidgenössische Materialprüfungs- und Forschungsanstalt (Empa), also known as the Swiss Federal Laboratories for Materials Science and Technology, is an interdisciplinary Swiss research institute within the ETH Domain. Founded in 1880, it conducts cutting-edge research on materials and technologies with applications in nanostructured materials, energy, mobility, built environment and environmental solutions, bridging fundamental science and industrial innovation. Empa aims to provide sustainable technological solutions to major societal challenges through collaborative research and technology transfer. In FutuRaM, Empa leads WP1 and contributes to WP2-8. https://www.empa.ch/

Universiteit Leiden

Universiteit Leiden is a major research university in the Netherlands with strong expertise in the natural sciences and life sciences, including chemistry, biology, environmental science and interdisciplinary science-technology research. Its Faculty of Science hosts advanced research in areas such as biodiversity, sustainability, quantum technology and biomedical sciences, often in collaboration with industry and science parks. Leiden's science programmes integrate cutting-edge methods in material science, analytical technologies and interdisciplinary solutions for global challenges. In FutuRaM, ULEI leads WP2 and contributes to all other WPs providing data for construction and demolition waste from buildings and slags and ashes. https://www.universiteitleiden.nl/en

Technische Universität Berlin

Technische Universität Berlin (TU Berlin) is a leading technical university in Germany renowned for research and education in engineering, natural sciences, materials science, and technology innovation. Its research spans core areas including mechanical and electrical engineering, materials science and engineering, chemistry, physics, and environmental technologies, with strong industry collaboration and interdisciplinary programmes. TU Berlin contributes to advancements in digitalisation, energy systems, sustainable technologies and material-centred research through internationally recognised scientific output. In FutuRaM, TUB leads WP3 and participates in WP1,2,4,6-8. https://www.tu.berlin/circulareconomy

Ludwig-Maximilians-Universität München

Ludwig-Maximilians-Universität München (LMU) is one of Europe's leading research universities, committed to excellence in research and teaching across a broad spectrum of disciplines. Its Natural Sciences, Physics, Earth & Environment, Life & Health research areas are highly regarded, contributing to foundational science and interdisciplinary innovation. LMU's research profile includes advanced work in physics, environmental science, data science and biological systems, supported by extensive international collaborations and research partnerships. In FutuRaM, LMU leads WP5 with the development of the UNFC concept and case studies and participates across WP1-8. https://www.en.mineralogie.geowissenschaften.uni-muenchen.de/index.html

Bureau de Recherches Géologiques et Minières

The Bureau de Recherches Géologiques et Minières (BRGM) is France's public geological survey and a national reference institution in Earth sciences. It generates scientific research, expertise and data for managing subsurface resources, geological risks, water, mineral resources and the circular economy. BRGM supports policy-making and innovation in geology, environmental risk prevention and sustainable resource use at national, European and international levels. In FutuRaM, BRGM leads WP6 and participates in WP1-5 and WP7-8, contributing with data on dismantled wind turbines. https://www.brgm.fr/fr

Sociedade Portuguesa de Inovação

Sociedade Portuguesa de Inovação (SPI) is a Portuguese innovation consulting organisation established in 1996 that promotes science, technology and innovation for regional, national and international development. It works with public administrations, companies, universities and research centres to support innovation strategy, project management, internationalisation and knowledge exchange. SPI's services include facilitating partnerships, supporting R&D projects, and fostering competitiveness and growth across diverse sectors worldwide. In FutuRaM, SPI leads communication, dissemination and exploitation activities in WP7. https://www.spi.pt/en/

Chalmers Tekniska Hoegskola AB

Chalmers University of Technology (Chalmers) is a Swedish university in Gothenburg focused on engineering, science and technology education, research and innovation. Its mission is to advance knowledge and contribute to societal development through research, education and collaboration with industry and academia. Chalmers is internationally recognised for engineering excellence and sustainable innovation. In FutuRaM, Chalmers leads Task 2.3 and participates in WP1-4 and WP7-8 being waste stream leader for end-of-life vehicles. https://www.chalmers.se/

University College London

University College London (UCL) is a multidisciplinary global university based in London, UK, with a mission to integrate education, research, innovation and enterprise for the long-term benefit of humanity. It is recognised for world-leading research, a diverse international community, and approaches that address real-world challenges across disciplines from sciences to the humanities. UCL's academic and research excellence supports global impact and collaboration with partners worldwide. In FutuRaM, UCL participates in WP1-5 and WP7-8 and contributes with construction and demolition waste from buildings data. https://www.ucl.ac.uk/

Vlaamse Instelling voor Technologisch Onderzoek

The Vlaamse Instelling voor Technologisch Onderzoek (VITO), or Flemish Institute for Technological Research, is an independent research centre in Belgium dedicated to cleantech and sustainable development. VITO develops technological innovations, evidence-based advice and scientific solutions for energy, environment, materials and digital challenges, supporting businesses and public authorities in the transition to a sustainable and circular economy. In FutuRaM, VITO leads the slags and ashes work and contributes to all WPs (WP1–8). https://vito.be/nl

Geološki Zavod Slovenije

Geološki Zavod Slovenije (GeoZS) is Slovenia's multidisciplinary public research institute in geosciences, serving as the national geological institution. It conducts basic and applied research in geology and related fields, collects and interprets geological data, and produces maps, models and expert reports to inform sustainable land use and natural resource management. GeoZS contributes expertise to governmental decision-making and participates in European geological research networks. In FutuRaM, GeoZS contributes across WP1–8, including geological data provision and mine waste registry expertise. https://www.geo-zs.si/

Sveriges Geologiska Undersökning

The Sveriges Geologiska Undersökning (SGU) is Sweden's national geological survey and government agency responsible for mapping, documenting and providing geological information on bedrock, soil and groundwater. SGU supports sustainable resource management, environmental planning and the development of the mineral and rock sectors, and contributes geological data for policy-making and research. It also oversees national objectives related to groundwater quality and sustainable use of geological resources. In FutuRaM, SGU leads MINW-related work and participates in WP1-8. https://www.sgu.se/

Geological Survey of Finland

The Geological Survey of Finland (GTK) is a government-governed expert research institution providing impartial geological research and services to support decision-making in industry, academia and wider society. GTK focuses on mineral resources, groundwater, energy, the environment and digital geological solutions to promote sustainable and carbon-neutral development. Its data and insights inform policies, innovation and economic competitiveness in Finland and beyond. In FutuRaM, GTK contributes to WP3-8, providing expertise on mine waste data, databases and resource recovery. https://www.gtk.fi/

Bundesanstalt für Geowissenschaften und Rohstoffe

The Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), or Federal Institute for Geosciences and Natural Resources, is Germany's central geoscientific advisory authority and national geological service. As a federal research institution under the Federal Ministry for Economic Affairs and Energy, BGR conducts research and provides scientific expertise on geology, raw materials, energy resources, soil science and geodata management. It supports government decision-making, sustainable resource use and international cooperation in geoscience and resource security. In FutuRaM, BGR contributes to WP1, WP3, WP7 and WP8. https://www.bgr.bund.de/EN/Home/homepage_node_en.html

Erion WEEE

Erion WEEE is the leading national Producer Responsibility Organisation within the Italian Erion System dedicated to the management of WEEE. Operating as a non-profit collective scheme, it arranges the collection, treatment and traceable recycling of WEEE on behalf of its producer members in full compliance with Italian and EU extended producer responsibility legislation. Erion WEEE integrates data across the WEEE supply chain to maximise environmental benefits and supports the circular economy by reincorporating recovered materials into production flows. In FutuRaM, Erion participates in WP3-5 as an affiliated entity of WF and conducts a sampling activity. https://erionweee.it/it/

Boliden Mineral AB

Boliden Mineral AB is a Swedish mining and metals company specialising in the exploration, extraction, processing and recycling of base and precious metals including copper, zinc, nickel, lead, gold and silver. It operates mines and smelters across Europe and integrates advanced technological processes to ensure resource efficiency, responsible production and contribution to sustainable industrial value chains. Boliden's work supports the supply of metals essential for modern technologies, electrification and the energy transition. In FutuRaM, BOL contributes a mining case study for WP5 and WP6. https://www.boliden.com/

Ecosystem

ecosystem is a French non-profit producer responsibility organisation accredited by the public authorities to manage WEEE, lamps, and batteries placed on the French market. It supports producers in meeting extended producer responsibility obligations, including collection, depollution, recycling, repair and reuse, and compliance with national regulations. ecosystem offers services such as eco-design guidance, producer formalities with ADEME, and tailored collection solutions for both household and professional waste streams. It collaborates with European networks like PRONEXA to streamline reporting and compliance processes across markets. In FutuRaM, ecosystem contributes with compositional WEEE data and participates in WP3-5. https://www.ecosystem.eco/

Ecogenesys

Ecogenesys (formally operating as Repic Ltd) is the UK's largest not-for-profit producer compliance scheme for WEEE, batteries and packaging. Founded by UK producers in 2004, it administers and discharges regulatory obligations under the WEEE regulations on behalf of its members, supporting compliant collection, recycling and reporting. Ecogenesys provides expertise, guidance, and cost-effective compliance solutions, working with local authorities, waste partners and treatment facilities to ensure proper environmental outcomes. In FutuRaM, Ecogenesys participates in WP3-5, providing industry insights, data, and piloting case studies. https://ecogenesys.co.uk/

WEEECycling

WEEECycling is a French circular economy company specialising in recycling electronic waste into high-purity metals and raw materials. Using advanced hydrometallurgical and pyrometallurgical processes, it recovers precious and strategic metals from electronic and industrial waste, reducing reliance on traditional mining and lowering environmental impact. WEEECycling's solutions serve industries such as electronics, aerospace, defence and jewellery with recycled critical metals. In FutuRaM, WEEECycling contributes to a recycling case study in WP5 and provides input to WP3, WP4 and WP2 foresight activities. https://www.weeecycling.com/fr/

Lovisagruvan

Lovisagruvan AB is a Swedish publicly listed mining company operating an underground mine in the Bergslagen region focused on extracting high-grade zinc, lead and silver ores. Established in 2004, its core operations include ore production and ongoing exploration and development projects to extend resource potential. Lovisagruvan supplies base metals critical for industrial use and advances sustainable mining practices through technical development and collaborative projects. In FutuRaM, Lovis contributes a mining waste case study in WP5. https://www.lovisagruvan.se/

University of Belgrade Faculty of Mining & Geology

The University of Belgrade Faculty of Mining and Geology is Serbia's primary academic institution training engineers and researchers in the fields of geology and mining engineering. The faculty's programmes focus on geological sciences, mineral exploration, mining technology and earth materials, preparing graduates for technical and research roles in natural resources, energy and environmental sectors. It also participates in international research collaborations and capacity-building activities. In FutuRaM, BU contributes to Balkan mining waste case studies for WP5 and WP6. https://rgf.bg.ac.rs/eng/

Duncan Kushnir

Duncan Kushnir is an individual expert and contributor to research projects in the raw materials and secondary resource sectors, including participation in EU-funded initiatives focused on CRMs and circular economy research. His involvement typically spans analysis, coordination, or scientific support for collaborative research activities addressing materials supply, resource efficiency and sustainability. This reflects his role as a technical partner in multi-institution research contexts. In FutuRaM, DKu contributes expertise to WP4. http://duncankushnir.com/

RECHARGE

RECHARGE is the European industry association representing the advanced rechargeable and lithium batteries value chain. Founded in 1998, it advocates for the sustainable development of innovative and competitive rechargeable battery technologies that support decarbonised energy and mobility, circular economy goals and resource efficiency. RECHARGE's membership spans raw material suppliers, manufacturers, OEMs, logistics and recyclers, and it engages in technical and policy discussions at European and international levels. In FutuRaM, RECHARGE participates in WP3 and WP4. https://rechargebatteries.org/

Stiftung Gemeinsames Rücknahmesystem Batterien

The Stiftung GRS Batterien (GRS Batteries Foundation) is a German non-profit centre of competence for extended producer responsibility and the circular economy in the battery sector. It develops and implements sustainable battery take-back, collection and recycling solutions under the German Battery Act, supporting manufacturers, distributors and stakeholders in fulfilling product responsibility obligations. GRS also engages in research, development and communication to improve battery recycling and circularity. In FutuRaM, GRS supports data collection in WP3 and contributes to battery case studies in WP5. https://www.grs-batterien.de/

European Metals Recycling

European Metals Recycling (EMR) is a global leader in the metal recycling industry, operating a network of sites across the UK, Europe and beyond to process and recycle scrap metal and other end-of-life materials. Founded in 1994, EMR handles millions of tonnes of metals annually, providing high-quality recycled ferrous and non-ferrous materials for industrial use and reducing the need for primary extraction. The company is committed to sustainability and innovation in the circular economy through advanced recycling technologies and strategic partnerships. In FutuRaM, EMR acts as a stakeholder for consultation in WP5 and provides data and a case study for construction and demolition waste. https://uk.emrgroup.com/

Mace

Mace is a global programme and project delivery consultancy and construction expert headquartered in London, UK. It operates across consulting, project management, construction delivery and facilities services, delivering major built environment projects including infrastructure, data centres, life science facilities and regeneration schemes. Since its founding in 1990, Mace has expanded internationally, combining innovation with sustainability and technical excellence in the construction sector. In FutuRaM, MACE provides construction and demolition waste data in WP3 and a case study in WP5. https://www.macegroup.com/

Otanmäki Mine Oy

Otanmäki Mine Oy is a Finnish mining and exploration company developing the historic Otanmäki mine area into a producer of CRMs such as vanadium, ilmenite and iron-based products for international markets. The company's project integrates circular economy principles by recovering valuable minerals from old mine tailings before expanding primary mining operations. Otanmäki Mine is positioned as a future-oriented supplier of strategic materials within the EU and participates in mineral exploration including rare earth elements alongside academic partners. In FutuRaM, OM provides a mining case study and UNFC-related expertise. https://www.otanmaki.fi/en/home/

The logos below represent the diverse organisations that contributed to the successful delivery of the FutuRaM project.

Coordinator

Scientific Coordinator

Annex I

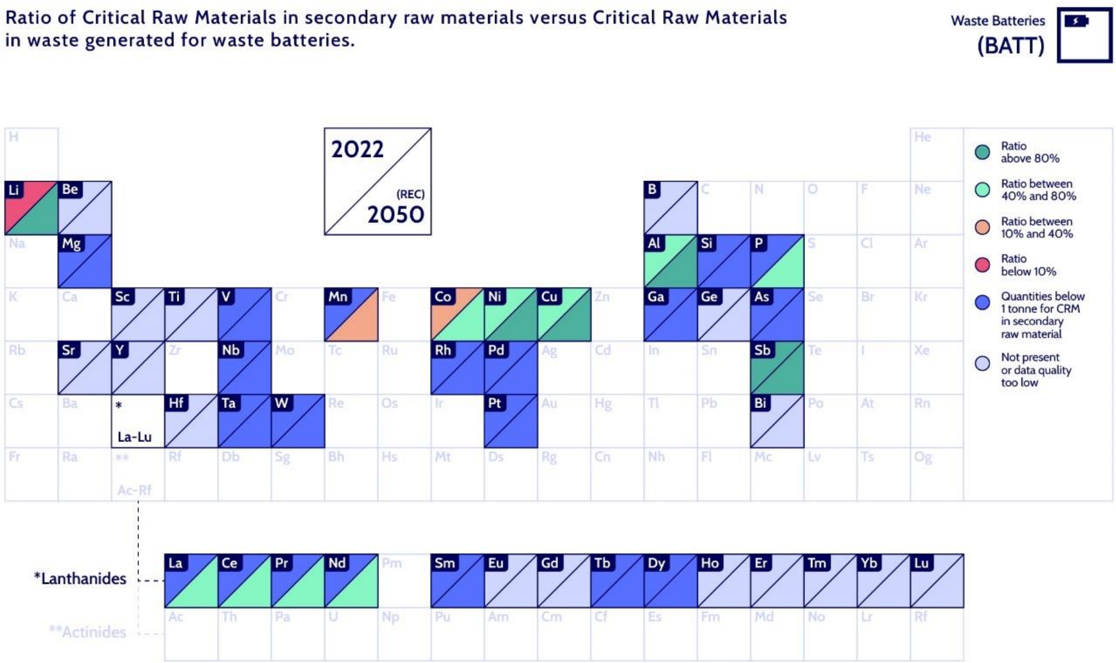

Figure A. 1: Ratio of CRMs in secondary raw materials versus CRM in waste generated for waste batteries in 2022 and 2050 for the REC scenario. Each periodic table cell is divided diagonally: the upper-left triangle represents the 2022 ratio, while the lower-right triangle represents the 2050 (REC scenario) ratio. This ratio has been calculated as the amount of CRM in secondary raw materials divided by the amount of CRM in waste generated.

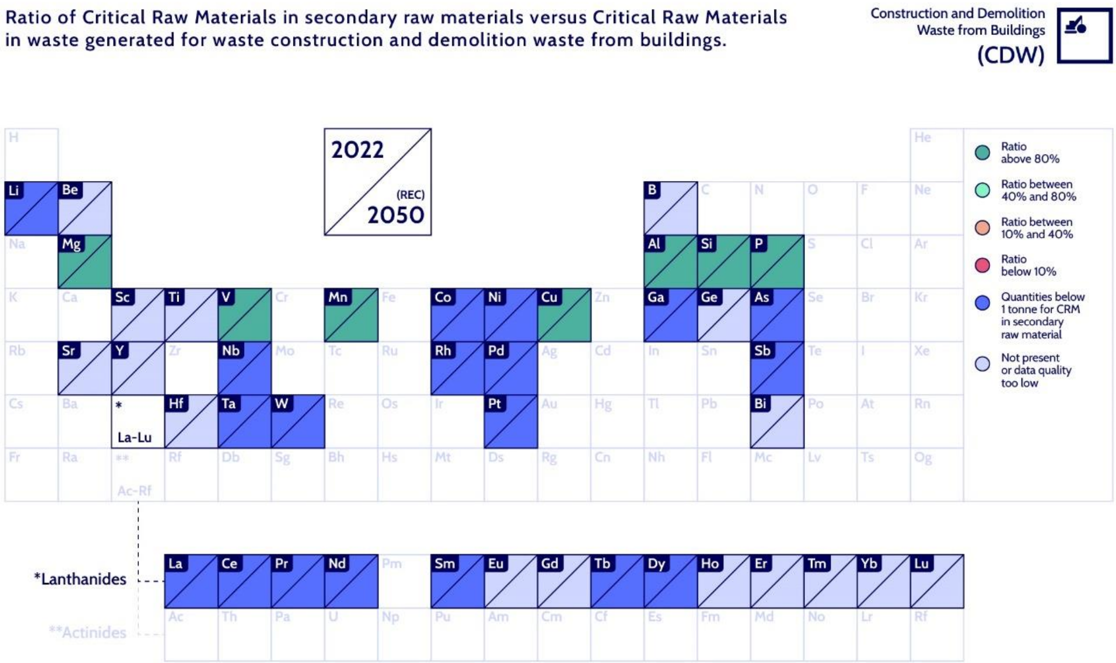

Figure A. 2: Ratio of CRMs in secondary raw materials versus CRM in waste generated for construction and demolition waste from buildings in 2022 and 2050 for the REC scenario. Each periodic table cell is divided diagonally: the upper-left triangle represents the 2022 ratio, while the lower-right triangle represents the 2050 (REC scenario) ratio. This ratio has been calculated as the amount of CRM in secondary raw materials divided by the amount of CRM in waste generated.

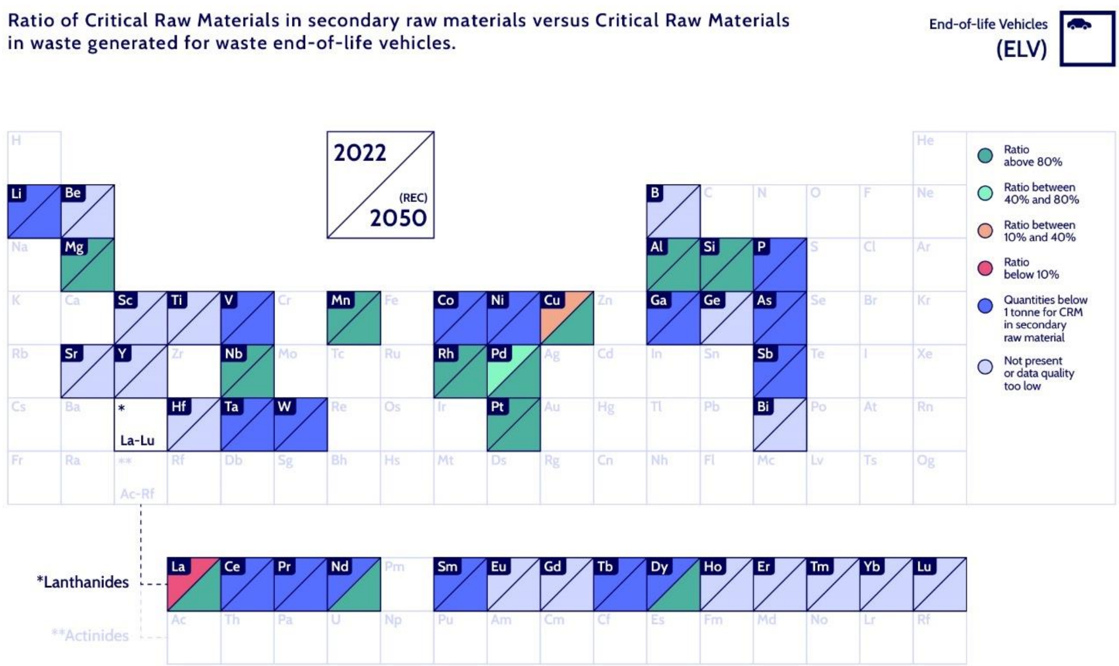

Figure A. 3: Ratio of CRMs in secondary raw materials versus CRM in waste generated for end-of-life vehicles in 2022 and 2050 for the REC scenario. Each periodic table cell is divided diagonally: the upper-left triangle represents the 2022 ratio, while the lower-right triangle represents the 2050 (REC scenario) ratio. This ratio has been calculated as the amount of CRM in secondary raw materials divided by the amount of CRM in waste generated.

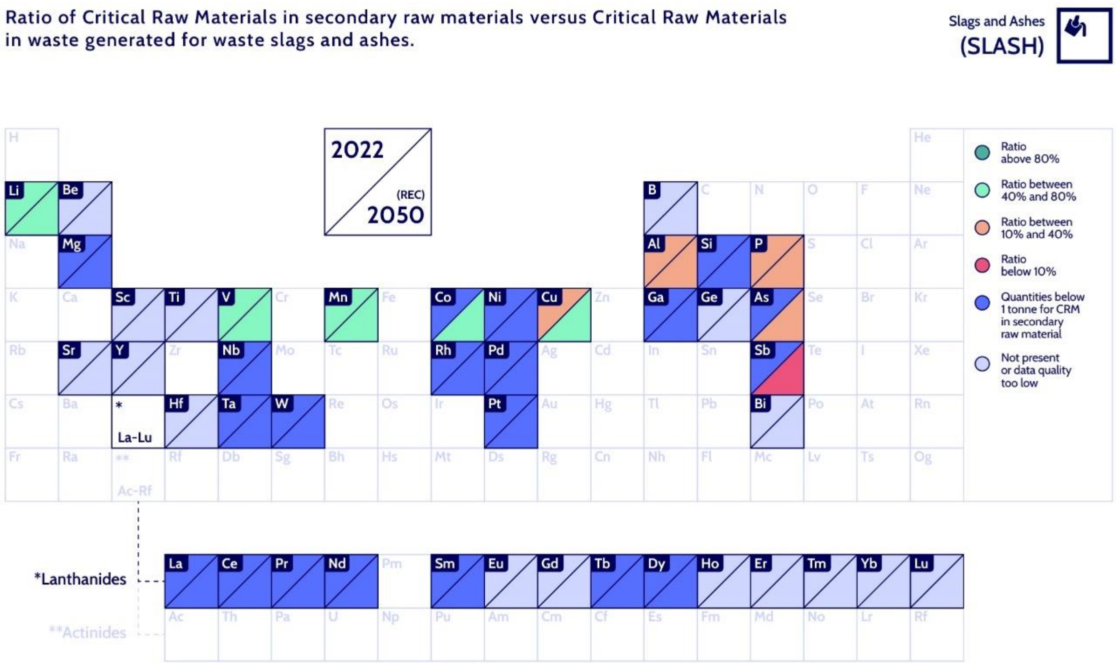

Figure A. 4: Ratio of CRMs in secondary raw materials versus CRM in waste generated for slags and ashes in 2022 and 2050 for the REC scenario. Each periodic table cell is divided diagonally: the upper-left triangle represents the 2022 ratio, while the lower-right triangle represents the 2050 (REC scenario) ratio. This ratio has been calculated as the amount of CRM in secondary raw materials divided by the amount of CRM in waste generated.

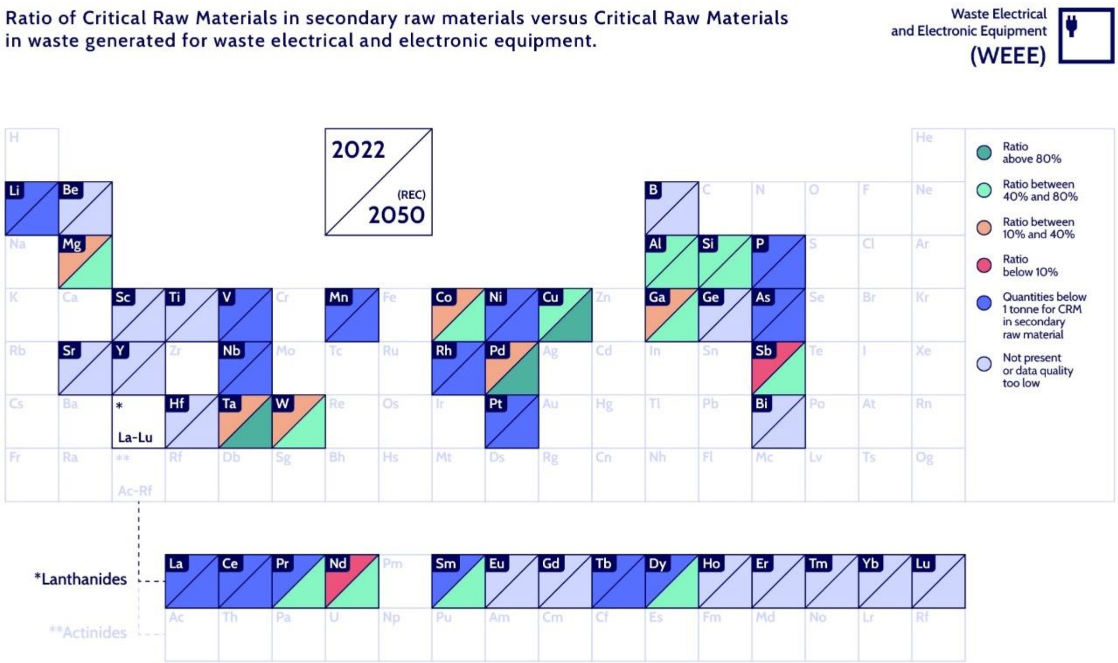

Figure A. 5: Ratio of CRMs in secondary raw materials versus CRM in waste generated for waste electrical and electronic equipment in 2022 and 2050 for the REC scenario. Each periodic table cell is divided diagonally: the upper-left triangle represents the 2022 ratio, while the lower-right triangle represents the 2050 (REC scenario) ratio. This ratio has been calculated as the amount of CRM in secondary raw materials divided by the amount of CRM in waste generated.

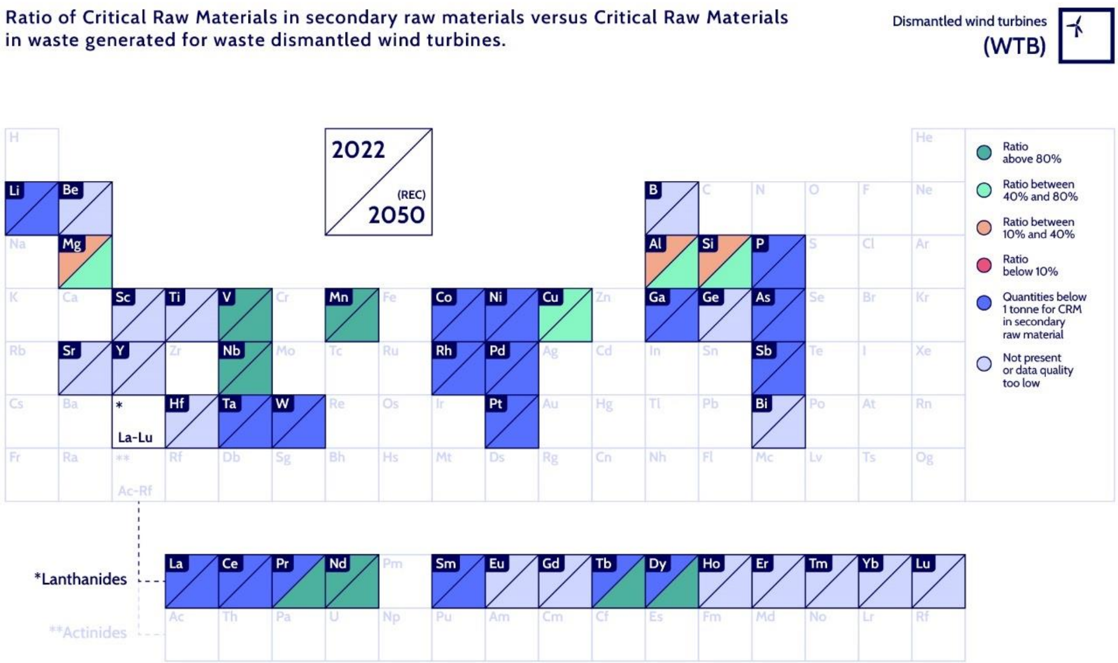

Figure A. 6: Ratio of CRMs in secondary raw materials versus CRM in waste generated for dismantled wind turbines in 2022 and 2050 for the REC scenario. Each periodic table cell is divided diagonally: the upper-left triangle represents the 2022 ratio, while the lower-right triangle represents the 2050 (REC scenario) ratio. This ratio has been calculated as the amount of CRM in secondary raw materials divided by the amount of CRM in waste generated.

Annex II

Table A. 1: List of project deliverables.

Deliverable number	Deliverable name	WP	Lead partner	Zenodo reference or link
D1.1	Consolidated and harmonised FutuRaM concepts, methods, models, procedures and recommendations	1	Empa	https://doi.org/10.5281/zenodo.18696893 (draft)
D1.2	Proposal on secondary raw materials statistics to the EC	1	UNITAR	https://doi.org/10.5281/zenodo.19385894 (draft)
D1.3	Draft reporting standard in line with UNFC	1	Empa	https://doi.org/10.5281/zenodo.18873691
D2.1	Report on environmental and socio-economic barriers to secondary raw materials recovery	2	ULEI	https://zenodo.org/records/20022185 (draft)
D3.1	Extended waste stream composition assessment to enable secondary raw materials assessment	3	TUB	https://doi.org/10.5281/zenodo.17542668
D4.1	Future trends of secondary raw materials and critical raw materials	4	UNITAR	https://doi.org/10.5281/zenodo.17579480
D5.1	Reports of case studies for secondary raw materials availability assessment in alignment with the UNFC	5	LMU	https://doi.org/10.5281/zenodo.17945112
D6.1	Secondary raw materials – Knowledge	6	BRGM	https://www.urbanmineplatform.eu/

	base dissemination portal			
D7.1	Report on stakeholder groups and relevant initiatives and projects identified	7	WEEE Forum	Not available
D7.2	Communication, dissemination & exploitation plan	7	SPI	https://doi.org/10.5281/zenodo.19604917 (draft)
D7.3	Business plan to ensure sustainability in the long-term	7	SPI	https://doi.org/10.5281/zenodo.19605478 (draft)
D7.4	Advocacy Report	7	SPI	https://doi.org/10.5281/zenodo.19605792 (draft)
D7.5	Final Project Report	7	UNITAR	https://doi.org/10.5281/zenodo.19470905
D8.1	Risk Register	8	WEEE Forum	Not available
D8.2	Data Management Plan	8	Empa	https://doi.org/10.5281/zenodo.19478641
D8.3	Procedures on Ethics Requirements	8	WEEE Forum	Not available

Annex III

Table A. 2: List of project scientific publications.

Publication	Title	Authors	Reference
Müll und Abfall	The role of circular construction in the carbon cycle - A material flow analysis for the city of Berlin	Katharina Kippert, Prof. Dr.-Ing. Vera Susanne Rotter, Johannes Scholz [Editors] (2023)	https://doi.org/10.37307/j.1863-9763.2023.10
Journal of Hazardous Materials	Speciation of toxic pollutants in Pb/Zn smelter slags by X-ray Absorption Spectroscopy in the context of the literature	Dan Ting Chen, Amitava Roy, Yu Qian Li, Anna Bogush, Wing Yin Au, Julia A. Stegemann (2023)	https://doi.org/10.1016/j.jhazmat.2023.132373
Minerals	Secondary Deposits as a Potential REEs Source in South-Eastern Europe	Robert Šajn, Jasminka Alijagić, Ivica Ristović (2024)	https://doi.org/10.3390/min14020120
Journal of Geochemical Exploration	Geostatistical modelling of mine tailings and comparative analysis of sampling methodologies: A case study of the Otanmäki ilmenite tailings storage facility project	Tuomas Leskelä, Janne Hokka, Teemu Karlsson (2025)	https://doi.org/10.1016/j.gexplo.2025.107759
Nature Communications	Revealing the Interplay between Decarbonisation, Circularity, and Cost-effectiveness in Building Energy Renovation	Chunbo Zhang, Mingming Hu, Benjamin Sprecher, Romain Sacchi, Xining Yang, Shiyu Yang, Teun Johannes Verhagen, Chi Zhang, Bernhard Steubing, Arnold Tukker (2025)	https://doi.org/10.1038/s41467-025-62442-1
Resources, Conservation and Recycling	A dynamic model to hindcast historical material stocks and flows from current stocks: Application to the buildings of 1159 administrative regions of the EU27, 1970–2050	Catrin Böcher, Sónia Cunha, Tomer Fishman, Ester van der Voet, Katharina Kippert, José M. Mogollón (2025)	https://doi.org/10.1016/j.resconrec.2025.108198

Resources Conservation and Recycling	T-reX: Quantifying waste and material footprints in current and future Life Cycle Assessment (LCA) databases	Stewart Charles McDowall, Elizabeth Lanphear, Stefano Cucurachi, Carlos Felipe Blanco (2025)	https://doi.org/10.1016/j.resconrec.2025.108464
Cell Reports Sustainability	Aligning circular economy and low-carbon economy for a sustainable built environment	Chunbo Zhang, Paul Behrens, Rupert Myers (2025)	https://doi.org/10.1016/j.crsus.2025.100609
Cleaner Engineering and Technology	Sustainable recovery and classification of anthropogenic resources [Special issue call]	Julia Stegemann., Sunday Leonard, Peng Yen Liew., Susanne Rotter, Patrick Wäger. [Editors] (2025)	https://www.sciencedirect.com/special-issue/326883/sustainable-recovery-and-classification-of-anthropogenic-resources
Communications Earth & Environment	Second-hand smartphones reduce carbon emissions, yet shorter use times limit actual gains	Levon Amatuni, Christian Clemm, Benjamin Sprecher, Arnold Tukker & José M. Mogollón (2026)	https://doi.org/10.1038/s43247-025-03170-8
Resources, Conservation and Recycling	Circular Economy can substantially reduce EU steel supply chain emissions: A quality-focused circularity assessment	Aymara Wagner, José M. Mogollón, Paola Federica Albizzati, Anna Walker, Arnold Tukker, Davide Tonini (2026)	https://doi.org/10.1016/j.resconrec.2026.108825
***Discussion Paper**	UNFC G-axis use for recycling projects: A discussion paper on the degree of confidence of estimates of future product quantities associated with recycling projects.	Ulrich Kral, Soraya Heuss-Aßbichler, Iman Dorri, Dirk Nelen, Marina von Vietinghoff-Scheel, Matthias Rösslein, Patrick Wäger, Ronald Arvidsson, Daniel Monfort, Tales Yamamoto (2026)	https://doi.org/10.5281/zenodo.17992646