**From Rubbish to Resource: Waste-Stream-Specific Scenario Narratives for the Future of Secondary Raw Material Recovery in the EU**

Stewart Charles McDowall*a\* ,* Carlos Felipe Blanco*a, c, ­and* Stefano Cucurachi*a*

*aInstitute of Environmental Sciences (CML), Leiden University, P.O. Box 9518, Leiden, 2300RA, South Holland, The Netherlands*

*cNetherlands Organisation for Applied Scientific Research (TNO), Princetonlaan 6, 3584 CB, Utrecht, The Netherlands*

*\* Corresponding author: s.c.mcdowall@cml.leidenuniv.nl*

# Abstract

Securing the future supply of raw materials—particularly critical raw materials (CRMs)—is essential to promoting and sustaining economic and societal well-being. Effective forecasting of this supply requires consideration of secondary raw materials (2RMs) contained in diverse waste streams, alongside primary raw materials (1RMs) extracted from the environment. Given the deep uncertainty inherent in long-term forecasting, it is prudent to methodically explore a broad range of possible developments.

This paper presents the narrative construction phase of a scenario development process that explored future pathways for waste management and material recovery up to 2050. These storylines were developed within the Horizon Europe-funded project FutuRaM, which aims to establish methodology, reporting, and guidance to strengthen the raw materials knowledge base within the EU and beyond.

Three scenarios—Business as Usual (BAU), Recovery (REC), and Circularity (CIR)—were constructed to reflect divergent societal, political, economic, and technological trajectories. Each scenario consists of an overarching narrative, complemented by detailed qualitative projections regarding the future composition and volume of six specific waste categories. The scenario development process employed a structured approach integrating forecasting and backcasting techniques, identification of key drivers and uncertainties, extensive stakeholder engagement, and the creation of coherent narrative storylines grounded in current trends, stated policy goals, and published forecasts.

These scenario narratives can directly inform strategic decision-making, policy formulation, and long-term planning by clarifying plausible futures, trade-offs, and key intervention levers in waste and resource systems. Their utility can be further enhanced by using them as a structured foundation for quantitative modelling, in which qualitative assumptions are translated into scenario parameters and explored with system models to compare pathways, test sensitivities, and assess system-wide implications.

# Keywords

Circular Economy, Scenario Development, Storyline Narratives, Backcasting and Forecasting, Waste and Resource Management, Secondary Raw Materials, Critical Raw Materials, Stakeholder Engagement

List of abbreviations

1RM Primary Raw Material

2RM Secondary Raw Material

BATT Waste Batteries (waste stream name)

BAU Business-as-usual (scenario name)

CDW Construction and Demolition Waste (waste stream name)

CE Circular Economy

CIR Circularity (scenario name)

CRM Critical Raw Material

EEE Electrical and Electronic Equipment

ELV End-of-Life Vehicles (waste stream name)

EoL End-of-Life

EoU End-of-Use

EoW End-of-Waste

EPR Extended Producer Responsibility

EU European Union

EU27+4 EU + Iceland, Norway, Switzerland, and the UK

EV Electric Vehicle

FutuRaM Future of Raw Materials (EU Horizon 2020 project)

GDP Gross Domestic Product

IAM Integrated Assessment Model

ICE Internal Combustion Engine

IEA International Energy Agency

IRTC International Round Table on Materials Criticality

LCA Life Cycle Assessment

LIB Lithium-ion Battery

LMT Light Means of Transport

MFA Material Flow Analysis

MIN Mining Waste (waste stream name)

NIMBY Not In My Backyard (parochial protectionism)

RCP Representative Concentration Pathway

REC Recovery (scenario name)

REE Rare Earth Elements

re-X A broad set of circular economy strategies (“reduce”, “reuse”, “repair”, “recycle” etc.)

SLASH Slags and Ashes (waste stream name)

SRM Strategic Raw Material

SSP Shared Socioeconomic Pathway

TRL Technology Readiness Level

UK The United Kingdom of Great Britain and Northern Ireland

UN United Nations

UNFC United Nations Framework Classification for Resources

WEEE Waste Electrical and Electronic Equipment (waste stream name)

WFD Waste Framework Directive

# Introduction

## Context and motivation

Europe’s material economy depends on a secure and sustainable supply of raw materials. Primary raw materials (1RMs) extracted from virgin resources underpin manufacturing, energy, mobility, and digital infrastructure, but their extraction and processing can entail significant environmental and social impacts (Mononen et al., 2022). Additionally, the EU’s reliance on foreign imports for many of these materials results in a high level of exposure to geopolitical risks and global market volatility (Carrara et al., 2023). Secondary raw materials (2RMs)—materials recovered from products, components, and residues at their end-of-life—offer a complementary source that can reduce dependence on 1RMs, lower life-cycle burdens, and support circular-economy objectives (European Commission et al., 2021). Within the broader category of raw materials, critical raw materials (CRMs) are those with high economic importance and elevated supply risk; ensuring their availability is central to decarbonisation and digitalisation strategies in the EU (European Commission et al., 2023; International Energy Agency (IEA), 2023a).

The availability and recoverability of 2RMs depend on dynamic, interlinked drivers: product design and durability; collection, sorting, and recycling infrastructure; market acceptance and quality of secondary outputs; energy systems; trade and industrial policy; and consumer behaviour (Huisman et al., 2017; Li et al., 2022). These factors evolve under uncertainty on multi-decadal time horizons and interact across sectors and policy domains. As a result, decision-makers require forward-looking analyses that can systematically explore alternative futures, illuminate trade-offs, and test the implications of policy and technology choices (Amer et al., 2013; Mahmoud et al., 2009).

Scenario analysis provides such a lens and is widely used in environmental and resource domains to investigate long-term developments under uncertainty. Numerous scenario sets exist for energy systems and mobility transitions at national, EU, and global scales (Commission et al., 2021; International Energy Agency (IEA), 2023c, 2023b; OECD, 2012; Skea et al., 2021). By contrast, relatively few scenario sets centre explicitly on 2RM/CRM recovery systems and the waste streams that supply them. Where they do exist, they are often sector-specific (e.g., e-waste (Parajuly et al., 2019), traction batteries (Abdelbaky et al., 2020)) or more narrowly focussed CRM outlook reports (Buisson et al., 2024; International Energy Agency (IEA), 2025). Thus, there remains a gap in comprehensive, multi-stream perspectives on future 2RM supply supported by robust, transparent data.

## FutuRaM’s aim and scope

Addressing this, the Horizon Europe project FutuRaM develops the knowledge base on the availability and recoverability of 2RMs within the EU—with particular attention to critical raw materials (CRMs)—to support evidence-based decisions by industry, investors, and policy-makers (FutuRaM consortium & European Commission, 2023; FutuRaM consortium, 2022).

FutuRaM focusses on the EU-27 plus Iceland, Norway, Switzerland, and the UK (EU27+4) over 2025–2050 and targets six waste streams with significant 2RM and CRM potential: batteries (BATT), waste electrical and electronic equipment (WEEE), end-of-life vehicles (ELV), construction and demolition waste (CDW), mining residues (MIN), and slags and ashes (SLASH). The project integrates material stock-flow information; considers economic, technological, regulatory, social, environmental, and geopolitical drivers and interactions with manufacturing, energy, and transport systems; and aligns outputs, where appropriate, with the United Nations Framework Classification for Resources (UNFC) (United Nations Economic Commission for Europe (UNECE), 2023).

Within this programme, Work Package 2 (WP2) develops a set of plausible, internally consistent scenarios that (i) characterise future 2RM supply from the six waste streams, (ii) identify key drivers and uncertainties, and (iii) provide a structured basis for subsequent quantification and model coupling. The scenarios are intended to inform public and private decisions by enabling systematic assessment of policy and technology options and their implications for 2RM/CRM availability and related environmental–economic outcomes. Within this scope, we develop scenario narratives to structure and inform subsequent quantification.

## Policy context for 2RM/CRM scenarios

Government strategies and legislation at the local, state, and EU levels provide both direction and constraints for 2RM/CRM systems. The **European Green Deal** sets the overarching objective of climate neutrality by 2050 and promotes resilient, sustainable industrial value chains (European Commission, 2019). The **Circular Economy Action Plan** outlines measures to improve resource efficiency, product durability and repairability, waste prevention, and high-quality recycling, with close links to the EU Industrial Strategy (European Commission, 2020). Together, these frameworks create strong signals favouring design for circularity, increased recovery rates, and market development for 2RMs.

The **Critical Raw Materials Act** introduces specific supply-security benchmarks: by 2030, not more than 65% of annual EU consumption of each strategic raw material should stem from a single non-EU country; within the EU, capacities should be sufficient to extract ≥10%, process ≥40%, and recycle ≥15% of annual consumption (European Commission, 2023). These benchmarks inform the REC and CIR scenarios, which examine the technology- and system-level changes needed to approach them via domestic recovery and circularity measures.

Waste-stream-specific legislation is also pertinent. BATT, ELV, and WEEE are governed by dedicated directives and regulations that set collection, treatment, and recycling requirements (European Commission, 2012, 2023b, 2023a, 2023c). These instruments shape the feasible ranges of collection rates, treatment efficiencies, and design obligations used in the scenarios. Notably, several statutory targets—particularly in batteries—are ambitious to the point that meeting them would require rapid structural reforms and performance improvements across the recovery chain. Accordingly, BAU does not assume full attainment of these targets within the study horizon, whereas REC and CIR explore pathways that deliberately mobilise technological and systemic measures to meet or approach them.

A non-exhaustive list of relevant policies that were considered in this study are presented in appendix A3

## Scenario types and their use in this study

In futures studies, scenario exercises are commonly grouped into three families that address different questions (Börjeson et al., 2005, 2006; Cordova-Pozo & Rouwette, 2023; Dreborg, 1996; Skea et al., 2021)

* **Predictive** — What will happen? These scenarios explore likely developments given current conditions and stated policies, typically using forecasting assumptions. They are informative for baseline planning but are contingent on assumptions and may under-represent low-probability disruptions.
* **Explorative** — What could happen? These map a space of plausible futures by varying external drivers and internal responses. They support preparedness across a range of outcomes without attaching probabilities or preferences.
* **Normative** — How can a specified target be reached? These work backwards from desired end-states (e.g., policy targets) to identify feasible pathways and enabling measures. They are purpose-oriented and depend on the choice of goals.

In practice, robust scenario work often combines these families and integrates qualitative narratives with quantitative parameters (Amer et al., 2013; Bishop et al., 2007). This study adopts a mixed-method scenario approach—integrating forecasting and backcasting—tailored to 2RM/CRM systems. The three scenarios are internally consistent and comparable across the six waste streams. They are specified at a level that provides a robust foundation for subsequent quantification—sufficiently detailed to support parameterisation and model-based analysis using methods such as material flow analysis (MFA) and life cycle assessment (LCA).

## Contribution of this paper

This paper documents the narrative construction phase of FutuRaM’s scenario development. It:

1. develops three internally consistent, cross-comparable scenario storylines—BAU, REC), and CIR—covering six waste streams;
2. synthesises policy targets, technology trajectories, market developments, and expert judgement to identify key drivers, constraints, and uncertainties for 2RM/CRM recovery;
3. specifies transparent assumptions and traceable logic chains that map qualitative storyline elements to scenario parameters, thereby providing a structured basis for subsequent quantification and model coupling within FutuRaM; and
4. clarifies the treatment of EU targets and benchmarks across scenarios, distinguishing baseline (BAU) assumptions from deliberate policy/technology mobilisation in REC and CIR.

The remainder of the paper describes the scenario method, presents the BAU/REC/CIR narratives by waste stream, and discusses implications for strategy and policy.

# Methodology

This section outlines the scenario development workflow applied in FutuRaM (Figure 1). Herein is detailled Steps 1–6; parameterisation of scenario variables (Step 7) is reported in Appendix 6,quantitative modelling and implementation (Steps 8–9) fall outside the scope of this study. Selected outputs from Step 4 are presented in the Results (subsection 3.1) and supporting appendices (A5).

## Step 1: Establish framework and scope

**Framework.** Scenarios were designed to ensure scientific rigour, transparency, and policy relevance. They are (i) evidence-based and methodologically robust; (ii) coherent and internally consistent while spanning a range of plausible futures and key uncertainties; (iii) decision-oriented, clarifying potential consequences of alternative choices; (iv) participatory, drawing on domain experts and stakeholders; (v) transparent and well documented to enable replication and open dissemination; (vi) adaptive, with provisions for periodic updating; (vii) systems-oriented, capturing interconnections among sectors, waste streams, and policy domains; (viii) long-term in perspective; (ix) integrative of quantitative modelling and qualitative narratives; and (x) communicated clearly to support both practitioner uptake and scholarly contribution. To facilitate consistent communication, a shared vocabulary was established at the outset (Appendix A1).

**Scope.** The scenarios examine plausible futures for waste management, resource recovery, and the circular economy across the EU-27 plus Iceland, Norway, Switzerland, and the UK (EU27+4) over 2025–2050, with projection years at 2025, 2030, 2035, 2040, 2045, and 2050. Temporal granularity was limited to avoid spurious precision given long-term uncertainty. The analysis centres on six FutuRaM waste streams—WEEE, ELV, BAT, CDW, MIN, and SLASH—together with interfaces to manufacturing, energy, and transport systems, and the relevant environmental, economic, social, technological, and geopolitical policy domains.

## Step 2: Determine methodology

**Selection criteria and methods considered.** We identified methods and tools suited to FutuRaM’s objectives using criteria of relevance and applicability to context; feasibility (time, budget, expertise, data); transparency and documentation; flexibility to incorporate new evidence; accessibility for non-experts; effectiveness and efficiency; and stakeholder acceptability. Candidate methods are summarised in Appendix A2.

**Core scenario set and candidate dimensions.** The grant proposal defined three core scenarios—Business as Usual (BAU), Recovery (REC), and Circularity (CIR)—to explore how secondary raw material (2RM) availability is shaped by the evolution of 2RM recovery systems and re-X strategies. During scoping, additional dimensions were considered, notably supply-chain security and the pace of the energy transition. Their inclusion was tested using the procedures below. The reasons for ultimately not adopting further dimensions are discussed in Section 4.

**Multi-criteria and cross-impact analysis.** To avoid uncontrolled growth in scenario variants, we applied a matrix-based multi-criteria and cross-impact analysis to evaluate internal consistency and plausibility of combinations (Steubing et al., 2016). For instance, “low” progress in the energy transition was judged inconsistent with “high” progress in recycling/circularity indicators and could be excluded. By contrast, supply-chain security varied more independently, but credible geopolitical speculation was not feasible; incorporating it as a scenario dimension would introduce excessive uncertainty. Instead, potential supply constraints will be analysed via sensitivity tests and, where appropriate, explorative multi-objective optimisation to address questions such as: What happens to the 2RM system if element x is constrained, and what responses are optimal? Additional rationale is provided in the Section 4.

**Delphi process.** Early stages of scenario building were supported by a Delphi process to aggregate expert judgement across waste streams and recovery-system domains (Hsu & Sandford, 2019). Steps included expert selection, initial questionnaires, iterative rounds with controlled feedback, and convergence toward consensus.

## Step 3: Marker-scenario mapping

We conducted a structured literature review to identify and analyse marker scenarios relevant to FutuRaM. This mapping served to (i) build on established knowledge; (ii) benchmark assumptions, drivers, and methodological approaches; (iii) identify gaps; and (iv) enhance comparability and credibility of our scenarios. Insights from marker scenarios informed the selection of drivers, the structuring of storylines, and the alignment of projection years and sectoral linkages. The consulted marker scenarios are listed in Appendix A4.

## Step 4: Identify key drivers and select scenario elements

**Purpose and approach.** This step identified the social, economic, technological, environmental, and policy factors that shape the waste-management system over time. The process combined literature review, internal expert elicitation, and stakeholder engagement to assess trends, uncertainties, and emerging issues. It was iterative, with feedback loops to ensure coverage of the most influential drivers and to maintain consistency with scope and objectives.

**Sub-method and workflow.** Figure 2 depicts the sub-method for identifying and defining scenario elements:

* **Preliminary collection and screening.** Candidate elements were compiled from peer-reviewed literature, statistics, policy documents, and project datasets, then screened against predefined criteria for relevance, reliability, plausibility, and model utility. Overlapping items were consolidated (e.g., recyclability mandates with design-for-recyclability), and elements judged irrelevant, non-modellable, or unreliable (e.g., corruption, data protection, supply-chain conflict) were excluded.
* **Assessment and categorisation.** Retained items were organised by thematic relevance and characteristics, yielding 21 key elements (Table 1). While CIR and REC share many elements, they differ in how targets are achieved: CIR emphasises re-X strategies (reduce, reuse, repair, remanufacture, recycle), whereas REC prioritises advances in recovery technology and infrastructure—an important distinction for subsequent quantitative modelling.
* **Scope classification.** Each element was classified according to its relationship to the waste-management system: **internal** (within scope for detailed research and modelling, e.g., composition and design changes), **external** (included in storylines, varying over time but constant across scenarios, e.g., population, GDP), or **outside** (excluded from scenarios but, where relevant, examined in sensitivity analysis, e.g., supply constraints).

Selected Step-4 outputs are presented in the Results (subsection 3.1) and the appendices (A5 and A6). The validated element set informed the design of storyline themes (Step 5) and the drafting of narratives (Step 6).

## Step 5: Develop storyline themes

The overarching scenario themes were guided by the FutuRaM charter and the grant proposal’s core scenario set. Themes focus on how 2RM availability evolves under different combinations of recovery-system development and re-X strategies. The three scenarios are:

* **Business as Usual (BAU)** — Predictive: projects outcomes if current policies and trajectories persist, assuming continuity in waste management and resource recovery systems.
* **Recovery (REC)** — Normative: prioritises technological and infrastructural improvements in recovery systems to meet EU material-use and recovery targets.
* **Circularity (CIR)** — Normative and explorative: aligns with the EU Circular Economy Action Plan (European Commission, 2020), examining systemic adoption of re-X strategies to achieve targets and reduce dependence on primary resources.

A graphical depiction of the scenarios is provided in Figure 3. The rationale for not expanding the scenario set with additional dimensions is discussed in Section 4.

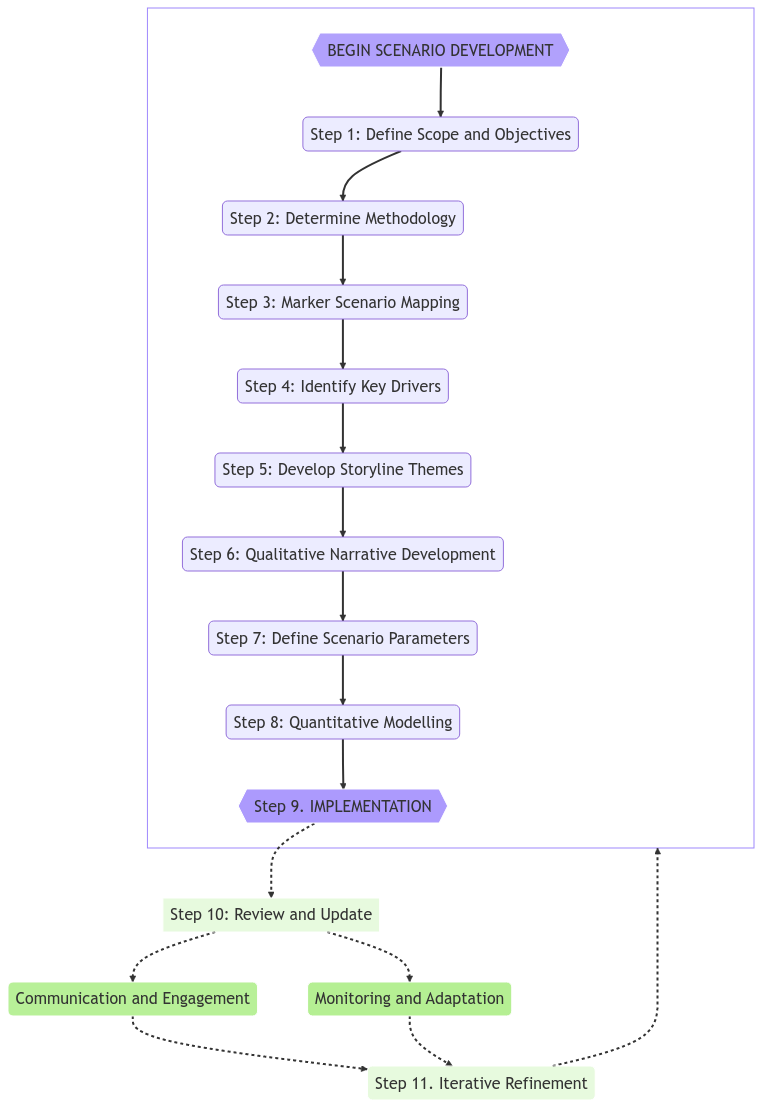
## Step 6: Develop qualitative narrative storylines

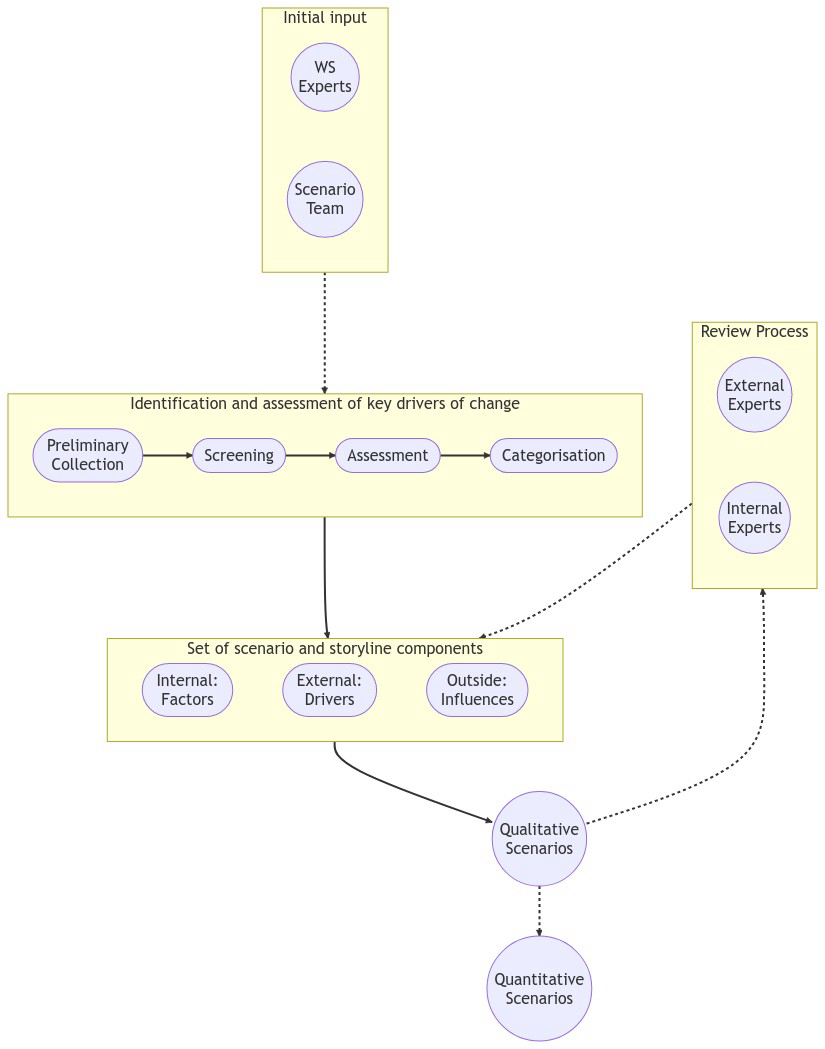
Narratives were constructed through an iterative process that combined systematic evidence gathering with structured consultation. Data on trends, targets, policies, and marker scenarios were collated to define candidate drivers and elements. These inputs were scrutinised in workshops and Delphi-style rounds with consortium experts and, where appropriate, external stakeholders, to test plausibility, resolve inconsistencies, and prioritise influential factors. Draft narratives for BAU, REC, and CIR were reviewed for internal coherence and alignment with the agreed scope, then refined through successive feedback cycles.

Each storyline integrates qualitative insights with model-ready descriptors to enable later parameterisation. Assumptions, causal links, and uncertainty ranges were documented to support transparency and to flag items for sensitivity analysis. The outputs of Step 6 thus provide: (i) coherent narratives that explain how and why system trajectories diverge across scenarios; (ii) a traceable mapping from qualitative drivers to quantitative variables; and (iii) an auditable record of literature sources, expert judgements, and decisions.

The main outcome of this study, the scenario storyline narratives are presented in the Results (subsection 3.2). More details about the waste-stream-specific impacts of the scenarios is presented in Appendix A7.

**Forward link to Step 7.** Parameter values and time paths for model variables (e.g., technology performance, collection and sorting rates, design and composition shifts) are to be quantified in Step 7 using trends and forecasts, subject to the consistency constraints defined in Steps 2–6. These parameters were analysed in preparation for quantification and reported in Appendix A6. **Steps 8–9** (quantitative modelling and implementation) are outside the scope of this study.

Figure 1. A flowchart representation of the methodology used for the scenario storyline development process in FutuRaM

Figure 2. An illustration of the methodology used for identifying, defining, screening, and integrating the key elements of the scenarios developed in FutuRaM

# Results

## Scenario element selection

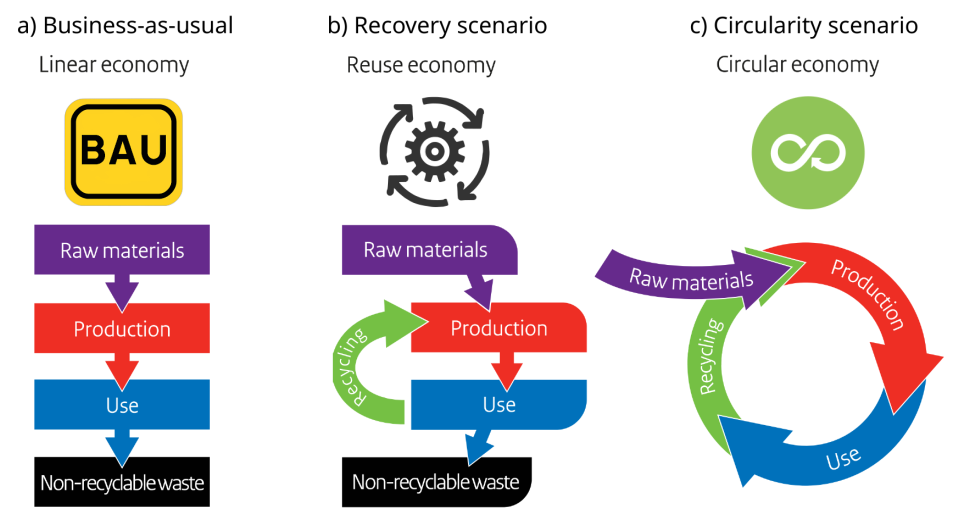
**Results from the preliminary collection of scenario elements are summarised in Appendix A5. Table 1 lists the drivers and factors retained after the screening process. Appendix A6 presents the final, categorised set of scenario elements and indicates which are carried forward for parameterisation and subsequent modelling. Elements were excluded when judged out of scope, insufficiently specific to the focal waste streams, or infeasible to quantify.**

Table 1. Scenario drivers and factors retained after screening. Items were omitted if they were out of scope, not sufficiently specific to the waste streams, or infeasible to quantify. “Scenario variances” denote a qualitative stakeholder assessment of the expected trend for each driver/factor in the three scenarios—Business as Usual (BAU), Recovery (REC), and Circularity (CIR).

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Domain** | **Factor/Driver** | **Scenario variance** | | |
|  |  | **BAU** | **REC** | **CIR** |
| Economic | CO2 market price | I | I | I |
| Economic | Economic growth | I | I | I |
| Economic | Energy prices | I | I | I |
| Economic | Market saturation of (electronic) products | I | I | II |
| Economic | Raw material vs 2RM prices | I | I | I |
| Economic | Re-industrialisation of EU | I | I | I |
| Environmental | Climate change impacts | I | I | I |
| Environmental | Climate change mitigation efforts | I | I | I |
| Environmental | Increased drive for environmental protection | I | III | III |
| Environmental | Resource shortages | I | I | I |
| Legal/Political | Ecodesign/re-X mandates | I | II | III |
| Legal/Political | Governance: corruption vs compliance | I | I | I |
| Legal/Political | International trade and co-operation (vs. autarky) | I | I | I |
| Legal/Political | Product information transparency | I | III | III |
| Legal/Political | Progress toward renewable energy targets | I | I | I |
| Legal/Political | Stricter environmental regulations | I | III | III |
| Legal/Political | Subsidies/taxation to promote circularity | I | I | I |
| Legal/Political | Supply chain due diligence laws | I | II | III |
| Social | Hoarding of end-of-life consumer products | III | II | II |
| Social | NIMBY attitudes toward projects | I | I | I |
| Social | Participation in re-X activities | I | II | III |
| Social | Population change | I | I | I |
| Social | Urbanisation | I | I | I |
| Technical | Digitisation | I | I | I |
| Technical | 2RM system integration | I | III | III |
| Technical | Product technology (design for re-X) | I | III | III |
| Technical | Recovery technology (recycling system) | I | III | III |

## Qualitative narrative development: The scenario storylines

This subsection presents abbreviated qualitative storylines for the three scenarios—**Business as Usual (BAU)**, **Recovery (REC)**, and **Circularity (CIR)**—summarising their system-wide logic and expected trajectories. Figure 3 illustrates the distinct economic logics embodied by each scenario: trend continuation in BAU, technology-led improvements in recovery systems in REC, and systemic adoption of re-X strategies in CIR. More detailed information about the waste-stream-specific impacts of each scenario is given in appendix A7.

Figure 3. A schematic representation of the three discrete economic models embodied by the three scenarios developed in FutuRaM: a) Business-as-usual (BAU), b) Recovery (REC), c) Circularity (CIR). Adapted from Government of the Netherlands (2016).

### Scenario I: Business-as-usual (BAU)

The BAU scenario projects present trends through to 2050 with minimal deviation in consumption patterns and in the organisation of the secondary raw material (2RM) system (International Energy Agency (IEA), 2022). While incremental gains occur—e.g., moderate resource-efficiency improvements, gradual advances in recovery technology, and a steady energy transition—transformational change is constrained by economic pressures, social preferences, political inertia, and entrenched interests. Primary extraction remains the dominant source meeting the EU’s growing material demand.

#### System trajectory and assumptions

BAU is a **forecasting-led** pathway: it extrapolates current drivers and institutions, assuming today’s policy ambition and enforcement largely persist. Minor efficiency gains are absorbed by rising demand, leaving overall material throughput closely coupled to GDP growth. The linear take–make–dispose model continues to shape production and consumption, and the 2RM system improves only at the margin.

#### Material demand and supply

Material demand remains tightly linked to economic activity, so total consumption increases over time. Primary mining and extraction continue as the leading supply sources, reinforcing reliance on traditional extraction methods. Base metals benefit from established markets and economies of scale and are comparatively well recycled; by contrast, many rare and specialty metals are still lost because technologies and economics limit their recovery. EU mining remains limited and geographically concentrated in a few member states; known domestic potentials—e.g., lithium (PT, FR, UK) and rare earths (SE)—are not realised. Import dependency therefore escalates, increasing exposure to supply disruptions and market volatility (International Energy Agency (IEA), 2022; Mancini et al., 2013).

#### Waste management and recovery performance

Recycling and recovery rates remain low relative to potential, with persistent losses of critical raw materials. Producer responsibility schemes and data availability improve only incrementally; collection performance and contamination continue to limit output quality and value. Investments in sorting, pre-treatment, and recovery capacity are selective and insufficient to change system-level outcomes. As a result, significant 2RM opportunities are missed, and landfilling or low-value outlets remain prevalent in several streams.

#### Policy and governance

Many EU targets for ecodesign, recycling, recovery, and waste prevention are **not** met. Regulatory tightening is constrained and uneven across member states, providing weak incentives for high-quality recyclates or design changes. Where policies advance, implementation and monitoring gaps blunt impact. Without stronger and more consistent measures, innovation remains patchy and the cost of secondary outputs often fails to match primary alternatives at required specifications.

#### Environmental and socio-economic outcomes

Environmental pressures from extraction persist, contributing to ecosystem degradation, biodiversity loss, and climate impacts (Intergovernmental Panel on Climate Change (IPCC), 2022) Relative to pathways with stronger circular measures, BAU exhibits higher cumulative energy and material footprints. At the same time, heightened import reliance exposes EU industry to price spikes and supply shocks, increasing planning uncertainty and potentially delaying investment in new recovery technologies (Carrara et al., 2023; International Energy Agency (IEA), 2025; Mancini et al., 2013). Industrial priorities emphasise short-term cost efficiency over long-term resilience and sustainability. Transitions to renewable energy and e-mobility proceed, but at the present pace rather than on an accelerated trajectory.

#### Dependencies and risks

Key vulnerabilities include: (i) persistent coupling of demand and GDP; (ii) limited progress on design-for-circularity and product information, which constrains high-quality recovery; (iii) under-investment in 2RM technologies and infrastructure; and (iv) import-related exposure to geopolitical and market risks. These factors reinforce lock-in to linear practices, making it harder to realise future gains without stronger policy and market signals.

#### Positioning relative to other scenarios

BAU serves as a **reference** against which the Recovery (REC) and Circularity (CIR) scenarios can be evaluated. Compared with REC, BAU exhibits lower recovery performance, weaker output quality, and higher landfilling; compared with CIR, it lacks the upstream design, use-phase, and sufficiency levers needed to decouple services from primary extraction. In short, BAU represents the lower-bound pathway where incremental improvements occur but the structure of the system—and its associated risks—largely persists.

### Scenario II: Recovery (REC)

The recovery scenario centres on harnessing pre-consumer and post-consumer waste as a significant source of secondary raw materials (2RMs). It moves decisively beyond the status quo by upgrading recovery performance and infrastructure, yet overall material throughput continues to track growing demand rather than absolute reductions. The modelling approach combines **backcasting** for dimensions governed by policy targets with **forecasting** for areas without binding targets, linking desired outcomes to present conditions and projecting feasible pathways from current baselines.

#### System focus and technological change

Waste treatment is the pivotal actor. The emphasis is on rolling out and optimising advanced recovery technologies to improve sorting fidelity, material purity, and process efficiency. Digitalisation—spanning artificial intelligence, automation, robotics, and enhanced process control—raises plant productivity and stabilises quality, allowing higher-value recyclates to re-enter manufacturing. Investments concentrate on upgrading sorting, pre-treatment, and recovery facilities, and on data systems that disclose product composition and design attributes, which in turn enable better characterisation and targeted recovery. Producer responsibility schemes mature, driving higher take-back and collection across key streams and reinforcing steady feedstock to recyclers.

#### Policy, governance, and market organisation

EU targets for recycling and recovery are reached due to a more expansive, efficient, and effective waste management system. Regulatory instruments are tightened to promote high-quality outputs (e.g., contamination limits, de-risked offtake), improving the economics of recovery. Standardisation and clearer guidance support EU-wide implementation and compliance; cross-border coordination and knowledge transfer help diffuse good practice. Alongside regulation, public investment and R&D programmes crowd in private capital for plant upgrades and process innovation, while transparency requirements expand the availability of product and material data relevant to recovery planning.

#### Material supply and risk profile

Higher domestic recovery partially mitigates supply risk by reducing exposure to volatile global markets; nonetheless, import dependence persists for several critical inputs where domestic end-of-life stocks, technology readiness, or economics remain constraining (International Energy Agency (IEA), 2023a). Urban mining and recovery from selected waste streams and tailings are explored more systematically, with pilots scaling where yields and costs are favourable. Industrial actors increase the share of secondary inputs where price–quality conditions permit, but adoption varies across sectors and member states.

#### Environmental and socio-economic outcomes

Relative to business-as-usual (BAU), environmental burdens decline due to higher recovery rates and lower landfilling. However, upstream pressures linked to aggregate consumption growth remain significant—this is a system that **recovers more**, not one that **uses less**. Employment expands in recycling, recovery, and associated services as collection improves and plants scale. Cost efficiency in 2RM production improves through learning and quality gains, further reinforcing uptake in manufacturing where specifications can be met.

#### Diffusion dynamics and behavioural dimensions

Innovation diffusion is uneven. Frontrunner regions and sectors demonstrate higher yields and faster quality improvements; laggards remain closer to BAU performance. Public awareness of recycling improves, but behaviour change is still concentrated at the **end-of-pipe** (separating and returning products) rather than **sufficiency** (avoiding or reducing consumption). As a result, the system attains higher circular **recovery** without fully addressing demand-side drivers.

#### Dependencies and implementation risks

Realising the scenario’s gains depends on sustained investment in recovery infrastructure and digital capabilities; robust enforcement of quality standards; and continued maturation of producer responsibility schemes. Key risks include: (i) inconsistent implementation and monitoring across member states; (ii) quality shortfalls that depress secondary material prices or restrict their use in high-specification applications; and (iii) slower-than-expected technology learning, which would limit cost and performance improvements. These risks are partially offset by clearer regulatory signals, improved data availability on product composition and design, and public procurement practices that accept certified secondary content.

#### Positioning relative to other scenarios

Compared with BAU, REC delivers higher recovery, lower landfilling, and better-quality secondary outputs through technology, standards, and organisation. In contrast with a full **circularity** pathway, REC places most of its leverage at end-of-life rather than at design and use; it moderates—but does not decouple—material demand. Consequently, import reliance is reduced only **partially**, and remains material for certain critical inputs.

### Scenario III: Circularity (CIR)

#### System trajectory and assumptions

CIR deploys waste prevention, ecodesign, reuse, repair, remanufacturing, and high-quality recycling to the maximum feasible extent, with the explicit aim of decoupling material services from primary resource extraction. The modelling approach combines **backcasting** for factors with binding targets and **forecasting** for factors without them, linking desired outcomes to present conditions and defining consistent pathways from now to 2050.

#### Material demand and supply (towards decoupling)

Relative to BAU and REC, total material throughput is moderated by upstream measures (design for longevity, sharing and service models) and higher 2RM use. 2RM recycling and recovery rates rise markedly; secondary materials gain wider acceptance in production as standards and data improve. Reliance on imports declines as domestic circular flows expand, although strategic procurement remains important in specific value chains. Renewable energy and cleaner process technologies are applied throughout 2RM production and use to support a low-carbon trajectory.

#### Waste management and recovery performance

End-of-life systems shift from volume handling to **quality-focused** recovery. Standardised collection, advanced sorting, and traceable feedstocks (e.g., product passports, waste tracking) raise output purity and value, enabling high-quality, loop-closing recycling. Reuse, repair, refurbishment, and remanufacture absorb a larger share of post-consumer inflows; residual fractions are more readily segregated and recovered at high efficiency. Investments prioritise design-compatible recovery, contamination control, and certification that unlock secondary inputs for high-specification applications.

#### Policy and governance

EU targets for recycling, recovery, ecodesign, and waste prevention are **met**, supported by stricter product-design guidelines, robust implementation, and monitoring. Regulatory instruments reward durability, reparability, standardisation, and disassembly; producer responsibility schemes are extended to drive high collection and take-back. Digital information requirements (e.g., product passports) become baseline practice across value chains, improving planning and verification. New business models—product–service systems, leasing, and take-back—scale and moderate traditional consumption patterns (geissdorfer2020circbusinessmodels). Fiscal reform complements regulation (e.g., shifting taxation from labour to resource depletion; flexible VAT rates for repair), while phasing out environmentally harmful subsidies. Member States implement EU measures and tailor complementary regional initiatives; international coordination supports alignment with broader commitments (un2015sdg).

#### Mechanisms of resource efficiency

CIR enhances resource efficiency via four complementary strategies:

1. **Narrowing** material flows through reduced or shared product use and improved manufacturing efficiency;
2. **Slowing** flows by extending product and component lifetimes via reuse, repair, refurbishment, and remanufacture;
3. **Closing** loops through high-quality recycling that reduces landfilling and incineration and lowers demand for primary inputs;
4. **Substituting** finite inputs with renewable or lower-impact alternatives where feasible.

#### Design, behaviour, and information

Re-X strategies are embedded from the design phase onward (repairability, remanufacturability, standardised components, easy disassembly) (Boulos et al., 2015; Pardo & Schweitzer, 2018; Singhal et al., 2020). Predictive maintenance and monitoring extend service life in sectors such as transport and manufacturing. Transparency tools—digital product passports and waste tracking—standardise information on composition, durability, and repairability, enabling efficient disassembly, reuse, and high-quality recycling, and fostering collaboration along value chains. Public awareness and education increase participation in repair, reuse, and service models, reinforcing demand for long-lived, upgradable products.

#### Environmental and socio-economic outcomes

CIR retains product, material, and resource value in the economy for longer while minimising waste generation, consistent with a sustainable, low-carbon, resource-efficient, and competitive EU economy. Anticipated effects include:

* **Economic:** greater resilience to resource scarcity and price volatility; emergence of efficient production and consumption models; new business opportunities; diversified employment in circular activities.
* **Environmental:** lower cumulative energy use and mitigation of irreversible ecological damages across climate, biodiversity, and pollution pressures.
* **Social:** broader participation in repair, reuse, and service models; enhanced inclusion via local circular enterprises and skills development.

#### Dependencies and enablers

Delivery depends on: (i) sustained investment in design-compatible recovery infrastructure and digital information systems; (ii) consistent enforcement of product-design and recovery standards; (iii) mature producer responsibility with verified performance; (iv) stable market pull for certified secondary content (including public procurement); and social/consumer engagement. These enablers reduce quality risk, improve economics for 2RMs, and support continued diffusion of circular practices.

#### Positioning relative to other scenarios

Compared with BAU, CIR achieves substantially higher recovery quality and volume **and** moderates demand via upstream design and behavioural levers. Compared with REC, CIR shifts the centre of gravity upstream—placing design, durability, and service models alongside end-of-life performance. The CIR scenario is, thereby, advancing from “recover more” to “use better and less,” with stronger progress towards decoupling economic growth from 1RM consumption.

# Discussion

#### What this study adds

This paper addresses a clear gap: while many scenario sets exist for energy and mobility, few centre on the waste-derived supply of raw materials and its implications for critical raw materials (CRMs). We contribute a transparent, EU27+4–focused scenario framework with three internally consistent storylines—Business as Usual (BAU), Recovery (REC), and Circularity (CIR)—that are explicitly grounded in waste-stream realities. The narratives integrate qualitative evidence (policies, technology trajectories, market drivers) with model-ready descriptors, creating a traceable bridge from storylines to subsequent parameterisation and quantitative modelling.

#### Interpreting the three storylines

BAU offers a predictive baseline of incremental change, useful as a reference for policy appraisal. REC is a normative pathway that concentrates on technology and infrastructure in collection, sorting, and processing to raise recovery performance and approach statutory targets for 2RMs relevant to CRMs. CIR is a normative/explorative pathway that layers demand-side and design-side levers—re-X strategies such as reduce, reuse, repair, remanufacture, recycle—on top of improved recovery, aiming to decouple material services from 1RM extraction. Taken together, the trio delineates a wide but decision-relevant envelope of futures for 2RM supply, enabling systematic testing of how policy and technology choices propagate through the resource-recovery system.

#### Policy relevance: focusing on controllable levers

A key design choice was to prioritise variables that decision-makers can influence (“policy knobs”), including: product design requirements (durability, reparability, standardisation), collection and sorting performance, recycling yields and quality, end-market development for 2RMs, and enabling governance (standards, reporting, extended producer responsibility). By structuring the scenarios around these levers, the narratives remain directly interpretable for regulators, industry, and investors and are well suited to downstream tools such as life cycle assessment and material flow analysis.

The authors considered adding explicit axes for supply-chain security and the pace of the energy transition. Both are highly salient for CRMs but proved problematic as core scenario dimensions. Credible trajectories for supply-chain security would require geopolitical forecasting beyond the evidence base and would inflate uncertainty and scenario count without commensurate insight. Similarly, varying the energy transition orthogonally to BAU/REC/CIR created internal inconsistencies (e.g., “low transition–high circularity” combinations) and a combinatorial expansion that diluted the focus on waste-system levers. Instead, these influences can be explored through targeted sensitivity analysis and optional module coupling. For example, exogenous supply constraints can be imposed in shock tests, and simplified price modules can probe how alternative 1RM–2RM price paths shape collection and processing responses. This approach preserves clarity and decision usefulness while acknowledging real-world volatility.

#### Strengths of the approach

Methodologically, three features strengthen credibility and transferability. First, we used marker-scenario mapping to align assumptions and highlight gaps relative to established scenario families, improving comparability. Second, cross-impact and multi-criteria checks were applied to test internal consistency and to reduce false-plausible combinations before narrative drafting. Third, structured expert elicitation (Delphi-style) and stakeholder workshops were used to challenge assumptions, surface disagreements, and converge on the most influential drivers. The result is a set of storylines that are both transparent—assumptions and rationales are documented—and practicable—parameters and projection years are specified to enable quantification.

#### Limitations and caveats

Several limitations merit attention. The geographical focus (EU27+4) supports policy relevance but constrains generalisability to other institutional contexts; transfer will require careful adaptation of drivers and policy instruments. The time horizon (2025–2050) and discrete projection years balance tractability and detail but cannot capture short-term shocks or continuous dynamics; we caution against over-interpreting mid-point values. Data gaps persist for some waste streams and sub-components (e.g., informal flows, secondary output quality), and expert judgement was necessary in places; while triangulated, expert elicitation carries bias risk. Finally, the present contribution covers narrative construction; full insight into performance trade-offs depends on subsequent parameterisation (Step 7) and quantitative modelling (Steps 8–9), which are outside this paper’s scope.

#### Implications for modelling and evidence needs

The narratives provide clear cues for model coupling. REC and CIR, in particular, specify parameter families (collection rates, sorting efficiencies, process yields, design shifts) and boundary conditions (policy targets, technology readiness) that can be translated into time paths and tested against constraints. Two priorities emerge: (i) systematic sensitivity analyses for supply constraints, price dynamics, and technology learning rates; and (ii) selective coupling to market and trade modules to capture feedbacks that materially affect 2RM uptake. Progress also depends on improving evidence for product composition, durability, and design trends, and on better quality metrics for secondary outputs—areas where targeted data collection would materially reduce uncertainty.

#### Outlook and use

We view the narratives as living artefacts. They can be updated as legislation, technology, and markets evolve, while preserving a consistent backbone for tracking change. Practically, the storylines support three near-term uses: (1) screening of policy packages for internal coherence (e.g., aligning design mandates with recovery infrastructure timelines); (2) investment planning for collection, sorting, and high-quality recycling capacity; and (3) prioritisation of R&D on recovery technologies and circular-design practices most consequential for CRM-relevant 2RMs. By keeping the scenarios centred on controllable levers and by documenting assumptions transparently, the framework aims to enable robust, evidence-informed decisions amid persistent uncertainty.

# Conclusions

This paper has developed three internally consistent narrative scenarios—Business as Usual (BAU), Recovery (REC), and Circularity (CIR)—to explore how waste management and recovery systems could shape the availability of secondary raw materials (2RMs) relevant to critical raw materials (CRMs) in the EU27+4 to 2050. The storylines integrate policy, technology, and market evidence with structured expert input, marker-scenario mapping, and cross-impact checks, yielding transparent, model-ready descriptors and projection years suitable for subsequent quantification.

A deliberate design choice was to centre the scenarios on levers that decision-makers can influence—product design and standards, collection and sorting performance, recycling yields and quality, and end-market development for 2RMs—rather than on highly exogenous axes. Proposed dimensions such as supply-chain security and the pace of the energy transition were therefore not adopted as core axes; instead, they will be addressed through sensitivity analysis and optional coupling to market/trade and optimisation modules. This preserves interpretability while acknowledging genuine sources of volatility.

The narratives now provide a concrete basis for parameterisation and for the development and testing of quantitative models. Priority tasks include (i) translating storyline cues into time paths for collection, sorting, process efficiency, and design shifts; (ii) systematic sensitivity tests for supply constraints and 1RM–2RM price dynamics; and (iii) targeted data improvements on product composition, durability, and secondary-output quality.

While results are scoped to the EU27+4 and a 2025–2050 horizon, the framework is transferable with appropriate localisation. By focusing on controllable levers and documenting assumptions clearly, the scenarios are intended to support evidence-informed policy and investment decisions under deep uncertainty.

# Supplementary Material

The supplementary material supplied in the appendices of this manuscript contain the following sections:

1. Terminology definitions
2. Scenario development methods
3. Overview of relevant policy instruments
4. Overview of marker scenarios
5. Scenario elements identified the initial collection phase
6. Drivers and factors identified in the screening phase
7. Waste-stream-specific scenario impacts

# Data availability

All publicly available data related to the development of the scenarios and the composition of this manuscript is available in online repositories hosted by Zenodo (https://doi.org/10.5281/zenodo.16995460) and Github (<https://github.com/Stew-McD/T-reX_LCA-MacroStudy>)

# Acknowledgements

This research project was financially supported by the European Union’s Horizon 2020 research and innovation programme under the grant agreement No. 101058522 (project FutuRaM — [futuram.eu](https://futuram.eu/)). The authors would like to thank the reviewers for their valuable comments and suggestions.

# CRediT authorship contribution statement

**Stewart Charles McDowall:** Conceptualisation, Methodology, Investigation, Data curation, Formal analysis, Validation, Visualisation, Writing: original draft, Writing: review & editing, Visualisation.

**Carlos Felipe Blanco:** Conceptualisation, Methodology, Validation, Writing: review & editing, Funding acquisition, Supervision.

**Stefano Cucurachi:** Conceptualisation, Methodology, Validation, Writing: review & editing, Funding acquisition, Supervision.

Figure 4: CRediT authorship visualisation

# Declarations

**Competing interests**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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**Use of artificial intelligence**

The authors declare that no generative artificial intelligence tools were used in the generation of the research data or results reported in this paper. Generative AI was used solely to assist in the editing and refinement of the manuscript text, with all content reviewed and approved by the authors.

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# Appendices

## Terminology definitions

Table A1. To promote clarity in the scenario development process, the following set of terminology was defined for use in discussions, reports, and other stakeholder interactions. This glossary was modelled on that of Skea (2021), with additional definitions sourced from Arizona (2023).

| Term | Meaning | Context level | Also called | Source |
| --- | --- | --- | --- | --- |
| Scenario | An outline or model of an expected or supposed sequence of events. Plausible descriptions of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces. Plausible futures of a system under different conditions; “scenario’” as a “hypothetical sequence of events constructed for the purpose of focusing attention on causal processes and decision points. | Highest level | Pathway, future typology | Arizona, 2023 |
| Normative scenario | Goal-oriented scenario: identify decisions and investments that must be made to achieve desired future outcomes. Example: Constraining cumulative emissions. | Scenario type | Backcasting | Skea, 2021 |
| Exploratory scenario | Exploration of plausible alternative developments to test whether decision-making is robust against different outcomes. Generally, involving a qualitative storyline about a possible future, complemented by quantitative analysis. Example: Socio-economic scenarios. | Scenario type | Plausible scenarios | Skea, 2021 |
| Outlook | To provide a most likely estimate of future trends as a guide for decision-making. | Scenario type | Forecast, projection | Skea, 2021 |
| Scenario characteristics | A combination of the vague attributes that make up the qualitative storyline for a scenario.  For example, in WEC (2019) the scenario titled Modern Jazz is described as: “A market-led, digitally disrupted world with faster-paced and more uneven economic growth. Recent signals suggest that this entrepreneurial future might accelerate clean energy access on both global and local scales, whilst presenting new systems’ integration, cybersecurity, and data privacy challenges”. | Scenario description | Qualitative storyline descriptors | Skea, 2021 |
| Scenario scale | Description of the spatial extent or temporal extent of a scenario. For us, mostly EU toward 2050. | Scenario component |  | Arizona, 2023 |
| Scenario dimensions | Uncertainties around which scenarios are constructed, represented as axes in some methods. In our case they might end up being, level of circularity, free-trade/autarky, progress in energy transition. | Scenario component |  | Arizona, 2023 |
| Scenario literature | Journal articles, grey literature, etc., from which data is sourced that can be used to justify decisions in scenario development. | Scenario component |  | Skea, 2021 |
| Scenario logics | Methods for structuring the relationships between different drivers and assumptions in scenarios | Scenario component |  | Arizona, 2023 |
| Time horizon | End date of the scenario’s forecast | Scenario attribute |  | Skea, 2021 |
| Snapshot | The position of scenario/s at a particular point of time | Scenario attribute |  | Skea, 2021 |
| Storyline and simulation | Combination of qualitative narrative development and quantitative modelling | Scenario component |  | Arizona, 2023 |
| Marker scenario | Generally, a widely accepted scenario which can be used a guide or to provide background information. E.g., SSP1-5, and the GEC models from the IEA. If applicable, these can be extended upon or combined to help build our models. | Scenario description | Basis scenario | Skea, 2021 |
| SSP | Shared Social Pathways. They “describe plausible major global developments that together would lead in the future to different challenges for mitigation and adaptation to climate change. The SSPs are based on five narratives describing alternative socio-economic developments, including sustainable development, regional rivalry, inequality, fossil-fuelled development, and middle-of-the-road development. The long-term demographic and economic projections of the SSPs depict a wide uncertainty range consistent with the scenario literature.” | Marker scenario examples |  | (Intergovernmental Panel on Climate Change (IPCC), 2022) |
| Drivers | Underlying causes of system change that are external from the system of analysis. They come from higher scales and are not affected by what happens within the system. | Scenario component | Factors | Arizona, 2023 |
| Factors | Causes of system change that are internal from the system of analysis. Can be (hopefully) quantified, or at least estimated | Scenario component (internal) |  | Skea, 2021 |
| Factor variables | Discrete elements which are subject to change and have effects on one or more factors | Factor component |  | Skea, 2021 |
| Factor parameters | Discrete elements which are NOT subject to change (possibly based on assumptions and simplifications) and have effects on one or more factors | Factor component |  | Skea, 2021 |
| Trends | An inclination in a particular direction | Attribute of drivers or factors | System development | Skea, 2021 |
| Likelihood | The likelihood of an occurrence, an outcome, or a result, where this can be estimated probabilistically | Attribute of drivers or factors | Probability | Arizona, 2023 |
| Virtually certain | >99/% probability of occurrence | Attribute of drivers or factors | Probability | Arizona, 2023 |
| Very likely | >90% | Attribute of drivers or factors | Probability | Arizona, 2023 |
| Likely | >66% | Attribute of drivers or factors | Probability | Arizona, 2023 |
| More likely than not | >50% | Attribute of drivers or factors | Probability | Arizona, 2023 |
| About as likely as not | 33–66% | Attribute of drivers or factors | Probability | Arizona, 2023 |
| Unlikely | <33% | Attribute of drivers or factors | Probability | Arizona, 2023 |
| Very unlikely | <10% | Attribute of drivers or factors | Probability | Arizona, 2023 |
| Exceptionally unlikely | <1% | Attribute of drivers or factors | Probability | Arizona, 2023 |

## Scenario development methods

Table A2. A summary of the methods and tools considered, including a brief description of each and its relevance to the specific context and objectives of the FutuRaM scenario development process.

| Method | Description | Key Characteristics |
| --- | --- | --- |
| Delphi | Structured expert consultation to gather and distil knowledge and judgments | Iterative rounds of surveys/questionnaires, Expert consensus building |
| MCA | Decision-support technique to evaluate and rank scenarios based on criteria | Consideration of multiple dimensions in quantifying qualitative factors |
| Forecasting | Use of historical data and statistical methods to predict future trends | Reliance on quantitative models, Time series analysis |
| Backcasting | Working backward from a desired future vision to identify necessary steps | Focus on desired outcomes and future targets, Identification of necessary actions |
| Scenario Planning | Development of multiple future scenarios to understand the range of possibilities | Identification of key drivers and uncertainties, Narrative construction for each scenario |
| Morphological Analysis | Exploration of different combinations of variables/factors | Matrix-based exploration of variables and combinations |
| Cross-Impact Analysis | Analysis of interdependencies and interactions between variables/factors | Identification of relationships and cross-impacts |
| Morphological Box | Systematic exploration of the potential combinations of different components | Identification of component options and combinations |
| Gausemeier approach | A scenario development method involving the identification of future developments, evaluation of influencing factors, and determination of desired and undesired developments | Systematic analysis of future developments and factors |
| Schwartz' 8-Step Scenario Model | Scenario building model consisting of eight steps: identify the focal issue, determine the key forces, construct the scenario framework, identify driving forces, assess the uncertainties, develop the scenarios, analyse the scenarios, and monitor and adjust the scenarios | Systematic progression through stages of scenario development |
| Schoemaker's 10-Step Scenario Model | Scenario building model consisting of ten steps: identify the focal issue, determine the scope, identify the key driving forces, develop the scenarios, define the scenario logic, assess the scenarios, refine the scenarios, examine implications, formulate actions, and communicate results | Emphasis on thorough analysis and evaluation of scenarios |

## Overview of relevant policy documents

Table A3. An overview of policy actions identified as relevant to the future supply of secondary raw materials (2RMs) in the EU

| Policy | Country | Year | Status | Jurisdiction |
| --- | --- | --- | --- | --- |
| EU Directive 2006/66/EC Battery Directive | EU | 2006 | In force | International |
| Royal Decree 975/2009 about environmental protection and extractive industries | Spain | 2009 | In force | National |
| Finland’s Minerals Strategy | Finland | 2010 | In force | National |
| Resource Security Action Plan | UK | 2012 | In force | National |
| Supply of Mineral Resources (SoS MinErals) | UK | 2012 | In force | National |
| Horizon 2020: Climate action, environment resource efficiency, and raw materials | EU | 2013 | Ended | International |
| National Strategy for Energy Research | France | 2016 | In force | National |
| European Battery Alliance | EU | 2017 | In force | National |
| Resources for France Plan | France | 2018 | In force | National |
| Battery fund: 3.2 billion euros for research and innovation | EU | 2019 | In force | International |
| EU Sustainable Batteries Regulation | EU | 2020 | Announced | Regional |
| Green Deal: Circular Economy Action Plan | EU | 2020 | In force | International |
| Circular Economy Action Plan | Spain | 2021 | In force | National |
| Horizon Europe Strategic Plan (2021 – 2024) | EU | 2021 | In force | International |
| National Battery Strategy 2025 | Finland | 2021 | In force | National |
| National Planning Policy Framework | UK | 2021 | In force | National |
| Minerals Security Partnership | EU | 2022 | Announced | International |
| Resilience for the future: The UK's critical minerals strategy | UK | 2022 | In force | National |
| European Institute of Innovation and Technology: Raw Materials Project Call | EU | 2023 | Announced | International |

## Overview of marker scenarios

Table A4. An overview of marker scenarios identified as relevant to the future supply of secondary raw materials (2RMs) in the EU

| Literature | Type | Waste Stream | Temporal Coverage | Location | Number of scenarios | Link |
| --- | --- | --- | --- | --- | --- | --- |
| The Shared Socioeconomic Pathways (SSPs) and their energy, land use, and greenhouse gas emissions implications: An overview | Academic | All | Scenario to 2100 | Global | 5 SSPs | [∞](https://www.sciencedirect.com/science/article/pii/S0959378016300681) |
| Environmental Impacts of Global Offshore Wind Energy Development until 2040 | Academic | CDW | Scenario: 2019–2040 | Global | 4 (based on IEA) | [∞](https://pubs.acs.org/doi/full/10.1021/acs.est.2c02183) |
| Global greenhouse gas emissions from residential and commercial building materials and mitigation strategies to 2060 | Academic | CDW | Scenario: 2020–2060 | Global | 2 (based on SSP2) | [∞](https://www.nature.com/articles/s41467-021-26212-z) |
| Modelling global material stocks and flows for residential and service sector buildings towards 2050 | Academic | CDW | Scenario: 2020–2060 | Global | 1 (SSP2) | [∞](https://www.sciencedirect.com/science/article/abs/pii/S0959652619335280) |
| The evolution and future perspectives of energy intensity in the global building sector 1971–2060 | Academic | CDW | Scenario: 2020–2060 | Global | 1 (SSP2) | [∞](https://www.sciencedirect.com/science/article/pii/S0959652621013172) |
| Tracking Construction Material over Space and Time Prospective and Geo-referenced modelling of Building Stocks and Construction Material Flows | Academic | CDW | Scenario to 2060 | Global | 6 | [∞](https://onlinelibrary.wiley.com/doi/full/10.1111/jiec.12739) |
| Global construction materials database and stock analysis of residential buildings between 1970–2050 | Academic | CDW | Scenario to 2060 | Global | 1 (SSP2) | [∞](https://www.sciencedirect.com/science/article/abs/pii/S0959652619340168) |
| A comprehensive set of global scenarios of housing, mobility, and material efficiency for material cycles and energy systems modelling | Academic | CDW | Scenario to 2060 | Global | Low energy demand, SSP1, SSP2 | [∞](https://onlinelibrary.wiley.com/doi/full/10.1111/jiec.13122) |
| Global scenarios of resource and emission savings from material efficiency in residential buildings and cars | Academic | CDW, ELV | Scenarios to 2050 | Global | SSP1, SSP2 | [∞](https://www.nature.com/articles/s41467-021-25300-4) |
| Matching global cobalt demand under different scenarios for co-production and mining attractiveness | Academic | BAT | 2050 | Global | 5 | [∞](https://link.springer.com/content/pdf/10.1186/s40008-016-0035-x.pdf) |
| Copper at the crossroads: Assessment of the interactions between low-carbon energy transition and supply limitations | Academic | Copper | 2050 | Global | 2: 2 °C and 4 °C | [∞](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7391239/pdf/main.pdf) |
| The impact of climate policy implementation on lithium, cobalt and nickel demand: The case of the Dutch automotive sector up to 2040 | Academic | ELV, Batteries | Scenario: 2019–2040 | NL | 2 (Based on policies) | [∞](https://www.sciencedirect.com/science/article/pii/S0301420721003603) |
| The rise of electric vehicles—2020 status and future expectations | Academic | ELV, BAT | up to 2050 | Global | various | [∞](https://iopscience.iop.org/article/10.1088/2516-1083/) |
| Scenarios for the Return of Lithium-ion Batteries out of Electric Cars for Recycling | Academic | ELV, Battery | Scenario to 2050 | Global | 2 | [∞](https://www.sciencedirect.com/science/article/pii/S2212827115004849) |
| The dynamic equilibrium mechanism of regional lithium flow for transportation electrification | Academic | ELV, BAT | Scenario to 2050 | Global | 1 (projection) | [∞](https://pubs.acs.org/doi/10.1021/acs.est.8b04288) |
| Future material demand for automotive lithium-based batteries | Academic | ELV, BAT | Scenario to 2050 | Global | 4 (based on IEA) | [∞](https://www.nature.com/articles/s43246-020-00095-x) |
| Analysis of the Li-ion battery industry in light of the global transition to electric passenger light-duty vehicles until 2050 | Academic | ELV, BAT | Scenario to 2050 | Global | Combination of SSPs and RCPs | [∞](https://iopscience.iop.org/article/10.1088/2634-4505/ac49a0) |
| Circular economy strategies for electric vehicle batteries reduce reliance on raw materials | Academic | ELV, BAT | Scenario to 2050 | Global | Reference + 4 technologies | [∞](https://www.nature.com/articles/s41893-020-00607-0) |
| Summary and critical review of the International Energy Agency’s special report: The role of critical minerals in clean energy transitions | Academic | Energy | 2050 | Global | n/a | [∞](https://zaguan.unizar.es/record/107468/files/texto_completo.pdf) |
| Review of critical metal dynamics to 2050 for 48 elements | Academic | Energy | Scenario to 2050 | Global | 1 compiled from various renewable technologies | [∞](https://www.sciencedirect.com/science/article/pii/S0921344919305750) |
| Major metals demand, supply, and environmental impacts to 2100: A critical review | Academic | Energy | Scenario to 2100 | Global | 1 review of 197 studies | [∞](https://www.sciencedirect.com/science/article/pii/S0921344920304249) |
| Requirements for Minerals and Metals for 100% Renewable Scenarios | Academic | Energy | Scenario to 2050 | Global | 1.5 degree scenario | [∞](https://link.springer.com/chapter/10.1007/978-3-030-05843-2_11) |
| The 3-machines energy transition model: Exploring the energy frontiers for restoring a habitable climate | Academic | Energy | 2100 | Global | 20, rapid transition stabler 1.5 °C and return to 350 ppm | [∞](http://www.doi.org/10.1029/2022ef002875) |
| Modelling the demand and access of mineral resources in a changing world | Academic | Energy, Construction | 2060 | Global | RTS, BD2S IEA | [∞](https://hal.archives-ouvertes.fr/hal-03426225/document) |
| Rare earths in the energy transition: what threats are there for the ‘vitamins of modern society’? | Academic | Rare earths | 2050 | Global | 2: 2°C and 4°C | [∞](https://www.ifpenergiesnouvelles.com/article/les-terres-rares-transition-energetique-quelles-menaces-les-vitamines-lere-moderne) |
| A slag prediction model in an electric arc furnace process for special steel production | Academic | SLASH | None | Global | n/a | [∞](https://www.sciencedirect.com/science/article/pii/S2351978921001633) |
| Decarbonising the iron and steel sector for a 2°C target using inherent waste streams | Academic | SLASH | Scenario to 2050 | Global | 1 (2 degree climate goal) | [∞](https://www.nature.com/articles/s41467-021-27770-y) |
| Environmental Implications of Future Demand Scenarios for Metals: Methodology and Application to the Case of Seven Major Metals | Academic | Various | Scenario to 2050 | Global | 4 (UN GEO-4) | [∞](https://onlinelibrary.wiley.com/doi/10.1111/jiec.12722) |
| Resource Demand Scenarios for the Major Metals | Academic | Various | Scenario to 2050 | Global | 4 (UN GEO-4) | [∞](https://pubs.acs.org/doi/10.1021/acs.est.7b05154) |
| Raw material depletion and scenario assessment in European Union – A circular economy approach | Academic | Various | None | EU | n/a | [∞](https://www.sciencedirect.com/science/article/pii/S2352484719306031) |
| Material bottlenecks in the future development of green technologies | Academic | Various | Scenario to 2050 | Global | 1 (BAU) | [∞](https://www.sciencedirect.com/science/article/abs/pii/S1364032118303861) |
| Reuse assessment of WEEE: Systematic review of emerging themes and research directions | Academic | WEEE | None | Global | n/a | [∞](https://www.sciencedirect.com/science/article/pii/S0301479721003972) |
| A systematic literature review on the circular economy initiatives in the European Union | Academic | Circularity | None | EU | Circular strategies | [∞](https://www.sciencedirect.com/science/article/abs/pii/S2352550920302232) |
| Material Flow Accounting: Measuring Global Material Use for Sustainable Development | Academic | Various | Scenario to 2100 | Global | 1 (BAU) | [∞](https://www.annualreviews.org/doi/10.1146/annurev-environ-102016-060726) |
| Circular Economy Action Plan | Action plan | Various | Scenario to 2050 | EU | 35 actions to climate neutrality | [∞](https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en) |
| Construction and demolition waste: challenges and opportunities in a circular economy | Report | CDW | None | EU | n/a | [∞](https://www.eea.europa.eu/publications/construction-and-demolition-waste-challenges) |
| IEA world energy model | Report | Energy | Scenario to 2050 | Global | 4 | [∞](https://www.iea.org/reports/world-energy-model/understanding-weo-scenarios) |
| Bloomberg scenarios | Report | Energy | Scenario to 2050 | Global | 3 | [∞](https://about.bnef.com/new-energy-outlook/) |
| The Role of Critical Minerals in Clean Energy Transitions | Report | Energy | None | Global | n/a | [∞](https://iea.blob.core.windows.net/assets/ffd2a83b-8c30-4e9d-980a-52b6d9a86fdc/TheRoleofCriticalMineralsinCleanEnergyTransitions.pdf) |
| Transitions to 2050 decide now act for climate | Report | Energy | Scenario to 2050 | France | 4 to reach 2.1C by 2100 | [∞](https://transitions2050.ademe.fr/en) |
| Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system | Report | Energy | Scenario to 2050 | EU | low and high material demand scenarios | [∞](https://op.europa.eu/en/publication-detail/-/publication/19aae047-7f88-11ea-aea8-01aa75ed71a1/language-en) |
| Inventaires des besoins en matière, énergie, eau et sols des technologies de la transition énergétique | Report | Energy | Scenario to 2050 | France | 1 | [∞](https://librairie.ademe.fr/energies-renouvelables-reseaux-et-stockage/4654-surfer.html) |
| Minerals in the future of Europe | Report | MinW | Scenario to 2050 | EU | 3 (2050 net-zero, digital, circular) | [∞](https://publications.europa.eu/en/publication-detail/-/publication/9dbd3b04-ae4d-11eb-bb1a-01aa75ed71a1) |
| Minerals, Critical Minerals and the US Economy | Report | MinW | None | US | n/a | [∞](https://www.usgs.gov/blogs/natural-resources-snapshot/minerals-critical-minerals-and-us-economy) |
| Minéraux stratégiques — État des lieux et propositions pour une vision partagée | Report | MinW | None | FR | n/a | [∞](https://www.entreprises.gouv.fr/secteurs-professionnels/strategie-mineraux-critiques) |
| The Critical Raw Materials (CRM) initiative – Underpinning the strategic approach to the EU’s raw materials policy | Report | MinW | None | EU | n/a | [∞](https://op.europa.eu/en/publication-detail/-/publication/9e0f3d9e-ecf5-11ea-ad08-01aa75ed71a1/language-en) |
| Towards the Circular Economy: Accelerating the scale-up across global supply chains | Report | Circularity | None | Global | n/a | [∞](http://www3.weforum.org/docs/WEF_Towards_the_Circular_Economy_Report_2020.pdf) |
| The Circular Economy in Europe | Report | Circularity | None | EU | n/a | [∞](https://ec.europa.eu/environment/circular-economy/index_en.htm) |
| Global material flows and resource productivity: Forty years of evidence | Report | Circularity | None | Global | n/a | [∞](https://www.unenvironment.org/resources/report/global-material-flows-and-resource-productivity) |
| The circular economy concept: contextualisation and multiple perspectives | Report | Circularity | None | Global | n/a | [∞](https://www.nature.com/articles/s41599-019-0272-1) |
| Global material flows database | Database | Various | None | Global | n/a | [∞](https://resources.metabolismofcities.org/) |
| International Resource Panel | Reports | Various | None | Global | n/a | [∞](https://www.resourcepanel.org/) |
| World Business Council for Sustainable Development | Reports | Various | None | Global | n/a | [∞](https://www.wbcsd.org/) |
| Ellen MacArthur Foundation | Reports | Various | None | Global | n/a | [∞](https://www.ellenmacarthurfoundation.org/) |
| European Environment Agency | Reports | Various | None | EU | n/a | [∞](https://www.eea.europa.eu/) |
| International Energy Agency | Reports | Energy | None | Global | n/a | [∞](https://www.iea.org/) |
| United Nations Environment Programme | Reports | Various | None | Global | n/a | [∞](https://www.unenvironment.org/) |
| United Nations Industrial Development Reports | Reports | Various | None | Global | n/a | [∞](https://www.unido.org/) |
| World Bank | Reports | Various | None | Global | n/a | [∞](https://www.worldbank.org/) |
| World Economic Forum | Reports | Various | None | Global | n/a | [∞](https://www.weforum.org/) |

## Scenario elements identified in the initial collection phase

Table A5. A list of scenario elements identified in the initial phase of driver/factor collection by FutuRaM stakeholders

| Driver | Definition |
| --- | --- |
| Accessibility | Ease of access to goods, services, or infrastructure |
| Accessibility/Infrastructure | Availability and adequacy of infrastructure to support accessibility |
| Availability of recovery technologies | Existence and accessibility of technologies for material recovery |
| Change of products in the scope WEEE directive | Inclusion or exclusion of certain products within the scope of the WEEE directive |
| Climate change impacts (flooding, etc.) | Consequences of climate change, such as increased flooding or extreme events |
| Climate change mitigation efforts | Actions taken to reduce greenhouse gas emissions and combat climate change |
| CO2 market | Trading system for carbon emissions permits or credits |
| Compliance with rules | Adherence to regulations, guidelines, or standards |
| Composition change | Alteration or modification of the composition of materials or products |
| Conflict in supply chain | Disputes or conflicts within the supply chain of raw materials or products |
| Corruption | Dishonest or unethical behaviour, typically involving misuse of power |
| Cultural values / Consciousness | Beliefs, attitudes, and awareness of individuals and society |
| Data protection | Safeguarding personal data and ensuring privacy |
| Digital product passports | Digital documentation providing information about a product's lifecycle |
| Digitalization | Integration and adoption of digital technologies and processes |
| Ecodesign | Designing products with consideration for their environmental impact |
| Education level | Level of education attained by individuals or the overall population |
| Electricity price | Cost of electricity for consumers or businesses |
| Employment rates | Percentage of the working-age population that is employed |
| Energy efficiency of buildings | Performance and efficiency of energy consumption in buildings |
| Exchange rates | Value of one currency relative to another currency |
| Gasoline/petrol price | Cost of gasoline/petrol for vehicles |
| GDP/PPP | Gross Domestic Product (GDP) adjusted for purchasing power parity (PPP) |
| Improved durability | Enhanced longevity and resistance of products or materials |
| Improved recyclability | Increased ability of products or materials to be recycled or reused |
| Improved repairability | Enhanced ability to repair and maintain products or equipment |
| Increased intrinsic drive for environmental protection | Growing internal motivation to protect and conserve the environment |
| Industrialization of Europe | Development and growth of industrial activities in European countries |
| Inflation | Increase in the general price level of goods and services over time |
| Infrastructure | Physical structures and facilities necessary for the functioning of society |
| Intellectual property issues | Legal rights and protections for intellectual creations and innovations |
| Interest rates | Cost of borrowing money or the return on investment |
| Land rights | Legal rights to ownership, use, or access to land |
| Material efficiency | Effective use and management of materials to minimize waste and loss |
| Miniaturization | Process of making products or components smaller and more compact |
| New mines in rich EU countries? | Establishment of new mines in economically prosperous European countries |
| NIMBY to projects | Not-In-My-Backyard opposition to the location of certain projects |
| Obligatory recycling standards for treatment facilities | Mandatory standards for recycling processes in treatment facilities |
| Obligatory removal of CRMs from waste | Required removal or extraction of critical raw materials from waste streams |
| Obsolescence | State of being outdated or no longer in use or demand |
| Population | Total number of people in a given area or region |
| Product prices | Prices of goods or products in the market |
| Raw material prices | Prices of primary materials used in production processes |
| Recyclability mandates | Requirements or regulations promoting the recyclability of products |
| Reduced consumerism | Shift towards decreased consumption and a more sustainable lifestyle |
| Redundancy | Availability of backup systems or alternative options |
| Renewable energy targets | Set goals or objectives for increasing the use of renewable energy sources |
| Repairability mandates | Requirements or regulations promoting the repairability of products |
| Resource shortage | Insufficient availability or scarcity of natural resources |
| Sharing economy | Economic system based on sharing resources and services |
| 2RM prices | Prices of secondary raw materials or recycled materials |
| Stricter environmental regulations | Increased regulations and policies aimed at reducing environmental impact |
| Subsidies | Financial support or incentives provided by governments or organizations |
| Supply chain due diligence laws | Regulations or laws requiring companies to assess and manage supply chain risks |
| Target enforcement | Implementation and enforcement of specific targets or goals |
| Taxation (raw materials, landfill) | Imposition of taxes on raw materials or landfill activities |
| Trade barriers | Barriers or restrictions to international trade or commerce |
| Transparency | Openness, accountability, and information accessibility |
| Treatment cost | Cost of waste treatment, disposal, or recycling processes |
| Urbanisation | Increase in the population living in urban areas |
| Volunteering | Engagement in unpaid activities for the benefit of others |
| Water supply constraints | Limitations on the availability or access to freshwater resources |
| Work-life balance | Equilibrium between work and personal life |

## Scenario drivers and factors categorised for quantification in subsequent modelling

Table A6. A list of the scenario elements categorised for quantification. The Roman numerals in the columns BAU, REC, and CIR represent the magnitude of the future trend for the element in the scenario. Internal, external, and outside refer to the classification type of the scenario element.

| Domain | Element | Internal | External | Outside | BAU | REC | CIR | Model Parameters Affected |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Economic | Subsidies and taxation to promote circular strategies | ✔ |  |  | I | I | III | Demand, waste generation, lifetimes, sharing, collection, |
| Political | Targets and enforcement to promote circular strategies | ✔ |  |  | I | I | III | Demand, waste generation, lifetimes, sharing, collection |
| Society | Participation in re-X activities | ✔ |  |  | I | I | III | Demand, waste generation, lifetimes, sharing, collection, |
| Economic | Subsidies and taxation to promote recovery strategies | ✔ |  |  | I | III | I | Recycling rates, recovery capacity, recovery impacts, collection |
| Political | Targets and enforcement to promote recovery strategies | ✔ |  |  | I | III | I | Recycling rates, recovery rates, capacity |
| Political | Supply chain due diligence laws | ✔ |  |  | I | III | III | Composition, export |
| Political | Stricter environmental regulations | ✔ |  |  | I | III | III | Composition, waste generation, lifetimes, export, recovery rates, recovery capacity, recovery impacts |
| Political | Stricter waste management regulations | ✔ |  |  | I | III | III | Composition, waste generation, lifetimes, export, recovery rates, recovery capacity, recovery impacts |
| Technology | Product technology | ✔ |  |  | I | III | III | Lifetimes, recovery rates, recovery impacts |
| Technology | Recovery technology | ✔ |  |  | I | III | III | Recovery rates, recovery capacity, recovery impacts |
| Technology | Integration of 2RM recovery system across Europe | ✔ |  |  | I | III | III | Recycling rates, recovery rates, recovery capacity, recovery impacts |
| Economic | Progress toward renewable energy targets |  | ✔ |  | stable | stable | stable | Composition, demand, waste generation, recovery impacts |
| Economic | Economic growth |  | ✔ |  | stable | stable | stable | Composition, demand, waste generation |
| Society | Population |  | ✔ |  | stable | stable | stable | Demand, waste generation |
| Economic | Primary vs. secondary raw material prices |  | ✔ |  | n/a | n/a | n/a | Considered in sensitivity analysis |
| Economic | Energy prices |  | ✔ |  | n/a | n/a | n/a | Considered in sensitivity analysis |
| Economic | Carbon price |  | ✔ |  | n/a | n/a | n/a | Considered in sensitivity analysis |
| Environment | Resource supply constraints |  | ✔ |  | n/a | n/a | n/a | Considered in sensitivity analysis: |
| Economic | International trade and co-operation (vs. autarky) |  |  | ✔ | n/a | n/a | n/a | Not model input (resource supply constraints is a proxy) |
| Economic | Re-industrialisation of EU |  |  | ✔ | n/a | n/a | n/a | Not model input |
| Society | Resistance to recovery projects (NIMBY) |  |  | ✔ | n/a | n/a | n/a | Not model input (considered in NFC assessments) |

## Waste-stream-specific scenario impacts

### Scenario I: Business-as-usual (BAU)

#### Batteries (BATT)

In the BAU scenario, the management of end-of-life batteries remains largely unchanged. The lack of technological innovation and regulatory incentives leads to continued low recovery rates of valuable materials from battery waste.

* A growing volume of battery waste due to the increased use of electronic transport and renewable energy storage systems.
* Lack of technological innovation and regulatory incentives lead to low recovery rates for certain battery types and certain elements.
* Collection systems for battery waste remain sporadic and unstandardised.
* Primary extraction remains the dominant source of battery materials.
* Share of LIB will increase (EV, LMT, Industrial LIB uptake).
* LIB battery chemistries will change, and new LIB technologies will enter the market, though not with a focus on recycling and recovery.
* Larger portable batteries: shift towards lithium-ion batteries.
* Small format batteries in EEE: no significant change in battery chemistry.
* Use of critical resources continues but is already decreasing (BATT chemistry already changing towards less CRM content).
* Large-scale reuse of batteries is minimal.
* Collection rates do not fulfil the EU targets.
* Recycling efficiencies do not fulfil the EU targets.
* Recovery rates do not fulfil the EU targets.

#### End-of-life Vehicles (ELV)

The BAU scenario maintains the current approach to end-of-life vehicles, with minimal improvements in the recovery and recycling process. The absence of effective technologies and regulatory incentives results in low recovery rates of valuable materials from ELVs.

* Legislation banning new internal combustion engine vehicles from 2035.
* Current recovery technologies are unable to significantly improve the extraction of valuable materials from ELVs.
* Consumer demand continues to drive high production of new vehicles.
* ELV collection systems remain at their current efficiency.
* A significant proportion of vehicle components continue to end up as waste.
* Gradual and slow improvement of recycling chain technology efficiency.
* No new legislation to improve recovery and support circular strategies compared to 2023.

#### Waste Electrical and Electronic Equipment (WEEE)

In the BAU scenario, the treatment of WEEE does not significantly change. The lack of technological progress and effective regulation results in low recovery rates of valuable materials from WEEE.

* Limited improvements in the recovery of valuable materials from WEEE.
* High consumer demand for new electronics continues to drive high WEEE generation.
* Ineffective collection systems and lack of public interest result in significant amounts of WEEE ending up in landfills.
* No significant growth in collaboration between government and industry for WEEE recovery.
* The majority of WEEE continues to be treated with common domestic waste, with low recycling rates.
* No groundbreaking technologies and practices to improve recovery and circularity.
* Reuse of products and components is not widely utilised.
* Changes in legislation (e.g., circular economy and product design targets, targets for collection and recycling) are not strictly implemented.
* The BAU and REC scenarios are similar from the put-on-market perspective (production and consumption remain the same), but the recovery stage makes the difference.

#### Mining Waste (MIN)

The BAU scenario sees the continuation of current practices in mining waste management. The absence of advanced recovery technologies and regulatory incentives leads to low recovery rates of valuable materials from mining waste.

* Limited technological advancements lead to static recovery rates of valuable materials from mining waste.
* Continued reliance on primary extraction as the dominant source of raw materials.
* Minimal advances in collaboration between government and industry for mining waste recovery.
* Low levels of traceability and management of mining waste.
* Mining waste remains a significant environmental challenge.
* Mining waste recovery projects remain too expensive.
* Little incentive for the private sector and public sector, except for monitoring environmental risks of existing deposits.

#### Construction and Demolition Waste (CDW)

In the BAU scenario, the management of CDW remains largely unchanged.

* Focus on new construction to meet demand, no changes in CDW generation rate.
* No increase in refurbishment or renovation activities relative to new construction rates.
* Continue meeting the 2020 EU target from the Waste Directive of 70% CDW recovery (including preparation for re-use, recycling, and other material recovery, including backfilling).
* Recovery of metals remains at already high levels (>90%).
* Recovery of minerals remains at already high levels (>70%) by using them as aggregates in road construction and backfilling.
* Recycling of wind turbines stays around 85% (mainly metals); permanent magnets continue to be recycled as part of the metal fractions.
* Base metals are recovered as before, with limited improvements in recovery technologies and regulatory incentives.
* Repowering trends for wind turbines persist.
* Excluding wind turbines, there is no particular focus on the recovery of CRMs from CDW, where they constitute only a small fraction of the total mass (e.g., embedded in scrap steel).

#### Slags, Ashes, and Other Residues (SLASH)

In the BAU scenario, SLASH continues to be treated as low- or negative-value waste. The absence of economically profitable recovery technologies or regulatory mandates leads to low improvements in the recovery rates of CRMs from SLASH.

**Slags**

Slags are waste products from the metallurgical industry, containing mainly minerals with some metals that could not be recovered during the metallurgical process. Reasons for non-recovery include:

1. Current technology does not allow further recovery.
2. The metals are not of economic interest.

* More than 90% of slags are minerals; slags that meet environmental criteria (end-of-waste criteria) are valorised as aggregates for the construction industry or as SCM (cement replacement materials).
* Slags containing high concentrations of heavy metals are landfilled.
* The volume of slags will stay stable. From 2013 to 2023, metal production was stable, resulting in stable slag production.
* Due to the energy transition, slags from “classic” furnaces will decrease, while slags from electric arc furnaces will increase.
* Limited facilities exist to recover CRMs/2RMs; metallurgical companies recover as much metal as is economically viable.

**Ashes**

Ashes are waste products from the incineration of fossil fuels, biomass, or waste. Two main types exist: fly ashes and bottom ashes.

* Coal fly ashes are used to replace cement up to 30%.
* Biomass ashes (bottom and fly) are used as fertiliser or landfilled, depending on composition.
* Fly ashes from waste incineration are landfilled; bottom ashes are further treated in some EU countries.

From bottom ashes, fractions rich in Fe, Al, Cu, and Zn are separated for reuse in industry; Cu-rich fractions also yield PGMs, Ag, and Au. The mineral aggregates portion is used in construction if it meets environmental criteria; untreated ashes are landfilled.

* In the last 10–20 years, some EU countries shifted from landfilling to incineration, increasing ash volumes from waste incineration.
* Coal use declined, reducing coal ash volumes; further decline is expected.
* Biomass incineration increased; future trends uncertain due to land use pressures.
* Almost all coal fly ashes are used as SCM (high-value stream up to €80/ton).
* Biomass fly ashes lack sorting facilities; waste incineration bottom ashes have sorting facilities in some countries, but coverage is incomplete, leaving room for improvement.

### Scenario II: Recovery (REC)

#### Batteries (BATT)

Under the recovery scenario, end-of-life batteries become a crucial source of secondary raw materials, primarily due to the increased adoption of electric vehicles and renewable energy storage systems. Technological innovation drives the recovery and recycling process, ensuring valuable materials are extracted from waste batteries for reuse.

* Increase in end-of-life batteries due to the growth of electric vehicles and renewable energy storage.
* Advanced recovery technologies facilitate the efficient extraction of valuable materials from battery waste.
* Standardised collection systems enhance the quantity and quality of battery waste available for recovery.
* Collaboration between industry and government lead to investments in research and development of battery recovery technologies.
* Battery passports have a strong impact on collection, material recovery rates and recycling rates.
* **Collection:**
  + Portable battery collection increases according to the trend seen in the WEEE waste stream.
  + Improved collection of light means of transport batteries.
  + Improved regulation and collection of industrial batteries.
* **Material recovery:**
  + Improved recycling technologies.
  + Battery Pass will improve material recovery.
  + Higher recovery rate for lithium.
  + Increase in recycling by average weight.
  + Recycling of plastics.
* Ambitious goals of recycling/recovery rates compete with reuse, so reuse remains low.
* Improved public awareness means fewer batteries end up in the municipal waste stream and less hoarding.
* There is competition for the batteries from the reuse vs. recycling market.
* **Design for recycling:**
  + Material and composition selection for recycling.
  + Higher requirements on design for disassembly.
  + Information available to promote efficient recovery.

#### End-of-life Vehicles (ELV)

The recovery scenario envisions a more effective and technology-driven end-of-life vehicle treatment process. Advancements in recovery technologies allow for improved extraction of valuable materials from vehicles at their end of life, although consumerism still drives high demand for new vehicles.

* Innovations in recovery technologies allow for a higher recovery rate of CRM-containing materials from ELVs.
* The total number of vehicles produced remains high due to consumer demand.
* Improved systems for ELV collection are established, ensuring efficient management of ELV waste.
* Increased collaboration between the government and industry leads to investments in ELV recovery technologies.
* Focus on managing the end-of-life of vehicles.
* EU recovery targets are reached (current and proposed targets, including increased and new targets).
* Common/bulk materials (Fe, non-Fe, plastics) and precious metals (Au, Ag, Pd, Pt) reach high mass recycling rates and high element recycling rates. Other CRMs currently not recovered reach a moderate level of recovery.
* For instance:
  + More advanced dismantling and processing steps (e.g., components and materials).
  + More specialised recovery of certain components and materials (e.g., electric motors including permanent magnets and embedded REE) as suggested in the proposal for a revised ELV directive.
  + More public and private interest in developing recycling chains.
  + Increased collection rate due to greater public and business participation, driven by target-based incentives with strong regulations and monitoring.
* **Design for recycling:**
  + Higher requirements on design for disassembly.
  + Information available to enable recovery.

#### Waste Electrical and Electronic Equipment (WEEE)

Under the recovery scenario, WEEE becomes a significant resource for secondary raw materials. Technological advancements in the sector improve the efficiency of WEEE treatment, although the consumerism-driven demand for new electronics remains high.

* Advanced technologies enable higher recovery rates of valuable materials from WEEE.
* Despite advancements in design for recyclability, WEEE generation remains high due to consumer demand for new electronics.
* Standardised and segregated collection systems for WEEE are implemented, improving the supply of materials for recovery.
* Increased industry-government collaboration leads to further development in WEEE recovery technologies.
* Consumer behaviour remains a significant hurdle for more efficient WEEE management.
* Higher recycling rates — making full use of disposed parts. For instance:
  + More automation of the dismantling and processing steps (e.g., AI).
  + Recycling technology improvements (e.g., small component recovery).
  + More effective collection infrastructure.
  + Financial support provided to recyclers/operators.
  + Bans on WEEE exports push for increased domestic recycling.
* **Design for recovery:** Ecodesign mandates changes in weight and composition of EEE to reduce complexity and improve recoverability.
* Higher public awareness and participation in WEEE management.
* Higher compliance from the public, producers, and businesses.
* Strong regulations and monitoring with higher collection and recycling targets; fines imposed for non-compliance.
* Greater focus on end-of-life management of WEEE.

#### Mining Waste (MIN)

Under the recovery scenario, technological advancements enable the extraction of residual valuable materials from mining waste, transforming it into a more valuable resource.

* Technological advancements facilitate the extraction of valuable materials from mining waste.
* Despite progress in recovery technologies, primary extraction remains the dominant source of raw materials due to high consumer demand.
* Government and industry collaboration supports the development of technologies for recovering materials from mining waste.
* Increased traceability and management of mining waste through digitalisation.
* Mining waste remains a significant environmental challenge.

#### Construction and Demolition Waste (CDW)

**Sources:** (eu2008wastedirective)

Under the recovery scenario, Construction and Demolition Waste (CDW) becomes an important resource for secondary raw materials, though mostly base metals and aggregates. Despite some progress in eco-design and material efficiency, the construction industry continues to generate significant amounts of waste or ‘downcycled’ materials.

* Focus on new construction to meet demand, no change in CDW generation rate.
* No increase in refurbishment or renovation activities.
* Enhancement of recycling quality to recover materials at higher value.
* Increased investment and an enhanced regulatory system in waste management, contributing to higher recovery rates.
* Creation of new waste recovery infrastructure to improve recovery.
* Widespread application of selective demolition and strict on-site waste sorting, increasing recovery of waste.
* Recovery of minerals is intensified with a stronger focus on closed-loop recycling (e.g., cement and aggregate are separated, aggregate is used, but cement is not treated).
* Recovery of other materials such as glass, plastics, and wood is also intensified.
* Better separation of waste at source leads to higher quality secondary raw materials.
* Repowering trends for wind turbines stay the same.
* Improved recycling of wind turbine blades, especially regarding plastics; permanent magnets are recycled at a functional level.

#### Slags, Ashes, and Other Residues (SLASH)

In the recovery scenario, SLASH is recognised as a potential resource for secondary raw materials. Advances in recovery technologies enable the extraction of valuable metals from SLASH; however, the total volume of CRMs recovered from this material remains low, except in cases of supply constraint.

* Digital solutions enhance the traceability and management of SLASH.
* More functional collection infrastructure.
* Financial support provided to recyclers/operators.
* Introduction of 2RM/CRM recovery targets (e.g., recovery of P from biomass ash for fertiliser).
* Higher awareness and participation of relevant sectors in SLASH issues and management.
* Strong regulations and monitoring with higher collection and recycling targets.

**Slags**

* Advanced recovery technologies allow for the extraction of valuable metals and minerals from slags.
* New recovery technologies are installed in the metallurgical industry.
* All metals are recovered from the slags; slag itself contains only minerals or trace metal elements.
* Due to low metal content, slags are ideal resources for the construction industry.

**Ashes**

* New recovery technologies are installed in the incineration industry.
* A shift in the volume and quality of ashes is expected.
* Coal fly ash volumes decrease over time to almost zero.
* Biomass ash volumes and quality remain stable.
* Waste incineration ashes: in the recovery scenario, there is a shift from landfill/incineration towards recycling, reuse, and repair.
  + In high-landfill countries, this will increase ash volumes.
  + In low-landfill, high-incineration countries, ash volumes decrease, and composition changes, with less CRM content due to better pre-sorting.

### Scenario III: Circularity

#### Batteries (BATT)

In the circularity scenario, battery waste treatment undergoes a massive transformation. The shift towards electric vehicles and renewable energy storage significantly increases the quantity of end-of-life batteries. However, thanks to new regulations, technological advancements, and business models, the majority of battery components are recycled or reused.

* Massive increase in end-of-life batteries due to the shift to electric vehicles and renewable energy storage.
* New regulations incentivise battery manufacturers to design for recycling.
* Battery recycling technologies improve, enabling higher recovery rates of valuable metals.
* Standardised collection systems for battery waste are established, improving recycling efficiency.
* Service-based business models such as leasing ensure manufacturers retain ownership of batteries, promoting circularity.
* Greater transparency through digital product passports aids in effective battery waste management.
* Battery passport and publicly accessible information from the new Battery Regulation provided by the economic operator placing the battery on the market enables high re-use rates.
* Increased repairability/modularity.
* Reduced demand from the sharing economy and more sustainable transport choices.
* New emerging technologies better suited for reuse/repair.
* Ambitious targets set by business and public policy.

#### End-of-life Vehicles (ELV)

For ELVs, the circular economy model affects vehicle design, use, and disposal. Emphasising extended vehicle life through repair and remanufacturing, this scenario also focuses on recovering materials from vehicles at the end of their life.

* Vehicle design shifts towards repairability, upgradability, and recyclability, increasing vehicle lifespan.
* Standardised ELV collection systems are established, ensuring efficient waste management.
* Innovative technologies enable higher recovery rates of metals and other valuable materials from ELVs.
* Service-based models such as vehicle leasing and sharing reduce the total number of vehicles produced.
* Digital product passports provide component information to aid recycling or reuse.
* Focus on managing the use phase of vehicles.
* Circular strategies take place before material recovery, delaying recovery.
* Information is available to enable these strategies.
* EU vehicle policy influences materials in vehicles through lightweighting and downsizing:
  + Increase in average occupancy and vehicle-kilometres per trip.
  + Decrease in average lifetime (in years) as utilisation factors increase.
* Increased circular strategies from greater public and business participation, driven by target-based incentives and strong regulations.

#### Waste Electrical and Electronic Equipment (WEEE)

In the circularity scenario, WEEE becomes a valuable resource instead of a disposal challenge. Through product design changes and advanced recovery technologies, a significant share of WEEE materials is reclaimed and fed back into production.

* Electronic products are designed for longevity, repairability, upgradability, and recyclability.
* Advanced technologies enable higher recovery rates of precious metals from WEEE.
* Improved WEEE collection systems ensure a steady material supply for recovery.
* Digitalisation and data use enhance traceability and efficiency in WEEE management.
* Service-based models promote product-as-a-service instead of ownership, reducing WEEE generation
* Increased durability and lifespans.
* Increased repairability.
* More sharing and product-service systems, with some equipment having reduced lifetime.
* Expanded second-hand market.
* Less hoarding.
* Higher formal collection and recycling rates.
* Focus is more on production and use phases than end-of-life.
* **Design for circularity:** Ecodesign mandates repairability, durability, no obsolescence, modularity, and continual software upgrades
* Chargers and batteries are interoperable across products and easily disassembled.
* Strong regulations and monitoring with higher reuse and circular targets, and fines for non-compliance.
* Support and infrastructure for circular strategies (e.g., repair shops, spare parts access).
* Greater use of connected products, smart tech, and IoT to monitor and extend product life.

#### Mining Waste (MIN)

In this scenario, mining waste impacts are two-fold: primary mining demand drops due to efficiency and recovery rates, and mining waste itself becomes a valuable resource.

* Decrease in primary mining reduces mining waste generation.
* Advanced technologies extract valuable materials from mining waste.
* Policies and regulations incentivise mining waste reuse.
* Digital solutions improve tracking and management of mining waste.
* Stakeholder collaboration promotes circular practices in mining.

#### Construction and Demolition Waste (CDW)

In the circularity scenario, CDW generation is reduced, and material recovery is improved.

* Less demolition and new construction lowers CDW volumes.
* Buildings designed for disassembly and reuse extend material life and reduce waste.
* Longer lifetimes for buildings and wind turbines (less repowering).
* Wind turbine blades refurbished/repaired for reuse.
* Improved recycling technologies reduce downcycling.
* Policies and regulations incentivise recycled material use in construction.
* Improved CDW collection and separation systems.
* Digital tools improve resource management in construction and renovation.
* Selective deconstruction allows reuse of individual construction components.

#### Slags, Ashes, and Other Residues (SLASH)

In the circularity scenario, SLASH is recognised as a potential resource for secondary raw materials. Recovery conditions are similar to the recovery scenario, but overall waste generation decreases.

* Digital solutions enhance traceability and management.
* More functional collection infrastructure.
* Financial support to recyclers/operators.
* 2RM/CRM recovery targets (e.g., P from biomass ash for fertiliser).
* Higher awareness and sector participation in SLASH management.
* Strong regulations and monitoring with higher collection/recycling targets.

**Slags**

* Advanced recovery technologies extract valuable metals and minerals.
* New recovery technologies are installed in metallurgical industries.
* All metals are recovered; slag contains only minerals or trace metals.
* Slags become ideal resources for the construction industry.

**Ashes**

* New recovery technologies are installed in incineration plants.
* Shift in ash volumes and quality is expected.
* Coal fly ash declines to almost zero.
* Biomass ash volumes and quality remain stable.
* Waste incineration ashes:
  + In high-landfill countries, increased volumes due to diversion from landfill.
  + In low-landfill, high-incineration countries, reduced volumes and less CRM content due to better pre-sorting.