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FutuRaM

Future availability of secondary raw materials

Work Package 2

Future Availability of Secondary Raw Materials

Scenario Storylines & Scenario Quantification
Draft Report — Version 3

Funded by the European Union

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DRAFT REPORT — VERSION 3

REVIEW NOTICE

Latest Revision: Friday 1st December, 2023 at 14:08
This is a draft report for internal review
The chapters beyond the Scenario Storylines chapter are in the first draft stage and are undergoing continual development.

CHANGE LOG

New in version 3:

- Revised the scenario storylines and methodology chapters based on internal review.
- Added the quantification chapter, which is not in the first draft stage.
- This chapter includes detailled descriptions of the scenario parameters and, in the case of the external elements, their quantification.
- Internal elements will be quantified using a bottom-up approach whereby waste streams interpret the scenario parameters through correlations with their product groups. This will be discussed at the next workshop.

CONTRIBUTING

Please contribute to the work on the scenario work in the following ways:

- In a CSV file with the format: 'name, line start, line end, comment, reference' (if reference is applicable, please provide the DOI or BibTeX).
- Please use consistent formatting for the page numbers and any referencing.
- FutuRaM members add their comments to the shared document found at this link .
- The same template can be downloaded from here and sent to SCM for inclusion in the shared document.
- You can also contribute directly to the LaTeX source files on the WP2 GitHub repository .

WASTE STREAM NOTICE

Waste Streams, please check your sections

- Review the waste stream impact sections for each scenario
- Add more references, especially for the targets, regulations, and projections.
- Contribute to the main points raised by the reviewers of the first drafts (see below).
- Read the quantification chapter and develop your plan to interpret the scenarios in your waste stream.
- Consider how the scenario parameters and your waste stream model codebase will interface.
- Consider how your waste stream model will interface with the integrated model.

QUANTIFICATION

- Read the quantification chapter and develop your plan to interpret the scenarios in your waste stream.
- Consider how the scenario parameters and your waste stream model codebase will interface.
- Consider how your waste stream model will interface with the integrated model.
- Contribute to the data collection in the future technology and product list here.

DISCUSSION POINTS

- How to transfer general targets into product-specific values?

  general CRM/SRM → waste streams → product groups

  We would need a set of constraints for each of the recovery flows and processes, as well as the individual waste flows (by code) in each WS, to backcast this.
- Consideration of possible future resource constraints in the scenarios.

  We suggest covering this in sensitivity analysis and multi-objective-optimisation.
- Economic considerations (prices, subsidies, PPP vs. GPD etc.).
- Geopolitical Considerations (supply risk, trade, etc.).
- Scenarios relationship with the United Nations Framework Classification (UNFC).
- Choice of background energy scenario (i.e. STEP from the IEA)

SOME LINKS

- Quantification: chapter 4
- Appendices: chapter 13
- WP2 folder on the FutuRaM Sharepoint See for more details.

Front Matter

Chapter Contents

I. REPORT DETAILS

Project:	Future Availability of Secondary Raw Materials
Acronym:	FutuRaM
Grant Agreement:	1010585
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Author (s):	Stewart Charles McDowall
E-Mail:	s.c.mcdowall@cml.leidenuniv.nl
Reviewed By:	
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Date Of Submission:	2023–11–22
Dissemination Level:	Internal document

Table 1.1: Version history

VER. NO.	DATE	REASONS FOR RELEASE	RESPONSIBLE
1.0	2023-09-11	First draft for review	Stewart Charles McDowall
2.0	2023-11-11	Second draft for review	Stewart Charles McDowall
3.0	2023-11-22	Addition of scenario quantification	Stewart Charles McDowall

II. NOTICE

III. PREFACE

The FutuRaM project aims to quantify the current and future availability of secondary raw materials (SRM), focusing on critical raw materials (CRMs) [80]. This study is concerned with six waste streams in the EU member states, as well as Iceland, Norway, Switzerland, and the United Kingdom (EU27+4). In this report, the EU27+4 will henceforth be referred to as the EU, unless specified otherwise.

THE WASTE STREAMS COVERED IN FUTURAM ARE:

- **Waste batteries (BAT)**
- **Construction and demolition waste (CDW)**
- **End-of-life vehicles (ELV)**
- **Mining waste (MIN)**
- **Slags and ashes (SLASH)**
- **Waste electrical and electronic equipment (WEEE)**

Work package two (WP2) is conducting foresight studies for materials that are either classified as critical to the EU economy or are significant due to factors such as their large volumes, commercial importance, and environmental impacts [80, 1, 22, 141]. WP2 is tasked with developing a set of coherent scenarios for material use and waste/recovery over time across various sectors in the EU. This report describes the three distinct scenarios and the process by which they were developed.

THE THREE SCENARIOS THAT HAVE BEEN DEVELOPED IN FUTURAM ARE:

- BAU **I. Business-as-usual (BAU)**
- **II. Recovery (REC)**
- **III. Circularity (CIR)**

IV. REPORT CONTENTS

V. LIST OF TABLES

VI. LIST OF FIGURES

VII. EXECUTIVE SUMMARY

This report presents the first phase of the scenario development process — the storyline narrative phase. Three distinct future scenarios have been drafted up to the year 2050: Business as Usual, Recovery, and Circularity. These scenarios are designed to be internally consistent and provide an overview of the potential future landscape of waste management and SRM recovery within the EU.

The scenario development process employs a methodology that integrates both forecasting and back-casting techniques to build a comprehensive, future-facing knowledge base that can aid fact-based decision-making [81, 23, 82, 83, 76, 84, 85].

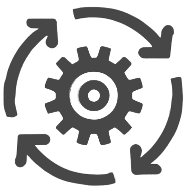
In the next phases of scenario development, future product composition and recovery technology will be assessed, scenario elements will be quantified, and all data will be integrated with the quantitative models for waste generation and SRM recovery.

The FutuRaM project aims to offer a nuanced understanding of the potential future waste management and resource recovery landscape within the EU. This approach provides insights into key drivers, uncertainties, and the possible impacts of policy and technological advancements. Additionally, by aligning SRM recovery efforts with the United Nations Framework Classification for Resources (UNFC) [150], the project aims to facilitate the commercial exploitation of SRMs and CRMs by manufacturers, recyclers, and investors. With the comprehensive knowledge base that we are developing, FutuRaM aims to support informed decision-making by policymakers and government, as well as industry and community stakeholders.

FUTURAM'S THREE FUTURE SCENARIOS

Scenario I: Business-as-usual (BAU)

The BAU scenario extrapolates current trends into the future with limited change. Using forecasting techniques, it projects a potential future where there are minor advancements in resource efficiency, recovery technology, and the energy transition, but primary extraction of raw materials remains the dominant practice.



Scenario II: Recovery (REC)

The Recovery scenario imagines a future leveraging advanced technology to significantly enhance SRM recovery from waste streams. It outlines a future where the EU successfully meets its recycling and recovery targets through an effective waste management system and circular design principles [24, 86]. This scenario sees an increased recovery rate of SRMs, extensive use of digitalisation and automation in recycling processes, and new or strengthened waste regulations in line with EU targets.

Scenario III: Circularity (CIR)

The Circularity scenario captures the ideal of a fully realised circular economy, going beyond end-of-life recovery to minimise waste at every production and consumption stage. It predicts a future where the EU's targets for recycling, recovery, and circularity are met through extensive stakeholder collaboration, new business models, and increased use of renewable energy and circular economy technologies [2, 87, 88].

VIII. OVERVIEW OF THE SCENARIO STORYLINES

Scenario I: Business-as-usual (BAU)

BAU

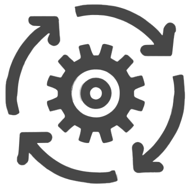
See section 3.1 for the full scenario description and waste-stream-specific scenario impact narratives.

This scenario envisions the future based on the current situation, extending to 2050 with very little deviation from present consumption patterns and without substantial development of the secondary raw material (SRM) recovery system. While there may be advances in some areas such as resource efficiency, recovery technology, and the energy transition, substantial modifications remain hindered by economic, social, and political constraints. The extraction of primary raw materials continues to be the predominant source utilised to satisfy the EU's growing SRM demand.

In the Business as usual (linear economy) scenario, the following are key characteristics:

- A forecasting model is used to predict the future based on the current situation and the development of existing trends.
- EU targets including those for eco-design, recycling and recovery are not met, and the current linear model largely persists.
- Material demand remains coupled with economic growth, perpetuating a trend of increasing consumption.
- Primary mining and extraction persist as the leading sources of raw materials, underlining the dependency on traditional extraction methods.
- Recycling and recovery rates continue to lag, leading to increased production of SRM-containing waste that signals missed opportunities for resource reuse.
- The EU's dependency on imports of SRMs escalates, heightening the risk of supply disruptions [25].
- Investment in new SRM recovery technologies remains minimal, stifling innovation and advancements in this field.
- The industrial focus remains on cost-effective material production and use, disregarding the long-term sustainability aspect.
- Material scarcity and price fluctuations pose potential risks to the EU industry, highlighting the vulnerability of this business model [26].
- Without any significant updates to environmental regulations, the negative impacts on ecosystems and biodiversity intensify.
- Mining activity in the EU remains limited and concentrated in only a few member states. Current exploration projects (e.g., for Lithium in PT, FR, UK and rare earths in SE) are not realised.
- The transitions to renewable energy and e-mobility continue at their current pace.

Scenario II: Recovery (BAU)



See section 3.2 for the full scenario description and the waste-stream-specific scenario impact narratives.

In the recovery scenario, the central emphasis is on harnessing sophisticated technologies to salvage SRMs from waste streams at the end of their lifecycle. While there are noticeable strides towards the incorporation of 'circular design' principles and re-X strategies (which focus on reducing, reusing, recycling, repairing, and refurbishing), material demand increases similarly to the BAU scenario. This is, however, mitigated to some extent by the implementation of a comprehensive material recovery system.

Key features of this technology-promoted recovery scenario include:

- This scenario uses a combination of forecasting and backcasting methods to envision the future.
- The backcasting method is used for scenario factors that are covered by governmental targets, starting with the desired outcome and working backwards to the present.
- The forecasting method is used for scenario factors that are not covered by governmental targets, starting with the current situation and extending to the future.
- EU targets for recycling and recovery are met, due to the EU's waste management system becoming more expansive, efficient and effective.
- Technological innovation drives increased recovery rates of SRMs, enabling the more efficient use of waste.
- Digitalisation and automation are more extensively used in recycling processes, leading to enhanced productivity and efficiency.
- Business models like leasing and take-back schemes emerge, altering traditional consumption patterns (here, the focus is on take-back for recycling).
- Ecodesign mandates are implemented, again, here, with a focus on end-of-life recovery.
- There is greater exploration and exploitation of alternative sources such as urban mining, waste streams, and tailings, presenting novel opportunities for resource acquisition.
- New waste regulations and guidelines for SRM recovery are implemented, enforcing better management and extraction of SRMs.
- Investment in research and development for SRM recovery technologies experiences an upswing, promoting continuous innovation in this field.
- Closer collaboration and information sharing between industry and government institutions (e.g., waste tracking and digital product passports) streamline processes and expedite decision-making.
- New jobs are created in the recycling and recovery sector, offering economic benefits and improving overall employment rates.
- SRM production and use become more efficient and cost-effective, fostering economic sustainability.

Scenario III: Circularity

See section 3.3 for the full scenario description and the waste-stream-specific scenario impact narratives.

In this scenario, we move in the direction of the maximum achievable state of material efficiency as government policy, private innovation and social changes are rapidly driving the transition toward a circular economy. The emphasis here rests heavily on re-X strategies that are implemented in the design phase of products (e.g., repairability and re-manufacturability) and that are actualised by changes in consumer behaviour (e.g reduction, refusal, engagement in the 'sharing economy' and curtailment of the 'throw-away' mindset).

Further, being enabled by the widespread adoption of 'circular design' principles and improvements in information transparency (e.g., waste tracking and digital product passports) the system for the treatment of post-consumer waste can divert a significant amount of their inflows (to, for example, re-use and re-manufacture) with the residual fraction being readily segregated into purer, more efficiently recoverable, material streams.

This scenario envisions a future where government policies are in synergy with private sector innovation and societal changes, driving a wholesale transition towards a circular economy. Unlike the recovery scenario, where the focus is on the end-of-life recovery of materials, this scenario emphasises minimising waste at all stages, starting from the design phase itself.

The circular economy scenario is characterised by the following:

- This scenario uses a combination of forecasting and backcasting methods to envision the future.
- The backcasting method is used for scenario factors that are covered by governmental targets, starting with the desired outcome and working backwards to the present.
- The forecasting method is used for scenario factors that are not covered by governmental targets, starting with the current situation and extending to the future.
- EU targets for recycling and recovery are met, as are those for circularity, due to advances in waste management, ecodesign and re-X strategies.
- A circular economy is implemented, prioritising waste reduction, resource efficiency, and a shift from the 'take-make-dispose' model.
- A notable increase in SRM recycling and recovery rates, indicating an efficient use of resources.
- A larger emphasis on designing products for reuse and recycling, making waste a valuable resource rather than a problem.
- More extensive use of renewable energy and clean technologies in SRM production and use, supporting a low-carbon economy.
- Collaboration between stakeholders — including industry, government, and consumers — improves, enhancing the implementation of circular practices.
- New business models like leasing and take-back schemes emerge, altering traditional consumption patterns [89].
- Digitalisation and data use are heightened to improve efficiency and traceability, aiding in effective resource management.

- Investment in research and development for circular economy technologies increases, driving innovation and adoption.
- Awareness and education around sustainable consumption and production practices are amplified, leading to behavioural changes in society.
- Reliance on imports decreases, suggesting greater self-sufficiency and sustainability.
- The creation of new jobs within the recycling, recovery and re-X sectors boosts the economy and alleviates social inequality.
- Stricter waste regulations and product design guidelines are introduced, accelerating the transition towards circularity.

405

IX. ABBREVIATIONS

Table 1.2: List of abbreviations

ACRONYM	DEFINITION
AI	Artificial Intelligence
BAU	Business as Usual
BATT	Waste Batteries
BRGM	French Geological Survey (Bureau de Recherches Géologiques et Minières)
CDW	Construction and Demolition Waste
CE	Circular Economy
CRM	Critical Raw Material
CU	Chalmers University
EEE	Electrical and Electronic Equipment
ELV	End-of-Life Vehicles
Empa	Swiss Federal Laboratories for Materials Science and Technology
EoL	End-of-Life
EoU	End-of-Use
EoW	End-of-Waste
EU	European Union
EU27+4	EU + Iceland, Norway, Switzerland and the United Kingdom
EPR	Extended Producer Responsibility
GDP	Gross Domestic Product
GEC	Global Energy and Climate [Model]
GTK	Geological Survey of Finland
LCA	Life Cycle Assessment
LCC	Life Cycle Cost Assessment
LMU	Ludwig Maximilian University of Munich
LU	Leiden University
MIN	Mining Waste
R&D	Research and Development
REACH	Registration, Evaluation, Authorization, and Restriction of Chemicals
RECHARGE	EU rechargeable battery industry association
SGU	Geological Survey of Sweden
SLASH	Slags and Ashes
S-LCA	Social Life Cycle Assessment
SLCA	Sustainability Life Cycle Assessment
SRM	Secondary Raw Material
TRL	Technology Readiness Level
TUB	Technische Universität Berlin
UCL	University College London
UNITAR	United Nations Institute for Training and Research

Continued on next page

Table 1.2 — Continued from previous page

ACRONYM	DEFINITION
UNFC	United Nations Framework Classification for Resources
VITO	Flemish Institute for Technological Research
WEEE	Waste Electrical and Electronic Equipment
WEEE Forum	Waste Electrical and Electronic Equipment Forum
WFD	Waste Framework Directive

X. TERMINOLOGY (ABBREVIATED)

The following table provides an abbreviated list of terminology used in this report. See section 13.1 for a complete list.

Table 1.3: List of terminology (abbreviated)

TERM	DEFINITION
Backcasting	A method for predicting future trends based on a desired future state.
Business-as-usual	A scenario that assumes no significant changes in current trends and policies.
Circular economy	An economic system that prioritises waste reduction and resource efficiency.
Critical Raw Material	A raw material that is economically and strategically important to the EU, but with a high risk of supply disruption.
Forecasting	A method for predicting future trends based on historical data.
Recovery	The process of recovering SRMs from waste streams.
Re-X	A general term for circular strategies such as reuse, repair, refurbishment, remanufacturing and recycling.
Scenario	A plausible and coherent description of how the future may develop based on a set of assumptions.
Secondary Raw Material	A material that has been recovered from waste and can be used as a substitute for a primary raw material.
Storyline	A qualitative description of a scenario, including the key drivers, actors and events.

XI. DESCRIPTION OF FUTURAM WORK PACKAGE 2

A full breakdown of the tasks and subtasks in WP2, along with the responsible partners is provided in section 13.9. The following sections provide a brief description of each task.

More information can be found in the grant agreement [151], the consortium agreement [152], the project management plan [153] and the Milestone 6 report [154].

> **DELIVERABLE**
>
> **D2.1:** Report on the environmental and socioeconomic barriers to SRM recovery — *Month 47: May 2026*

XI.1. Objectives

WP2 will conduct foresight studies for materials critical to the EU economy, or materials that have significant impacts on EU sustainability because of their large volumes. WP2 will develop a set of coherent scenarios for material use and waste/recovery over time in various sectors in the EU: WEEE, ELV, BAT, CDW, MINW, SLASH.

Context

Source: [151]

MODELLING THE FUTURE OF WASTE GENERATION AND SRM RECOVERY

In WP2, modelling the foresight requires dealing with much unknown information and developments. A convincing mathematical model on the future thus requires a strong narrative developed from stakeholders and existing literature regarding how future circular behaviours, recycling and recovery technologies, and the overall material economy will develop. Furthermore, if the mathematical model used is too detailed, there will be many data gaps, leading to it being impractical to use and potentially leading to unrealistic results. This means a good balance needs to be found between data availability and its translation into a quantification of future narratives. The narratives applied to each scenario will follow plausible developments by taking into account stated MS policies by each regarding the material economy (with a special emphasis on the waste and recycling stages) and optimistic outlooks of both recycling technology using learning curves, and of increasing circular behaviour following global best practice. The rate of development towards each of these scenarios will be used for sensitivity and uncertainty analyses, such that a measure of the variability within each scenario is established.

OPEN SCIENCE

Considering the multidisciplinary character of FutuRaM and its aim to provide consistent and robust data, procedures, models, and methods, a critical discussion, harmonisation and integration of the concepts, perspectives and is crucial for the success of the project.

The consortium is committed to making the data available in open formats during the project and free of charge for the EC and all stakeholders to use and publish, along with other relevant reports tailored for the use of the EC and respecting FutuRaM's open science principles.

GENDER

Within the FutuRaM, project no specific population group will be targeted. In contrast, the consortium is aware that research often has a diversity problem since many groups are underrepresented, e.g. women, ethnic minorities, people with disabilities and socially disadvantaged populations and we will consider specific measures that will help to address specifically these groups.

We will especially consider the involvement of a variety of stakeholders in WP7.

In work packages 2, 3 and 5 we will use Delphi panels, which have an equal representation of gender and an appropriate age distribution that encapsulates multiple perspectives. In the modelling of WP2 and 4 (foresight and stock and flow models), consumption of household electronics may increase with increasing gender equality, and behavioural aspects of waste separation which could be an aspect of foresight of stock and flows.

XII. TASK DESCRIPTIONS

Task 2.1. **Develop scenario storyline (ULEI, TUB, Empa, Chalmers, WEEE Forum, BRGM, UNITAR, SGU) (M01-M18):** This task involves scanning, mapping, and assessing scenarios used in the grey, scientific, policy, and industry literature/reporting for the different waste streams, (e.g., the Shared Socioeconomic Pathways, the International Resource Panel Scenarios, the International Energy Agency Scenarios, etc) to develop cogent storylines for the three planned scenarios. These will cut across sectors and will be used for the Stock-Flow models (WP4) and will include the translation of general concepts such as stated policies, sustainable development, circular economy, to each sector. FutuRaM will develop at minimum three scenarios (1. Sustainability, 2. Recoverability, and 3. Business-as-usual).

Task 2.2. **Integrate future technologies into the scenarios (Chalmers, ULEI, TUB, Empa, WEEE Forum, BRGM, UNITAR, UCL, LMU, SGU, VITO) (M03-M20):** This task will review current and emerging technologies used in the various sectors for product manufacturing and end-of-life handling, with a special emphasis on material production, use, and recycling. Together with the storylines developed in Task 2.1, it will adapt the market share of these technologies for each sector to determine the future development of each sector.

Task 2.3. **Forecast material composition and products for each scenario (TUB, ULEI, UNITAR, Chalmers, BRGM, Empa, VITO) (M7-M20):** Following the scenarios from T2.1, the material compositions and future products for each sector will be determined based on the product and commodity demand and technology realisation (T2.2). This task will be coupled to the data collection in WP3 and WP4.

Task 2.4. **Quantify environmental and socioeconomic impacts of SRM recovery under each scenario (ULEI, TUB, Empa, UNITAR, WEEE Forum, BRGM, UCL, LMU) (M18-M36):** This task will use the information generated in Tasks 2.1-2.3, together with the material flow analysis from WP4, to quantify the future environmental and socioeconomic feedbacks for each waste sector and scenario according to future recovery technology.

Task 2.5. **Assess the environmental and socioeconomic impacts and bottlenecks of future SRM recovery (ULEI, TUB, Empa, UNITAR, Chalmers, UNITAR. WEEECycling) (M37-M47):** This task will develop a report based on an assessment on the pressures and bottlenecks associated with environmental and socioeconomic issues related to each waste sector, including the associated changes and impacts on imports and of primary raw materials production (D2.1).

XII.1. Interconnection with other work packages in FutuRaM

REVIEW NOTICE

Does anyone have the original, editable version of this figure?

Figure 1.1 shows the interconnection between WP2 and the other work packages in FutuRaM [151].

Back to ToC

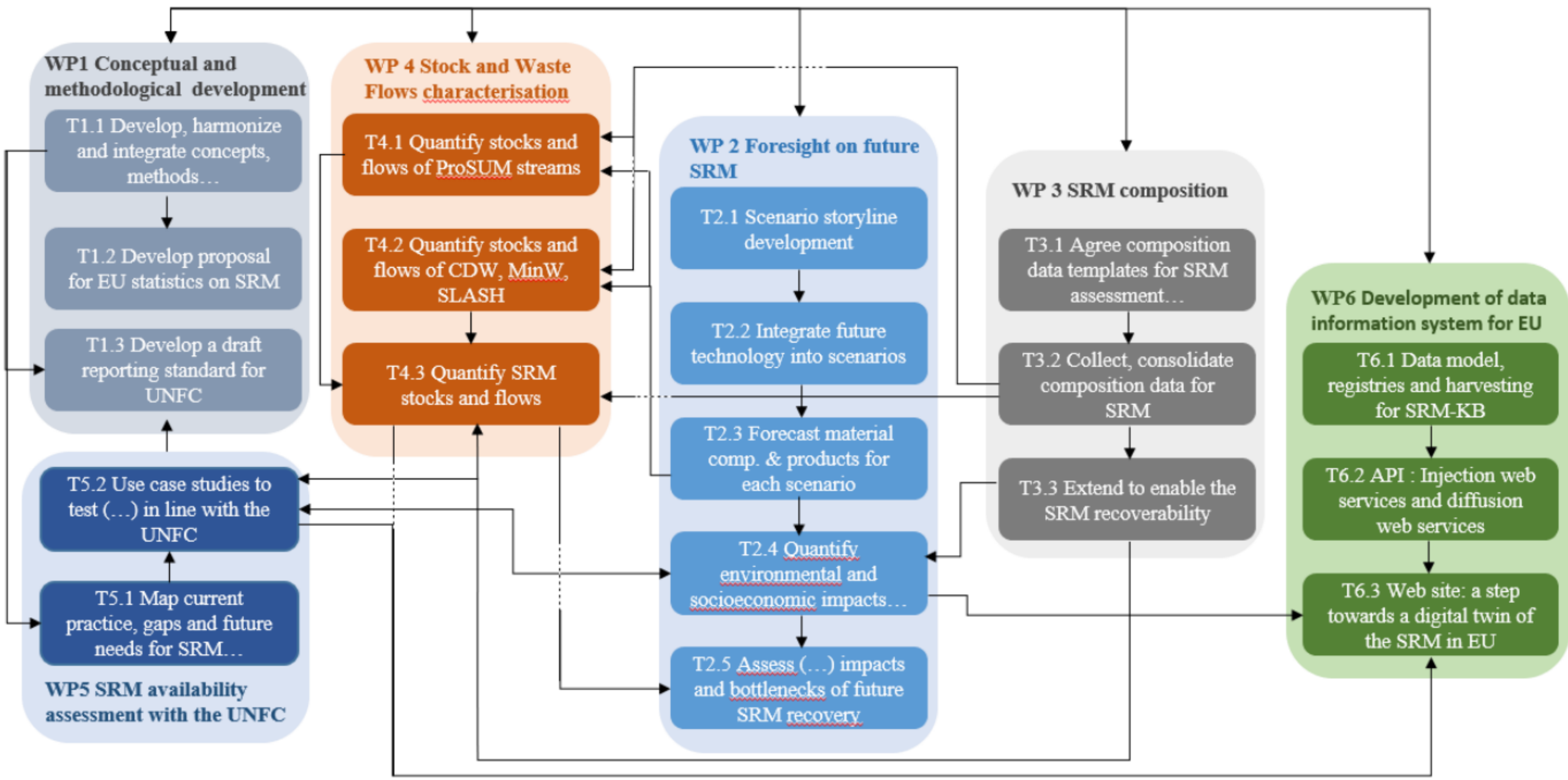


Figure 1.1: Interconnection between WP2 and the other work packages in FutuRaM

XII.2. Work package two milestones

Table 1.4: WP2.1 — Milestone list

M#	MILESTONE NAME	WP	DUE DATE	RESP. PARTNER	MEANS OF VERIFICATION
MS11	Mapping of published scenarios and Storyline/scenario description	2	Dec. 2023	ULEI	Datasets on available scenarios are fed into D1.1 and qualitative descriptions of 3 futures for the six waste streams are circulated
MS17	Mapping of future technologies for each sector	2	Feb. 2024	ULEI	Dataset covering sector-specific current and emerging technologies in both the production of products and their end-of-life treatment made available to WP1 Lead and consortium members, including quantitative descriptions of future product market shares related to 6 waste streams
MS20	Integration of social, environmental, and economic assessments	2	May 2026	ULEI	Social, environmental, and economic impacts of SRM recovery have been quantified for each scenario and waste stream. Information delivered to the consortium.

F 48

XII.3. Subtasks for Task 2.1 — Scenario storyline development

Table 1.5: WP2.1 — Subtask list

WP	TASK	SUB-TASK	NAME	WS	DESCRIPTION	START	END	PARTNERS	STATUS
2	2.1	2.1	Scenario mapping	Cross-cutting	Map various studies from the academic, policy, and grey literature for future scenarios and assess the applicability within FutuRaM	M01	M05	WEEE Forum, UNITAR, BRGM, CU, GTK, LMU, RECHARGE, SGU, TUB, LU, VITO, Empa, UCL	✓
2	2.1	2.2	Scenario methods	Cross-cutting	Compile various methodologies for scenario development and assess their applicability for developing scenarios on material recovery and circular economy for Europe	M02	M05	WEEE Forum, UNITAR, BRGM, CU, GTK, LMU, RECHARGE, SGU, TUB, LU, VITO, Empa, UCL	✓
2	2.1	2.3	Scenario storylines	Cross-cutting	Flesh out the storylines of the 3 main scenarios	M05	M08	UNITAR, CU, TUB, LU	✓
2	2.1	2.4	Qualitative scenario development	Cross-cutting	Use the chosen methods and qualitative methods to develop the three main scenarios to be used in FutuRaM (e.g. BAU, increased material recovery, and full circular economy)	M07	M11	UNITAR, CU, SGU, LU, VITO, UCL	✓(V3)

Back to ToC

XII.4. Consortium partner contributions to WP2

Table 1.6 lists the consortium partner contributions to WP2, in terms of person months for each sub-task. The table is based on the FutuRaM grant agreement [151].

WP #	WP Name	Total PMs	Task No.	Start	End		WEEE Forum	UNITAR	BRGM	Chalmers	GTK	LMU	RECHARGE	SGU	TUB	Leiden Uni	VITO	Empa	UCL	Total
						ALL TASKS	3	19	8	10	2	12	1	1	21	28	4	8	7	124
2	Foresight on Secondary Raw Materials	151.0	2.1	2022-06-01	2023-11-30	Develop scenario storyline	1	5	1	2				.5	2	1		1		13.5
			2.2	2022-08-01	2024-01-30	Integrate future technologies into the scenarios	1	4	2	6	1	1	.5	.5	6	1	2	1	3	29
			2.3	2022-12-01	2024-01-30	Forecast material composition and products for each scenario	1	4	2	2	1		.5		8	4	2	2		26.5
			2.4	2023-11-01	2025-05-31	Quantify environmental and socioeconomic impacts of SRM recovery under each scenario		2	2			11			2	11		3	4	35
			2.5	2025-06-01	2026-04-30	Assess the environmental and socioeconomic impacts and bottlenecks of future SRM recovery		4	1						3	11		1		20

Table 1.6: Consortium partner contributions to WP2 (person months per sub-task)

Methodology

CHAPTER CONTENTS

2.1. THE CONCEPTUAL FRAMEWORK FOR SCENARIO DEVELOPMENT

The conceptual framework for scenario development is based on the following principles.

The scenarios should:

- Be based on the best available scientific knowledge and data.
- Provide a coherent and consistent picture of possible futures.
- Provide decision makers with knowledge related to the possible consequences of their decisions.
- Consider a range of plausible future outcomes, accounting for uncertainties and alternative trajectories.
- Be developed in a participatory and collaborative manner, involving relevant stakeholders and experts.
- Be transparent and well-documented, allowing for replication and further analysis (e.g., publication in peer-reviewed journals and open-access repositories).
- Be flexible and adaptable, allowing for updates and adjustments as new information becomes available.
- Consider the interconnections and interactions between different sectors, waste streams, and policy domains.
- Take into account the broader societal, economic, and environmental context in which the waste streams operate.
- Incorporate a long-term perspective, considering the potential impacts and implications over several decades.
- Capture both quantitative and qualitative aspects, integrating data-driven modelling with qualitative narratives and storylines.
- Be regularly reviewed and updated to reflect evolving knowledge, technological advancements, and policy developments.
- Be used as a tool for learning and exploration, encouraging dialogue and collaboration among stakeholders.
- Inform policy and decision-making processes, providing insights into the potential consequences of different choices and interventions.
- Be communicated effectively to a wide range of audiences, ensuring accessibility and clarity of information.
- Contribute to the advancement of knowledge and understanding in the field of waste management, resource recovery, and circular economy.

By adhering to these principles, the FutuRaM project aims to develop robust, informative, and policy-relevant scenarios that support sustainable decision-making and contribute to the transition towards a more circular and resource-efficient economy.

2.2. Scenario storyline development process

Building scenarios involves several steps and various methodologies, these will differ depending on the specific context and objectives of the exercise [81, 23, 82, 83, 76, 90, 91, 92, 93].

The following section provides an overview of the scenario development process used in FutuRaM. Figure 2.1 provides a visual representation of the process.

2.2.1. Step 1: Define the scope and objectives

Scope and objectives of the scenario development process

The scope and objectives of the scenario development process are defined in the context of the overall aim, scope, and objectives of the FutuRaM project.

Aim of FutuRaM:

FutuRaM will develop the Secondary Raw Materials knowledge base on the availability and recoverability of secondary raw materials (SRMs) within the European Union (EU), with a special focus on critical raw materials (CRMs). The project research will enable fact-based decision-making for the recovery and use of SRMs within and outside the EU, and disseminate the data generated via an accessible knowledge base developed in the project [152, 153].

Scope of FutuRaM:

FutuRaM will establish a methodology, reporting structure, and guidance to improve the raw materials knowledge base up to 2050. FutuRaM will focus on six waste streams: batteries; electrical and electronic equipment; vehicles; mining; slags and ashes; and construction and demolition.

It will integrate SRM and CRM data to model their current stocks and flows and consider economic, technological, geopolitical, regulatory, social and environmental factors to further develop, demonstrate, and align SRM recovery projects with the United Nations Framework Classification for Resources (UNFC) [150].

This will enable the commercial exploitation of SRMs and CRMs by manufacturers, recyclers, and investors, and the knowledge base developed in the project will support policymakers and governmental authorities.

Selected objectives of the FutuRaM project are presented in Table 2.1 [152, 153].

Scope of Work Package 2 (WP2):

Given this context, the scope of the scenario development process is to develop a set of plausible scenarios that explore the future of waste management, resource recovery, and circular economy in the EU.

The scenarios will be used to identify key drivers and uncertainties that will influence the future of waste management and resource recovery. The scenarios will also be used to evaluate the potential impacts of different policy interventions and technological advancements.

Thematic scope

The scenarios will be centred on the six waste streams of FutuRaM: WEEE, ELV, BAT, CDW, MIN, and SLASH. Additionally, consideration will be given to sectors and policy domains that are relevant to these waste streams and the general context of the system. These include manufacturing, energy, and transportation, as well as policies related to the environment, the economy, society, technology, and geopolitics.

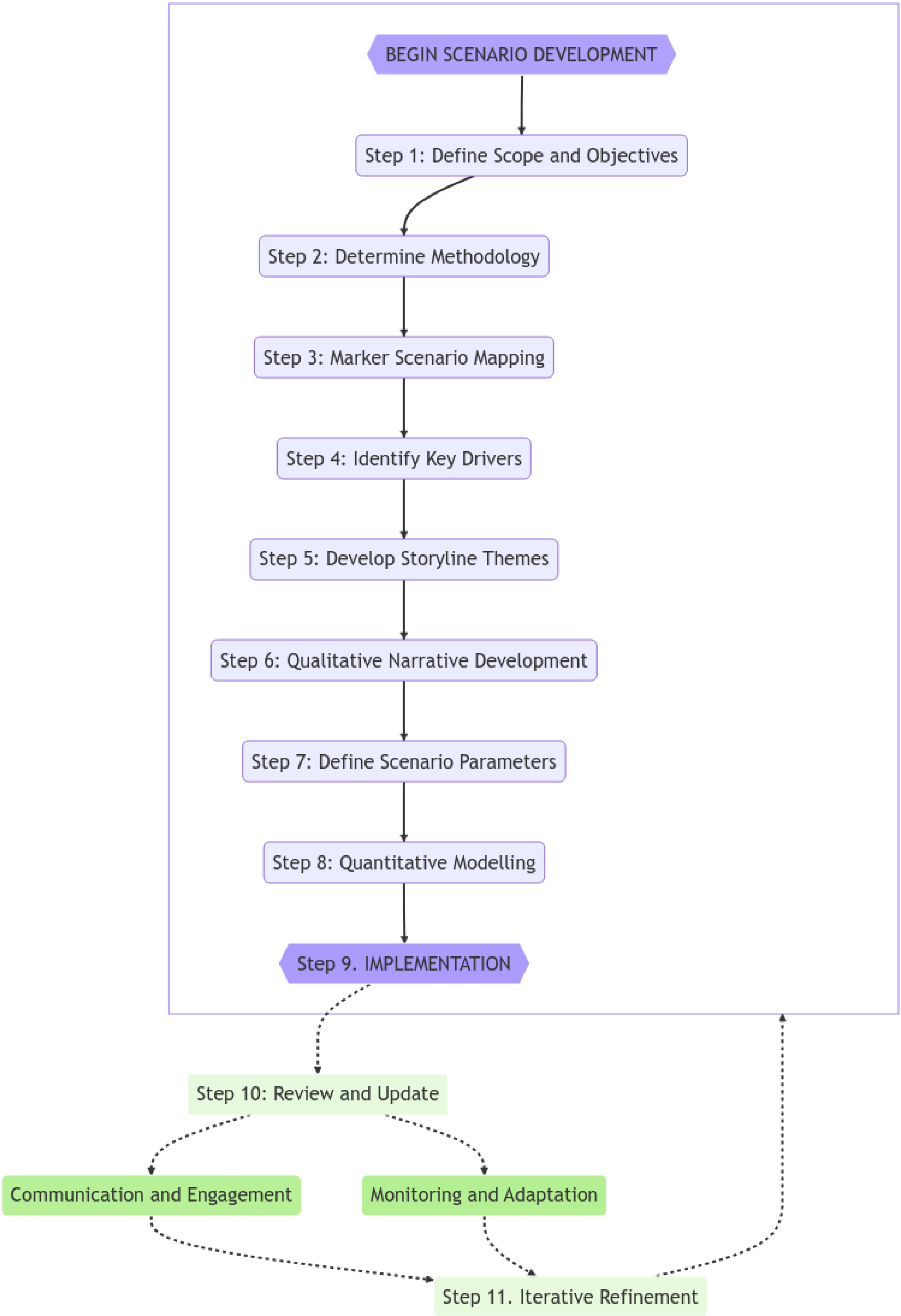


Figure 2.1: Scenario storyline development process

Table 2.1: Selected objectives of the FutuRaM project

NEED	ACTION
A successful transition to a climate-neutral, circular and digitised EU economy relies heavily on a secure supply of raw materials.	FutuRaM will quantify the future availability of SRMs for three future scenarios for the EU material economy. Forecast material demand, SRM supply for each scenario, and raw material imports to evaluate EU material autonomy.
Presently, several socioeconomic scenarios have been developed at national, EU, and/or global scales to assess the energy and mobility transition. Still lacking are specific scenarios for the SRM and CRM recovery systems	FutuRaM will develop stock-flow models for six waste streams based on holistic scenarios to map current and future material use in the economy of the EU-27 plus Iceland, Norway, Switzerland and the United Kingdom. FutuRaM will extend existing model approaches by a set of distinct scenarios that cover circular economy, high SRMs recoverability, and business as usual.

Geographic scope

The scenarios will be developed for the EU-27 plus Iceland, Norway, Switzerland and the United Kingdom (EU27+4). The scenarios will consider the current and future waste management practices and resource recovery technologies in these countries. Additionally, the scenarios will consider the current and future policies and targets related to waste management and resource efficiency in these countries. To some extent, the scenarios will also consider the current and future trade relationships between these countries and other countries around the world.

Temporal scope

The scenarios will be developed for the time horizon of 2025–2050. This time horizon is aligned with the long-term targets of the EU, including the EU Green Deal, the EU Circular Economy Action Plan, and the EU Industrial Strategy.

The discrete stages in the forecasts are planned to be: 2025, 2030, 2035, 2040, 2045 and 2050.

The temporal resolution of the scenarios will be determined during the quantification phase of the scenario development process.

While it is possible to develop scenarios with a high (or even continuous) temporal resolution, that of these scenarios will be determined based on the availability and quality of data. It is important to acknowledge that providing too high a temporal resolution may lead to a false sense of accuracy and precision.

Furthermore, the scenarios will be developed with the understanding that the further into the future we look, the more uncertain the predictions become [83, 94, 95].

Consideration of EU legislation and policy targets

The scenarios developed in FutuRaM consider targets that the EU is setting for specific elements, materials, and waste streams. The targets incorporated into FuTuRaM's scenarios are aligned with the ambitions of the EU's Green Deal [3] and its Critical Raw Materials (CRM) act [1].

Additionally, the consumer-product-centric waste streams BATT, ELV, and WEEE have specific EU legislation that is directly applicable to them and will be considered in detail in the scenarios [4, 5, 6, 142, 7,

WP2 — Aims and objectives definition

Table 2.2: FutuRaM WP2 aims and objectives

AIM	OBJECTIVE
Quantifying the current and future availability of secondary raw materials (SRM), particularly critical raw materials (CRM), for the identified waste streams from 2025 until 2050.	Developing a set of plausible scenarios that encompass these waste streams and provide quantitative estimates of the current and future availability of SRM and CRMs.
Informing private and public sector decision-making processes by assessing the impacts of different legislative and policy strategies related to waste management and resource efficiency	The scenarios will cover a range of such strategies, grouped in coherent sets in each of the three storylines including recycling, reuse, remanufacturing, and landfilling. Integration of the scenario with the system model will allow assessment of the impacts of these strategies not only on the availability of SRM and CRMs, but also on the environment, the economy, and society.

8].

GENERAL POLICIES AND LEGISLATION

The EU Green Deal [3] is a set of policy initiatives by the European Commission with the overarching aim of making the EU climate-neutral in 2050.

This policy portfolio is a response to the Paris Agreement and the United Nations Sustainable Development Goals. It covers a wide range of economic sectors with an emphasis on investments towards building local, 'sustainable' industries.

The scope of FutuRaM is aligned with the EU Green Deal's goal of ensuring the sustainable sourcing and use of raw materials, reducing dependency on imports, and promoting resource security. These goals can conflict with each other; however, the modelling in FutuRaM will explore the trade-offs between them (e.g., optimising local sourcing may result in higher negative externalities).

The EU Circular Economy Action Plan [2] is a policy framework developed by the European Commission to promote the circular economy in the European Union.

It sets out a comprehensive set of measures and targets to improve resource efficiency, reduce waste, and foster sustainable production and consumption. The Action Plan includes initiatives related to product design, waste management, recycling, and resource efficiency, among others. The Action Plan is a key element of the European Green Deal and is closely linked to the EU Industrial Strategy.

The Circular Economy Action Plan:

- Aims to promote the transition to a more circular economy in the EU.
- Sets out a range of measures to promote the sustainable use of resources, reduce waste, and increase recycling.
- Includes proposals for new legislation, such as an EU-wide framework for the circular economy, and revisions to existing legislation, such as the WEEE Directive.
- Emphasises the importance of product design for the circular economy and proposes measures to promote eco-design and repairability.
- Includes initiatives to promote the use of secondary raw materials, such as the establishment of a European Raw Materials Alliance.
- Aims to reduce greenhouse gas emissions and improve resource efficiency in the EU.
- Calls for increased cooperation and dialogue among stakeholders in the circular economy.

The Critical Raw Materials Act (CRM Act) [1] is an EU regulation that aims to ensure a secure and sustainable supply of raw materials to the EU.

The Act identifies a list of strategic raw materials, which are crucial to technologies important to Europe's green and digital ambitions and for defence and space applications, that are subject to potential supply risks. The regulation will cover the entire raw materials value chain, from primary extraction to manufacturing to potential recovery as a secondary raw material.

For example: According to the CRM act, by 2030, a single 'third country' (ex-EU, ex-Schengen) should produce no more than 65% of the EU's annual consumption of each strategic raw material.

Clear benchmarks have been set for the domestic capacities of the EU in 2030:

- Extract at least 10% of the EU's annual consumption
- Process at least 40% of the EU's annual consumption
- Recycle at least 15% of the EU's annual consumption

These benchmarks have been included in the scenarios developed in FutuRaM. Specifically, in the Recovery scenario (REC), where the emphasis is on the recovery of materials from waste streams, and the Circularity scenario (CIR) where the emphasis is on the implementation of 're-X' strategies, such as recycling, remanufacturing, and reuse.

Many of these targets, benchmarks and mandates — despite being included in legislation — are considered too optimistic to be included in the Business-as-usual scenario (BAU) as they often make expectations whose attainment is likely highly unrealistic without radical reform of the waste management system, For example, the targets in the Battery Act suggest near-complete recovery for several elements [8].

Extent of policy and legislation inclusion in the scenarios

The targets that result from the planned and ongoing review processes are non-negotiable and legally binding and thus should be incorporated into our scenarios. These targets, however, are only applicable to post-consumer products, namely WEEE, BAT and ELV. This envisioned future in which legally binding targets for collection, reuse and/or material recycling are achieved can be implemented as the Recovery scenario.

If there are no targets set for a specific consumer product category, then approach targets similar to the WEEE directive and in line with the EU Green Deal. For the Recovery, and especially for the Circularity scenario, FutuRaM will also consider the effects of proposed ecodesign requirements for sustainable products (e.g., longer lifetimes, increased reusability, repairability, recyclability).

However, for waste that does not consist of discarded consumer products, but instead results from industrial production activities, in particular for MIN and SLASH, we must still produce specific scenarios related to mining, metallurgy, and waste and fuel combustion. The production of new mining wastes will depend on new local mining activity.

Predicted production in the EU until 2050 will be forecast (equally across the three scenarios) and the flows into the MIN waste stream can be calculated with the respective transfer coefficients. The recovery of historical MIN stock, which is a target of the CRM Act, should be modelled differently. It requires a hypothesis about the percentage of historical tailings recoverable by commodity and country.

The scenarios will account for increasing resource use effectiveness and production process efficiency thus indicating lower volumes and quality of generated production residues (both by-products and waste such as red mud, waste rock, slags, etc.) per unit of product (expressed either as product mass or product value), whether that product is a metal (e.g., a copper cathode), metal alloy (e.g., aluminium alloy n° 5183) or metal product (e.g., cold rolled stainless steel sheet).

Excepting the BAU storyline, WEEE, ELV, and BATT waste material recovery will follow the targets in the EU.

For SLASH and MIN, we will evaluate recent trends in waste generation and extract plausible ranges of generation toward 2050.

For CDW, embedded WEEE will follow EU targets, and bulk waste will incorporate storylines and scenarios that are congruent with predicted demolition rates (where renovation is the alternative emphasised in the CIR storyline).

Various drivers will be assigned to move between these ranges and will be key to the specific, harmonized storyline for the scenario. Finally, the targets and storylines will be aligned with assumptions on technology development.

Consideration of geopolitical developments

The storylines also attempt to consider geopolitical considerations and thus supply chain resiliency for satisfying the product demand in the scenarios. We must omit, however, possible changes in waste flow volumes and composition that could arise from any material supply constraints.

The reasoning for this is that it would needlessly confuscate the interpretation of the modelling results as the incertitude of these potentialities is very high and this realm is outside the scope of FutuRaM's mandate and expertise.

The most volatile aspect of the 'criticality calculation' is the risk profile of the producing country. For many material-exporting nations, this is not something that can be reliably forecast, especially not over the next 30 years. Thus, it will be assumed that the growth in material demand for (among other needs) the energy and mobility transitions can be satisfied either by an increase in mining and metallurgy activities within the EU or by growing imports from raw material-producing countries outside the EU.

That is, if we go for increased domestic EU production to minimize geopolitical supply risk, it may indicate more EU production residue generation even under increased production efficiency and resource effectiveness. The increase of domestic industrial activity, as a response to an envisioned increased internal demand, supposes an equivalent rise of societal approval for mining and refining activities on EU territory.

If the increased demand is, however, satisfied by imports from non-EU countries, which we know have domestic resource consumption also growing significantly due to the energy and mobility transition, our assumption would be to shift the mining and refining activities from EU countries towards resource-rich non-EU countries.

This shift would also imply an increased risk for geopolitical instability and/or security of supply of critical raw materials to the EU.

This situation is front of mind for many in policy and business and the EU is 'applying a policy mix that aims to increase domestic capacity, diversify suppliers, and support the multilateral rules-based trade environment.'

However, '…most experts predict that reshoring or nearshoring will be of limited importance. With time, though, resilience may improve through international cooperation, diversification and the accelerated uptake of digital technologies.' [27]

Note: supply constrictions will be considered in the model's sensitivity analysis and the codebase will be designed to allow for the optimisation of the SRM recovery system based on any value statements (such as profit, environmental impacts, supply and demand).

2.2.2. Step 2: Determine methodology

Methodology types and selection criteria

The second step in the scenario development process is to determine the methodology to be used. This involves identifying the most appropriate methods and tools for the specific context and objectives of the scenario development process. The methodology should be selected based on the following criteria:

Relevance:
The methodology should be relevant to the specific context and objectives of the scenario development process.

Applicability:
The methodology should be applicable to the specific context and objectives of the scenario development process.

Feasibility:
The methodology should be feasible given the available resources (e.g., time, budget, expertise, data, etc.).

Transparency:
The methodology should be transparent and well-documented, allowing for replication and further analysis.

Flexibility:
The methodology should be flexible and adaptable, allowing for updates and adjustments as new information becomes available.

Accessibility:
The methodology should be accessible to a wide range of stakeholders, ensuring that it can be understood and used by non-experts.

Effectiveness:
The methodology should be effective in achieving the objectives of the scenario development process.

Efficiency:
The methodology should be efficient in terms of time, cost, and resources required to implement it.

Acceptability:
The methodology should be acceptable to stakeholders, ensuring that it is perceived as fair and legitimate.

Further details are given in this section, and the table in section 13.3 provides an overview of the methods and tools considered, along with a brief description of each and its relevance to the specific context and objectives of the FutuRaM scenario development process.

Choice of methodology

The grant proposal for the FutuRaM project outlined that there should be at least three scenarios developed, namely business as usual, recovery, and circularity. This remains the case; however, during the scenario development process, additional scenarios or scenario dimensions were considered, including supply chain security and the energy transition.

Considered dimension — Supply chain security:

Due to various political developments in 2022, the question of the security of the EU's supply chains for CRMs was brought into focus. This led to the proposal from stakeholders to consider a scenario dimension that would explore the security of the EU's supply chains for CRMs.

Considered dimension — Energy transition:

The energy transition is a key topic in the EU's policy agenda, and the FutuRaM project is concerned with the role of CRMs in the energy transition. Therefore, the proposal was made to consider a scenario dimension that would explore the energy transition in the EU.

Method — Multi-criteria analysis and cross-impact analysis

In order to assess the potential inclusion of these additional scenario dimensions, a multi-criteria analysis and a cross-impact analysis were conducted [96]. The addition of extra dimensions increases the possible number of scenarios significantly. By assessing the consistency and plausibility of these combinations with a matrix-based method, it was possible to reduce the number of scenarios.

For example, low progress in the energy transition is unlikely to concur with high progress in recycling/circularity indicators and can be excluded. In contrast, different levels for the supply chain security dimension would result in an additional scenario, as this dimension is considered independent of the others.

Ultimately, supply chain security was eliminated as a scenario dimension. This is due to the consortium's inability to speculate on geopolitical developments and the added incertitude it would introduce to the scenarios.

The potential of supply constraints will, however, be considered in the future sensitivity analysis of the model, as well as potentially through an array of explorative multi-object optimisation procedures. This can produce projects to answer the question, 'What would happen to the SRM system if element x is constrained, and what would be the optimal response to this constraint?'

Method — Delphi

The Delphi method [97] was used in the initial stages of the scenario-building process to gather and aggregate the opinions of experts or stakeholders. Internal consultation with consortium members who were experts in their respective waste streams or other aspects of the recovery system was conducted.

The method involves steps such as the selection of experts, generation of initial questionnaires, iterative rounds of responses, and convergence and consensus building. For the later stages of the process, further rounds of consultation will be conducted with external stakeholders, including representatives from industry, academia, and government.

Choice of Scenario Type

The general types of scenarios are summarized in Table 2.3. In the context of futures studies, various approaches and methodologies are employed to understand the potential trajectories of future developments [23, 82, 83, 90, 91, 92].

We can classify scenario studies into three primary categories, each addressing distinct questions about the future. These categories are tailored to better align with the specific objectives of scenario usage:

Predictive Scenarios (Answering 'What Will Happen?'):

Pros:
These scenarios offer insights into potential future outcomes, aiding in long-term planning.

Cons:
They are contingent on assumptions and may not account for unexpected events.

Applicability:
Predictive scenarios are valuable when the aim is to forecast future developments under certain conditions.

Explorative Scenarios (Answering 'What Can Happen?'):

Pros:
Explorative scenarios explore a wide range of potential future scenarios, fostering preparedness for various outcomes.

Cons:
They do not prioritize the likelihood or desirability of scenarios.

Applicability:
These scenarios are beneficial when considering multiple potential futures and the need to adapt to diverse outcomes.

Normative Scenarios (Answering 'How Can a Specific Target Be Reached?'):

Pros:
Normative scenarios focus on achieving predefined objectives and offer guidance on strategies to attain them.

Cons:
They are inherently normative, starting with specific goals in mind.

Applicability:
Normative scenarios are suitable when the objective is to work towards predefined targets and develop actionable plans to reach them.

The choice of scenario category is influenced not only by the characteristics of the system under study but also by the user's worldview, perceptions, and study objectives. Additionally, the user's perspective plays a crucial role in determining the most suitable approach. For instance, the decision to employ predictive, explorative, or normative scenarios hinges on the user's goals and the nature of the questions they seek to answer.

Furthermore, considerations regarding the predictability of the future and the potential for influencing it can impact the selection of scenario types. For example, some users may argue that uncertainty in certain parameters makes long-term predictions less meaningful, while others may see value in using forecasting and optimisation models to stimulate discussions and inform decision-making processes.

In practice, a combination of qualitative and quantitative techniques can be employed to create scenarios tailored to specific needs. For instance, a blend of techniques may be used to generate forecasts, especially when external factors are uncertain. Likewise, strategic scenarios often begin with external scenario generation and proceed to identify available policy options.

Table 2.3: Types of scenario (adapted from [23, 82])

SCENARIO CATEGORY	SCENARIO TYPE	OUTCOME	TIMEFRAME	SYSTEM STRUCTURE	FOCUS ON FACTORS
Predictive *what will happen?*	Forecasts	Typically quantitative, sometimes qualitative	Often short	Typically one	Typically external
	What-if	Typically quantitative, sometimes qualitative	Often short	One to several	External and, possibly, internal
Explorative *what can happen?*	External	Typically qualitative, quantitatively possible	Often long	Often several	External
	Strategic	Qualitative and quantitative	Often long	Often several	Internal under influence of the external
Normative	Preserving	Typically quantitative	Often long	One	Both external and internal
	Transforming	Typically qualitative with quantitative elements	Often very long	Changing, can be several	Not applicable

Back to ToC

The scenarios developed in the FutuRaM project are a combination of predictive and normative:

BAU:

What will happen if current trends continue? This scenario is predictive in nature, based on the assumption that the current trends and developments in waste management and resource recovery systems will continue into the future.

Recovery:

What will it take to achieve the EU's targets for material use and recovery?
Focus on technology This scenario is normative, focusing on manipulating the technology and infrastructure of the recovery system to achieve the EU's targets and mandates.

Circularity:

What will it take to achieve the EU's targets for material use and recovery?
Focus on re-X strategies This scenario is a combination of normative and explorative, considering the targets and mandates of the EU's circular economy action plan and exploring re-X strategies in the recovery system.

The methodology and scenario types were selected based on their relevance, applicability, feasibility, transparency, flexibility, accessibility, effectiveness, efficiency, and acceptability to the scenario development process.

2.2.3. Step 3: Marker-scenario mapping

Justification and methodology

This preliminary step in the scenario development process involves conducting a literature study to identify existing scenarios that are relevant to the FutuRaM project. This step is crucial as it serves several important purposes and provides valuable insights for the overall scenario development process. It helps the scenario development team to build on existing knowledge, identify relevant scenarios, gain insights and inspiration, fill knowledge gaps, and enhance credibility and comparability.

Building on existing knowledge
Conducting a literature study allows the FutuRaM project team to tap into existing knowledge and expertise in the fields of waste management, resource recovery, and circular economy. It provides a foundation of existing scenarios that have been developed by other researchers, organizations, or institutions. By building on this existing knowledge, the FutuRaM project can leverage the insights, methodologies, and findings from previous scenario studies, saving time and resources.

Identifying relevant scenarios
Marker scenario mapping helps identify scenarios that are relevant to the specific objectives and scope of the FutuRaM project. By reviewing the literature, the project team can assess the applicability of existing scenarios to their research questions and determine which scenarios align with the waste streams, sectors, and policy domains being considered. This step ensures that the scenarios selected for further analysis are well-suited to address the project's goals.

Gaining insights and inspiration
Reviewing existing scenarios provides the FutuRaM project team with valuable insights and inspiration for the development of their own scenarios. It allows them to understand the different approaches, assumptions,

and methodologies used in previous scenario studies. This knowledge can inform the design and structure of the FutuRaM scenarios, helping to ensure a rigorous and well-founded approach.

Filling knowledge gaps

Marker scenario mapping helps identify any gaps or areas of limited knowledge in the existing scenario landscape. It allows the FutuRaM project team to identify topics or aspects that have not been adequately addressed in previous scenarios. This awareness of knowledge gaps can guide the project team in focusing their efforts on areas where new insights and contributions can be made, leading to a more comprehensive and innovative scenario development process.

Enhancing credibility and comparability

By conducting a literature study and referencing existing scenarios, the FutuRaM project can enhance the credibility and comparability of their own scenarios. The project team can reference and compare their findings, assumptions, and results with those from previous studies, contributing to the overall body of knowledge in the field. This promotes transparency, robustness, and consistency in the scenario development process and allows for better benchmarking and evaluation of the FutuRaM scenario set.

Content of the marker scenario mapping for application to FutuRaM's scenarios

Table 13.4 in section 13.4 presents an overview of the marker scenarios considered in the FutuRaM project. The table is not intended to be exhaustive but rather to provide an overview of the different scenarios that have been developed in the fields of waste management, resource recovery, and circular economy.

2.2.4. Step 4: Identification of key drivers of change

In this step, the key drivers of change that will shape the future of the scenarios are identified. Key drivers are the factors or forces that have a significant influence on the waste management system and its development over time. These drivers can be social, economic, technological, environmental, or policy-related.

The purpose of identifying key drivers of change is to understand the factors that will have the greatest impact on waste management and to ensure that the scenarios capture the range of possible outcomes influenced by these drivers.

The process of identifying key drivers involves a combination of literature review, expert consultations, and stakeholder engagement. It requires a comprehensive analysis of relevant trends, uncertainties, and emerging issues that may affect the waste management system.

The key drivers identified in this step will be used to develop the storyline themes and scenario parameters in the next step.

Figure 2.2 illustrates the process of identifying key drivers of change.

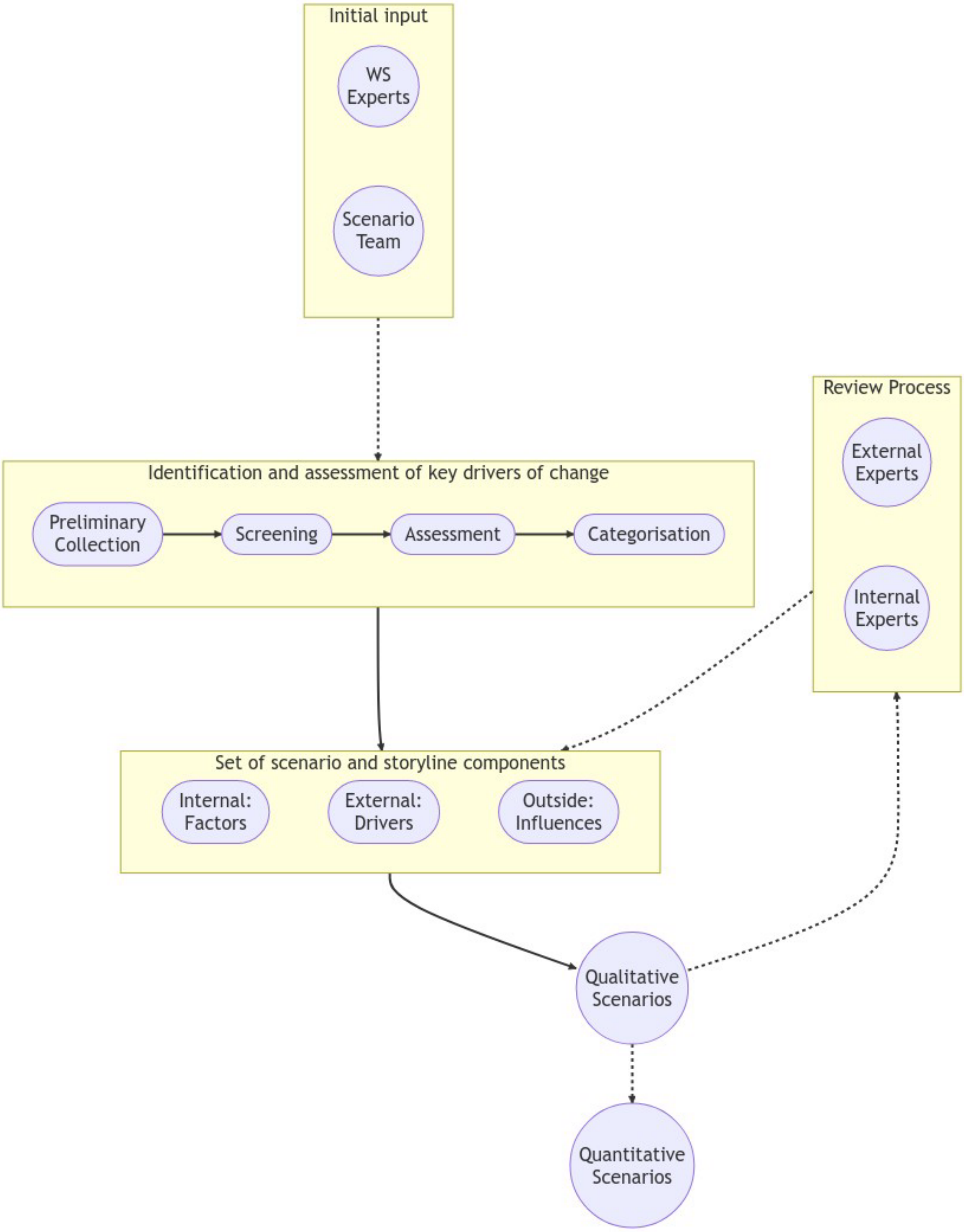


Figure 2.2: An illustration of the process used for identifying key drivers of change

Methodology and results of this stage in FutuRaM's scenario development:

The overall goal of this process is to identify and include elements in the storylines and scenarios that are relevant, plausible, and influential in shaping the future.

The selection, screening, and categorisation steps ensure that the elements chosen for the development of storylines and scenarios are consistent, coherent, and aligned with the objectives and scope of the scenario exercise.

1. **Preliminary collection:**

   This step involved gathering a pool of potential elements that could be included in the storylines and scenarios.

   These elements were derived from expert input from waste streams and the scenario development team, including taking knowledge from the literature review and existing scenarios identified in Step 2 — Marker scenario mapping.

   This step was conducted using the PESTLE analysis framework. The PESTEL (or PESTLE) framework is a strategic tool used to understand the macro-environmental factors that can affect a system.

   A PESTEL analysis can help identify opportunities and threats linked to each of these factors, understand the broader context, and shape scenarios accordingly [98, 77].

   The acronym PESTEL stands for:

   Political:
   These factors refer to the impact of government policies, regulations, and political stability. This includes issues like tax policy, labour laws, environmental regulations, trade restrictions and reforms, tariffs, and political stability.

   Economic:
   These factors relate to the broader economic environment, including factors like economic growth, exchange rates, inflation rates, interest rates, disposable income of consumers and businesses, and the general health of the economy.

   Sociocultural:
   These factors include societal trends and characteristics that could affect your business. They include demographic trends (like age, gender, and ethnicity), cultural trends, lifestyle preferences, consumer attitudes, and broader societal expectations.

   Technological:
   These factors refer to the impact of emerging technologies, research and development activities, automation, the rate of technological change, and the adoption of technology within your market.

   Environmental:
   These factors refer to ecological aspects that can affect a system. This includes environmental regulations, consumer attitudes towards sustainability, climate change, and other natural events.

   Legal:
   These factors include laws and regulations with which your business must comply. These can include labour law, consumer law, health and safety law, and restrictions on the import or export of goods.

   The 68 elements identified in the initial screening stage are listed in section 13.5.

2. **Screening:**

   In the screening step, the collected elements are evaluated and assessed based on specific criteria. This was conducted through a literature study and internal consultation of scientists in the project. This evaluation helps determine the relevance, reliability, and significance of each element for the development of storylines and scenarios. Many elements were aggregated, especially if they were deemed to follow similar trends to others (e.g., recyclability mandates and improved recyclability in project design). Elements that did not meet the predefined criteria or were deemed irrelevant, 'un-modellable' or unreliable were excluded from further consideration (e.g., corruption, data protection, and supply chain conflict).

   The 28 elements that were identified in this stage are listed in section 13.6.

   In Figure 2.3, an excerpt of a spreadsheet illustrates part of the screening process for the FutuRaM scenarios, which was informed by the waste streams. In this exercise, the elements were evaluated based on their relevance to the waste streams and their potential impact on the waste management system.

   The elements were also assessed based on their plausibility and likelihood of occurrence in the future. The elements that were deemed relevant, plausible, and influential were included in the storylines and scenarios.

THIS TABLE IS FOR THE ASSESSMENT OF THE RELEVENCE OF EACH SCENARIO ELEMENT TO INDIVIDUAL WASTE STREAM FLOWS	ELV			BAT					WEEE					
DRIVER/FACTOR	Bulk metals	Critical raw materials	Average	Portable Batteries	Industrial Batteries	Automotive (SLI) Batteries	EV Batteries	Average	CAT-I - Temperature exchanger	CAT-II Screens	CAT-III Lamps	CAT-IVa Large equipments	CAT-IVb PV	CAT-' Smal equi nts
Population				5.00	5.00	4.00	5.00	4.75	5.00	5.00	5.00	5.00	5.00	5.
Resource shortage	3.00	5.00	4.00	5.00	5.00	2.00	5.00	4.25	4.00	5.00	4.00	4.00	5.00	4.
Treatment cost				4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.
Digital product passports	3.00	3.00	3.00	4.00	4.00	4.00	4.00	4.00	3.00	3.00	3.00	3.00	3.00	3.
Obsolescency	1.00	5.00	3.00	4.00	4.00	3.00	4.00	3.75						
Digitalization	1.00	5.00	3.00	4.00	4.00	3.00	4.00	3.75						
SRM prices				4.00	4.00	2.00	4.00	3.50	4.00	4.00	4.00	4.00	4.00	4.
Product prices				3.00	4.00	1.00	4.00	3.00	3.00	5.00	3.00	3.00	3.00	3.
Recyclability mandates	4.00	5.00	4.50	3.00	3.00	3.00	3.00	3.00	2.00	3.00	2.00	2.00	2.00	3.
Conflict in supply chain	4.00	5.00	4.50	4.00	4.00	0.00	4.00	3.00	2.00	3.00	2.00	2.00	3.00	2.
Obligatory recycling standards for treatment facilities				3.00	3.00	3.00	3.00	3.00	2.00	2.00	2.00	1.00	1.00	2.
Improved durability	4.00	5.00	4.50	3.00	3.00	1.00	3.00	2.50						
Composition change				3.00	3.00	0.00	4.00	2.50						
Subsidies				2.00	3.00	1.00	3.00	2.25	3.00	2.00	3.00	4.00	4.00	2.
Availability of recovery technologies				3.00	3.00	0.00	3.00	2.25	1.00	4.00	1.00	1.00	4.00	4.
Taxation (raw materials, landfill)	4.00	4.00	4.00	2.00	2.00	3.00	2.00	2.25	2.00	2.00	2.00	2.00	4.00	2.
Obligatory removal of CRMs from waste				3.00	3.00	0.00	3.00	2.25	1.00	2.00	2.00	1.00	2.00	2.
Corruption	2.00	2.00	2.00	3.00	3.00	0.00	3.00	2.25	1.00	1.00	1.00	1.00	1.00	1.
Supply chain due diligence laws	4.00	4.00	4.00	0.00	4.00	0.00	4.00	2.00	0.00	1.00	0.00	0.00	1.00	1.
Improved recyclability	4.00	5.00	4.50	2.00	2.00	0.00	2.00	1.50						
Ecodesign				2.00	2.00	0.00	2.00	1.50						
Trade barriers	3.00	5.00	4.00	2.00	2.00	0.00	2.00	1.50	2.00	3.00	2.00	2.00	3.00	2.
Industrialisation of Europe	4.00	5.00	4.50	0.00	2.00	0.00	3.00	1.25	3.00	3.00	1.00	3.00	3.00	1.
Reduced consumerism	5.00	3.00	4.00	0.00	1.00	4.00	0.00	1.25	1.00	3.00	2.00	1.00	0.00	2.
Accessibility/Infrastructure			#DIV/0!	3.00	0.00	0.00	0.00	0.75	3.00	4.00	4.00	3.00	3.00	4.
New mines in rich EU countries?	3.00	5.00	4.00	1.00	1.00	0.00	1.00	0.75	3.00	2.00	3.00	4.00	4.00	2.
Miniturisation	3.00	5.00	4.00	1.00	0.00	0.00	0.00	0.25						
Sharing economy	4.00	4.00	4.00	1.00	0.00	0.00	0.00	0.25	1.00	1.00	1.00	3.00	1.00	1.
Repairability mandates	5.00	5.00	5.00	0.00	0.00	0.00	0.00	0.00	2.00	3.00	3.00	3.00	2.00	3.
Renewable energy targets				0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.00	0.

Figure 2.3: An excerpt of a spreadsheet used as part of the screening process

3. **Assessment:**

   Once the screening process was complete, the remaining elements were aggregated and categorized based on their thematic relevance or characteristics. This categorisation helps organize the elements into meaningful groups or themes that align with the objectives and scope of the scenarios. The 21 elements that were identified in this stage are listed in Table 2.4. Note that CIR and REC are very similar for many scenario elements, the main difference being the way in which the targets are achieved. That is, for CIR, re-X strategies are promoted, whereas, for REC, the focus is on technological advancements in the recovery system. This distinction will have a significant impact on how the scenarios are quantitatively modelled and on the subsequent outcomes of these models.

Table 2.4: List of drivers and factors identified in the screening phase

DOMAIN	DRIVER/FACTOR	DEFINITION	INTERNAL	BAU	REC	CIR
TECH	Recovery technology	Implementation and advancements in waste recovery technologies	TRUE	I	III	III
TECH	Product technology	Changes in product function or composition	TRUE	I	III	III
TECH	Integration of SRM system across EU	Integration of a secondary raw material recovery system across EU countries	TRUE	I	III	III
ENV	Increased drive for environmental protection	Growing concern and motivation for environmental conservation	TRUE	I	III	III
ECO	Progress toward renewable energy targets	Advancements and achievements in renewable energy generation	TRUE	III	III	III
ECO	Subsidies and taxation to promote circularity	Financial incentives or taxes to encourage circular economy	TRUE	I	II	III
SOC	Participation in re-X activities	Engagement in refuse-reduce-repair-reuse activities	TRUE	I	I	III
POL	Stricter environmental regulations	Tightening of environmental laws and regulations	TRUE	II	III	III
POL	Stricter waste management regulations	Strengthening of waste management laws and regulations	TRUE	II	III	III
POL	Supply chain due diligence laws: implementation and enforcement	Obligations for identifying and mitigating negative impacts in supply chains	TRUE	I	III	III
POL	Compliance with waste targets	Meeting specific waste management and recycling targets	TRUE	I	III	III
ENV	Resource shortages	Limited availability of natural resources	FALSE	n/a	n/a	n/a
ECO	Raw material vs SRM prices	Price dynamics and competition between raw materials and secondary raw materials	FALSE	n/a	n/a	n/a
ENV	Climate change impactsmitigation	Effects and actions related to climate change	FALSE	n/a	n/a	n/a
ECO	International trade and co-operation (vs. autarky)	Collaborative trade agreements and global cooperation	FALSE	n/a	n/a	n/a
ECO	Energy prices	Costs and fluctuations in energy prices	FALSE	n/a	n/a	n/a
ECO	Economic growth	Overall economic expansion and development	FALSE	n/a	n/a	n/a
ECO	Re-industrialisation of EU	Shift towards increased industrial activities in the EU	FALSE	n/a	n/a	n/a
SOC	NIMBY to projects	Opposition to local projects and developments	FALSE	n/a	n/a	n/a
SOC	Population and urbanisation	Growth and urban development of population	FALSE	n/a	n/a	n/a
ECO	CO2 market price	Price and market dynamics of carbon emissions	FALSE	n/a	n/a	n/a

Back to ToC

4. **Categorisation**

The scenario elements were then assessed based on their potential impact on the waste management system. For each element, an assessment was made as to whether it was within the scope of FutuRaM to include them as variables in the models, and therefore also the scenarios and their storylines.

Those deemed to be within the scope are 'internal' and will be intensively researched and modelled (e.g., composition and design changes).

Those deemed to be outside the scope are 'external' and will be included in the storylines, will vary over time, but will not vary across the three scenarios (e.g., population and GPD).

Those deemed to be outside the scope and also outside the influence of the waste management system are 'outside' and will not be included in the storylines or scenarios, though, in some cases, may be considered in the sensitivity analysis (e.g., supply constraints).

Justification for keeping certain elements outside of the scenario models:

The purpose of the FutuRaM project is not to provide all-encompassing scenarios that attempt to capture every possible future development. Such scenarios are inherently inaccurate and can give a false sense of certainty to the model's outcomes. Instead, the focus of FutuRaM is specifically on the Sustainable Resource Management (SRM) system and its implications for the future. Therefore, the scenarios developed within FutuRaM should selectively incorporate elements that have a direct impact on the SRM system.

Furthermore, the scenarios should prioritize elements that can be considered as 'policy knobs', meaning variables or factors that can be adjusted or controlled to test different settings. By including these, the scenarios can explore the effects of different policy decisions or interventions on the SRM system's outcomes. This targeted approach ensures that the scenarios generated are relevant to the project's objectives and facilitate meaningful analysis.

It is crucial to avoid excessive complexity and convolution in scenario modelling. When there are too many convoluted elements included, the results of the modelling exercise can become, at best, difficult to understand and interpret. At worst, the outcomes may become practically useless due to the overwhelming interactions and uncertainties introduced by the complex elements. Therefore, careful consideration is necessary to strike a balance between incorporating essential factors and maintaining the clarity and usefulness of the scenario modelling results.

Examples:

Resource shortages:

Resource shortages can be highly unpredictable and subject to various external factors such as geopolitical events, natural disasters, or technological advancements. The precise timing and extent of resource shortages are challenging to forecast accurately, making it difficult to include them within the model without introducing significant uncertainty.
This is especially true for the long-term time horizon of the FutuRaM scenario set. This factor will, however, be considered in the sensitivity analysis of the model and additionally, the codebase will be designed to allow for the optimization of the SRM recovery system based on any supply-demand value statements.

Raw material vs SRM prices:

The dynamics and competition between raw materials and secondary raw materials can be complex and influenced by various market factors, technological advancements and policy interventions. As with resource shortages, these dynamics are challenging to forecast accurately, making it difficult to include them within the model without introducing significant uncertainty.

It will, however, be possible to couple the model with a market model to explore the effects of different price dynamics on the SRM system's outcomes. This could be considered in a multi-objective optimization procedure performed as an extension to the model.

2.2.5. Step 5: Develop storyline themes

Given that the scenario themes and directions were broadly dictated by the FutuRaM project charter, the rough shapes of the storyline narratives were already defined. That is: the effects on the availability of SRMs from the development of the SRM recovery system and the development of re-X strategies.

2.2.6. Step 6: Qualitative narrative development

The scenario storylines will be described in detail in the next section. This step involved taking the themes defined by the charter and the elements identified in the previous steps and working with the internal waste stream groups to develop qualitative estimates about how each of these elements (at their different levels) may have an impact on the amounts and composition of the SRM flows in their purview.

2.2.7. Step 7: Definition of scenario parameters

The scenario parameters are the set of quantitative values or functions that will be used to define the scenario inputs for the model. Details of these parameters can be found in chapter 4.

2.2.8. Step 8: Quantitative modelling

Full details of the scenario quantification process can be found in chapter 4.

2.2.9. Step 9: Implementation

The scenario implementation will be performed in the next stages of the project.

2.2.10. Step 10: Review process

The review process is intended to ensure that the elements included in the storylines and scenarios are relevant, plausible, and consistent with the scenario objectives and scope.

The first stage of the review process is to open the scenario development process to the wider FutuRaM consortium. This will be done by sharing the scenario development process and the results of the assessment and categorisation step with the consortium and inviting feedback and suggestions. The feedback will be used to refine the elements and their categorisation and to identify any elements that may have been missed in the initial assessment.

The second stage will involve opening the scenario development process to external stakeholders and subject matter experts.

The scenario review process will be performed repeatedly over all stages of the project. This document is a living document and will be updated as the project progresses.

Conclusion of methodology section

The methodology used for the FutuRaM scenario development ensured that the selected elements were relevant, plausible, and influential. The use of the PESTEL analysis framework and Delphi method during the preliminary collection phase provided a comprehensive overview of the macro-environmental factors.

Furthermore, the screening process and the assessment by internal experts ensured that the selected elements were coherent, consistent, and aligned with the objectives and scope of the scenario exercise.

The final list of scenario elements is suited to the goal of the FutuRaM project — to quantify the future availability of SRMs and to evaluate EU material autonomy — and will be used to develop the three FutuRaM scenarios into a quantitative model.

Scenario storylines

CHAPTER CONTENTS

3.1. SCENARIO I: BUSINESS-AS-USUAL

3.1.1. Context

> **Can the Supply of Natural Resources Really Be Infinite? Yes!**
> Hold your hat — our supplies of natural resources are not finite in any economic sense. Nor does past experience give reason to expect natural resources to become more scarce. Rather, if history is any guide, **natural resources will progressively become less costly, hence less scarce**, and will constitute a smaller proportion of our expenses in future years. Population growth is likely to have a long-run beneficial impact on the natural-resource situation.
> — *Julian Lincoln Simon in The Ultimate Resource [70, 71]*

> Population growth, along with over-consumption per capita, is driving civilisation over the edge: billions of people are now hungry or micronutrient malnourished, and climate disruption is killing people. [Societal collapse] is a near certainty in the next few decades, and the risk is increasing continually as long as perpetual growth of the human enterprise remains the goal of economic and political systems. As I've said many times, **'perpetual growth is the creed of the cancer cell'**
> — *Paul Ehrlich [155], see also [72, 73, 99]*

3.1.2. Storyline narrative

This scenario envisions the future based on the current situation, extending to 2050 with very little deviation from present consumption patterns and the secondary raw material (SRM) system [28]. While there may be advances in some areas such as resource efficiency, recovery technology, and the energy transition, substantial modifications remain hindered by economic, social, and political constraints. The primary extraction of raw materials continues to be the primary source to meet the EU's demand.

In the Business As Usual (BAU) scenario, we are projecting the trajectory of the present into the future, extending up to the mid-century mark, 2050, with minimal disruption to existing consumption habits and the secondary raw material (SRM) system. This scenario unfolds on the assumption that the current pace and direction of technological, economic, and social development continue unhindered, and is characterised by a strong persistence of today's patterns.

In this scenario, we see moderate improvements in resource efficiency, advancements in recovery technology, and a slow transition towards greener energy sources. However, these developments are only minor tweaks to the existing system, failing to disrupt or fundamentally alter the established structure. The potential for transformational change remains largely untapped due to various hurdles. Economic constraints, social resistance to change, political inertia, and entrenched interests act as barriers to change, stifling efforts toward a more sustainable SRM system.

Primary extraction of raw materials remains the dominant source for raw materials consumed in the EU, continuing the linear 'take-make-dispose' model of resource consumption (see Figure 3.1). Base metals are well recycled, given their developed markets and economies of scale but rare/special metals are wasted because recycling technologies and economics do not allow for their recovery. Recycling and recovery rates remain stubbornly low, resulting in significant CRM waste. Meanwhile, material demand continues to rise in tandem with GDP growth, further exacerbating the resource pressure.

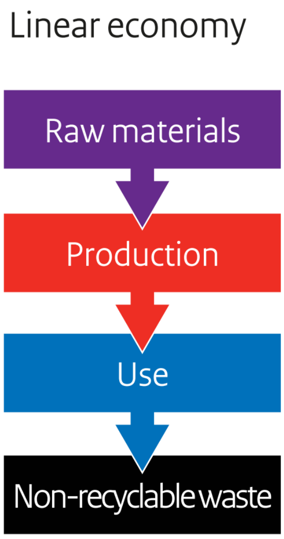


Figure 3.1: The linear economy model in the business-as-usual scenario [9]

Moreover, the environmental impacts of mining and extraction persist as a significant concern. These operations continue to degrade ecosystems, leading to loss of biodiversity and contributing to climate change [29]. Simultaneously, the EU becomes increasingly dependent on imports of SRMs, raising concerns about supply chain security and geopolitical risks [29].

Innovation in SRM recovery technologies is hampered by a lack of investment and regulatory support. The focus remains predominantly on cost-effective material production and use, with little regard for environmental implications or long-term sustainability. Material scarcity and price fluctuations, therefore, may become a considerable risk to the EU industry, limiting stable penetration of new recovery technology and threatening economic stability.

Moreover, the tightening of environmental regulations is restricted, inadequately addressing emerging challenges or incentivising sustainable practices. The lack of regulatory progress may further exacerbate environmental damage and biodiversity loss.

In essence, the BAU scenario is characterised by a continuation of current trends and practices, a future where the potential for a sustainable SRM system is unrealised due to the stranglehold of prevailing economic, social, and political constraints.

In the Business-as-usual (linear economy) scenario, the following are key characteristics:

- A forecasting model is used to predict the future based on the current situation and the development of existing trends.
- Many EU targets for recycling and recovery are not met, and the current linear model largely persists.
- Material demand keeps pace with GDP growth, perpetuating a trend of increasing consumption. Primary mining and extraction persist as the leading sources of raw materials, underlining the dependency on traditional extraction methods.
- Recycling and recovery rates continue to lag, leading to an accumulation of SRM waste that signals missed opportunities for resource reuse.

- The environmental repercussions of mining and extraction, such as land degradation and water pollution, continue to be a pressing concern, reflecting the ecological toll of this linear model.
- The EU's dependency on imports of SRMs escalates, heightening the risk of supply disruptions. While supply disruption can serve to stimulate investment in new SRM recovery, volatility stifles innovation and advancements in this field.
- The industrial focus remains on cost-effective material production and use, disregarding the long-term sustainability aspect.

3.1.3. Waste stream specific scenario impacts

BATT (Battery waste)

Sources: [24, 86, 7, 8]

In the business-as-usual (BAU) scenario, the management of end-of-life batteries remains largely unchanged. The lack of technological innovation and regulatory incentives leads to a continued low recovery rate 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 Li-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

ELV (End-of-Life Vehicles)

Sources: [86, 142, 30, 31, 32, 33]

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 ICEVs 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 in comparison to 2023

WEEE (Waste Electrical and Electronic Equipment)

Sources: [5, 6, 34, 35, 36, 78]

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 the REC scenarios are similar from the put-on-market perspective (e.g., production and consumption remain the same), but it's the recovery stage that makes the difference.

MIN (Mining Waste)

Sources:

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.

CDW (Construction and Demolition Waste)

Sources: [10]

In the BAU scenario, the management of Construction and Demolition Waste (CDW) remains largely unchanged.

- Focus on new construction to meet demand, no changes in CDW generation rate.
- No increase or refurbishment or renovation activities relative to new construction rates.
- Continue meeting the 2020 EU target from the Waste Directive [10] of 70% CDW recovery (including preparation for re-use, recycling, and other material recovery, including backfilling)
- Recovery of metals remains on already high levels (90%) [100].
- Recovery of minerals remains on already high levels (70%) by using them as aggregates in road construction and backfilling [100].
- Recycling of wind turbines stays around 85% (mainly metals), permanent magnets continue to be recycled as part of the metal fractions.[CITATION]
- Base metals are recovered as they have been, though there are 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).

SLASH (Slags and Ashes)

Sources: [143, 144, 101, 145, 102]

In the BAU scenario, SLASH continues to be treated generally 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 and contain mainly minerals with some metals that could not be recovered during the metallurgical process. The reasons the metals are not recovered are:

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

More than 90% of the slags are minerals, therefore the slags that are in line with the 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 2013-2023, there was a stable production of metals, which results in a stable production of slags.
- Due to the energy transition, it is expected the volume of slags from "classic" furnaces (eg BOF) will reduce and the number of slags from electric arc furnace will go up.
- There are limited facilities to recover CRMs/SRMs, but the metallurgical companies do their best to recover as much of the metals as per their economic interests.

ASHES

Ashes are the waste products from the incineration of fossil fuels, biomass, or waste. We distinguish two main types: fly ashes and bottom ashes. Coal fly ashes are used as SCM to replace cement up to 30%. Biomass (bottom and fly) ashes are used (based on the composition) as fertilizer or landfilled. Fly ashes from waste incineration are landfilled, while the bottom ashes are — depending on the location in the EU — further treated.

The fractions that are rich in ferrous metals, aluminium, copper, and zinc are separated and used as input materials for the Fe, Cu, Zn, Al industries. By processing the Cu-rich fractions, PGMs, Ag, and Au are also recovered. The main part of the bottom ashes consists of mineral aggregates, which are used in the construction industry (when they are in line with the environmental criteria). In case the ashes are not treated (or only partly treated), they will be landfilled.

- In the last 10–20 years in some EU countries, we have seen a shift from landfilling towards incineration. This will lead to an increase in the volume of ashes from waste incineration.
- There was a drop in the use of coal as a fuel source, so the volume of coal ashes dropped over the last 10 years and is expected to drop further.
- At the same time the volume of biomass incineration went up. It is uncertain if this volume will increase in the future further (due to the high pressure on land that is needed to produce this biomass).
- Almost all coal fly ashes are used as SCM (high-value stream up to 80 EUR/ton). For Biomass fly ashes there are no sorting facilities, while for waste inceration bottom ashes, there are sorting installations in place, but for the moment, they are not present in all EU countries, and therefore, there is still room for improvement.

3.2. SCENARIO II: RECOVERY

3.2.1. Context

> We are in a period of economic transition. The 'cowboy economy' of the past is obsolescent, if not obsolete. Environmental services are no longer free goods, and this fact is driving major changes. Recycling is the wave of the (immediate) future. **The potential savings in terms of energy and capital have long been obvious. The savings in terms of reduced environmental impact are less obvious but increasingly important.** The obstacle to greater use recycling has been the fact that economies of scale still favor large primary mining and smelting complexes over (necessarily) smaller and less centralized recyclers. But this advantage is declining over time as the inventory of potentially recyclable metals in industrialized society grows to the point that efficient collection and logistic systems, and efficient markets, justify significant investments in recycling. **Increasing energy and other resource costs, together with increasing costs of waste treatment and disposal, will favor this shift in any case.** But government policies, driven by unemployment and environmental concerns, taken together, may accelerate the shift by gradually reducing taxes on labor and increasing taxes on extractive resource use.
>
> *— Robert U. Ayres [103]*

> One does not require much of an imagination to picture how complex it is to physically and chemically separate these components again to ultimately retrieve the metals. **It's just about as difficult as recycling your morning cup of coffee into its ingredients…** There are no simple answers here — at some point, the amount of effort also outweighs the value of the metal content. This knowledge should prompt a consciousness shift in our utilization of our limited resources…
> **The inconvenient truth is that closing the loop is impossible!** Therefore, an honest discussion involves speaking transparently about losses in the process: in the form of energy, metals, and dust, for example. There are technological and economic limits to closing the loop.
>
> *— Prof. Dr. Dr. h.c. mult. Markus Reuter [156]*

3.2.2. Storyline narrative

In the recovery scenario, the central emphasis is on harnessing sophisticated technologies to salvage SRMs from waste streams at the end of their lifecycle. While there are noticeable strides towards the incorporation of 'circular design' principles and re-X strategies, they are mostly seen at the end-of-life and material demand is akin to that observed in the BAU scenario. This is, however, mitigated by the implementation of a comprehensive material recovery system. Figure 3.2 presents a simplified visual depiction of the dominant material flow paths in the recovery scenario.

In this scenario, the central actor is the waste treatment sector, with the spotlight falling on the enhancement of recovery technology. The implementation and optimisation of cutting-edge technologies, such

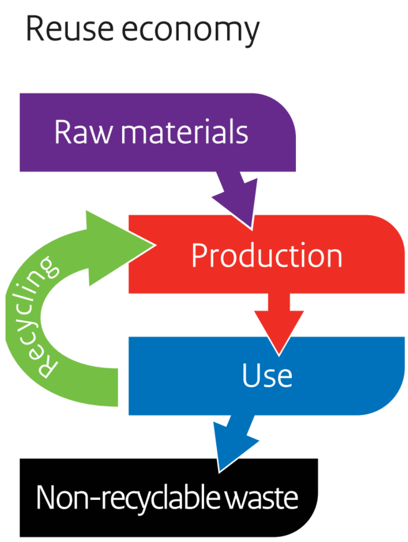


Figure 3.2: The reuse economy model in the recovery scenario [9]

as Artificial Intelligence (AI), automation, and advanced robotics, play a significant role in revolutionising waste treatment processes. These technologies streamline waste sorting, improve the quality of recovered materials, and increase the overall efficiency of the recovery process.

This scenario calls for an emphasis on policy development and standardisation to foster EU-wide development, integration, and compliance. Here, the role of governments and policy-makers becomes crucial in setting more ambitious recovery targets, developing conducive regulatory frameworks, and enforcing compliance. This multi-pronged approach also involves strengthening cross-border cooperation, harmonising waste management standards, and promoting knowledge and technology transfer among EU member states.

To realise more ambitious environmental impact reduction targets, significant progress needs to be made in both technological and policy aspects. Enhancing technological capabilities will improve recovery rates, while robust policy measures will ensure these advancements are integrated into the wider economy in a regulated manner. The future of this scenario depends on the successful fusion of advanced technology, regulatory harmonisation, and a commitment to continuous improvement in waste management and SRM recovery.

Key characteristics of this technology-promoted recovery scenario include:

- This scenario uses a combination of forecasting and backcasting methods to envision the future.
- The backcasting method is used for scenario factors that are covered by governmental targets, starting with the desired outcome and working backwards to the present.
- The forecasting method is used for scenario factors that are not covered by governmental targets, starting with the current situation and extending to the future.
- EU targets for recycling and recovery are met, due to the EU's waste management system becoming more expansive, efficient and effective.
- Technological innovation drives increased recovery rates of SRMs, enabling the more efficient use of waste.
- Digitalisation and automation are more extensively used in recycling processes, leading to enhanced productivity and accuracy.
- There is greater exploration and exploitation of alternative sources such as urban mining, waste streams, and tailings, presenting novel opportunities for resource acquisition.

- New waste regulations and guidelines for SRM recovery are implemented, enforcing better management and extraction of SRMs.
- Investment in research and development for SRM recovery technologies experiences an upswing, promoting continuous innovation in this field.
- Closer collaboration and information sharing between industry and government institutions streamline processes and expedite decision-making.
- New jobs are created in the recycling and recovery sector, offering economic benefits and improving overall employment rates.
- SRM production and use become more efficient and cost-effective, fostering economic sustainability.
- Environmental impact from mining and extraction is reduced, signalling a more sustainable approach to resource acquisition.
- The EU's dependence on primary extraction is reduced, with SRM recovery becoming a more significant source of raw materials.

3.2.3. Waste stream specific scenario impacts

BATT (Battery waste)

Sources: [24, 86, 7, 8]

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.
- Industry and government collaboration 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 (LMT) 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 that fewer batteries end up in the municipal waste stream and there is less hoarding.
- Against this: there is competition for the batteries from the reuse vs. recycling market.
- Design for recycling (DFR):
  - Material and composition selection for recycling [86].
  - Higher requirements on disassemblability.
  - Information available to promote efficient recovery.

ELV (End-of-Life Vehicles)

Sources: [86, 142, 30, 31, 32, 33]

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 end-of-life of vehicles
- EU recovery targets are reached (currently implemented/proposed targets, but also increased and new targets)
- Common/bulk materials (Fe, Non-Fe, plastics etc.,) 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
  - Increase in collection rate due to increase in participation from the public and businesses, i.e., target-based incentives with strong regulations and monitoring
- Design for recycling (DFR):
  - Higher requirements on 'disassemblability'.
  - Information available to enable recovery.

WEEE (Waste Electrical and Electronic Equipment)

Sources: [5, 6, 34, 35, 36, 78]

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 the 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 rate — make full use of the disposed parts. For instance:
  - more automation of the dismantling and processing steps (e.g., AI)
  - recycling technologies improvements (e.g., small components recovery is also happening)
  - more effective collection infrastructure
  - financial support provided to recyclers/operators
  - bans on WEEE exports push for increased domestic recycling [37]
- 'Design for recovery' principle — Ecodesign mandates changes in weight and composition of EEE so complexity and the type of materials used
- Higher public awareness and participation on WEEE issue and management
- Higher compliance from the public, the producers and the businesses
- Strong regulations and monitoring are in place with higher collection and recycling targets which are set and implemented and fines are set for those who fail to achieve the targets
- Focus is given more to the EoL management of WEEE

MIN (Mining Waste)

Sources:

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 support the development of technologies for the recovery of materials from mining waste.
- Increased traceability and management of mining waste through digitalisation.
- Mining waste remains a significant environmental challenge.

CDW (Construction and Demolition Waste)

Sources: [10]

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. Some progress in eco-design and material efficiency, but the construction industry continues to generate significant amounts of waste or 'downcycled' materials.

- Focus on new construction to meet demand, no changes in CDW generation rate.
- No increase or refurbishment or renovation activities.
- Enhancement of the quality of recycling to recover materials at higher value.
- Increased investment and enhanced regulatory system in waste management, contributing to increased recovery.

- Creation of new waste recovery infrastructure that improves recovery.
- Widespread application of selective demolition and strict on-site waste sorting leasing to an increase in 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 like glass, plastics, and wood is also intensified.
- Better separation of waste at source leads to a higher quality of secondary raw materials.
- Repowering trends for wind turbines stay the same.
- Improved recycling of wind turbine blades is notable, especially regarding plastics; permanent magnets are recycled at a functional level.

SLASH (Slags and Ashes)

Sources: [143, 144, 101, 145, 102]

In the recovery scenario, SLASH are recognized 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 SRM/CRM recovery targets. For example, recovery of P from biomass ash for fertilizer.
- Higher awareness and participation of relevant sectors on SLASH issues and management.
- Strong regulations and monitoring are in place 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, and the slag itself only contains minerals or metals as trace elements.
- Due to the low metal content, the slags are ideal resources for the construction industry.

ASHES

- New recovery technologies are installed in the incineration industry.
- We expect a shift in the volume and quality of the ashes.
- Coal fly ashes are the same as in BAU reducing over time to almost zero.
- Biomass ashes have the same volume and quality.

- Waste incineration ashes: due to the recovery scenario there will be a shift from landfill and incineration towards recycling, reuse, and repair. In countries with a high landfill rate, this will lead to higher volumes of ashes. In countries with a low landfill rate, and a high volume of incineration: this will lead to lower volumes of ashes, and a shift in the composition (with less CRM content in the ashes, due to better pre-sorting)

3.3. SCENARIO III: CIRCULARITY

3.3.1. Context

> A circular economy is one that is regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles. This new economic model seeks to ultimately decouple global economic development from finite resource consumption.
>
> — *Ellen MacArthur Foundation [38]*

> **A Circular Economy in the Netherlands by 2050!**
> Imagine we are in the year 2050. In the Netherlands we are living within the planetary boundaries of the Earth rather than permanently crossing them. This is because our relationship with nature, which used to be highly disturbed and led to climate change, has changed for the better …
> … The Netherlands now has a circular economy.
> … The Dutch Government intends to achieve a fully circular economy by 2050 and to halve the use of primary abiotic raw materials by 2030.
>
> — *National Circular Economy Programme, Government of the Netherlands [11]*

> **Circularity of the Dutch economy has barely increased**
> Of all natural resources that were deployed in the Dutch economy in 2020, 13 percent consisted of recycled materials. This percentage is virtually the same as in 2014. In terms of recycling, the circularity of the Dutch economy has barely increased.
>
> — *CBS (Statistics Netherlands) [146]*

> The circular economy promises radical technological transformations in a couple of decades, “nothing less than to open up new and immense horizons for industry”, “provide multiple value creation mechanisms”, produce “better welfare, GDP, and employment outcomes” [38]. Looking at these claims, one wonders whether policymakers really believe that in 30 years EU citizens will live in an inclusive economy with zero waste, zero emissions, with a perpetual economic growth, continuously absorbing massive flows of immigrants while protecting and enhancing the ecological processes and environmental biodiversity.
>
> …for a young scientist it is not advisable and even shocking to say in policy circles that:
>
> (i) Reaching zero emissions for metabolic systems is impossible (open/living systems must breathe),
>
> (ii) The economic process is entropic and therefore a circular economy enabling perpetual economic growth is impossible (it is the biosphere and not the technosphere that recycles matter, while energy cannot be recycled), and
>
> (iii) The existing technosphere has been built on and relied on fossil fuels for over 200 years, and it cannot be completely replaced in 30 years reaching zero emissions while fulfilling all the sustainable development goals (including rapid economic growth in the developing world).
>
> *— M. Giampietro and S.O. Funtowicz [104]*

3.3.2. Storyline narrative

A circular economy focuses on significantly enhancing resource efficiency. This can be achieved through four primary strategies:

1. Minimizing resource use (narrowing the loop) through shared utilization or opting out of certain product use, along with improved manufacturing efficiencies;
2. Prolonging the life and utility of products and their components (slowing the loop) via reuse and repair, thereby reducing the need for new raw materials;
3. Recycling materials (closing the loop) to diminish the quantity of material incinerated or sent to landfills, consequently cutting down the demand for new raw materials;
4. Replacing finite resources with renewable ones (like bioresources) or alternative primary resources that have a lower environmental impact.

In this scenario, we move in the direction of the maximum achievable state of material efficiency as government policy, private innovation and social changes are rapidly driving the transition toward a circular economy. The emphasis here rests heavily on re-X strategies that are implemented in the design phase of products (e.g., repairability and re-manufacturability) and that are actualised by changes in consumer behaviour (e.g reduction, refusal, engagement in the ‘sharing economy’ and curtailment of the ‘throw-away’ mindset).

Figure 3.3 presents a simplified visual depiction of the dominant material flow paths in the recovery scenario.

Further, being enabled by the widespread adoption of ‘circular design’ principles and improvements in information transparency (e.g., waste tracking and digital product passports) the system for the treatment of post-consumer waste can divert a significant amount of their inflows (to, for example, re-use and re-manufacture) with the residual fraction being readily segregated into purer, more efficiently recoverable, material streams.

This scenario envisions a future where government policies are in synergy with private sector innovation and societal changes, driving a wholesale transition towards a circular economy. Unlike the recovery scenario,

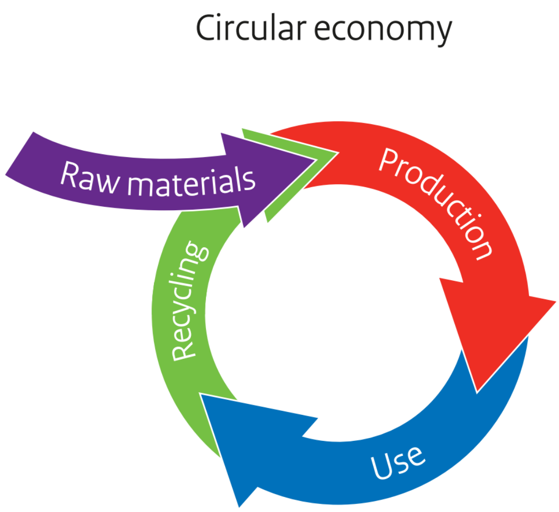


Figure 3.3: The simplified circular economy model in the circularity scenario [9]

where the focus is on the end-of-life recovery of materials, this scenario emphasises minimising waste at all stages, starting from the design phase itself, where both policymakers and designers are moving away from short-lived products towards products designed for longevity.

The emphasis is on re-X strategies that are integrated throughout the entirety of a product's lifecycle. This includes repairability, where products are designed to be easily fixed rather than replaced; and re-manufacturability, where products or their components are designed to be restored to their original state, extending their lifespan and reducing the need for new resources. This scenario calls for a drastic change in consumer behaviour, where reduction in consumption and waste, refusal of non-sustainable options, and active participation in the 'sharing economy' become the norm rather than the exception.

In the circularity scenario, the widespread adoption of 'circular design' principles becomes a cornerstone of production. In a circular design approach, products are designed and produced in a way that considers their entire lifecycle, including eventual disassembly and reuse. New economic models make it costly for producers to generate short-lived products and material waste. Companies are now giving priority to the design of products that are easily repairable, can be disassembled, and reused. The rise of technology has paved the way for predictive maintenance tools. These allow businesses to keep a tab on material conditions through sensors and carry out repairs before a malfunction occurs, a method gaining traction in transport and manufacturing.

Additionally, this scenario envisions an improvement in transparency, with measures such as waste tracking and digital product passports becoming standard. Waste tracking allows for efficient management of waste flows, aiding in effective resource planning, while digital product passports provide information about a product's composition and how it can be properly disassembled, reused, or recycled. Material composition, including raw materials, is transparent to all involved in the value chain, promoting closer collaboration. Producers see the advantage of being open about their product details to aid in repair, repurposing, and recycling activities. This transparency about product components, durability, and reparability increases consumer demand for products that are designed to last and can be reused or recycled.

3.3.3. Scenario needs and impacts

In the proposed scenario, the European Union (EU) embarks on a pivotal transition towards a circular economy. This framework emphasises the retention of product, material, and resource value within the economic matrix for extended durations, simultaneously minimising waste generation. This transition is integral to the EU's strategic goal of cultivating a sustainable, low-carbon, resource-efficient, and globally competitive economy.

The implications of this shift are multifaceted. It presents an avenue for the EU to rejuvenate its economic architecture while providing businesses with a protective shield against challenges such as resource scarcity and price volatility. This revised economic model fosters the emergence of efficient, innovative production and consumption methods, thus offering novel business opportunities. Moreover, the circular economy approach has palpable socio-economic benefits, including diverse job creation and enhanced social integration.

From an environmental perspective, the transition aids in the reduction of the cumulative energy footprint and helps mitigate irreversible ecological damages. This encompasses challenges related to climate shifts, biodiversity conservation, and comprehensive pollution control. Several studies accentuate the overarching benefits of this economic approach, highlighting potential reductions in prevalent carbon dioxide emissions.

The successful implementation of this vision necessitates a collaborative approach involving various stakeholders, encompassing businesses, consumers, and regulatory entities. A robust regulatory framework is indispensable, designed to promote optimal practices and delineate clear progression benchmarks. This comprehensive framework encompasses the entirety of the circular economy's value chain, from production to consumption, extending into realms of repair, remanufacturing, and waste management, culminating in the reintroduction of secondary raw materials into the economic cycle.

Environmental fiscal reforms are crucial for a circular economy transition. Taxes should pivot from labour to resource depletion, promoting a double dividend. The EU can leverage the VAT directive and the European semester process to endorse flexible rates on circular services like repair. It's imperative to abolish harmful subsidies, notably on fossil fuels, which are inherently linear and which Member States have pledged to eliminate. The tax framework should incentivise pioneers challenging the established linear economy. Analysing tax shifts at the national level can determine tax effectiveness and pinpoint instruments that best bolster circularity.

The contribution of member states is paramount. They play a dual role, both in the actualisation of EU directives and in the integration of complementary regional initiatives. The principles of a circular economy possess global applicability, necessitating harmonised strategies within the EU and with external international partners. Such synergised efforts are crucial for the fulfilment of broader international commitments, notably the U.N. 2030 Agenda for Sustainable Development [12]. The ultimate objective remains the establishment of a sustainable future characterised by judicious consumption and production protocols.

3.3.4. Waste stream specific scenario impacts

BATT (Battery waste)

Sources: [24, 86, 7, 8]

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 the efficiency of the recycling process.
- Service-based business models like leasing ensure manufacturers retain ownership of the 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 (SoH, SoC, Predicted lifetime/warranty, etc.) given by the economic operator that places the battery on the market enables high re-use rates.
- Increased repairability/modularity.
- Reduced demand from 'sharing economy' and more 'sustainable' transport choices.
- New emerging technologies more suited for reuse/repair.
- Ambitious targets set by business and public policy.

ELV (End-of-Life Vehicles)

Sources: [86, 142, 30, 31, 32, 33]

For End-of-Life Vehicles (ELVs), the circular economy model affects the way vehicles are designed, used, and discarded. Emphasising extended vehicle life through repair and remanufacturing, this scenario also focuses on the recovery of materials from vehicles at the end of their life.

- Vehicle design shifts towards repairability, upgradability, and recyclability, increasing the lifespan of vehicles.
- Standardised systems for ELV collection are established, ensuring efficient waste management.
- Innovative technologies enable higher recovery rates of metals and other valuable materials from ELVs.
- Service-based models like vehicle leasing and sharing could reduce the total number of vehicles produced.

- Digital product passports provide information about vehicle components, aiding in effective recycling or reuse.
- Focus on managing the use-phase of vehicles.
- Circular strategies take place before material recovery so that material recovery is "delayed".
- Information available to enable these strategies.
- EU vehicles policy has implications for materials in vehicles, such as 'lightweighting' and down-sizing
    - Increase in average occupancy and average vehicle-kilometres per trip.
    - Decrease in average lifetime (in terms of years): As the utilisation factor increases.
- Increase in circular strategies due to an increase in participation from the public and businesses, i.e., target-based incentives with strong regulations and monitoring.

WEEE (Waste Electrical and Electronic Equipment)

Sources: [5, 6, 34, 35, 36, 78]

In the circularity scenario, WEEE becomes a valuable resource instead of a disposal challenge. Thanks to product design changes and the application of advanced recovery technologies, a significant percentage of the materials in WEEE is reclaimed and fed back into the production cycle.

- Electronic products are designed for longevity, repairability, upgradability, and recyclability.
- Advanced technologies enable higher recovery rates of precious metals from WEEE.
- Collection systems for WEEE are improved, ensuring a steady supply of materials to feed the recovery system.
- Digitalisation and data use enhance traceability and efficiency in WEEE management.
- Service-based models for electronics promote the use of products as a service rather than ownership, reducing WEEE generation [89].
- Increased durability and lifespans.
- Increased repairability.
- More sharing and product-service systems, correspond to a reduction in the lifetime (for some equipment).
- More reuse practices (expanded second-hand market).
- Less hoarding.
- Higher formal collection and recycling rate.
- Focus is given more to the production and use phase rather than the EoL (End-of-Life).
- 'Design for circularity' principle: Ecodesign mandates repairability, durability, no obsolescence, modularity, and that continual software upgrades are possible [13, 147].
- Electronically compatible chargers and battery packs can be used by different products.
- The above also means that chargers and batteries are not integrated into the product and that the product is designed to be easily disassembled.
- Strong regulations and monitoring are in place with higher reuse and circular targets, which are set and implemented, and fines are imposed on the member states that fail to achieve the targets.

- Support and development of circular strategies infrastructure (e.g., easy information access for repairability, repair shops, accessibility to spare components on the market, etc.).
- Greater use of connected products, smart technologies, and the IoT. Used to monitor and diagnose product performance in situ which, can extend product and component life.

MIN (Mining Waste)

Sources:

In this scenario, the impact on mining waste is two-fold. Firstly, the need for primary mining is reduced due to lower demand, efficient resource use and high recovery rates of materials. Secondly, mining waste itself is treated as a valuable resource, with advanced technologies being used to extract residual valuable materials.

- A Decrease in primary mining reduces the generation of mining waste.
- Advanced technologies are employed to extract valuable materials from mining waste.
- Policies and regulations incentivise the reuse of mining waste in various applications.
- Digital solutions improve tracking and management of mining waste.
- Collaboration between stakeholders promotes circular practices in the mining industry.

CDW (Construction and Demolition Waste)

Sources: [10]

Construction and Demolition Waste (CDW) is another sector that sees significant improvement in the circularity scenario. This scenario reduces the generation of CDW and promotes the recovery of valuable materials from the waste stream.

- Less demolition and new construction results in a reduction of CDW.
- Buildings are designed for disassembly and reuse, increasing the lifespan of materials and reducing CDW.
- Longer lifetimes for buildings (more renovation and refurbishment) and wind turbines (less repowering, i.e. changing of wind turbines before the end of theoretical lifespan).
- Wind turbine blades are refurbished or repaired and then reused.
- Recycling technologies for CDW improve, allowing higher recovery rates of materials and less 'downcycling'.
- Policies and regulations incentivise the use of recycled materials in construction.
- Standardised systems for CDW collection and separation are improved.
- Digital tools like building information modelling (BIM) improve resource management in construction and renovation.
- Focus on dismantling and selective deconstruction: constructions are taken apart in a way that individual parts can be reused.

SLASH (Slags and Ashes)

Sources: [143, 144, 101, 145, 102]

In the circularity scenario, SLASH are 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. In the circularity scenario, the conditions are very similar to that of the recovery scenario, except that volumes will decrease, due to a general decrease in waste generation.

- Digital solutions enhance the traceability and management of SLASH.
- More functional collection infrastructure.
- Financial support provided to recyclers/operators.
- Introduction of SRM/CRM recovery targets. For example, recovery of P from biomass ash for fertiliser.
- Higher awareness and participation of relevant sectors on SLASH issues and management.
- Strong regulations and monitoring are in place 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, and the slag itself only contains minerals or metals as trace elements.
- Due to the low metal content, the slags are ideal resources for the construction industry.

ASHES

- New recovery technologies are installed in the incineration industry.
- We expect a shift in the volume and quality of the ashes.
- Coal fly ashes are the same as in BAU reducing over time to almost zero.
- Biomass ashes have the same volume and quality.
- Waste incineration ashes: due to the recovery scenario there will be a shift from landfill and incineration towards recycling, reuse, and repair. In countries with a high landfill rate, this will lead to higher volumes of ashes. In countries with a low landfill rate, and a high volume of incineration: this will lead to lower volumes of ashes, and a shift in the composition (with less CRMs in the ashes, due to better pre-sorting)

Quantification

CHAPTER CONTENTS

4.1. INTRODUCTION

In the FutuRaM project, scenario elements are categorised based on their influence and relevance to the secondary raw material (SRM) system. This categorisation aids in refining the focus of the scenarios and ensuring they are relevant, manageable, and useful.

Following the process detailed in chapter 2, the resultant scenario elements were classified in preparation for quantification. These elements are listed in Table 13.8.

Internal Elements:
(section 4.4 and section 4.5) These are directly within the scope of FutuRaM and significantly impact the waste management system. They are integral to the models and scenarios. For example, changes in waste composition and recovery methods fall under this category. These elements are thoroughly researched and modeled as they are central to understanding and projecting the SRM system's future.

External Elements:
(section 4.3) Elements deemed external are still relevant to the scenarios but are not as directly related as the internal elements. External elements are set as the background of the three scenarios, allowing a better focus on the main variables of importance to FutuRaM. These elements do not vary across the three different scenarios but they do change over time. These elements include demographics, economic growth, and the renewable energy transition.

Outside Elements:
(section 4.3) These are factors outside the scope and influence of the waste management system and are not included in the scenario storylines or directly in the models. They may be considered in sensitivity analysis but are not primary drivers in the scenario development. For instance, resource supply constraints are external factors that could impact the waste management system but are too unpredictable and complex to model directly within the scenarios. Their inclusion could introduce significant uncertainty and make the models less interpretable and actionable. These elements are, however, considered important, and their possible impacts on the SRM system will be explored in exercises of sensitivity analysis and optimisation.

The rationale behind this categorisation is to maintain focus and clarity in the scenario modeling. Including too many complex and indirectly related elements can convolute the scenarios, making them overly complex and less useful for practical decision-making and policy analysis. By concentrating on integral elements — or those that can be controlled or influenced by associated policy decisions — FutuRaM ensures that its scenarios are both manageable and directly relevant to its objectives of exploring different futures of the SRM system. This approach strikes a balance between realism and practicality, ensuring the scenarios are both meaningful and actionable.

4.1.1. Quantification and Implementation of scenario elements in the models

External drivers

For each external driver in the scenarios, the values are defined globally and each waste stream will interpret this into their models using a "top-down" approach. This will require the development of correlations between the scenario driver and the parameter in the waste stream model. The resolution of this will be different for each scenario driver and each waste stream.

Internal elements

For the internal elements in the scenarios, a global value can often not be defined. For these elements, the waste stream models will define the values for each scenario using a "bottom-up" approach. This will require the estimation of future trends for each parameter and scenario for the product/waste groupings in each waste stream. Then, a global value can be calculated by taking a weighted average for each of the groups.

The outcome of these estimations will be a range of values for each time series, for each parameter in each waste stream for each scenario.

Figure 4.1 depicts a schema for the interconnection between the models for the quantification and implementation of the scenario elements.

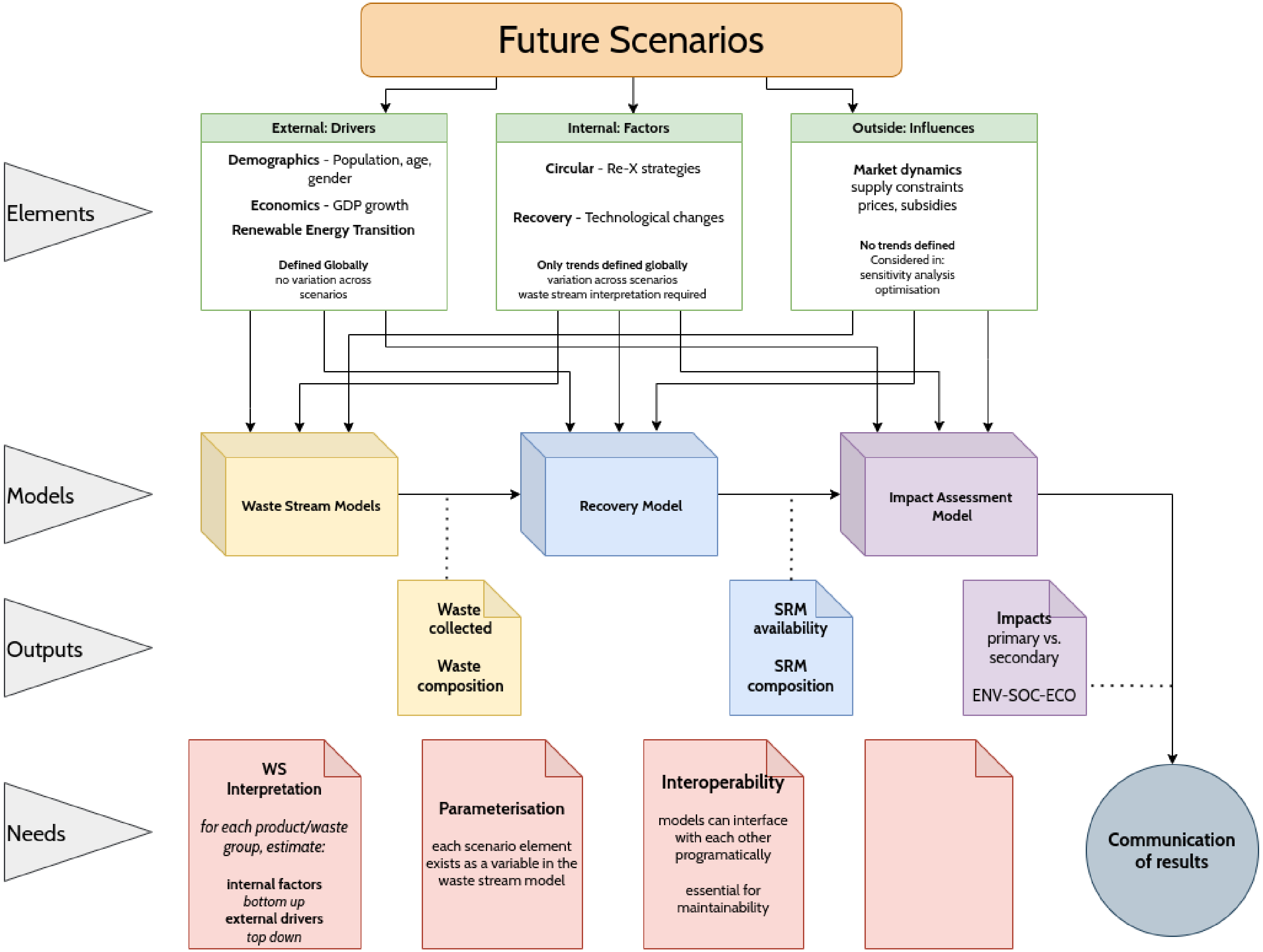


Figure 4.1: Quantification and Implementation of scenario elements in the models

Back to ToC

Methodology for quantification

The methodology for quantification of the scenario elements is as follows:

1. Define the parameters for each waste stream model
2. Define the parameters for each scenario element in relation to the parameters in the waste stream model
3. Define the correlations between the scenario elements and the parameters
4. Estimate the future trends for each parameter in each scenario for every set of product/waste groupings
5. Using the constraints of the waste stream parameter for each product group, define the coefficients of the functions between the scenario elements and the parameters

Figure 4.2 depicts a schema for the development of correlations between elements and parameters in the waste stream models and the scenarios. The values of the functions between the pairs need to be defined.

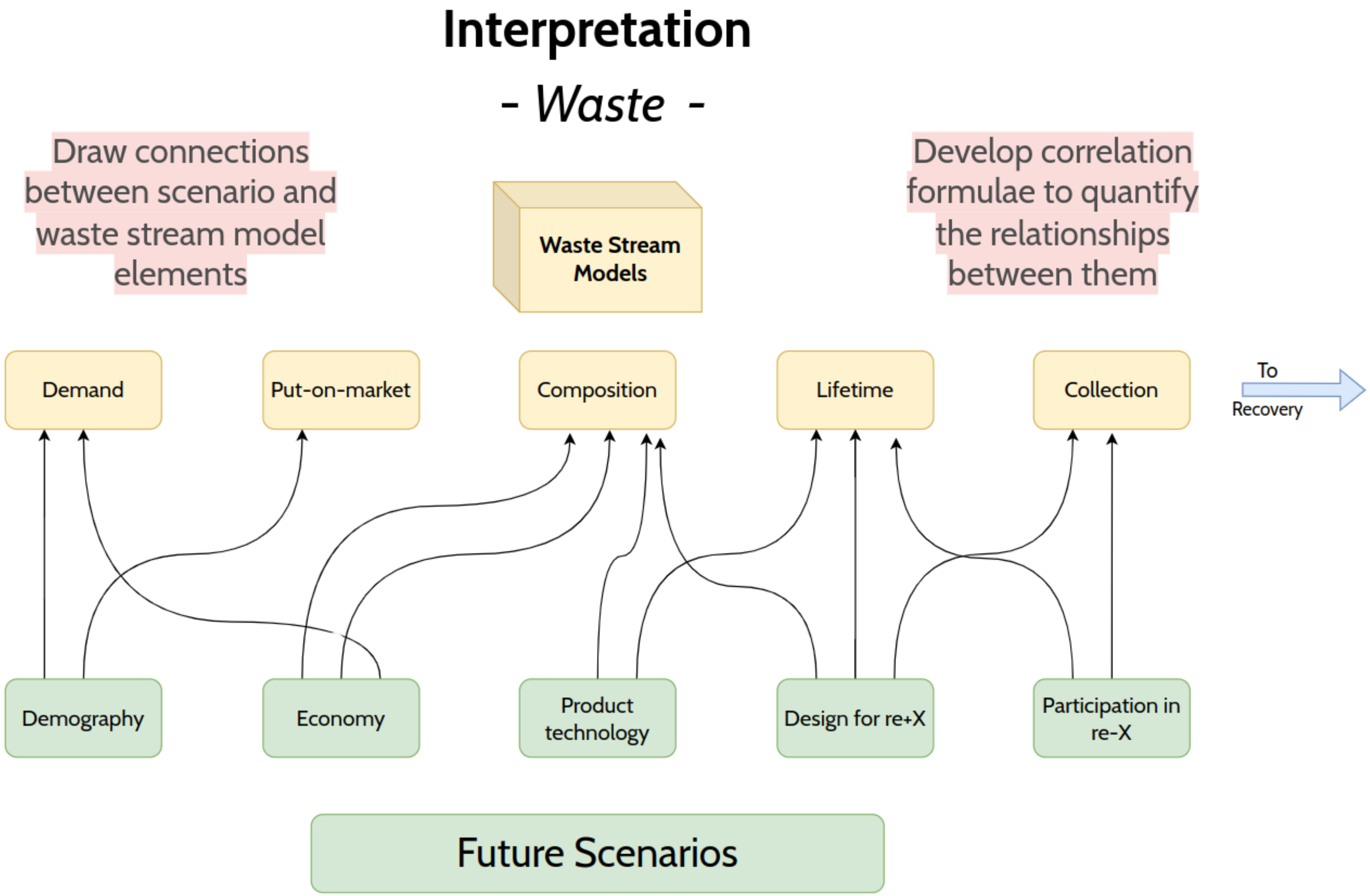


Figure 4.2: Development of correlations between elements and parameters in the waste stream models and the scenarios

Methodology for estimating future trends

After the correlations between the scenario elements and the parameters in the waste stream models have been defined, the future trends for each parameter in each scenario for every set of product/waste groupings can be estimated.

For some parameters, the future trends can be estimated using a simple linear regression. For other parameters, the future trends will be estimated using a more complex model. The exact methodology for estimating the future trends for each parameter in each scenario for every set of product/waste groupings will be determined on a case-by-case basis.

Consideration of historical and current data, knowledge of the waste stream, and analysis of the scenarios will be used to determine the most appropriate modelling method.

An exact value is not to be sought, but rather a distribution, with constraints regarding the minimum and maximum values and the rate of change over time.

Using this, simple models can be approximated using the method of curve fitting. The choice of model (linear, exponential, etc.) will be determined by the data and the scenario. For example, a new technology or a rapid change in policy may result in an initial exponential change in the parameter, the beginning of the typical sigmoidal curve (or even a step change). This may then level off to a linear trend, then a logarithmic relationship as the technology or policy matures.

Figure 4.3 illustrates a sigmoidal curve with its characteristic three phases of growth. Typically, a sigmoidal curve (depicted as a solid black line) commences with an exponential phase, transitions into a linear phase (encompassing the inflection point where the growth rate peaks), and concludes with an asymptotic phase, where the curve nears a constant asymptote 'a' as time tends towards infinity. In certain instances, the initial exponential phase might be remarkably brief, to the point of seeming non-existent. However, the linear and asymptotic stages are consistent features across all sigmoidal curves. Attenuating curves share similarities but are distinct in that they do not have the initial exponential phase, resembling a sigmoidal curve that initiates at its inflection point around tÕ. The logistic function is a special case of the sigmoidal function, with the inflection point at x=0.

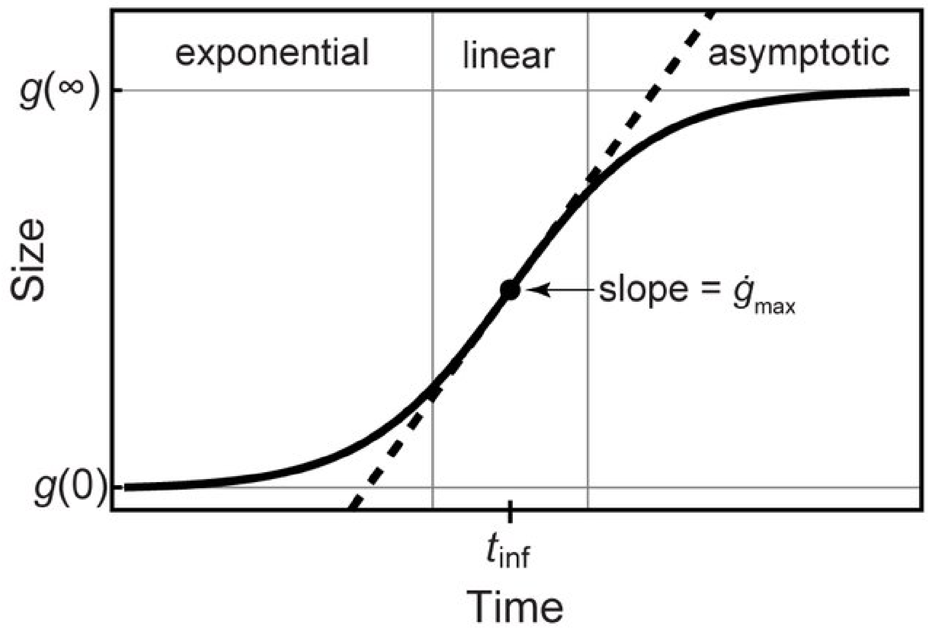


Figure 4.3: An example of a sigmoidal function (s-curve)

The s-curve is a generalisation of the logistic function, which is defined as:

$$f(x) = \frac{L}{1 + e^{-k(x-x_0)}} \tag{4.1}$$

where:

- x_0 = the x-value of the sigmoid's midpoint,
- L = the curve's maximum value, and
- k = the logistic growth rate or steepness of the curve.
- e = the natural logarithm base (also known as Euler's number),

Important to note here is that what, during some period, may appear to be a constant linear (or other) change, may in fact be a segment of a sigmoidal curve. This is important to consider when estimating future trends, for some changes, the period from 2020-2050 may be short enough that the nature of the transition does not change, although it would when viewed over a longer time range.

The comic in Figure 4.4 plots the frequency of the usage of the term 'sustainable' over time, forecasting that by 2109, all sentences will consist only of the word 'sustainable', repeated again and again. 'Fittingly', the author also notes that '100 years is a lot longer than many of our resources will last'.

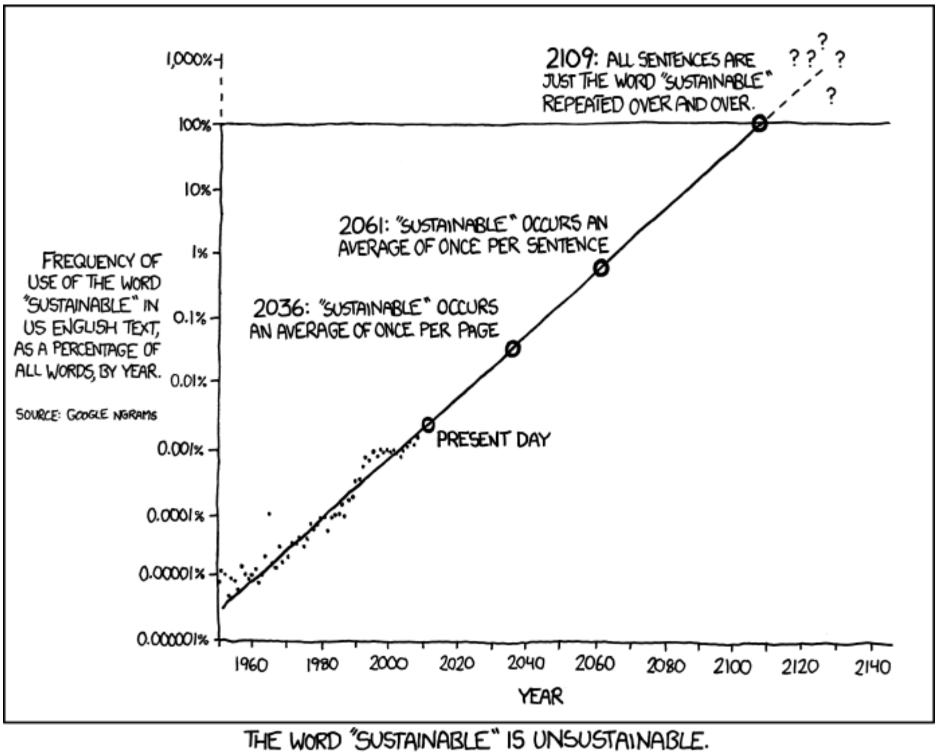


Figure 4.4: The word 'sustainable' is unsustainable [157]

It is of course a generalisation to assume that all growth rates follow this trend, but it is mostly close enough to reality to be useful. This will be the standard approach for estimating future trends in the FutuRaM project unless there is reason to believe that the nature of the transition is different (which it often is!).

Further details are provided in the relevant sections of this chapter and will be updated as the project progresses.

4.2. SUMMARY

REVIEW NOTICE

This summary will be compiled once the individual waste stream sections for each parameter are complete.

4.3. EXTERNAL ELEMENTS

4.3.1. Introduction

External drivers

Scenario elements

- **Demographic change:**
  population, median age, urbanisation, gender
- **Economic growth:**
  GDP
- **Renewable energy transition:**
  energy mix

Waste model parameters include:

- **Put-on-market**
- **Composition**

Recovery model parameters include:

- **Recovery processes:**
  market penetration of recovery technologies
- **Transfer coefficients:**
  function of recovery technologies
- **Recovery system size:**
  BAU - set by trends in BAU, CIR & REC - defined by model outcomes within constraints

Impact model parameters include:

- **Foreground inventory:**
  inputs and outputs of recovery system
- **Background inventory:**
  energy mix, impact of primary production

In the FutuRaM project, scenario elements are categorised based on their influence and relevance to the secondary raw material (SRM) system. This categorization aids in refining the focus of the scenarios and ensuring they are relevant, manageable and useful.

Following the process detailed in chapter 2, several scenario elements were classified as "external" or "outside".

The following "external" elements are incorporated into the scenarios as background information but are not directly modelled. They are assumed to be constant across the three scenarios, but change over time.

- Demographic change
- Economic growth
- Renewable energy transition

The following "outside" elements are not incorporated into the scenarios, but are considered important and will be explored in sensitivity analysis and optimisation.

- Resource supply constraints
- International trade and co-operation
- Re-industrialisation of EU
- Resistance to recovery projects ("NIMBY")

These elements are detailed in Table 4.1.

Table 4.1: List of external scenario elements

DOMAIN	ELEMENT	INTERNAL	EXTERNAL	OUTSIDE	BAU	REC	CIR	MODEL PARAMETERS AFFECTED
ECO	Progress toward renewable energy targets		✓		-	-	-	composition, demand, waste generation, recovery impacts
ECO	Economic growth		✓		-	-	-	composition, demand, waste generation
SOC	Population		✓		-	-	-	demand, waste generation
ECO	Primary vs. secondary raw material prices		✓		~	~	~	considered in sensitivity analysis
ECO	Energy prices		✓		~	~	~	considered in sensitivity analysis
ECO	Carbon price		✓		~	~	~	considered in sensitivity analysis
ENV	Resource supply constraints		✓		~	~	~	considered in sensitivity analysis:
ECO	International trade and co-operation (vs. autarky)			✓	n/a	n/a	n/a	not model input (resource supply constraints is a proxy)
ECO	Re-industrialisation of EU			✓	n/a	n/a	n/a	not model input
SOC	Resistance to recovery projects (NIMBY)			✓	n/a	n/a	n/a	not model input (considered in UNFC assessments)

4.3.2. Summary

REVIEW NOTICE

This summary will be compiled once the individual waste stream sections for each parameter are complete.

Demographic change

INDEPENDENT VARIABLES

- Population
- Median age
- Urbanisation

DEPENDENT VARIABLES

- Demand
- Waste generation
- Waste composition

Economic growth

INDEPENDENT VARIABLES

- GDP growth

DEPENDENT VARIABLES

- Demand
- Waste generation
- Waste composition

Renewable energy transition

INDEPENDENT VARIABLES

- Energy mix

Dependent variables

- Demand
- Waste generation
- Waste composition
- Recovery impacts

Resource supply constraints

NOTE

This element is not forecast or modelled directly, but is considered in sensitivity analysis and optimisation.
Supply constraint is independent of its cause (e.g. resource depletion, political instability), thus, it can act as a proxy for other elements such as international trade and co-operation.

Independent variables

- Resource availability

Dependent variables

- Resource prices
- Settings of the recovery system to counteract supply crunch
- Waste composition (incorporating lag and substitution effects)

Market dynamics

NOTE

As with resource supply constraints, consideration of complex market dynamics are limited to sensitivity analysis and optimisation. General trend forecasts in supply and demand are considered in the scenarios, however, as functions of the other elements, such as GPD and population.

Independent variables

- Raw material prices
- Secondary raw material prices

Dependent variables

- Recovery system settings
- Recovery system capacity
- Recovery system profitability
- Secondary raw material supply

4.3.3. Demographic factors: *Population, age, urbanisation*

Definition

Demographic factors encompass a range of population characteristics, including age distribution, population growth rates, urbanisation levels, migration patterns, and household composition. These factors are crucial determinants in forecasting demand patterns, labour market dynamics, and consumption trends, which in turn affect supply chains and resource management.

In the context of the scenarios and modelling within FutuRaM, demographic factors could influence the demand for certain commodities, the availability of labour for new recycling technologies, and the generation of waste materials. As populations grow and become more urbanised, the demand for electronics, energy, and transportation increases, which in turn raises the demand for critical raw materials necessary for these technologies. Age distributions can affect the workforce available for the recycling industry and potentially shift consumption patterns, as older populations might consume differently compared to younger demographics.

SCENARIO TRENDS FOR: Demographics

Scenario I — Business-as-usual:

Current trends

Scenario II — Recovery:

Current trends

Scenario III — Circularity:

Current trends

Justification for setting as an external scenario factor

Demographics undoubtedly exert a significant influence on supply and demand patterns within any resource environment. [39] As such, demographic factors play a role in shaping the demand for CRMs and the efficiency of waste management systems. However, within the scope of FutuRaM's scenario modelling, these demographic elements are treated as background variables.

A standard set of demographic projections is applied across all scenarios, contributing to the baseline assumptions but not serving as the primary driver of change in the model. By setting demographics as an external factor, FutuRaM's scenarios can abstract from the nuanced impacts of demographic changes, allowing for a clearer interpretation of how policy levers directly affect SRM outcomes.

Furthermore, the structure of FutuRaM's models is designed to be sufficiently adaptable to account for future demographic shifts. As new data become available, they can be integrated into the existing models, allowing for regular updates that keep pace with the evolving demographic landscape. This flexibility ensures that the model's outputs remain both relevant and grounded in the most current understanding of demographic factors, while the focus stays on the core objectives of resource management and the evaluation of policy efficacy.

REVIEW NOTICE

Data for other demographic factors such as urbanisation, gender or persons per household can be added here if the waste stream models require it.

Population projections

Sources for demographic data

The population projections in this report have been produced from the most recent data provided by Eurostat and the UK Office of National Statistics (ONS) [63, 64, 105].

It was decided to 're-model' this data, rather than extract it from the population figures in the SSP2 baseline scenario datasets [106, 107] to which the background of FutuRaM's scenarios are (broadly) aligned. This allows the use of the most up-to-date and 'raw' data possible.

Figure 4.5 shows the normalised population projections for the EU27+3 and the UK. The index is set to 1 for the year 2020. An interactive figure can be viewed here

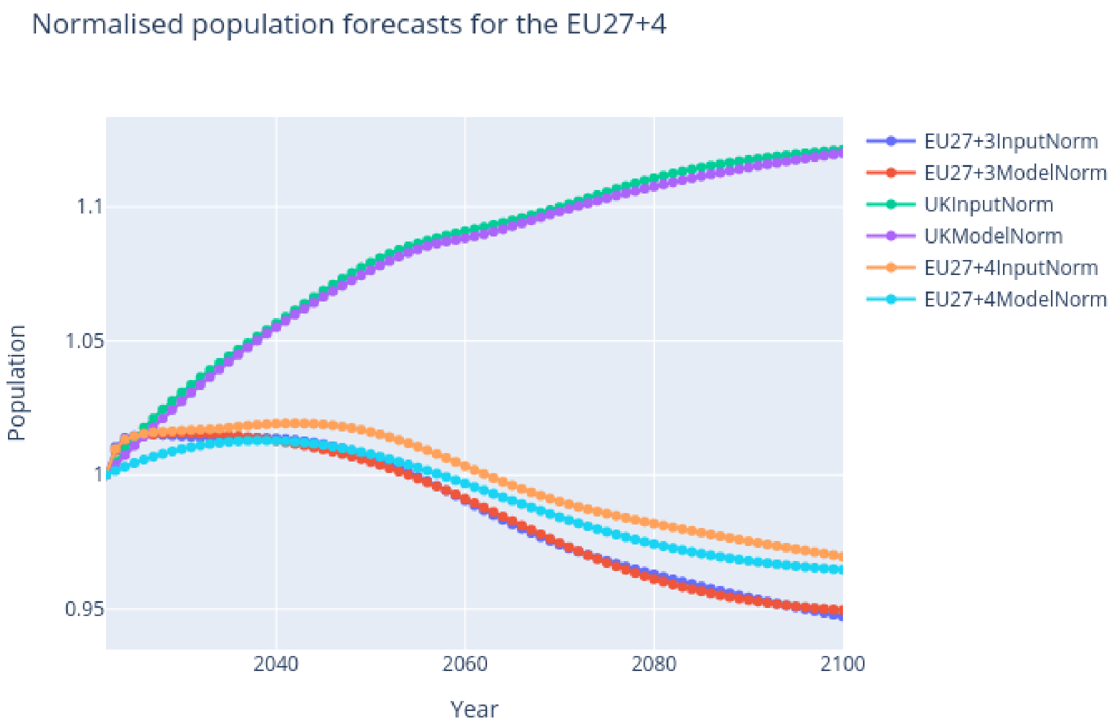


Figure 4.5: Population projections for the EU27+3 and the UK

EU27 + 4

Data source: [63]

POPULATION MODELLING RESULTS:

The full results of the population modelling are presented in Table 4.2.

HIGHLIGHTS:

- The EU population is projected to rise from 446.7 million in 2022, peaking at 453.3 million in 2026 (+1.5%), before decreasing to 447.9 million in 2050 and further to 419.5 million in 2100.
- An increase of 5.8 years is expected in the median age of the EU population between 2022 and 2100.
- By 2100, the number of individuals aged 80 and over in the EU is projected to reach 64.0 million.

Populations evolve over time due to demographic factors: births, deaths, and migration. Each of these factors influences the population's structure. Presently, the EU is experiencing a trend of ageing in its population due to the prevailing levels of fertility and mortality.

EUROPOP2023 offers deterministic projections based on 'what-if' scenarios. These scenarios are formed on anticipated courses for fertility, mortality, and migration. A partial convergence is assumed among the countries in the EUROPOP2023 projection concerning fertility, mortality, and migration patterns. The methodology employed is primarily based on past projection exercises. Furthermore, this study accounts for the impact of the COVID-19 pandemic and the mass influx due to the conflict between Russia and Ukraine.

It is projected by Eurostat that all EU Member States and the three EFTA countries will experience continued population ageing. The population in 2100 is predicted to be lower than in 2022, with a decline in the working-age demographic. There's an observed trend of ageing within the elderly demographic itself. Migration can both alleviate and accelerate the ageing process. It depends on whether there's an influx or outflow of the working-age population. For instance, the search for better job opportunities can lead to a considerable outflow. Consequently, age dependency ratios are set to rise, posing challenges for public expenditure on pensions, healthcare, and long-term care.

METHOD

Eurostat provides international projections for the European Union (EU) and the European Free Trade Association countries, which include Iceland, Liechtenstein, Norway, and Switzerland. Unlike the UN's projections, Eurostat's are deterministic in nature. Their most recent projection, dating from 2020, presents a base variant along with four other variants, starting with the baseline year 2019. In the base variant, it is forecasted that the EU-27 population will decline by nearly 7 percent or about 30 million people by 2100. However, in the medium term, the population is expected to grow until 2025, reaching about 449 million people, before reducing to 416 million by 2100. Country-specific, sex, and age data are available in Eurostat's database.

The final projection starts with the 2022 population divided by sex and age. Mortality rates are applied to determine the number of deaths. Numbers for non-EU and EU immigrants are computed. For the years 2022 and 2023, refugees under TP are also included. Emigrants, including refugees under TP for the years 2024 to 3033, are then subtracted. Based on this, the end-of-year population and the working-age population are computed. Using these figures, additional non-EU immigrants are calculated, and the end-of-year population is re-assessed. This allows for the computation of live births, total deaths, immigration, and emigration for 2022.

SCENARIOS

Eurostat also considers five alternative scenarios besides the baseline for EUROPOP2023. These are:

lower fertility, lower mortality, zero net migration, decreased non-EU immigration, and increased non-EU immigration. For instance, the lower fertility scenario posits a total fertility rate that's 20% less than the baseline for each projection year (2023 – 2100). This implies fewer live births yearly compared to the baseline. The lower mortality scenario suggests a life expectancy at birth in 2100 that's two years more than the baseline. Migration scenarios include zero net migration, 33% less non-EU immigration each year, and 33% more non-EU immigration every year throughout the projection horizon.

UK

Data source: [64]

- New data will be released January 2024.
- No scenarios were developed due to the additional uncertainty in the underlying data related to the CoViD-19 pandemic-related fluctuations.

Population modelling results:

The full results of the population modelling are presented in Table 4.2.

Population Projections

The UK population in mid-2020 was estimated at 67.1 million. Over the decade to mid-2030, it's projected to rise by 2.1 million (3.2% increase), in comparison to a 6.9% increase between 2010 and 2020. Over the next 25 years, the projected growth is 3.9 million (5.8%), less than the 15.6% growth between mid-1995 and mid-2020.

In contrast to the EU27+3, the UK population is projected to continue to continue growing (slowly) until 2100, the end of the projection period, when it reaches 76 million.

Assumptions:

- Long-term averages are based on a 22-year period, excluding the 1990s.
- Long-term average falls within the ranges given by expert advisory feedback.
- Estimated international migration data is used for the years ending mid-2021 and mid-2022.
- Linear interpolation is used from mid-2022 up to mid-2026.
- A three-year average of data from mid-2020 to mid-2022 is used for starting the linear interpolation for mid-2022.
- UK completed family size to reach 1.59 children per woman by 2045.
- Annual improvement in UK mortality rates will be 1.2% for most ages by 2045.
- Net international migration to the UK will average +205,000 from mid-2027 onwards.

Methodology

Projections are produced for successive years from one mid-year to the next. Age-based calculations are made to account for net migration, deaths, and births. Details such as migration timing, death rates, birth rates, and the ratio of male-to-female births are factored into the calculations. Projections are made for each UK country and then aggregated for broader regions.

STRENGTHS AND LIMITATIONS

Projections are based on the latest available data but are not forecasts. The inherent uncertainty in the data and the unpredictability of future events means projections may not align with future outcomes. Factors like political and economic changes can also impact population growth, and events like the UK leaving the EU or the COVID-19 pandemic are not explicitly factored in. While this bulletin focuses on projections up to mid-2045, the data includes projections up to mid-2120, which have greater inherent uncertainty.

MERGING THE EU27+3 AND THE UK INTO A UNIFIED POPULATION MODEL

As the world undergoes the demographic transition, the relevance of Verhulst's logistic model has resurged, providing an adequate representation of current population growth trends. This logistic population growth dynamic is critical for achieving global sustainable development.

These projections are informed by the finite reserves of primary exhaustible resources and the ongoing trend of declining birth rates. These indications suggest a shift towards a new equilibrium state for the planet that aligns with heightened industrial and technological capacities and improved healthcare standards. By constructing logistic models that depict the growth dynamics of the global population and individual continents, we can forecast population sizes and their growth rates for the next two centuries. The insights garnered present opportunities for the regulation and optimal management of global demographic resources.

Projection Methodology

Methodology source: [105]

Population projections underpin many political and economic decisions at various levels. Often, the users lack the expertise to fully grasp the methods and limitations of the projections they rely on.

Population development is contingent upon three primary factors: fertility, net migration, and mortality. Usually, a projection starts with the age- and sex-specific numbers at a given time. Using estimates for the future development of the three determinants, the population is projected forward. Forecasts often refine mortality and migration by age and sex.

Projection methodologies fall into deterministic and stochastic categories. Deterministic models, being the most widespread, set parameters in one or more scenarios. Their strengths lie in ease of use, adaptability to changes in parameters, and straightforwardness for non-experts. A prominent deterministic method is the cohort component method (CCM) which separately simulates fertility, migration, and mortality before integrating them into a projection. Given a population P_{t-1} at the end of period $t-1$, the CCM updates this using births B_t, net migration M_t, and deaths D_t as:

$$P_t = P_{t-1} + B_t + M_t - D_t$$

However, deterministic models face challenges. They:

- Overlook the probabilistic nature of population processes.
- Rely on rigid future assumptions with low individual probabilities of occurrence.
- Limit the number of considered scenarios, inadequately reflecting future risk.
- Lack probabilistic quantification for identified futures.
- May be biased by experts' subjective assessments.

In contrast, stochastic models view parameters as random variables. While deterministic models might assume fixed values for determinants like G_t, M_t, and S_t in certain scenarios, stochastic models see these as probabilistic, represented as:

$$\tilde{B}_t = \tilde{B}_{t-1} + \tilde{G}_t + \tilde{M}_t - \tilde{S}_t$$

Yet, it's essential to understand that no forecast offers absolute truth. Their aim isn't predicting unexpected events, but extrapolating core demographic trends. Both deterministic and stochastic methods exist to quantify forecast uncertainty.

Applying these results in real-world scenarios warrants a cautious approach. Past trends might not persist in the future. For instance, population growth isn't just about demographics but also infrastructure. Can a housing market accommodate growth? Will cities meet their limits? Projections inherently carry assumptions. For instance, regions must meet housing demands, and urban challenges arise from positive population growth, such as the need for expanded childcare or public transport infrastructure.

Predicting and managing future global population growth stands as a paramount challenge for humanity. Most contemporary researchers believe there's a ceiling to the planet's 'carrying capacity'. Come 2022, Earth's population is anticipated to hit the eight billion mark. UN predictions suggest that by 2100, this number will rise to ten billion. However, there's an observable trend towards smaller family sizes, with birth rates currently hovering around the replacement rate of 2.1 children per woman. Should global fertility rates align with family replacement levels (2.0) by 2100, Earth's population is projected to stabilise between ten and eleven billion. The emergence of new statistical data necessitates updates to global population growth models. Where once the Verhulst logistic model was deemed inadequate for characterising global population growth dynamics, the tapering growth rate now reaffirms its applicability. Many recent studies have leveraged the logistic growth model. Our analyses confirm that Earth's population growth rate aligns closely with a quadratic function, mirroring the Verhulst equation (Fig. 4). All subsequent computations will employ the Verhulst logistic model:

$$\frac{dY}{dt} = a \cdot Y - b \cdot Y^2 \tag{4.2}$$

The solution to equation (8) will be sought as a logistic function:

$$Y = g + \frac{b}{1 + A\exp(-a(t - t_0))} \tag{4.3}$$

Function $Y(t)$ parameters were ascertained using the least squares method, ensuring maximal alignment between the function's value and the existing statistical data. The parameter g was presumed equal to the initial population size at the start of observations ($t_0 = 1900$).

CURVE FITTING EXPLANATION

Terms with subscript 1 describe the initial logistic component, charting population growth from 2022 to 2042.

Subscript 2 terms Correspond to the second logistic component, which outlines post-2042 population decline.

$\mathbf{b_1}$ Represents the initial population at the start of the observation period - Europe's population in 1900 per the model's parameters.

$\mathbf{b_1}$ Denotes the carrying capacity of population growth, effectively indicating the population apex achievable via the first logistic function.

$\mathbf{A_1}$ Influences the gradient of the first growth phase. Higher values result in steeper population inclines.

$\mathbf{a_1}$ Represents the growth rate of the initial logistic function, dictating how swiftly the population nears the carrying capacity b_1.

$\mathbf{t_1}$ Marks the inflection point in the first logistic phase, signifying the period of maximum growth velocity.

$\mathbf{b_2}$ Illustrates the decline's carrying capacity, indicating the population decrease as projected by the second logistic function.

$\mathbf{A_2}$ Determines the gradient of the decline phase, with larger values resulting in sharper declines.

$\mathbf{a_2}$ Represents the rate of decline in the latter logistic function, determining the speed at which the population reaches the decline's carrying capacity b_2.

$\mathbf{t_2}$ Highlights the inflection point during the decline phase, marking the period where the decrease is most rapid.

Table 4.2: Population projections for the EU27+4

YEAR	MEDIAN AGE	EU27+4 (million)	EU27+3 (million)	UK (million)
2023	43	530.1	462.0	68.1
2024	43	531.9	463.4	68.4
2025	43	532.6	463.8	68.7
2026	44	533.1	464.1	69.0
2027	44	533.4	464.1	69.2
2028	44	533.5	464.0	69.4
2029	44	533.6	464.0	69.7
2030	45	533.7	463.9	69.9
2031	45	533.8	463.8	70.1
2032	45	533.9	463.7	70.3
2033	45	534.0	463.6	70.4
2034	45	534.1	463.5	70.6
2035	45	534.3	463.5	70.8
2036	46	534.5	463.6	71.0
2037	46	534.7	463.6	71.1
2038	46	534.9	463.6	71.3
2039	46	535.0	463.5	71.5
2040	46	535.1	463.4	71.6
2041	46	535.1	463.3	71.8
2042	46	535.1	463.2	72.0
2043	46	535.1	463.0	72.1
2044	46	535.1	462.8	72.3
2045	47	534.9	462.5	72.4
2046	47	534.8	462.2	72.6
2047	47	534.6	461.8	72.8
2048	47	534.3	461.4	72.9
2049	47	533.9	460.9	73.0
2050	47	533.6	460.4	73.2

Incorporation of demographic factors into individual waste stream models

> **WASTE STREAM NOTICE**
>
> This section will be filled out with the details of exactly how the demographic parameters are incorporated into your stock and flow models

BATT (BATTERY WASTE)

- X

CDW (CONSTRUCTION AND DEMOLITION WASTE)

- X

ELV (END-OF-LIFE VEHICLES)

- X

MIN (MINING WASTE)

- X

SLASH (SLAGS AND ASHES)

- X

WEEE (WASTE ELECTRICAL AND ELECTRONIC EQUIPMENT)

- X

Conclusion

> **REVIEW NOTICE**
>
> This conclusion will be compiled once the individual waste stream sections for each parameter are complete.

4.3.4. Economic factors: *GDP growth*

Definitions

Gross Domestic Product (GDP) PPP

A measure of a country's economic output that accounts for differences in price levels between countries. By using PPPs and the common currency of international dollars, GDP PPP is adjusted for price level differences across countries, providing a more accurate measure of the economic output and living standards, as it reflects the real purchasing power of the citizens.

Purchasing Power Parity (PPP)

An economic theory that allows the comparison of the purchasing power of various world currencies to one another. It involves a comparison of the relative prices of a standard set of goods and services in different countries, thus providing a measure of the relative cost of living and enabling a more accurate comparison of economic well-being.

SCENARIO TRENDS FOR: GDP growth

BAU **Scenario I — Business-as-usual:**

Slow stable growth

Scenario II — Recovery:

Slow stable growth

Scenario III — Circularity:

Slow stable growth

Sources of data

The GPD projections for FutuRaM's future scenarios are based on economic data from the OECD as well as population data from Eurostat and the UK's ONS [63, 64, 65]

Results of projections

As an 'external element', the GDP projections do not differ across the scenarios, only as a function of time.

The results of the projections are shown in Figure 4.6. An interactive figure can be viewed here

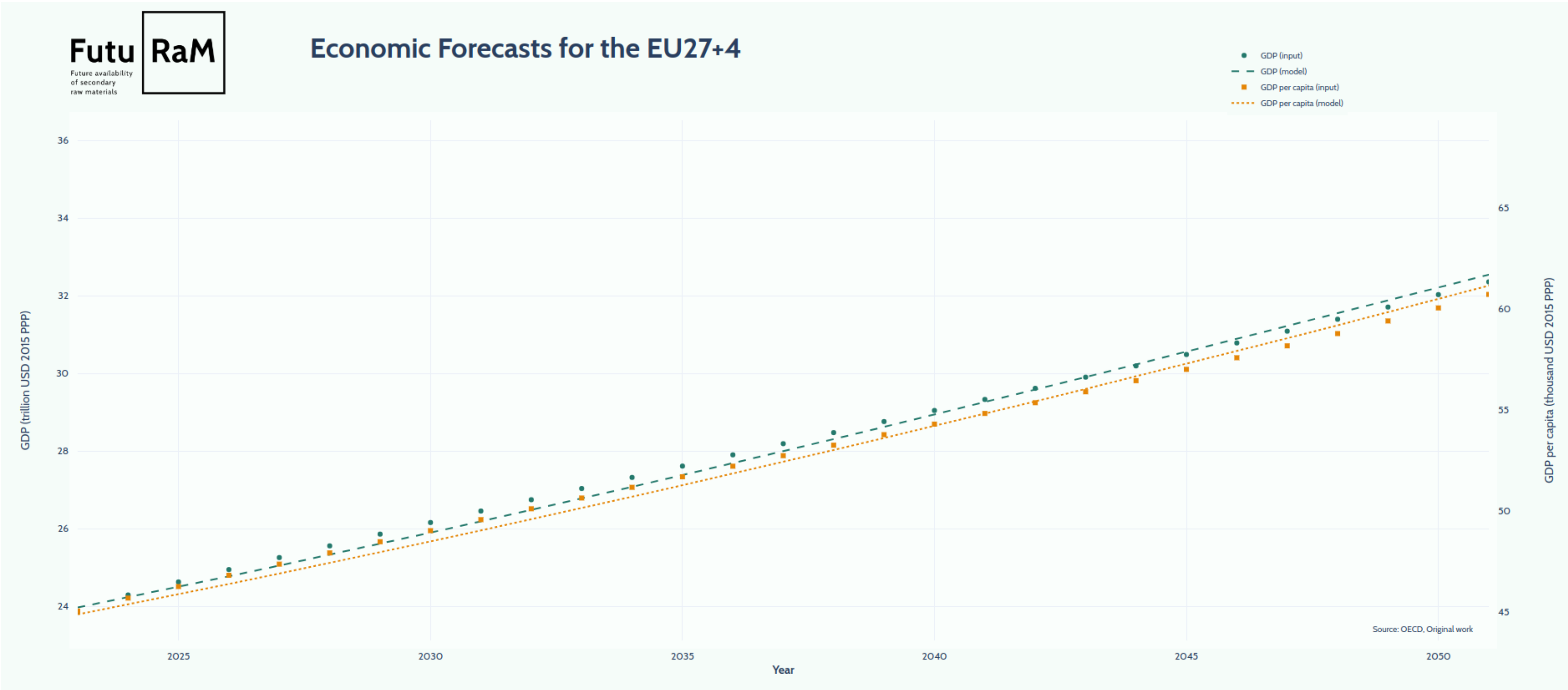


Figure 4.6: GDP projections for the EU27+4

Methodological Overview of OECD's GDP Projection Framework

[65, 40, 108, 158]

The OECD's approach to projecting GDP is rooted in the principle that income levels across various nations will gravitate towards those observed in the most advanced economies, an idea put forth by [41, 74]. This convergence is modelled through an enriched version of the Solow growth model, factoring in a dual-sector configuration [109], which the OECD dubs the ENV-Growth model. Rather than focusing solely on convergence in income, the ENV-Growth model prioritises the growth factors that will drive GDP over time.

For GDP projections up to 2060, the OECD combines model-based assessments with expert evaluations, considering the economic dynamics of individual countries and the global market. These forecasts are denominated in the constant US dollars and PPPs of 2010, based on data from OECD and World Bank, which use the Atlas method for calculating PPPs [40, 66]. The data originate from the OECD Long-Term Baseline Scenario. This scenario, which is integral to the OECD Economic Outlook, serves as a comparative standard to gauge the possible effects of structural reforms, assuming a policy-neutral environment. Conversely, long-term projections diverge from the medium-term forecasting model, which is predominantly demand-driven, by focusing on a supply-side perspective that takes into account labour and capital availability and productivity growth rates.

Determinants of Long-term Growth

[40, 110]

Recognizing the multifaceted nature of economic advancement, GDP growth projections consider an array of influences such as demographics, educational attainment, technological progress, energy access, and capital flow patterns. The MaGE framework facilitates GDP estimation by charting dynamic paths that reflect the structural interplay defining the economic landscape until 2050 [110].

The ENV-Growth model's projections span a century and include a wider selection of countries, enhancing the original methodologies developed by the OECD Economics Department [108, 158]. It introduces considerations for energy usage and resource revenue from oil and gas sectors, aligning with the enhanced sectoral approach for fossil fuels presented by [42].

The model's foundation lies in its projection of the five pivotal elements driving economic growth:

- Physical capital
- Employment, shaped by population trends, age demographics, participation rates, and unemployment scenarios
- Human capital, based on education and its consequential effect on labour productivity
- Energy demand and resource extraction for exporting countries
- Total factor productivity (TFP)

The determinants of growth are not restricted to these factors; they also encompass a spectrum of social, economic, and institutional influences, including workforce education, trade openness, institutional integrity, fiscal strategies, regulatory frameworks, and demographic shifts. The underlying potential for economic catch-up through technology transfer and innovation is underscored by the differential in income between each country and the global technology frontrunner.

In the context of employment, projections from IIASA inform the total employment figures, combining time-specific participation rates for different age cohorts with projected unemployment trends. Education assumptions translate gender and age-specific educational projections into a human capital index, which then informs labour productivity enhancements.

For physical capital, the model follows a standard capital accumulation methodology with a set depreciation rate, with the investment rate per unit of GDP edging towards a balanced growth path level determined by the production function's structural parameters.

Energy and natural resources are integrated as productive components for consumers and as extra income from specific oil and gas sectors for producer nations. The model calibrates domestic energy productivity to historical improvement rates, progressing towards an efficiency frontier indicative of cutting-edge energy appliances. The economic contribution of energy resources to producer countries is extrapolated from resource depletion models that describe the dynamics between reserves and resources and the temporal evolution of marginal production costs.

FutuRaM's economic forecasts, while not based directly on the SSP data, are consistent with the SSP2 baseline derived from similar sources and models [106, 107, 111, 112, 113, 114], offering a comprehensive picture of potential economic trajectories.

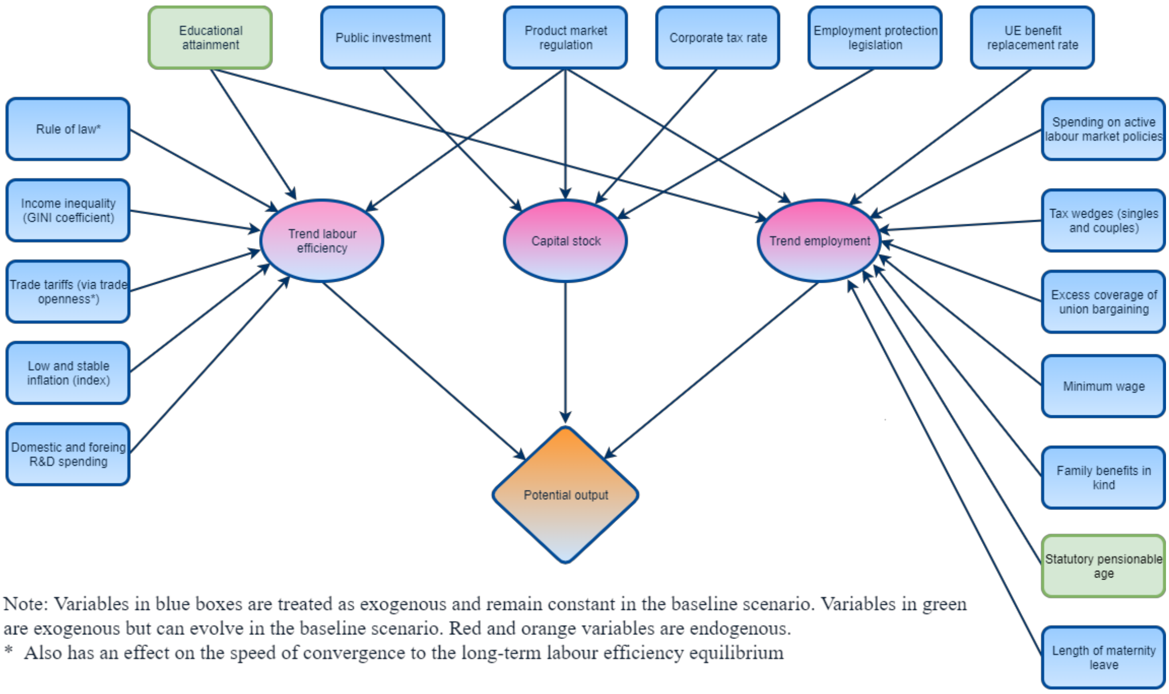


Figure 4.7: Factors incorporated in the long-term GDP model [40]

Implications of GDP Growth on FutuRaM's Waste Models

GDP growth has significant implications for models concerning secondary raw material recovery and waste generation. For example, increasing GDP tends to lead to higher consumption levels, which can result in more waste generation across various streams. However, higher income also provides greater resources for investment in recovery technologies and infrastructure. Below are some examples for each of the specified waste streams.

BATT (BATTERY WASTE)

As GDP grows, the demand for electronic devices and electric vehicles typically increases, leading to a higher turnover of batteries. This could necessitate advancements in recovery methods for battery components, such as lithium and cobalt, to reduce reliance on primary sources and mitigate environmental impact.

CDW (CONSTRUCTION AND DEMOLITION WASTE)

Economic growth often spurs construction activity, thereby increasing CDW. Increasing GDP as a ratio of waste generation could lead to enhanced recycling processes, promoting the circular economy by converting waste into secondary raw materials for new construction projects.

ELV (END-OF-LIFE VEHICLES)

The number of ELVs rises with economic prosperity, as people can afford newer vehicles more often. This creates opportunities to recover valuable materials and components, necessitating more efficient recycling processes.

MIN (MINING WASTE)

As economies expand, so does the demand for minerals, potentially increasing mining waste. With increased GDP, there could be more investment in techniques to minimise waste generation and recover valuable materials from mining by-products.

SLASH (SLAGS AND ASHES)

Higher GDP can correlate with increased industrial activity, producing more slags and ashes. Enhanced recovery techniques can transform these by-products into useful secondary raw materials, such as aggregates in construction.

WEEE (WASTE ELECTRICAL AND ELECTRONIC EQUIPMENT)

GDP growth can lead to shorter replacement cycles for electronic goods, increasing the amount of WEEE. There's a potential for improved recovery of precious metals and rare earth elements, driving innovation in e-waste recycling technologies.

Incorporation of economic growth into individual waste stream models

> **WASTE STREAM NOTICE**
>
> This section will be filled out with the details of exactly how this parameter is incorporated into your stock and flow models

BATT (BATTERY WASTE)

- X

CDW (CONSTRUCTION AND DEMOLITION WASTE)

- X

ELV (END-OF-LIFE VEHICLES)

- X

MIN (MINING WASTE)

- X

SLASH (SLAGS AND ASHES)

- X

WEEE (WASTE ELECTRICAL AND ELECTRONIC EQUIPMENT)

- X

Conclusion

Economic growth can therefore act as both a driver of waste generation and a catalyst for innovation in the recovery of secondary raw materials. The challenge for models like FutuRaM lies in accurately predicting these trends and proposing effective strategies to balance economic benefits with environmental sustainability.

REVIEW NOTICE

This conclusion will be more completely compiled once the individual waste stream sections for each parameter are complete.

4.3.5. The Renewable Energy Transition

Definition

The term "energy transition" refers to the current global shift from fossil fuels to renewable energy sources to meet the urgent need to reduce greenhouse gas emissions, combat climate change, and enhance energy security. This transition encompasses a fundamental transformation of energy supply and consumption patterns, including the increased use of sustainable energy to achieve a low-carbon economy. Historical shifts in energy sources—from biomass to coal, and later to oil and natural gas—reflect the ongoing evolution of energy use. The present focus is on scaling up renewables such as solar and wind, which are becoming increasingly cost-competitive. Key aspects of the transition include adopting electric vehicles, improving public transportation, advancing energy-efficient technologies for building heating, and developing energy storage and grid solutions to support the integration of variable renewable energy sources.

Future energy mix in the EU

The projected electricity mix for the EU is presented in Figure 4.8. An interactive figure can be viewed here 🔗

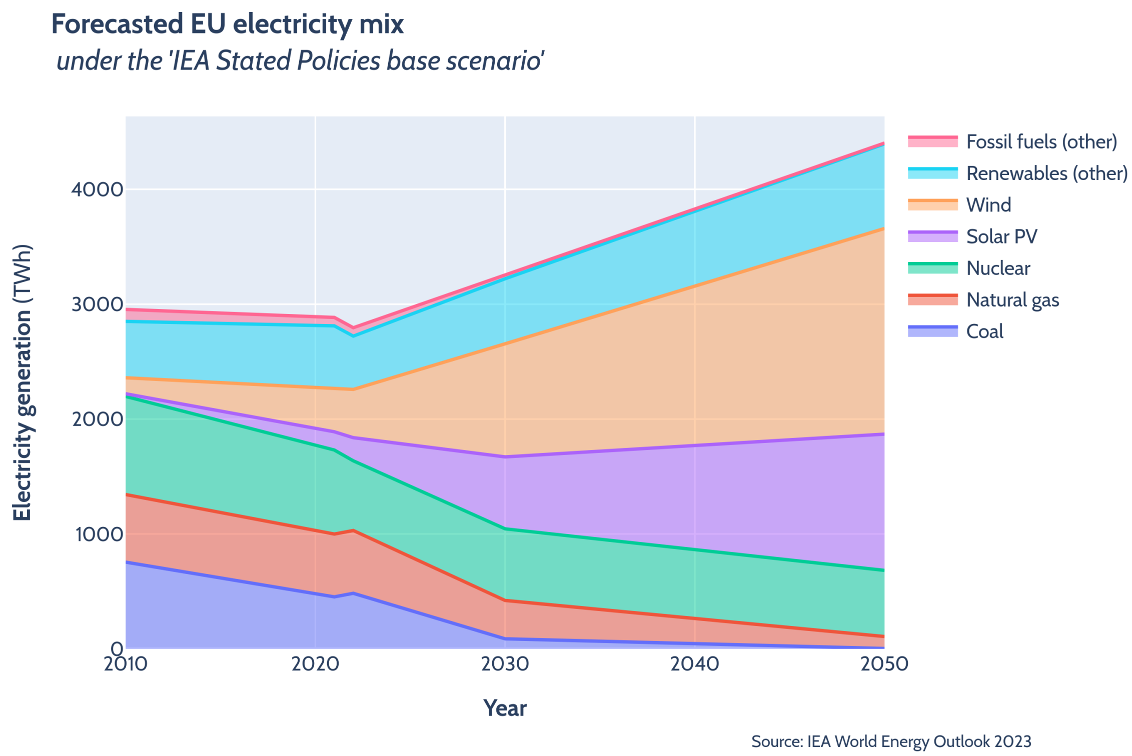


Figure 4.8: EU electricity mix forecast until 2050

Brief context of renewable energy in the EU

Renewable energy is integral to the EU's shift towards a low-carbon economy and reducing reliance on imported fossil fuels—a response accentuated by the urgency to curtail dependence on Russian energy sources. The EU's strategic move is encapsulated in the REPowerEU Plan of Action, introduced in May

2022, and agreed upon in 2023 which prescribes an aggressive uptake of renewables, emphasizing wind and solar PV, alongside hydrogen, heat pumps, and batteries, vital for energy storage and transportation decarbonisation [43, 14, 15, 44].

In analysing the renewable sector in FutuRaM, the focus is on solar PV, wind turbines, electrolysers, batteries, and residential heat pumps. Other renewable sources like bioenergy, hydro, geothermal, and ocean energy, while part of the portfolio, are expected to have minimal impact on critical materials demand and are not central to this analysis.

Justification for setting as an external scenario factor

The ongoing global energy transition is a profound shift that holds implications for almost every facet of society, especially regarding CRMs, other raw materials and the system of waste management. This transition from fossil fuels towards renewable energy sources demands a significant increase in various CRMs, influencing their supply and demand curves extensively. In the development of FutuRaM's scenarios, the energy transition is recognised as a fundamental driver of change. However, for the purposes of focussed and strategic scenario modelling, it has been categorised as an external factor.

This classification allows for a delineation between direct policy levers within the purview of SRM systems and broader macro-environmental trends that, while influential, are not the primary subject of analysis within FutuRaM. As such, the project's scenarios incorporate a consistent baseline projection of the energy transition's effects, shared across the three scenarios, ensuring that the core analysis remains centred on material-centric policy outcomes and targets of the CRM act. This ensures that the resulting insights are actionable and tailored to the nuances of material management and recycling systems. It reflects a strategic choice to maintain scenario tractability and avoid the dilution of policy implications that could arise from an overly broad scope of variables.

Moreover, the scenario architecture within FutuRaM is constructed with inherent flexibility, permitting later incorporation of amendments to the background energy transition trends. This adaptability is essential to ensure that, as the energy landscape evolves and new data becomes available, the scenarios can be revised and updated, thereby preserving the relevance and accuracy of the project's findings over time.

Relevant technologies in the renewable energy sector

The cornerstone technologies in renewable energy—batteries, electrolysers, wind turbines, heat pumps, and solar PV—play pivotal roles across various sectors (Figure 85). Heat pumps serve industrial processes, while solar PV and batteries support ICT, defence, and mobility with energy and uninterrupted power supplies, respectively [43].

Wind energy, expected to surge, will benefit from cost-efficient, innovative turbines designed for increased productivity in offshore and low-wind conditions. Projections from GECO present two scenarios: a conservative estimate shows wind capacity expanding from 732 GW (2020) to 1,400 GW (2030), and to 4,050 GW by 2050. An optimistic forecast anticipates a rise to 2,500 GW by 2030 and 8,400 GW by 2050.

Solar PV is poised for exponential growth due to advancements enhancing efficiency and lowering costs. GECO's cautious scenario predicts growth from 710 GW (2020) to 2,950 GW (2030), reaching 7,500 GW by 2050. The optimistic scenario projects a tenfold increase by 2030 and sixteenfold by 2050 compared to 2020 levels.

Addressing the intermittency of wind and solar power necessitates adequate storage solutions and robust grid systems, with electrolysers emerging as a crucial technology for renewable hydrogen production, forecasted to exceed 1 GW capacity by the end of 2022 [45].

Additionally, digitalisation, robotics, and 3D printing are set to boost the renewable sector's productivity and optimisation across its value chain. Heat pump sales are also on an upward trend, with a peak expected in 2045, ranging between 15 million (low demand) and 38 million units (high demand) by 2050.

Material demand in the renewable sector is dominated by wind turbines, electrolysers, and solar PV, with wind energy leading in consumption of critical materials.

Supply Chain bottlenecks in renewable energy

Supply chain bottlenecks present a significant challenge in the deployment of renewable energy technologies, particularly for wind turbines, solar PV, electrolysers, and heat pumps. The production of NdFeB permanent magnets for wind turbines demands rare earth elements (REEs) like neodymium, dysprosium, praseodymium, and terbium, with the EU being highly dependent on imports for both raw and processed materials such as permanent magnet alloys and components like blades.

Solar PV technologies necessitate strategic raw materials, including silicon metal and rare metals like gallium and germanium, with China dominating the production of silicon ingots and wafers. This reliance on imports extends across the value chain, including the crystalline silicon cell production where the EU's contribution is minimal.

The battery industry utilizes strategic raw materials such as lithium, manganese, and cobalt, with raw materials and components largely imported. A shift is anticipated towards nickel-rich batteries or alternative chemistries to reduce reliance on high-cobalt-content lithium-ion batteries (LIBs) due to the oligopoly control of critical components in Asia.

Electrolysers for hydrogen production use a range of strategic raw materials, particularly from the platinum group metals (PGMs), but also silicon metal, aluminium, copper, and magnesium, with the EU facing challenges in sourcing these materials. For heat pumps, strategic raw materials needed include magnesium and copper, but no significant bottlenecks have been identified, with most critical materials used in microchips and IT controllers.

Across all technologies analysed, a common pattern of heavy reliance on imports, particularly from China, is observed at different stages of the value chains. The EU's primary sourcing and processing capabilities for critical raw materials are notably low, creating dependencies at multiple levels. Despite a strong manufacturing capacity for wind turbine assembly, the EU is entirely reliant on imports for the value chain of rare-earth permanent magnets. Similarly, for solar PV, the dependence on imports is comprehensive. The recent surge in Chinese manufacturing market share for heat pumps and the developing value chain for batteries in the EU are also noteworthy.

A breakdown of the materials required for each technology is given in Table 4.3.

Table 4.3: Raw materials essential to the renewable energy sector

SUPPLY RISK	MATERIAL	CRM	BATT	H2	WIND	SOLAR (PV)	HEAT PUMPS
5.3	HREE (rest)	●		●			
4.8	Gallium	●				●	
4.4	Niobium	●		●	●		
4.1	Magnesium	●		●			
4.1	REE (magnets)	●		●	●		●
3.8	Boron	●		●	●	●	●
3.5	LREE (rest)	●		●			
3.3	Phosphorus	●	●			●	
2.7	PGM	●		●			
2.6	Strontium	●		●			
2.4	Scandium	●		●			
2.3	Vanadium	●		●			
1.9	Lithium	●	●				
1.8	Geranium	●				●	
1.8	Natural graphite	●	●	●			
1.8	Antimony	●				●	
1.7	Cobalt	●	●	●			
1.6	Arsenic	●				●	
1.4	Silicon metal	●		●	●	●	●
1.3	Baryte	●		●			
1.3	Tantalum	●		●			
1.2	Manganese	●	●	●			●
1.2	Tungsten	●		●			
1.2	Aluminium	●	●	●	●	●	●
1.1	Fluorspar	●	●			●	●
0.9	Tin			●		●	
0.8	Molybdenum			●	●	●	●
0.8	Silver			●		●	●
0.8	Zirconium			●			
0.7	Chromium			●	●		●
0.7	Potash			●			
0.6	Indium					●	
0.5	Nickel	●	●	●	●	●	●
0.5	Iron ore		●	●	●	●	●
0.5	Titanium			●			
0.4	Gold			●			●
0.3	Tellurium					●	
0.3	Limestone			●			

Continued on next page

Table 4.3 — Continued from previous page

SUPPLY RISK	MATERIAL	CRM	BATT	H2	WIND	SOLAR (PV)	HEAT PUMPS
0.3	Selenium					●	
0.3	Silica				●	●	
0.2	Cadmium					●	
0.2	Zinc			●	●	●	●
0.1	Copper	●	●	●	●	●	●
0.1	Aggregates				●		
0.1	Lead				●	●	

The integration of the energy transition has significant implications for the management of Critical Raw Materials (CRMs) across various waste streams due to changing material requirements and waste profiles [25, 43, 67, 46].

For example:

BATT (Battery waste)

- Increased deployment of Li-ion batteries for energy storage will lead to a surge in waste batteries, necessitating improved recycling technologies to recover CRMs.
- The transition to renewable energy sources may lead to changes in the battery composition, affecting recycling processes and the types of CRMs that need to be managed.

ELV (End-of-Life Vehicles)

- The shift towards electric vehicles will transform the composition of ELVs, increasing the relevance of CRMs used in electric powertrains and batteries.
- This transition requires the adaptation of ELV recycling infrastructure to efficiently process and recover new types of CRMs.

WEEE (Waste Electrical and Electronic Equipment)

- As energy systems become more digitized and interconnected, WEEE will contain a broader array of CRMs, prompting the need for more sophisticated recycling methods.
- The growing volume of WEEE will challenge current recycling capacity and technology, calling for significant innovation in CRM recovery techniques.

CDW (Construction and Demolition Waste)

- Green building materials and energy-efficient technologies may introduce new CRMs into CDW, changing the material recovery landscape.
- The promotion of deconstruction over demolition could preserve the integrity of materials containing CRMs, allowing for better recovery rates.

MIN (Mining Waste)

- The drive for clean energy technologies is expected to increase the mining of specific CRMs, potentially leading to higher volumes of mining waste that must be managed sustainably.

SLASH (Slags and Ashes)

- The energy transition could increase the generation of certain industrial wastes such as slags, which may contain valuable CRMs.

Implementation in EU Law

Fit for 55 Package (2021)

The "Fit for 55" package is a collection of policy initiatives proposed by the European Commission in July 2021 aimed at revising and updating EU legislation to reflect the increased ambition of reducing net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels [16]. This target was a significant step up from the previous goal of a 40% reduction and is part of the European Union's plan to become climate-neutral by 2050 — an objective set out in the European Green Deal[3].

The package includes proposals to revise the EU Emissions Trading System (ETS), to increase the use of renewable energy, to improve energy efficiency, and to implement carbon pricing mechanisms, among other measures. The intention is to align existing laws with the 2030 climate target and to set the legal foundation for Europe's transition to a green economy. This includes changes across various sectors including transportation, building, and energy production to reduce emissions and promote sustainable practices.

REPOWEREU PLAN (2022)

The invasion of Ukraine by Russia has caused significant disruption to energy markets in Europe and globally. To eliminate reliance on an unreliable supplier, the European Commission has devised the REPowerEU plan [15]. This initiative focuses on energy conservation, the production of clean energy, and the diversification of energy sources, supported by financial and legal measures to develop Europe's necessary new energy infrastructure and systems.

Accelerating Clean Energy Renewable energy sources, being both cost-effective and environmentally friendly, can be produced locally, thereby reducing dependency on imported energy. The REPowerEU plan aims to expedite the green transition and trigger substantial investments in renewable energy. It also seeks to facilitate the rapid transition of industry and transport from fossil fuels, reducing both emissions and dependency.

This includes a variety of measures focused on renewable energy and energy efficiency, such as:

- Increasing the EU's 2030 renewable energy target of the 'Fit for 55 package' from 40% to 45%.
- Accelerating the deployment of photovoltaic (PV) energy.
- Introducing the European Solar Rooftop Initiative.
- Doubling the deployment rate of individual heat pumps.
- Decarbonising the industry by promoting electrification and renewable hydrogen.
- Speeding up renewable energy project and grid infrastructure permit processes.
- Increasing the EU's binding energy savings target for 2030 to 13%.

The May 2022 REPowerEU plan by the European Commission, in response to the energy market disruptions due to Russia's invasion of Ukraine, is designed to rapidly cut down on the EU's reliance on Russian fossil fuels. It raises the renewable energy target of the Fit for 55 package from 40% to 45%.

This ambitious goal for renewable energy use, coupled with REPowerEU's strategies to reduce energy demand, necessitates substantial increases in renewable capacity across the electricity, transport, and heating and cooling sectors. The Commission forecasts that to meet the 2030 objectives, renewable electricity should reach 69%, 32% in transport, and a yearly growth of at least 2.3 percentage points in heating and cooling.

RENEWABLES ENERGY DIRECTIVE (2023)

The recent legislation strengthening the EU Renewable Energy Directive marks an advancement towards the European Green Deal and REPowerEU ambitions. With the provisional agreement, the EU's binding renewable energy target for 2030 is now at least 42.5%, aiming potentially to reach 45%. This target significantly surpasses the previous goal of 32% and is nearly double the present proportion of EU renewable energy.

A distinct enhancement over the REPowerEU plan is the establishment of definitive binding targets for renewable energy. The legislation optimises permitting procedures, acknowledges renewable energy as an overriding public interest, and designates acceleration zones for expedited development in strategically identified regions.

The directive also introduces specific directives across various sectors:

- In heating and cooling, it sets forth progressive annual renewable targets and a 49% renewable energy consumption benchmark in buildings by 2030.
- It for the first time includes the industrial sector under its ambit, establishing indicative and binding targets for the use of renewable energy and renewable hydrogen, respectively.
- For the transport sector, it specifies a reduction in greenhouse gas intensity and sets sub-targets for advanced biofuels and renewable fuels of non-biological origin, underpinning the EU's renewable hydrogen objectives.
- It further enhances the "guarantees of origin" system to improve consumer information and supports the integration of the energy system through electrification and waste heat capture.

In summary, the agreement accelerates the EU's strides towards energy autonomy, promises to reduce energy costs over time, and decreases dependence on imported fossil fuels. It intensifies the EU's pledge to a decarbonised economy and aligns with REPowerEU's broader goals but with specific, more ambitious targets and refined processes for rapid renewable energy adoption.

While the reinforced EU Renewable Energy Directive is a pivotal step towards the EU's "Fit for 55" framework and the overarching European Green Deal goals, it has not been without its critics. The Directive's ambitious targets for 2030 have spurred a range of responses from member states and institutions, with concerns centered around feasibility, economic impact, and the varying capabilities of nations to meet these objectives [17].

The following is a summary of the key points raised by member states and the European Commission in their statements on the directive [17]:

Belgium
Belgium supports the directive while voicing *"serious concerns"* over the feasibility of increased renewable energy targets, citing *"demographical and geographical limitations"* and the presence of energy-intensive industries. The national contributions and sectoral sub-targets are deemed *"extremely difficult to achieve"* and potentially *"unachievable"* within the proposed timeline.

Poland
Poland boasts a rapidly growing renewable sector but cannot support the proposed directive, stating it is unrealistic and could destabilize the energy grid and security. They assert that the targets lack realism and flexibility, and stress that the energy transition should be *"accessible to society"* and in favor of European industry.

Romania
Romania is committed to decarbonisation but expresses concern that the high level of ambition may lead to increased costs and discourage certain sectors, making them *"un-competitive."* They highlight the importance of national specificities and energy mixes in setting targets and advocate for technology neutrality.

Slovak Republic
Slovakia finds the EU RES target for 2030 *"very ambitious"* and difficult, stressing that additional contributions may not reflect the real potential for renewable development in the country. The statement also points to concerns over hydrogen production support not being satisfactorily addressed.

European Commission

The Commission acknowledges the significant efforts required from Member States to meet the targets, noting the high adaptation costs for certain industries. It concedes that achieving the directive's objectives will involve significant public and private investment and national budget implications. The Commission emphasizes the need for complementary decarbonisation efforts involving other non-fossil energy sources.

Challenges to the expansion of renewable energy in the EU

In addition to the internal conflict among member states [17], a recent IEA analysis concluded that EU's renewable energy expansion is constrained by inadequate policy support, complex permitting, and grid upgrades' pace. [45]

Current forecasts indicate that the solar PV and wind capacity expansions fall short of the REPowerEU plan's renewable electricity targets for 2030. The European Commission Staff Working Document states that achieving a 69% share of renewable electricity requires 592 GW of solar PV and 510 GW of wind by 2030, translating to annual additions of 48 GW for solar PV and 36 GW for wind [47].

These figures significantly exceed the IEA's main case projections of 39 GW for solar PV and 17 GW for wind between 2022 and 2027, resulting in a renewable generation share of 54% in the electricity sector—15 percentage points below the desired 69% by 2030.

Therefore, to fulfill the necessary installed capacity for generating 69% of electricity from renewables by 2030, the annual net additions for solar PV need to increase by 22%, and for wind, more than double [159]. The EU estimates that the total amount required for these investments will exceed €360bn before 2030 [47].

Policy Support:

Uncertainty from infrequent auctions and limited visibility hampers utility-scale solar PV and distributed PV projects, with issues in current auction designs and support scheme extensions affecting growth and profitability.

Permitting:

A primary bottleneck due to complex regulations, land restrictions, social opposition, and permitting office inefficiencies increases costs and extends project lead times.

Grid Congestion:

Insufficient grid capacity and upgrade challenges caused by permitting hurdles, labour shortages, and opposition slow the integration of new renewable plants.

The IEA analysis states that improvements addressing these issues could boost solar and wind deployment by 30% by 2027. An accelerated case requires increased policy support, regulatory reforms, and quicker infrastructure development [159].

For utility-scale solar PV, competitive auctions must be introduced or extended, with revised auction designs to reflect current market conditions. Distributed PV could see growth with better support and remuneration for self-consumption.

Despite potential policy and regulatory advances, wind energy, particularly onshore, faces persistent permitting difficulties, and offshore wind is bogged down by grid connection delays.

Finally, market interventions and the energy crisis debate could influence renewable investments, stressing the need for careful reform processes involving all stakeholders to maintain investor confidence.

Incorporation of the energy transition into the FutuRaM scenarios

REVIEW NOTICE

There will need to be a discussion about choice of energy scenario and the use of this data:
(1) if it is to be used commercially, we will need a license from the IEA;
(2) more detailed data is available for purchase
(3) the choice of scenario and alignment with the WSs.
There are alternatives, such as the EU reference scenario [48] and the POTEnCIA central scenario, which is similar, although somewhat outdated [49]

In light of the information presented above, as well as the nature of the three scenarios, FutuRaM will use a moderate growth scenario for the energy transition. The data for this is sourced from the projections of the International Energy Agency (IEA) using the "base case" of their "Stated Policies (STEP)" scenario [68].

The IEA's World Energy Outlook 2023 presents a range of scenarios, including the Stated Policies (STEP) scenario, the Sustainable Development Scenario (SDS) — which is the IEA's pathway to achieving the Paris Agreement goals — and the Net Zero Emissions scenario. Full details of the scenarios are available in the documentation of the IEA's Global Energy and Climate (GEC) Model [160].

A comparison of the IEA's projections for the renewable energy transition in the EU under the STEP and APS scenarios is presented in Table 4.4.

Table 4.4: Normalized renewable energy supply in the EU using the year 2010 as a base reference

Year	Historical	Stated Policies	Announced Pledges
2010	1.00	–	–
2021	1.66	–	–
2022	1.66	–	–
2030	–	3.33	3.69
2050	–	5.69	7.23

A summary of the IEA's scenarios is presented in Table 4.5.

Table 4.5: Definitions and Objectives of the GEC Model 2023 Scenarios

	Net Zero Emissions by 2050 Scenario	**Announced Pledges Scenario**	**Stated Policies Scenario**
Definitions	A pathway to achieve net zero CO2 emissions by 2050 within the energy sector, updated fully in 2023. Universal access to electricity and clean cooking achieved by 2030.	Assumes all climate pledges as of end of August 2023, including NDCs and net zero targets, are met on time.	Reflects energy-related policies in place or under development as of end of August 2023 and planned capacities for clean energy technologies.
Objectives	To detail sector-specific actions needed to achieve net zero energy-related CO2 emissions by 2050 and other sustainable development goals.	To assess how current pledges align with the 1.5 °C global warming limit, showing the ambition gap and the steps needed for universal energy access.	To benchmark the achievements and limitations of current policies, highlighting the gap in implementation to meet decarbonisation targets.

THE STATED POLICIES SCENARIO (STEP)

The Stated Policies Scenario (STEPS) is an energy model that offers a conservative projection based on existing and developing energy policies, without assuming full achievement of governments' announced goals. It undertakes a detailed, sector-by-sector assessment including a variety of factors such as pricing, efficiency standards, and infrastructure projects as of the end of August 2023.

Although it incorporates far-reaching governmental targets, such as net zero emissions and complete energy access, these are not presumed to be fully implemented without evaluating the regulatory, financial, and infrastructural context of each country.

The STEPS assumes that current time-bound policies will be continued with similar measures but does not speculate on the future intensification or reduction of policies unless there is evidence to suggest this. For the first time in 2023, it also accounts for industry actions, such as the manufacturing capacities for clean energy technologies and their market impact.

Overall, the STEPS indicates that while existing commitments can make a substantial impact, there remains a significant gap to reach the ambitions of the Announced Pledges Scenario or the Net Zero Emissions by 2050 Scenario.

THE FUTURE ENERGY MIX IN THE EU

In a global sense, the energy transition manifests in FutuRaM's forecasts by way of the background energy mix. In Figure 4.8 is the IEA's projection of the energy mix in the EU for the Stated Policies scenario. Additional forecasts for rare earth elements (REEs) supply and demand related to wind energy and e-mobility are offered by the JRC [67].

IMPACT OF THE ENERGY TRANSITION ON THE FUTURAM SCENARIOS

REVIEW NOTICE

— Many more details to be added later once we have confirmed the scenario choice and the alignment with the WSs
— One advantage of the IEA data is that it is aligned with other data sets, such as CRM supply and demand forecasts
— The figures below are just an example of some of the impacts that we could portray here. Better figures will be generated later.

The following figures illustrate some of the impacts that scenario choice can have on raw material demand forecasts [25]

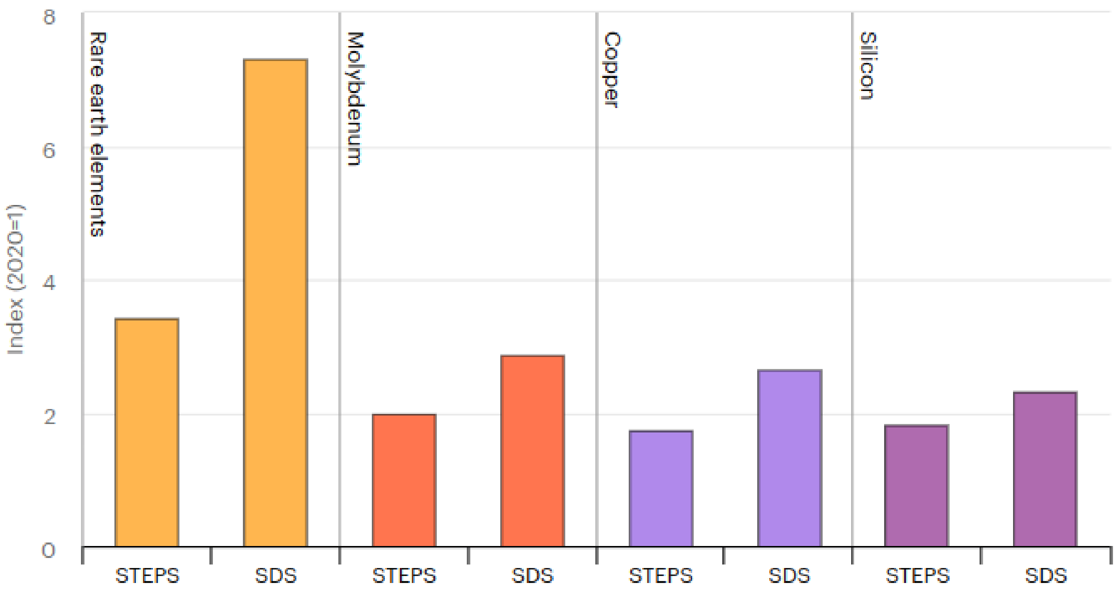


Figure 4.9: Change in demand for selected elements

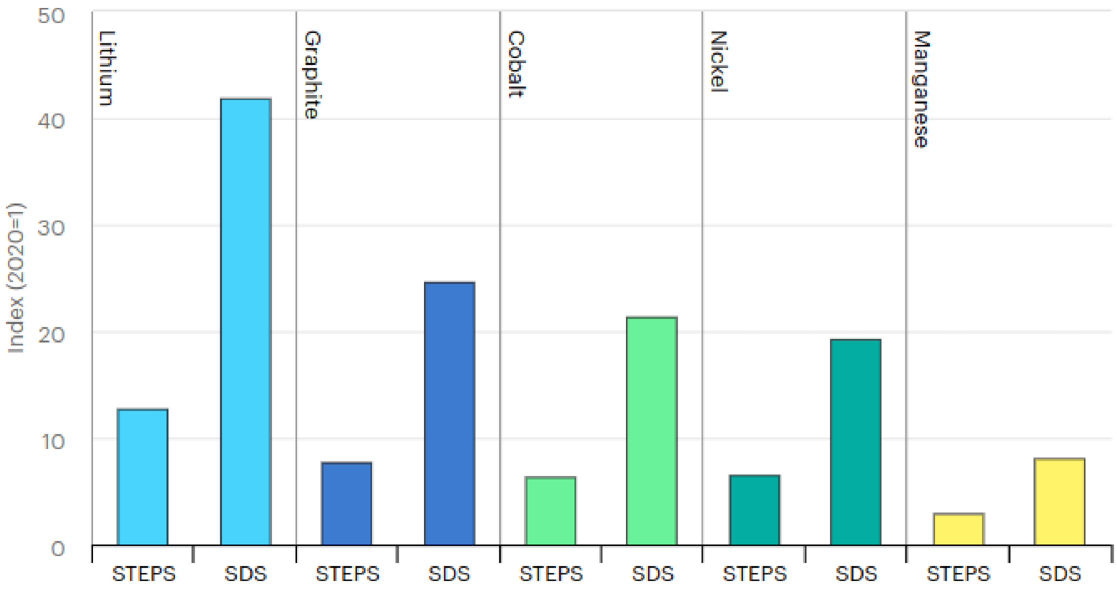


Figure 4.10: Change in demand for battery relevant elements

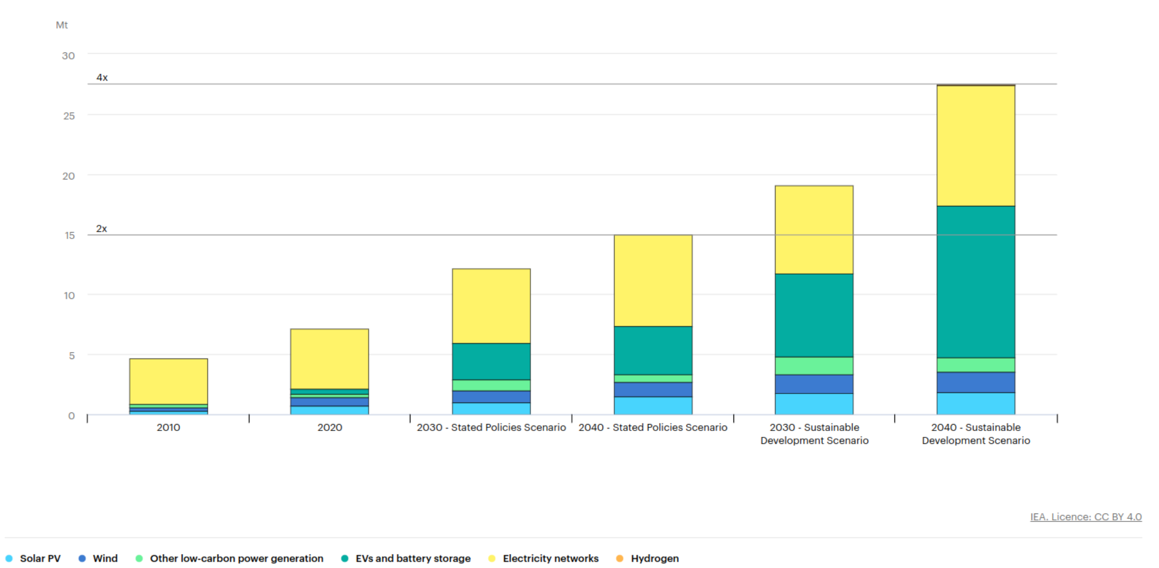


Figure 4.11: Global mineral demand (total) under various scenarios

Incorporation of the energy transition into individual waste stream models

WASTE STREAM NOTICE

This section will be filled out with the details of exactly how this parameter is incorporated into your stock and flow models

BATT (BATTERY WASTE)

- X

CDW (CONSTRUCTION AND DEMOLITION WASTE)

- X

ELV (END-OF-LIFE VEHICLES)

- X

MIN (MINING WASTE)

- X

SLASH (SLAGS AND ASHES)

- X

WEEE (WASTE ELECTRICAL AND ELECTRONIC EQUIPMENT)

- X

4.3.6. Supply constraints and market dynamics

REVIEW NOTICE

The precise methodology to be applied to determine the effects of hypothetical supply constraints and market dynamics on the model's outcomes has not yet been determined. This will be developed once the precise structure of the model has been finalised.

Introduction

Supply constraints refer to limitations in the availability of resources that can impact industries and markets. These constraints can arise from various sources, such as natural resource depletion, geopolitical issues, economic factors, or environmental regulations. In the context of waste generation, collection, and recovery, supply constraints can significantly affect the dynamics of the entire system.

Market dynamics refer to the interactions between supply and demand that determine the prices of goods and services. These dynamics are influenced by various factors, such as the availability of resources, technological change, the state of the economy, and governmental policies.

Incorporating these economic factors into waste management models is essential to understand and predict the behavior of waste systems under different economic conditions. Accurate modeling can aid in making informed decisions regarding waste management policies and practices.

The following section details the importance of supply constraints and market dynamics and introduces the proposed strategy for incorporating these 'outside' elements in the modelling work in FutuRaM.

Impacts of supply constraints and market dynamics

IMPACT ON WASTE GENERATION

Constraints on the supply of materials can lead to alterations in waste composition. For instance, scarcity in a particular raw material can decrease the production and subsequent waste of products made from that material.

IMPACT ON COLLECTION AND RECOVERY SYSTEMS

The availability of resources dictates the priorities of waste collection and recovery systems. Material scarcity can shift the focus towards recycling, while abundance might lead to alternative materials being preferred.

LAG TIMES TO RECOVERY

The scarcity of materials can extend the time products remain in use before entering the waste stream, affecting the timing and efficiency of waste recovery systems.

Economic Factors Influencing Waste Management

Economic aspects like prices, subsidies, and taxation play a crucial role in waste management, especially in the context of supply constraints.

Influence of Raw Material Prices

High prices for primary raw materials can incentivize the recycling of secondary materials. This economic motivation can lead to advancements in recycling technology and increased recycling efforts.

Secondary Raw Material Pricing

The pricing of secondary raw materials, often influenced by the availability and price of primary materials, affects their attractiveness for recycling. Competitive pricing of secondary materials can promote their use over primary materials.

Governmental Policies: Subsidies and Taxation

Policies involving subsidies for recycling activities or taxation on primary raw materials can shape the waste management landscape. These fiscal tools can encourage or discourage recycling based on their design and application.

Market Dynamics and Policy Interventions

Market dynamics, influenced by policy interventions, can also impact waste management. For example, a policy promoting the use of recycled materials can alter market preferences and boost recycling efforts.

Incorporation of supply constraints and market dynamics into the model

Sensitivity Analysis

Sensitivity analysis is an instrumental approach in modelling to ascertain the impact of supply constraints and market dynamics on the waste management system. This technique involves systematically varying parameters within the model and observing the resultant effects on the output. It is particularly beneficial in identifying which variables have the most significant influence on the system's behaviour.

Global Sensitivity Analysis, an extension of this concept, examines the entire parameter space, offering a comprehensive view of potential model responses to changes in input factors. This method is crucial in revealing the relative importance of different variables and can highlight areas where the system is most susceptible to economic fluctuations.

By utilising sensitivity analysis, decision-makers can better understand the robustness of their systems and formulate strategies that are resilient to economic uncertainties.

EXAMPLE

Impact of Raw Material Prices and Government Subsidies on Recovery System:

Scenario:
The model tests scenarios with significant fluctuations in raw material prices. In certain scenarios, a government subsidy is introduced to set a minimum price for recycled materials, ensuring their economic viability.

Analysis:
Sensitivity analysis evaluates the effect of raw material price changes on the profitability and viability of the recovery system. It also tests the impact of government subsidies in stabilising the system against these fluctuations.

Outcome:
This analysis can reveal the dependency of recovery operations on raw material market prices and the effectiveness of government subsidies in mitigating associated risks.

EXAMPLE

Reduction of a Valuable Material in the Waste Stream:

Scenario:
The model explores a situation where a previously abundant and valuable material becomes scarce in the waste stream.

Analysis:
This sensitivity analysis investigates the impact of reduced availability of this valuable material on the overall profitability of the waste management system.

Outcome:
It identifies critical thresholds where a reduction in material significantly affects the system's financial viability, guiding strategies for diversifying material recovery or exploring alternative revenue sources.

OPTIMISATION

Optimisation techniques are employed to identify the most efficient operational settings for the waste management system under diverse economic conditions. By modelling various local scenarios that encapsulate different economic realities —- such as varying levels of resource scarcity, price dynamics of primary versus secondary materials, and the impact of subsidies or taxes —- the model aims to find the optimal balance. This balance could be in terms of cost-effectiveness, resource utilization, environmental impact, or a combination of these factors. Optimization provides a framework to make data-driven decisions that can enhance the efficiency and sustainability of the waste management system.

Multi-Objective Optimisation is a key aspect of this process, where multiple conflicting objectives are considered simultaneously. This approach is essential in waste management systems, where there is often a need to balance economic goals with environmental sustainability.

By employing optimisation techniques, particularly Multi-Objective Optimisation, the model can provide insights into the trade-offs and synergies between different objectives, thereby facilitating more informed and balanced decision-making in waste management policies and operations.

EXAMPLE

Responding to Sudden Demand Increase for a Previously Less Valuable Material (Element X):

Scenario:

The model simulates a sudden increase in demand and price for a specific material (Element X) that was previously less valuable.

Analysis:

The system's response is optimized to maximise profitability under this new market condition, involving adjustments in collection and processing priorities towards Element X.

Outcome:

The optimisation indicates the most effective strategies for reallocating resources and operations to capitalise on the increased demand for Element X, enhancing profitability.

EXAMPLE

Optimizing for Environmental and Economic Goals amid Rising Carbon Emission Costs:

Scenario:

The model considers a significant increase in the cost of carbon emissions, impacting the expense of recovery operations.

Analysis:

The optimisation aims to balance environmental impact (carbon footprint) with economic viability, exploring operational adjustments like adopting more carbon-efficient recovery processes or prioritising materials with higher primary carbon footprints (offsets and substitution).

Outcome:

This approach yields insights into effective strategies for maintaining profitability while minimising environmental impact, aiding the system in achieving a dual bottom line of environmental sustainability and financial health.

Relevance of supply constraints and market dynamics for FutuRaM's waste streams

BATT (Battery waste)

- Fluctuating availability and prices of lithium and cobalt can significantly impact the recycling value and processes for batteries.
- Governmental policies on battery disposal and recycling can alter the landscape of battery waste management, influencing recycling rates and methodologies.

CDW (Construction and Demolition Waste)

- Variations in the construction market and raw material prices can influence the generation and composition of construction and demolition waste.
- Economic incentives and regulatory frameworks for sustainable construction practices can drive the recycling and reuse rates of CDW.

ELV (End-of-Life Vehicles)

- Changes in the metal market, particularly for steel and aluminium, can impact the profitability of recycling ELVs.
- Environmental regulations on vehicle disposal and recycling can shape the recovery strategies for ELV waste.

MIN (Mining Waste)

- Market demand for specific minerals can influence the focus and intensity of recovery efforts from mining residues.
- Policy changes regarding mine waste management can lead to shifts in recovery and disposal practices for mining residues.

SLASH (Slags and Ashes)

- The variability in the composition of slags and ashes due to different industrial processes and raw materials can significantly influence recovery and recycling strategies.
- Market conditions for secondary raw materials derived from slags and ashes, such as metals, can greatly affect the economic viability of their recovery and recycling processes.

WEEE (Waste Electrical and Electronic Equipment)

- Fluctuations in precious metal prices can affect the economics of recycling electronic waste.
- Evolving technology and product lifecycles can influence the generation and composition of WEEE, affecting recycling strategies.

Incorporation of supply constraints and market dynamics into individual waste stream models

WASTE STREAM NOTICE

This section will be filled out with the details of exactly how this parameter is incorporated into your stock and flow models

BATT (BATTERY WASTE)

- X

CDW (CONSTRUCTION AND DEMOLITION WASTE)

- X

ELV (END-OF-LIFE VEHICLES)

- X

MIN (MINING WASTE)

- X

SLASH (SLAGS AND ASHES)

- X

WEEE (WASTE ELECTRICAL AND ELECTRONIC EQUIPMENT)

- X

4.3.7. Conclusion

REVIEW NOTICE

This conclusion will be compiled once the individual waste stream sections for each parameter are complete.

4.4. INTERNAL ELEMENTS — TECHNOLOGICAL CHANGE

4.4.1. Introduction

Technological Change

Scenario elements

- **Product technology (composition)**
- **Recovery technology**
- **Recovery system development**

Waste model parameters include:

- **Lifetimes:**
  function of product technology
- **Composition:**
  function of product composition, durability, design-for-repair, etc.

Recovery model parameters include:

- **Recovery processes:**
  market penetration of recovery technologies
- **Transfer coefficients:**
  function of recovery technologies
- **Recovery system size:**
  BAU - set by trends in BAU, CIR & REC - defined by model outcomes within constraints

Product technology and recovery technology development will differ across scenarios and across product groups in each waste stream. These differences must be integrated into individual stock-flow models through interpretations of the scenarios and the conversion of these into estimations of the changes.

recognising the need for assumptions about technological advancements in products and recovery processes. The document stresses the importance of addressing product technology development until 2050, as this will vary in importance across different waste streams.

4.4.2. Methodology

1. **Scenario Analysis:**
   Different future scenarios are explored to understand how technological development might unfold. This includes examining existing and new technologies, their properties over time, and how they are diffused into the market.
2. **Waste Stream Focus:**
   The approach varies in importance across different waste streams like EEE, ELV, BATT, CDW, and SLASH. For each stream, specific assumptions and approaches need to be tailored.
3. **Data Collection:**
   Gathering data from various sources, including patents, scientific publications, business reports, and expert opinions, to inform assumptions about technology development.
4. **Modelling Approach:**
   Utilizing dynamic Material Flow Analysis (dMFA) for modelling, covering a timeline from 2000 to

2050. This includes historical data analysis and future projections based on assumptions.

5. **Technology Diffusion:**
   Understanding the rate and manner in which technologies gain market share, depicted through S-curves. This involves considering factors like price, legislation, and organizational support.

6. **Assumptions on Technology Development:**
   Outlining specific assumptions at the level of each waste stream and aligning these assumptions across streams where possible.

7. **Integration into SF Models:**
   Incorporating the assumptions about product and recovery technology development into SF models to reflect the scenario-based variations.

8. **Transparency and Communication:**
   Ensuring that the chosen approaches and assumptions are clearly stated for transparency and ease of understanding.

The methodology is designed to provide a comprehensive understanding of how future technology developments can impact various aspects of waste management and resource recovery in a circular economy context.

4.4.3. Summary

REVIEW NOTICE

This summary will be compiled once the individual waste stream sections for each parameter are complete.

4.4.4. Future product and waste composition: *Description*

Future compositions, technologies and products will be assessed based on technology outlooks and stakeholder interviews and may include sector-specific Delphi surveys. Information needs and availability for composition data as well as the type of relevant recoverable embodied SRMs varies across the waste streams. Thus, specific data collection strategies will be developed and used for each waste stream.

Task 2.2 and 2.3

Following the scenarios from T2.1, the material compositions and future products for each sector will be determined based on the product and commodity demand and technology realisation (T2.2). This task will be coupled to the data collection in WP3 and WP4

Definition

SCENARIO TRENDS FOR: Future product and waste composition

BAU **Scenario I — Business-as-usual:**

Stable

Scenario II — Recovery:

Strong shift toward design for design for recycling, remanufacturing, recovery

Scenario III — Circularity:

Strong shift toward durability and design for re-X, especially re-use, repair

Method

The general method for determining future product and waste composition will be based on the following steps:

- **Step 1:** Collection of data on current product and waste composition (WP3)
- **Step 2:** Grouping of code lists into broader categories (WP3)
- **Step 3:** Identification of future products based on technology outlooks, literature review, and stakeholder interviews
- **Step 4:** Estimation of constraints for market entry, replacement, and market share of future products (WP2) in each scenario
- **Step 5:** Modelling of future product and waste composition based on the results of steps 1-4

Relevance of future product and waste composition to Critical Raw Materials in Waste Streams

The integration of future product and waste composition has implications for the management of Critical Raw Materials (CRMs) across various waste streams, such as BATT (waste batteries), ELV (end-of-life vehicles), WEEE (waste electrical and electronic equipment), and CDW (construction and demolition waste).

Batteries (BATT)

End-of-Life Vehicles (ELV)

Waste Electrical and Electronic Equipment (WEEE)

Construction and Demolition Waste (CDW)

4.4.5. Future product and waste composition: *Scenarios*

WASTE STREAM NOTICE

This section will be filled out with the details of exactly how this parameter is incorporated into your stock and flow models

Summary

REVIEW NOTICE

This summary will be compiled once the individual waste stream sections for each parameter are complete.

BAU *Scenario I: Business-as-usual*

x

BATT (Battery waste)

CDW (Construction and Demolition Waste)

ELV (End-of-Life Vehicles)

MIN (Mining Waste)

SLASH (Slags and Ashes)

WEEE (Waste Electrical and Electronic Equipment)

Scenario II: Recovery

x

BATT (Battery waste)

CDW (Construction and Demolition Waste)

ELV (End-of-Life Vehicles)

MIN (Mining Waste)

SLASH (Slags and Ashes)

WEEE (Waste Electrical and Electronic Equipment)

Scenario III: Circularity

x

BATT (BATTERY WASTE)

CDW (CONSTRUCTION AND DEMOLITION WASTE)

ELV (END-OF-LIFE VEHICLES)

MIN (MINING WASTE)

SLASH (SLAGS AND ASHES)

WEEE (WASTE ELECTRICAL AND ELECTRONIC EQUIPMENT)

4.4.6. Future recovery technology: *Description*

Definition

This task will review current and emerging technologies used in the various sectors for product manufacturing and end-of-life handling, with a special emphasis on material production, use, and recycling. Together with the storylines developed in Task 2.1, it will adapt the market share of these technologies for each sector to determine the future development of each sector.

SCENARIO TRENDS FOR: Future recovery technology

Scenario I — Business-as-usual:
Stable

Scenario II — Recovery:
Strong increase

Scenario III — Circularity:
Increase

Context

Resource efficiency hinges on the effective integration and optimisation of product lifecycles, end-of-life (EOL) processing, the quality of recycled materials, recycling practices, and metallurgical technologies. The extent to which materials are diverted from landfills—owing to their complex make-up precluding economic recovery—is a key measure of this efficiency [115]. Landfills, often the result of creating recyclates lacking economic viability, signify lapses in material management. While the second law of thermodynamics sets recyclability boundaries, these inefficiencies are frequently the consequence of preventable errors such as substandard product design, inefficient collection systems, and lack of process refinement.

To perpetuate resource availability and facilitate the flow of materials into sustainable products, it is imperative to establish well-conceived systems that reclaim these resources from EOL items and repurpose them. Grasping the influence of product design and the efficacy of recycling systems on closing material loops necessitates holistic methodologies that align with fundamental tenets, as delineated in this article.

To shape policy and engineer resource supply and recycling infrastructures, one requires an in-depth comprehension of recycling and high-temperature processing technologies, alongside insights into product design impacts and potential shifts in products and consumer behaviours. The formulation of a resilient system design is critical to amplifying resource efficiency—for instance, by minimising reliance on landfills—while also guaranteeing a consistent supply of metals for products within the renewable energy domain and other sectors pivotal to sustainability.

Resource efficiency is ultimately gauged by the proficiency in interlinking products, EOL processing, quality of recyclates, recycling, and metallurgical technology, and thereby determining how much material ends up in landfill due to its complex composition that negates economic value. Instances of poor material stewardship leading to landfills are attributed to the inability to generate economically feasible recyclates. While the second law of thermodynamics dictates the limitations of recyclability, such shortcomings are also attributable to avoidable blunders such as inadequate product design, collection systems, and process optimisation.

Method

The general method for determining future recovery technology will be based on the following steps:

- **Step 1:** Collection of data on current recovery technology (WP4)
- **Step 2:** Identification of future recovery technology based on technology outlooks, literature review, and stakeholder interviews
- **Step 3:** Estimation of constraints for process data, market entry, replacement, and market share of future recovery technology in each scenario
- **Step 4:** Modelling of future recovery technology based on the results of steps 1-4

Relevance of future recovery technology to Critical Raw Materials in Waste Streams

The integration of the future recovery technology has implications for the management of Critical Raw Materials (CRMs) across various waste streams, such as BATT (waste batteries), ELV (end-of-life vehicles), WEEE (waste electrical and electronic equipment), and CDW (construction and demolition waste).

BATT (Battery waste)

ELV (End-of-Life Vehicles)

WEEE (Waste Electrical and Electronic Equipment)

CDW (Construction and Demolition Waste)

MIN (Mining Waste)

SLASH (Slags and Ashes)

4.4.7. Future recovery technology: *Scenarios*

WASTE STREAM NOTICE

This section will be filled out with the details of exactly how this parameter is incorporated into your stock and flow models

Summary

REVIEW NOTICE

This summary will be compiled once the individual waste stream sections for each parameter are complete.

Scenario I: Business-as-usual

x

BATT (BATTERY WASTE)

CDW (CONSTRUCTION AND DEMOLITION WASTE)

ELV (END-OF-LIFE VEHICLES)

MIN (MINING WASTE)

SLASH (SLAGS AND ASHES)

WEEE (WASTE ELECTRICAL AND ELECTRONIC EQUIPMENT)

Scenario II: Recovery

x

BATT (BATTERY WASTE)

CDW (CONSTRUCTION AND DEMOLITION WASTE)

ELV (END-OF-LIFE VEHICLES)

MIN (MINING WASTE)

SLASH (SLAGS AND ASHES)

WEEE (WASTE ELECTRICAL AND ELECTRONIC EQUIPMENT)

Scenario III: Circularity

x

BATT (BATTERY WASTE)

CDW (CONSTRUCTION AND DEMOLITION WASTE)

ELV (END-OF-LIFE VEHICLES)

MIN (MINING WASTE)

SLASH (SLAGS AND ASHES)

WEEE (WASTE ELECTRICAL AND ELECTRONIC EQUIPMENT)

Conclusion

REVIEW NOTICE

This conclusion will be compiled once the individual waste stream sections for each parameter are complete.

4.5. INTERNAL ELEMENTS — THE CIRCULAR ECONOMY

4.5.1. Introduction

Main sources: [87, 11, 50, 116, 18, 117, 51, 118, 75, 52, 119]

Circular Strategies

Scenario elements

- **R0-2:**
  Refuse, Reduce, Reuse (including 'sharing economy')
- **R3:**
  Repair
- **R4-5:**
  Refurbish and Remanufacture

Waste model parameters include:

- **Put-on-market:**
  function of consumer behaviour (internal)
- **Lifetimes:**
  function of repair rate, durability, design-for-repair
- **Waste composition:**
  function of product composition, durability (weight), design-for-repair, etc.
- **Collection rate:**
  function of consumer engagement in re-X strategies, collection infrastructure, legislation, export rate

Recovery model parameters include:

- **Transfer coefficients:**
  function of design-for-(re-X) strategies, recovery technology (internal)
- **Recovery system size:**
  function of collection rate

The Circular Economy and its re-X strategies

The re-X strategies underpin the circular economy, embodying a range of actions and approaches. These strategies are conceptualised in various ways, depending on the focus and perspective of different authors. The description that follows is based on the framework provided by [119], with a detailed mapping of these strategies illustrated in Figure 4.12.

R0: Refuse

— This concept is applied both in consumer and producer contexts. For consumers, it means choosing not to buy or use products or services that are not needed or are unsustainable, thereby preventing waste creation. For producers, it involves refusing the use of specific hazardous materials and designing production processes to avoid waste. This approach is integral to shifting towards a more post-material lifestyle and reducing packaging waste.

R1: Reduce

— Reduce is used in a consumer-oriented, producer-oriented, and generic sense. It encompasses using products less frequently, with more care, and for longer, and making repairs for life extension.

For producers, it involves using less material per unit of production, a concept known as dematerialization. It also includes participation in the sharing economy through pooling and sharing products.

R2: Resell/Reuse

— Resell and Reuse involve bringing products back into the economy after initial use, either by reselling or reusing them for the same or a different purpose. This concept includes direct reuse of products such as second-hand sales and reuse in fabrication like refurbishment and remanufacturing. Quality inspections, minor repairs, and online consumer-to-consumer auctions are part of this strategy.

R3: Repair

— Repair aims to extend the product's lifespan by bringing it back to working order, fixing minor defects, or replacing broken parts. It can be performed by various actors, including the customer, repair companies, or through non-commercial peer-to-peer repair workshops. Planned repairs and ad-hoc repairs are both included under this concept.

R4: Refurbish

— Refurbishing typically applies to large multi-component products where many components are replaced or repaired, resulting in an overall upgrade of the product. This process brings the product up to a state-of-the-art level using newer, more advanced components, and is often seen in industries like aviation and construction.

R5: Remanufacture

— Remanufacture involves disassembling, checking, cleaning, and replacing or repairing the full structure of a product in an industrial process. It is distinguished from refurbishing by the extent of disassembly and replacement of components, often resulting in a product that is like new but with a shorter expected lifespan due to the use of recycled components.

R6: Repurpose

— Repurposing involves adapting discarded goods or components for another function, giving the material a distinct new lifecycle. This can result in both low and high-value end-products and is popular in industrial design and art communities. Examples include transforming defective microchips into jewellery or plastic sheeting into handbags.

END OF CIRCULAR STRATEGIES

— The following strategies belong to the recovery system

R7: Recycle Materials

— Recycling involves processing mixed streams of post-consumer products or post-producer waste streams using technological equipment to capture pure materials. It usually results in secondary materials that do not maintain any of the original product structure and can be re-applied anywhere. Recycling typically requires high energy inputs for collection and re-processing.

R8: Recover (energy)

— Recovery primarily refers to capturing energy embodied in waste, linking it to incineration combined with producing energy, or the use of biomass. It is also used to describe the collection of used products for disassembly, sorting, and cleaning for utilization, and the extraction of elements or materials from end-of-life composites.

R9: Re-mine

— Re-mining involves the retrieval of materials after the landfilling phase, including extracting valuable parts from disposed products and mining valuable resources stored in old landfills or urban mining. This practice is becoming more lucrative with technological advancements, allowing for the effective extraction of resources from waste stock.

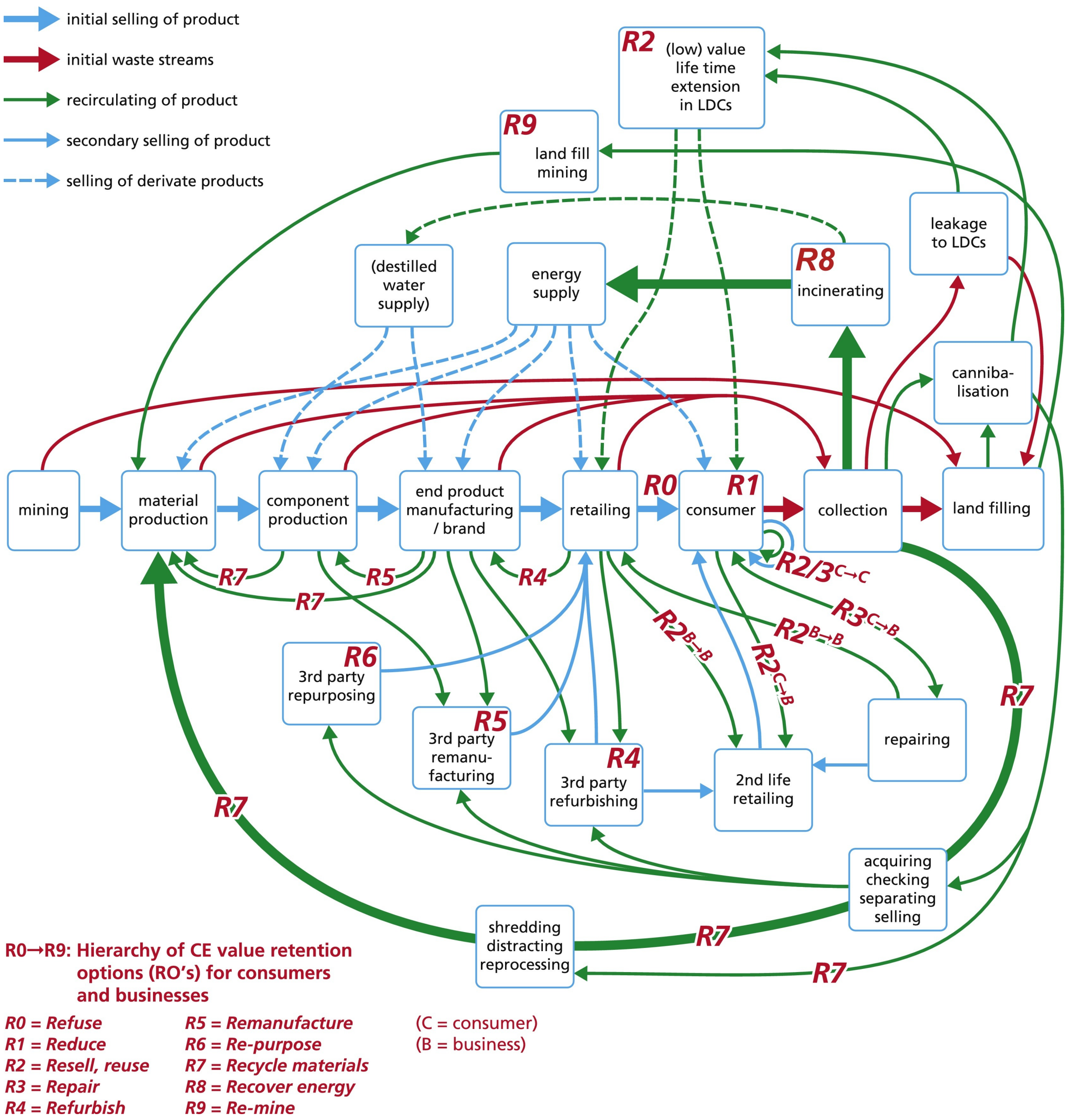


Figure 4.12: A detailled mapping of the re-X strategies in the circular economy [119]

EU CIRCULAR ECONOMY INDICATORS (CEIs)

See the EU working documents [18] and [19] for more detailled asssment of progress relating to the CEIs. Table 4.6 presents an overview of the EU's CEIs including their target for 2023.

Table 4.7 lists the relevant EU circular indicators (CEIs) along with their significance for FutuRaM's models and their changes between 2000–2022.

Indicator	Sub-indicators	2030 target or direction for improvement
Production and consumption		
1 Material consumption	1a Material footprint 1b Resource productivity	Reduce Increase – decoupling
2 Green public procurement		
3 Waste generation	3a Total waste generation per capita 3b Total waste generation (excluding major mineral waste) per GDP 3c Generation of municipal waste per capita 3d Food waste 3e Generation of packaging waste per capita 3f Generation of plastic packaging waste per capita	Significantly reduce total waste generation Halve the amount of residual (non-recycled) municipal waste Reduce (target proposal by 2023) Reduce by 5% compared to 2018 Reduce
Waste management		
4 Overall recycling rates	4a Recycling rate for municipal waste 4b Recycling rate for all waste excluding major mineral waste	60%
5 Recycling rates for specific waste streams	5a Recycling rate for overall packaging waste 5b Recycling rate for plastic packaging waste 5c Recycling rate for electrical and electronic equipment waste that is separately collected	70% 55%
Secondary raw materials		
6 Contribution of recycled materials to raw-material demand	6a Circular material-use rate 6b End-of-life recycling input rates	Double
7 Trade in recyclable raw materials	7a Imports from outside the EU 7b Exports to outside the EU 7c Intra-EU trade	
Competitiveness and innovation		
8 Private investments, jobs and gross value added*	8a Private investments 8b Employment 8c Gross value added	Increase
9 Innovation	9 Patents related to waste management and recycling	Increase
Global sustainability and resilience		
10 Global sustainability from circular economy	10a Consumption footprint 10b GHG emissions from production activities	Reduce to remain within the PB** Reduce
11 Resilience from circular economy	11a Material import dependency 11b EU self-sufficiency for raw materials	Decrease Increase

Notes: * in circular-economy sectors. ** PB: Planetary boundaries for all impact categories

Table 4.6: EU Circular Economy Indicators (CEIs) and their targets for 2023 [19]

Table 4.7: EU circular indicators (CEIs) and their significance for FutuRaM's models

CODE	TITLE	WS MODEL RELEVANCE	RECOVERY MODEL RELEVANCE	RATIO 2022:2000
CEI_CIE011	Persons employed in circular economy sectors	Product technology, lifetimes, collection rates	Capacity	1.28
CEI_CIE012-GVA	Gross added value related to circular economy sectors	Product technology, lifetimes, collection rates	Capacity	1.4
CEI_CIE012-INV	Private investment related to circular economy sectors	Product technology, lifetimes	Process technology	0.8
CEI_CIE020	Patents related to recycling and secondary raw materials	Product technology, lifetimes	Process technology	0.8
CEI_PC020	Material footprint	Demand	Efficiency	0.89
CEI_PC030	Resource productivity	Demand	Capacity	1.38
CEI_PC031	Generation of municipal waste per capita	Waste generation	Capacity	1.03
CEI_PC032	Generation of waste excluding major mineral wastes per GDP unit	Waste generation	Capacity	0.86
CEI_PC034	Waste generation per capita	Waste generation	Capacity	0.93
CEI_SRM030	Circular material use rate	Collection rates	Capacity	1.41
CEI_WM010	Recycling rate of all waste excluding major mineral waste	Collection rates	Capacity	1.09
CEI_WM011	Recycling rate of municipal waste	Collection rates	Efficiency	1.78
CEI_WM060	Recycling rate of waste of electrical and electronic equipment (WEEE) separately collected	Collection rates	Efficiency	0.99

Figure 4.13 depicts the CEIs, their trends from 2000-2022, and their linear forecasts until 2050. An interactive figure can be viewed here 🔗. Note that the linear trends are not deemed to be representative of the actual future values, but are used to illustrate the trends and the magnitude of the changes. There will be constraints defined to limit and shape the growth of the CEIs in each of the scenarios. The settings for this will be determined from the waste stream quantification and the scenario storylines.

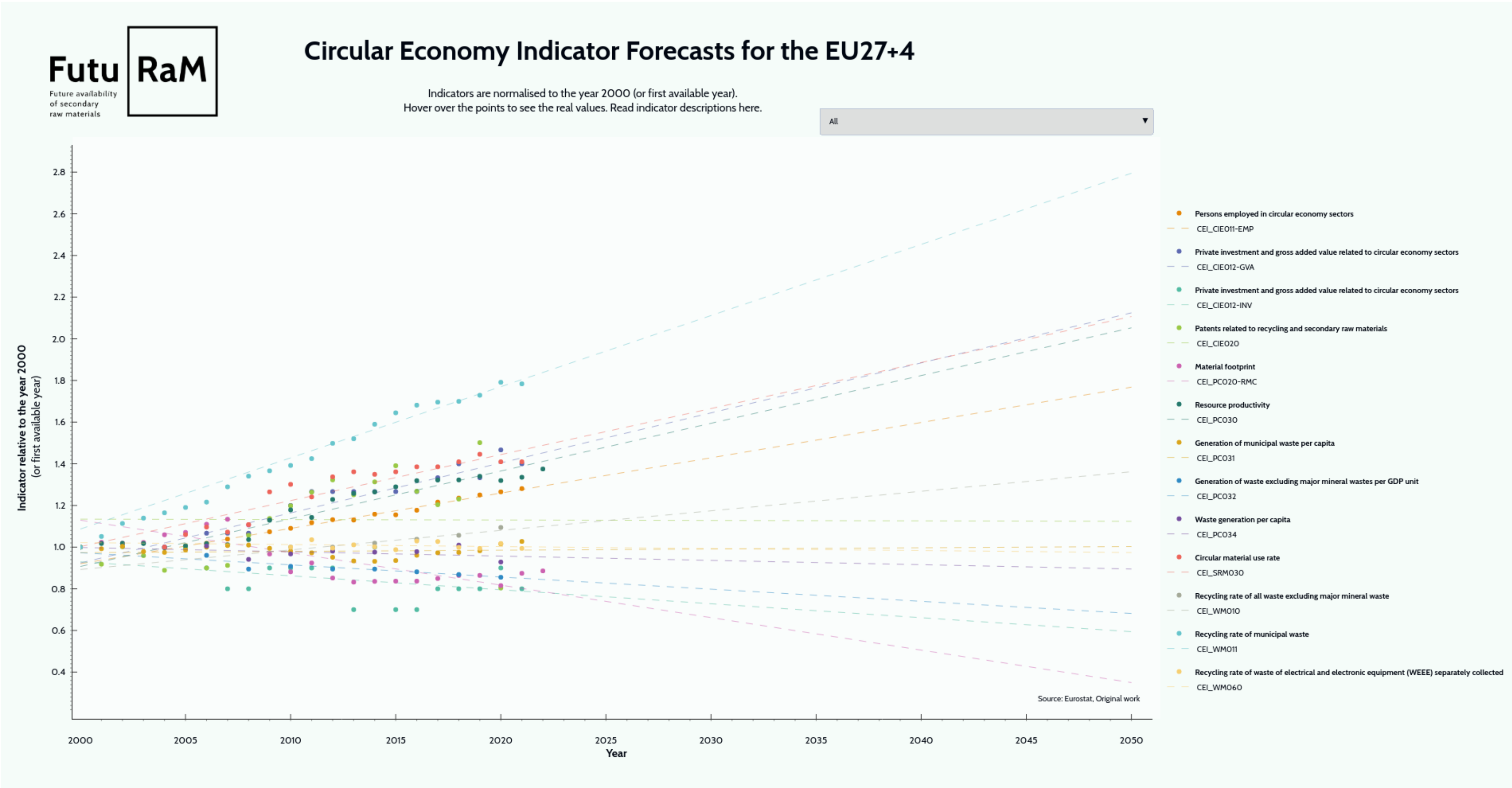


Figure 4.13: EU Circular Economy Indicators (CEIs) - trends from 2000-2022 and linear forecasts

4.5.2. Summary

The environmental and socio-economic impacts of raw material use are most effectively addressed at the product group level. Examining a product group as a whole, rather than focusing on individual resources or materials, allows for a comprehensive understanding and management of its utilisation and the environmental impacts across the production chain and product lifecycle [52].

Additionally, setting impact targets for product groups aligns more closely with the capacity of stakeholders within the chain to modify resource usage or mitigate related environmental impacts.

Although the nature and magnitude of raw material use impacts can differ significantly among product groups, necessitating tailored impact targets, there is also a need for simplicity in target setting. A manageable and communicable approach for governments is to aim for a significant reduction, such as halving the environmental impact at the product group level.

The benefit of establishing more general effect targets lies in the flexibility it offers for varying focuses across different product groups. A target set at the product group level is not only clear and easily communicable but also acknowledges the complexity and diversity inherent in a circular economy.

REVIEW NOTICE

This section will be completed once the individual waste stream sections for each parameter are complete.

4.5.3. The EU Circular Economy Indicators: *Description*

Main sources: [18, 19, 69]

SCENARIO TRENDS FOR: The EU Circular Economy Indicators

BAU **Scenario I — Business-as-usual:**

Stable

Scenario II — Recovery:

Strong increase in recycling and recovery related indicators

Scenario III — Circularity:

Strong in circularity related indicators

Economic Indicators

CEI_CIE011: PERSONS EMPLOYED IN CIRCULAR ECONOMY SECTORS & CEI_CIE012: PRIVATE INVESTMENT AND GROSS ADDED VALUE RELATED TO CIRCULAR ECONOMY SECTORS

Indicator metadata:

Context:
Targets economic activities that contribute to the circular economy, delineating those activities through established environmental policy frameworks and classifications.

Indicator Description:
The indicator encompasses “Private investments”, “Persons employed” and “Gross value added”. Eurostat has developed a method to derive these key economic variables, incorporating a multi-step approach: establishing a conceptual framework based on international environmental policy definitions, mapping and classifying relevant activities against an integrated system of economic classifications (using NACE, CPA, and PRODCOM codes), and finally compiling data using defined estimation procedures. The primary outputs of this process are the measurements of employment in FTE, gross value added at factor cost, and investments in tangible goods, each quantified in million euros.

Unit:
Economic metrics are presented in million euros, with employment figures given in full-time equivalents (FTE); both sets of figures are also contextualised as percentages of GDP and total employment, respectively.

Source Data:
Data is sourced from a combination of Structural Business Statistics, National Accounts, Prodcom surveys, and the Labour Force Survey, enriched by additional sector-specific statistics.

CEI_CIE020: PATENTS RELATED TO RECYCLING AND SECONDARY RAW MATERIALS

Indicator metadata:

Context:

This indicator is integral to the Circular Economy set, focusing on 'competitiveness and innovation' and serving to gauge progress towards a more circular economy.

Indicator Description:

The indicator enumerates the number of patent families pertinent to recycling and secondary raw materials, leveraging the Cooperative Patent Classification to ensure unique counts.

Unit:

The unit of measure is the number of patent families, with a secondary metric of patents per million inhabitants.

Source Data:

Sourced from the European Patent Office (EPO), the data are extracted and analyzed by the Joint Research Centre (JRC), using the PATSTAT database.

CEI_PC030: Resource productivity

Indicator metadata:

Context:

Embedded within the Circular Economy indicator suite, this metric tracks progress in 'Production and consumption', emphasizing material use efficiency to gauge economic growth relative to resource use.

Indicator Description:

Resource productivity is articulated as GDP over DMC, showcasing the efficiency of material utilization within an economy. This indicator assists in understanding the dynamics between economic performance and environmental pressure.

Unit:

Measured in three distinct units: euro per kg in chain-linked volumes (2015), PPS per kg, and as an index (2000=100) for temporal and spatial comparisons.

Source Data:

The European Statistical System (ESS) supplies the data, with Eurostat disseminating information on DMC and GDP, derived from the Material Flow Accounts and GDP and main components datasets, respectively.

Waste and Material Indicators

CEI_PC020: Material footprint

Indicator metadata:

Context:

The 'Material footprint' indicator is a critical component of the Circular Economy monitoring framework, highlighting the 'production and consumption' thematic area. It reflects the EU's impact on global resources, pertinent to the EU's consumption exceeding its production, especially concerning goods manufactured in Asia and consumed in Europe.

Indicator Description:

This indicator assesses the global demand for material extraction driven by EU consumption and investment. The Material Footprint provides insight into the environmental burden shifted to other regions due to the EU's consumption patterns. It is expressed through the Raw Material Consumption (RMC) metric, indicating the material extraction required for goods consumed within the EU.

Unit:
The unit of measure is tonnes per capita.

Source Data:
Data source: European Statistical System (ESS) Data provider: Statistical Office of the European Union (Eurostat). Material flow accounts in raw material equivalents – modelling estimates (env_ac_rme). Material flow accounts in raw material equivalents by final uses of products - modelling estimates (env_ac_rmefd).

CEI_PC031: GENERATION OF MUNICIPAL WASTE PER CAPITA

Indicator metadata:

Context:
The 'Generation of municipal waste per capita' indicator is integral to the Circular Economy indicator set, falling under the 'production and consumption' thematic area. It underscores efforts to sustain product and material value in the economy, minimize waste generation, and drive waste prevention strategies in alignment with the Waste Hierarchy.

Indicator Description:
This indicator tracks municipal waste generated and managed by local authorities or entities appointed by them. It predominantly accounts for household waste, although it may include waste from commercial activities, offices, and public institutions, reflecting consumer behaviour and the impact of waste reduction measures.

Unit:
The unit of measure is kilograms per capita, based on the annual average population.

Source Data:
The data is provided by Eurostat, consistent with the high-quality standards of the European Statistical System (ESS), deriving from the Municipal waste by waste operations report, collected under the OECD/Eurostat Joint Questionnaire. Data submission is voluntary, known as a 'gentlemen's agreement'.

CEI_PC032: GENERATION OF WASTE EXCLUDING MAJOR MINERAL WASTES PER GDP UNIT

Indicator metadata:

Context:
The 'Generation of municipal waste per capita' indicator is integral to the Circular Economy indicator set, falling under the 'production and consumption' thematic area. It underscores efforts to sustain product and material value in the economy, minimize waste generation, and drive waste prevention strategies in alignment with the Waste Hierarchy.

Indicator Description:
This indicator tracks municipal waste generated and managed by local authorities or entities appointed by them. It predominantly accounts for household waste, although it may include waste from commercial activities, offices, and public institutions, reflecting consumer behaviour and the impact of waste reduction measures.

Unit:
The unit of measure is kilograms per capita, based on the annual average population.

Source Data:
The data is provided by Eurostat, consistent with the high-quality standards of the European Statis-

tical System (ESS), deriving from the Municipal waste by waste operations report, collected under the OECD/Eurostat Joint Questionnaire. Data submission is voluntary, known as a gentlemen's agreement.

CEI_PC034: WASTE GENERATION PER CAPITA

Indicator metadata:

Context:

The 'Waste generation per capita' indicator is a key component of the Circular Economy monitoring framework, aimed at assessing the effectiveness of EU policies focused on waste reduction and resource efficiency within the 'production and consumption' thematic area.

Indicator Description:

This indicator reflects the total waste generation within a country, including major mineral wastes from all economic activities and households. It is an essential measure for evaluating the impact of waste prevention measures, allowing comparison of Member States' performance over time.

Unit:

The unit of measure is kilogram per capita

Source Data:

The data originates from the European Statistical System (ESS), specifically Eurostat, which collates information reported by countries under the Waste Statistics Regulation (EC) No 2150/2002.

CEI_SRM030: CIRCULAR MATERIAL USE RATE

Indicator metadata:

Context:

As a core metric within the Circular Economy indicator set, the 'Circular material use rate' is crucial for monitoring advancements in the utilization of 'secondary raw materials'. It encapsulates the circular economy's goal to enhance material recycling, reduce waste, and curb the reliance on primary raw material extraction.

Indicator Description:

This indicator assesses the proportion of recycled material re-entering the economy against the overall material consumption, serving as a benchmark for the 'circularity rate'. It signifies the efficiency of resource use by contrasting the circular use of materials against the aggregate domestic material consumption (DMC), adjusted for waste trade.

Unit:

The indicator is presented as a percentage, depicting the share of recycled material in total material usage, reflecting the level at which secondary materials replace primary resources.

Source Data:

Data is sourced from the European Statistical System (ESS) and Eurostat, employing a trio of statistical resources: waste treatment statistics, material flow accounts, and international trade data.

CEI_WM010: RECYCLING RATE OF ALL WASTE EXCLUDING MAJOR MINERAL WASTE

Indicator metadata:

Context:

This indicator is pivotal for measuring advancements in 'waste management'. It gauges the efficiency of resource use by monitoring the volume of materials recycled and reincorporated into the economy, thus encapsulating the essence of material conservation and loss reduction.

Indicator Description:

The recycling rate is formulated by the proportion of waste recycled versus the total waste treated, excluding significant mineral waste, rendered in percentage terms. It encompasses both hazardous and non-hazardous waste across all sectors, including household and secondary waste from waste treatment processes, thereby providing a comprehensive snapshot of the national recycling efforts.

Unit:

Expressed in percentage

Source Data:

Eurostat, under the aegis of the ESS, supplies this data. It incorporates waste treatment information aligned with the Waste Statistics Regulation, fine-tuned with international trade data, to accurately reflect the recycling of domestically produced waste.

CEI_WM011: Recycling rate of municipal waste

Indicator metadata: ↗

Context:

As an integral part of the Circular Economy indicators, this measure serves as a barometer for the progression towards a more circular economy, with a focus on 'waste management'. It assesses the re-utilisation of consumer waste in the economy, capturing the complexities inherent in the diverse composition of municipal waste.

Indicator Description:

This indicator quantifies the proportion of municipal waste that is recycled, relative to the total amount of municipal waste produced, presented as a percentage. The breadth of municipal waste includes household refuse and similar commercial and public waste, representing a snapshot of the waste management quality from a consumer perspective.

"In order to comply with the objectives of this Directive, and move to a European circular economy with a high level of resource efficiency, Member States shall take the necessary measures designed to achieve the following targets: (a) by 2020, the preparing for re-use and the recycling of waste materials such as at least paper, metal, plastic and glass from households and possibly from other origins as far as these waste streams are similar to waste from households, shall be increased to a minimum of overall 50 % by weight;" — Article 11.2 of the Waste Framework Directive. [10]

Unit:

The metric of evaluation is a percentage

Source Data:

Data source: European Statistical System (ESS) Data provider: Statistical Office of the European Union (Eurostat) based on data reported by the countries: Municipal waste by waste operations ↗ collected via a subset of the OECD/Eurostat Joint Questionnaire, section waste. Data are provided under a so-called gentlemen's agreement.

CEI_WM060: Recycling rate of waste of electrical and electronic equipment (WEEE) separately collected

Indicator metadata: ↗

Context:

This indicator is a crucial component of the Circular Economy suite, offering insights into the progression towards enhanced sustainability in 'waste management'. WEEE, or e-waste, is a rapidly expanding waste stream within the EU that encapsulates items like computers, TVs, refrigerators, and mobile phones. Given the valuable materials found in e-waste, improving recycling processes is of paramount importance.

Indicator Description:

The indicator measures the efficiency of WEEE recycling by calculating the ratio of the weight of WEEE processed for recycling/re-use against the total weight of WEEE collected separately, in compliance with Article 11(2) of the WEEE Directive 2012/19/EU [5, 6]. The indicator's transition from 'Recycling rate of e-waste' to its current form is to align more closely with the CE monitoring framework revisions.

The applicability of Directive 2012/19/EU is twofold:

- Applicable up to the year 2018 for EEE classified under 10 product categories as outlined in Annex I of the Directive, with Annex II providing a corresponding indicative product list.
- Applicable from the year 2019 forward, where all EEE will be classified within 6 product categories as delineated in Annex III.

Unit:

The percentage serves as the unit of measure

Source Data:

Data procurement is executed by the ESS and supplied by Eurostat. The indicator's underlying data stems from:

- For WEEE by waste operations: (env_waselee).
- For WEEE by waste management operations - open scope, 6 product categories (from 2018 onwards): (env_waseleeos).

4.5.4. The EU Circular Economy Indicators: *Scenarios*

WASTE STREAM NOTICE

This section will be filled out with the details of exactly how this parameter is incorporated into your stock and flow models

Summary

REVIEW NOTICE

This summary will be compiled once the individual waste stream sections for each parameter are complete.

BAU

Scenario I: Business-as-usual

xx

BATT (BATTERY WASTE)

CDW (CONSTRUCTION AND DEMOLITION WASTE)

ELV (END-OF-LIFE VEHICLES)

MIN (MINING WASTE)

SLASH (SLAGS AND ASHES)

WEEE (WASTE ELECTRICAL AND ELECTRONIC EQUIPMENT)

Scenario II: Recovery

xx

BATT (Battery waste)

CDW (Construction and Demolition Waste)

ELV (End-of-Life Vehicles)

MIN (Mining Waste)

SLASH (Slags and Ashes)

WEEE (Waste Electrical and Electronic Equipment)

Scenario III: Circularity

XX

BATT (BATTERY WASTE)

CDW (CONSTRUCTION AND DEMOLITION WASTE)

ELV (END-OF-LIFE VEHICLES)

MIN (MINING WASTE)

SLASH (SLAGS AND ASHES)

WEEE (WASTE ELECTRICAL AND ELECTRONIC EQUIPMENT)

4.5.5. Refuse, Reduce, Reuse: *Description*

Refuse, Reduce, and Reuse are the first three short loops (R0-2) in the circular economy scheme. They exist close to the consumer and can be linked to commercial or non-commercial actors engaged in extending the product's lifespan [120].

SCENARIO TRENDS FOR: Refuse, reduce, reuse

BAU **Scenario I — Business-as-usual:**
Stable

Scenario II — Recovery:
Stable

Scenario III — Circularity:
Strong increase

These strategies are pivotal in the circular economy, effectively reducing the environmental impact of products or services.

- **R0 — Refuse:** Choosing not to purchase products or services that are unnecessary or unsustainable.
- **R1 — Reduce:** Decreasing the quantity of products or services used or needed.
- **R2 — Reuse:** Utilising products or services again for the same or a different purpose.

These strategies will be incorporated into FutuRaM's modelling framework through:

- Waste volume reduction from:
  - Reduction in overall demand, that is, the put on market (POM) of a product or service.
  - Reduction in the amount of material used in a product or service (efficiency).
  - Extension of the lifetime of products from reuse.
- Changes in the composition of waste, as some products are more amenable to being refused or reused than others.

Definitions

REFUSE

Refuse encompasses consumer and producer decisions aimed at minimising waste creation and reducing environmental impact. For consumers, it involves choosing not to purchase products that are not environmentally friendly and reducing overall consumption. In the production context, it signifies the deliberate avoidance of certain materials or processes to enhance circularity, such as eschewing hazardous substances or designing to minimise waste. Refuse, as a concept, prioritises waste prevention at the source and is integral to fostering a more circular economy [119].

REDUCE

Reduce refers to strategies aimed at minimising the use of natural resources, including energy, raw materials, and thereby reducing waste generation. This concept is multifaceted:

- For consumers, it involves using products less frequently, caring for and repairing products to extend their life, and participating in the sharing economy.
- For producers, it focuses on using less material per production unit, often referred to as 'de-materialisation', and incorporating these principles early in the Concept and Design Life Cycle.

Reduction is also linked to the notion of Reuse, as decreasing the quantity of products (like cars) can incentivise their reuse. Policy measures to enforce reduction, such as banning single-use plastics or imposing environmental taxes, are essential for effective implementation [121].

REUSE

Reuse is about extending the life of products in their original form for as long as possible, thus conserving resources and energy. It involves maintaining and repairing products to keep them in use and developing business models that support these practices. Examples include:

- Reusable packaging initiatives in various industries.
- Encouraging the reuse of items like clothing, furniture, and electronics.
- Deposit-refund systems that incentivise product return and reuse.

Reuse strategies are vital for reducing the consumption of new products and avoiding the dichotomy of 'new for the rich, reused for the poor', promoting equitable and sustainable consumption patterns [116].

4.5.6. Refuse, Reduce, Reuse: *Scenarios*

WASTE STREAM NOTICE

This section will be filled out with the details of exactly how this parameter is incorporated into your stock and flow models

Summary

REVIEW NOTICE

This summary will be compiled once the individual waste stream sections for each parameter are complete.

BAU *Scenario I: Business-as-usual*

XX

BATT (BATTERY WASTE)

CDW (CONSTRUCTION AND DEMOLITION WASTE)

ELV (END-OF-LIFE VEHICLES)

MIN (MINING WASTE)

SLASH (SLAGS AND ASHES)

WEEE (WASTE ELECTRICAL AND ELECTRONIC EQUIPMENT)

Scenario II: Recovery

xx

BATT (Battery waste)

CDW (Construction and Demolition Waste)

ELV (End-of-Life Vehicles)

MIN (Mining Waste)

SLASH (Slags and Ashes)

WEEE (Waste Electrical and Electronic Equipment)

Scenario III: Circularity

XX

BATT (BATTERY WASTE)

CDW (CONSTRUCTION AND DEMOLITION WASTE)

ELV (END-OF-LIFE VEHICLES)

MIN (MINING WASTE)

SLASH (SLAGS AND ASHES)

WEEE (WASTE ELECTRICAL AND ELECTRONIC EQUIPMENT)

4.5.7. Repair: *Description*

[122, 123, 124, 125, 53]

Definition

Right to repair refers to the concept that end users, business users as well as consumers, of (generally) technical, electronic or automotive devices should be allowed to freely repair these products. Four requirements are of particular importance:

- The device should be constructed and designed in a manner that allows repairs to be made easily;
- End users and independent repair providers should be able to access the original spare parts and necessary tools (software as well as physical tools) at fair market conditions;
- Repairs should, by design, be possible and not be hindered by software programming; and
- The repairability of a device should be clearly communicated by the manufacturer.

SCENARIO TRENDS FOR: Repair

BAU **Scenario I — Business-as-usual:**
Stable

Scenario II — Recovery:
Stable

Scenario III — Circularity:
Strong increase

Context

Discarded products are often viable goods that can be repaired but are often tossed prematurely, resulting in 35 million tons of waste, 30 million tons of resources and 261 million tons of greenhouse gas emissions in the EU every year [54]

Repairing is one of the most relevant strategies within the Circular Economy (CE) concept since it contributes to waste prevention and extends product and components' lifespan. Thus, reparability becomes an essential issue from the early product design phases, where materials, geometries, and joints are defined. Despite some repairability indicators that can be found in the literature and are applied worldwide, there is a lack of connection between repairability and the early decision-making process for improving it from the design of components or subsystems of a product.

However, repair is often seen as difficult by consumers. The 'right to repair' initiative complements several other proposals presented by the Commission to achieve sustainable consumption throughout the entire lifecycle of a product, setting the framework for a true 'right to repair' across the EU. Obstacles to owner repair can lead to higher consumer costs or drive consumers to single-use devices instead of making repairs.

The right to repair is a legal right for owners of devices and equipment to freely modify and repair products such as automobiles, electronics, and farm equipment. This right is framed in opposition to restrictions such as requirements to use only the manufacturer's maintenance services, restrictions on access to tools and components, and software barriers.

A right to repair can exist either in a closed access system, where the consumer is restricted to the repair services provided by the manufacturer or authorized repairers — a situation closer to the current reality. Or, a right to repair can evolve in an open access system, which implies full access to spare parts, tools, repair manuals and digital permission to repair. Policy options for a right to repair differ based on whether they encourage one or the other approach. Some argue an open access system is the only form of right to repair that is consumer-empowering and can yield the expected benefits. Others argue for a more complex system, moving towards open access but with some safeguards on a sectoral or product category basis. A cost-benefit analysis could help identify the sectors or product categories where a full open-access system would be most beneficial.

The goals of the right to repair are to favour repair instead of replacement and make such repairs more affordable leading to a more sustainable economy and reduction in waste.

International and European Right to Repair Initiatives

[124, 125, 53]

- **Availability of Spare Parts and Repair Information:**
  - US state-level legislation includes laws like Massachusetts' requirement for car manufacturers to provide repair tools and information.
  - The EU has measures like France's mandate for sellers to inform about the availability of spare parts, and Slovenia's requirement for maintenance and spare parts for at least 3 years after guarantee expiration.
- **Legal Guarantees:**
  - European legal guarantee periods often exceed the EU directive's minimum, encouraging repair culture.
  - For example, Sweden has a 3-year guarantee period, and Finland ties the period to the expected lifespan of the product.
- **Design Requirements:**
  - Legislation like Washington State's (USA) proposed fair repair bill is aimed at promoting repairable product designs by prohibiting the creation of electronics that obstruct repairability.
- **Financial Incentives:**
  - Cities like Graz offer subsidies for electronic device repairs and countries like Belgium provide écochèques to incentivize repair over replacement.
- **Copyright Law Exemptions:**
  - In the US, certain copyright law exemptions facilitate repairability, such as the ability to unlock phones, although the exemption renewal process is cumbersome.
- **Consumer Information:**
  - France's reparability index helps inform consumers by rating products on repairability criteria, promoting repair-friendly designs.
- **Voluntary Labels and Green Public Procurement:**

  - Ecolabels such as EPEAT and various national labels incorporate repairability to different degrees.
  - Green Public Procurement practices push the market towards sustainable, repairable products.

- **Communication and Awareness:**
  - Initiatives include repair-focused websites, awareness campaigns, and the establishment of repair hubs to build a repair-oriented culture.

Implementation in EU Law

[54, 20]

European Product Policy has to date focused on the environmental performance of products via the Ecodesign and Ecolabelling Directives. The Ecodesign Directive sets minimum standards of performance for products, which results in poorly performing products being removed from the market whilst also driving innovation in the design and manufacture of new products to improve their performance. The Ecolabelling Directive provides consumers with clear information on product performance to inform their buying decisions. Originally cast for energy-using products, the directives have been extended to energy-related products and the assessment methodologies have been developed to include other aspects including materials and water consumption.

Further measures considered include:

- Amending Directive 2005/29/EC to prohibit presenting products as allowing repair when such repair is not possible, as well as omitting to inform consumers that it is not possible to repair goods in accordance with legal requirements.
- Amending Directive 2005/29/EC to prohibit omitting to inform the consumer that the good is designed to limit its functionality when using consumables, spare parts, or accessories that are not provided by the original producer.
- Traders to provide, before the conclusion of the contract, for all types of goods, where applicable, the reparability score of the good as provided by the producer in accordance with Union law, to allow consumers to make an informed transactional decision and choose goods that are easier to repair.
- Ensuring information such as on the availability of spare parts and a repair manual, should no reparability score be available at the Union level.

To this end, new 'Digital Product Passports' providing information about products' environmental sustainability, will empower consumers and businesses to make informed choices when purchasing products, facilitate repairs and recycling, and improve transparency about products' lifecycle impacts on the environment. The passports also help public authorities to better perform checks and controls.

In addition, as part of the implementation of the EU Circular Economy Action Plan [2], the European Commission has carried out a study for the analysis and development of a possible scoring system to inform about the ability to repair and upgrade products [53] and has an ongoing project in the Product Bureau to develop and propose new metrics [161, 55].

Development of a metric for repairability

[53, 54, 20, 161, 55, 126, 127, 128]

The trend in consumer goods towards reduced durability and repairability has been contributing to an increase in waste electronic and electrical equipment (WEEE). The Organization for Economic Co-operation and Development has suggested that extending product lifetimes through enhanced durability and repairability is a viable solution to this growing issue. The European Commission's Circular Economy Action Plan reinforces this viewpoint, advocating for maintaining the value in products for as long as possible by imposing durability and repairability requirements. In response, several scoring systems for repairability have been developed to guide standardization efforts, aid market surveillance authorities, and inform consumer decision-making.

For a scoring system to be effective, it should provide an objective evaluation of repairability that aligns with the established design principles in the literature. Comparative analyses of various repairability scoring systems for different products have been undertaken in previous studies. However, the thoroughness of these systems is sometimes not fully evaluated, and some of the most recent systems have not been comprehensively reviewed.

Literature on the subject identifies specific design features and principles that significantly affect product repairability, and these should be central to any scoring system aimed at accurately measuring repairability. Assessing these design elements against selected scoring systems can shed light on their inclusiveness.

The objectivity of these scoring systems is another critical aspect, evaluated by examining their scoring methodologies. Selection criteria for these systems include their availability in English, the use of quantitative or semi-quantitative assessment methods to enable objective comparison, and their recognition as the most current versions from their respective issuing organizations or groups.

In 2021, France took a pioneering step by integrating the reparability index into national legislation. [21] This move compels producers to transparently communicate the repairability of their products through consumer labelling. The reparability index stands as a key development in empowering consumers to make informed choices regarding the repairability of products. The widespread issue of repairing common electronic devices like laptops and smartphones often stems from the unavailability of tools, spare parts, or repair instructions.

An exemplary repair index would encompass elements such as product design, the availability of repair information, and additional services like the availability of spare parts. These aspects are crucial for the repair process. Data indicates that a substantial number of electronic product repairs are hindered by the lack of available spare parts.

France's method mandates transparency regarding product repairability, yet relies on producers' self-assessment, prompting questions about the objectivity of such evaluations. The rapid implementation is advantageous, but the credibility of self-assessment remains a concern.

With sustainability becoming increasingly important, France's repairability index marks an assertive step towards the broader adoption of such measures. Looking ahead, enhancements like a durability index may offer greater insights into the long-term usability of products.

In parallel, organizations such as TÜV SÜD are actively supporting the repairability testing landscape, aligning with standards like the French Repairability Scoring Index to ensure products fulfil specified repairability criteria [148]. Their approach factors in documentation, disassembly, and the availability of spare parts and repair services, highlighting a practical, though less detailed, framework compared to France's comprehensive index.

Benefits and risks

ENVIRONMENTAL BENEFITS AND RISKS

[53, 129]

The implementation of the right to repair holds considerable promise for the reduction of environmental impacts if applied appropriately. It must be recognized that electronic equipment replacement often occurs not solely due to product failure. Influencing factors such as perceived obsolescence contribute significantly, as evidenced by a study in Austria revealing only 30% of replacements were attributable to malfunctioning products [123].

Direct measurement of the impact of a right to repair is challenging, with the need to consider additional variables such as obsolescence perception, device performance, and consumer behaviour trends in determining potential extensions in consumer electronics' average lifespan.

Moreover, the environmental benefit of repair is contingent not only on the increased product lifespan post-repair but also on the environmental footprint of the spare parts required for repair. Circuit boards, for example, carry substantial environmental impacts, and their replacement could still result in significant environmental costs. Common repairs typically involve less impactful components such as screens, casings, batteries, or software [122].

Cordella et al. [122] report that compared to the baseline of replacing smartphones every two years, extending the device's life through repair can substantially diminish the carbon footprint. A one-year extension, with a battery change, can reduce greenhouse gas (GHG) emissions by 29%, and by 44% with a two-year extension.

With 472 million Europeans owning a mobile phone, there are 8.11 Mt CO_2-eq. in annual emissions solely from phones. Extending the life of a mobile phone by just one year, including component replacements, could reduce emissions to 6.23 Mt CO_2-eq. annually [54]. A further extension by an additional year could decrease emissions to 4.91 Mt CO_2-eq., effectively removing the equivalent of over 2 million cars from European roads.

Nevertheless, these potential reductions should be interpreted with caution as they are based on estimations and may not account for potential rebound effects. For instance, economic savings from prolonged use of electronic devices could lead to rebound effects where savings are offset by additional consumption stemming from the economic savings [130].

Finally, repair activities offer a more energy-efficient alternative within the Circular Economy compared to recycling and remanufacturing, which demand extensive energy input and high material throughput. When feasible, repair should be prioritized over other circular economy strategies [53].

Manufacturers' Perspective

- Compliance with eco-design standards could reduce profit margins.
- Risk of increased liability and the need to ensure long-term availability of spare parts.
- Potential decrease in turnover due to extended product lifecycles.
- Reduction in EU imports could foster the EU's technological independence, as per the EU Chips Act.
- Loss in turnover potentially offset by repair services and spare parts supply.

Broader Economic and Environmental Implications

- Right to Repair could enhance competitiveness by increasing product longevity and added value.
- Positive impact on professional repair services, spare parts provision, and tool providers.
- SMEs and local repair shops likely to benefit significantly.

- Potential for the development of new European leaders in repair services.
- A more repairable design could improve recycling processes and increase component harvesting.

Relevance of Repairability to Critical Raw Materials in Waste Streams

The integration of the 'Right to Repair' ethos and the promotion of repairability has implications for the management of Critical Raw Materials (CRMs) across various waste streams, such as BATT (waste batteries), ELV (end-of-life vehicles), WEEE (waste electrical and electronic equipment), and CDW (construction and demolition waste).

BATTERIES (BATT)

Batteries are a crucial repository of CRMs like lithium, cobalt, and nickel. Enhancing their repairability can lead to:

- Refurbishing batteries for second-life applications.
- Design modifications for easier replacement of battery cells.
- Reduced extraction of new raw materials, mitigating the environmental footprint.

END-OF-LIFE VEHICLES (ELV)

Vehicles are a significant source of CRMs such as platinum and palladium (catalytic converters) and rare earth elements (electronics and magnets). 'Right to Repair' can:

- Influence design changes for modularity and ease of part replacement.
- Prolong the utility of CRMs and lessen new resource extraction.

WASTE ELECTRICAL AND ELECTRONIC EQUIPMENT (WEEE)

The WEEE stream contains valuable CRMs like gold, silver, and rare earth elements. Promoting repairability results in:

- Prolonged life spans for electronic devices.
- A reduction in the volume of CRMs entering the waste stream.
- Conservation of valuable materials through repair and refurbishment.

CONSTRUCTION AND DEMOLITION WASTE (CDW)

CRMs feature in many building materials as well as wind turbines which are part of this waste stream, and advocating for repairability in construction can:

- Lead to buildings designed for deconstruction, not demolition.

The emphasis on repairability and 'Right to Repair' legislation can lead to reduced CRM demand, decreased environmental impact through less mining, creation of economic incentives for repair industries, and improved resource security by minimizing reliance on raw material extraction. This approach is in line with fostering a circular economy, aiming for a sustainable management of resources within the EU.

4.5.8. Repair: *Scenarios*

WASTE STREAM NOTICE

This section will be filled out with the details of exactly how this parameter is incorporated into your stock and flow models

Summary

REVIEW NOTICE

This summary will be compiled once the individual waste stream sections for each parameter are complete.

BAU *Scenario I: Business-as-usual*

xx

BATT (Battery waste)

CDW (Construction and Demolition Waste)

ELV (End-of-Life Vehicles)

MIN (Mining Waste)

SLASH (Slags and Ashes)

WEEE (Waste Electrical and Electronic Equipment)

Scenario II: Recovery

xx

BATT (BATTERY WASTE)

CDW (CONSTRUCTION AND DEMOLITION WASTE)

ELV (END-OF-LIFE VEHICLES)

MIN (MINING WASTE)

SLASH (SLAGS AND ASHES)

WEEE (WASTE ELECTRICAL AND ELECTRONIC EQUIPMENT)

Scenario III: Circularity

xx

BATT (BATTERY WASTE)

CDW (CONSTRUCTION AND DEMOLITION WASTE)

ELV (END-OF-LIFE VEHICLES)

MIN (MINING WASTE)

SLASH (SLAGS AND ASHES)

WEEE (WASTE ELECTRICAL AND ELECTRONIC EQUIPMENT)

4.5.9. Remanufacturing and Refurbishing: *Description*

Definition

Remanufacturing involves disassembling the full structure of a multi-component product, inspecting, cleaning, repairing, or replacing necessary parts, and reassembling it to its original state or better. This process can include both reused and new components, aiming to achieve a quality level that meets or exceeds the new product [119, 131, 132].

Refurbishing, often confused with remanufacturing, is the process where the overall structure of a large multi-component product remains intact, while components are replaced or repaired, resulting in an overall 'upgrade' of the product. It aims to bring the product up to a specified quality, possibly incorporating newer, more advanced components [119].

SCENARIO TRENDS FOR: Remanufacturing and Refurbishing

BAU **Scenario I — Business-as-usual:**
Stable

Scenario II — Recovery:
Stable

Scenario III — Circularity:
Strong increase

Context

Remanufacturing and refurbishing are essential strategies in the circular economy, aimed at extending product lifecycles and reducing waste. They are particularly relevant in the medium loops (R4-R6) of product recovery, where they serve as business activities indirectly linked to the consumer [56].

International and European Trends

Remanufacturing is gaining momentum globally, particularly in the U.S. and Europe. Governments are legislating manufacturers to assume responsibility for their products post-use, emphasizing recyclability and waste reduction. The market for environmentally friendly products, valued at over USD 200 billion, is driving corporations to adopt remanufacturing and other green practices [133, 57].

Implementation in EU Law

EU laws increasingly mandate manufacturers to engage in product recovery, including remanufacturing. This aligns with the EU's broader goals of sustainable development, resource efficiency, and transitioning to a circular economy [3, 56].

Economic Scale and Regional Focus in Europe

The remanufacturing industry in Europe generates around €30bn in turnover and employs about 190,000 people. Key regions like Germany, the UK, Ireland, France, and Italy have significant remanufacturing activities. Germany leads in remanufacturing turnover, particularly in aerospace, automotive, and heavy-duty off-road (HDOR) sectors [56].

Benefits and Risks

Environmental Benefits and Risks:
Remanufacturing significantly reduces environmental impact by conserving raw materials and energy, while risks may include the potential for resource-intensive processes if not efficiently managed.

Manufacturers' Perspective:
For manufacturers, remanufacturing offers economic benefits, with costs typically 40–60% lower than manufacturing new products. It also enhances corporate image and competitive advantage in a market increasingly sensitive to environmental concerns [133].

Broader Economic and Environmental Implications:
Remanufacturing contributes to a sustainable economy, offering a less resource-intensive alternative to new production. It supports employment, innovation, and reduces dependency on raw material extraction.

Benefits and Risks

Environmental Benefits and Risks:
Remanufacturing significantly reduces environmental impact by conserving raw materials and energy. However, risks may include the potential for resource-intensive processes, especially if not managed efficiently, and the need for effective sorting and inspection policies to decide on the remanufacturability of returned products [134].

Manufacturers' Perspective:
For manufacturers, remanufacturing offers economic benefits, with costs typically 40–60% lower than manufacturing new products. It also enhances corporate image and competitive advantage in a market increasingly sensitive to environmental concerns. Additionally, manufacturers' identity, brand reputation, and technological capabilities play a crucial role in the success of remanufacturing initiatives [133, 134].

Broader Economic and Environmental Implications:
Remanufacturing contributes to a sustainable economy, offering a less resource-intensive alternative to new production. It supports employment, innovation, and reduces dependency on raw material extraction. Key factors such as government regulations, collection strategies, and public awareness about environmental benefits are crucial in promoting remanufacturing. Moreover, design for remanufacturing and skilled labor are essential for efficient remanufacturing processes [134].

Market Dynamics:
Factors like consumer purchase intentions, pricing strategies, and the fear of cannibalization significantly influence the market for remanufactured products. Consumers' willingness to return used products and their perception of remanufactured products also play a crucial role in shaping the remanufacturing market [134].

Regulatory and Strategic Aspects:
Government regulations, such as take-back laws and extended producer responsibility, incentivize remanufacturing. Strategic elements like inventory control, scheduling, and material matching are

vital for operational efficiency in remanufacturing. Management prescience is required to spearhead remanufacturing business and maintain circularity in the economy [134].

Figure 4.14 illustrates an example of a remanufacturing process (in this case, for vehicle components), highlighting the key steps and the inputs and outputs [135].

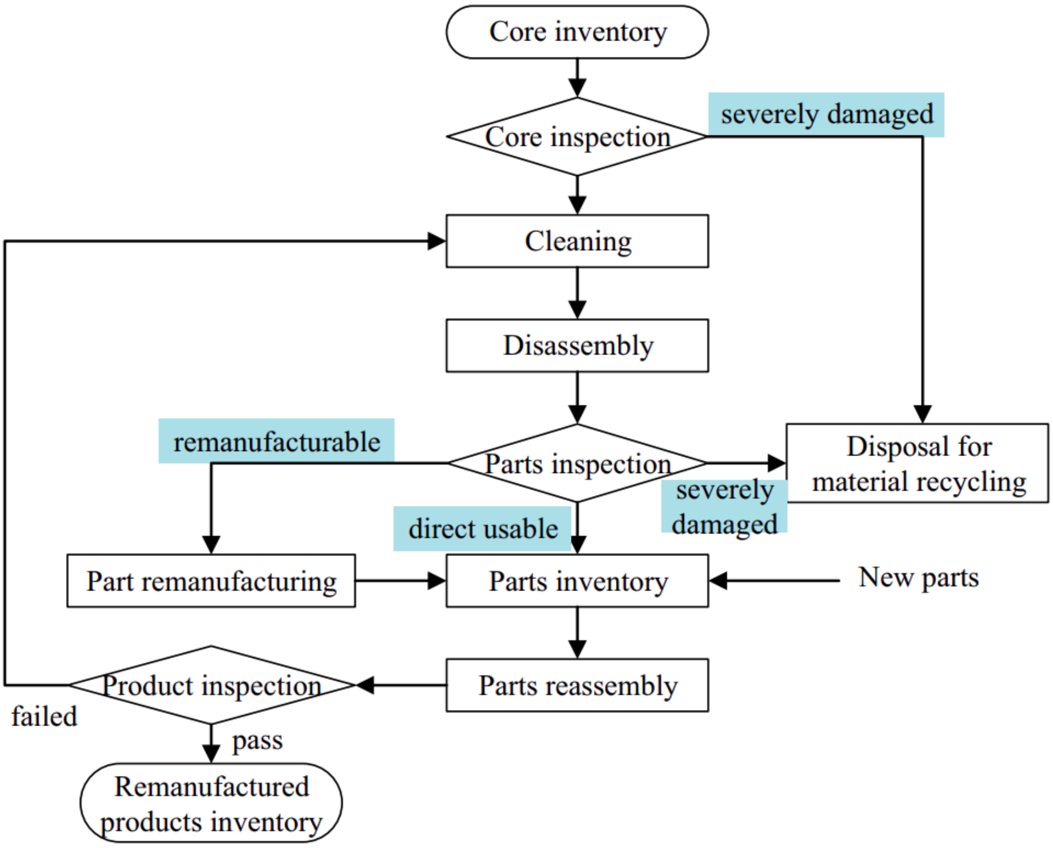


Figure 4.14: An example of a generic remanufacturing process for vehicle components [135]

Relevance of Remanufacturing and Refurbishing in FutuRaM's Waste Streams

BATT (Battery waste)

- Electric Vehicle Batteries: Remanufacturing can involve replacing degraded cells or modules to extend their lifespan, thereby conserving lithium and cobalt.
- Laptop Batteries: Through remanufacturing, individual cells within the battery pack can be replaced or upgraded, enhancing the overall battery life and efficiency.

ELV (End-of-Life Vehicles)

- Automotive Engines: Remanufacturing can include refurbishing engine components, such as pistons and bearings, to restore performance and efficiency.
- Transmission Systems: Rebuilding transmission systems with replaced or refurbished gears and bearings can significantly extend the life of the vehicle.

WEEE (Waste Electrical and Electronic Equipment)

- Smartphones: Remanufacturing can involve replacing batteries, screens, and other components to restore them to like-new condition.
- Printers and Copiers: Components such as toner cartridges, drums, and fusers can be remanufactured to extend their service life and improve functionality.

CDW (Construction and Demolition Waste)

- Structural Steel Elements: In construction and demolition, steel beams and columns can be refurbished and reused in new construction projects.
- Wooden Beams and Flooring: Wooden elements can be remanufactured through processes like sanding, treating, and reinforcing for reuse in construction.

4.5.10. Remanufacturing: *Scenarios*

WASTE STREAM NOTICE

This section will be filled out with the details of exactly how this parameter is incorporated into your stock and flow models

Global trends

Summary

REVIEW NOTICE

This summary will be compiled once the individual waste stream sections for each parameter are complete.

BAU *Scenario I: Business-as-usual*

XX

BATT (BATTERY WASTE)

CDW (CONSTRUCTION AND DEMOLITION WASTE)

ELV (END-OF-LIFE VEHICLES)

MIN (MINING WASTE)

SLASH (SLAGS AND ASHES)

WEEE (WASTE ELECTRICAL AND ELECTRONIC EQUIPMENT)

Scenario II: Recovery

xx

BATT (BATTERY WASTE)

CDW (CONSTRUCTION AND DEMOLITION WASTE)

ELV (END-OF-LIFE VEHICLES)

MIN (MINING WASTE)

SLASH (SLAGS AND ASHES)

WEEE (WASTE ELECTRICAL AND ELECTRONIC EQUIPMENT)

Scenario III: Circularity

xx

BATT (Battery waste)

CDW (Construction and Demolition Waste)

ELV (End-of-Life Vehicles)

MIN (Mining Waste)

SLASH (Slags and Ashes)

WEEE (Waste Electrical and Electronic Equipment)

4.5.11. The Sharing Economy: *Description*

[136, 58, 59, 60, 61, 137]

Definition

The sharing economy is a socio-economic system that emphasizes the collaborative sharing of goods and services via community-based online platforms. It represents a shift from traditional ownership, where assets were exclusively leased, to a flexible model allowing for both personal use and lease. This flexibility is a hallmark of the sharing economy, which has grown significantly in response to advancements in technology, such as e-commerce and mobile connectivity, coupled with a societal push for more sustainable living and efficient resource use.

SCENARIO TRENDS FOR: The sharing economy

Scenario I — Business-as-usual:
Stable

Scenario II — Recovery:
Stable

Scenario III — Circularity:
Strong increase

Context

As the concept of ownership transforms, particularly among the younger generation, the sharing economy has increasingly taken root in the EU market. This shift towards more communal and cost-effective ways of accessing goods and services is supported by a new wave of consumer behavior, underpinned by technological innovation and a pressing need to reduce environmental waste and resource duplication.

While the sharing economy is broad and its definition fluid, it is often associated with collaborative consumption, though the two can differ in motives and mechanisms. Collaborative consumption may span consumer-to-consumer and business-to-consumer interactions, whereas the sharing economy typically operates within the consumer-to-consumer sphere. The sharing economy is thereby defined as an innovative marketplace where entities engage in the distribution and utilization of products and resources, with scalability achieved through technological means.

This socio-economic model has not only disrupted traditional business sectors but has also brought new value to the global economy, with rapid and profound market penetration. Financial forecasts have been bullish, with revenue for sharing platform providers expected to increase from USD 18.6 billion in 2017 to an estimated USD 40.2 billion in 2022. Moreover, the overall value of the global sharing economy is projected to expand significantly, from USD 14 billion in 2014 to USD 335 billion in 2025, reflecting an unprecedented growth trajectory over a mere twelve years[137]. Such growth reflects the substantial economic potential and transformative power of the sharing economy in contemporary markets.

Scope within the EU Economy

The sharing economy has made a significant economic contribution to the EU, with an estimated €26.5 billion added to the GDP in 2016 [58]. This figure is expected to grow, indicating the sharing economy's increasing importance within the EU's economic structure.

Environmental Prospects

[136, 58, 60]

See [137] Table 2 for a summary of the studies on the environmental impacts of the sharing economy.

The sharing economy has the potential to reshape consumption behaviors and reduce environmental impacts by promoting the sustainable use of resources. This economic paradigm encourages the efficient employment of underutilised goods, which can lead to a decrease in the need for new products, thus conserving resources and mitigating greenhouse gas emissions. It fosters a lifestyle that lessens the adverse environmental effects of consumption while improving quality of life.

Central to the sharing economy is the promotion of moderate consumption patterns. This approach aims to reduce the excessive purchasing habits of certain populations to alleviate ongoing environmental harm. The sharing economy's alignment with green consumption practices encompasses waste reduction, energy conservation, and the adoption of sustainable resources, all while managing and moderating excessive consumption.

The impact on the fast fashion industry serves as a pertinent example, with the sector's frequent turnover to keep pace with changing trends leading to significant textile waste. Collaborative consumption through the sharing economy can mitigate this waste by encouraging the reuse and extension of clothing's service life. Clothing libraries are an example of how the sharing economy can provide environmental benefits by prolonging the usable life of garments.

Eco-efficiency is enhanced when environmental resources are utilised more effectively, leading to an increased use of products with minimal environmental burden. This is exemplified in collaborative fashion consumption, which could reduce the prevalent overconsumption in the fashion industry. By facilitating the exchange of underused clothing, the sharing economy can increase the lifecycle of garments and encourage the production of more durable products.

Beyond the realm of fashion, car sharing and shared accommodation are other aspects of the sharing economy with notable environmental benefits. Car sharing can significantly reduce the number of vehicles needed, thereby lowering exhaust emissions. Similarly, shared accommodations have been associated with significantly lower carbon dioxide emissions compared to conventional hotel stays.

However, the question of whether the sharing economy indeed delivers environmental benefits remains contested. [137, 138] Detractors highlight the potential for an increase in environmental burdens, particularly if the heightened usability of shared goods escalates greenhouse gas emissions. The environmental and socio-economic impacts engendered by the collaborative economy are intricate and highly variable across different business models. Generally speaking, collaborative consumption models that optimise the use of existing assets tend to exhibit a lower environmental footprint compared to their traditional counterparts. Nevertheless, there is a risk that the financial savings afforded by collaborative consumption could spur additional spending and consumption, which might negate the direct environmental savings. Despite such reservations, the prevailing view is that the sharing economy, by transforming consumption from ownership to communal use, can yield considerable environmental advantages.

Implications for Waste Streams

The adoption of sharing economy principles can influence various waste streams, including:

- **BATT (Waste Batteries):** As devices are shared and utilized more efficiently, the frequency of battery disposal could decline, mitigating the waste battery stream.
- **CDW (Construction and Demolition Waste):** The sharing of construction equipment and machinery could potentially slow down the turnover rate of these items, reducing associated waste.
- **WEEE (Waste Electrical and Electronic Equipment):** Sharing electronic devices extends their lifecycle and reduces the rate at which they are discarded, thereby impacting electronic waste volumes.
- **ELV (End-of-Life Vehicles):** A shift towards car-sharing services could reduce the demand for manufacturing new vehicles, potentially leading to a downturn in the generation of automotive waste.

The trajectory of the sharing economy indicates a shift towards collective usage patterns. Its continuing evolution could play a critical role in the future of critical raw material recovery systems by affecting demand and the lifecycle of products, which, in turn, influences waste stream outputs. The broader implications for the raw materials sector are significant, suggesting a possible recalibration of recovery strategies for critical raw materials in light of emerging consumption patterns.

Challenges in Measuring Sharing Economy Growth

Identifying a universal metric for the growth of the sharing economy is challenging due to its diverse and dynamic nature. Current measures, such as STOXX Global sharing economy indices, Solactive Sharing Economy Index and the INDXX US Sharing Economy Index, largely revolve around the market sizes of prominent sharing economy companies, such as Uber and Airbnb. These indices, while useful, predominantly reflect the scalability of these businesses rather than the sharing economy's broader impacts on production and waste reduction.

In the absence of a standardised metric, the assessment of the sharing economy's expansion is often best approached through product-specific data. This involves examining the adoption rates and usage trends of sharing services at the product level to infer growth patterns. Such a detailed, product-centric analysis allows for a closer inspection of the sharing economy's implications on resource utilisation and waste generation, offering insights that aggregate economic data may overlook.

4.5.12. The Sharing Economy: *Scenarios*

WASTE STREAM NOTICE

This section will be filled out with the details of exactly how this parameter is incorporated into your stock and flow models

Summary

REVIEW NOTICE

This summary will be compiled once the individual waste stream sections for each parameter are complete.

Scenario I: Business-as-usual

XX

BATT (BATTERY WASTE)

CDW (CONSTRUCTION AND DEMOLITION WASTE)

ELV (END-OF-LIFE VEHICLES)

MIN (MINING WASTE)

SLASH (SLAGS AND ASHES)

WEEE (WASTE ELECTRICAL AND ELECTRONIC EQUIPMENT)

Scenario II: Recovery

xx

BATT (BATTERY WASTE)

CDW (CONSTRUCTION AND DEMOLITION WASTE)

ELV (END-OF-LIFE VEHICLES)

MIN (MINING WASTE)

SLASH (SLAGS AND ASHES)

WEEE (WASTE ELECTRICAL AND ELECTRONIC EQUIPMENT)

Scenario III: Circularity

XX

BATT (BATTERY WASTE)

CDW (CONSTRUCTION AND DEMOLITION WASTE)

ELV (END-OF-LIFE VEHICLES)

MIN (MINING WASTE)

SLASH (SLAGS AND ASHES)

WEEE (WASTE ELECTRICAL AND ELECTRONIC EQUIPMENT)

Conclusion

REVIEW NOTICE

This conclusion will be compiled once the individual waste stream sections for each parameter are complete.

4.6. CONCLUSION

REVIEW NOTICE

This conclusion will be compiled once the individual waste stream sections for each parameter are complete.

Interpretation

REVIEW NOTICE

This section will be constructed at a later stage of the project.

Modelling: Waste generation

REVIEW NOTICE

Development of the codebase for the waste generation models is ongoing. This section will be constructed at a later stage of the project.

Modelling: Recovery system

REVIEW NOTICE

Development of the codebase for the recovery model is ongoing.
This section will be constructed at a later stage of the project.

Modelling: Integration

REVIEW NOTICE

This section will be constructed at a later stage of the project.

Impacts

Task 2.4

Quantify environmental and socioeconomic impacts of SRM recovery under each scenario (ULEI, TUB, Empa, UNITAR, WEEE Forum, BRGM, UCL, LMU) (M18-M36)
This task will use the information generated in Tasks 2.1–2.3, together with the material flow analysis from WP4, to quantify the future environmental and socioeconomic feedbacks for each waste sector and scenario according to future recovery technology.

REVIEW NOTICE

This section will be constructed at a later stage of the project.

Bottlenecks

Task 2.5

Assess the environmental and socioeconomic impacts and bottlenecks of future SRM recovery (ULEI, TUB, Empa, UNITAR, Chalmers, UNITAR, WEEECycle) (M37-M47)
This task will develop a report based on an assessment on the pressures and bottlenecks associated with environmental and socioeconomic issues related to each waste sector, including the associated changes and impacts on imports and of primary raw materials production (D2.1).

REVIEW NOTICE

This section will be constructed at a later stage of the project.

Conclusion

REVIEW NOTICE

This section will be constructed at a later stage of the project.

References

Literature referred to in section 13.4 is excluded from the following lists of references, except for those titles cited elsewhere in the report.

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Appendices

CHAPTER CONTENTS

13.1. TERMINOLOGY

The following is a suggested terminology for use in our discussions and reports related to scenarios.

This glossary is modelled on that used by [92]. Some additional definitions were sourced from [149].

Table 13.1: Terminology

TERM	DEFINITION	LEVEL/CONTEXT	ALSO CALLED	SOURCE
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	[92]
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	[92]
Outlook	To provide a most likely estimate of future trends as a guide for decision-making	Scenario type	Forecast, projection	[92]
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, cyber security and data privacy challenges"	Scenario description	Qualitative storyline descriptors	[92]
Scenario scale	Description of the spatial extent or temporal extent of a scenario. For us, mostly EU toward 2050.	Scenario component		[149]
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		[149]
Scenario literature	Journal articles, grey literature, etc., from which data is sourced that can be used to justify decisions in scenario development	Scenario component		[92]
Scenario logics	Methods for structuring the relationships between different drivers and assumptions in scenarios	Scenario component		[149]
Time horizon	End date of the scenario's forecast	Scenario attribute		[92]
Snapshot	The position of scenario/s at a particular point of time	Scenario attribute		[92]
Storyline and simulation	Combination of qualitative narrative development and quantitative modelling	Scenario component		[139, 140], in [149]

Continued on next page

Back to ToC

Table 13.1 — Continued from previous page

TERM	DEFINITION	LEVEL/CONTEXT	ALSO CALLED	SOURCE
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	[92]
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		[62]
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	[79], in [149]
Factors	Causes of system change that are internal from the system of analysis. Can be (hopefully) quantified, or at least estimated	Scenario component (internal)		[92]
Factor variables	Discrete elements which are subject to change and have effects on one or more factors	Factor component		[92]
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		[92]
Trends	An inclination in a particular direction	Attribute of drivers or factors	System development	[92]
Likelihood	The likelihood of an occurrence, an outcome, or a result, where this can be estimated probabilistically	Attribute of drivers or factors	Probability	[149]

13.2. LIST OF RELEVANT POLICY ACTIONS

The following table contains a description of policy actions that are relevant to the future of secondary raw material supply in the EU.

Table 13.2: List of relevant policy actions

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

Back to ToC

13.3. SCENARIO DEVELOPMENT METHODS

Table 13.3 provides an overview of the methods and tools considered, along with a brief description of each and its relevance to the specific context and objectives of the FutuRaM scenario development process.

Table 13.3: Scenario development methods

METHOD	DESCRIPTION	KEY CHARACTERISTICS	LIMITATIONS	APPLICATION
Delphi	Structured expert consultation to gather and distil knowledge and judgments	Iterative rounds of surveys/questionnaires, Expert consensus building	Time-consuming process, May be influenced by dominant opinions or group dynamics	Policy development, Technology foresight, Long-term planning
MCA	Decision-support technique to evaluate and rank scenarios based on criteria	Consideration of multiple dimensions in quantifying qualitative factors	Policy assessment, Project evaluation, Strategic planning	
Forecasting	Use of historical data and statistical methods to predict future trends	Reliance on quantitative models, Time series analysis	Assumption of future patterns based on past data, Sensitivity to data quality and accuracy	Economic forecasting, Demand/supply projections, Financial planning
Backcasting	Working backward from a desired future vision to identify necessary steps	Focus on desired outcomes and future targets, Identification of necessary actions	Uncertainty in future outcomes, Difficulty in determining feasible pathways	Sustainable development planning, Policy design, Long-term goal setting
Scenario Planning	Development of multiple future scenarios to understand the range of possibilities	Identification of key drivers and uncertainties, Narrative construction for each scenario	Subjectivity in scenario construction, Lack of predictive accuracy	Strategic management, Risk assessment, Policy analysis
Morphological Analysis	Exploration of different combinations of variables/factors	Matrix-based exploration of variables and combinations	Complexity in analysing a large number of variables and combinations	Technology assessment, Innovation analysis, System design
Cross-Impact Analysis	Analysis of interdependencies and interactions between variables/factors	Identification of relationships and cross-impacts	Assumptions about causal relationships, Difficulty in capturing complex dynamics	Policy analysis, Risk assessment, System modelling
Morphological Box	Systematic exploration of the potential combinations of different components	Identification of component options and combinations	Complexity in analysing a large number of components and combinations	Technology assessment, Innovation analysis, Decision-making
Gausemeier approach	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	Relies on expert judgment and subjective assessments	Strategic planning, Innovation management

Continued on next page

Back to ToC

Table 13.3 — Continued from previous page

METHOD	DESCRIPTION	KEY CHARACTERISTICS	LIMITATIONS	APPLICATION
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, analyze the scenarios, and monitor and adjust the scenarios	Systematic progression through stages of scenario development	Requires detailed data and analysis	Strategic planning, Decision-making
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	Can be time-consuming and resource-intensive	Strategic planning, Risk management

13.4. MARKER SCENARIO MAPPING

Table 13.4 below presents an overview of the marker scenarios that were considered in the scenario development phase of the FutuRaM project. The table is not intended to be exhaustive, but rather to provide an overview of the different scenarios that have been developed in the field of waste management, resource recovery, and circular economy.

Table 13.4: Overview of marker scenarios

LITERATURE	TYPE	WASTE STREAM	TEMPORAL COVERAGE	LOCATION	NUMBER OF SCENARIOS	LINK
The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview	Academic	All (narratives)	Scenario to 2100	Global	5 SSPs	
Environmental Impacts of Global Offshore Wind Energy Development until 2040	Academic	CDW	Scenario: 2019–2040	Global	4 (based on IEA)	
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)	
Modelling global material stocks and flows for residential and service sector buildings towards 2050	Academic	CDW	Scenario: 2020–2060	Global	1 (SSP2)	
The evolution and future perspectives of energy intensity in the global building sector 1971–2060	Academic	CDW	Scenario: 2020–2060	Global	1 (SSP2)	
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 scenarios concerning per-capita floor area, building stock turnover, and construction material.	
Global construction materials database and stock analysis of residential buildings between 1970–2050	Academic	CDW	Scenario to 2060	Global	1 (SSP2)	
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	
Global scenarios of resource and emission savings from material efficiency in residential buildings and cars	Academic	CDW, ELV	Scenarios to 2050	Global	SSP1, SSP2	
Matching global cobalt demand under different scenarios for co-production and mining attractiveness	Academic	BAT	2050	Global	5	
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	
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)	
The rise of electric vehicles—2020 status and future expectations	Academic	ELV, BAT	up to 2050	Global	various	

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Table 13.4 — Continued from previous page

LITERATURE	TYPE	WASTE STREAM	TEMPORAL COVERAGE	LOCATION	NUMBER OF SCENARIOS	LINK
Scenarios for the Return of Lithium-ion Batteries out of Electric Cars for Recycling	Academic	ELV, Battery	Scenario to 2050	Global	2	
The dynamic equilibrium mechanism of regional lithium flow for transportation electrification	Academic	ELV, BAT	Scenario to 2050	Global	1 (projection)	
Future material demand for automotive lithium-based batteries	Academic	ELV, BAT	Scenario to 2050	Global	4 (based on IEA)	
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	
Circular economy strategies for electric vehicle batteries reduce reliance on raw materials	Academic	ELV, BAT	Scenario to 2050	Global	Reference + 4 technologies	
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	
Review of critical metal dynamics to 2050 for 48 elements	Academic	Energy	Scenario to 2050	Global	1 compiled from various renewable technologies	
Major metals demand, supply, and environmental impacts to 2100: A critical review	Academic	Energy	Scenario to 2100	Global	1 review of 197 studies	
Requirements for Minerals and Metals for 100% Renewable Scenarios	Academic	Energy	Scenario to 2050	Global	1.5 degree scenario	
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	
Modelling the demand and access of mineral resources in a changing world	Academic	Energy, Construction	2060	Global	RTS, BD2S IEA	
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	
A slag prediction model in an electric arc furnace process for special steel production	Academic	SLASH	None	Global	n/a	
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)	
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)	

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Table 13.4 — Continued from previous page

LITERATURE	TYPE	WASTE STREAM	TEMPORAL COVERAGE	LOCATION	NUMBER OF SCENARIOS	LINK
Resource Demand Scenarios for the Major Metals	Academic	Various	Scenario to 2050	Global	4 (UN GEO-4)	
Raw material depletion and scenario assessment in European Union — A circular economy approach	Academic	Various	None	EU	n/a	
Material bottlenecks in the future development of green technologies	Academic	Various	Scenario to 2050	Global	1 (BAU)	
Reuse assessment of WEEE: Systematic review of emerging themes and research directions	Academic	WEEE	None	Global	n/a	
A systematic literature review on the circular economy initiatives in the European Union	Academic	Circularity	None	EU	Circular strategies	
Material Flow Accounting: Measuring Global Material Use for Sustainable Development	Academic	Various	Scenario to 2100	Global	1 (BAU)	
Circular Economy Action Plan	Action plan	Various	Scenario to 2050	EU	35 actions to climate neutrality	
Construction and demolition waste: challenges and opportunities in a circular economy	Report	CDW	None	EU	n/a	
IEA world energy model	Report	Energy	Scenario to 2050	Global	4	
Bloomberg scenarios	Report	Energy	Scenario to 2050	Global	3	
The Role of Critical Minerals in Clean Energy Transitions	Report	Energy	None	Global	n/a	
Transitions to 2050 decide now act for climate	Report	Energy	Scenario to 2050	France	4 to reach 2.1C by 2100	
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	
Inventaires des besoins en matière, énergie, eau et sols des technologies de la transition énergétique	Report	Energy	Scenario to 2050	France	1	
Minerals in the future of Europe	Report	MinW	Scenario to 2050	EU	3 (2050 net-zero, digital, circular)	
Minerals, Critical Minerals and the US Economy	Report	MinW	None	US	n/a	
Minéraux stratégiques — État des lieux et propositions pour une vision partagée	Report	MinW	None	FR	n/a	

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Table 13.4 — Continued from previous page

LITERATURE	TYPE	WASTE STREAM	TEMPORAL COVERAGE	LOCATION	NUMBER OF SCENARIOS	LINK
The Critical Raw Materials (CRM) initiative — Underpinning the strategic approach to the EU's raw materials policy	Report	MinW	None	EU	n/a	
Towards the Circular Economy: Accelerating the scale-up across global supply chains	Report	Circularity	None	Global	n/a	
The Circular Economy in Europe	Report	Circularity	None	EU	n/a	
Global material flows and resource productivity: Forty years of evidence	Report	Circularity	None	Global	n/a	
The circular economy concept: contextualisation and multiple perspectives	Report	Circularity	None	Global	n/a	
Global material flows database	Database	Various	None	Global	n/a	
International Resource Panel	Reports	Various	None	Global	n/a	
World Business Council for Sustainable Development	Reports	Various	None	Global	n/a	
Ellen MacArthur Foundation	Reports	Various	None	Global	n/a	
European Environment Agency	Reports	Various	None	EU	n/a	
International Energy Agency	Reports	Energy	None	Global	n/a	
United Nations Environment Programme	Reports	Various	None	Global	n/a	
United Nations Industrial Development Reports	Reports	Various	None	Global	n/a	
World Bank	Reports	Various	None	Global	n/a	
World Economic Forum	Reports	Various	None	Global	n/a	

13.5. DRIVERS AND FACTORS IDENTIFIED IN THE INITIAL COLLECTION PHASE

Table 13.5 lists the elements that were identified in the initial phase of driver/factor collection.

Table 13.5: Drivers and factors identified in the initial collection phase

METHOD	DESCRIPTION
Stricter environmental regulations	Increased regulations and policies aimed at reducing environmental impact
Inflation	Increase in the general price level of goods and services over time
Employment rates	Percentage of the working-age population that is employed
Exchange rates	Value of one currency relative to another currency
Interest rates	Cost of borrowing money or the return on investment
Gasoline price	Cost of gasoline for vehicles
Electricity price	Cost of electricity for consumers or businesses
Raw material prices	Prices of primary materials used in production processes
CO2 market	Trading system for carbon emissions permits or credits
Education level	Level of education attained by individuals or the overall population
Volunteering	Engagement in unpaid activities for the benefit of others
Transparency	Openness, accountability, and information accessibility
Compliance with rules	Adherence to regulations, guidelines, or standards
Cultural values / Consciousness	Beliefs, attitudes, and awareness of individuals and society
Accessibility	Ease of access to goods, services, or infrastructure
Land rights	Legal rights to ownership, use, or access to land
Work-life balance	Equilibrium between work and personal life
Urbanisation	Increase in the population living in urban areas
Water supply constraints	Limitations on the availability or access to freshwater resources
Increased intrinsic drive for env. protection	Growing internal motivation to protect and conserve the environment
NIMBY to projects	Not-In-My-Backyard opposition to the location of certain projects
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
Redundancy	Availability of backup systems or alternative options
Material efficiency	Effective use and management of materials to minimize waste and loss
Energy efficiency of buildings	Performance and efficiency of energy consumption in buildings

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Table 13.5 — Continued from previous page

METHOD	DESCRIPTION
Change of products in the scope WEEE directive	Inclusion or exclusion of certain products within the scope of the WEEE directive
GDP/PPP	Gross Domestic Product (GDP) adjusted for purchasing power parity (PPP)
Improved repairability	Enhanced ability to repair and maintain products or equipment
Target enforcement	Implementation and enforcement of specific targets or goals
Data protection	Safeguarding personal data and ensuring privacy
Infrastructure	Physical structures and facilities necessary for the functioning of society
Intellectual property issues	Legal rights and protections for intellectual creations and innovations
Population	Total number of people in a given area or region
Resource shortage	Insufficient availability or scarcity of natural resources
Treatment cost	Cost of waste treatment, disposal, or recycling processes
Digital product passports	Digital documentation providing information about a product's lifecycle
Obsolescence	State of being outdated or no longer in use or demand
Digitalization	Integration and adoption of digital technologies and processes
SRM prices	Prices of secondary raw materials or recycled materials
Product prices	Prices of goods or products in the market
Recyclability mandates	Requirements or regulations promoting the recyclability of products
Conflict in supply chain	Disputes or conflicts within the supply chain of raw materials or products
Obligatory recycling standards for treatment facilities	Mandatory standards for recycling processes in treatment facilities
Improved durability	Enhanced longevity and resistance of products or materials
Composition change	Alteration or modification of the composition of materials or products
Subsidies	Financial support or incentives provided by governments or organizations
Availability of recovery technologies	Existence and accessibility of technologies for material recovery
Taxation (raw materials, landfill)	Imposition of taxes on raw materials or landfill activities
Obligatory removal of CRMs from waste	Required removal or extraction of critical raw materials from waste streams
Corruption	Dishonest or unethical behaviour, typically involving misuse of power
Supply chain due diligence laws	Regulations or laws requiring companies to assess and manage supply chain risks

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Table 13.5 — Continued from previous page

METHOD	DESCRIPTION
Improved recyclability	Increased ability of products or materials to be recycled or reused
Ecodesign	Designing products with consideration for their environmental impact
Trade barriers	Barriers or restrictions to international trade or commerce
Industrialization of Europe	Development and growth of industrial activities in European countries
Reduced consumerism	Shift towards decreased consumption and a more sustainable lifestyle
Accessibility/Infrastructure	Availability and adequacy of infrastructure to support accessibility
New mines in rich EU countries?	Establishment of new mines in economically prosperous European countries
Miniaturization	Process of making products or components smaller and more compact
Sharing economy	Economic system based on sharing resources and services
Repairability mandates	Requirements or regulations promoting the repairability of products
Renewable energy targets	Set goals or objectives for increasing the use of renewable energy sources

13.6. Drivers and factors identified in the screening phase

The following table lists the scenario elements that were identified in the screening phase of driver/factor collection.

Table 13.6: List of drivers and factors identified in the screening phase

DOMAIN	DRIVER/FACTOR	DEFINITION	BAU	REC	CIR
Economic	CO2 market price	Price of carbon dioxide (CO2) emissions in carbon markets	I	I	I
Economic	Economic growth	Rate of economic growth	I	I	I
Economic	Energy prices	Prices of energy resources	I	I	I
Economic	Market saturation	Level of saturation reached in the market for certain products or services	I	I	II
Economic	Raw material vs SRM prices	Price comparison between raw materials and Secondary Raw Materials (SRMs)	I	I	I
Economic	Re-industrialisation of EU	Process of revitalizing industrial activities in the European Union	I	I	I
Environmental	Climate change impacts (flooding, etc.)	Impacts of climate change such as flooding and other related events	I	I	I
Environmental	Climate change mitigation efforts	Efforts made to mitigate the effects of climate change	I	I	I
Environmental	Increased drive for env. protection	Growing motivation and drive to protect the environment	I	III	III
Environmental	Resource shortage	Shortage of natural resources	I	I	I
Legal/Political	Ecodesign/re-X mandates	Establishment of ecodesign requirements for specific product groups to improve circularity, energy performance, and other environmental sustainability aspects	I	II	III
Legal/Political	Governance: corruption vs compliance	Contrasting levels of corruption and compliance within governance systems	I	I	I
Legal/Political	International trade and co-operation (vs. autarky)	Level of international trade and cooperation versus self-sufficiency	I	I	I
Legal/Political	Product information transparency	Provision of transparent product information to consumers, manufacturers, importers, repairers, recyclers, or national authorities	I	III	III
Legal/Political	Progress toward renewable energy targets	Progress made in achieving renewable energy targets	I	I	I
Legal/Political	Stricter environmental regulations	Implementation of more stringent rules and regulations for environmental protection	I	III	III
Legal/Political	Subsidies/taxation to promote circularity	Provision of subsidies or implementation of taxation policies to incentivize circularity	I	I	I
Legal/Political	Supply chain due diligence laws	Implementation and enforcement of laws requiring companies to address negative human rights and environmental impacts in their value chains	I	II	III
Social	Hoarding	The act of stockpiling and keeping excessive amounts of products	III	II	II
Social	NIMBY to projects	Opposition of local communities to the location of new projects, such as mining, in their vicinity	I	I	I
Social	Participation in re-X activities	"Involvement in activities related to the ""re-"" concepts, including refusing, reducing, repairing, and reusing products"	I	II	III
Social	Population	Size and growth of the population	I	I	I

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Table 13.6 — Continued from previous page

DOMAIN	DRIVER/FACTOR	DEFINITION	BAU	REC	CIR
Social	Urbanisation	Rate of urban population growth	I	I	I
Technical	Digitisation	Adoption and integration of digital technologies	I	I	I
Technical	Integration of SRM system across EU	Integration of a Secondary Raw Materials (SRM) system across the European Union	I	III	III
Technical	Product technology	Changes in product function or composition that lead to changes in waste stream composition and quantity	I	III	III
Technical	Recovery technology	Technologies and processes for recovering materials from waste	I	III	III

13.7. DRIVERS AND FACTORS AFTER CATEGORISATION

The 21 elements that were identified in this stage are listed in Table 13.7.

Note that CIR and REC are very similar for many scenario elements, the main difference being the way in which the targets are achieved. That is, for CIR, re-X strategies are promoted, whereas, for REC, the focus is on technological advancements in the recovery system.

This distinction will have a significant impact on how the scenarios are quantitatively modelled and on the subsequent outcomes of these models.

Table 13.7: List of drivers and factors identified in the screening phase

DOMAIN	DRIVER/FACTOR	DEFINITION	INTERNAL	BAU	REC	CIR
TECH	Recovery technology	Implementation and advancements in waste recovery technologies	TRUE	I	III	III
TECH	Product technology	Changes in product function or composition	TRUE	I	III	III
TECH	Integration of SRM system across EU	Integration of a secondary raw material recovery system across EU countries	TRUE	I	III	III
ENV	Increased drive for environmental protection	Growing concern and motivation for environmental conservation	TRUE	I	III	III
ECO	Progress toward renewable energy targets	Advancements and achievements in renewable energy generation	TRUE	III	III	III
ECO	Subsidies and taxation to promote circularity	Financial incentives or taxes to encourage circular economy	TRUE	I	II	III
SOC	Participation in re-X activities	Engagement in refuse-reduce-repair-reuse activities	TRUE	I	I	III
POL	Stricter environmental regulations	Tightening of environmental laws and regulations	TRUE	II	III	III
POL	Stricter waste management regulations	Strengthening of waste management laws and regulations	TRUE	II	III	III
POL	Supply chain due diligence laws: implementation and enforcement	Obligations for identifying and mitigating negative impacts in supply chains	TRUE	I	III	III
POL	Compliance with waste targets	Meeting specific waste management and recycling targets	TRUE	I	III	III
ENV	Resource shortages	Limited availability of natural resources	FALSE	n/a	n/a	n/a
ECO	Raw material vs SRM prices	Price dynamics and competition between raw materials and secondary raw materials	FALSE	n/a	n/a	n/a
ENV	Climate change impactsmitigation	Effects and actions related to climate change	FALSE	n/a	n/a	n/a
ECO	International trade and co-operation (vs. autarky)	Collaborative trade agreements and global cooperation	FALSE	n/a	n/a	n/a
ECO	Energy prices	Costs and fluctuations in energy prices	FALSE	n/a	n/a	n/a
ECO	Economic growth	Overall economic expansion and development	FALSE	n/a	n/a	n/a
ECO	Re-industrialisation of EU	Shift towards increased industrial activities in the EU	FALSE	n/a	n/a	n/a
SOC	NIMBY to projects	Opposition to local projects and developments	FALSE	n/a	n/a	n/a

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Table 13.7 — Continued from previous page

DOMAIN	DRIVER/FACTOR	DEFINITION	INTERNAL	BAU	REC	CIR
SOC	Population and urbanisation	Growth and urban development of population	FALSE	n/a	n/a	n/a
ECO	CO2 market price	Price and market dynamics of carbon emissions	FALSE	n/a	n/a	n/a

13.8. DRIVERS AND FACTORS FOR QUANTIFICATION

The following Table 13.8 lists the categorised scenario elements that were quantified and incorporated into the modelling.

Table 13.8: List of 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	PARAMETERS AFFECTED
ECO	Subsidies and taxation to promote circular strategies	✓			I	I	III	demand, waste generation, lifetimes, sharing, collection,
POL	Targets and enforcement to promote circular strategies	✓			I	I	III	demand, waste generation, lifetimes, sharing, collection
SOC	Participation in re-X activities	✓			I	I	III	demand, waste generation, lifetimes, sharing, collection,
ECO	Subsidies and taxation to promote recovery strategies	✓			I	III	I	recycling rates, recovery capacity, recovery impacts, collection
POL	Targets and enforcement to promote recovery strategies	✓			I	III	I	recycling rates, recovery rates, capacity
POL	Supply chain due diligence laws	✓			I	III	III	composition, export
POL	Stricter environmental regulations	✓			I	III	III	composition, waste generation, lifetimes, export,recovery rates, recovery capacity, recovery impacts
POL	Stricter waste management regulations	✓			I	III	III	composition, waste generation, lifetimes, export, recovery rates, recovery capacity, recovery impacts
TECH	Product technology	✓			I	III	III	lifetimes, recovery rates, recovery impacts
TECH	Recovery technology	✓			I	III	III	recovery rates, recovery capacity, recovery impacts
TECH	Integration of SRM recovery system across Europe	✓			I	III	III	recycling rates, recovery rates, recovery capacity, recovery impacts
ECO	Progress toward renewable energy targets		✓		-	-	-	composition, demand, waste generation, recovery impacts
ECO	Economic growth		✓		-	-	-	composition, demand, waste generation
SOC	Population		✓		-	-	-	demand, waste generation
ECO	Primary vs. secondary raw material prices		✓		n/a	n/a	n/a	considered in sensitivity analysis

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Table 13.8 — Continued from previous page

DOMAIN	ELEMENT	INTERNAL	EXTERNAL	OUTSIDE	BAU	REC	CIR	PARAMETERS AFFECTED
ECO	Energy prices		✓		n/a	n/a	n/a	considered in sensitivity analysis
ECO	Carbon price		✓		n/a	n/a	n/a	considered in sensitivity analysis
ENV	Resource supply constraints		✓		n/a	n/a	n/a	considered in sensitivity analysis:
ECO	International trade and co-operation (vs. autarky)			✓	n/a	n/a	n/a	not model input (resource supply constraints is a proxy)
ECO	Re-industrialisation of EU			✓	n/a	n/a	n/a	not model input
SOC	Resistance to recovery projects (NIMBY)			✓	n/a	n/a	n/a	not model input (considered in UNFC assessments)

13.9. WORK BREAKDOWN STRUCTURE FOR WP2

Table 13.9 lists tasks and subtasks for work package two, along with the responsible partner and the planned start and end dates for each task. This table was sourced from the FuTuRaM project management plan [153].

Table 13.10 shows the Gaant chart for the entire FutuRaM project. This chart was sourced from the FuTuRaM grant agreement, page 37 [151].

WP	Task	SubTask	SubTask Name	Waste Group	Step (Optional)	Description SubTask/Step	WEEE Forum	UNITAR	BRGM	Chalmers	GTK	LMU	RECHARGE	SGU	TUB	Leiden Uni	VITO	Empa	UCL	Start	End
2	2.1	2.1.1	Scenario mapping	ALL		Map various studies from the academic, policy, and gray literature for future scenarios and assess the applicability within FutuRaM	X	X	X	X	X	X	X	X	X	X	X	X	X	M01	M05
2	2.1	2.1.2	Scenario methods	ALL		Compile various methodologies for scenario development and assess their applicability for developing scenarios on material recovery and circular economy for Europe	X	X	X	X	X	X	X	X	X	X	X	X	X	M02	M05
2	2.1	2.1.3	Scenario storylines	ALL		Flesh out the storylines of the 3 main scenarios		X		X					X	X				M05	M08
2	2.1	2.1.4	Qualitative scenario development	ALL		Use the chosen methods and qualitative methods to develop the three main scenarios to be used in FutuRaM (e.g. BAU, increased material recovery, and full circular economy)		X		X				X		X	X		X	M07	M11
2	2.2	2.2.1	Emerging technology assessment for future material use	ALL		Compile information on emerging technologies for sectors associated with waste streams, including changing material use	X	X	X	X	X	X	X	X	X	X	X	X	X	M03	M10
2	2.2	2.2.2	Emerging technology assessment for recovery	ALL		Compile information on emerging technologies for sectors associated with waste streams, including changing material use	X	X	X	X	X	X	X	X	X	X	X	X	X	M07	M11
2	2	2.2.3	Technology quantification	ALL		Develop methods for a quantified assessment of technology impementation (e.g. market share)		X		X						X				M11	M16
2	2.2	2.2.4	Technology intergration	ALL		Quantitatively integrate future technologies into the scenarios		X		X						X				M16	M20
2	2.2	2.2.5	Technology integration	ALL		Quantitatively integrate future technologies into the scenarios with Tasks 4.1 and 4.2														M14	M20
2	2.3	2.3.1	Future product/resource material composition	ALL		Compile (and possibly harmonize) present and future material use based on emerging technology assessment (Subtask 2.2.1)		X	X	X				X	X	X	X	X	X	M06	M18
2	2.3	2.3.2	Methods for data gaps in future compositions	ALL		Identify methods for imputing missing composition data		X							X	X				M14	M20
2	2.3	2.3.3	Create database of future waste stream compositions	ALL		Create database of material compositions for future products/waste streams for each scenario in combination with WP3		X							X	X				M18	M20
2	2.4	2.4.1	Harmonization of future material waste stream material recovery	ALL		Complile preliminary results from Tasks 4.1 and 4.2 and WP3, and harmonize intial waste stream results, feeding back to these tasks		X	X	X				X	X	X	X	X	X	M18	M21
2	2.4	2.4.2	Develop methods for environmental and social and economic assessments	ALL		Evaluate the use of S-LCA, tecnoeconomic assessments, cost-benefit analysis, multi-criteria analysis using information from both the waste stream models and the UNFC case studies			X	X		X				X		X		M18	M30
2	2.4	2.4.3	Perform social, economic and environmental assessments	ALL		Implement methods chosed from subtask 2.4.2 to assess the social, economic, and environmental impacts for each scenario (thus quantify environmental and socioeconomic impacts of SRM recovery under each scenario)			X	X		X				X		X		M30	M36
2	2.4	2.4.4	Feedback with UNFC methodology	ALL		Adapt/modify/streamline the methodology for application within the context of the UNFC			X			X		X		X	X	X	X	M24	M36
2	2.5	2.5.1	Compile information for the report	ALL		Compile all the modelling and case study information thus far and prepare for report writing	X	X	X	X	X	X	X	X	X	X	X	X	X	M37	M43
2	2.5	2.5.2	Report writing	ALL		Write the report on the bottlenecks, environmental, and socioeconomic impacts of secondary material recovery	X	X	X	X		X		X	X	X	X	X	X	M44	M45
2	2.5	2.5.3	Report reviewing	ALL		Report review by stakeholders and partners	X	X								X				M46	M46
2	2.5	2.5.4	Report revising	ALL		Revise report based on recommendations	X	X								X				M47	M47
2	2.5	2.5.5	Report delivery	ALL		Deliver final report										X				M48	M48

Table 13.9: Work breakdown structure for work package two

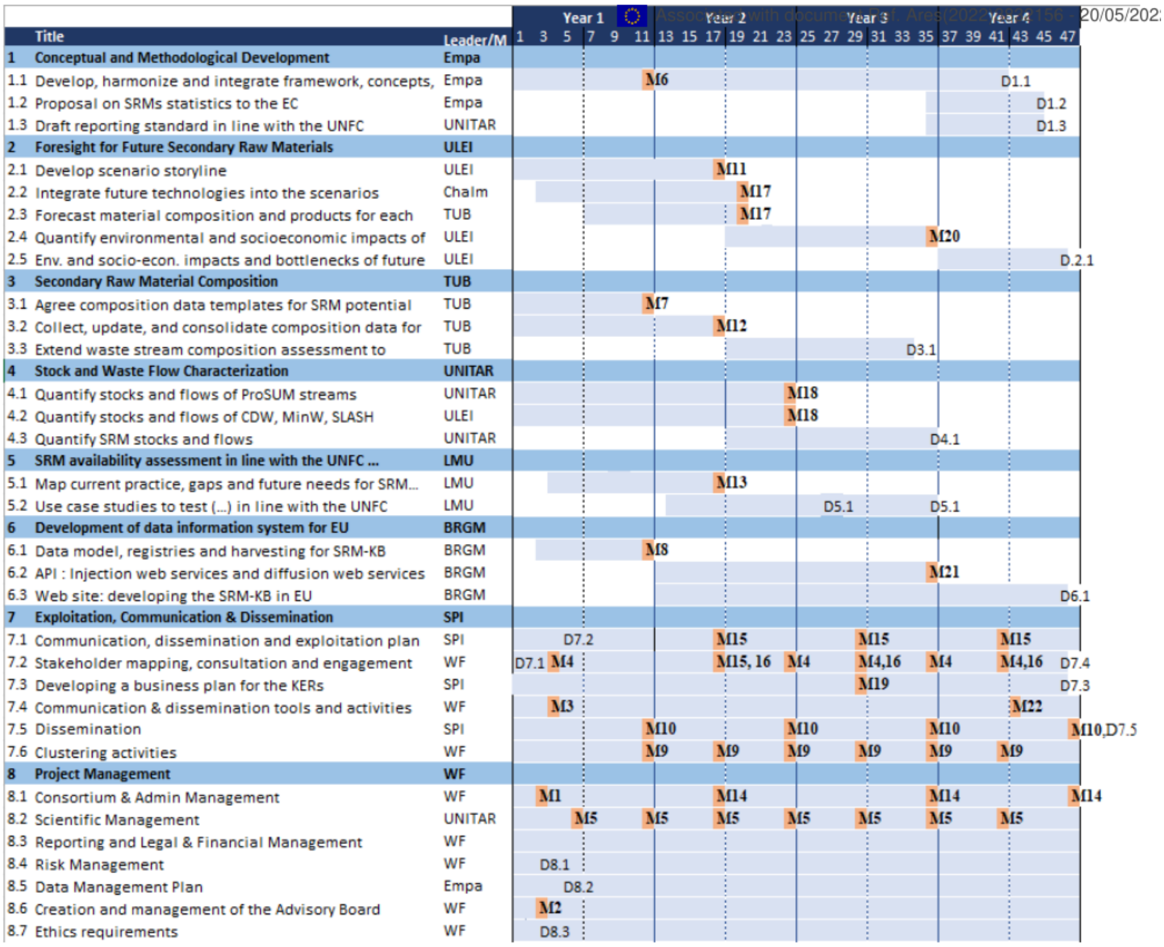

Table 13.10: Gaant chart for the entire FutuRaM project

END OF REPORT

4491

FutuRaM

Future availability of secondary raw materials