FutuRaM

Future availability of secondary raw materials

Work Package 2

Future recovery of secondary raw materials

Scenario Development

DRAFT REPORT

VERSION: 2.1

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THIS IS A DRAFT REPORT

please submit comments and corrections
to s.c.mcdowall@cml.leidenuniv.nl or directly:

- In a CSV file with the format: 'line number, comment, name, reference' (if reference is applicable, please provide the DOI or BibTeX).
- FutuRaM members can do this directly via this link.
- Or directly as a pull request to the LaTeX source files on the WP2 GitHub repository.

TODO

TO DO

- Add more references, especially for the targets, regulations, and projections.
- Waste stream groups to re-check the sections related to their waste streams.
- Discuss main points raised by reviewers:
  - Consideration of possible resource constraints in the scenarios.
    - We suggest covering this in sensitivity analysis and optimisation playground.
  - How to transfer general targets to individual waste streams?
    - 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.
  - Economic Considerations.
    - Addressing the fact that industrial ecology scenarios often exclude or have a limited view of economic factors.
  - Geopolitical Considerations.
    - How geopolitical changes and directions are being factored into the scenarios.
  - Scenario Relation with UNFC.
    - Addressing the relevance of the scenarios with the United Nations Framework Classification (UNFC).
  - E-mobility.
    - Do we hold it level across the scenarios?
    - In Germany, the Autolobby & Deutschland GmBh have killed the ICE ban...

I. Preface

The FutuRaM project aims to quantify the current and future availability of secondary raw materials (SRM), focusing on critical raw materials (CRMs) [1]. 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 electrical and electronic equipment (WEEE)
- waste batteries (BAT)
- end-of-life vehicles (ELV)
- mining waste (MIN)
- slags and ashes (SLASH)
- construction and demolition waste (CDW)

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 [1, 2, 3, 4]. 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 scenarios that have been developed in FutuRaM are:

- Business-as-usual (BAU)
- Recovery (REC)
- Circularity (CIR)

II. 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. The scenarios are designed to be internally consistent and to 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 backcasting techniques to construct a comprehensive, future-facing knowledge base that can aid fact-based decision-making [5, 6, 7, 8, 9, 10].

Scenario 1: Business as Usual (BAU)

The BAU scenario extends the current situation into the future with limited deviation from existing patterns. Utilising forecasting techniques, it assesses a potential future where there are minor advancements in resource efficiency, recovery technology, and the energy transition, but in which primary extraction of raw materials remains the dominant practice.

Scenario 2: Recovery (REC)

The Recovery scenario envisions a future that employs sophisticated technology to dramatically enhance SRM recovery from waste streams. It presents a future where the EU successfully meets its recycling and recovery targets through an effective waste management system and circular design principles [11, 12]. The scenario envisions an increased recovery rate of SRMs, extensive use of digitalisation and automation in recycling processes, and the implementation of new (or enforcement of existing) waste regulations in alignment with EU targets.

Scenario 3: Circularity (CIR)

The Circularity scenario encapsulates the fullest possible realisation of a circular economy, extending beyond end-of-life recovery of materials to minimising waste at all stages of production and consumption. It envisions a future where the EU's targets for recycling, recovery, and circularity are met through extensive stakeholder collaboration, the emergence of new business models, and increased use of renewable energy and circular economy technologies [13, 14, 15].

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

Through the development of these scenarios, the FutuRaM project aims to provide a nuanced understanding of the potential future waste management and resource recovery landscape within the EU. This approach offers insights into key drivers, uncertainties, and the potential impacts of policy interventions and technological advancements. By aligning SRM recovery projects more closely with the United Nations Framework Classification for Resources (UNFC) [16], the project aims to enable the commercial exploitation of SRMs and CRMs by manufacturers, recyclers, and investors. Ultimately, the comprehensive knowledge base developed through this process is designed to support and inform the decision-making processes of policymakers and governmental authorities.

III. Contents

IV. List of Figures

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VI. Summary of scenario storylines

Scenario I: Business-as-usual (BAU)

See section 2.1 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 [17].

- 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 [18].
- 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

See section 2.2 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 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 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 2.3 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 [19].
- 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.

VII. Acronyms

Table 0.1: List of acronyms

Acronym	Definition
AI	Artificial Intelligence
BAU	Business as Usual
BATT	Waste Batteries
CDW	Construction and Demolition Waste
CE	Circular Economy
CRM	Critical Raw Material
EEE	Electrical and Electronic Equipment
ELV	End-of-Life Vehicles
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
LCA	Life Cycle Assessment
MIN	Mining Waste
R&D	Research and Development
REACH	Registration, Evaluation, Authorization, and Restriction of Chemicals
SLASH	Slags and Ashes
S-LCA	Social Life Cycle Assessment
SRM	Secondary Raw Material
UNFC	United Nations Framework Classification for Resources
WEEE	Waste Electrical and Electronic Equipment
WFD	Waste Framework Directive

VIII. Terminology (abbreviated)

The following table provides an abbreviated list of terminology used in this report.

See section 5.1 for a complete list.

Table 0.2: 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.

IX. Description of FutuRaM work package task 2.1

Associated milestones

Table 0.3: Milestone list

Milestone	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

Associated subtasks

Table 0.4: Subtask list

WP	Task	Sub Task	Name	Waste Group	Description of sub-task	Start	End	Contributors	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, Chalmers, GTK, LMU, RECHARGE, SGU, TUB, Leiden Uni, VITO, Empa, UCL	x
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, Chalmers, GTK, LMU, RECHARGE, SGU, TUB, Leiden Uni, VITO, Empa, UCL	x
2	2.1	2.3	Scenario storylines	Cross-Cutting	Flesh out the storylines of the 3 main scenarios	M05	M08	UNITAR, Chalmers, TUB, Leiden Uni	x
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, Chalmers, SGU, Leiden Uni, VITO, UCL	DRAFTED

Chapter 1

Methodology

1.1 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 the future.
- 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. The methodology ensures that the scenarios capture the complexity and interconnectedness of the waste streams, taking into account, where possible, factors such as legislation, technology, geopolitics, and societal values. Ultimately, the goal is to provide decision-makers with valuable insights and tools to navigate the challenges and opportunities associated with secondary raw materials in a rapidly changing world.

1.2 Scenario storyline development process

Building scenarios involves several steps and methodologies, which can vary depending on the specific context and objectives [5, 6, 7, 8, 20, 21, 22, 23]. The following section provides an overview of the scenario development process used in FutuRaM. Figure 1.1 provides a visual representation of the process.

1.2.1 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:

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.

Scope:

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) [16], a tool that enables a better understanding of the viability of raw material projects. 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 1.1.

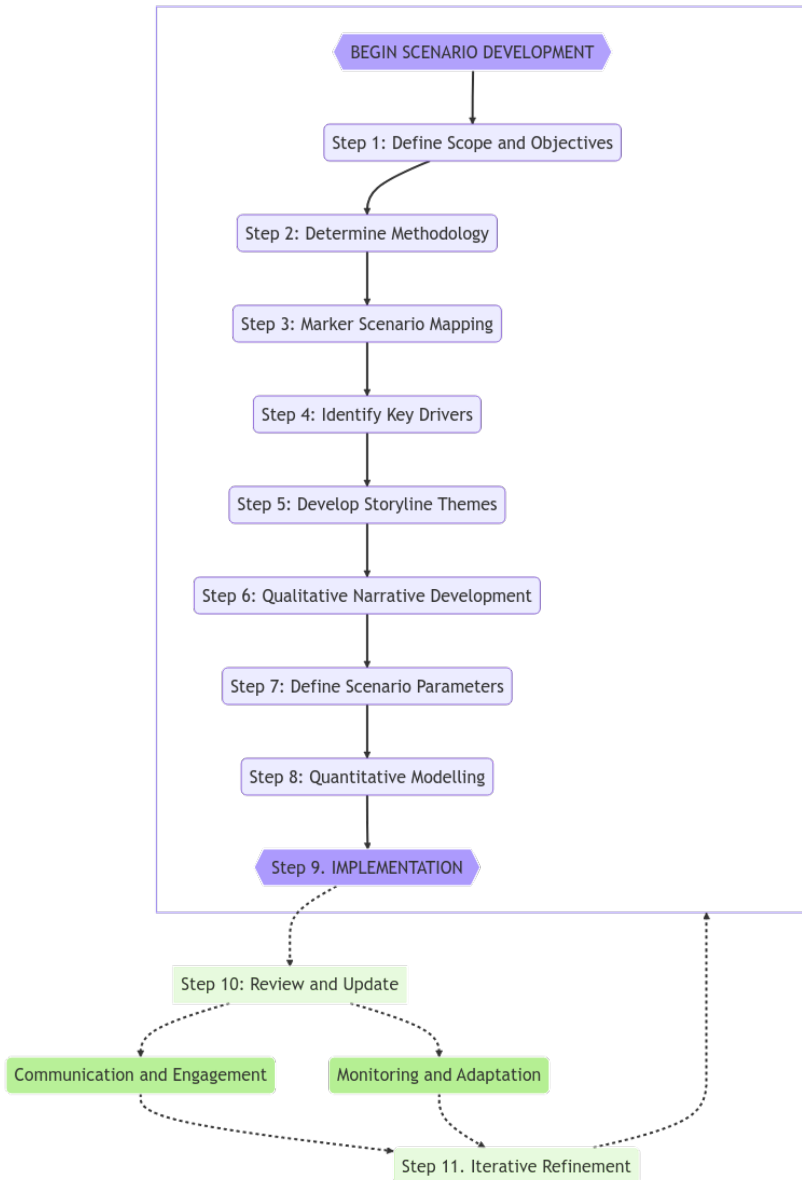

Figure 1.1: Scenario storyline development process

Table 1.1: Selected objectives of FutuRaM

Need	Action
A successful transition to a climate-neutral, circular and digitised EU economy relies heavily on a secure supply of raw materials. In order to strengthen EU autonomy and reduce over-dependency, we must boost domestic sourcing, both for primary and SRMs	FutuRaM will quantify the future availability of SRMs for three future scenarios for the EU material economy, from following current consumption trends to moderate or rapid transitioning toward a climate-neutral, circular, and digitised EU economy (WP2). The material demand and the SRMs 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. While some of these studies have partially included CRM demand and focused on the potential supply risks for achieving climate targets, these prospective scenarios have not been effectively harmonised across industrial sectors, and generally lack information on SRMs and the recovery industry in general. Transitions toward sustainable societies are likely to involve major changes and increased complexity in the material economy. Further research into current and future SRMs and CRMs present in the urban mine is thus urgent to prepare the industry for their eventual recovery. In addition, scenarios that include other Circular goals such as lifetime extension need to be better assessed in terms of material cycles	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 United Kingdom (EU27+4) and quantify their eventual end-of-life fate. FutuRaM will extend existing model approaches by a set of distinct scenarios which cover circular economy (e.g., lifetime extension through repair and remanufacturing), high SRMs recoverability, and business as usual. These scenarios will incorporate emerging recycling technologies in line with stakeholder dialogues that consider normative boundary conditions such as carbon neutrality by 2050.

Scope definition:

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.

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 [7].

Aims and objectives definition

The specific objectives of the FutuRaM scenario-building process are presented in Table 1.2.

Table 1.2: 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 on not only the availability of SRM and CRMs, but also on the environment, the economy, and society.

Consideration of EU legislation and policy targets

The scenarios developed in FutuRaM include the targets that the EU is setting for specific elements/materials/waste streams, following, in particular, the ambitions of the EU Green Deal [24] and the proposed critical raw materials (CRM) legislation [2]. Additionally, the consumer-product-centric waste streams BATT, ELV, and WEEE have specific EU legislation that will be considered in the scenarios.

General policies and legislation

The EU Green Deal [24] 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 and it covers a wide range of economic sectors with an emphasis on investments toward building up 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, and 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 [13] 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 it is closely linked to the EU Industrial Strategy.

The 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
- Emphasizes 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) [2] is a proposed 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 manufacture to its potential recovery as a secondary raw material.

By 2030, one single 'third country' (ex-EU, ex-Schengen) country shall produce not 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, where the emphasis is on the recovery of materials from waste streams and the Circularity scenario where the emphasis is on the implementation of 're-X' strategies, such as recycling, remanufacturing, and reuse. These benchmarks are considered too optimistic to be included in the Business-as-usual scenario as they suggest near-complete recovery for several elements.

Waste stream-specific legislation and policy targets

With respect to the waste streams that are analysed in FutuRaM, the following waste stream-specific developments aligned with EU targets have been considered:

- BATT: Battery and waste battery regulation (2023) [25]
  - Establishes rules for the collection, treatment, and recycling of batteries and accumulators in the EU
  - Requires Member States to set up collection and recycling systems for waste batteries and accumulators
  - Sets specific recycling targets for different types of batteries and accumulators
  - Prohibits the use of certain hazardous substances in the manufacturing of batteries and accumulators
  - Requires labelling and information for consumers on the proper disposal of batteries and accumulators
  - Requires producers to take responsibility for the costs of collecting, treating, and recycling waste batteries and accumulators
  - Aims to reduce the environmental impact of batteries and accumulators throughout their life cycle.
- BATT: Introduction of battery passport in 2026 [26]
- Mandatory minimum levels of recycled content for industrial, and vehicle batteries.
- Batteries incorporated in appliances have to be removable and replaceable by 2027.
- ELV: Proposed revision currently under review [27]:
  - Sets out rules for the collection, treatment, and recycling of end-of-life vehicles (ELV) in the EU
  - Requires Member States to set up collection systems for ELV and ensure that they are treated and recycled in a more environmentally sound manner.

  - Enforce collection targets, ban export of unroadworthy vehicles.
  - Strengthen 'Extended Producer Responsibility' to encourage better quality waste treatment.
  - Proposes provisions for the design and dismantling of certain CRM-rich components.

- WEEE Directive (about to be evaluated with a review likely in 2024):
  - Sets out rules for the collection, treatment, and recycling of waste electrical and electronic equipment (WEEE) in the EU
  - Requires Member States to establish collection systems for WEEE and ensure that it is treated and recycled in an environmentally sound manner
  - Sets collection and recycling targets for different types of WEEE
  - Requires producers to take responsibility for the costs of treating and recycling WEEE
  - Requires the use of the waste hierarchy for WEEE management
  - Aims to prevent the generation of WEEE and promote its reuse and recycling
  - Requires the labelling of electrical and electronic equipment to facilitate its proper disposal.

- CDW: Inside the CDW stream are important waste flows such as wind turbines and solar panels. The permanent magnets in wind turbines are a source of rare earth elements (REEs) and the solar panels contain indium and gallium. The CRM Act will also cover the recycling of these waste flows.

- MIN: The CRM Act will also cover the mining waste stream. As stated by the European Commission [4]:

  > The act promotes the recovery of critical raw materials from mining waste. The EU, due to its history of mining, has numerous old mining sites and tailings across the EU which can contain precious critical raw materials, but whose potential has not been analysed so far. The Act obliges current operators to assess the possibility of such recovery and to gather information on the

critical raw materials content of the waste they are generating as well as on the waste stored on their sites. For closed and abandoned mines, the Act makes Member States responsible for gathering this data – from permitting files as well as targeted sampling campaigns – and publishing it in an openly accessible database. This will allow potential operators to identify potential sites of interest and implement such recovery projects with public authorities.

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.' [28]

'**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 supply-demand value statements.**

1.2.2 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 **??** 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 [29]. 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 [30] 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 1.3.

In the context of futures studies, various approaches and methodologies are employed to understand the potential trajectories of future developments [6, 7, 20, 21, 22]. 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.

The choice of scenario category is driven by the user's objectives, worldview, and perceptions, making it a crucial factor in the scenario selection process. This user-centric approach ensures that scenarios are not only relevant but also effectively inform decision-making processes. While further refinement is needed based on user feedback, this report provides valuable guidance for scenario use.

Table 1.3: (adapted from [6])

Scenario category	Scenario type	Quantitative/qualitative	Time-frame	System structure	Focus on internal or external 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 *how can a target be reached?*	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

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.

1.2.3 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 scenarios.

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

section 5.3 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.

1.2.4 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 1.2 illustrates the process of identifying key drivers of change.

Methodology and results of this stage in FutuRaMs 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 categorization 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 [31, 32].

   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 ethnic-

ity), 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 5.4.

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 5.5.

In Figure 1.3, 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.

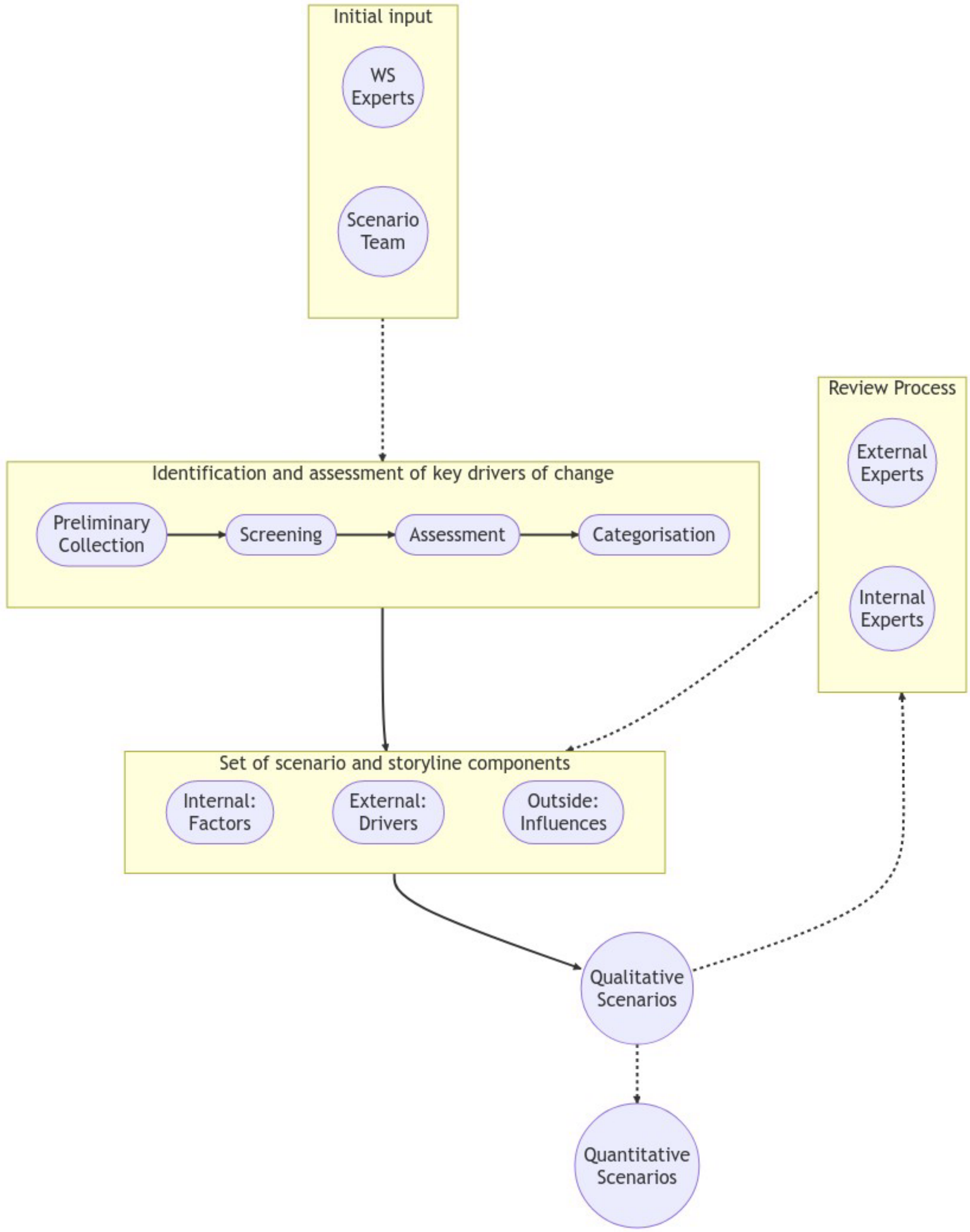

Figure 1.2: An illustration of the process used for identifying key drivers of change

THIS TABLE IS FOR THE ASSESSMENT OF THE RELEVENCE OF EACH SCENARIO ELEMENT TO INDIVIDUAL WASTE STREAM FLOWS	ELV			BAT					WEEE					
	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
DRIVER/FACTOR														
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 1.3: 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 categorised 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 1.4. Note that CIR and REC are very similar for many 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.

Table 1.4: (the numerals indicate the degree to which the drivers are present in each scenario, ‘n/a’ signifies that the driver will not be assessed directly in the scenario modelling)

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 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 scenarios. This factor will, however, be considered in the sensitivity analysis of the model and additionally, the codebase will be designed to allow for the optimisation 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 optimisation procedure performed as an extension to the model.

Conclusion

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.

1.2.5 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.

1.2.6 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.

1.2.7 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. These parameters will be defined in the next stages of the project.

1.2.8 Step 8: Quantitative modelling

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

1.2.9 Step 9: Implementation

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

1.2.10 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 categorization step with the consortium and inviting feedback and suggestions. The feedback will be used to refine the elements and their categorization 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.

Chapter 2

Scenario storylines

2.1 Scenario 1: Business-as-usual

2.1.1 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 [33]. 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 towards 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. 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.

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 [34]. Simultaneously, the EU becomes increasingly dependent on imports of SRMs, raising concerns about supply chain security and geopolitical risks [34].

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.

2.1.2 Waste stream specific scenario impacts

BATT (Battery waste) [11, 12, 25, 26]

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) [12, 27, 35, 36]

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) [37, 38, 39, 40, 41]

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 Recovery 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.

Mining waste (MIN)

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

- Limited technological advancements lead to static recovery rates of valuable materials from mining waste.
- Continued reliance on primary extraction as the dominant source of raw materials.
- Minimal advances in collaboration between government and industry for mining waste recovery.

- Low levels of traceability and management of mining waste.
- Mining waste remains a significant environmental challenge.
- Mining waste recovery projects remain too expensive.
- Little incentive for the private sector and public sector, except for monitoring environmental risks of existing deposits.

CDW (Construction and Demolition Waste) [42]

In the BAU scenario, the management of Construction and Demolition Waste (CDW) remains largely unchanged. Lack of progress in recovery technologies and regulatory incentives will lead to low recovery rates of CRM-containing materials from CDW.

- Base metals are recovered as they have been [43], though there are limited improvements and no particular focus on the recovery of CRMs from CDW.
- Continued generation of CDW due to the demand in the construction sector.
- Renovation as an alternative to new construction is not widely adopted.
- The majority of CDW (excluding base metals) continues to be treated as waste or backfill, with low recycling rates.
- CDW recovery (including preparation for re-use, recycling and other material recovery, including backfilling)
- Recovery of metals remains on already high levels (¿90%)
- Recovery of minerals remains on already high levels (¿70%) by using them as aggregates in road construction and backfilling
- Recycling of wind turbines stays around 85% (mainly metals), permanent magnets continue to be recycled as part of the metal fractions

SLASH (Slags and Ashes)

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.

- Increased generation of SLASH because SRMs are not recovered and end up in incineration and smelter residues.
- Low quality of SLASH due to:
  - poor sorting and separation of waste streams (e.g., consumer electronics and batteries, end up in general waste streams and are incinerated)
  - high 'contamination' from the above-described failures of segregation.
  - large proportion coming from mixed waste incineration
- Lack of technological advancements results in low recovery rates of valuable materials from SLASH.
- Continued high generation of SLASH due to the reliance on traditional energy sources.
- Minimal incentives for the recovery and reuse of materials from SLASH.
- Low levels of traceability and management of SLASH.
- SLASH continues to be a significant environmental challenge due to the high volume generated.
- Some products from SLASH are recovered in low added value, for example, as aggregates for roads or additives in cement.

2.2 Scenario 2: Recovery

2.2.1 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.

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 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.

2.2.2 Waste stream specific scenario impacts

BATT (Battery waste) [11, 12, 25, 26]

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 [12].
  - Higher requirements on disassemblability.
  - Information available to promote efficient recovery.

ELV (End-of-Life Vehicles) [12, 27, 35, 36]

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) [37, 38, 39, 40, 41]

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 [44]

- '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

Mining waste (MIN)

Under the recovery scenario, technological advancements enable the extraction of residual valuable materials from mining waste, transforming it into a 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) [42]

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.

- Advanced recovery technologies allow for higher recovery rates of valuable materials from CDW.
- Despite improvements in design and material efficiency, CDW generation remains high due to the construction demand.
- Eliminating the disposal of any avoidable CDW, through the implementation and expansion of incentives, and regulatory measures.
- The focus of this scenario is to significantly reduce the amount of CDW that ends up in treatment plants without any useful applications, e.g., landfilling, incineration, and land spreading.
- This scenario is characterized by a high recovery rate, achieved via:
  - increased investment and enhanced regulatory system in waste management
  - leading to more waste recovery infrastructure
  - widespread application of selective demolition and on-site waste sorting

  .
- Recovery of minerals is intensified with a stronger focus on closed-loop recycling (e.g., concrete waste is used as aggregates in concrete; recovery of cement is explored).
- 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.
- Improved recycling of wind turbine blades is notable, especially regarding plastics; permanent magnets are recycled at a functional level.

SLASH (Slags and Ashes)

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.

- Advanced recovery technologies allow for the extraction of valuable metals and minerals from SLASH.
- Despite improvements in energy production, SLASH generation remains significant due to the continued reliance on traditional energy sources.
- New regulations incentivize the recovery and reuse of materials from SLASH.
- Digital solutions enhance the traceability and management of SLASH.
- SLASH remains a significant environmental challenge due to the volume generated.
- Transferring down-cycling to recycling or even upcycling.
- Recycling technology improvements (e.g., cement additives using biomass ash are under investigation)
- 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. Recovery of Zn and Pb from Zn and Pb smelter slag.
- 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.

2.3 Scenario 3: Circularity

2.3.1 Storyline narrative

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 emphasis is on re-X strategies that are integrated right from the product design stage. 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. This means that every component of the product can either be biologically broken down without any harm to the environment or technically reprocessed into new products, creating a closed loop of materials.

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.

2.3.2 Waste stream specific scenario impacts

BATT (Battery waste) [11, 12, 25, 26]

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) [12, 27, 35, 36]

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 downsizing
  - 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) [37, 38, 39, 40, 41]

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 [19].
- 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 [45, 46].
- 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.

Mining waste (MIN)

In this scenario, the impact on mining waste is two-fold. Firstly, the need for primary mining is reduced due to 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) [42]

Construction and Demolition Waste (CDW) is another sector that sees significant improvement in the circularity scenario. Emphasising design for disassembly and the use of recyclable materials, this scenario drastically reduces the generation of CDW and promotes the recovery of valuable materials from the waste stream.

- Buildings are designed for disassembly, increasing the lifespan of materials and reducing CDW.
- Recycling technologies for CDW improve, allowing higher recovery rates of materials.
- Policies and regulations incentivise the use of recycled materials in construction.
- Standardised systems for CDW collection and separation are established.
- Digital tools like building information modelling (BIM) improve resource management in construction.
- This scenario envisions an almost closed-loop system where CDW is considered a resource, with an emphasis on minimising waste generation and maximising resource efficiency in recovery.
- Waste reduction is prioritized through the implementation of eco-designs, including designing out waste (DOW), lightweight design (LWD), and design for dismantling (DFD).
- Reuse and repair standards and networks are established to boost the reuse of end-of-life building components and equipment.
- If reuse is no longer possible, waste is recycled through high-efficiency recycling facilities rather than down-cycled or used for energy recovery.

- This scenario is characterized by meeting all material needs through recovery (including mineral wastes from other industries) with high material efficiency achieved through the development of new business models, advanced designs and recycling technologies, strict waste management regulations, and innovative products and services.
- Plausible target: Achieving a 100% recovery rate of avoidable CDW by 2050, with a recycling rate accounting for 30% and component reuse accounting for 20%. Raw material consumption should be reduced by 50% compared to the 2020 level.
- Example of treatment technological development: Waste concrete is primarily recycled through an innovative mobile dry process. Biodiesel-based thermal treatment is applied to further pyrolyze the fine aggregate to recover cement. Lightweight design is implemented to reduce concrete use.

SLASH (Slags and Ashes)

In the circularity scenario, the approach to SLASH dramatically changes. Instead of being treated as waste, SLASH is seen as a valuable secondary raw material. Advances in technology allow for the extraction of valuable metals and minerals from SLASH, that then re-enter the material cycle.

- A shift in perception treats SLASH as a valuable resource instead of waste.
- Advanced technologies enable the extraction of valuable metals and minerals from SLASH.
- New regulations incentivise the use of SLASH in various applications, such as in the construction industry.
- Digital solutions enhance the tracking and management of SLASH.
- Collaboration between industries utilises SLASH in new and innovative ways.
- Reduce the generation of SLASH by increasing the efficiency of the manufacturing side. For example, developing higher efficient production of metals and reducing by-products such as smelter slag. For ash from the incineration of solid biomass, maximizing the use

of biomass by setting proper temperature, time, and furnace conditions to reduce ash contents and improve the efficiency of power and heat generation. For ash, developing other renewable technologies from bioenergy to reduce the incineration of solid biomass, e.g., biogas.

- Reduce the generation of SLASH by increasing the proportion of higher calorific waste and decreasing lower calorific waste, e.g., MSW (Municipal Solid Waste).
- Developing domestic feedstock supply for bioenergy or metal production to reduce the cost of transportation and others.
- Higher formal collection and recycling rate compared to BAU, but lower compared to the Recovery scenario.

Chapter 3

Quantification

To be completed in the next stages of the project.

Chapter 4

References

Literature considered in 5.3 the marker scenario mapping process is excluded from the following list of references, excepting those cited elsewhere in the report.

[1] T. E. Graedel, E. M. Harper, N. T. Nassar, et al. "On the materials basis of modern society". In: *Proceedings of the National Academy of Sciences* (2015). ISSN: 0027-8424. DOI: 10.1073/pnas.1312752110.

[2] *European Critical Raw Materials Act*. European Commission, 2023. URL: https://single-market-economy.ec.europa.eu/publications/european-critical-raw-materials-act%5C%5Fen.

[3] *Study on the critical raw materials for the EU 2023 – Final report*. Tech. rep. 2023. DOI: https://doi/10.2873/725585.

[4] *Questions and Answers: The European Critical Raw Materials Act*. European Commission. 2023. URL: https://ec.europa.eu/commission/presscorner/detail/en/qanda%5C%5F23%5C%5F1662.

[5] Karl H Dreborg. "Essence of backcasting". In: *Futures* 9 (1996). ISSN: 0016-3287. DOI: 10.1016/s0016-3287(96)00044-4. URL: https://www.sciencedirect.com/science/article/pii/S0016328796000444.

[6] Lena Boerjeson, Mattias Hoejer, Karl-Henrik Dreborg, et al. *Towards a user's guide to scenarios - a report on scenario types and scenario techniques*. Tech. rep. 2005. URL: https://www.osti.gov/etdeweb/biblio/20688312.

[7] Muhammad Amer, Tugrul U. Daim, and Antonie Jetter. "A review of scenario planning". In: *Futures* (2013). ISSN: 0016-3287. DOI: 10.1016/j.futures.2012.10.003. URL: https://www.sciencedirect.com/science/article/pii/S0016328712001978.

[8] Saskia Sardesai, Markus Stute, and Josef Kamphues. "A Methodology for Future Scenario Planning". In: *Next Generation Supply Chains: A Roadmap for Research and Innovation*. Ed. by Rosanna Fornasiero et al. Springer International Publishing, 2021. ISBN: 978-3-030-63505-3. DOI: 10.1007/978-3-030-63505-3_2. URL: 10.1007/978-3-030-63505-3%5C%5f2.

[9] Elisabeth A Lloyd and Vanessa J Schweizer. "Objectivity and a comparison of methodological scenario approaches for climate change research". In: *Synthese* (2014).

[10] Fulvio Ardente and Fabrice Mathieux. "Environmental assessment of the durability of energy-using products: method and application". In: *Journal of Cleaner Production* (2014). ISSN: 0959-6526. DOI: 10.1016/j.jclepro.2014.03.049. URL: https://www.sciencedirect.com/science/article/pii/S0959652614002807.

[11] Vivienne Halleux. *New EU regulatory framework for batteries: Setting sustainability requirements*. Tech. rep. 2021. URL: https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/689337/EPRS%5C%5FBRI(2021)689337%5C%5FEN.pdf.

[12] Harald Helander and Maria Ljunggren. "Battery as a service: Analysing multiple reuse and recycling loops". In: *Resources, Conservation and Recycling* (2023). ISSN: 0921-3449. DOI: 10.1016/j.resconrec.2023.107091. URL: https://www.sciencedirect.com/science/article/pii/S0921344923002276.

[13] *A New Circular Economy Action Plan For a Cleaner and More Competitive Europe*. European Commission, 2020. DOI: 10.2779/05068.

[14] Julian Kirchherr, Denise Reike, and Marko Hekkert. "Conceptualizing the circular economy: An analysis of 114 definitions". In: *Resources, Conservation and Recycling* (2017). ISSN: 0921-3449. DOI: 10.1016/j.resconrec.2017.09.005. URL: https://www.sciencedirect.com/science/article/pii/S0921344917302835.

[15] Teresa Domenech and Bettina Bahn-Walkowiak. "Transition towards a resource efficient circular economy in Europe: policy lessons from the EU and the member states". In: *Ecological Economics* (2019).

[16] *United Nations Framework Classification for Resources (UNFC)*. United Nations Economic Commission for Europe. 2023. URL: https://unece.org/sustainable-energy/sustainable-resource-management/united-nations-framework-classification.

[17] *Energy Technology Perspectives 2023*. Tech. rep. 2023. DOI: 10.1787/7c6b23db-en. URL: https://www.oecd-ilibrary.org/content/publication/7c6b23db-en.

[18] Lucia Mancini, Camillo De Camillis, and David Pennington. *Security of supply and scarcity of raw materials: Towards a methodological framework for sustainability assessment*. Tech. rep. 2013.

[19] Martin Geissdoerfer, Marina P.P. Pieroni, Daniela C.A. Pigosso, et al. "Circular business models: A review". In: *Journal of Cleaner Production* (2020). ISSN: 0959-6526. DOI: 10.1016/j.jclepro.2020.123741.

[20] Peter Bishop, Andy Hines, and Terry Collins. "The current state of scenario development: An overview of techniques". In: *Foresight - The journal of future studies* (2007). DOI: 10.1108/14636680710727516.

[21] Kathya Cordova-Pozo and Etiënne A.J.A. Rouwette. "Types of scenario planning and their effectiveness: A review of reviews". In: *Futures* (2023). ISSN: 0016-3287. DOI: 10.1016/j.futures.2023.103153.

[22] Jim Skea, Renée van Diemen, Joana Portugal-Pereira, et al. "Outlooks, explorations and normative scenarios: Approaches to global energy futures compared". In: *Technological Forecasting and Social Change* (2021).

[23] Philip W.F van Notten, Jan Rotmans, Marjolein B.A van Asselt, et al. "An updated scenario typology". In: *Futures* (2003). ISSN: 0016-3287. DOI: 10.1016/s0016-3287(02)00090-3. URL: https://www.sciencedirect.com/science/article/pii/S0016328702000903.

[24] *The European Green Deal*. European Commission, 2019. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%5C%3A52019DC0640.

[25] *REGULATION (EU) 2023/1542 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 12 July 2023 concerning batteries and waste batteries, amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and repealing Directive 2006/66/EC*. European Commission, 2023. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%5C%3A32023R1542.

[26] *Proposal for a Regulation of the European Parliament and of the Council Concerning Batteries and Waste Batteries, Repealing Directive 2006/66/EC and Amending Regulation (EU) No 2019/1020*. European Commission, 2020.

[27] *End-of-life vehicles Regulation*. European Commission. 2023. URL: https://environment.ec.europa.eu/topics/waste-and-recycling/end-life-vehicles/end-life-vehicles-regulation%5C%5Fen.

[28] Marcin SZCZEPANSKI. “Resilience of global supply chains: Challenges and solutions”. In: (2021).

[29] Bernhard Steubing, Christopher Mutel, Florian Suter, et al. “Streamlining scenario analysis and optimization of key choices in value chains using a modular LCA approach”. In: *The International Journal of Life Cycle Assessment* (2016).

[30] Chia-Chien Hsu and Brian A. Sandford. “The Delphi Technique: Making Sense of Consensus”. In: *Practical Assessment, Research, and Evaluation* (2019). ISSN: 1531-7714. DOI: 10.7275/pdz9-th90. URL: https://scholarworks.umass.edu/pare/vol12/iss1/10.

[31] Konstantinos Kokkinos, Vayos Karayannis, Nicholas Samaras, et al. “Multi-scenario analysis on hydrogen production development using PESTEL and FCM models”. In: *Journal of Cleaner Production* (2023). ISSN: 0959-6526. DOI: 10.1016/j.jclepro.2023.138251. URL: https://www.sciencedirect.com/science/article/pii/S0959652623024095.

[32] Manel Sansa, Ahmed Badreddine, and Taieb Ben Romdhane. “Sustainable design based on LCA and operations management methods: SWOT, PESTEL, and 7S”. In: (2021).

[33] *World energy outlook 2022*. Tech. rep. 2022. URL: https://iea.blob.core.windows.net/assets/830fe099-5530-48f2-a7c1-11f35d510983/WorldEnergyOutlook2022.pdf.

[34] Hoesung Lee, Katherine Calvin, Dipak Dasgupta, et al. *Climate Change 2023 Synthesis Report Summary for Policymakers*. Tech. rep. 2024.

[35] A. Løvik, C. Marmy, M. Ljunggren, et al. *Material composition trends in vehicles: critical raw materials and other relevant metals*. Tech. rep. Eur 30916 En. 2021. DOI: 10.2760/351825.

[36] N. Tazi, M. Orefice, C. Marmy, et al. *Initial analysis of selected measures to improve the circularity of critical raw materials and other materials in vehicles*. Tech. rep. 2023. DOI: 10.2760/207541.

[37] K. Parajuly, R. Kuehr, A. K. Awasthi, et al. *Future E-waste Scenarios*. Tech. rep. StEP (Bonn), UNU ViE-SCYCLE (Bonn) and UNEP IETC (Osaka), 2019.

[38] United Nations Institute for Training United Nations Environment Programme and Research. *Electronic and Electrical Waste Outlook in West Asia*. Tech. rep. 2023. URL: https://wedocs.unep.org/20.500.11822/42147.

[39] Vanessa Forti, Cornelis P Balde, Ruediger Kuehr, et al. *The Global E-waste Monitor 2020: Quantities, flows and the circular economy potential*. Tech. rep. 2020.

[40] *Directive 2012/19/EU of the European Parliament and of the council of 4 July 2012 on waste electrical and electronic equipment (WEEE) text with EEA relevance*. European Commission, 2012. URL: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:197:0038:0071:EN:PDF.

[41] *Directive 2012/19/EU of the European Parliament and of the council of 4 July 2012 on waste electrical and electronic equipment (WEEE) (recast)*. European Commission, 2012. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%5C%3A32012L0019.

[42] *Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (Text with EEA relevance)*. European Commission, 2008. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%5C%3A02008L0098-20180705.

[43] Julia Moschen-Schimek, Thomas Kasper, and Marion Huber-Humer. "Critical review of the recovery rates of construction and demolition waste in the European Union – An analysis of influencing factors in selected EU countries". In: *Waste Management* (2023). ISSN: 0956-053x. DOI: 10.1016/j.wasman.2023.05.020. URL: https://www.sciencedirect.com/science/article/pii/S0956053X23003616.

[44] Jaco Huisman, Ioana Botezatu, Lucia Herreras, et al. "Countering WEEE illegal trade (CWIT) summary report". In: *Market Assessment, Legal Analysis, Crime Analysis and Recommendations Roadmap* (2015).

[45] *EUR-Lex - 32014L0053 - EN - EUR-Lex*. European Commission, 2023. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32014L0053.

[46] *Long-awaited common charger for mobile devices will be a reality in 2024*. European Commission. URL: https://www.europarl.europa.eu/news/en/press-room/20220930IPR41928/long-awaited-common-charger-for-mobile-devices-will-be-a-reality-in-2024.

[47] Center for Climate Adaptation Science and Solutions at the University of Arizona. *Glossary - Scenario Planning for the Institute of the Environment*. 2023. URL: https://www.adaptationscenarios.org/glossary.

Chapter 5

Appendices

5.1 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 [22]. Some additional definitions were sourced from [47].

Table 5.1: 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	Skea
Exploratory scenario	Exploration of plausible alternative developments to test whether decision-making is robust against different outcomes. Generally, involving a qualitative storyline about a possible future, complemented by quantitative analysis. Example: Socio-economic scenarios	Scenario type	Plausible scenarios	Skea
Outlook	To provide a most likely estimate of future trends as a guide for decision-making	Scenario type	Forecast, projection	Skea
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	Skea
Scenario scale	Description of the spatial extent or temporal extent of a scenario. For us, mostly EU toward 2050.	Scenario component		UniArizona
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		UniArizona
Scenario literature	Journal articles, grey literature, etc., from which data is sourced that can be used to justify decisions in scenario development	Scenario component		
Scenario logics	Methods for structuring the relationships between different drivers and assumptions in scenarios	Scenario component		Rowland et al. 2014 reported in UniArizona

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Table 5.1 — Continued from previous page

Term	**Definition**	**Level/Context**	**Also called**	**Source**
Time horizon	End date of the scenario's forecast	Scenario attribute		Skea
Snapshot	The position of scenario/s at a particular point of time	Scenario attribute		Skea
Storyline and simulation	Combination of qualitative narrative development and quantitative modelling	Scenario component		Mahmoud et al. 2009, Wollenberg et al. 2000 reported in UniArizona
Marker scenario	Generally, a widely accepted scenario which can be used a guide or to provide background information. E.g., SSP1-5, and the GEC models from the IEA. If applicable, these can be extended upon or combined to help build our models.	Scenario description	Basis scenario	Skea
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		PBL
IEA and GEC	Global Energy and Climate Model of the International Energy Agency. Used to create their forecasts: Net Zero Emissions (NZE), Announced Pledges Scenario (APS), and Stated Policies Scenario (STEPS)	Marker scenario examples		IEA
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	Walker et al. 2012, reported in UniArizona
Factors	Causes of system change that are internal from the system of analysis. Can be (hopefully) quantified, or at least estimated	Scenario component (internal)		

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Table 5.1 — Continued from previous page

Term	Definition	Level/Context	Also called	Source
Factor variables	Discrete elements which are subject to change and have effects on one or more factors	Factor component		
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		
Trends	An inclination in a particular direction	Attribute of drivers or factors	System development	
Likelihood	The likelihood of an occurrence, an outcome, or a result, where this can be estimated probabilistically.	Attribute of drivers or factors	Probability	Rowland et al. 2014, IPCC standard

5.2 Scenario development methods

The following table 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 5.2: 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

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Table 5.2 – Continued from previous page

Method	Description	Key characteristics	Limitations	Application
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
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

5.3 Marker scenario mapping

The following table 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 field of waste management, resource recovery, and circular economy.

Table 5.3: Overview of marker scenarios

Literature	Type	Waste stream	Temporal Coverage	Location	Number of scenarios	
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	Link
Environmental Impacts of Global Offshore Wind Energy Development until 2040	Academic	C&D	Scenario: 2019–2040	Global	4 (based on IEA)	Link
Global greenhouse gas emissions from residential and commercial building materials and mitigation strategies to 2060	Academic	C&D	Scenario: 2020–2060	Global	2 (based on SSP2)	Link
Modelling global material stocks and flows for residential and service sector buildings towards 2050	Academic	C&D	Scenario: 2020–2060	Global	1 (SSP2)	Link
The evolution and future perspectives of energy intensity in the global building sector 1971–2060	Academic	C&D	Scenario: 2020–2060	Global	1 (SSP2)	Link

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Literature	Type	Waste stream	Temporal Coverage	Location	Number of scenarios	Link
Tracking Construction Material over Space and Time Prospective and Geo-referenced modelling of Building Stocks and Construction Material Flows	Academic	C&D	Scenario to 2060	Global	6 scenarios concerning per-capita floor area, building stock turnover, and construction material.	Link
Global construction materials database and stock analysis of residential buildings between 1970–2050	Academic	C&D	Scenario to 2060	Global	1 (SSP2)	Link
A comprehensive set of global scenarios of housing, mobility, and material efficiency for material cycles and energy systems modelling	Academic	C&D	Scenario to 2060	Global	Low energy demand, SSP1, SSP2	Link
Global scenarios of resource and emission savings from material efficiency in residential buildings and cars	Academic	C&D, ELV	Scenarios to 2050	Global	SSP1, SSP2	Link

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Table 5.3 — Continued from previous page

Literature	Type	Waste stream	Temporal Coverage	Location	Number of scenarios	Link
Matching global cobalt demand under different scenarios for co-production and mining attractiveness	Academic	BAT	2050	Global	5	Link
Copper at the crossroads: Assessment of the interactions between lowcarbon energy transition and supply limitations	Academic	Copper	2050	Global	2: 2°C and 4°C	Link
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)	Link
The rise of electric vehicles—2020 status and future expectations	Academic	ELV, BAT	up to 2050	Global	various	Link
Scenarios for the Return of Lithium-ion Batteries out of Electric Cars for Recycling	Academic	ELV, Battery	Scenario to 2050	Global	2	Link
The dynamic equilibrium mechanism of regional lithium flow for transportation electrification	Academic	ELV, BAT	Scenario to 2050	Global	1 (projection)	Link
Future material demand for automotive lithium-based batteries	Academic	ELV, BAT	Scenario to 2050	Global	4 (based on IEA)	Link

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Table 5.3 — Continued from previous page

Literature	Type	Waste stream	Temporal Coverage	Location	Number of scenarios	Link
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	Link
Circular economy strategies for electric vehicle batteries reduce reliance on raw materials	Academic	ELV, BAT	Scenario to 2050	Global	Reference + 4 technologies	Link
Summary and critical review of the International Energy Agency's special report: The role of critical minerals in clean energy transitions	Academic	Energy	Global	IEA 2021		Link
Review of critical metal dynamics to 2050 for 48 elements	Academic	Energy	Scenario to 2050	Global	1 compiled from various renewable technologies	Link
Major metals demand, supply, and environmental impacts to 2100: A critical review	Academic	Energy	Scenario to 2100	Global	1 review of 197 studies	Link
Requirements for Minerals and Metals for 100% Renewable Scenarios	Academic	Energy	Scenario to 2050	Global	1.5 degree scenario	Link

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Table 5.3 — Continued from previous page

Literature	Type	Waste stream	Temporal Coverage	Location	Number of scenarios	Link
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	Link
Modelling the demand and access of mineral resources in a changing world	Academic	Energy, construction	2060	Global	RTS, BD2S IEA	Link
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	Link
A slag prediction model in an electric arc furnace process for special steel production	Academic	Slags	None	Global	0	Link
Decarbonising the iron and steel sector for a 2°C target using inherent waste streams	Academic	Slags	Scenario to 2050	Global	1 (2 degree climate goal)	Link
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)	Link

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Table 5.3 — 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)	Link
Raw material depletion and scenario assessment in European Union — A circular economy approach	Academic	Various	None	EU	0	Link
Material bottlenecks in the future development of green technologies	Academic	Various	Scenario to 2050	Global	1 BAU	Link
Reuse assessment of WEEE: Systematic review of emerging themes and research directions	Academic	WEEE	None	Global	0	Link
A systematic literature review on the circular economy initiatives in the European Union	Academic	Circularity	None	EU	Circular strategies	Link
Material Flow Accounting: Measuring Global Material Use for Sustainable Development	Academic	Various	Scenario to 2100	Global	1 BAU	Link
Circular Economy Action Plan	Action plan	Various	Scenario to 2050	EU	35 actions to climate neutrality	Link

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Table 5.3 — Continued from previous page

Literature	Type	Waste stream	Temporal Coverage	Location	Number of scenarios	Link
Construction and demolition waste: challenges and opportunities in a circular economy	Report	C&D	None	EU	0	Link
IEA world energy model	Report	Energy	Scenario to 2050	Global	4	Link
Bloomberg scenarios	Report	Energy	Scenario to 2050	Global	3	Link
The Role of Critical Minerals in Clean Energy Transitions	Report	Energy	None	Global	0	Link
Transitions to 2050 decide now act for climate	Report	Energy	Scenario to 2050	France	4 to reach 2.1C by 2100	Link
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	Link
Inventaires des besoins en matière, énergie, eau et sols des technologies de la transition énergétique	Report	Energy	Scenario to 2050	France	1	Link

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Table 5.3 — Continued from previous page

Literature	Type	Waste stream	Temporal Coverage	Location	Number of scenarios	Link
Minerals in the future of Europe	Report	MinW	Scenario to 2050	EU	3 (2050 net-zero, digital, circular)	Link
Minerals, Critical Minerals and the US Economy	Report	MinW	None	US	0	Link
Minéraux stratégiques — État des lieux et propositions pour une vision partagée	Report	MinW	None	FR	0	Link
The Critical Raw Materials (CRM) initiative — Underpinning the strategic approach to the EU's raw materials policy	Report	MinW	None	EU	0	Link
Towards the Circular Economy: Accelerating the scale-up across global supply chains	Report	Circularity	None	Global	0	Link
The Circular Economy in Europe	Report	Circularity	None	EU	0	Link
Global material flows and resource productivity: Forty years of evidence	Report	Circularity	None	Global	0	Link
The circular economy concept: contextualisation and multiple perspectives	Report	Circularity	None	Global	0	Link
Global material flows database	Database	Various	None	Global	0	Link

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Table 5.3 — Continued from previous page

Literature	Type	Waste stream	Temporal Coverage	Location	Number of scenarios	Link
International Resource Panel	Reports	Various	None	Global	0	Link
World Business Council for Sustainable Development	Reports	Various	None	Global	0	Link
Ellen MacArthur Foundation	Reports	Various	None	Global	0	Link
European Environment Agency	Reports	Various	None	EU	0	Link
International Energy Agency	Reports	Energy	None	Global	0	Link
United Nations Environment Programme	Reports	Various	None	Global	0	Link
United Nations Industrial Development Reports	Reports	Various	None	Global	0	Link
World Bank	Reports	Various	None	Global	0	Link
World Economic Forum	Reports	Various	None	Global	0	Link

5.4 Drivers and factors identified in the initial collection phase

The following table lists the elements that were identified in the initial phase of driver/factor collection.

Table 5.4: 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 5.4 – Continued from previous page

Driver/factor	Definition
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 5.4 – Continued from previous page

Driver/factor	**Definition**
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

5.5 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 5.5: 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

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Table 5.5 — Continued from previous page

Domain	Driver/factor	Definition	BAU	REC	CIR
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
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