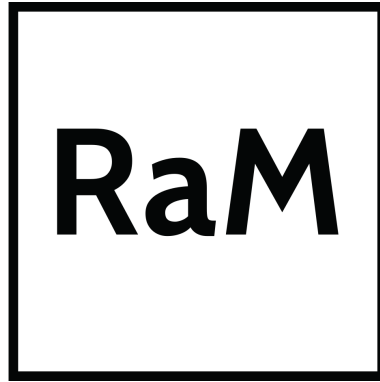


Futu RaM

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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October 19, 2023

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)

24 II. Executive Summary

25 This report presents the first phase of the scenario development process — the storyline
26 narrative phase. Three distinct future scenarios have been drafted up to the year 2050, Business
27 as usual, Recovery and Circularity. The scenarios are designed to be internally consistent and to
28 provide an overview of the potential future landscape of waste management and SRM recovery
29 within the EU. The scenario development process employs a methodology that integrates both
30 forecasting and backcasting techniques to construct a comprehensive, future-facing knowledge
31 base that can aid fact-based decision-making [5, 6, 7, 8, 9, 10].

32 **Scenario 1: Business as Usual (BAU)**

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

37 **Scenario 2: Recovery (REC)**

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

44 **Scenario 3: Circularity (CIR)**

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

50 In subsequent phases of the scenario development process, future product composition

51 and recovery technology will be examined, scenario elements will be quantified, and all scenario
52 data will be integrated and coupled with the quantitative models for waste generation and
53 SRM recovery.

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

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122 VI. Summary of scenario storylines

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

124 See section 2.1 for the full scenario description and waste-stream-specific scenario impact
125 narratives.

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

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

- 134 • A forecasting model is used to predict the future based on the current situation and the
135 development of existing trends.
- 136 • EU targets including those for eco-design, recycling and recovery are not met, and the
137 current linear model largely persists.
- 138 • Material demand remains coupled with economic growth, perpetuating a trend of in-
139 creasing consumption.
- 140 • Primary mining and extraction persist as the leading sources of raw materials, underlining
141 the dependency on traditional extraction methods.
- 142 • Recycling and recovery rates continue to lag, leading to increased production of SRM-
143 containing waste that signals missed opportunities for resource reuse.
- 144 • The EU's dependency on imports of SRMs escalates, heightening the risk of supply
145 disruptions [17].

- 146 • Investment in new SRM recovery technologies remains minimal, stifling innovation and
147 advancements in this field.
- 148 • The industrial focus remains on cost-effective material production and use, disregarding
149 the long-term sustainability aspect.
- 150 • Material scarcity and price fluctuations pose potential risks to the EU industry, highlighting
151 the vulnerability of this business model [18].
- 152 • Without any significant updates to environmental regulations, the negative impacts on
153 ecosystems and biodiversity intensify.
- 154 • Mining activity in the EU remains limited and concentrated in only a few member states.
155 Current exploration projects (e.g., for Lithium in PT, FR, UK and rare earths in SE) are not
156 realised.
- 157 • The transitions to renewable energy and e-mobility continue at their current pace.

158 **Scenario II: Recovery**

159 See section 2.2 for the full scenario description and the waste-stream-specific scenario impact
160 narratives.

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

167 **Key characteristics of this technology-promoted recovery scenario include:**

- 168 • This scenario uses a combination of forecasting and backcasting methods to envision
169 the future.

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

196 **Scenario III: Circularity**

197 See section 2.3 for the full scenario description and the waste-stream-specific scenario impact
198 narratives.

199 In this scenario, we move in the direction of the maximum achievable state of material
200 efficiency as government policy, private innovation and social changes are rapidly driving the
201 transition toward a circular economy. The emphasis here rests heavily on re-X strategies that
202 are implemented in the design phase of products (e.g., repairability and re-manufacturability)
203 and that are actualised by changes in consumer behaviour (e.g reduction, refusal, engagement
204 in the 'sharing economy' and curtailment of the 'throw-away' mindset). Further, being enabled
205 by the widespread adoption of 'circular design' principles and improvements in information
206 transparency (e.g., waste tracking and digital product passports) the system for the treatment
207 of post-consumer waste can divert a significant amount of their inflows (to, for example, re-
208 use and re-manufacture) with the residual fraction being readily segregated into purer, more
209 efficiently recoverable, material streams. This scenario envisions a future where government
210 policies are in synergy with private sector innovation and societal changes, driving a wholesale
211 transition towards a circular economy. Unlike the recovery scenario, where the focus is on
212 the end-of-life recovery of materials, this scenario emphasises minimising waste at all stages,
213 starting from the design phase itself.

214 **The circular economy scenario is characterised by the following:**

- 215 • This scenario uses a combination of forecasting and backcasting methods to envision
216 the future.
- 217 • The backcasting method is used for scenario factors that are covered by governmental
218 targets, starting with the desired outcome and working backwards to the present.
- 219 • The forecasting method is used for scenario factors that are not covered by governmental
220 targets, starting with the current situation and extending to the future.
- 221 • EU targets for recycling and recovery are met, as are those for circularity, due to advances
222 in waste management, ecodesign and re-X strategies.

- 223 • A circular economy is implemented, prioritising waste reduction, resource efficiency, and
224 a shift from the 'take-make-dispose' model.
- 225 • A notable increase in SRM recycling and recovery rates, indicating an efficient use of
226 resources.
- 227 • A larger emphasis on designing products for reuse and recycling, making waste a valuable
228 resource rather than a problem.
- 229 • More extensive use of renewable energy and clean technologies in SRM production and
230 use, supporting a low-carbon economy.
- 231 • Collaboration between stakeholders — including industry, government, and consumers —
232 improves, enhancing the implementation of circular practices.
- 233 • New business models like leasing and take-back schemes emerge, altering traditional
234 consumption patterns [19].
- 235 • Digitalisation and data use are heightened to improve efficiency and traceability, aiding
236 in effective resource management.
- 237 • Investment in research and development for circular economy technologies increases,
238 driving innovation and adoption.
- 239 • Awareness and education around sustainable consumption and production practices are
240 amplified, leading to behavioural changes in society.
- 241 • Reliance on imports decreases, suggesting greater self-sufficiency and sustainability.
- 242 • The creation of new jobs within the recycling, recovery and re-X sectors boosts the
243 economy and alleviates social inequality.
- 244 • Stricter waste regulations and product design guidelines are introduced, accelerating the
245 transition towards circularity.

VII. Acronyms

Table O.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

247 VIII. Terminology (abbreviated)

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

249 See section 5.1 for a complete list.

Table O.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 O.3: Milestone list

Milestone	Milestone name	WP	Due date	Resp. partner	Means of verification
MS11	Mapping of published scenarios and Story-line/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 O.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

254 **Chapter 1**

255 **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.

- 279 • Be regularly reviewed and updated to reflect evolving knowledge, technological advance-
280 ments, and policy developments.
- 281 • Be used as a tool for learning and exploration, encouraging dialogue and collaboration
282 among stakeholders.
- 283 • Inform policy and decision-making processes, providing insights into the potential con-
284 sequences of different choices and interventions.
- 285 • Be communicated effectively to a wide range of audiences, ensuring accessibility and
286 clarity of information.
- 287 • Contribute to the advancement of knowledge and understanding in the field of waste
288 management, resource recovery, and circular economy.

289 By adhering to these principles, the FutuRaM project aims to develop robust, informative,
290 and policy-relevant scenarios that support sustainable decision-making and contribute to the
291 transition towards a more circular and resource-efficient economy. The methodology ensures
292 that the scenarios capture the complexity and interconnectedness of the waste streams, taking
293 into account, where possible, factors such as legislation, technology, geopolitics, and societal
294 values. Ultimately, the goal is to provide decision-makers with valuable insights and tools to
295 navigate the challenges and opportunities associated with secondary raw materials in a rapidly
296 changing world.

297 1.2 Scenario storyline development process

298 Building scenarios involves several steps and methodologies, which can vary depending on the
299 specific context and objectives [5, 6, 7, 8, 20, 21, 22, 23]. The following section provides an
300 overview of the scenario development process used in FutuRaM. Figure 1.1 provides a visual
301 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.

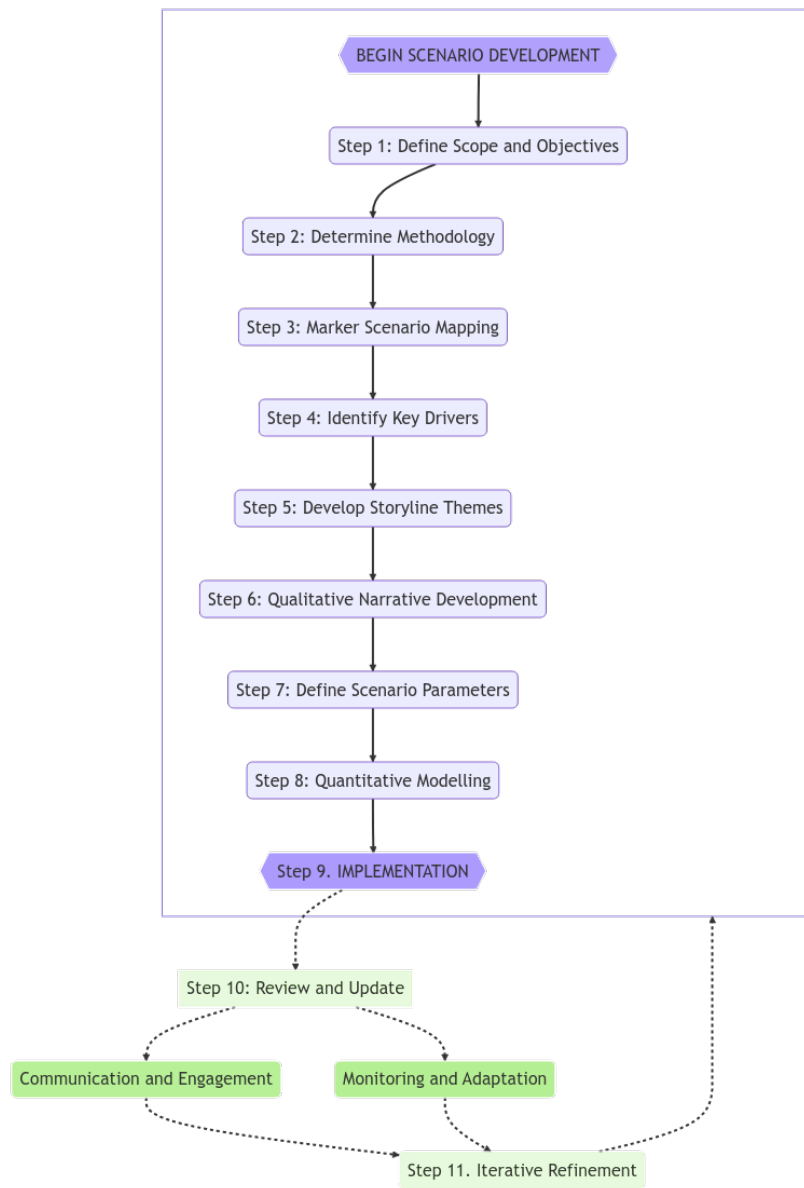


Figure 1.1: Scenario storyline development process

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

352 resolution, that of these scenarios will be determined based on the availability and quality of
353 data. It is important to acknowledge that providing too high a temporal resolution may lead
354 to a false sense of accuracy and precision. Furthermore, the scenarios will be developed with
355 the understanding that the further into the future we look, the more uncertain the predictions
356 become [7].

357 **Aims and objectives definition**

358 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

- 386 • Includes proposals for new legislation, such as an EU-wide framework for the circular
387 economy, and revisions to existing legislation, such as the WEEE Directive
- 388 • Emphasizes the importance of product design for the circular economy and proposes
389 measures to promote eco-design and repairability
- 390 • Includes initiatives to promote the use of secondary raw materials, such as the establish-
391 ment of a European Raw Materials Alliance
- 392 • Aims to reduce greenhouse gas emissions and improve resource efficiency in the EU
- 393 • Calls for increased cooperation and dialogue among stakeholders in the circular economy.

394 **The Critical Raw Materials Act (CRM act)** [2] is a proposed EU regulation that aims to
395 ensure a secure and sustainable supply of raw materials to the EU. The Act identifies a list
396 of strategic raw materials, which are crucial to technologies important to Europe's green and
397 digital ambitions and for defence and space applications, that are subject to potential supply
398 risks. The regulation will cover the entire raw materials value chain, from primary extraction to
399 manufacture to its potential recovery as a secondary raw material.

400 By 2030, one single 'third country' (ex-EU, ex-Schengen) country shall produce not more
401 than 65% of the EU's annual consumption of each strategic raw material. Clear benchmarks
402 have been set for the domestic capacities of the EU in 2030:

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

406 These benchmarks have been included in the scenarios developed in FutuRaM. Specifically,
407 in the Recovery scenario, where the emphasis is on the recovery of materials from waste
408 streams and the Circularity scenario where the emphasis is on the implementation of 're-X'
409 strategies, such as recycling, remanufacturing, and reuse. These benchmarks are considered
410 too optimistic to be included in the Business-as-usual scenario as they suggest near-complete
411 recovery for several elements.

412 Waste stream-specific legislation and policy targets

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

- 415 • BATT: Battery and waste battery regulation (2023) [25]
 - 416 – Establishes rules for the collection, treatment, and recycling of batteries and accu-
417 mulators in the EU
 - 418 – Requires Member States to set up collection and recycling systems for waste bat-
419 teries and accumulators
 - 420 – Sets specific recycling targets for different types of batteries and accumulators
 - 421 – Prohibits the use of certain hazardous substances in the manufacturing of batteries
422 and accumulators
 - 423 – Requires labelling and information for consumers on the proper disposal of batteries
424 and accumulators
 - 425 – Requires producers to take responsibility for the costs of collecting, treating, and
426 recycling waste batteries and accumulators
 - 427 – Aims to reduce the environmental impact of batteries and accumulators throughout
428 their life cycle.
- 429 • BATT: Introduction of battery passport in 2026 [26]
- 430 • Mandatory minimum levels of recycled content for industrial, and vehicle batteries.
- 431 • Batteries incorporated in appliances have to be removable and replaceable by 2027.
- 432 • ELV: Proposed revision currently under review [27]:
 - 433 – Sets out rules for the collection, treatment, and recycling of end-of-life vehicles
434 (ELV) in the EU
 - 435 – Requires Member States to set up collection systems for ELV and ensure that they
436 are treated and recycled in a more environmentally sound manner.

- 437 – Enforce collection targets, ban export of unroadworthy vehicles.
- 438 – Strengthen ‘Extended Producer Responsibility’ to encourage better quality waste
- 439 treatment.
- 440 – Proposes provisions for the design and dismantling of certain CRM-rich compo-
- 441 nents.
- 442 • WEEE Directive (about to be evaluated with a review likely in 2024):
 - 443 – Sets out rules for the collection, treatment, and recycling of waste electrical and
 - 444 electronic equipment (WEEE) in the EU
 - 445 – Requires Member States to establish collection systems for WEEE and ensure that
 - 446 it is treated and recycled in an environmentally sound manner
 - 447 – Sets collection and recycling targets for different types of WEEE
 - 448 – Requires producers to take responsibility for the costs of treating and recycling
 - 449 WEEE
 - 450 – Requires the use of the waste hierarchy for WEEE management
 - 451 – Aims to prevent the generation of WEEE and promote its reuse and recycling
 - 452 – Requires the labelling of electrical and electronic equipment to facilitate its proper
 - 453 disposal.
- 454 • CDW: Inside the CDW stream are important waste flows such as wind turbines and solar
- 455 panels. The permanent magnets in wind turbines are a source of rare earth elements
- 456 (REEs) and the solar panels contain indium and gallium. The CRM Act will also cover the
- 457 recycling of these waste flows.
- 458 • MIN: The CRM Act will also cover the mining waste stream. As stated by the European
- 459 Commission [\[4\]](#):

460 The act promotes the recovery of critical raw materials from mining waste. The

461 EU, due to its history of mining, has numerous old mining sites and tailings

462 across the EU which can contain precious critical raw materials, but whose

463 potential has not been analysed so far. The Act obliges current operators

464 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

493 either as product mass or product value), whether that product is a metal (e.g., a copper cathode),
494 metal alloy (e.g., aluminium alloy n° 5183) or metal product (e.g., cold rolled stainless steel
495 sheet).

496 Excepting the BAU storyline, WEEE, ELV, and BATT waste material recovery will follow the
497 targets in the EU. For SLASH and MIN, we will evaluate recent trends in waste generation and
498 extract plausible ranges of generation toward 2050. For CDW, embedded WEEE will follow
499 EU targets, and bulk waste will incorporate storylines and scenarios that are congruent with
500 predicted demolition rates (where renovation is the alternative emphasised in the CIR storyline)
501 Various drivers will be assigned to move between these ranges and will be key to the specific,
502 harmonized storyline for the scenario. Finally, the targets and storylines will be aligned with
503 assumptions on technology development.

504 **Consideration of geopolitical developments**

505 The storylines also attempt to consider geopolitical considerations and thus supply chain
506 resiliency for satisfying the product demand in the scenarios. We must omit, however, possible
507 changes in waste flow volumes and composition that could arise from any material supply
508 constraints. The reasoning for this is that it would needlessly confusate the interpretation
509 of the modelling results as the incertitude of these potentialities is very high and this realm
510 is outside the scope of FutuRaM's mandate and expertise. The most volatile aspect of the
511 'criticality calculation' is the risk profile of the producing country. For many material-exporting
512 nations, this is not something that can be reliably forecast, especially not over the next 30
513 years. Thus, it will be assumed that the growth in material demand for (among other needs) the
514 energy and mobility transitions can be satisfied either by an increase in mining and metallurgy
515 activities within the EU or by growing imports from raw material-producing countries outside
516 the EU. That is, if we go for increased domestic EU production to minimize geopolitical supply
517 risk, it may indicate more EU production residue generation even under increased production
518 efficiency and resource effectiveness. The increase of domestic industrial activity, as a response
519 to an envisioned increased internal demand, supposes an equivalent rise of societal approval
520 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.).

- 546 • **Transparency:** The methodology should be transparent and well-documented, allowing
547 for replication and further analysis.
- 548 • **Flexibility:** The methodology should be flexible and adaptable, allowing for updates and
549 adjustments as new information becomes available.
- 550 • **Accessibility:** The methodology should be accessible to a wide range of stakeholders,
551 ensuring that it can be understood and used by non-experts.
- 552 • **Effectiveness:** The methodology should be effective in achieving the objectives of the
553 scenario development process.
- 554 • **Efficiency:** The methodology should be efficient in terms of time, cost, and resources
555 required to implement it.
- 556 • **Acceptability:** The methodology should be acceptable to stakeholders, ensuring that it is
557 perceived as fair and legitimate.

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

561 **Choice of methodology**

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

566 **Considered dimension — Supply chain security:** Due to various political developments in
567 2022, the question of the security of the EU's supply chains for CRMs was brought into focus.
568 This led to the proposal from stakeholders to consider a scenario dimension that would explore
569 the security of the EU's supply chains for CRMs.

570 **Considered dimension — Energy transition:** The energy transition is a key topic in the
571 EU's policy agenda, and the FutuRaM project is concerned with the role of CRMs in the energy
572 transition. Therefore, the proposal was made to consider a scenario dimension that would
573 explore the energy transition in the EU.

574 **Method — Multi-criteria analysis and cross-impact analysis** In order to assess the potential
575 inclusion of these additional scenario dimensions, a multi-criteria analysis and a cross-impact
576 analysis were conducted [29]. The addition of extra dimensions increases the possible number
577 of scenarios significantly. By assessing the consistency and plausibility of these combina-
578 tions with a matrix-based method, it was possible to reduce the number of scenarios. For
579 example, low progress in the energy transition is unlikely to concur with high progress in re-
580 cycling/circularity indicators and can be excluded. In contrast, different levels for the supply
581 chain security dimension would result in an additional scenario, as this dimension is considered
582 independent of the others. Ultimately, supply chain security was eliminated as a scenario
583 dimension. This is due to the consortium's inability to speculate on geopolitical developments
584 and the added incertitude it would introduce to the scenarios. The potential of supply con-
585 straints will, however, be considered in the future sensitivity analysis of the model, as well
586 as potentially through an array of explorative multi-object optimisation procedures. This can
587 produce projects to answer the question, 'What would happen to the SRM system if element x
588 is constrained, and what would be the optimal response to this constraint?'

589 **Method — Delphi** The Delphi method [30] was used in the initial stages of the scenario-
590 building process to gather and aggregate the opinions of experts or stakeholders. Internal
591 consultation with consortium members who were experts in their respective waste streams
592 or other aspects of the recovery system was conducted. The method involves steps such as
593 the selection of experts, generation of initial questionnaires, iterative rounds of responses,
594 and convergence and consensus building. For the later stages of the process, further rounds
595 of consultation will be conducted with external stakeholders, including representatives from
596 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: Types of scenario (adapted from [6])

Scenario category	Scenario type	Quantitative/qualitative	Time-frame	System structure	Focus on internal or external factors
Predictive <i>what will happen?</i>	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 <i>what can happen?</i>	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 <i>how can a target be reached?</i>	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

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

643 • **BAU:**

644 *What will happen if current trends continue?*

645 This scenario is predictive in nature, based on the assumption that the current trends and
646 developments in waste management and resource recovery systems will continue into
647 the future.

648 • **Recovery:**

649 *What will it take to achieve the EU's targets for material use and recovery?*

650 *Focus on technology*

651 This scenario is normative, focusing on manipulating the technology and infrastructure
652 of the recovery system to achieve the EU's targets and mandates.

653 • **Circularity:**

654 *What will it take to achieve the EU's targets for material use and recovery?*

655 *Focus on re-X strategies*

656 This scenario is a combination of normative and explorative, considering the targets and
657 mandates of the EU's circular economy action plan and exploring re-X strategies in the
658 recovery system.

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

662 1.2.3 Step 3: Marker-scenario mapping

663 Justification and methodology

664 This preliminary step in the scenario development process involves conducting a literature
665 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

774 were deemed relevant, plausible, and influential were included in the storylines and
775 scenarios.

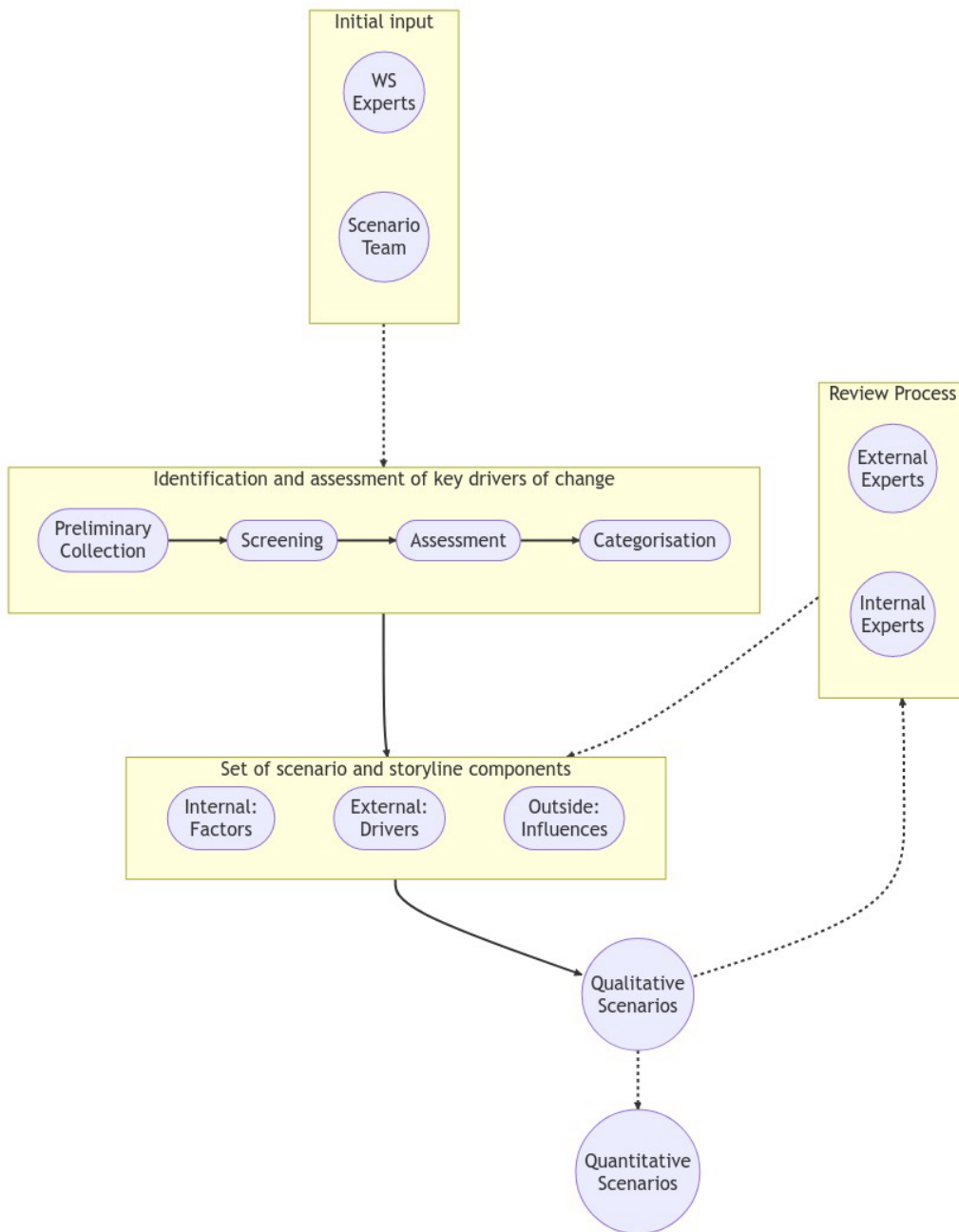


Figure 1.2: An illustration of the process used for identifying key drivers of change

THIS TABLE IS FOR THE ASSESSMENT OF THE RELEVANCE 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 exchange	CAT-II Screens	CAT-III Lamps	CAT-IVa Large equipments	CAT-IVb PV	CAT-V Small equipments
DRIVER/FACTOR														
Population				5.00	5.00	4.00	5.00	4.75	5.00	5.00	5.00	5.00	5.00	5.00
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	4.00
Treatment cost				4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
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	3.00
Obsolescence	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	4.00
Product prices				3.00	4.00	1.00	4.00	3.00	3.00	5.00	3.00	3.00	3.00	3.00
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	2.00
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	2.00
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	2.00
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	2.00
Availability of recovery technologies				3.00	3.00	0.00	3.00	2.25	1.00	4.00	1.00	1.00	4.00	4.00
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	2.00	2.00
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	2.00
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	1.00
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	1.00
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	2.00
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	1.00
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	2.00
Accessibility/Infrastructure			#DIV/0!	3.00	0.00	0.00	0.00	0.75	3.00	4.00	4.00	3.00	3.00	4.00
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	2.00
Miniaturisation	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	1.00
Reparability 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	3.00
Renewable energy targets				0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.00	0.00

Figure 1.3: An excerpt of a spreadsheet used as part of the screening process

776 3. Assessment

777 Once the screening process was complete, the remaining elements were aggregated and
778 categorised based on their thematic relevance or characteristics. This categorisation helps
779 organize the elements into meaningful groups or themes that align with the objectives
780 and scope of the scenarios.

781 The 21 elements that were identified in this stage are listed in Table 1.4. Note that CIR
782 and REC are very similar for many elements, the main difference being the way in which
783 the targets are achieved. That is, for CIR, re-X strategies are promoted, whereas, for REC,
784 the focus is on technological advancements in the recovery system. This distinction will
785 have a significant impact on how the scenarios are quantitatively modelled and on the
786 subsequent outcomes.

Table 1.4: List of drivers and factors identified in the screening phase

Domain	Driver/factor	Definition	Internal	BAU	REC	CIR
Recovery technology	TECH	Implementation and advancements in waste recovery technologies	TRUE	I	III	III
Product technology	TECH	Changes in product function or composition	TRUE	I	III	III
Integration of SRM system across EU	TECH	Integration of a secondary raw material recovery system across EU countries	TRUE	I	III	III
Increased drive for environmental protection	ENV	Growing concern and motivation for environmental conservation	TRUE	I	III	III
Progress toward renewable energy targets	ECO	Advancements and achievements in renewable energy generation	TRUE	III	III	III
Subsidies and taxation to promote circularity	ECO	Financial incentives or taxes to encourage circular economy	TRUE	I	II	II
Participation in re-X activities	SOC	Engagement in refuse-reduce-repair-reuse activities	TRUE	I	I	I
Stricter environmental regulations	POL	Tightening of environmental laws and regulations	TRUE	II	III	III
Stricter waste management regulations	POL	Strengthening of waste management laws and regulations	TRUE	II	III	III

Continued on next page

Table 1.4 — Continued from previous page

Domain	Driver/factor	Definition	Internal	BAU	REC	CIR
Supply chain due diligence laws: implementation and enforcement	POL	Obligations for identifying and mitigating negative impacts in supply chains	TRUE	O	III	III
Compliance with waste targets	POL	Meeting specific waste management and recycling targets	TRUE	O	III	III
Resource shortages	ENV	Limited availability of natural resources	FALSE	na	na	na
Raw material vs SRM prices	ECO	Price dynamics and competition between raw materials and secondary raw materials	FALSE	na	na	na
Climate change impactsmitigation	ENV	Effects and actions related to climate change	FALSE	na	na	na
International trade and co-operation (vs. autarky)	ECO	Collaborative trade agreements and global cooperation	FALSE	na	na	na
Energy prices	ECO	Costs and fluctuations in energy prices	FALSE	na	na	na
Economic growth	ECO	Overall economic expansion and development	FALSE	na	na	na
Re-industrialisation of EU	ECO	Shift towards increased industrial activities in the EU	FALSE	na	na	na

Continued on next page

Table 1.4 — Continued from previous page

Domain	Driver/factor	Definition	Internal	BAU	REC	CIR
NIMBY to projects	SOC	Opposition to local projects and developments	FALSE	na	na	na
Population and Urbanisation	SOC	Growth and urban development of population	FALSE	na	na	na
CO2 market price	ECO	Price and market dynamics of carbon emissions	FALSE	na	na	na

787 4. Categorisation

788 The scenario elements were then assessed based on their potential impact on the waste
789 management system. For each element, an assessment was made as to whether it was
790 within the scope of FutuRaM to include them as variables in the models, and therefore
791 also the scenarios and their storylines. Those deemed to be within the scope are 'internal'
792 and will be intensively researched and modelled (e.g., composition and design changes).
793 Those deemed to be outside the scope are 'external' and will be included in the storylines,
794 will vary over time, but will not vary across the three scenarios (e.g., population and
795 GPD). Those deemed to be outside the scope and also outside the influence of the
796 waste management system are 'outside' and will not be included in the storylines or
797 scenarios, though, in some cases, may be considered in the sensitivity analysis (e.g.,
798 supply constraints).

799 Justification for keeping elements outside of the scenario models:

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

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

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

818 Examples:**819 • Resource shortages:**

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

828 • Raw material vs SRM prices:

829 The dynamics and competition between raw materials and secondary raw materials
830 can be complex and influenced by various market factors, technological advancements
831 and policy interventions. As with resource shortages, these dynamics are challenging
832 to forecast accurately, making it difficult to include them within the model without
833 introducing significant uncertainty. It will, however, be possible to couple the model
834 with a market model to explore the effects of different price dynamics on the SRM
835 system's outcomes. This could be considered in a multi-objective optimisation procedure
836 performed as an extension to the model.

837 Conclusion

838 The methodology used for the FutuRaM scenario development ensured that the selected
839 elements were relevant, plausible, and influential. The use of the PESTEL analysis framework
840 and Delphi method during the preliminary collection phase provided a comprehensive overview
841 of the macro-environmental factors. Furthermore, the screening process and the assessment
842 by internal experts ensured that the selected elements were coherent, consistent, and aligned
843 with the objectives and scope of the scenario exercise. The final list of scenario elements is
844 suited to the goal of the FutuRaM project — to quantify the future availability of SRMs and to

845 evaluate EU material autonomy — and will be used to develop the three FutuRaM scenarios
846 into a quantitative model.

847 **1.2.5 Step 5: Develop storyline themes**

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

852 **1.2.6 Step 6: Qualitative narrative development**

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

858 **1.2.7 Step 7: Definition of scenario parameters**

859 The scenario parameters are the set of quantitative values or functions that will be used to
860 define the scenario inputs for the model. These parameters will be defined in the next stages
861 of the project.

862 **1.2.8 Step 8: Quantitative modelling**

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

864 1.2.9 Step 9: Implementation

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

866 1.2.10 Step 10: Review process

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

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

874 The second stage will involve opening the scenario development process to external stake-
875 holders and subject matter experts.

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

878 **Chapter 2**

879 **Scenario storylines**

880 2.1 Scenario 1: Business-as-usual

881 2.1.1 Storyline narrative

882 This scenario envisions the future based on the current situation, extending to 2050 with very
883 little deviation from present consumption patterns and the secondary raw material (SRM)
884 system [33]. While there may be advances in some areas such as resource efficiency, recovery
885 technology, and the energy transition, substantial modifications remain hindered by economic,
886 social, and political constraints. The primary extraction of raw materials continues to be the
887 primary source to meet the EU's demand.

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

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

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

907 exacerbating the resource pressure.

908 Moreover, the environmental impacts of mining and extraction persist as a significant
909 concern. These operations continue to degrade ecosystems, leading to loss of biodiversity and
910 contributing to climate change [34]. Simultaneously, the EU becomes increasingly dependent
911 on imports of SRMs, raising concerns about supply chain security and geopolitical risks [34].

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

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

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

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

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

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

941 2.1.2 Waste stream specific scenario impacts

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

943 In the business-as-usual (BAU) scenario, the management of end-of-life batteries remains
944 largely unchanged. The lack of technological innovation and regulatory incentives leads to a
945 continued low recovery rate of valuable materials from battery waste.

- 946 • A growing volume of battery waste due to the increased use of electronic transport and
947 renewable energy storage systems.
- 948 • Lack of technological innovation and regulatory incentives lead to low recovery rates for
949 certain battery types and certain elements.
- 950 • Collection systems for battery waste remain sporadic and unstandardised.
- 951 • Primary extraction remains the dominant source of battery materials.
- 952 • Share of LIB will increase (EV, LMT, Industrial LIB uptake)
- 953 • LIB Battery Chemistries will change and new LIB technologies will enter the market.
954 Though, not with a focus on recycling and recovery.
- 955 • Larger portable batteries: shift towards Li-ion batteries
- 956 • Small format batteries in EEE: no significant change in battery chemistry.

- 957 • Use of critical resources continues but is already decreasing (BATT chemistry already
958 changing towards less CRM content)
- 959 • Large-scale reuse of batteries is minimal
- 960 • Collection rates do not fulfil the EU targets
- 961 • Recycling efficiencies do not fulfil the EU targets
- 962 • Recovery rates do not fulfil the EU targets

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

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

- 967 • Legislation banning new ICEVs from 2035
- 968 • Current recovery technologies are unable to significantly improve the extraction of
969 valuable materials from ELVs.
- 970 • Consumer demand continues to drive high production of new vehicles.
- 971 • ELV collection systems remain at their current efficiency.
- 972 • A significant proportion of vehicle components continue to end up as waste.
- 973 • Gradual and slow improvement of recycling chain technology efficiency
- 974 • No new legislation to improve recovery and support circular strategies in comparison to
975 2023

976 **WEEE (Waste Electrical and Electronic Equipment) [37, 38, 39, 40, 41]**

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

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

995 **Mining waste (MIN)**

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

- 999 • Limited technological advancements lead to static recovery rates of valuable materials
- 1000 from mining waste.
- 1001 • Continued reliance on primary extraction as the dominant source of raw materials.
- 1002 • Minimal advances in collaboration between government and industry for mining waste
- 1003 recovery.

- 1004 • Low levels of traceability and management of mining waste.
- 1005 • Mining waste remains a significant environmental challenge.
- 1006 • Mining waste recovery projects remain too expensive.
- 1007 • Little incentive for the private sector and public sector, except for monitoring environ-
- 1008 mental risks of existing deposits.

1009 **CDW (Construction and Demolition Waste) [42]**

1010 In the BAU scenario, the management of Construction and Demolition Waste (CDW)
 1011 remains largely unchanged. Lack of progress in recovery technologies and regulatory incentives
 1012 will lead to low recovery rates of CRM-containing materials from CDW.

- 1013 • Base metals are recovered as they have been [43], though there are limited improvements
 1014 and no particular focus on the recovery of CRMs from CDW.
- 1015 • Continued generation of CDW due to the demand in the construction sector.
- 1016 • Renovation as an alternative to new construction is not widely adopted.
- 1017 • The majority of CDW (excluding base metals) continues to be treated as waste or backfill,
 1018 with low recycling rates.
- 1019 • CDW recovery (including preparation for re-use, recycling and other material recovery,
 1020 including backfilling)
- 1021 • Recovery of metals remains on already high levels (>90%)
- 1022 • Recovery of minerals remains on already high levels (>70%) by using them as aggregates
 1023 in road construction and backfilling
- 1024 • Recycling of wind turbines stays around 85% (mainly metals), permanent magnets
 1025 continue to be recycled as part of the metal fractions

1026 **SLASH (Slags and Ashes)**

1027 In the BAU scenario, SLASH continues to be treated generally as low or negative-value
 1028 waste. The absence of economically profitable recovery technologies or regulatory mandates
 1029 leads to low improvements in the recovery rates of CRMs from SLASH.

- 1030 • Increased generation of SLASH because SRMs are not recovered and end up in incinera-
 1031 tion and smelter residues.
- 1032 • Low quality of SLASH due to:
 - 1033 – poor sorting and separation of waste streams (e.g., consumer electronics and bat-
 1034 teries, end up in general waste streams and are incinerated)
 - 1035 – high 'contamination' from the above-described failures of segregation.
 - 1036 – large proportion coming from mixed waste incineration
- 1037 • Lack of technological advancements results in low recovery rates of valuable materials
 1038 from SLASH.
- 1039 • Continued high generation of SLASH due to the reliance on traditional energy sources.
- 1040 • Minimal incentives for the recovery and reuse of materials from SLASH.
- 1041 • Low levels of traceability and management of SLASH.
- 1042 • SLASH continues to be a significant environmental challenge due to the high volume
 1043 generated.
- 1044 • Some products from SLASH are recovered in low added value, for example, as aggregates
 1045 for roads or additives in cement.

1046 2.2 Scenario 2: Recovery

1047 2.2.1 Storyline narrative

1048 In the recovery scenario, the central emphasis is on harnessing sophisticated technologies to
 1049 salvage SRMs from waste streams at the end of their lifecycle. While there are noticeable strides

1050 towards the incorporation of 'circular design' principles and re-X strategies, they are mostly
1051 seen at the end-of-life and material demand is akin to that observed in the BAU scenario. This
1052 is, however, mitigated by the implementation of a comprehensive material recovery system.

1053 In this scenario, the central actor is the waste treatment sector, with the spotlight falling on
1054 the enhancement of recovery technology. The implementation and optimisation of cutting-
1055 edge technologies, such as Artificial Intelligence (AI), automation, and advanced robotics, play
1056 a significant role in revolutionising waste treatment processes. These technologies streamline
1057 waste sorting, improve the quality of recovered materials, and increase the overall efficiency of
1058 the recovery process.

1059 This scenario calls for an emphasis on policy development and standardisation to foster
1060 EU-wide development, integration, and compliance. Here, the role of governments and policy-
1061 makers becomes crucial in setting more ambitious recovery targets, developing conducive
1062 regulatory frameworks, and enforcing compliance. This multi-pronged approach also involves
1063 strengthening cross-border cooperation, harmonising waste management standards, and
1064 promoting knowledge and technology transfer among EU member states.

1065 To realise more ambitious environmental impact reduction targets, significant progress
1066 needs to be made in both technological and policy aspects. Enhancing technological capabilities
1067 will improve recovery rates, while robust policy measures will ensure these advancements are
1068 integrated into the wider economy in a regulated manner. The future of this scenario depends
1069 on the successful fusion of advanced technology, regulatory harmonisation, and a commitment
1070 to continuous improvement in waste management and SRM recovery.

1071 Key characteristics of this technology-promoted recovery scenario include:

- 1072 • This scenario uses a combination of forecasting and backcasting methods to envision
1073 the future.
- 1074 • The backcasting method is used for scenario factors that are covered by governmental
1075 targets, starting with the desired outcome and working backwards to the present.
- 1076 • The forecasting method is used for scenario factors that are not covered by governmental
1077 targets, starting with the current situation and extending to the future.

- 1078 • EU targets for recycling and recovery are met, due to the EU's waste management system
1079 becoming more expansive, efficient and effective.
- 1080 • Technological innovation drives increased recovery rates of SRMs, enabling the more
1081 efficient use of waste.
- 1082 • Digitalisation and automation are more extensively used in recycling processes, leading
1083 to enhanced productivity and accuracy.
- 1084 • There is greater exploration and exploitation of alternative sources such as urban mining,
1085 waste streams, and tailings, presenting novel opportunities for resource acquisition.
- 1086 • New waste regulations and guidelines for SRM recovery are implemented, enforcing
1087 better management and extraction of SRMs.
- 1088 • Investment in research and development for SRM recovery technologies experiences an
1089 upswing, promoting continuous innovation in this field.
- 1090 • Closer collaboration and information sharing between industry and government institu-
1091 tions streamline processes and expedite decision-making.
- 1092 • New jobs are created in the recycling and recovery sector, offering economic benefits
1093 and improving overall employment rates.
- 1094 • SRM production and use become more efficient and cost-effective, fostering economic
1095 sustainability.
- 1096 • Environmental impact from mining and extraction is reduced, signalling a more sustain-
1097 able approach to resource acquisition.
- 1098 • The EU's dependence on primary extraction is reduced, with SRM recovery becoming a
1099 more significant source of raw materials.

1100 2.2.2 Waste stream specific scenario impacts

1101 BATT (Battery waste) [11, 12, 25, 26]

1102 Under the recovery scenario, end-of-life batteries become a crucial source of secondary raw
1103 materials, primarily due to the increased adoption of electric vehicles and renewable energy
1104 storage systems. Technological innovation drives the recovery and recycling process, ensuring
1105 valuable materials are extracted from waste batteries for reuse.

- 1106 • Increase in end-of-life batteries due to the growth of electric vehicles and renewable
1107 energy storage.
- 1108 • Advanced recovery technologies facilitate the efficient extraction of valuable materials
1109 from battery waste.
- 1110 • Standardised collection systems enhance the quantity and quality of battery waste
1111 available for recovery.
- 1112 • Industry and government collaboration lead to investments in research and development
1113 of battery recovery technologies.
- 1114 • Battery passports have a strong impact on collection, material recovery rates and recycling
1115 rates.
- 1116 • Collection
 - 1117 – Portable battery collection increases according to the trend seen in the WEEE waste
1118 stream.
 - 1119 – Improved collection of light means of transport (LMT) batteries.
 - 1120 – Improved regulation and collection of Industrial batteries.
- 1121 • Material recovery
 - 1122 – Improved recycling technologies
 - 1123 – Battery Pass will improve material recovery
 - 1124 – Higher recovery rate for lithium
 - 1125 – Increase in recycling by average weight
 - 1126 – Recycling of plastics
- 1127 • Ambitious goals of recycling/recovery rates compete with reuse, so reuse remains low.

- 1128 • Improved public awareness means that fewer batteries end up in the municipal waste
1129 stream and there is less hoarding.
- 1130 • Against this: there is competition for the batteries from the reuse vs. recycling market.
- 1131 • Design for recycling (DFR):
 - 1132 – Material and composition selection for recycling [12].
 - 1133 – Higher requirements on disassemblability.
 - 1134 – Information available to promote efficient recovery.

1135 **ELV (End-of-Life Vehicles) [12, 27, 35, 36]**

1136 The recovery scenario envisions a more effective and technology-driven end-of-life vehicle
1137 treatment process. Advancements in recovery technologies allow for improved extraction of
1138 valuable materials from vehicles at their end of life, although consumerism still drives high
1139 demand for new vehicles.

- 1140 • Innovations in recovery technologies allow for a higher recovery rate of CRM-containing
1141 materials from ELVs.
- 1142 • The total number of vehicles produced remains high due to consumer demand.
- 1143 • Improved systems for ELV collection are established, ensuring efficient management of
1144 ELV waste.
- 1145 • Increased collaboration between the government and industry leads to investments in
1146 ELV recovery technologies.
- 1147 • Focus on managing end-of-life of vehicles
- 1148 • EU recovery targets are reached (currently implemented/proposed targets, but also
1149 increased and new targets)
- 1150 • Common/bulk materials (Fe, Non-Fe, plastics etc.) and precious metals (Au, Ag, Pd, Pt)
1151 reach high mass recycling rates and high element recycling rates. Other CRMs currently
1152 not recovered reach a moderate level of recovery.

- 1153 • For instance,
- 1154 – More advanced dismantling and processing steps (e.g., components and materials)
- 1155 – More specialised recovery of certain components and materials (e.g., electric motors
- 1156 including permanent magnets and embedded REE) as suggested in the proposal
- 1157 for a revised ELV directive.
- 1158 – More public and private interest in developing recycling chains
- 1159 – Increase in collection rate due to increase in participation from the public and
- 1160 businesses, i.e., target-based incentives with strong regulations and monitoring
- 1161 • Design for recycling (DFR):
- 1162 – Higher requirements on ‘disassemblability’.
- 1163 – Information available to enable recovery.

1164 **WEEE (Waste Electrical and Electronic Equipment) [37, 38, 39, 40, 41]**

1165 Under the recovery scenario, WEEE becomes a significant resource for secondary raw
 1166 materials. Technological advancements in the sector improve the efficiency of WEEE treatment,
 1167 although the consumerism-driven demand for new electronics remains high.

- 1168 • Advanced technologies enable higher recovery rates of valuable materials from WEEE
- 1169 • Despite advancements in design for recyclability, WEEE generation remains high due to
- 1170 the consumer demand for new electronics
- 1171 • Standardised and segregated collection systems for WEEE are implemented, improving
- 1172 the supply of materials for recovery
- 1173 • Increased industry-government collaboration leads to further development in WEEE
- 1174 recovery technologies
- 1175 • Consumer behaviour remains a significant hurdle for more efficient WEEE management
- 1176 • Higher recycling rate — make full use of the disposed parts. For instance:

- 1177 – more automation of the dismantling and processing steps (e.g., AI)
- 1178 – recycling technologies improvements (e.g., small components recovery is also
- 1179 happening)
- 1180 – more effective collection infrastructure
- 1181 – financial support provided to recyclers/operators
- 1182 – bans on WEEE exports push for increased domestic recycling [44]
- 1183 • 'Design for recovery' principle — Ecodesign mandates changes in weight and composition
- 1184 of EEE so complexity and the type of materials used
- 1185 • Higher public awareness and participation on WEEE issue and management
- 1186 • Higher compliance from the public, the producers and the businesses
- 1187 • Strong regulations and monitoring are in place with higher collection and recycling targets
- 1188 which are set and implemented and fines are set for those who fail to achieve the targets
- 1189 • Focus is given more to the EoL management of WEEE

1190 **Mining waste (MIN)**

1191 Under the recovery scenario, technological advancements enable the extraction of residual
1192 valuable materials from mining waste, transforming it into a valuable resource.

- 1193 • Technological advancements facilitate the extraction of valuable materials from mining
- 1194 waste.
- 1195 • Despite progress in recovery technologies, primary extraction remains the dominant
- 1196 source of raw materials due to high consumer demand.
- 1197 • Government and industry collaboration support the development of technologies for
- 1198 the recovery of materials from mining waste.
- 1199 • Increased traceability and management of mining waste through digitalisation.
- 1200 • 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.

1226 SLASH (Slags and Ashes)

1227 In the recovery scenario, SLASH are recognized as a potential resource for secondary raw
1228 materials. Advances in recovery technologies enable the extraction of valuable metals from
1229 SLASH, however, the total volume of CRMs recovered from this material remains low, except
1230 in cases of supply constraint.

- 1231 • Advanced recovery technologies allow for the extraction of valuable metals and minerals
1232 from SLASH.
- 1233 • Despite improvements in energy production, SLASH generation remains significant due
1234 to the continued reliance on traditional energy sources.
- 1235 • New regulations incentivize the recovery and reuse of materials from SLASH.
- 1236 • Digital solutions enhance the traceability and management of SLASH.
- 1237 • SLASH remains a significant environmental challenge due to the volume generated.
- 1238 • Transferring down-cycling to recycling or even upcycling.
- 1239 • Recycling technology improvements (e.g., cement additives using biomass ash are under
1240 investigation)
- 1241 • More functional collection infrastructure.
- 1242 • Financial support provided to recyclers/operators.
- 1243 • Introduction of SRM/CRM recovery targets. For example, recovery of P from biomass
1244 ash for fertilizer. Recovery of Zn and Pb from Zn and Pb smelter slag.
- 1245 • Higher awareness and participation of relevant sectors on SLASH issues and manage-
1246 ment.
- 1247 • Strong regulations and monitoring are in place with higher collection and recycling targets.

1248 2.3 Scenario 3: Circularity

1249 2.3.1 Storyline narrative

1250 In this scenario, we move in the direction of the maximum achievable state of material ef-
1251 ficiency as government policy, private innovation and social changes are rapidly driving the
1252 transition toward a circular economy. The emphasis here rests heavily on re-X strategies that
1253 are implemented in the design phase of products (e.g., repairability and re-manufacturability)
1254 and that are actualised by changes in consumer behaviour (e.g reduction, refusal, engagement
1255 in the 'sharing economy' and curtailment of the 'throw-away' mindset). Further, being enabled
1256 by the widespread adoption of 'circular design' principles and improvements in information
1257 transparency (e.g., waste tracking and digital product passports) the system for the treatment
1258 of post-consumer waste can divert a significant amount of their inflows (to, for example, re-
1259 use and re-manufacture) with the residual fraction being readily segregated into purer, more
1260 efficiently recoverable, material streams. This scenario envisions a future where government
1261 policies are in synergy with private sector innovation and societal changes, driving a wholesale
1262 transition towards a circular economy. Unlike the recovery scenario, where the focus is on
1263 the end-of-life recovery of materials, this scenario emphasises minimising waste at all stages,
1264 starting from the design phase itself.

1265 The emphasis is on re-X strategies that are integrated right from the product design stage.
1266 This includes repairability, where products are designed to be easily fixed rather than replaced;
1267 and re-manufacturability, where products or their components are designed to be restored
1268 to their original state, extending their lifespan and reducing the need for new resources. This
1269 scenario calls for a drastic change in consumer behaviour, where reduction in consumption
1270 and waste, refusal of non-sustainable options, and active participation in the 'sharing economy'
1271 become the norm rather than the exception.

1272 In the circularity scenario, the widespread adoption of 'circular design' principles becomes a
1273 cornerstone of production. In a circular design approach, products are designed and produced
1274 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.

- 1299 • Battery passport and publicly accessible Information from the new Battery Regulation
1300 (SoH, SoC, Predicted lifetime/warranty, etc.) given by the economic operator that places
1301 the battery on the market enables high re-use rates.
- 1302 • Increased repairability/modularity.
- 1303 • Reduced demand from 'sharing economy' and more 'sustainable' transport choices.
- 1304 • New emerging technologies more suited for reuse/repair.
- 1305 • Ambitious targets set by business and public policy.

1306 **ELV (End-of-Life Vehicles) [12, 27, 35, 36]**

1307 For End-of-Life Vehicles (ELVs), the circular economy model affects the way vehicles
1308 are designed, used, and discarded. Emphasising extended vehicle life through repair and
1309 remanufacturing, this scenario also focuses on the recovery of materials from vehicles at the
1310 end of their life.

- 1311 • Vehicle design shifts towards repairability, upgradability, and recyclability, increasing the
1312 lifespan of vehicles.
- 1313 • Standardised systems for ELV collection are established, ensuring efficient waste man-
1314 agement.
- 1315 • Innovative technologies enable higher recovery rates of metals and other valuable mate-
1316 rials from ELVs.
- 1317 • Service-based models like vehicle leasing and sharing could reduce the total number of
1318 vehicles produced.
- 1319 • Digital product passports provide information about vehicle components, aiding in effec-
1320 tive recycling or reuse.
- 1321 • Focus on managing the use-phase of vehicles.
- 1322 • Circular strategies take place before material recovery so that material recovery is “de-
1323 layed”.

- 1324 • Information available to enable these strategies.
- 1325 • EU vehicles policy has implications for materials in vehicles, such as 'lightweighting' and
- 1326 downsizing
 - 1327 – Increase in average occupancy and average vehicle-kilometres per trip.
 - 1328 – Decrease in average lifetime (in terms of years): As the utilisation factor increases.
- 1329 • Increase in circular strategies due to an increase in participation from the public and
- 1330 businesses, i.e., target-based incentives with strong regulations and monitoring.

1331 **WEEE (Waste Electrical and Electronic Equipment) [37, 38, 39, 40, 41]**

1332 In the circularity scenario, WEEE becomes a valuable resource instead of a disposal challenge.
 1333 Thanks to product design changes and the application of advanced recovery technologies, a
 1334 significant percentage of the materials in WEEE is reclaimed and fed back into the production
 1335 cycle.

- 1336 • Electronic products are designed for longevity, repairability, upgradability, and recyclabil-
 1337 ity.
- 1338 • Advanced technologies enable higher recovery rates of precious metals from WEEE.
- 1339 • Collection systems for WEEE are improved, ensuring a steady supply of materials to feed
 1340 the recovery system.
- 1341 • Digitalisation and data use enhance traceability and efficiency in WEEE management.
- 1342 • Service-based models for electronics promote the use of products as a service rather
 1343 than ownership, reducing WEEE generation [19].
- 1344 • Increased durability and lifespans.
- 1345 • Increased repairability.
- 1346 • More sharing and product-service systems, correspond to a reduction in the lifetime (for
 1347 some equipment).

- 1348 • More reuse practices (expanded second-hand market).
- 1349 • Less hoarding.
- 1350 • Higher formal collection and recycling rate.
- 1351 • Focus is given more to the production and use phase rather than the EoL (End-of-Life).
- 1352 • 'Design for circularity' principle: Ecodesign mandates repairability, durability, no obsoles-
- 1353 cence, modularity, and that continual software upgrades are possible [45, 46].
- 1354 • Electronically compatible chargers and battery packs can be used by different products.
- 1355 • The above also means that chargers and batteries are not integrated into the product
- 1356 and that the product is designed to be easily disassembled.
- 1357 • Strong regulations and monitoring are in place with higher reuse and circular targets,
- 1358 which are set and implemented, and fines are imposed on the member states that fail to
- 1359 achieve the targets.
- 1360 • Support and development of circular strategies infrastructure (e.g., easy information
- 1361 access for repairability, repair shops, accessibility to spare components on the market,
- 1362 etc.).
- 1363 • Greater use of connected products, smart technologies, and the IoT. Used to monitor
- 1364 and diagnose product performance in situ which, can extend product and component
- 1365 life.

1366 **Mining waste (MIN)**

1367 In this scenario, the impact on mining waste is two-fold. Firstly, the need for primary mining
1368 is reduced due to efficient resource use and high recovery rates of materials. Secondly, mining
1369 waste itself is treated as a valuable resource, with advanced technologies being used to extract
1370 residual valuable materials.

- 1371 • A Decrease in primary mining reduces the generation of mining waste.
- 1372 • Advanced technologies are employed to extract valuable materials from mining waste.

- 1373 • Policies and regulations incentivise the reuse of mining waste in various applications.
- 1374 • Digital solutions improve tracking and management of mining waste.
- 1375 • Collaboration between stakeholders promotes circular practices in the mining industry.

1376 **CDW (Construction and Demolition Waste) [42]**

1377 Construction and Demolition Waste (CDW) is another sector that sees significant improve-
1378 ment in the circularity scenario. Emphasising design for disassembly and the use of recyclable
1379 materials, this scenario drastically reduces the generation of CDW and promotes the recovery
1380 of valuable materials from the waste stream.

- 1381 • Buildings are designed for disassembly, increasing the lifespan of materials and reducing
1382 CDW.
- 1383 • Recycling technologies for CDW improve, allowing higher recovery rates of materials.
- 1384 • Policies and regulations incentivise the use of recycled materials in construction.
- 1385 • Standardised systems for CDW collection and separation are established.
- 1386 • Digital tools like building information modelling (BIM) improve resource management in
1387 construction.
- 1388 • This scenario envisions an almost closed-loop system where CDW is considered a re-
1389 source, with an emphasis on minimising waste generation and maximising resource
1390 efficiency in recovery.
- 1391 • Waste reduction is prioritized through the implementation of eco-designs, including
1392 designing out waste (DOW), lightweight design (LWD), and design for dismantling (DFD).
- 1393 • Reuse and repair standards and networks are established to boost the reuse of end-of-life
1394 building components and equipment.
- 1395 • If reuse is no longer possible, waste is recycled through high-efficiency recycling facilities
1396 rather than down-cycled or used for energy recovery.

- 1397 • This scenario is characterized by meeting all material needs through recovery (including
1398 mineral wastes from other industries) with high material efficiency achieved through the
1399 development of new business models, advanced designs and recycling technologies,
1400 strict waste management regulations, and innovative products and services.
- 1401 • Plausible target: Achieving a 100% recovery rate of avoidable CDW by 2050, with a
1402 recycling rate accounting for 30% and component reuse accounting for 20%. Raw
1403 material consumption should be reduced by 50% compared to the 2020 level.
- 1404 • Example of treatment technological development: Waste concrete is primarily recy-
1405 cled through an innovative mobile dry process. Biodiesel-based thermal treatment is
1406 applied to further pyrolyze the fine aggregate to recover cement. Lightweight design is
1407 implemented to reduce concrete use.

1408 **SLASH (Slags and Ashes)**

1409 In the circularity scenario, the approach to SLASH dramatically changes. Instead of being
1410 treated as waste, SLASH is seen as a valuable secondary raw material. Advances in technology
1411 allow for the extraction of valuable metals and minerals from SLASH, that then re-enter the
1412 material cycle.

- 1413 • A shift in perception treats SLASH as a valuable resource instead of waste.
- 1414 • Advanced technologies enable the extraction of valuable metals and minerals from
1415 SLASH.
- 1416 • New regulations incentivise the use of SLASH in various applications, such as in the
1417 construction industry.
- 1418 • Digital solutions enhance the tracking and management of SLASH.
- 1419 • Collaboration between industries utilises SLASH in new and innovative ways.
- 1420 • Reduce the generation of SLASH by increasing the efficiency of the manufacturing side.
1421 For example, developing higher efficient production of metals and reducing by-products
1422 such as smelter slag. For ash from the incineration of solid biomass, maximizing the use

- 1423 of biomass by setting proper temperature, time, and furnace conditions to reduce ash
1424 contents and improve the efficiency of power and heat generation. For ash, developing
1425 other renewable technologies from bioenergy to reduce the incineration of solid biomass,
1426 e.g., biogas.
- 1427 • Reduce the generation of SLASH by increasing the proportion of higher calorific waste
1428 and decreasing lower calorific waste, e.g., MSW (Municipal Solid Waste).
 - 1429 • Developing domestic feedstock supply for bioenergy or metal production to reduce the
1430 cost of transportation and others.
 - 1431 • Higher formal collection and recycling rate compared to BAU, but lower compared to
1432 the Recovery scenario.

1433 Chapter 3

1434 Quantification

1435

To be completed in the next stages of the project.

1436 **Chapter 4**

1437 **References**

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1585 **Chapter 5**

1586 **Appendices**

1587 5.1 Terminology

1588 The following is a suggested terminology for use in our discussions and reports related to
1589 scenarios.

1590 This glossary is modelled on that used by [\[22\]](#). Some additional definitions were sourced
1591 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

1592 **5.2 Scenario development methods**

1593 The following table provides an overview of the methods and tools considered, along with a
1594 brief description of each and its relevance to the specific context and objectives of the FutuRaM
1595 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

1596 **5.3 Marker scenario mapping**

1597 The following table presents an overview of the marker scenarios considered in the FutuRaM
1598 project. The table is not intended to be exhaustive, but rather to provide an overview of the
1599 different scenarios that have been developed in the field of waste management, resource
1600 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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Table 5.3 — Continued from previous page

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

1601 **5.4 Drivers and factors identified in the initial collection phase**

1602 The following table lists the elements that were identified in the initial phase of driver/factor
1603 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

1604 5.5 Drivers and factors identified in the screening phase

1605 The following table lists the scenario elements that were identified in the screening phase of
1606 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