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Sustainability Spotlight Statement

View Article Online
DOI: 10.1039/D5SU00930H

Emerging technologies often lack effective tools for early-stage environmental and health assessment, risking unsustainable design choices. Addressing this gap is crucial, as early decisions can lock in negative impacts. The Life Cycle-Based Risk and Opportunity Mapping (LCBROM) method enables transparent, collaborative evaluation of innovations at low technology readiness levels, systematically identifying both risks and opportunities across all life cycle stages. By fostering dialogue among stakeholders and highlighting critical hotspots, LCBROM guides safer, more sustainable innovation trajectories. Its ease of use, broad applicability, and low resource demand make it a valuable pre-assessment tool, supporting the EU's Safe and Sustainable by Design (SSbD) framework and advancing responsible environmental decision-making in technology development.



Life Cycle Based Risk and Opportunity Mapping: A systematic collaborative procedure to integrate environmental and health aspects in early innovation as possible scoping and pre-screening to the safe and sustainable by design (SSbD) assessments

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1

2 **Key words:** Safe and sustainable early innovations, Safe and Sustainable by Design (SSbD)
3 pre-assessment, SSbD scoping, Hotspot analysis, LCA dialogue, Sustainable innovation,
4 Life cycle based opportunity mapping, Life cycle thinking

5

6

7 **Abstract**

8 This article presents a method for life cycle based evaluation of early-stage innovations,
9 addressing the lack of tools for assessing environmental aspects of emerging technologies.
10 The approach supports the development of clean technologies, chemicals, and materials by
11 fostering dialogue between inventors and evaluators through information exchange and
12 preliminary assessments, even when data is uncertain. Aligned with the EU Chemicals
13 Strategy for Sustainability under the European Green Deal, the Joint Research Center (JRC)
14 introduced a framework for Safe and Sustainable by Design (SSbD) chemicals and
15 materials, emphasizing application during early innovation stages when design choices can
16 still be influenced. The proposed method, Life Cycle Based Risk and Opportunity Mapping
17 (LCBROM), can be applied initially in an SSbD assessment to serve as scoping analysis and
18 be revisited during the further stages of the SSbD process, promoting transparency and
19 knowledge sharing among involved parties. Tested in four case studies focused on
20 developing smart, safe materials and devices for clean air and water, LCBROM revealed
21 that opportunity mapping is essential for engaging innovators but requires a benchmark
22 technology or defined consequences of inaction; several screening methods exist for
23 emerging technologies, yet none are widely adopted; and LCBROM meets four critical
24 criteria for low-TRL tools: ease of use, inclusion of all relevant impacts, broad applicability,
25 and low cost. The method enhances communication between developers, problem owners,
26 and experts, improving mutual understanding, and continues to be refined and validated in
27 ongoing research programs.

28 **Introduction**

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29 In early innovation, there are typically challenges addressing all design principles and
30 considering various stakeholders with different interests. A well-known problem in
31 technology assessment is linked to what is known as the “Collingridge dilemma” - many
32 impacts of new technologies on society are initially not fully understood and also not fully
33 determined. Decisions that are taken during an innovation process are based on current
34 knowledge and assumptions and lead to commitments and investments, which also means
35 that once a trajectory is chosen, many options can no longer be pursued, due to, among
36 others, lack of remaining funding. A review of Collingridge’s approach and subsequent
37 research on responsible innovation points out that a main contribution remains the more
38 transparent and explicit analysis of conditions during an innovation process. Qualities to
39 address challenges are among others inclusion, openness, incrementalism, flexibility and
40 reversibility¹. Collingridge addresses large scale developments that involve many different
41 stakeholder groups including society in general. Based on similar prerequisites with focus
42 on involved parties, the (eco-) design paradox acknowledges a lack of information during
43 early stages and lack of options to change and improve design, mostly related to costs.² As a
44 response to the need to collect information and knowledge about data gaps in early
45 innovation, we suggest the use of Life Cycle based Risk and Opportunity Mapping
46 (LCBROM), conceptually illustrated in Figure 1.

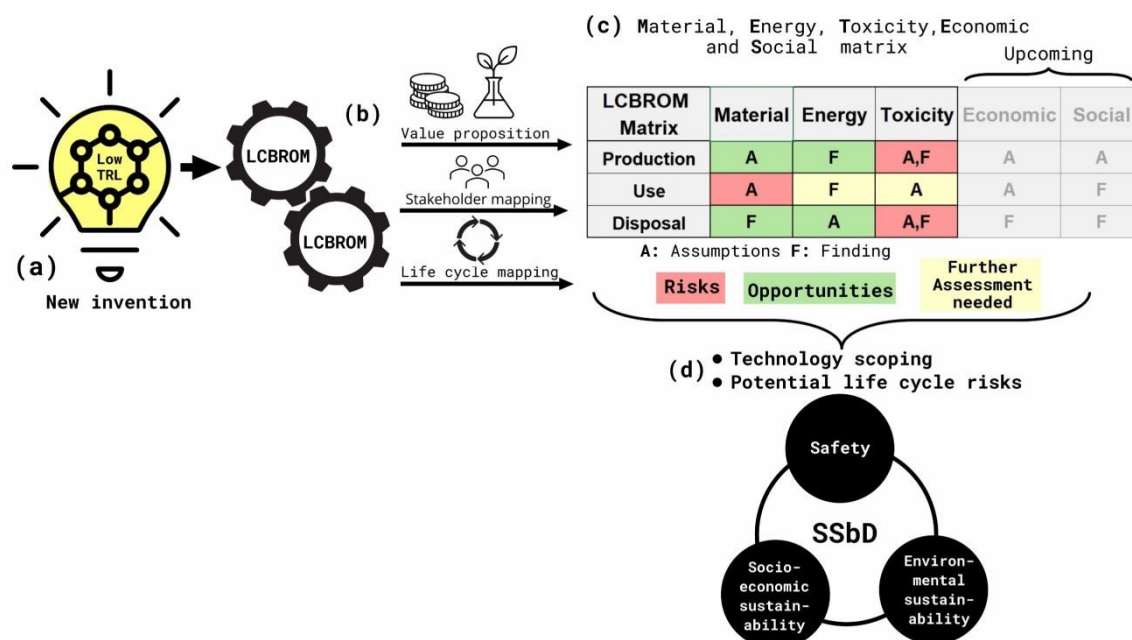
47 LCBROM is a predominantly qualitative screening approach to investigate potential risks as
48 “red flags” and “critical hot spots” based on available information in early innovation by
49 considering all life cycle stages (material sourcing, production, use, and disposal). When a
50 benchmark/reference technology with known risks and shortcomings is established and
51 shall be replaced, the advantages of the innovation can be highlighted as opportunities by
52 comparison. The goal of LCBROM is to analyze concerns and opportunities for innovations
53 at low technology readiness levels (TRL)² to guide the development toward a more safe and
54 sustainable solution. Where quantitative results from other studies are available in a
55 suitable format (e.g., from previous transparent and reviewed life cycle assessments of
56 related materials or processes) they should be considered. For some substances,
57 complementary hazard and risk assessments may be performed to better understand results
58 related to toxicity impacts. Transferable results from completed LCBROM studies may be
59 stored as modules in a repository for easy access at later occasions. This also requires
60 storing documentation of assumptions and background data to evaluate and adjust where
61 necessary.

62 In 2020, the European Commission (EC) presented the Chemicals Strategy for Sustainability
63 as part of the European Green Deal.³ The strategy calls for a transition toward the use of
64 safe and sustainable chemicals, materials and processes. To address these development
65 goals, the Joint Research Centre (JRC) has published the Safe and Sustainable by Design
66 (SSbD) framework for chemicals and materials, along with a definition and criteria for the
67 evaluation procedures.⁴ A revised version of the framework published in 2025 considers
68 feedback from initial case studies and road-testing and suggests as initial stage a scoping
69 analysis.⁵

70 A main pillar of the SSbD framework concerns the (re)design of chemicals and materials. It
71 is intended to guide inventors toward safer and more sustainable design at an early
72 development stage, when parameters are not yet fixed and there is still a high degree of
73 freedom for changes and optimization. Both radical and incremental changes can be dealt
74 with. The framework presents a (non-exhaustive) list of design principles to consider



75 during the (re)design. The initial scoping analysis includes a system description and a
 76 description of the intended innovation based on a set of SSbD principles (SSbD1 to SSbD9)
 77 that are derived from different contexts such as green chemistry, green engineering, energy
 78 efficiency, sustainability chemistry criteria, golden rules and circularity chemistry
 79 principles. The principles address aspects of resource use and emissions in a life cycle
 80 perspective and refer to environmental aspects as well as social risks, The main part of the
 81 SSbD framework covers safety and sustainability assessment of the chemical/material.⁵ To
 82 facilitate the SSbD scoping, LCBROM can serve as a starting point for exploring the entire
 83 life cycle of the innovation (the innovation being a chemical, process, material, or product).
 84 Throughout this process, innovation is assessed qualitatively and, where possible,
 85 quantitatively against environmental impact categories that emphasize human- and
 86 environmental-related risks and opportunities in different life cycle steps. Opportunities are
 87 in this context reduced impacts and can also be related to a better performance of the
 88 innovation, or less side effects, including waste streams and emissions. During the
 89 LCBROM, the technology developer gains indicative insight into how their innovation, with
 90 its intended implementation, potentially affects humans and the environment across
 91 different life cycle phases by identifying key hotspots. For this to be effective, the safety and
 92 sustainability expert leading the assessment must develop an understanding of the function
 93 of the innovation, how it is integrated into a product system or process application, as well
 94 as its production, use, and disposal scenarios. The purpose of the LCBROM is not to replace
 95 any quantitative assessment, but rather to pinpoint potential hotspots for upcoming
 96 assessments and to identify knowledge and information gaps. Consequently, parts of the
 97 life cycle for which available information is sufficient to indicate low or negligible negative
 98 impacts on human and/or environmental health and safety can be accepted as is without
 99 further consideration in the stage of the first assessment.



100

101

102

103 Figure 1. The LCBROM methodology to assess (a) early innovations in chemicals, materials, or processes. The
 104 (b) collaborative LCBROM assessment includes a value proposition for the innovation, a mapping of relevant



105 *stakeholders for further assessment, and a life cycle mapping of the process or product system. Risks and*
106 *opportunities at all life cycle stages are systematically analyzed and summarized in a (c) Material, Energy, and*
107 *Toxicity (MET) matrix. This methodology serves as a (d) pre-assessment for SSbD, supporting technology*
108 *scoping and identifying potential hotspots for life cycle risks in early innovations.*

109 Several other tools have been proposed for assessing environmental aspects of innovations
110 at low TRL in the past. An early example is the 5 x 5 matrix by Graedel et al. called the
111 Environmentally Responsible Product Assessment Matrix (ERPA).⁶ In that matrix, an
112 innovation is assessed regarding material choice, energy use, solid residues, liquid residues,
113 and gaseous residues using a life cycle perspective. The assessment is qualitative in its
114 nature, in which expert input, surveys and checklists are used to derive a figure of merit for
115 the innovation. Another tool that may be used for assessments in early innovation is the
116 concept of Material Input Per Service (MIPS) unit developed at the Wuppertal Institute.⁷
117 MIPS considers predominantly resource use and assumes that this correlates to potential
118 emissions. Detailed evaluation of different types of contaminants and the severity of their
119 effects are beyond the scope. Other examples are the Life-Cycle e-Valuation by Lang-Koetz
120 et al., the methodology for integrating sustainability considerations into process design by
121 Azapagic et al. and the Environmental Effect Analysis (EEA) by Lindahl & Tingström.⁸⁻¹⁰
122 General strategies have been outlined as extension of life cycle assessment (LCA), hybrid
123 analysis and toolbox.¹¹ The method presented herein, LCBROM, has been inspired by the
124 already existing tools, but essential elements have been added and adjusted to ensure that
125 the method i) is easy-to-use, ii) includes all relevant impacts, iii) has a wide applicability
126 domain, and iv) has low resource demand in terms of time and money.

127 Long before the EC launched the SSbD framework, Lang-Koetz et al. (among others)
128 recognized the need for environmental assessments of product ideas and concepts in early
129 innovation, and how this could be done by applying life cycle thinking and integrating
130 environmental assessment into the innovation process.⁸ In our work, we have built upon the
131 research questions explored by Lang-Koetz et al. while also incorporating opportunity
132 mapping, which we recognize as a powerful driver for decision-makers. Moreover, the
133 discussion of opportunities in terms of value proposition of the innovation can strengthen
134 the engagement of technology developers. This approach fosters greater involvement in the
135 assessment, which may be lower if the focus is solely on risks and environmental concerns.
136 Hence, our research explored the question: ***How can risks and opportunities of innovations***
137 ***be assessed at low TRL?***

138 In this article, we introduce a method to be used for life cycle based appraisal in early
139 innovation to fill the gap of tools for evaluating emerging technologies. To test out the
140 method, it has been applied in four case studies in the research programme Mistra
141 TerraClean: i) Development of a technology to concentrate rare earth elements (REEs) from
142 water from a discontinued mine; ii) Application of iron sulphide doped activated carbon to
143 remove mercury from a side stream in an enrichment plant; iii) Chemical modification of
144 PEX material to prevent unwanted bacterial growth in the distribution of drinking water;
145 iv) Removal of CO₂ from indoor air with filters based on cellulose nano fibrils and activated
146 carbon. All the technologies from the case studies were at low TRL when the technology
147 concept and application were formulated. The first of the described case studies will be
148 used as an example in this article. All applications in the case studies are related to material
149 and device development to treat emissions to water and air from current processes smartly
150 and to treat contaminated areas while recovering resources.



151 **Methodology**152 The structured development of LCBROM

153 This article highlights the absence of tools that can assess human- and environmental
154 impact of emerging technologies in an easy, comprehensive, and cost-efficient way. We
155 address this issue by presenting a method that can serve as a tool for fulfilling these
156 requirements. While doing so, we also present the structural procedure for our method
157 development, inspired by the development of the Circular Strategies Scanner which was
158 developed using the Design Research Methodology (DRM).^{12,13}

159 We initiated the method development during the fall of 2022. To describe its development
160 journey, we have chosen to divide it into three phases, all containing a descriptive study
161 and a prescriptive study. Figure 2 describes the aim and main outcome of each phase while
162 Table S1 in the Supplementary Information (SI) describes more details on each phase,
163 including the main activities.



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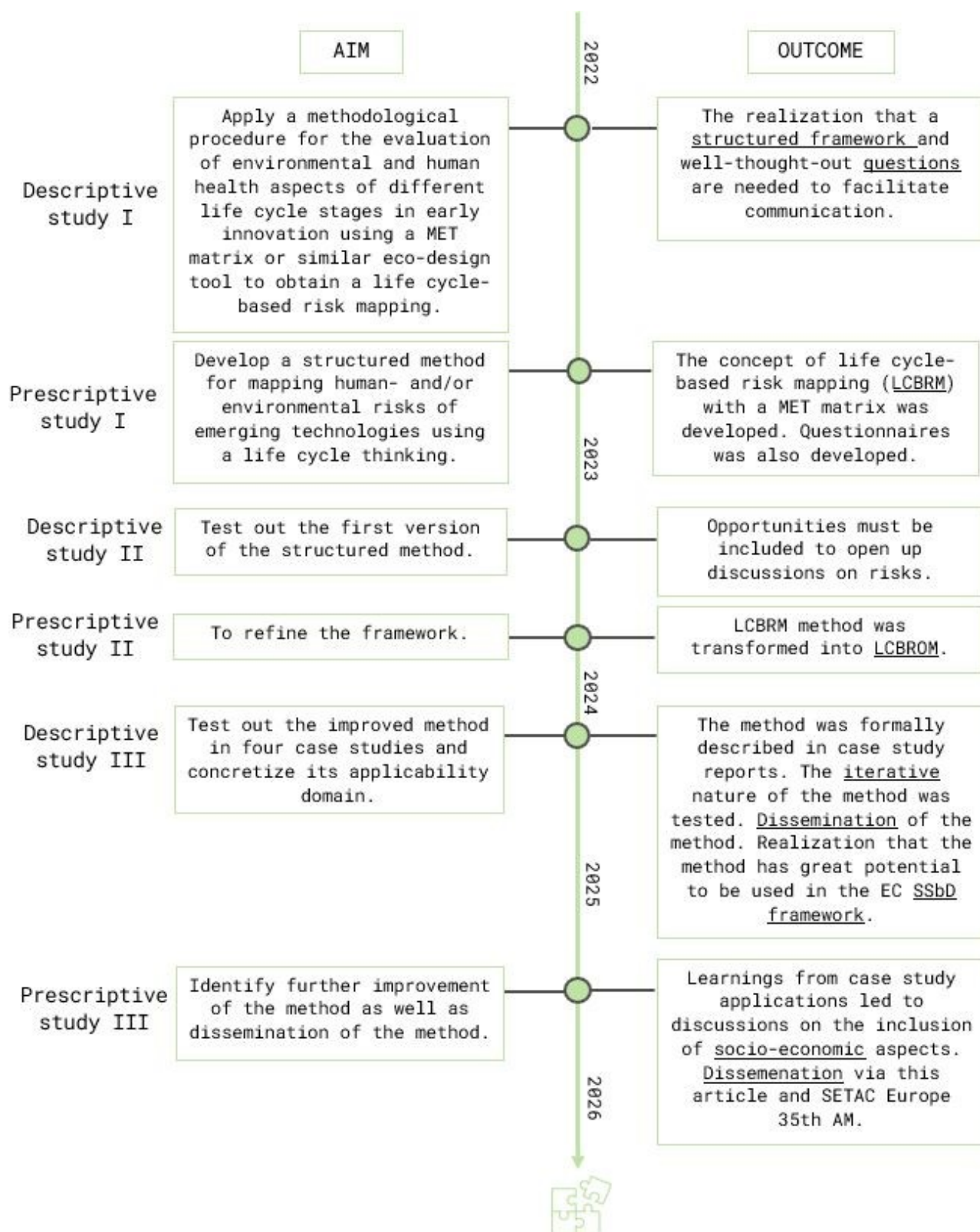


Figure 2. The structured development of LCBROM divided into three phases, all of which contained a descriptive study and a prescriptive study.

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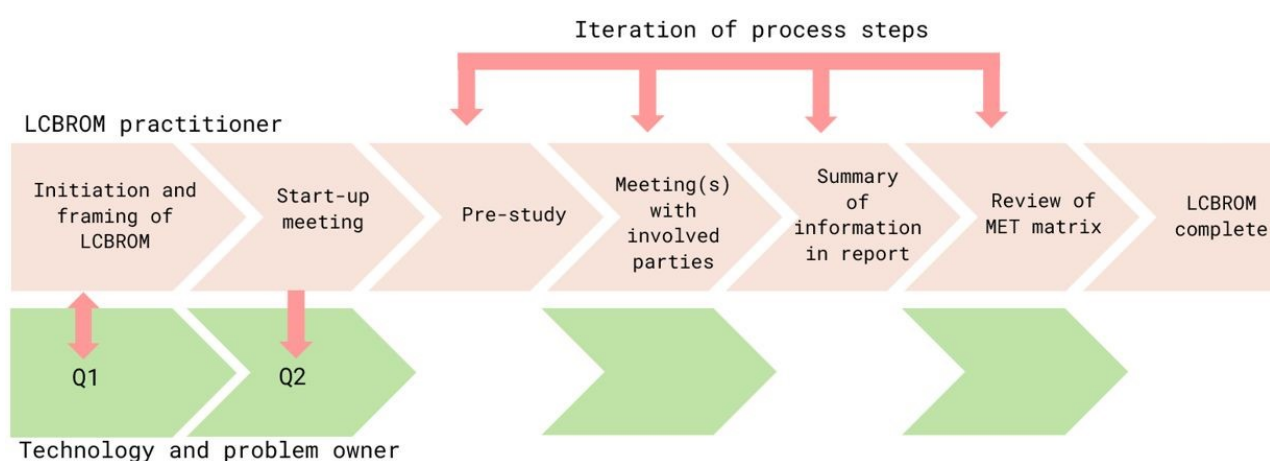
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169 The procedure for carrying out an LCBROM

170 The LCBROM method is based on an iterative process, illustrated in Figure 3, with
 171 continuous interaction between involved parties and identification of stakeholders to derive
 172 potential risks and opportunities of the innovation. Risks and opportunities at all life cycle
 173 stages are systematically analyzed and summarized in a Material, Energy, and Toxicity
 174 (MET) matrix[†]. It is recommended to have the MET matrix in mind throughout the whole
 175 assessment. To guide the LCBROM practitioner, a non-exhaustive list of questions to keep
 176 in mind during the assessment is presented in Table S2 in the SI.

177



178

Technology and problem owner

179 *Figure 3. Flowchart describing the steps of the LCBROM method. The arrows represent the iterative nature of*
 180 *the process. Q1 and Q2 indicate questionnaires that may be used in the Initiation and framing of LCBROM as*
 181 *well as during the start-up meeting for early information gathering, both available in Table S3 in the*
 182 *Supplementary Information.*

183

184 Initiation and framing of LCBROM assessment

185 An LCBROM is ideally initiated once there is a distinct application for the innovation and
 186 laboratory experiments show positive results. The first step for the LCBROM practitioner
 187 (often someone with an LCA background, not necessarily involved in material
 188 development) is to perform an initial mapping of involved parties and stakeholders. As
 189 there are several actors involved with different expertise and goals, this mapping is an
 190 essential part of the LCBROM method to ensure that the LCBROM practitioner can access
 191 the right information and data needed to perform a useful assessment. The core team in the
 192 LCBROM assessment could be rather small in the beginning, for example, a three-person
 193 team with competencies in LCA, risk assessment, and technology systems, and successively
 194 expanded during the course of the assessment. The mapping facilitates this expansion of the
 195 LCBROM team. Not all actors need to be actively involved in the assessment. As an
 196 example, representatives for a competing solution might be excluded from this stage. It is,
 197 however, recommended to identify independent experts who can support the development
 198 by defining the state of the art.



199 Note that the mapping done here does not imply that the affected stakeholders, as defined
200 in social life cycle assessment, are already covered. For a social assessment, it is required to
201 identify who is affected by the innovation once it is fully implemented, and typically that
202 includes workers, local communities, society, value chain actors, consumers and children.
203 Identifying which stakeholder groups might be affected and in which subcategories
204 changes can be expected is an additional task to familiarize technology developers with
205 concepts of social assessment. Involving representatives at an early stage is challenging, as
206 the location and supply chain have not been decided. Options to further develop the MET
207 matrix and include economic and social aspects are cursory discussed in the outlook, but
208 have not been fully explored in the case studies presented herein. This is equally the case for
209 any type of cost or economic assessment. Identifying necessary investments as a basis for
210 capital expenditure and resources to operate an innovative process is recommended, costs
211 for a scaled-up and integrated industrial process are expected to decrease compared to low
212 TRL. The revised SSbD framework addresses socio-economic sustainability assessment and
213 distinguishes between aspects that are independent of technology feature and can be
214 evaluated at an early stage with low TRL and those that need a clear understanding of the
215 actual implementation.⁵ This will be considered in an expanded version of the MET matrix
216 to a METES matrix, also accounting for economic (E) and social (S) aspects. This expansion
217 was not tested in case studies.

218 Once the mapping is completed, an information meeting is recommended at which the
219 LCBROM method can be presented. During such a meeting, we suggest that the strengths
220 and limitations of LCBROM are discussed to ensure reasonable expectations of the
221 upcoming assessment, both in terms of actual results and what will be required from
222 involved parties.

223 After the information meeting, a questionnaire (Q1) may be sent to the identified
224 participants. The purpose of Q1 is to document the problem definition, including a
225 background describing a specific case, benchmark technologies (if any) with known risks
226 and shortcomings, and participants as well as stakeholders involved in the case. Note that
227 the purpose of the questionnaire is to support the LCBROM practitioner in determining
228 what information is needed at the start of the LCBROM assessment. Depending on the
229 dynamics of a working group (e.g., technology owner, problem owner, and LCBROM
230 practitioner), an approach without questionnaires may be applied to populate the MET
231 matrix, for example, using documentation from dialogues or workshops.

232 Start-up meeting

233 The purpose of the start-up meeting is to initiate the LCBROM assessment. The following
234 topics may be discussed.

- 235 • Introduction of the LCBROM purpose and method
- 236 • Problem definition
- 237 • Introduction of the technology/material and the intended application
- 238 • Discussion on benchmark technologies
- 239 • Discuss any uncertainties regarding Q1 (if relevant)
- 240 • Discuss how to handle confidentiality, e.g., patent applications and the need for a
241 non-disclosure agreement.



242 The purpose of the meeting(s) with involved parties in the assessment is to populate the
243 MET matrix. Moreover, the meetings provide an opportunity to initiate a dialogue among
244 involved parties about technological developments and the associated life cycle based risks
245 and opportunities. The workshop allows participants to learn from one another and to
246 establish a common ground and a trusting atmosphere where ideas and information can be
247 freely shared. To simplify that process, a second questionnaire (Q2) may be sent after the
248 start-up meeting to allow the technology owner and problem owner to reflect upon the
249 technology from a material, energy, and toxicity perspective. For that reason, the questions
250 in Q2 may be briefly discussed at the end of the start-up meeting. The questions in Q2 lay
251 the foundation for the agenda of the upcoming meeting(s), hence, no answers to Q2 are
252 expected beforehand.

253 Pre-study

254 At this step, the LCBROM practitioner is supposed to initiate a literature review, scanning
255 the availability of existing studies of the benchmark technology. Such studies could, for
256 example, be LCAs and/or risk assessments. The answers added to Q1 may serve as
257 keywords for this literature review. Depending on whether (life cycle impact assessment)
258 methods are up to date and described transparently, this can either be used immediately or
259 replicated to fill in data in the matrix.

260 The pre-study also includes documentation of the problem definition in the report template.
261 Potential usage(s) of the innovation should be described to facilitate a life cycle perspective
262 of the appraisal. If there are no specific use cases for which the innovation is being
263 developed, it is recommended to define an assumed case to consider the full life cycle and
264 identify opportunities. Benchmarks should be at least state-of-the-art, meaning that the
265 technology to which the innovation is being compared should be the most advanced and
266 sophisticated alternative currently available.

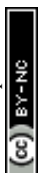
267 Meeting(s) with involved parties

268 As the LCBROM procedure is iterative, several meetings are likely needed during the
269 process. The involved parties and LCBROM practitioner(s) should discuss the questions in
270 Q2 and fill in a MET matrix. When answering the questions, both risks and opportunities
271 should be considered. If any risk mitigation measures are planned, this should also be
272 described. Knowledge gaps identified during the discussion should end up as action points
273 for further work by either the LCBROM practitioner, material developer, or problem owner
274 to reduce uncertainties of the appraisal.

275 Summary of information in a report

276 The draft report for the LCBROM is continuously updated throughout the entire process.
277 Toward the end of the appraisal, the LCBROM practitioner is supposed to refine the
278 information already added to the template and wrap up the mapping using the MET
279 matrix, introduced in Figure 4, and finalize conclusions and recommendations.

280 Every cell in the MET matrix combines either material, energy, or toxicity related to the life
281 cycle stage, such as material use in production or energy use during disposal. Input added



282 to the matrix should be self-explanatory in the sense that the reader should understand the
283 underlying message without consulting the bulk text.

284 Depending on whether different aspects are identified as opportunities, risks, or areas
285 requiring further investigation, a color coding is suggested (e.g., a traffic light system
286 assigning green to opportunities, red to risks and yellow to findings that require further
287 research) to provide a better overview. Data gaps should be denoted DG and be left
288 uncolored. Although most information in the MET matrix comes with uncertainties due to
289 low TRL, some may be particularly uncertain, and highlighting those with an italic font is
290 recommended. LCBROM practitioners may also have different opinions about certain
291 aspects due to lack of information, which can be solved by applying the yellow category in
292 the traffic light system indicating that further research on the topic is needed.

293 The results from an LCBROM can be used for several purposes, depending on the scope of
294 the mapping and a future assessment. If the objective of the appraisal is to guide the
295 innovation towards a more sustainable alternative compared to a benchmark technology,
296 the results may be used for decision-making, including a decision about potential next
297 steps, such as a more complete assessment. In general, it is not just the MET matrix itself
298 that represents the main result. Equally important are the lessons learned during the
299 appraisal regarding life cycle mapping and system understanding, which may lead to an
300 optimization of the new invention ((re)design) if negative impacts are identified. The
301 method also helps envision potential value chains for the new technology.

302 **How does the LCBROM method support SSbD assessment for technologies in early** 303 **innovation?**

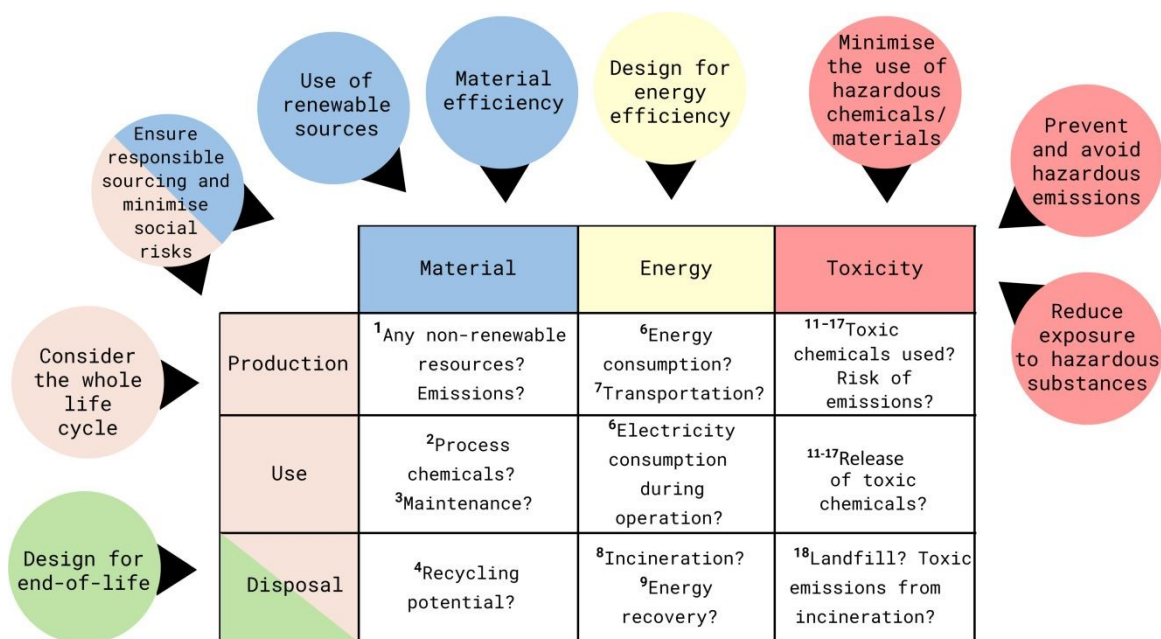
304 LCBROM is a tool for early review of the life cycle stages and potential risks and
305 opportunities of an innovation for which there is an insufficient amount of data available
306 for performing more sophisticated assessments, such as LCAs. The integration of human
307 and environmental health evaluations in early innovation of chemicals/materials has been
308 climbing the agenda for the last couple of years. Not least because of the publication of the
309 SSbD framework and its methodological guidance.^{5,14} Even though LCBROM was not
310 originally developed for the sole purpose of SSbD assessments, its usefulness is expected to
311 be high. Hence, this section exemplifies how the method can support SSbD assessments.

312 The (re)design phase

313 Improvements made during the design phase potentially have a larger impact on the
314 environmental performance than improvements implemented at a higher TRL when many
315 decisions are already established.¹⁵ LCBROM allows the innovation to be successively
316 improved using a systematic MET matrix as a tool to evaluate the completeness and balance
317 of information. Applying the SSbD design principles to the MET matrix facilitates the
318 evaluation of the (re)designed material against Material, Energy, and Toxicity using a life
319 cycle perspective at an early stage. The connection between the MET matrix and the eight
320 (non-exhaustive) SSbD design principles is illustrated in Figure 4. Note that the revised
321 framework contains a ninth principle Ensure responsible sourcing and minimize social risk,
322 which are foremost applicable for socio-economic aspects and were not included in the tool
323 testing.⁵



324



325

326 Figure 4. SSbD design principles (colored bubbles) connection to the MET matrix used in
 327 LCBROM. The questions provide examples of discussion points for an LCBROM and the numbers
 328 refers to specific questions in the more comprehensive (although non-exhaustive) list of questions in
 329 Table S2 in the SI.

330 Scoping

331 Scoping in SSbD is the initial analysis phase that establishes the assessment's purpose,
 332 system boundaries, and the chemical or material to be examined. It lays the groundwork for
 333 all subsequent safety and sustainability evaluations. During this phase, the system and its
 334 life cycle stages are defined.¹⁴ The LCBROM procedure can serve as a structured approach
 335 for this scoping exercise, helping to develop a clear problem definition, map the life cycle
 336 stages, identify relevant involved parties and potential external stakeholders, and discuss
 337 (re)design options at an early design stage.

338 The safety and sustainability assessment

339 *Safety assessment*

340 The starting point for an SSbD assessment according to the SSbD framework is to
 341 investigate the intrinsic physico-chemical properties of the chemical/material being
 342 developed. This is intended as a common entry point for the safety assessment and
 343 environmental sustainability assessment and is followed by an initial assessment of intrinsic
 344 hazards.⁵ Even though the LCBROM method does not serve as a tool itself to assess the
 345 intrinsic hazard of the chemical/material, it requires that the technology developer start
 346 thinking of the innovation in terms of toxicity early on and add information to the MET
 347 matrix. Depending on the competencies in the working group and resources available,
 348 exploratory toxicity assessments can be performed to add to the MET matrix. This has been
 349 tested in a couple of case studies, one of which is introduced for illustration in this paper.



350 The life cycle perspective, more specifically, cradle-to-gate (gate being the production and
351 processing phase), is introduced early on in the SSbD framework and proposed also for the
352 risk and exposure assessment. Having performed an LCBROM before the SSbD assessment
353 would result in a smoother transition toward expanding the scope, since the life cycle and
354 the supply chain are identified. Occupational hazards in a preliminary supply chain can
355 thus be identified. As the purpose of LCBROM is not to deliver a quantitative assessment, it
356 is not intended to replace any occupational risk assessments. However, it may pinpoint
357 hotspots to separate those areas of the life cycle that may require further attention.
358 Requirements for protective equipment and prevention through layout (encasing processes
359 and logistics) can be identified and discussed with the technology developer.

360 The following step of the SSbD framework is focusing on human health and environmental
361 aspects in the (final) application phase of the innovation. Mapping potential risks and
362 opportunities of the use phase is included in the LCBROM method and could potentially
363 serve as a starting point for the quantitative assessments in this step.

364 The innovations considered in the four case studies (introduced earlier in this article) were
365 mostly applied by professional users. From a toxicity perspective, it is important to establish
366 whether the innovation is intended for consumers and/or professionals. Consumers are
367 likely not trained to use personal protective equipment (PPE) while professionals are,
368 meaning that the risk of exposure may be higher for consumers than for professionals.
369 Innovations that are used indoors may also contribute more to exposure.

370 Assessing the innovation regarding energy consumption during different life cycle stages is
371 an important part of the LCBROM. In the use phase, energy consumption can be related to
372 climate change and pollution if fossil energy carriers are used.

373 *Environmental sustainability assessment*

374 The core of the environmental sustainability assessment is life cycle assessment (LCA)
375 following the procedure suggested for product environmental footprints, which poses a
376 challenge for materials in early innovation (i.e., those at low TRL). Challenges associated
377 with LCA in early innovation were pointed out by Hetherington et al.¹⁶ For example, the
378 challenge of future unknown features and data gaps was discussed. There may be data gaps
379 considering different life cycle stages, upscaling parameters, and emissions. In addition to
380 those challenges pointed out by Hetherington et al., it is very costly to perform a full LCA,
381 both in terms of effort and money. Hence, there is a need for life cycle based tools for
382 assessing innovations at low TRL when many options with minor differences between them
383 are available, which was also pointed out by Moniruzzaman Moni et al.¹⁵ A common
384 approach is to model process systems based on a benchmark process and adjust parts based
385 on the specification. However, published data for benchmark processes may be aggregated
386 and thus representative for average industry processes, but not suitable to guide the
387 development of innovations and identify relevant parameters.

388 Challenges of performing an LCA at low TRL (< 5) were specifically pointed out in the first
389 version of the SSbD framework.⁴ To overcome such challenges, the framework suggests the
390 use of Prospective LCA. The revised framework introduces the term Maturity of the
391 innovation which may include different approaches (such as TRL) to define the maturity
392 level of the innovation. To assess innovations at low innovation maturity, the revised



393 framework emphasizes a broader scope of assessments focusing on the use of screening
394 level assessments and LCA based benchmarks instead of specifically suggesting prospective
395 LCA.⁵ Nevertheless, the interest for such LCAs is increasing and the challenges associated
396 with it may be solved using specifically designed frameworks. Examples of such
397 frameworks are proposed by Piccinno et al., Buyle et al., Arvidsson et al., and Thonemann
398 et al.^{17–20} However, we would argue that the use of prospective LCA would benefit from the
399 application of an LCBROM in advance. For example, applying LCBROM at TRL 1-2 would
400 allow the LCA practitioner to map the life cycle and understand what type of challenges
401 they may face during the upcoming assessment once the technology reaches TRL 3-5.
402 Additionally, the SSbD framework calls for the application of LCA for all uses and
403 production routes of the innovation. Performing a (prospective) LCA for all those scenarios
404 will be costly and time-consuming. Having applied LCBROM in advance would enable the
405 LCA practitioners to gain an understanding of which are the most likely areas of concern
406 and, hence, require extra effort in estimating their input parameters.

407 Applying the SSbD concept in early innovations requires tools and methods that are
408 adapted to low data availability and high uncertainty. Except for prospective LCA, there are
409 no such methods communicated in the SSbD framework or its guidance for the life cycle
410 based assessment. Some tools exist (or are under development), for example, the screening
411 level approach developed by Pizzol et al. that specifically addresses multi-component
412 nanomaterials.²¹ It uses extensive questionnaires that may be difficult for technology
413 developers to answer; hence, expert input may be required. Another example of an existing
414 tool is the ERPA matrix.⁶ Although there are existing tools, none seem to capture all the
415 necessary ingredients for being *the commonly applied* tool for emerging technologies: i) easy-
416 to-use, ii) inclusion of all relevant impacts, iii) wide applicability domain, and iv) low cost in
417 terms of time and money. We would argue that LCBROM could potentially fill that gap of
418 tools because of its iterative nature and use of general questions that can be applied to most
419 technology fields.

420 As already pointed out, there is not enough data to perform full LCAs at low TRL. Instead,
421 LCBROM can be used to map out relevant life cycle stages and identify potential risks that
422 the material use entails during upscaling. Additionally, if there is a benchmark technology
423 available on the market, LCBROM can also identify potential opportunities for the
424 innovation, based on known shortcomings of the benchmark technology. Identifying such
425 risks and opportunities will help to reduce lock-in to unsustainable decisions and to
426 continuously improve the material. As the material reaches higher TRL and more data
427 becomes available, the LCBROM can be further refined. Eventually, there will be enough
428 information on the innovation to perform a screening LCA and finally a full LCA, if
429 necessary. Hence, LCBROM could serve as a starting tool for the life cycle based assessment
430 of the SSbD framework for materials in early innovation.

431 *Socio-economic sustainability assessment*

432 The socio-economic sustainability assessment was added in the revised SSbD framework
433 and not available during our study.⁵ It is based on societal life cycle costing (LCC) and
434 social life cycle assessment (S-LCA), and proposes a limited selection of indicators to
435 evaluate social fairness, competitiveness, and societal life cycle costs. This step was
436 voluntary according to the 2022 version of the SSbD framework. but we have initiated
437 discussions on how to incorporate social and economic factors into the LCBROM approach.



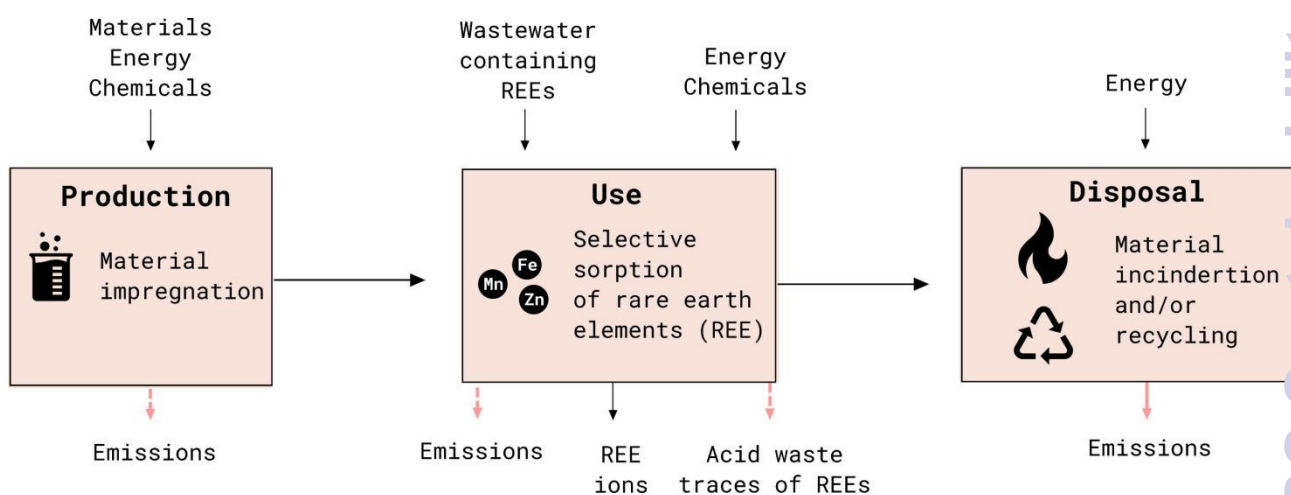
438 Starting a dialogue with problem owners and technology owners provides options to
439 identify involved parties and stakeholders and explore viewpoints. This was not explicitly
440 included in any of the case studies and is therefore out of the scope of this article.

441 Case study results

442 LCBROM has been applied in four case studies, one of which was exploring whether
443 mining wastewater can be turned into a source of REE. There are currently few regions that
444 can produce REEs, which may become an issue when the global demand continues to
445 increase, as a consequence of, for example, the increased use of electric-vehicle motors.²² To
446 overcome this issue, the case-study group was exploring an alternative REE recovery
447 method by concentrating REEs from a discontinued mine using a hollow fiber supported
448 liquid membrane (HFSLM).

449 A rough life cycle description of HFSLM is described in Figure 5, which consists of material
450 production via impregnation, use via selective sorption of REE, and disposal via
451 incineration and/or recycling. Within the use phase, there is a selective sorption of REEs to
452 optimize the REE recovery. The main purpose of this step was to remove elements that may
453 compete with REEs in terms of sorption sites and extractants. Thereafter, the low-
454 concentration water undergoes an up concentration by allowing the water to pass through
455 the liquid membrane to form metal complexes with organic extractants. These complexes
456 are thereafter diffused via a membrane where metal ions are delivered into a stripping
457 solution. The high concentration solution can now enter the separation stage, from which
458 separate REEs are obtained.²²

459



460

461 *Figure 5. Life cycle description of the technology used for retrieving REE from wastewater from discontinued*
462 *mines.*

463 An LCBROM was performed in parallel to early lab tests to support and guide the decisions
464 towards safer and more sustainable solutions. After the initial steps of the LCBROM were
465 performed (Initiation & framing of the appraisal and Start-up meeting), a pre-study was
466 conducted. During that study, solvent extraction was identified as the main benchmark
467 technology to be used for opportunity identification.²³ For that purpose, a literature review



468 was performed to identify the major challenges that solvent extraction faces from an
469 environmental point of view.

470 The first significant finding, also identified by Navarro & Zhao, was that there are very few
471 LCAs (or other articles focusing on the environmental impacts) of REE production, and
472 specifically the solvent extraction step.²⁴ In fact, we only found two articles focusing on the
473 solvent extraction phase.^{25,26}

474 This was somewhat surprising as the second finding was that the main contributor to the
475 overall environmental impact in REE production seems to be the solvent extraction step
476 (approximately 30% according to Vahidi & Zhao).²⁶ It should, however, be noted that most
477 articles highlight that there are, in general, very few LCAs on REE production in
478 combination with poor data quality and information.²⁷

479 The use of hydrochloric acid (HCl) in solvent extraction was identified as a challenge since
480 it is being used in high quantities, which generates a significant environmental impact.^{25,26}
481 For that reason, using lower amounts of HCl, or no such use at all, was highlighted as an
482 opportunity for the novel technology. On the other hand, both alternatives, solvent
483 extraction (benchmark) and HFSLM (innovation), use kerosene, which is a petroleum-
484 extracted mixture of aliphatic and aromatic hydrocarbons, cycloalkanes and alkylbenzenes
485 with varying structures and toxicities. As such, there is high uncertainty in establishing
486 safety risks with this mixture since various compounds in the mixture are more toxic than
487 others. Many of the potential components of kerosene are known to be mutagenic and
488 reproductive toxic as well as highly toxic to various organs. Due to its toxicity, the use of
489 kerosene was marked as a risk in the MET matrix. Table 1 provides a simplified MET matrix
490 from the case study, anonymized to avoid disclosure of confidential information.

491 *Table 1. Overview of a MET matrix from a case study in Mistra TerraClean. Color code: green = opportunities,*
492 *red = risks, yellow = further research is needed. Findings and assumptions are denoted F and A, respectively.*
493 *Note that some entries from the case study are excluded for simplicity.*

	Materials	Energy	Toxicity
Production	F: Possibly use of recycled and/or renewable polypropylene and polyethylene in the HFSLM.	F: Information from membrane suppliers indicates that the production process is not energy intensive.	A: Production of solvents and extractants may release toxic emissions.
Use	F: Upscaling is difficult because of gel formation which occurs at sub-optimal operating conditions.	F: Possibly less energy intense than the current? state-of-the-art technology.	F: Less hazardous extractants needed. F: Use of kerosene.
Disposal	F: Hazardous waste containing acids must be handled.	F: The HFSLM is likely to be incinerated.	A: Waste may contain traces of metals.

494



495 Once the first draft of the MET matrix was delivered to the technology owner, it was
496 presented to the steering group of the research programme, which brought in an early-stage
497 peer evaluation. Based on feedback from that presentation and the content of the MET
498 matrix, the iterative nature of LCBROM was tested. The findings of the LCBROM were
499 refined, and the technology owners decided to investigate the possibility of substituting
500 kerosene. That was first done via a toxicity assessment in which the hazards of kerosene
501 were mapped. Secondly, a literature review was performed, in which it was found that
502 alternatives for kerosene are available.

503 Due to the end of the Mista Terra Clean research programme, this study could not follow
504 the further development of the innovations towards a higher TRL, which would have
505 allowed for a more refined LCBROM. Despite this, the LCBROM demonstrated its potential
506 in identifying risks and opportunities to guide the innovation towards a more sustainable
507 alternative.

508 The appraisal also contributed to a learning process within the LCBROM team regarding
509 the method and it introduced a systematic life cycle perspective to the project partners,
510 especially the technology developers, who had not previously considered potential life
511 cycle impacts in their work processes. The LCBROM was therefore effective as a guiding
512 tool and was appreciated by the participants, particularly the technology owners.

513 For future work, it would be interesting to compare the results with those of a more
514 rigorous, quantitative assessment once the innovations reach a higher TRL, in order to
515 evaluate the precision of the predictions presented in the LCBROM.

516

517 Discussion

518 Using a matrix to summarize learnings from a life cycle based assessment has been done
519 since 1995, when the ERPA matrix was introduced.⁶ The appraisal is qualitative in its
520 nature, in which expert input, surveys and checklists are used to derive a figure of merit for
521 the innovation. LCBROM is a modernized version of this tool with some commonalities and
522 differences. An important difference is that the ERPA matrix is used as a grading system for
523 deriving a single score to be used for tracking improvements.⁶ As LCBROM is intended to
524 be used for hotspot identification for a variety of technology types, a scoring system has not
525 been deemed necessary at this point.

526 Another key difference between LCBROM and the ERPA matrix is the ability to identify
527 opportunities. To ensure that innovation results in a lower human and environmental
528 impact than the current technology, opportunity mapping is just as important as risk
529 mapping. Since LCBROM is designed for early-stage innovation, the developer has the
530 chance to refine the innovation regarding its production process, usage, and/or future waste
531 treatment in terms of material, energy, and/or chemical choices. Therefore, LCBROM
532 requires a reference technology to identify opportunities. If no reference can be established,
533 the comparison should be made against a scenario where no action is taken at all.

534 As established in the introduction, several other tools have been suggested throughout the
535 years in addition to the ERPA matrix. We see several similarities between these approaches



536 and LCBROM, for example, the qualitative life cycle based questions that identify pathways
537 for more sustainable innovation. Additionally, the EEA framework explicitly states that the
538 assessment is designed to be carried out in a multifunctional team¹⁰, which aligns with
539 LCBROM in the sense that a small team of experts is recommended to be involved.
540 Specifically, a three-person team is recommended in which competencies of LCA, risk
541 assessment, and technology systems are required.

542 A main characteristic that distinguishes LCBROM from other qualitative and/or semi-
543 qualitative life cycle based appraisal tools is the O in LCBROM, i.e., the mapping of
544 opportunities. We have found that the inclusion of opportunities in the assessments opens
545 up the willingness of different involved parties to put resources into performing human
546 health and environmental appraisals in early innovation. Problem owners understand that
547 this dialogue can help to identify advantages of alternative solutions beyond sufficient
548 performance and select among different options. The inclusion of opportunity mapping
549 allows the technology owners to tailor their offerings to avoid shortcomings of current
550 solutions while also reducing elements of “optimism bias”. For the technology owner, the O
551 may also be used to pitch the advantages of the innovation to potential investors, and
552 considering life cycle risks might make it even more attractive. Additionally, it allows for
553 the identification of multiple uses of the innovation and/or prolonged life cycle of the
554 material within the technology. Another characteristic that distinguishes LCBROM from
555 other approaches is that its result is presented in an easy-to-understand format using a MET
556 matrix. That facilitates a quick and transparent result communication to decision-makers
557 and other experts, which also allows for further improvements via iterations through quick
558 feedback routes. The latter has been tested in a couple of case studies with a positive
559 response.

560 During the development of the method and its application in case studies, it became clear
561 that the formalized stepwise approach and defined input information facilitated the
562 execution of the method. The MET matrix is intuitive and easy to understand, which is
563 important as there is a strong need for tools that can be used by small and medium-sized
564 enterprises (SMEs). Although SMEs may not have the resources and/or competence to carry
565 out an LCBROM themselves, SMEs possess technological expertise that is essential in the
566 execution of an LCBROM.

567 A well-thought-out and defined working group is crucial to obtaining a successful
568 LCBROM, as there must be a common understanding and driving force for performing the
569 appraisal, as well as the possibility of getting access to the right information. A common
570 understanding of the strengths and limitations of LCBROM is important to establish early
571 on. Additionally, to derive a successful LCBROM, non-disclosure agreements may have to
572 be signed. If no such agreement is signed, it can be difficult to identify risks and
573 opportunities if there is resistance in sharing sensitive information. However, if non-
574 disclosure agreements are signed, it may be difficult to publish the results from the
575 assessment, which ultimately may hinder further development of the method itself. To
576 solve such an issue, the LCBROM practitioners are recommended to carry out the
577 assessment as far as possible using the shared information and present the result to the
578 technology and problem owner. While doing so, it is important that the result is
579 communicated in a way that clearly points at the relation between uncertainty and data



580 gaps. It should also be explained that more reliable results will come with more transparent
581 information sharing.

582 **Future outlook**

583 Although the concept of the MET matrix is well established for eco-design projects, its use
584 for the purpose of assessing innovations at low TRL is under development. For that reason,
585 the LCBROM method has several areas for improvement, and some will be addressed in
586 upcoming case studies. An example of such an improvement is the expansion of the MET
587 matrix into a METES matrix: Material, Energy, Toxicity, Economy and Social aspects. The
588 socio-economic sustainability assessment in the SSbD framework, requires a structured
589 approach. Beyond that, it is of interest to test LCBROM for that purpose since the dialogue
590 with involved parties at an early stage provides a platform to address topics beyond
591 environmental issues. Such an expansion of the matrix may increase the involvement of
592 other actors who do not necessarily contribute to technology development but can have an
593 interest. Examples of such actors are independent experts, authorities setting regulations,
594 the general population and even competitors. The revised SSbD framework proposes a
595 selection of indicators that address social fairness, competitiveness and societal life cycle
596 costs and can be explored based on publicly available data.⁵

597

Material, Energy, Toxicity, Economic
and Social matrix

Aspect LC phase	Upcoming				
	Material	Energy	Toxicity	Economic	Social
Production	A	F	A, F	A	A
Use	A	F	A	A	F
Disposal	F	A	A, F	F	F

A: Assumptions F: Finding

Risks

Opportunities

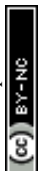
Further Assessment needed

598

599 *Figure 6: LCBROM matrix extension including economic and social categories.*

600 As with many other environmental assessments, it is challenging to summarize the results
601 in a way that is easy to communicate. As of now, the documented result of an LCBROM is
602 the MET matrix. To facilitate communication, the information written in the matrix must be
603 self-explanatory in the sense that the reader should not have to consult the bulk text of the
604 report to understand the results. Alternative ways of presenting the results from an
605 LCBROM must be investigated to further improve its accessibility and understandability for
606 non-experts.

607 The extended LCBROM matrix is suggested as a suitable format to capture the traditional
608 sustainability pillars. But other aspects can also be added to the matrix, such as politics or
609 legislation. A parallel can here be drawn to the PESTEL framework—covering Political,
610 Economic, Social, Technological, Environmental, and Legal factors—which offers a
611 structured way to analyse external influences and can inspire further development of the
612 MET matrix by integrating broader contextual dimensions.²⁸ The term traces back to 1967
613 when Aguilar presented ETPS (Economic, Technical, Political, and Social) in his book



614 Scanning the Business Environment.²⁹ Later, other practitioners added Environmental and
615 Legal aspects as additional entities.

616
617 Beyond Mistra TerraClean, the LCBROM method is being revised and tested in the EU-
618 funded research programmes BioSusTex, with a focus on new chemical raw material and
619 process developments for the textile sector (<https://www.biosustex.eu/>), and Bio-LUSH,
620 with a focus on using fibers from underexplored European plant resources in biobased
621 products (<https://biolush.eu/>).

622 Conclusions

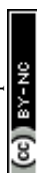
623 In this article, we propose a qualitative screening approach that can be used to support
624 SSbD assessments. It may be used as an initial step of an SSbD assessment to facilitate its
625 scoping process. . Additionally, the tool can be used in the environmental sustainability
626 assessment in early innovation when there is not enough data to perform a quantitative
627 LCA.

628 The method offers a structure that facilitates the identification of the most relevant issues
629 comprehensively without conducting an extensive assessment. It requires a collaboration
630 between several different experts and can be applied to most technology fields with
631 relatively low costs in terms of time and money.

632 LCBROM has been successfully applied in four case studies to materials and technologies
633 that are in the early stage of innovation. The main learning from its development and
634 application is the importance of having a state-of-the-art benchmark and/or a specific case
635 to relate the innovation to for opportunity identification. If no such reference is established,
636 opportunities can only be identified by considering a scenario where no action is made at
637 all.

638 Author contributions

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Funding Acquisition	Maja Halling, Tomas Rydberg and Jutta Hildenbrand
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Methodology	Therese Kärnman, Steffen Schellenberger, Marie Gottfridsson, Maja Halling, Kristin Johansson, Tomas Rydberg and Jutta Hildenbrand
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Resources	N/A
Software	N/A
Supervision	Maja Halling, Jutta Hildenbrand and Tomas Rydberg
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Visualization	Steffen Schellenberger and Therese Kärnman
Writing – Original Draft Preparation	Therese Kärnman
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639

640 **Conflicts of interests**

641 There are no conflicts to declare.

642 **Data availability**643 The data supporting this article have been included as part of the Supplementary
644 Information.645 **Acknowledgement**

646 We thank Mistra for funding the research programmes Mistra TerraClean II (2015/31) and
647 Mistra SafeChem (18/21), as well as the European Commission for supporting BioSusTex
648 (No. 101135372). We gratefully acknowledge Hanna Holmqvist for inspiring the LCBROM
649 methodology, and Olga Lysenko, Sahar Safarianbana, and Nilay Elginöz Kanat for their
650 contributions to the social and economic section of the METES matrix. Special thanks to
651 Nilay Elginöz Kanat at IVL Swedish Environmental Research Institute for the initial
652 external review. The article title is based on a presentation at the SETAC Europe 35th
653 Annual Meeting.

654 **References**

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656 matrix, although it is now out of print. Note that the accessible version by van Berkel uses the term
657 “toxic emissions”, this is broadened in the LCBROM matrix to include also aspects of toxicity related
658 to products and by-products.³⁰

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Data availability

The data supporting this article have been included as part of the Supplementary Information.

