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How prospective LCA handles time in circularity-oriented assessments: Evidence and gaps

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ABSTRACT

Prospective life cycle assessment (pLCA) is increasingly used to support circular economy (CE) strategies, however how time is represented, across foreground interventions and evolving background systems, remains heterogeneous and often underreported, with implications for comparability and decision quality. This study reviews how CE-oriented pLCA operationalizes and conceptualizes time evolution and identifies recurring temporal design choices relevant for impact assessment practice. We conducted a systematic literature review (Scopus and Web of Science), identifying 121 eligible publications. We extracted (i) the circular loops and R-strategies addressed, (ii) operational time handling (background databases and models, foreground management approaches, scenarios and elements of change), (iii) conceptual framings of time (as resource, structure, and process). Results show that applications focus on material recovery and recirculation (83%), while slowing and intensifying strategies are rarely assessed (6%), narrowing is marginal (3%), and dematerializing/service substitution cases are absent. Across studies, foreground changes are often reported, but background modelling is frequently opaque: 70 out of 121 studies (58%) do not specify the background model, and many omit explicit time slices or scenario labels, limiting interpretability and cross-study comparison. Finally, four temporal design configurations are identified, combining weak or partial foreground–background coupling with snapshot or pathway-based temporal evolution. This study makes temporal considerations in circularity-oriented pLCA actionable by translating a fragmented literature into four recurring temporal design configurations and a decision rule with requirements for selecting and documenting them. We conclude with recommendations to improve transparency, and increase the decision relevance of pLCA.

1. Introduction

Circularity has steadily gained traction as key model reshaping industrial systems, making a shift from the linear take-make-dispose model toward strategies that retain the value of products, components, and materials for as long as possible (Ghisellini et al., 2016; Kirchherr et al., 2017; Velenturf and Purnell, 2021). Rather than a single, unified model, circularity manifests as a family of approaches grounded in industrial ecology, cradle-to-cradle design, and the performance economy, unified by the pursuit of value retention at product, business-model, and system scales (Ghisellini et al., 2016; Velenturf and Purnell, 2021). Distinct circular loops enable circular economy (CE) reshaping materials and products flows through in-use stocks, most notably slowing, closing, narrowing, intensifying, and dematerializing loops (Bocken et al., 2016; Geissdoerfer et al., 2018).

Taken together, these mechanisms show that time is foundational to CE performance because value-retention loops unfold at varying speeds and with significant lags, with complex temporal understanding (Hendriks, 2024). This suggests that evaluating CE performance requires recognizing that systemic change hinges on timing actions to capture windows for socio-technical innovation (Hendriks, 2024). An additional layer of complexity is given by the unintended consequences of circularity, such as the rebound effect (Zink and Geyer, 2017), and thermodynamic limits, as circular processes invariably involve energy dissipation and material losses (Korhonen et al., 2018).

Life Cycle Assessment (LCA) can help navigating among this complexity, enabling the quantification of potential environmental impacts, the avoidance of problem-shifting across life cycle stages or

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impact categories, and the transparent evaluation of trade-offs (Peña et al., 2021; Rigamonti and Mancini, 2021). However, since CE strategies often involve long-term investments in novel technologies and infrastructures, their true impacts will materialize in the future, often under different socio-technical conditions. This necessitates a forward-looking, or ex-ante, approach.

Prospective Life Cycle Assessment (pLCA), which models product systems at a future point in time with a forward-looking approach, is recognized as a methodology for informing R&D, investments, and long-term transition planning (Arvidsson et al., 2024). More than conventional/retrospective LCA, pLCA makes time explicit in both foreground (the processes directly affected by the decision-maker) and background systems (the economy-wide systems that supply energy, materials, transport, and end-of-life services but are not under direct control) (Arvidsson et al., 2018). Existing review literature further shows that pLCA practice depends heavily on how scenarios are constructed and translated into model structure. In case of emerging technologies, upscaling is described as a three-step process involving projected technology scenario definition, preparation of a flowchart, and projected data estimation (Tsoy et al., 2020). More broadly, recent prospective review work shows that future results are highly sensitive to scenario variables and assumptions, with recurring drivers including background electricity mix, demand, recycling shares, and energy-efficiency improvements (Harpprecht et al., 2024). Its key distinguishing features include projecting foreground systems beyond their current Technology Readiness Levels (TRLs) and constructing scenarios to situate technologies within a range of plausible future situations (Bergerson et al., 2020; Tsoy et al., 2020; Sacchi et al., 2022; Erakca et al., 2024; Van Der Hulst et al., 2025). Temporal mismatches and temporal consistencies are pivotal at every step, influencing goal and scope definition, the upscaling of laboratory data for the life cycle inventory, and the interpretation of results against evolving baselines (Thonemann et al., 2020; Fang et al., 2025).

A central methodological challenge is accounting for temporal consistencies in the life-cycle inventory (LCI) for both foreground and background. Building the LCI in pLCA requires explicit, scenario-based reasoning about how these systems may evolve and how that evolution shapes future impacts. For the foreground, this entails representing production scale and performance improvements over time. Historical experience shows substantial efficiency gains in many technologies, justifying the use of two complementary strategies: predictive scenarios (most-likely developments) and scenario ranges (capturing uncertainty and extremes). For the background, using static present-day data while projecting the foreground forward creates temporal mismatches; the strategies, predictive scenarios and scenario ranges, are therefore recommended to align foreground and background in time (Arvidsson et al., 2018).

Importantly, adding temporal differentiation to the background can materially change results; and neglecting background evolution can induce large errors in some systems (Pinsonnault et al., 2014; Georgiades et al., 2023; Douziech et al., 2024). Sophisticated methods exist for modelling background systems by coupling LCIs with the outputs of Integrated Assessment Models (IAMs). Despite this, many prospective studies still adjust only a narrow subset of background processes, most commonly electricity, leaving other critical sectors effectively static (Marson et al., 2025; Nurdiawati et al., 2025). While robust frameworks for ensuring temporal consistency between foreground and background are emerging (Cucurachi et al., 2022; Langkau et al., 2023), confirming both the importance of temporal issues and the need to address them systematically (Vance et al., 2022), their application is heterogeneous and often incomplete.

Recent reviews converge on several conclusions regarding how pLCA handles time. First, temporal differentiations can be represented in process inventories, system inventories, and time-dependent characterization (Sohn et al., 2020). A further critique concerns the imbalance between time and changes at process and system level whose omission can misrepresent the timing and magnitude of impacts (Lang-Quantzendorff and Beermann, 2025). Second, temporal considerations tend to cluster around a limited set of decisions, including time horizon, temporal resolution, discounting, and time-dependent characterization (Lueddeckens et al., 2020).

Circularity represents a further stress for pLCA temporal validity. The mechanisms of circularity, codified in closing, slowing, intensifying, dematerializing and narrowing loops (Geissdoerfer et al., 2018), are intrinsically temporal. A failure to robustly model temporal considerations in pLCA risks producing assessments that are not just inaccurate, but potentially misleading, thereby undermining the ability to guide the transition toward a circular economy.

To address these challenges, this research aims to reveal how pLCA handles time in circularity-oriented assessment addressing these research questions (RQs) relevant to impact assessment quality and decision support:

- RQ1 How is the temporal evolution *operationalized* and applied in the background and foreground systems in circularity-oriented pLCA?
- RQ2 How can temporal evolution be *conceptualized* in the foreground and the background systems in circularity-oriented pLCA and what does this imply for circular strategies?
- RQ3 What *design configurations* recur across circularity-oriented pLCA?

RQ1 examines how CE-oriented pLCA operationalizes temporal evolution in modelling practice, with particular attention to foreground (approaches, scenarios, and elements of change) and background (databases and models). RQ2 investigates how studies conceptualize temporal evolution, i.e., what "time" is assumed to represent in circular assessments, by analyzing whether time is treated primarily as a measure of action (time as resource), as an ordering structure (time as structure), or as a flow of events (time as process), according to Blagoev et al. (2024), and how these choices shape interpretation of circular strategies. RQ3 synthesizes recurring temporal design choices into a set of design configurations that can support appraisal and comparability across CE transition pathways.

This study contributes to advance knowledge in three ways. First, it provides an evidence-based map of temporal evolution modelling in CE-oriented pLCA, highlighting where current studies enable, or prevent, robust interpretation and cross-study comparison. Second, it proposes four recurring temporal design configurations, identified through qualitative synthesis, to translate a fragmented literature into decision-relevant options for structuring time in circular strategies, including how foreground interventions relate to background change. Third, this study formulates a decision rule to select the appropriate configuration and associated reporting requirements based on key temporal indicators (dominant lifetime, loop feedback speed, and sensitivity to future background evolution), thereby strengthening reliability of pLCA as an impact assessment methodology for circular strategies.

Through the manuscript, we refer to the definition of temporal considerations as an "overarching term" representing any "aspect described in relation to the time dimension or dynamic of systems in the LCA framework", as defined in (Beloin-Saint-Pierre et al., 2020), and to the definition of temporal evolution as "the time-based changes in processes, emissions and environmental responses" proposed in Müller et al. (2025 p.3054).

The scope of this research is limited to pLCA, without the intent to intercept the temporal considerations emerging from the application of the dynamic LCA.

2. Methods

This study applies a systematic literature review (SLR), following the method proposed by Durach et al. (2017), which aligns with the study goal of advancing methodological pLCA practices in the field of circular economy. The review process is structured into the following steps: determine required characteristics of primary studies, retrieve sample of potential relevant literature ("baseline sample"), select pertinent literature ("synthesis sample"), and literature synthesis (Durach et al., 2017).

After the literature review, the sample of selected papers was analyzed to detect the main configurations (Ravn Boess et al., 2026) through a further qualitative synthesis (Suškevičs et al., 2023), based on how time is handled (as resource, as structure, and as process) and the elements of changes (production, demand, supply or a combination of these). The results are then discussed more broadly in relation to circularity, drawing on the butterfly diagram (Ellen Macarthur Foundation, 2019) and the key values chains requiring urgent and comprehensive actions (European Commission, 2020).

2.1. Systematic literature review

First, the required characteristics of primary studies were defined through the definition of inclusion/exclusion criteria. The inclusion and exclusion criteria were established to filter the most relevant studies for the review. Only studies that met the following criteria were included: scientific research articles or reviews about pLCA applied in the context of circular economy, written in English. As literature sometimes refers to pLCA using different synonyms (Heijungs, 2024), at this stage also all "ex-ante", "anticipatory", "predictive", "future-oriented" LCA applications were included, to be evaluated case by case. Conference proceeding, or book chapters and studies not written in English were systematically excluded. Second, the baseline sample was retrieved, identifying the studies published in peer-reviewed journals. The search was performed in Scopus and Web of Science in March 2026, without any time filter, and using the following combination of keywords: "("prospective LCA" OR "prospective life cycle assessment" OR "ex-ante LCA" OR "ex-ante life cycle assessment" OR "anticipatory LCA" OR "anticipatory life cycle assessment" OR "predictive LCA" OR "predictive life cycle assessment" OR "future oriented LCA" OR "future-oriented LCA" OR "future oriented life cycle assessment" OR "future-oriented life cycle assessment") AND (circular* OR clos* OR recover* OR recycl* OR narrow* OR dematerial* OR slow* OR intensif* OR refus* OR rethink* OR reus* OR repair* OR refurbish* OR remanufactur* OR repurpos*)" to capture a wide range of relevant studies.

At the conclusion of this step, 170 records were retrieved from Scopus and 166 from Web of Science.

The titles and abstracts of the corpus were screened independently by the authors to determine the relevance of each study to the research questions and overarching aim of the present study. 148 studies out of 170 and 132 studies out of 166 were maintained from Scopus and Web of Science, respectively. After this initial screening, the studies from both databases were combined, and duplicate records removed to ensure that each study appeared only once in the selection process. Following this step, a total of 155 studies were obtained.

The synthesis sample was, then, developed examining the relevance of each paper based on the full-text analysis, going beyond titles and abstract. Full-text articles were thoroughly reviewed to ensure they met the inclusion criteria and were aligned with the overarching aim of the study. At the end of this step, 25 papers were excluded from the analysis because they resulted not pLCA applications and/or were not related to circularity, leading to a final sample of 130 articles. The exclusion of each study was collectively discussed by the research team and based on full agreement of the authors (Baldi et al., 2024). The 130 articles were read in their entirety, during these phase 9 articles were classified as reviews.

The 130 articles included in the synthesis sample were examined separately to identify elements capturing how and under which circumstances connections among past, present and future are addressed in the development of background and foreground systems of the pLCA framework. The review articles were retained as part of the broader evidentiary corpus and informed the contextual framing of prospective modelling issues, including scenario construction, upscaling logic, and recurrent methodological challenges reported in the field. However, they were not included in the in-depth coding used for RQ2 and RQ3, because they did not provide extractable study-level assumptions on foreground–background temporal considerations that could be coded in a manner comparable to individual pLCA applications. In this sense, the reviews informed the interpretation of the field, but not the configuration-building exercise itself. This distinction is consistent with review works that synthesize prospective applications at an aggregate level rather than operationalizing a single study design (e.g., Tsoy et al., 2020). The in-depth analysis was thus conducted based on 121 studies. The complete list of articles analyzed and their main characteristics are shown in **Table S1,** columns 1 and 2 (Supplementary Material).

The literature synthesis was conducted through the following steps. First, the analysis addressed how background and foreground systems are developed in the different studies and linked them to different products/processes analyzed, circular loops (Geissdoerfer et al., 2018), and R-strategies (Potting et al., 2017) creating a map of the main features of background and foreground modelling approaches in case of circularity. The elements included in the background and foreground modelling, such as emerging technologies, policy instruments, or strategic interventions were systematically identified to understand the types of assumptions shaping prospective outcomes. Furthermore, attention was given to the elements used to underly the future scenarios, namely whether the scenarios were structured around shifts in production, demand, supply, or a combination of these. This allowed for an deepen analysis of how each study operationalizes the temporal evolution, *giving an answer to RQ1*.

Second, the temporal considerations were identified and categorized within the studies. This second step was inductive, meaning that the temporal considerations were not predefined in the analyzed studies but emerged from the methodological descriptions presented in the studies (Toniolo et al., 2024). This process allowed to uncover insights into temporal evolution in pLCA, as well as to categorize studies based on temporal considerations. While traditional systematic reviews often rely on predefined categories and fixed coding schemes, recent literature highlights the advantages of using an inductive approach to uncover new configurations, themes, and categories that are not necessarily anticipated by existing papers or frameworks (Durach et al., 2017). This approach is particularly valuable when exploring complex, multifaceted concepts like the temporal evolution in pLCA, which may be treated differently across studies.

This research drew on three lenses commonly used to understand how organizations manage and structure their time: time as resource, time as structure and time as process (Granqvist and Gustafsson, 2016; Rindova and Martins, 2022). Moreover, in order to provide a reference framework for the review, the temporal domains proposed by Blagoev et al. (2024) were adopted according to which: time as resource mirrors the interface between organizations and their external environments, time as a structure represents the reproduction of temporal structures to enable actions; time as a process is seen as a flow of events which interrelates past and future. Drawing on this, the three lenses were translated and elaborated into the context of pLCA, as illustrated in Table 1, and adopted to develop the coding scheme. Each article was interpreted by considering how the system under analysis relates to the background (time as resource), how temporal structuring unfolds within the foreground (time as structure), and how background and foreground interact over time (time as process). A more detailed description of the three lenses is reported in S2 (Supplementary material).

The coding scheme, used to interpret and classify the articles, was then developed through iterative reading, comparison across studies, and collective discussion among the authors. This was necessary because the review did not simply extract predefined variables, but also sought to identify how temporal evolution was conceptualized across heterogeneous pLCA applications. More specifically, the papers were initially

Table 1
Time domains reinterpretation for background and foreground systems in pLCA used to develop the coding scheme.

Temporal lenses	Time definition (Blagoev et al., 2024 p. 2158)	Time domain (Blagoev et al., 2024 p. 2158)	Time domain reinterpreted for pLCA
Time as Resource	"A measurement of action"	"At the interface of an organization and its external environment"	Interface with the background system. Time is interpreted as a mediator between the analyzed systems and the background system, which provide the contextual conditions.
Time as Structure	"A sociotemporal order"	Mostly "intra-organizationally"	Foreground level. Time is interpreted as the temporal structuring of the foreground system itself. Time is embedded within the analyzed system, shaping how product/processes under study unfold over time.
Time as Process	"A flow of events"	"At the level interaction"	Interaction between background and foreground. Time is interpreted as a bridge connecting past and future developments across both foreground and background systems.

read in distributed sets by the authors, and preliminary coding decisions were compared and discussed at regular intervals in order to refine the coding logic, clarify category boundaries, and resolve ambiguities. The coding framework changed substantially between the first and successive rounds of analysis as part of this inductive development process. Earlier coding decisions were therefore revisited in light of the refined criteria, so as to align the full sample with the final analytical structure. Disagreements emerged during collective review of interpretively difficult or borderline cases. These cases were re-examined jointly against the original text of the article and discussed until a shared interpretation was reached. In this sense, consistency was pursued through iterative adjudication, progressive clarification of coding rules, and retrospective alignment of earlier classifications. When reporting in the source articles was incomplete, we used the category "not specified" and did not infer unreported assumptions regarding model structure, scenario design, or time-slice definition. This conservative coding choice was adopted to avoid over-interpretation and to preserve the traceability of the analytical judgments. Evolving the coding scheme iteratively throughout the review process (Durach et al., 2017) with labels being refined, merged, or differentiated as the analysis progressed allowed to reveal how time is conceptualized, *giving an answer to RQ2*.

Table 2 presents the temporal coding scheme applied to the analyzed papers. The table distinguishes between background and foreground time handling and associates each of them with a specific label. An additional column provides a literature-based definition for each label. These definitions were identified through a targeted, non-systematic

Table 2
Coding scheme applied to the analyzed papers.

Temporal lens	Background time handling emerged in the analyzed studies		Foreground time handling emerged in the analyzed studies		Label	Definition	Source
	Developed	Description	Developed	Description			
Time as resource	No	Time is not mentioned	n.a.	n.a.	Temporal Myopia	A limited capacity of considering distant future when acting in the present	Opper and Burt (2021)
	No	Short time horizon	n.a.	n.a.	Short Term	Short temporal distance into the future	Chen et al. (2021)
	Yes	Focuses on a specific moment in the future	n.a.	n.a.	Temporal Focus	Adressing specific time periods	DesJardine and Bansal (2019)
	Yes/No	Considers how stakeholders' needs evolve over time	n.a.	n.a.	Intertemporal Tensions	A tension between short-term and long-term needs	Slawinski and Bansal (2015)
	Yes/No	Includes investment decisions, technology, or policy evolution	n.a.	n.a.	Activity Timing	Routine activities that vary little from one iteration to the next, with connections between actions and outcomes	Desai and Madsen (2022)
	No	Multiple points in the future considered	n.a.	n.a.	Time Compression	Shortening of production and distribution times and the reduction of time-to-market	Demartini and Mella (2011)
Time as structure	n.a.	n.a.	Yes	Multiple points in the future	Temporal Regularity	Pattern in the progression of events over time	Briscoe (2007)
	n.a.	n.a.	Yes	Single point in the future	Temporal Orientation	Arranging future in terms of timing and ordering	Das (1987)
	n.a.	n.a.	Yes	Multiple future points, integrating additional elements beyond core technology	Temporal Coordination	Engaging joint actions to face temporal complexities	Hilbolling et al. (2022)
	n.a.	n.a.	Yes	Multiple points in the future, where time is defined by process duration, not exact clock time	Sequence-based approach	Sequence of actions	Turner and Rindova (2018)
Time as process	Yes	Time evolves with the context	Yes	Single point in the future	Foreseeing	Envisioning of future events including social economc and political aspects	Flyverbom and Garsten, 2021
	Yes	Time evolves with the context	Yes	Multiple points in the future	Trajectory	Course of a phenomenon as it changes over time	Oborn et al. (2019)
	No	Independent from the foreground	Yes/No	Not specified	Long Present	An extended present	Kim et al. (2019)
	Yes	Shock analysis (disruptions in the context)	Yes	Scenario analysis (considering different future outcomes)	Discontinuity	A disjunction between the past and the present or future	Ybema (2010)

search of relevant academic papers. Based on this coding, 14 labels were selected, identified among the temporal exemplary concepts proposed by Blagoev et al. (2024). Each paper was screened and analyzed following the structured and transparent coding scheme in line with PRISMA-style recommendations for systematic reviews (Page et al., 2021).

2.2. Temporal configurations

To synthesize recurring temporal designs, we developed temporal design configurations through an iterative qualitative synthesis of the coded material. We examined how the three temporal lenses, time as resource, time as structure, and time as process, are combined with the elements leading change (production, demand, supply, or their combinations) across studies. Configuration descriptions were refined through iterative comparison, including the examination of borderline cases, to ensure clarity and internal distinction. The resulting configurations constitute a descriptive typology *addressing RQ3*. The typology is an interpretive, decision-oriented synthesis.

3. Results

The presentation of the results is organized as follows: first, how the temporal evolution is operationalized within pLCA in case of circularity is presented, focusing on how time is applied for background and foreground systems modelling and addressing RQ1 (Section 3.1); second, how temporal evolution is conceptualized across the background and foreground is presented and the meaning which can be attributed with reference to circularity giving an answer to RQ2 (Section 3.2). Finally, configurations in the conceptualization of the temporal evolution are presented, based on elements leading the changes (elements in production, in supply or in demand or a combination of these), as illustrated in Section 3.3.

3.1. Operationalization of the temporal evolution

Within the corpus of literature analyzed, most of the sample (83%) targets material recovery and recirculation typical of closed loops, while only a small share addresses 'slowing' (≈6%), 'intensifying' (≈6%), and 'narrowing' (≈2%); only three cases (≈3%) resulted not classifiable. Notably, we observe no explicit 'dematerializing' cases (service/substitution models). Among the R-strategies, most of the sample addresses R8-Recycling (63%), followed by R2-Reducing (14%) and R7-Repurpose (8%).

The elements used to structure prospective scenarios are predominantly technology centered, namely applied in 56 studies, followed by process-oriented studies (8) and product-focused studies (3). Combinations that pair technology with system context, e.g., technologies/supply/energy-system changes, technologies/demand forecasts, technologies and supply, or technologies/demand/energy systems/supply, appear only in a few of cases (mostly singletons or 2–3 instances each). These results show that prospective scenario in the circular economy context is led mainly by technological change and process choices, with supply/demand and energy-system linkages referenced less frequently and typically at case-study granularity rather than as a dominant structuring dimension.

Over half of the pLCA cases are production-driven (73/121; 60%), indicating that most scenarios hinge on process scale-up, efficiency learning, and cleaner energy inputs rather than market pull. A further 21% are supply-driven (25/121), consistent with pathways constrained by feedstock availability and critical-material recovery. Mixed demand–supply drivers are limited (7%), while purely demand-driven cases are rare (5%), reflecting the higher uncertainty of future adoption rates in prospective modelling. Only 2% combine demand or supply with production explicitly; one case combines demand and production; one case combines supply and production.

Specifically, the analysis considered the background database employed, such as Ecoinvent (Wernet et al., 2016) or other datasets, and the approach applied to background system modelling, including the use of integrated assessment models like REMIND, IMAGE, TIAM-UCL, GCAM, MESSAGEix, and including models developed by the authors of the selected studies themselves, unchanged static backgrounds, or cases where the modelling approach was not specified. For the foreground system, the presence or absence of an explicit scenario was noted, along with a description of its main characteristics when available. Most papers do not state which background model they use (69/121;~57%), and, more importantly for prospective interpretation, few clearly report the time frames/slices (e.g., 2030/2040/2050) and the scenario settings they rely on. Among the specified cases, 20 use author-developed backgrounds (~ 16%), 13 use IMAGE (~11%), 9 use REMIND (~7%), and 8 cite other models (~6%). This reporting gap matters because prospective results depend on when the background is sampled and which pathway (e.g., SSP/RCP or temperature target) underpins grid decarbonization, fuel mixes, and material production. Without explicit time slices, verifying whether near-term or long-term changes are considered is difficult; without scenario labels, it is unclear whether benefits arise under ambitious or moderate transitions.

Out of 121 studies, 101 explicitly report foreground management employing the following recurring approaches: (1) scale-up / upgrading (e.g., scale-up and scenario analysis, "upgrading, upscaling framework applications upscaling from lab to pilot scale), (2) process engineering and simulation (e.g. process simulation, process simulation using AspenPlus, process modelling and scale up, process calculation using scaling and extrapolation), (3) Scenario-driven evolution (e.g., scenario analysis, scenarios of recycling, scenario analysis based on regional policy changes and technological end-of-use options, applying technological learning effects), (4) Stock/flow coupling (e.g., dynamic stock-and-flow models, dynamic Material Flow Analysis coupled with the pLCA, application of different scenarios assessed through dynamic Material Flow Analysis), (5) Optimization (e.g., Mixed Integer Linear Programming (MILP) optimization model), and (6) empirical/industry-grounded inputs (e.g., data obtained from company or collected from the scientific literature and technical reports, technical data sheets about operating conditions, extrapolating from the best-achieved lab results). A small subset explicitly states no specific foreground system handling. Overall, the reviewed studies predominantly manage the foreground via scale-up and process simulation, often complemented by scenario analysis and Material Flow Analysis, with a few cases using optimization or industry datasets to shape prospective pathways. This pattern is consistent with prior review evidence on prospective LCA, where foreground modelling is commonly organized around projected technology scenarios, projected LCA flowcharts, and projected data estimation during upscaling (Tsoy et al., 2020). The prominence of scale-up, process simulation, and scenario-driven evolution in our sample therefore aligns with established prospective modelling practice, while showing how these choices are reconfigured in CE-oriented applications. Detailed coding results are reported in **Table S1** from column 3 to column 13 (Supplementary Material).

3.2. Conceptualization of the temporal evolution

The temporal considerations discussed in the studies were systematically analyzed in terms of the three lenses (time as resource, time as structure, time as process). Collectively, the analyzed studies present several differences in addressing the temporal considerations in the background and foreground systems. These variations demonstrate the diverse ways in which time evolution is conceptualized in pLCA studies. Detailed coding results are reported in **Table S1** from column 14 to column 16 (Supplementary Material).

The *time as resource* approach emerges in the analyzed literature through a variety of articulations, each capturing a different facet of how time interface between the system under study and its broader context.

In some cases, the temporal interface is analyzed within a limited time horizon as exemplified by (Raugei and Winfield, 2019), who apply conservative estimates based on projected process improvements, assuming that production will scale to full commercial levels in short-term. In such cases, the focus is placed on immediate technological development rather than long-term system transformation. A similar approach is adopted by Villares et al. (2016), who scale a laboratory system to an industrial level using a 'what can happen' scenario. Comparable short-term approaches can also be found in Villares et al. (2017). Emphasis on specific future temporal focus is given in several studies, as exemplified by Adrianto et al. (2023), who target a policy milestone year, focusing on technology scale up at a defined moment and by Alaux et al. (2024) analyzing the future evolution of electricity, energy and transport market mix but also scaling up by 2035. Comparable approaches applying a specific temporal focus are found in other 14 studies. Evolving stakeholder needs over time are discussed in Šimaitis et al. (2023) who explore how future recycling benefits of lithium-ion batteries are accounted for, highlighting the intertemporal tensions between current impacts and long-term end-of-life credits and showing that background assumptions about future recycling efficiencies can significantly distort present-day assessments, underscoring the importance of carefully aligning temporal dimensions evolving background systems. Schmidt et al. (2024) assessed the environmental trade-offs of PVC window profile recycling in Germany, revealing intertemporal tensions between short-term recycling burdens and long-term material recovery benefits. They show that environmental outcomes depend heavily on when and how future recycled material displaces virgin production. Similar analyses highlighting intertemporal tensions appear in other 10 studies. A temporal lag preceding or following a key decision or action, is central in Gonella et al. (2025), which adopt a scenario-based approach to model the background system, in order to account for anticipated developments in the energy and industrial sectors that supply inputs to production with an activity timing vision. A similar vision is applied by Huber et al. (2024) which scenario is compatible with a decarbonization pathway to reflect changes in energy production, electricity mix, technological efficiency. Related studies applying an activity timing vision are Heidak et al. (2025), Kręt-Grześkowiak et al. (2024), Liu et al. (2024), Mao et al. (2024), Raugei et al. (2021), Rossi et al. (2023). In some other studies, the impacts are evaluated at different years (e.g., 2030, 2040, 2050), allowing for a compressed view of future scenarios within a single assessment framework involving multiple future points in a condensed timeframe (Lundie et al., 2004; Arfelli et al., 2023). These approaches reflect the use of time compression to capture evolving background conditions and technological performance over time. In other cases, time is omitted or implicitly considered, analyzing environmental impacts without explicit temporal considerations in a sort of temporal myopia (Blagoev et al., 2024). They represent the majority of the studies analyzed.

With reference to *time as structure*, papers identify distinct approaches to structure time in future-oriented foreground systems. Some studies emphasize the importance of considering multiple future points with temporal regularity. For instance, Raugei et al. (2021) analyze the system's evolution at multiple future time points (2025, 2030, etc.) and Rincon et al. (2025) assess the process environmental impact at three distinct future time points (2023, 2030, and 2038), modelling a progression of impacts as the German electricity grid decarbonizes over time with regularity. Similar analyses appear in other 9 studies. Other studies adopt a future modelling connected with a clearly defined future state. Ravi et al. (2022) orient their analysis toward a single future state defined by the implementation of a new regional policy for sludge management (post-2026), while Papageorgiou et al. (2024) orient the analysis toward a single future point in time (2030) and evaluate different strategies for that target year. This reflects a temporal orientation toward achieving a specific future state. Similar approaches are also evident in other 54 studies. Other studies approach the future as a network of temporal coordinated moments, using different lifespans and structural elements (Kręt-Grześkowiak et al., 2024) and assessing institutional policy frameworks and aligning innovation pathways with policy agendas (Bruno et al., 2022). A temporal coordination among different moments and events is employed in 22 other analyzed papers. Some studies conceptualize time through the duration of processes rather than fixed dates, in a sort of sequence-based approach. Bartolozzi et al. (2020) and Behjat et al. (2025) exemplify this approach by framing technological evolution as a series of stages, a view adopted in other 33 analyzed studies.

The *time as process* approach emerges across the literature in several distinct ways. Several papers emphasize how time unfolds in relation to contextual developments, typically projecting toward a single future point. For example, Papageorgiou et al. (2024) use a retrospective analysis of the current urban system (2021) to foresee the creation and assessment of multiple potential future scenarios for 2030. Mediboyina et al. (2024) execute diverse scenarios analyses with different percentages to modify the national mix so they adopt a foreseeing approach by linking present trends to a defined future horizon. Other 25studies employ a foreseeing approach. A different approach can be identified in works that examine continuous future points with a sort of trajectory. Mao et al. (2024) is illustrative of this view, outlining a desirable future scenario, and also Mastrucci et al. (2024) who use a dynamic stock-and-flow model to the continuous evolution of China's building stock from 2020 to 2060. The results are presented as trajectories of change over time, viewing the future as an ongoing process connected to the present. Other 23 papers also align with this approach. In some studies time is not directly tied to short-term developments but instead emphasizes as a long present. Arfelli et al. (2023) assess technology at an early stage to full scale up implementation, and Magrini and Jagodzińska (2022) assess a current lab-scale concept to construct and evaluate a potential future pilot-scale reality. Other 70 studies also resonate with this temporal framing. A discontinuity perspective emerges in studies which explore temporal breaks or disruptions, often through scenario analysis that considers divergent outcomes. Alaux et al. (2024), Heidak et al. (2025) and Styles et al. (2022) exemplify this by addressing critical uncertainties and potential disruption.

3.3. Temporal configurations

Four configurations emerged from the analyzed studies (Table 3). The assignment of individual studies to each temporal design configuration is reported in **Table S1** last column, in the Supplementary Material.

Configuration 1 ($n = 31$) groups studies where *time as structure* emphasizes sequencing/duration (staging) and *time as process* is long-present, with change primarily production-driven and limited conceptual attention to evolving system contexts. Background inventories are overwhelmingly drawn from Ecoinvent and are typically left unchanged, while the foreground is explicitly managed in the majority of studies and operationalized through light scenario work or scale-up routines centered on the target technology. Scenario elements are correspondingly technology-centric, with little explicit coupling to market, supply, or energy-system trajectories. Studies belonging to Configuration 1 tend to treat the future largely as an extension of the present: time is made explicit mainly in the foreground (staging, duration or a single anchor year) while background changes are weak or implicit. This design supports rapid technology option screening but risks temporal myopia when system context is changing.

Configuration 2 ($n = 19$) groups studies where *time as structure* and *time as resource* emphasize multi-period coordination/regularity and intertemporal tensions, with change led by demand or supply, but with limited conceptual integration of disruptive regime shifts. Foreground changes are consistently managed, and background dynamics are often represented by author-developed models or by explicit coupling to IMAGE and REMIND; scenario frames combine technology pathways with demand, supply, and, in a subset, energy-system change, revealing

Table 3
Temporal design configurations emerged from the analyzed studies.

Configuration	Size (n of papers out of 121)	Element leading the change over time	Temporal flow (connecting present and future)	Temporal order	Temporal action	Scenario elements	Use case
1 Technology centric long-present based	31	Production	Long-present stance	Sequence-based approach (duration/staging)	Temporal myopia (weakly time-differentiated)	Technology-centric; limited coupling to supply/energy	Rapid technology adoption screening but without capturing changes at system level
2 Technology oriented trajectory based	19	Demand/ Supply	Trajectory-oriented	Coordination + regularity over multiple time points	Intertemporal tensions; activity timing explicit	Technology + demand + supply (+ energy subset)	Comparison across options under a defined future state but without capturing timing effects
3 Technology oriented long-present based	44	Production	Long-present stance	Temporal orientations (single future anchor)	Temporal myopia (weakly time-differentiated)	Technology + supply/energy links	Rapid technology adoption screening depending on stocks, lifetime distributions and delayed feedbacks
4 System oriented foreseeing based	27	Mixed	Foreseeing stance	Temporal coordination or orientation across system layers	Temporal focus; explicit timing assumptions	Technology + demand/supply + energy-mix evolution	For robustness-oriented impact assessment, but requires explicit transparent reporting of scenario assumptions, time anchoring, synchronization rules

a structurally temporal view of system transformation. Studies belonging to Configuration 2 are predominantly demand/supply-driven and distinctly trajectory-oriented; its foreground shows a balance of temporal coordination and temporal regularity, while background modelling is split between intertemporal tensions and activity timing. This configuration reflects studies that trace multi-point pathways and make the temporal structure of change explicit. It supports comparison across multi-period pathways, but often represents change as a set of time-sliced states rather than modelling within-life-cycle timing and feedback effects explicitly.

Configuration 3 (n = 44) groups studies where *time as structure* is anchored to temporal orientations (single target year/milestone) and *time as process* is long-present, with production-driven change and a focus on implementing interventions within a defined decision horizon. The temporal approach remains largely discrete, and background modelling is again mostly static relative to the baseline database; scenario descriptions broaden beyond pure technology, adding selective links to supply and energy elements without fully synchronizing them across time. Studies belonging to Configuration 3 often concentrate on temporal orientations, single, fixed future points used as decision anchors. Background dynamics are often implicit or minimized. These studies tend to scale technologies forward while holding crucial elements of the context weakly time-differentiated. This configuration could be used for slowing/remanufacturing only when stock/lifetime distributions are explicitly modelled in the foreground; otherwise, it risks collapsing residence-time effects.

Configuration 4 (n = 27) groups studies where *time as process* is foreseeing (explicit future change) and the concepts indicate coordination between intervention timing and evolving system contexts (e.g., energy mix, markets, policy), often with mixed demand/supply drivers. These papers often couple managed foreground changes with background models that are more frequently parameterized using integrated assessment or energy-system frameworks (e.g., IMAGE or REMIND alongside author-developed structures). Scenario elements extend beyond the focal technology to incorporate supply and energy-mix evolution, indicating a more explicit coordination of timing assumptions across system layers. Studies belonging to Configuration 4 split among production driven, supply driven and demand driven cases, it adopts a foreseeing relational stance and combines temporal coordination in the foreground with a pronounced temporal focus. It is useful for robustness-oriented impact assessment, but requires transparent reporting of scenario assumptions, time anchoring, and synchronization rules.

Table 4 presents a typology that locates the configurations along (i) temporal representation (snapshot vs pathway) and (ii) foreground–background coupling (weak vs strong), proving a map of the four configurations onto two cross-cutting dimensions; it does not constitute an independent classification procedure. We considered foreground–background coupling “partial” when background evolution was explicitly specified and time-anchored (e.g., via time slices or scenario labels) in a way that was consistent with the foreground implementation. This included cases where only selected background elements (e.g., electricity mix or market context) were aligned to the same temporal framing as the foreground. Fig. 1 represents the three temporal lenses used to interpret time in circularity-oriented pLCA and their synthesis into temporal design configurations.

Table 4
Temporal design configurations identified.

	Weak foreground–background coupling	Partial foreground–background coupling
Snapshot	C1 Technology centric long-present based	C3 Technology oriented long-present based
Pathway	C2 Technology oriented trajectory based	C4 System oriented foreseeing based

4. Discussion

The appropriateness of a temporal design configuration depends on the speed of feedbacks and asset lifetimes in a given value chain: where products turn over rapidly and interventions mainly affect near-term substitutions, simpler temporal designs can be proportionate; where stocks are long-lived and benefits depend on delayed returns, quality trajectories, and system transitions, pathway-based designs can be necessary. Where asset lives are short and feedbacks fast, most clearly in packaging and several plastics applications, the dominant questions are near-term substitutions and operational levers. In these contexts, foreground-focused designs typical of studies belonging to Configuration 1 and 3 can be proportionate for decisions within a 3–5-year window, however, even short-horizon claims are not background-neutral: electricity, waste-management conditions, and market-mediated substitution can materially shift results, making explicit background specification and sensitivity analyses essential (Saavedra Del Oso et al., 2023; De Souza et al., 2023).

Drawing on key value chains requiring urgent and comprehensive actions (European Commission, 2020) and the technical wing the butterfly diagram (Ellen Macarthur Foundation, 2019), Electronics/ICT

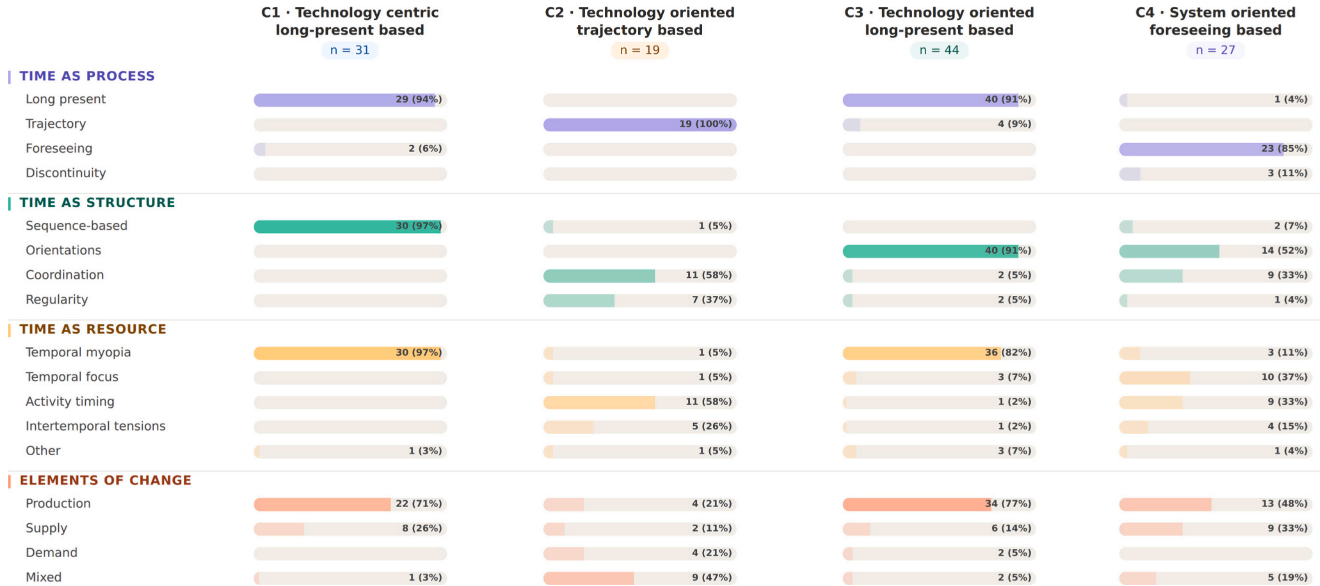

Fig. 1. Three temporal lenses used to interpret time in circularity-oriented pLCA and their synthesis into temporal design configurations.

studies are characterized by rapid turnover, and substitution benefits depend on return-lag distributions, WEEE collection, and types of alloys. In this setting, Configuration 1 and Configuration 3 could contribute to design-for-repair and component-harvesting for the next cycle; credible claims about high-value recycling or reuse streams require modelling that align modularity, take-back logistics, grade retention operational rather than implicit (García-Cruz et al., 2022; Heiho et al., 2023). By contrast, chains governed by long lifetimes, as construction and buildings, textiles, batteries and vehicles, and food–water–nutrients, require the temporal conceptualization captured by Configuration 2 and especially Configuration 4, because benefits emerge through delayed returns, stock-driven flows, and co-evolution with background transitions (Alaux et al., 2024; Mastrucci et al., 2024). For textiles, slowing strategies (repair, resale, rental) interact with closing strategies (fiber-to-fiber) through underutilization and logistics dynamics (Arfelli et al., 2023). For batteries and vehicles, second-life applications that introduce an additional temporal window that can compete with, or complement, material recovery; credible appraisal therefore needs designs that can represent allocation of service over time and the timing of avoided production versus delayed recycling benefits (Rossi et al., 2023; Ginster et al., 2024).

Finally, in the biological wing (Ellen Macarthur Foundation, 2019), including food, water, nutrients, timing is often the dominant mechanism: biogenic-carbon dynamics, nutrient cycling, seasonality, and methane-abatement policy effectively “set the clock”. Assessments that keep agriculture and energy static misplace burdens and credits across time, while Configurations 2 and 4 can operationalize residence times, seasonal mismatches, and delayed substitution in ways that are directly relevant for impact assessment and policy appraisal (Bruno et al., 2022; Papageorgiou et al., 2024; Huber et al., 2024).

For impact assessment practice, the key risk is not choosing a ‘wrong’ configuration, but applying a configuration misaligned with the dominant mechanism in the value chain (process timing vs transition timing) without transparent reporting of background model, time anchoring, and synchronization rules. Choosing a temporal design configuration is not a neutral modelling detail. The identified temporal configurations also have implications beyond model construction, because they condition what can be credibly appraised in policy and regulatory contexts. In particular, configurations based on weak foreground–background coupling and snapshot representations are more suitable for rapid option screening, early-stage comparison, or appraisal settings in which the main concern is the relative direction of impacts under a defined future state. However, they are less suited to situations in which the appraisal depends on delayed effects, evolving infrastructures, policy-driven background transitions, or feedbacks between circular interventions and system context. By contrast, pathway-oriented and more explicitly coupled configurations are better able to support policy appraisal where timing, sequencing, and background evolution are integral to the decision problem, for example when the environmental performance of a circular strategy depends on future electricity mixes, material supply, collection systems, or substitution effects. In this sense, temporal configuration is not merely a modelling preference, but a determinant of appraisal capacity: it shapes whether an assessment can address near-term screening, transition pathways, delayed benefits, or policy-dependent system change in a transparent and decision-relevant way.

The proposed decision rule can therefore be positioned as a scoping device within established appraisal workflows. Before selecting databases, scenario logic, or foreground modelling detail, the LCA practitioners can use the rule to determine whether the case is primarily a snapshot or pathway problem, and whether weak or partial foreground–background coupling is sufficient for the stated decision context. In practical terms, this means that the rule can be applied immediately after goal and scope definition, when the appraisal question, intervention horizon, asset lifetimes, loop speed, and expected sensitivity to background evolution are first clarified. Used in this way, the rule helps align the temporal design of pLCA with the needs of policy appraisal, regulatory assessment, or strategic environmental assessment by making explicit what type of temporal consideration is required and what level of temporal evolution between foreground and background is proportionate to the decision at hand.

The decisional rule, illustrated in Table 5, is proposed to align temporal choices with asset lifetimes, the speed of feedbacks, and the extent to which results depend on evolving background conditions (energy, supply, demand, infrastructure).

5. Conclusions

This review shows that time is frequently treated as an implicit or inconsistently reported modelling choice in CE-oriented pLCA, with direct implications for impact assessment credibility, interpretability, and comparability of evidence used to appraise circular strategies. Three findings are particularly relevant for practitioners and researchers. First, CE-oriented pLCA evidence is strongly skewed toward material recovery

Table 5
Decision rule for selecting temporal configuration and reporting requirements.

Step	Criteria
1. Define and report main temporal indicators	• Dominant lifetime (DL): Low (<5 years); Medium (5–15 years); High (>15 years). • Circular loop feedback speed (FS): Fast (e.g., reuse/repair, rapid refurbishing); Medium (e.g., remanufacturing of durable goods); Slow (e.g., building/ infrastructure stocks, large-scale plants). • Sensitivity on future background evolution (FB): Low (future changes in the background are unlikely to materially affect results); High (results are sensitive to background evolution, e.g., decarbonization pathways, technology change, material supply/ availability, demand).
2. Select temporal framing: Snapshot vs Pathway	Choose PATHWAY if DL is High or FS is Slow or the decision horizon ≥10 years. Otherwise, SNAPSHOT can be appropriate.
3. Select coupling: Weak vs Partial foreground–background coupling	Choose PARTIAL coupling if FB is High (and/or circular strategies plausibly affect demand/supply/technology conditions). Otherwise, WEAK coupling.
4. Minimum reporting requirements (by configuration)	**Snapshot + Weak coupling**: report base year; background database/model name and version; justification for static background and for using a single-year snapshot. **Snapshot + Partial coupling**: report base year; background database/model name and version; justification for using a single-year snapshot plus substitution rules; key assumptions related to the driver leading the change (as modelled); sensitivity on related parameters (e.g., substitution ratios, scrap quality/ availability). **Pathway + Weak coupling**: report time horizon; time slices (years); what changes per slice (foreground vs background); synchronization rule between foreground and background (same-year / lead–lag / averaging window). **Pathway + Partial coupling**: report all items above plus coupling statement; substitution/allocation rules; sensitivity/ uncertainty on coupling drivers (e.g., decarbonization rate, material constraints).

and recirculation, while slowing, intensifying and narrowing strategies are seldom assessed and dematerialization/service substitution is absent; this imbalance risks narrowing the evidence base available for policy and strategic appraisal of circular transitions. Second, temporal handling is often asymmetric between foreground and background systems: while foreground changes are commonly parameterized, background trajectories are frequently underreported: 59/121 (57%) do not specify the background model and many studies omit explicit time slices or scenario naming, undermining cross-study comparability and the auditability expected in impact assessment. Third, synthesizing the coded evidence yields four practical temporal design configurations that can guide study design and interpretation: (a) time designs with weak foreground–background coupling with single-point temporal representation useful for rapid technology adoption screening but without capturing changes at system level, (b) weak foreground–background coupling with pathway temporal representation applicable for comparison across options under a defined future but does not capture timing and sequencing effects along the pathway, (c) partial foreground–background coupling with single-point temporal representation, which can be applied for rapid technology adoption screening depending on stocks, lifetime distributions and delayed feedbacks, (d) partial foreground–background coupling with pathway temporal representation useful for robustness-oriented impact assessment, but requires transparent reporting of scenario assumptions, time anchoring, and synchronization rules.

In the following cases temporal modelling choices can proportionate or misleading. They can be proportionate for near-term screening when decisions hinge on short lifetimes and fast feedbacks, and background change is unlikely to alter rankings (e.g., incremental substitutions in mature systems). They can be potentially misleading when benefits depend on delayed returns, quality degradation/retention across cycles, or system transitions, because simplified designs can misplace burdens and credits over time.

For impact assessment practice, the central implication is that temporal evolution should be treated as part of the assessment design, explicitly justified and reported, rather than as hidden modelling detail. We recommend that CE-oriented pLCA studies (1) always disclose the background model and the scenario source; (2) specify the time horizon, time-slicing, and scenario labels used for both foreground and background; and (3) document the synchronization rule linking foreground implementation to background change (e.g., whether foreground adoption precedes, follows, or co-evolves with energy and market transitions). The proposed decision rule provides an operational and replicable guide to select and transparently report time-related assumptions relevant for circular loops and background evolution, translating temporality from an implicit modelling choice into an explicit one and improving pLCA for decision making on circular economy strategies.

Where pLCA is used for policy or investment appraisal, studies should explicitly state time anchoring and disclose how background conditions evolve (scenario labels/time slices and foreground–background alignment), enabling auditability and systematic sensitivity testing.

Future research should expand temporal designs suitable for underassessed circular strategies (especially slowing and demand-side change) and develop shared reporting standards that enable more robust comparison of circular transition pathways in impact assessment. Time configuration choice determines which temporal mechanisms enter or drop out of the assessment (e.g., implementation lags, quality trajectories across cycles, and foreground–background alignment) and, consequently, which impact shifts over time.

Overall, the results reveal a strong focus on technology-centric scenario building. This suggests a potential avenue for further investigation to better capture the socio-technical nature of circular transitions. Some inherent limitations of the study need to be acknowledged. Although the coding procedure was structured, collectively discussed, and iteratively aligned, some degree of interpretive judgment remains, particularly where primary studies provided incomplete reporting of temporal assumptions, background models, or scenario structure.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eiar.2026.108478.

Data availability

This research is a systematic literature review, the list of references and coding are reported in Supplementary Material

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