

Critical assessment of the scope and applicability of circularity indicators for the sustainable life cycle management of wind turbine blades

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ARTICLE INFO

Editor: Prof. Shabbir Gheewala

Keywords:

Circularity assessment
Composites
Decommissioning
End-of-life management
Wind industry
Wind turbine blade recycling

ABSTRACT

The decommissioning of wind turbines is expected to generate large volumes of composite wind turbine blade (WTB) waste that should be handled properly to avoid negative effects on the environment. Despite the growing interest in sustainable life cycle management (LCM) strategies applicable to WTBs, circularity indicators are still rarely used to support decision-making processes. This study addresses this gap by evaluating the scope and practical applicability of circularity indicators across WTB-LCM pathways, stages, and processes. A systematic literature review was conducted covering 158 peer-reviewed papers and identifying 120 circularity indicators, which were subsequently screened using three complementary matrices (extended RACER, circular composite design, and wind sector-specific criteria). This process led to the selection of 13 indicators considered most relevant to the wind industry. Although no single indicator comprehensively captures circularity across all stages and dimensions, the Materials Efficiency Metric was identified as the most suitable for the beginning and middle stages of the life cycle, while the Carbon Footprint Formula was considered most appropriate for the end-of-life stage. Nonetheless, both exhibit relevant limitations for decision-support in practice, as none of the selected indicators fully captures composite-specific quality parameters, such as fibre degradation, resin compatibility, or the potential for reintegration into high-value applications. Building on these findings, the study identifies three main directions for future research: (i) the development of circularity indicators that incorporate overlooked life cycle stages, such as installation, operation and maintenance; (ii) the integration of material quality parameters, such as fibre integrity and resin compatibility, into the design of new indicators; and (iii) the analysis of empirical case studies to determine the maximum circularity performance that could be achieved across the LCM of WTB, in order to support the development of circular innovations. These areas are essential for advancing more comprehensive, system-level assessments and supporting effective strategies for the sustainable energy transition.

1. Introduction

The European Union (EU) has set the goal to achieve carbon neutrality, aiming to supply 32% and 48% of its total electricity requirements with renewable energy sources (RES) by 2030 and 2050, respectively (European Commission, 2023). In this context, wind energy is one of the fastest growing RES and the EU seeks to increase its capacity from 18.3 GW (2023) to 393 GW (95%) by 2030 and 1300 GW (98%) by 2050 (Costanzo et al., 2024).

However, wind turbines (WTs) have a relatively short operational lifespan (20–25 years), creating difficulties, particularly in managing

wind turbine blades (WTBs) at their end-of-life (EoL) (Diez-Cañamero and Mendoza, 2023). WTBs are made from a complex mixture of materials, including glass and/or carbon fibres, thermoset composites, balsa wood and/or foams, and several coating and metals (Mishnaevsky et al., 2017). This complexity, combined with the growing size and weight of WTs, and the irreversible nature of thermoset composites, makes their recycling both technically and economically challenging (Kazemi et al., 2021).

Therefore, the sustainable life cycle management (LCM) of WTBs is being targeted by industry professionals, researchers and policymakers as a key area for circular innovation (Mendoza et al., 2022). It is

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<https://doi.org/10.1016/j.spc.2025.09.010>

Received 3 March 2025; Received in revised form 12 September 2025; Accepted 19 September 2025

Available online 24 September 2025

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estimated that WTb waste could account for 66,000 tonnes in 2025 (Schmid et al., 2020) up to 570 Mt by 2030 in the EU alone (Liu and Barlow, 2017). Some EU countries, such as Germany or Finland (Chatziparaskeva et al., 2022), have banned WTb landfills, to promote sustainable choices based on the hierarchy of circular economy (CE) strategies (Konietzko et al., 2020) and the so-called R-solutions (refuse, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, recover, remine) (Reike et al., 2022).

The implementation of CE strategies for sustainable WTb-LCM can be used to minimise resource extraction, while efficiently managing upcoming waste streams to reduce environmental impacts (Diez-Cañamero and Mendoza, 2023). This can be achieved through: i) narrowing resource loops (reducing material consumption), ii) slowing resource loops (extending products and materials lifecycles), iii) closing resource loops (recycling materials) and iv) regenerating resource flows (maintaining sustainability across generations) (Konietzko et al., 2020; Mendoza et al., 2022). Consequently, the assessment of alternative circular and sustainable WTb-LCM (especially focused on design, manufacturing waste and EoL management), has emerged as a topic of interest for academic and industrial research, within the framework of the EU CE Action Plan (European Commission, 2020).

2. State of the art

Focusing on alternative WTb design, Mishnaevsky et al. (2017) examined the materials used in WTbs (glass fibres, carbon and hybrid composites), including their properties, manufacturing methods and challenges associated with degradation during operation. They highlighted the need to automate manufacturing to reduce costs, improve quality and address the challenges of increased size while maintaining sustainability and structural integrity. Bonou et al. (2016) proposed an eco-design framework for WTbs, which applied of the life cycle assessment (LCA) (ISO, 2006). According to the authors, this approach can identify environmental hotspots and improvement opportunities in high impacts WTb materials and manufacturing. Previous studies do not include circularity indicators to assess WTb design efficiency, which prevents the identification of material improvements from another perspective complementary to LCA.

Several authors have investigated strategies to reduce WTb manufacturing waste. Oliveira et al. (2020) analysed the incorporation of WTb manufacturing waste into Portland cement mortar production, reducing dependence on natural resources and enhancing waste recovery. In contrast, Hao et al. (2020) study the use of recovered carbon fibres from WTb in high-value applications to close the material cycle. They identified economic, technical, and regulatory barriers and emphasises the need to expand the use of recycled fibres in new applications. Additionally, Psomopoulos et al. (2019) examined WTb waste management from a CE perspective, focusing on recycling technologies such as pyrolysis and mechanical recycling. However, the lack of markets for recycled materials and the technical and economic challenges of these technologies have hindered progress in this area. Despite these advances, the aforementioned studies lack a systematic approach that integrates circularity and LCA indicators to assess resource efficiency across recovery strategies. Incorporating these indicators would allow for a more comprehensive and scalable circularity assessment, to support the development of economically and environmentally viable solutions for WTb manufacturing waste.

As regards EoL management, Beauson et al. (2022) reviewed various WTb-EoL management pathways, including dismantling, reuse, recycling, and material recovery, highlighting the importance of conducting LCA to identify the most environmentally sustainable options. Nevertheless, the study did not employ circularity metrics to obtain additional insights into resource efficiency. Similarly, Lund and Madsen (2024) emphasised the need for further empirical studies on the WTb-EoL value chain, particularly regarding the development of standardised dismantling guidelines. Although their proposed roadmap outlines a framework

for sustainable WTb-EoL management, it lacks methodological guidance for conducting quantitative scenario comparisons and does not offer a specification of the most appropriate circularity indicators for assessment.

In a complementary approach, other studies analyse EoL management, focusing on circularity and LCA. Morini et al. (2021) analyse the environmental impact of WTbs using energy and carbon footprint indicators to support material selection in the design stage. Their findings demonstrate that replacing the resin with an epoxy/glass fibre resin significantly reduces embodied energy and carbon footprint. However, the study focuses only on energy-related indicators and system footprint, without incorporating complementary circularity indicators that assess material efficiency. Integrating additional indicators would enhance the analysis by accounting for resource optimisation and the sustainability of the system's life cycle.

In another study examining WTb repurposing, Nagle et al. (2022) evaluate three scenarios for carbon footprint reduction, stressing the importance of integrating CE strategies into material repurposing to maximise environmental and economic benefits. However, the analysis relies exclusively on the LCA methodology, which limits its scope, as LCA studies alone may not cover technical and quality specifications for products. Combining uenvironmental indicators and circularity indicators to provide a more accurate view of the resource and environmental impacts of products (Picatoste et al., 2024).

More recently, some studies have begun to apply circularity indicators to the assessment of wind energy technologies. For instance, Gast et al. (2024) assessed the circularity of three onshore WTbs in Germany by calculating a technology-level Circularity Index (CI) (Cullen, 2017) based on material flow analysis and energy inputs. Similarly, Adibi et al. (2017) proposed and applied a Global Resource Indicator (GRI) within a case study focusing on WTbs to complement LCA methods in evaluating resource availability. The GRI encompasses dimensions of scarcity, recyclability, and geopolitical availability, thereby providing a more nuanced evaluation of material circularity. Vestas (2019) incorporated circularity considerations into its LCA of the V117-4.2 MW WTb by calculating a Material Circularity Indicator (MCI) (Goddin et al., 2015). Although calculated independently of impact categories, the MCI provided significant insights into the potential for material recovery and reuse. Furthermore, expanding upon this trend, Demuytere et al. (2024) conducted a prospective circularity analysis on the decommissioning phase of an offshore wind farm in the North Sea. The research introduced a novel set of circularity indicators that concentrated on material flows and EoL destinations. This study underscores the disparity between materials and components concerning circular performance, emphasizing the necessity for material-specific collection or recycling targets to mitigate resource loss and enhance circular decommissioning pathways. Additionally, Kasner (2022) developed an integrated environmental efficiency indicator to assess material use across the life cycle of a wind farm. The indicator establishes a relationship between environmental inputs (emissions and cumulative energy demand) and the output of electricity generation, enabling a time-dependent evaluation of material efficiency across life cycle stages. It was applied within a wind farm case study, combining this novel metric with conventional LCA approaches to enhance the assessment of material use from a CE perspective. These studies offer circularity-related quantitative information and illustrate the need to integrate material efficiency and quality of recovery into EoL assessments for wind technologies. However, circularity assessment remains in its infancy, and the number of studies combining both LCA and circularity metrics—especially in the wind sector—remains limited. Moreover, most existing analyses focus on aggregate technology levels or on simplified scenarios, without differentiating between LCM pathways or assessing the indicator applicability across specific WTb stages and processes.

A notable contribution is the work of Diez-Cañamero and Mendoza (2023) which explores EoL strategies for WTbs by applying both the Product Circularity Indicator (PCI) (Bracquené et al., 2020) and Global

Warming (GW) impact (calculated by LCA) (Heijungs, 2014). The authors identified limitations in existing circularity metrics, particularly the lack of variables related to the quality and destination of recovered materials. While the study contributes to the integration of circularity and environmental assessment, it also exposes several critical limitations that reflect broader methodological gaps. First, the analysis is based on the consideration of a single circularity indicator, which limits the capacity to capture the multifaceted nature of the product circular performance. As a result, important aspects such as material degradation, technological feasibility, and the quality of secondary materials were narrowly addressed. Secondly, although the study advocates for a life cycle perspective and the use of multiple indicators across different analytical levels (micro, meso, macro), it does not offer a concrete framework or criteria for selecting or integrating these indicators. This demonstrates the lack of structured and operational tools to evaluate circularity indicators and support decision-making in circular design and EoL strategies for WTBs.

This paper, therefore, evaluates the scope and applicability of circularity indicators promote the sustainable WTB-LCM strategies. By analysing both their theoretical foundations and practical implementation, the study aims to support their broader adoption in the wind energy sector. Accordingly, the specific goals have been defined as follows:

- Characterise resource flows and sustainability aspects across key WTB-LCM stages to establish the key material flows within the system, providing the foundation for assessing indicator coverage (section 3.1).
- Assess the scope of circularity indicators by evaluating their relevance through three screening matrices to identify the most suitable indicators: RACER (Relevance, Acceptability, Credibility, Ease of Monitoring, and Robustness), composite circular design principles, and wind industry-specific circularity criteria (section 3.2).
- Examine the applicability of the most relevant indicators by analysing their variables in relation to WTB-LCM processes and resource flows (section 3.3).

3. Research methodology

A three -step methodology was applied, as illustrated in Figure 1.

The first step involved the definition of WTB-LCM pathways to characterise the technical, economic, environmental and social aspects associated with each life cycle stage, process, and resource in- and outflow (see section 3.1). In parallel (step 2), circularity indicators were i) identified through a systematic literature review, ii) screened using predefined criteria evaluation matrices, and iii) classified into sustainability dimensions, CE solutions, life cycle stages and resource flows (see section 3.2). In step 3, the scope and applicability of the selected indicators were subsequently determined by analysing the link between

their variables (formulas) and the resource in- and outflows from the WTB-LCM stages and processes (defined in step 1) (see section 3.3). Guidelines and recommendations for the creation of new circularity indicators are provided. Additionally, the study provides insights for fostering circular innovations and supportive policies to enhance sustainable WTB-LCM management (see Section 5).

3.1. Characterisation of WTB-LCM pathways

3.1.1. Definition of WTB-LCM pathways

Alternative WTB-LCM pathways were defined from design to EoL. The WTB life cycle was divided into three main phases: the beginning of life (BoL), the middle of life (MoL), and the EoL. Typically, BoL and MoL follow similar processes —design, manufacturing, installation, and operation and maintenance— following proposed approaches by Chan and Mo (2017) and Nixon-Pearson et al. (2022), although alternative designs can influence downstream phases. In contrast, the EoL phase depends on the end goal of each wind farm decommissioning project (Gaborieau et al., 2023). There exist six major pathways, each corresponding to the most common circular waste management strategies —reusing, repurposing, recycling (mechanical, thermal, and chemical), and co-processing— in alignment with the strategies proposed by Kramer et al. (2024) and Lund and Madsen (2024) (Figure 2).

The BoL phase of WTB begins with the design (DS) and manufacturing (MN) stages, in which material selection and production techniques significantly influence performance and recyclability (Nixon-Pearson et al., 2022). Conventional WTB design typically relies on composite materials such as fiberglass or carbon fibre-reinforced polymers (Schubel and Crossley, 2012). Manufacturers select these materials for their structural efficiency, while alternative compositions and manufacturing approaches significantly influence the circularity potential of WTBs (Veers et al., 2022). After production, quality control inspections verify structural integrity before transporting (T) WTBs to installation sites.

Thereafter, the WTBs enter the MoL phase, where they are installed (IN) on wind farms using cranes designed to support the weight of the WTB and ensure accurate alignment with the hub (Hechler and Operations, 2019). Once in place, the WTBs typically remain in service for 20–25 years, undergoing regular maintenance (O&M) and periodic repairs to maintain their performance and structural integrity (Besnard and Bertling, 2010). Finally, at the EoL, WTBs are dismantled (DM) and directed into various waste management pathways, including reuse (RE), repurposing (RP), recycling (mechanical (MR), thermal (TR), and chemical (CR)) and co-processing (CP). In many cases, WTBs must be cut into smaller segments (typically around 5 meters) immediately after dismantling in the field to enable cost-efficient transportation. This on-site processing significantly reduces logistical burdens but generates considerable particulate emissions, primarily dust produced during the

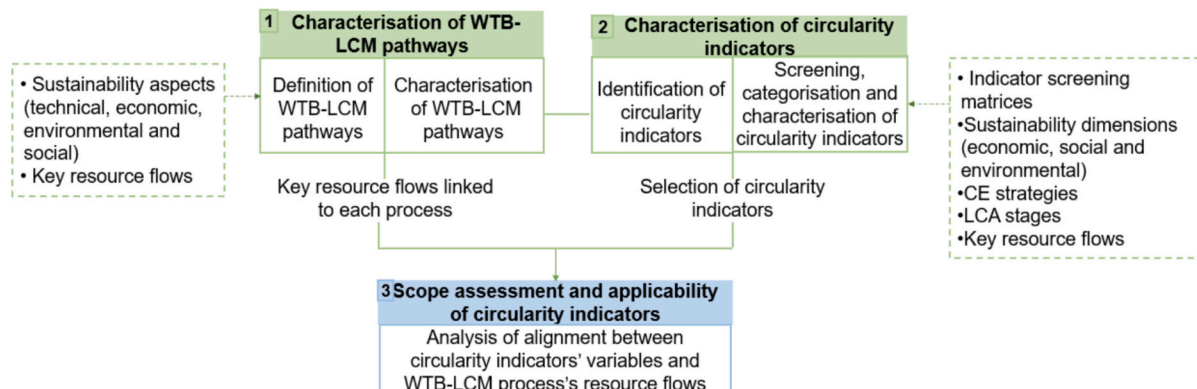


Figure 1. Research methodology. Acronyms: WTB-LCM (Wind Turbine Blade- Life cycle Management); CE (Circular economy); LCA (Life cycle assessment).

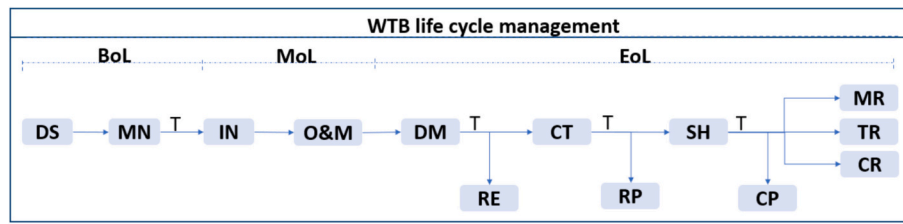


Figure 2. WTB-LCM pathways diagram. Acronyms: DS (Design); MN (Manufacturing); IN (Installation); O&M (Operation and Maintenance); DM (Dismantling); T (Transport); CT (Cutting); SH (Shredding); RE (Reuse); RP (Repurposing); MR (Mechanical Recycling); TR (Thermal Recycling); CR (Chemical Recycling); CP (Co-processing); BoL (Beginning of life); MoL (Middle of life); EoL (End of life).

sawing, grinding, or sanding of composite materials. These airborne particles pose serious concerns due to their potential environmental impacts and occupational health risks, including the inhalation of respirable fibres and synthetic polymer fragments. Such risks are exacerbated when cutting occurs without adequate containment or protective measures. To mitigate these effects, several strategies can be implemented, such as utilising local dust extraction systems, employing wet cutting techniques to suppress particle dispersion, deploying mobile containment solutions, or, when feasible, performing segmentation at off-site, controlled facilities. Although transporting whole WTBs increases logistical complexity and costs, it enables better control of emissions and safer working conditions. Ultimately, the choice of waste management pathway depends on the condition of the recovered materials and the applicable treatment strategies, with the overarching aim of extending material lifespans, reducing waste generation, and maximising resource recovery (Lund and Madsen, 2024).

Section S1 in the Supporting File (SF) provides detailed descriptions of the processes involved in each lifecycle stage (BoL, MoL, and EoL).

3.1.2. Characterisation of the WTB-LCM pathways

Firstly, each stage of the WTB life cycle was characterised by four aspects: technical, economic, environmental, and social (positive and/or negative). Although the technical aspect is not typically included in the conventional sustainability triad, it was incorporated in this work to encompass critical process-related characteristics (e.g., complexity,

scalability, maturity) that are essential for comparing the feasibility of implementing each pathway. The criteria for each aspect were determined based on the specifications outlined by Beauson et al. (2022), Jakobsen (2021), Joustra et al. (2021) and Nixon-Pearson et al. (2022).

Secondly, the main resource flows for each WTB life cycle stage were identified by analysing the inputs, transformations, and outputs of the technical processes involved. This analysis was conducted by the authors based on a review of scientific literature and technical reports (Caro et al., 2023; Lund and Madsen, 2024; Nixon-Pearson et al., 2022; Sproul et al., 2023) aiming to characterise each stage in terms of material and energy exchanges. This comprehensive mapping of resource flows provided the basis for evaluating the scope and applicability of circularity indicators by linking flow characteristics to indicator variables (see Section 4.2).

3.2. Characterisation of circularity indicators

3.2.1. Identification of circularity indicators

An analysis of academic literature, grey literature, and CE databases (such as the Circle Economy Lab, 2024) was conducted to identify circularity indicators applicable to the wind industry and, assess the LCM of WTBs. This led to the identification of 158 documents for detailed evaluation, as illustrated in Figure 3.

Table S1 (section S2) in the SF presents the combination of search streams and keywords used, together with the hits obtained by using

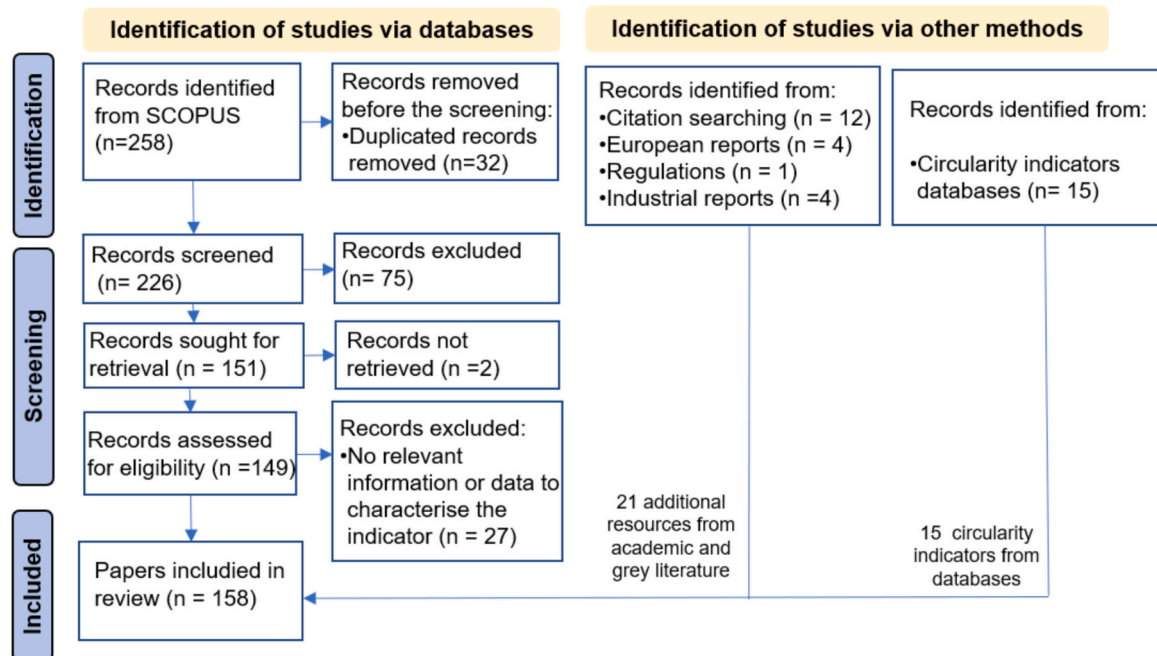


Figure 3. Systematic literature review, based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram (Page et al., 2021).

SCOPUS search engine. The first literature search was carried out by filtering documents by title, abstract, and keywords. Only articles written in English and published between 2010 and 2024 were considered.

After performing three searches (see Table S1), 258 documents were identified, which was reduced to 226 after eliminating duplicates. Subsequently, the sample was screened by reading the abstracts and eliminating documents not relevant to the study (e.g., out of scope, indicators not addressed, or indicators specifically developed for technologies or product systems outside the wind industry with no meaningful transferability), which reduced the sample by 75 documents. This ensured that only indicators either specifically tested in the wind industry or with potential applicability to it were retained for analysis. Finally, the resulting articles were read in full, eliminating those less relevant (based on whether circularity indicators are described and what extent), leading to the final sample of 122 documents. The analysis of journal papers was complemented by snowballing method (Mourão et al., 2020), and the consideration of European reports (e.g. Zampori, 2019), international regulations (e.g ISO 59020:2024), and industrial reports (e.g. Tanda et al., 2023). This identified additional circularity indicators, resulting in a further 21 documents for inclusion in the review. The final step focused on identifying and analysing 15 circularity indicator databases (e.g. Eurostat, 2025). The analysis of this grey literature contributed an additional 36 documents for analysis, bringing the total number of reviewed documents to 158. From this sample, a total of 120 circularity indicators were identified, of which only 8 (6.7%) had been specifically applied to the wind industry, namely those presented in the works of Diez-Cañamero and Mendoza (2023), Kasner (2022), Demuytere et al. (2024), Adibi et al. (2017), Mohamed Sultan et al., (2017), and Sherwood et al., (2022). These eight constitute the only documented applications in wind-related studies, yet they do not guarantee comprehensive coverage of the specificities of WTBs across their life cycle. The remaining indicators, although not previously applied to assess wind technology cases, were retained because they are defined in sector-neutral terms and can be parameterised with data available for WTBs; thus, they present a credible potential for application in this sector. For this reason, the subsequent analysis considered the full set of 120 indicators, thereby exposing both the existing gap and the opportunities for adapting circularity metrics to the challenges of WTB-LCM.

3.2.2. Screening, categorisation, and characterisation of circularity indicators

The scope of the 120 circularity indicators gathered from the literature review (which are listed and described in Table S2 of the SF) was assessed by using three “indicators screening checklists” to select those most suitable to support sustainable LCM of WTBs:

- RACER (Robust, Accepted, Credible, Easy and Relevant) checklist (Wiedmann et al., 2009) based on the ORIENTING project (Bachmann et al., 2021), which was extended by incorporating additional criteria proposed by Papageorgiou et al. (2021) and Patil and Ramakrishna (2023). Seven key analytical blocks were considered: stakeholder acceptance, credibility and appropriateness, applicability, transparency, scientific soundness, comprehensiveness and compatibility with the life cycle thinking approach (each block described in section S2 of the SF). The indicators were evaluated using the scoring system proposed by the ORIENTING project (Bachmann et al., 2021), which consists of assigning each criterion a score on a scale from 1 (least applicable) to 5 (most applicable) (see Tables S3 and S4 of section S3 of the SF for more details of the scoring system). To minimise potential bias, each author independently performed the scoring, after which the results were cross-checked and discussed until consensus was reached. This procedure aligns with methodological guidance, as reflexivity and structured consensus are recognised strategies for enhancing the rigour,

credibility, and validity of qualitative assessments, even when researchers themselves act as evaluators (Darawsheh, 2014). By explicitly identifying and resolving divergences, the process also provided transparency and strengthened the robustness of the RACER application while reducing the potential cascading effect of subjectivity on subsequent phases of the analysis.

Of the 120 indicators analysed, 65 achieved an overall score ranging from A- to A+, qualifying them for the next evaluation phase, as detailed in Table S5 of the SF. This selection threshold follows the guidelines proposed by Wiedmann et al. (2009), where indicators scoring at least A- are considered to meet a minimum level of robustness and relevance for further application in sustainability assessment frameworks.

Although frameworks such as the enhanced RACER checklist involve interpretive judgments, their use is widely accepted in both academic and institutional contexts (European Commission, 2009; Wiedmann et al., 2009) for evaluating the suitability of the indicators in the absence of standardised benchmarks. This approach has been applied in EU-funded projects such as IN-STREAM (Gerdes et al., 2011) and ORIENTING (ORIENTING Project, 2024) and is supported by institutions like the European Environment Agency (EEA, 2022). The subjectivity of RACER evaluations is not considered a methodological weakness per se, but rather a necessary and legitimate feature of expert-based assessments in multidimensional contexts, such as those involving circularity. As Eisenmenger et al., (2016) explained, RACER enables the appraisal of indicator quality and policy relevance even in the absence of quantitative thresholds, provided that transparency and consistency are maintained throughout the process. Furthermore, expert judgment is recognised in sustainability science as essential for addressing complex, non-binary criteria, particularly when indicators must balance technical feasibility, stakeholder acceptance, and systemic robustness (Niemeijer and de Groot, 2008; Singh et al., 2012). Barrientos et al., (2023) further demonstrated that expert-based scoring can lead to robust and operational results when supported by predefined evaluation rules, structured procedures, and full documentation.

- Circularity criteria checklist: The scope of the 65 RACER-complying indicators was determined by scoring the criteria against two checklists:
 - o Circular design of composites, incorporating specific criteria for the design of composite materials, based on the specifications provided by Joustra and Bessai, (2022), Joustra et al. (2021), and Joustra et al. (2022). This checklist includes four analytical blocks covering criteria related to handling and reconditioning, construction, product specifications and traceability, as presented in Table S6 of the SF.
 - o CE frameworks developed for wind farms, considering criteria across each lifecycle stage, including design, construction and installation, operation and maintenance, EoL and decommissioning. This checklist was developed based on the studies by Kramer and Beauson (2023), Lund and Madsen (2024) and Velenturf (2021). As presented in Table S7 of the SF.

In both these checklists, whether each criterion was fulfilled by the corresponding circularity indicator was assessed. The affirmative case was marked with an “X” as indicated in Table S6 of the SF. As a result, the number of criteria met by each indicator was counted, providing a quantitative assessment of their suitability. After applying the two final evaluation checklists, only those indicators that fulfilled more than ten criteria were retained. This threshold was defined empirically to ensure a sufficient level of relevance and completeness, based on the observation that none of the indicators assessed met more than half of the total criteria. In this context, the cut-off at ten allowed us to identify those indicators with the highest overall coverage across wind-specific and composite-related circularity aspects, while acknowledging the inherent difficulty for existing indicators to fully address the sector

multidimensional requirements. Thus, 13 indicators were short-listed as the most suitable for assessing circularity in the context of WTB-LCM. These indicators were considered the most practical for evaluating circularity performance within the WTB-LCM and are presented in Table 2, Section 4.2.

These 13 indicators were subsequently categorised based on the technical, economic, social and environmental aspects (Luthin et al., 2023), CE strategies (narrowing resource loop, slowing resource loop, closing resource loops and regenerating resource flow) (Wanaguru et al., 2022), LCA stages (subdivided into BoL, MoL and EoL), where within the EoL stage the classification follows the 9R framework developed by Potting et al. (2017). In this hierarchy, recycling (R8) and recovery (R9) preserve value only at the material level once the product has reached the end of its life, in contrast to product-level strategies (e.g., reuse, repair, refurbish, remanufacture, repurpose) that extend the service life of products and components. Finally, indicators were also categorised according to resource flows (e.g., energy, water, material, solid waste)

(Hilty and Aebischer, 2015) (see section S5 of the SF).

3.3. Scope assessment and applicability of circularity indicators

The methodological approach outlined by Jerome et al. (2022) and Reike et al., 2018 was used to analyse the relationship between the resource flows from the WTB-LCM pathways (section 3.1) and the variables of the circularity indicators (section 3.2). The process began with the analysis and classification of the variables associated with the 13 selected indicators, leading to the development of a unified and systematic database (see section 4.2). The variables were grouped into typologies, consolidating those that were redundant or conceptually similar into a final set of 71 variables.

Next, a correspondence matrix was developed to systematically link these variables to the resource flows within WTB-LCM pathways, ensuring analytical consistency through a literature-based approach. Following Polonioli (2015), each variable was assigned to a specific type of resource flow based on its functional role in the system. For instance,

Table 1

Main resource flows related to the major WTB-LCM stages. Note: (X) it depends on the dust collection method used (wet vs dry). (*): emissions refer to direct emissions (e.g. by fuel combustion) and not indirect emissions (e.g. by electricity production and consumption). Acronyms: DS (Design); MN (Manufacturing); T (Transport); IN (Installation); O&M (Operation and Maintenance); DM (Dismantling); SH (Shredding); RE (Reuse); RP (Repurposing); MR (Mechanical Recycling); TR (Thermal Recycling); CR (Chemical Recycling); CP (Co-processing). References: (Caro et al., 2023.; Lund and Madsen, 2024; Nixon-Pearson et al., 2022.; Sproul et al., 2023).

Category	Resource flows	Beginning of life			Middle of life		End of life			CP										
		DS	MN	T	IN	O&M	DM	RE	Sectioning & Cutting			RP	SH	Recycling						
									Circular saw		Diamond wire			Waterjet	MR	TR	CR			
Energy	Diesel			X	X	X	X		X	X									X	
	Electricity		X					X	X				X	X	X		X	X	X	
Water	Natural gas																X			
	Tap/cooling water		X						(X)	(X)	X	(X)	(X)			X	X			
Materials	Deionised water																	X		
	Equipment		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
	Air																X			
	Salt water (molten salts)																X			
	Diamond wires										X									
	Roadplates										X									
	Abrasives/mineral grit											X								
	Lubricants					X														
	Chemicals		X																X	
	Additives		X																X	
	Thermoplastics	X																		
	Balsa wood	X																		
	Coatings	X																		
	PVC	X																		
	Adhesive	x																		
	Carbon/Glass fibres	X																		
	Nylon	X																		
	Resins	X																		
	Wastes	Scraps		X				X		X	X	X	X	X						X
		Dust								X	X			X	X					X
Worn abrasives/grit											X									
Residual chemicals			X																X	
Filtered particles																	X			
Neutralised dissolution																			X	
Byproducts	Wastewater		X						(X)	(X)	X	X	(X)			X	X			
	Collected dust (in dry or wet form)								(X)	(X)	(X)		(X)			X				
	Oils															X				
	Gases															X				
	Recovered resins																		X	
	Cement clinker																		X	
Emissions*	CO ₂		X	X	X	X	X	X	X	X	X		(X)		X	X	X	X	X	
	Gases		X	X	X	X	X	X	X	X				X					X	
	Particles						X	X	X	X	X	X	X					X	X	
	Fumes		X													X			X	
	Organic volatile compounds (VOCs)		X																X	
	Water vapour		X						X	X	X					X				
Other	Land use				X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	

variables measuring raw material input (e.g., amount of linear materials entering the production system) were linked to primary resource flows, which represent the intake of virgin or non-recycled materials at the beginning of the production process. In contrast those related to waste generation (e.g., total waste production) were associated with material outputs. Similarly, energy consumption (e.g., energy required to recover material) was mapped to energy flows, and carbon emissions (e.g., impacts during the use phase) were linked to environmental emissions.

This structured mapping identified the coverage of the 13 circularity indicators, assessing within each analysed management pathway. This determined the most comprehensive and applicable indicators for each stage and pathway while also identifying gaps and opportunities for improvement. These insights contribute to refining circularity indicators and enhancing their applicability within WTB-LCM.

4. Results and discussion

4.1. Characterisation of WTB-LCM pathways

Table 1 below presents an overview of the resource flows across the different stages, while more detailed aspects can be found in Table S8 (section S4) in the SF.

Energy consumption is a critical factor determining the economic cost and life cycle environmental impact of industrial processes as it correlates with resource depletion and GHG emissions (Sharif et al., 2019). Therefore, understanding the relationship between energy use, environmental and economic impacts is essential for developing more circular and sustainable industrial practices. Three major types of energy sources are used during the WTB-LCM: diesel (mostly used in heavy machinery and generators), electricity (mostly used in WTB manufacturing, cutting, shredding, and waste treatment) and natural gas (used in the pyrolysis process).

Water flow is required for sectioning and cutting WTB, as well as a solvent for solvolysis. Water consumption generates significant impacts by producing wastewater, which contaminates natural water bodies, harms human health, and ecosystems (Zacchaeus et al., 2020). Thus, efficient water management plays a crucial role in reducing water pollution.

Various materials compose WTB, among which thermoset resins, carbon and glass fibres, balsa wood, and adhesives being the most critical due to their durability and strength (Sproul et al., 2023). However, the use of chemical agents and resins in WTB manufacturing complicates recycling, as separating materials remains a major challenge (Yousef et al., 2024).

With regard to diamond wire cutting is an energy-intensive process that also involves high cost and a short tool lifetime, as the wire wears out quickly (Kim et al., 2016). Additionally, diamond mining and processing for wire manufacturing contribute to habitat destruction and carbon emissions (Kumar and Melkote, 2018). For instance, waterjet cutting generates considerable waste, depending on the type of abrasives used and their disposal method. Mineral abrasives, such as garnet, can generate notable environmental burdens (Jerman et al., 2021). However, the reuse of abrasive materials enhances surface quality and reduces the consumption of virgin resources, bringing both economic and environmental benefits (Schnakovszky et al., 2014).

Chemical additives and solvents play a crucial role in solvolysis and composite production, influencing both economic costs and environmental impacts (Hahladakis et al., 2018). Solvolysis, particularly with organic solvents such as acetone, effectively degrades fibre-reinforced composites but presents sustainability challenges due to cost and toxicity. Similarly, additives such as sizing and compatibiliser agents which enhance fiber-polymer adhesion in reinforced thermoplastics, act as potential pollutants, requiring careful assessment in environmental impact studies (Hahladakis et al., 2018).

Molten salts can enhance pyrolysis efficiency and product quality by improving carbonisation, preventing metal atom aggregation, degrading

epoxy components, reducing pyrolysis temperatures, and stabilising biochar (Das and Sarmah, 2015; Lee et al., 2017; Su et al., 2019; Woo and Whale, 2022). However, their production and disposal pose environmental challenges, including the potential release of harmful by-products and high energy demand. Despite improving pyrolysis performance, their life cycle impacts required careful management to minimise negative environmental consequences (Tang et al., 2018; Yang et al., 2020).

Among the most relevant direct emissions are CO₂, and other gases from diesel-powered machinery; particulate matter and dust from WTB cutting and material treatment; pyrolysis fumes, and solvolysis VOCs (Table 1). Additionally, land use impacts arise from WTB dismantling and cutting, which require heavy machinery deployment, leading to topsoil removal (approximately 10 cm deep). More efficient cutting technologies, such as diamond wire cutters, mitigate this impact by allowing installation and attachment with road plates above ground, thereby reducing soil disturbance (Hilty and Aebischer, 2015).

Additional factors analysis, such as economic costs, toxicity, social risk, and circularity solutions, is presented in Section S4 (Table S9) of the SF.

4.2. Characterisation of circularity indicators

The final sample of 13 circularity indicators is presented in Table 2. These are the most potentially relevant indicators for analysing the circularity performance of the WTB-LCM based on the criteria used in the study (see section 3.2). However, they are not specific to WTBs but rather applicable to broader circularity assessments. Additionally, their relevance is not absolute, as it depends on their coverage of resource flows, which is analysed in Section 4.3. The final selection of the most appropriate indicators arises from the intersection of variables with resource flows. A more detailed explanation of these 13 indicators, including their formulas and associated variables, is provided in Section S5 (Table S10) of the SF.

This sample of circularity indicators offers different perspectives on assessing various aspects of circularity, from environmental-focused metrics and material flows to systemic performance. Each indicator has a distinct scope and presents limitations when used individually. However, combining multiple indicators enhances the analysis and yields more comprehensive insights (Van De Mheen and Vincent, 2023).

For instance, the Circularity Footprint Formula (CFF) (Zampori, 2019) focus on carbon emissions and resource use, offering valuable insights into the environmental performance of circular strategies in terms of greenhouse gas emissions. While it captures the climate-related benefits associated with circularity, it does not measure circularity itself and overlooks social and economic dimensions. Similarly, Circularity Quality of Materials (Qc) (Steinmann et al., 2019) and Retained Environmental Value (REV) (Haupt and Hellweg, 2019) address material retention and efficiency but are limited to specific life cycle stages such as transportation, installation, or dismantling.

Material flow-focused metrics such as the Material Circularity Indicator (MCI) (Goddin et al., 2019) and Circular Material Productivity (CMP) (Tanda et al., 2023) quantify circularity at the system level through material flow analysis but do not consider certain resource and environmental aspects. These metrics do not integrate transportation, installation, or dismantling phases, which can be critical for determining a product's overall circularity performance. While they emphasise material retention and efficiency, they exclude considerations of energy consumption, emissions, or resource intensity beyond material inputs and outputs. This limitation restricts their ability to assess environmental trade-offs comprehensively, resulting in an evaluation focused solely on material flow rather than a holistic sustainability assessment. The EoL recycling rate (EOL-RR) and its complementary metric (EOL-RRp) (Peiró et al., 2018) address recycling, offering broader coverage during the EoL stage. However, their exclusive focus on recycling limits their applicability to this process alone, lacking a life cycle perspective.

Table 2

List of the most relevant circularity indicators for potential application in the assessment of the circularity performance of WTB-LCM pathways. Acronyms: PEF (Product Environmental Footprint); OEF (Organisational Environmental Footprint); EoL (End-of-life); CE (Circular economy)

Indicator	Source	Description	Required data	Score type
Circularity Footprint Formula (CFF)	(Zampori, 2019)	Indicator defined by the PEF and OEF methods to model carbon emissions and resource use across waste flows in manufacturing, distribution, usage, and EoL stages, incorporating recycled and recyclable materials. It consists of three components: material, energy, and disposal formulas.	Material, energy and impacts data	Kg CO ₂ eq.
Material Circularity Indicator (MCI)	(Goddin et al., 2015)	It measures how much linear material flow is reduced and restorative flow is maximised for a product's components, as well as the product's usage duration and intensity compared to an industry average	Material, usage and impact data	0 (fully linear) to 1 (fully circular)
Product Circularity Indicator (PCI)	(Bracquené et al., 2020)	It evaluates a product's circularity across its life cycle, focusing on manufacturing efficiency, durability, second-life potential, and recyclability.	Lifecycle efficiency, material and impact data	0 (fully linear) to 1 (fully circular)
Material Efficiency Metric (MEM)	(Brändström and Eriksson, 2022)	Quantifies circularity by assessing material flow efficiency, integrating the principles of closing, reducing and slowing loops into a single value. It reflects the extent to which materials are retained, reused or recovered within a system, providing a holistic measure of circularity performance.	Material, waste and lifecycle efficiency data	%
Product-Level Circularity Metric (P-LCM)	(Linder et al., 2017)	Evaluates how effectively a product retains, reuses, or recycles materials within a CE, focusing solely on circularity without considering environmental performance or product quality.	Economic data	€
Circularity Indexes (CI)	(Cullen, 2017)	It measures how effectively materials are retained in a circular system by considering both material recovery and quality loss during reprocessing. It is calculated as the product of the fraction of recovered end-of-life material and the energy efficiency of material recovery	Energy and material data	0 (fully linear) to 1 (fully circular)
Circularity of Material Quality (Qc)	(Steinmann et al., 2019)	It measures the quality retention of recycled materials by assessing energy efficiency. This metric evaluates the energy saved through recycling compared to the energy needed to produce the same amount of primary material, providing insight into the sustainability of recycling efforts.	Energy and material data	Dimensionless
Material Circularity (MC)	(Tanda et al., 2023)	It expresses a company's performance in closing the loop as a percentage, calculated as the weighted average of % circular inflow and % circular outflow.	Material data	% and €/kg
Circular Material Productivity (CMP)	(Tanda et al., 2023)	It measures a company's circular material productivity, specifically assessing its effectiveness in decoupling financial performance from linear resource consumption.	Economic and material data	%
End Of Life Recycling Rate (EOL-RR)	(Peiró et al., 2018)	It quantifies the percentage of materials reclaimed from waste at the product EoL.	Production and transportation data	%
Complementary recycling potential indicator (EoL-RRp)	(Peiró et al., 2018)	It is defined as the 'potentially recyclable' fraction of an exemplary material from diverse end-use applications.	Material and economic data	%
Long Term in-Use Occupation (LTUO)	(Caro et al., 2023)	It is defined as the mass of raw material held in the material loop over time.	Material and usage data	%
Retained Environmental Value (REV)	(Haupt and Hellweg, 2019)	It measures the share of the environmental impact from the production of a material or product that is retained in products and materials recovered from reuse, remanufacturing, or recycling.	Impacts data	%

Table 3

Consolidated list of 71 circularity indicators' variables. Acronyms; CFF (Circular Footprint Formula); MCI (Material Circularity Index); PCI (Product Circularity Indicator); MEM (Material Efficiency Metric); P-LCM (Product-Level Circularity Metric); CI (Circularity Index); Qc (Circularity of Material Quality); MC (Material Circularity); CMP (Circular Material Productivity); EOL-RR (End Of Life Recycling Rate); EOL-RRp (Complementary recycling indicator); LTUO (Long Term in-Use Occupation); REV (Retained Environmental Value); FU (Functional Unit); EoL (End-of-Life); EU (Europe).

Theme	Variables	CFF	MCI	PCI	MEM	P-LCM	CI	Qc	MC	CMP	EOL-RR	EoL-RRp	LTUO	REV	
Energy	Efficiency of the energy recovery process for both heat and electricity	X													
	Lower heating value of the material in the product that is used for energy recovery	X													
	Required energy to recover material						X								
	Life cycle energy required for producing material with the same quality as the secondary material from primary inputs							X							
	Direct cradle-to-gate life cycle energy requirement for producing the secondary material from material that is to be recycled								X						
	Energy required for cleaning the material inputs per kg primary material to be recycled								X						
	Embodied cradle-to-gate life cycle energy in the primary materials required for dilution, necessary to obtain secondary material of sufficient quality								X						
	Cradle-to-gate life cycle energy required for producing of primary material							X	X						
	Feedstock materials	Quality of the primary materials	X												
		Efficiency of the material separation		X	X										
Efficiency of producing usable feedstock for subsequent processes				X											
Fraction of a product's biological feedstock from sustainable production									X						
Fraction of mass of a product's feedstock from recycled sources		X	X	X	X					X					
Efficiency to produce the recycled feedstock			X							X					
Recovered material in feedstock production			X	X	X					X					
Materials for production	Fraction of mass of a product's feedstock from reused sources									X					
	Proportion of renewable content in feedstock										X				
	Amount of linear materials entering the production system				X										
	Amount of virgin material used for packaging				X										
	Efficiency of converting inputs into final, usable products			X											
	Number of products that generate non-circulated material output in the value chain				X										
	Amount of fully circular products (produced without virgin materials)				X										
Obtained product	Recovered material in component production			X					X						
	Mass of product		X	X									X		
	Additional virgin material input required in the use phase				X										
Service life	Imports to the EU of EoL-manufactured products										X				
	Real lifetime of a product		X	X	X										
	Product lifetime in industry		X	X											
	Theoretical use intensity of a product as design target		X	X											
Reuse and recycling (actual and potential)	Real use intensity of a product as design target			X											
	Fraction of mass of a product going to component reuse		X	X	X										
	Proportion of the material in the product that will be recycled in subsequent system processes	X	X	X					X						
	Efficiency of the recycling process used for the portion of a product collected for recycling								X						
Secondary materials	Ratio of diluting material to primary material to be recycled									X					
	Amount of material that remains in potentially recyclable end-use applications				X				X			X			
	Production of secondary material from post-consumer functional recycling in EU sent to processing in EU										X				
	Production of secondary material from post-consumer functional recycling in EU sent to manufacture in EU										X				
	Quality of the ongoing secondary material	X													
Quality of the outgoing secondary material	X														

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Table 3 (continued)

Theme	Variables	CFF	MCI	PCI	MEM	P-LCM	CI	Qc	MC	CMP	EOL-RR	EoL-RRp	LTUO	REV
Waste	Proportion of in/output waste effectively recycled				X									
	Fraction of mass of a product being collected to go into a composting process								X					
	Recovered EoL material						X				X			
	Proportion of the material in the product that is used for energy recovery at EoL	X							X					
	Amount of waste from packaging				X									
	Waste volumes from repair and upgrade processes				X									
	Total waste production				X									
Environmental	Emissions and resources consumed arising from the recycling process of the recycled (reused) material, including collection, sorting and transportation process	X												
	Emissions and resources consumed arising from the recycling process at EoL, including collection, sorting and transportation process	X												
	Emissions and resources consumed arising from the acquisition and pre-processing of virgin material	X												
	Emissions and resources consumed arising from the acquisition and pre-processing of virgin material assumed to be substituted by recyclable materials	X												
	Emissions and resources consumed arising from the energy recovery process	X												
	Emissions and resources consumed that would have arisen from the specific substituted energy source, heat and electricity respectively	X												
	Emissions and resources consumed arising from disposal of waste material at the EoL of the analysed product, without energy recovery	X												
	Impact of the displaced product or material													X
	Impacts during the use-phase													X
	Impact of any value retention process													X
	Impact of the original product													X
	Allocation factor of burdens and credits between supplier and user of recycled materials	X												
	Allocation factor of energy recovery processes	X												
Economic	Economic value of all parts in the product					X								
	Economic value of recirculated parts					X								
	Market share of each "Potentially recyclable" end-use application of material in the EU											X		
	Revenue generated by that product or business unit									X				
Social	Unit demand per customer				X									
	Number of customers accessing functionality through circular models				X									
	Total material demand						X							

In contrast, life cycle-oriented indicators, such as the Product Circularity Indicator (PCI) (Bracquené et al., 2020) and the Product Level Circularity Metric (P-LCM) (Linder et al., 2017), provide a broader perspective by integrating factors such as manufacturing efficiency, durability and second-life potential. The Material Efficiency Metric (MEM) (Brändström and Eriksson, 2022) assesses material efficiency through material flow analysis, incorporating closing, narrowing, and slowing material loops into a single value. Long-term occupancy in use (LTUO) (Caro et al., 2023) quantifies material retention in the system over time, offering insights into resource longevity. These indicators adopt a system-wide approach, evaluating multiple life cycle phases rather than focusing solely on material flows. This enables a more comprehensive circularity assessment, particularly regarding product longevity, efficiency improvements, and reuse potential. Nonetheless, they do not account for material quality degradation over time or the environmental impact of transport and logistics. Additionally, while they offer a broader perspective on circularity, they fail to integrate social aspects, a limitation shared by all indicators reviewed in this study.

To further analyse their scope, these indicators were classified according to sustainability dimensions (technical, economic, environmental, and social), CE strategies (narrowing, slowing, closing, and regenerating resource loops), LCA stages (raw material extraction, manufacturing, distribution, use, and EoL), and resource flows (e.g., energy, water, material, solid waste). The classification of indicators reveals a strong environmental focus, with limited coverage of economic and technical aspects, and no consideration of social dimensions. The detailed classification is provided in Table S11 of the SF.

4.3. Scope assessment and applicability of circularity indicators

The variables associated with the 13 circularity indicators were extracted, grouped into broader thematic categories, and systematically linked to each indicator, as summarised in Table 3. A final sample of 71 variables was obtained, and subsequently structured to ensure coherence and relevance within the study. Table S12 of the SF details each variables' definition and application context.

The analysis reveals an uneven distribution of variables, with a

Table 4

Relationship between variables and the different stages involved in WTB-LCM. Acronyms: DS (Design); MN (Manufacturing); IN (Installation); O&M (Operation and Maintenance); DM (Dismantling); T (Transport); SH (Shredding); RE (Reuse); RP (Repurposing); MR (Mechanical Recycling); TR (Thermal Recycling); CR (Chemical Recycling); CP (Co-processing); EU (Europe); References: (Caro et al., 2023; Lund and Madsen, 2024; Nixon-Pearson et al., 2022; Sproul et al., 2023)

Themes	Variables	Beginning of life			Middle of life		End of life											
		DS	MN	T	IN	O&M	DM	RE	Cutting			RP	SH	Recycling			CP	
									Circular saw	Diamond wire	Waterjet			MR	TR	CR		
Energy	Efficiency of the energy recovery process for both heat and electricity															X		X
	Lower heating value of the material in the product that is used for energy recovery																X	X
	Required energy to recover material						X	X	X	X	X	X	X	X	X	X	X	X
	Life cycle energy required for producing material with the same quality as the secondary material from primary inputs		X						X	X	X		X	X	X	X		
	Direct cradle-to-gate life cycle energy requirement for producing the secondary material from material that is to be recycled		X						X	X	X		X	X	X	X		
	Energy required for cleaning the material inputs per kg primary material to be recycled												X	X	X	X		
	Embodied cradle-to-gate life cycle energy in the primary materials required for dilution, necessary to obtain secondary material of sufficient quality		X															
	Cradle-to-gate life cycle energy required for producing of primary material																	
	Quality of the primary materials	X	X					X				X		X	X	X	X	X
	Efficiency of the material separation								X	X	X		X	X	X	X		
Feedstock materials	Efficiency of producing usable feedstock for subsequent processes		X											X	X	X		
	Fraction of a product's biological feedstock from sustainable production	X	X															
	Fraction of mass of a product's feedstock from recycled sources	X	X															
	Efficiency to produce the recycled feedstock													X	X	X		
	Recovered material in feedstock production		X															
	Fraction of mass of a product's feedstock from reused sources	X	X															
	Proportion of renewable content in feedstock	X	X															
	Amount of linear materials entering the production system	X	X							X	X	X		X	X	X	X	X
	Amount of virgin material for packaging		X															
	Efficiency of converting inputs into final usable products		X							X	X	X		X	X	X	X	X
Materials for production	Number of products that generate non-circulated material output in the value chain	X	X															

(continued on next page)

Table 4 (continued)

Themes	Variables	Beginning of life			Middle of life		End of life										
		DS	MN	T	IN	O&M	DM	RE	Cutting			RP	SH	Recycling			CP
									Circular saw	Diamond wire	Waterjet			MR	TR	CR	
Obtained product	Amount of fully circular products (produced without virgin materials)		X					X				X		X	X	X	X
	Recovered material in component production		X														
	Mass of product		X														
Service life	Additional virgin material input required in the use phase					X											
	Imports to the EU of EoL-manufactured products		X	X													
	Real lifetime of a product					X		X									
Reuse and recyclable materials in the product	Product lifetime in industry					X		X									
	Theoretical use intensity of a product as design target	X				X											
	Real use intensity of a product as a design target	X				X											
Secondary materials	Fraction of mass of a product going to component reuse							X									
	Proportion of the material in the product that will be recycled in subsequent system processes								X	X	X		X	X	X	X	
	Efficiency of the recycling process used for the portion of a product collected for recycling												X	X	X		
Waste	Ratio of diluting material to primary material to be recycled												X	X	X		
	Amount of material that remains in potentially recyclable end-use applications												X	X	X		
	Production of secondary material from post-consumer functional recycling in EU sent to processing in EU												X	X	X	X	
Environmental	Production of secondary material from post-consumer functional recycling in EU sent to manufacture in EU												X	X	X	X	
	Quality of the ongoing secondary material												X	X	X	X	
	Quality of the outgoing secondary material												X	X	X	X	
Environmental	Proportion of in/output waste effectively recycled											X	X	X	X	X	
	Fraction of product mass collected for composting																
	Recovered EoL material						X	X	X	X	X	X	X	X	X	X	X
Environmental	Proportion of the material in the product that is used for energy recovery at EoL														X	X	
	Amount of waste from packaging		X														
	Total waste production		X		X		X	X	X	X	X	X	X	X	X	X	X
Environmental	Waste volumes from repair and upgrade processes					X											
	Emissions and resources consumed arising from the recycling process of the recycled (reused) material, including collection, sorting and transportation process			X					X	X	X	X	X	X	X		

(continued on next page)

Table 4 (continued)

Themes	Variables	Beginning of life			Middle of life		End of life										
		DS	MN	T	IN	O&M	DM	RE	Cutting			RP	SH	Recycling			CP
									Circular saw	Diamond wire	Waterjet			MR	TR	CR	
	Emissions and resources consumed arising from the recycling process at EoL, including collection, sorting and transportation process			X				X	X	X		X	X	X	X		
	Emissions and resources consumed arising from the acquisition and pre-processing of virgin material		X														
	Emissions and resources consumed arising from the acquisition and pre-processing of virgin material assumed to be substituted by recyclable materials		X														
	Emissions and resources consumed arising from the energy recovery process													X		X	
	Emissions and resources consumed that would have arisen from the specific substituted energy source, heat and electricity respectively											X	X	X	X		
	Emissions and resources consumed arising from disposal of waste material at the EoL of the analysed product, without energy recovery																
	Impact of the displaced product or material		X														
	Impacts during the use-phase				X												
	Impact of any value retention process						X				X		X	X	X	X	
	Impact of the original product	X	X														
	Allocation factor of burdens and credits between supplier and user of recycled materials		X				X	X	X	X		X	X	X	X		
	Allocation factor of energy recovery processes													X		X	
Economic	Economic value of all parts in the product	X	X														
	Economic value of recirculated parts						X	X	X	X		X	X	X	X	X	
	Market share of each "Potentially recyclable" end-use application of material in the EU											X	X	X	X		
	Revenue generated by that product or business unit		X				X				X		X	X	X	X	
Social	Unit demand per customer		X								X	X	X	X	X	X	
	Number of customers accessing functionality through circular models				X	X	X	X	X		X	X	X	X	X	X	
	Total material demand	X	X		X	X	X	X	X	X	X	X	X	X	X	X	

higher concentration on input materials (18%), reuse and recyclability (12%) and energy (15%), reflecting a focus on resource efficiency. Optimising material flows and reuse plays a key role in enhancing circularity. However, the low representation of economic (4%) and social (4%) variables suggests the need to integrate these aspects for a more comprehensive assessment of circularity.

Among the existing indicators, the PCI covers a broader range of variables, addressing reuse, recycling, and product life cycle but omitting energy and environmental aspects. The MCI, while similar to the PCI, incorporates additional variables but still lacks a fully integrated approach to circularity (Bracquené et al., 2020). Other indicators, such as the CFF or REV, analyse environmental impacts, without considering

critical aspects like quality of materials. EoL specific indicators (EOL-RR and EOL-RRp) focus on recycling rates (Peiró et al., 2018), but exclude energy and environmental variables. In contrast, the Qc indicator assesses the quality retention of recycled materials by measuring energy efficiency (Steinmann et al., 2019), yet it overlooks key factors such as environmental impact and waste generation. The MEM considers material use and waste generation var (Brändström and Eriksson, 2022) but does not account for environmental or energy dimensions, limiting its applicability in sustainable systems.

Additionally, the P-LCM and the CMP offer complementary approaches to circularity assessment. The P-LCM evaluates circularity at the product level (Linder et al., 2017), whereas the CMP assess a company's productivity in terms of circular material use (Tanda et al., 2023). However, both indicators present significant limitations, as they do not integrate environmental and social variables or account for energy-related aspects. This omission weakens their ability to provide a comprehensive assessment of circularity, as embedded energy, social implications, and environmental impacts play a fundamental role in determining the overall sustainability of circular strategies.

In conclusion, while existing circularity indicators address key aspects such as energy, material quality, and emissions, none offer a fully integrated assessment. Most indicators focus on only one or two dimensions, limiting their ability to provide a holistic view of circularity. Therefore, the development of an indicator that incorporates these three critical dimensions (material efficiency, environmental impact, and energy use) is essential. Such an approach would enable a more comprehensive evaluation of WTB-LCM while supporting the identification of opportunities to improve sustainability, resource efficiency, and impact reduction.

Subsequently, the scope of the circularity indicators was determined by analysing the link between their variables (Table 3) and the resource flows from the WTB-LCM stages (Table 1). Accordingly, Table 4 shows how well each stage is covered by the variables, identifying gaps and areas of strong representation. Additionally, Table S13 of the SF (Section S6) provides detailed matching between variables and flows for each process of the WTB-LCM.

The BoL shows the highest coverage in manufacturing (42%), variables related to feedstock materials and products effectively capture material flows within this process. This aligns with the emphasis on material efficiency in circularity assessments, where optimising input materials reduces environmental impact and enhances sustainability (Oladapo et al., 2024). In contrast, design has significantly lower coverage (15%) despite its crucial role in enabling circular models in the wind industry. Mestre and Cooper (2017) highlighted that design decisions determine the feasibility of CE strategies by shaping downstream operations, including waste management and resource recovery. Liu and Barlow (2017) emphasised that integrating sustainable design principles (such as maintenance and recyclability) facilitates later life cycle stages. Similarly, Schmidt et al. (2020) argued that reinforcing design strategies strengthens EoL management, improving system sustainability and establishing design as a pillar of CE in the wind sector. Conversely, transportation is the least represented BoL process (3% coverage), indicating that logistical aspects remain largely unaccounted for in circularity assessments.

Both processes in MoL show low coverage. Installation presents the lowest representation (1%), while operation and maintenance (O&M) reaches 11%. This suggests that current indicators do not sufficiently capture material and energy flows in these processes. Given that O&M extends the lifespan of WTBs and minimises environmental impact (Liu et al., 2019), its limited coverage highlights a gap in circularity assessments. Expanding indicators to include operational performance and maintenance strategies could improve their applicability to the wind sector.

Concerning the EoL, the representation of processes varies significantly. Dismantling (10%), repurposing (15%), reuse (18%), and cutting technologies (18%) are among the least covered, indicating that many

value-retention processes remain underrepresented in circularity assessment. This is particularly relevant given that reuse and repurposing were recognised as key strategies to extend product lifetimes and reduce raw material dependence (Linder et al., 2017). Their limited coverage suggests that current indicators place less emphasis on alternative EoL pathways and material conservation.

Conversely, recycling dominates, with thermal recycling (52%) followed by mechanical and chemical recycling (45%). This strong representation reflects the international push to close material loops through CE policies, aligning with industry efforts to enhance material recovery processes (Antony Jose et al., 2024). However, while recycling remains a key strategy, its predominance in circularity assessments may overlook the potential benefits of alternative EoL solutions, such as reuse and remanufacturing, which can further contribute to resource conservation and sustainability. Moreover, it should be noted that during mechanical recycling the fibres contained in WTBs are often partially destroyed or converted from continuous to short fibres, which compromises their structural performance in subsequent applications (Alavi et al., 2025). Similarly, pyrolysis, despite its potential to recover fibres, often results in fibres with degraded mechanical properties due to high processing temperatures and the presence of residual char, needing additional post-treatment steps (Naqvi et al., 2018). In this context, strategies such as repair, reuse, and repurposing offer more suitable alternatives for preserving the high specific properties of composite materials. These limitations reflect the need to consider material-specific constraints when assessing circular strategies for fibre-reinforced composites.

The findings highlight important gaps in circularity assessments for WTB-LCM. While the analysed indicators effectively measure circularity from different perspectives, their generalist nature means they were not specifically designed to assess the circularity of WTBs. As a result, even though their coverage is significant in some cases, it remains insufficient to fully capture the complexity of WTB-LCM. One key limitation is that these indicators do not integrate multiple critical variables (such as energy use, emissions, waste generation, and economic factors) into a single combined formula. Instead, they tend to focus on one or two aspects at a time, leading to a fragmented assessment of circularity. This lack of integration prevents a holistic evaluation of how circular strategies impact the entire WTB-LCM. A more comprehensive approach is needed, which incorporates multidimensional indicators capable of assessing material efficiency, environmental performance, and economic viability in a unified way. Future research should focus on developing tailored circularity indicators that provide a more systemic and representative evaluation of WTB sustainability.

After assigning the variables to their corresponding flows within the life cycle stages, the coverage percentage of each circularity indicator was determined. This assessment determines which stages are most comprehensively represented by the indicators. Table 5 shows the coverage percentage of each indicator across WTB-LCM. Higher values indicate broader representation, while lower values reflect limited coverage. The detailed calculation of these percentages is provided in Table S14 of the SF, and a more comprehensive breakdown of the individual coverage of each indicator in the final sample is available in Tables S15 to S27 of the SF.

In the BoL, circularity indicators show heterogeneous applicability. The MEM, PCL, and MC indicators demonstrate greater relevance in the DS and MN stages, emphasising their focus on material and energy efficiency within the production process. In contrast, the CFF indicator shows high coverage in T (67%), suggesting its effectiveness in capturing the logistical dimension within circularity analysis. Despite the significance of logistics in large-scale systems such as WTBs, most existing indicators do not explicitly incorporate it, even though it plays a crucial role in optimising circularity and reducing environmental impacts. The mobility of large structures poses significant sustainability challenges, reinforcing the need for new metrics that integrate transportation optimisation into circularity analyses, particularly in industries where logistics substantially influence overall system sustainability (Chen,

Table 5

Percentage coverage of the final sample of indicators on the different pathways of the WTB-LCM. Acronyms: CFF (Circular Footprint Formula); MCI (Material Circularity Index); PCI (Product Circularity Indicator); MEM (Material Efficiency Metric); P-LCM (Product-Level Circularity Metric); CI (Circularity Index); Qc (Circularity of Material Quality); MC (Material Circularity); CMP (Circular Material Productivity); EOL-RR (End of Life Recycling Rate); EOL-RRp (Complementary recycling indicator); LTUO (Long Term in-Use Occupation); REV (Retained Environmental Value).

WTB-LCM stages		CFF	MCI	PCI	MEM	P-LCM	CI	Qc	MC	CMP	EOL-RR	EoL-RRp	LTUO	REV
BoL	Design (DS)	9%	14%	18%	18%	5%	5%	5%	18%	5%	0%	0%	0%	5%
	Manufacture (MN)	11%	9%	18%	20%	2%	4%	11%	13%	4%	0%	0%	0%	4%
	Transport (T)	67%	0%	0%	0%	0%	0%	0%	0%	0%	33%	0%	0%	0%
MoL	Installation (IN)	0%	0%	0%	50%	0%	50%	0%	0%	0%	0%	0%	0%	0%
	Operation and maintenance (O&M)	0%	23%	31%	31%	0%	8%	0%	0%	0%	0%	0%	0%	8%
EoL	Dismantling (DM)	17%	0%	0%	17%	0%	50%	0%	0%	0%	17%	0%	0%	0%
	Reuse (RE)	9%	18%	18%	23%	5%	9%	0%	0%	5%	5%	0%	5%	5%
	Cutting (CT)	21%	11%	11%	11%	5%	16%	16%	0%	5%	5%	0%	0%	0%
	Repurposing (RP)	8%	0%	8%	25%	8%	25%	0%	0%	8%	8%	0%	0%	8%
	Shredding (SH)	15%	0%	11%	19%	4%	11%	15%	4%	4%	4%	7%	0%	0%
	Mechanical recycling (MR)	20%	7%	10%	17%	2%	7%	12%	5%	5%	7%	5%	0%	2%
	Thermal recycling (TR)	28%	7%	7%	14%	2%	7%	12%	5%	5%	7%	5%	0%	2%
	Chemical recycling (CR)	19%	8%	8%	16%	3%	8%	14%	3%	5%	8%	5%	0%	3%
	Co-processing (CP)	26%	9%	12%	18%	3%	9%	0%	3%	6%	9%	0%	3%	3%

2024; Maslowski et al., 2024).

Indicators applicability in the MoL decreases significantly, except for MEM, PCI, and CI, which maintain coverage rates between 30% and 50%. These indicators capture key aspects such as IN and O&M efficiency, important for optimising WTB circular performance. However, their limited applicability in this phase reveals methodological deficiencies in evaluating maintenance and repair strategies. Despite their increasing relevance in the wind industry, strategies remain underrepresented in most circularity indicators (Ren et al., 2021). Recent literature highlights the need for metrics that go beyond design and recycling, incorporating operational performance and maintenance efficiency through advanced predictive strategies (Malik and Bak, 2025). Integrating these metrics enables a more accurate and holistic circularity evaluation, supporting data-driven decision-making in the wind sector.

At the EoL, circularity indicators generally exhibit high coverage, reflecting their broad evaluative capacity at this stage. Applicability varies significantly across different processes, underscoring the complexity of circularity assessments and the necessity of integrating multiple metrics for a comprehensive system evaluation. While indicators such as CFF and MEM achieve high coverage, their specific focus constrains their scope: CFF quantifies emissions during processing, whereas MEM emphasises material efficiency. This limitation aligns with broader critiques in the literature, emphasising the need for holistic frameworks that incorporate environmental, economic, and material recovery dimensions to improve circularity assessments (Sproul et al., 2023).

The implementation of circularity indicators in the industry presents several challenges. The number of variables required for calculation increases data collection efforts, while limited data availability, particularly on material and energy flows, introduces uncertainty in circularity measurement across life cycle stages. Additionally, variability in calculation methodologies affects result comparability, highlighting the need for sector-wide metric harmonisation. Importantly, no single indicator has proven to be fully suitable for addressing all stages and dimensions of WTB-LCM, making it necessary to rely on multiple complementary indicators to capture the full complexity of circularity performance. Current circularity indicators offer uneven coverage across the WTB-LCM. While design and manufacturing benefit from material and energy efficiency metrics, logistics and maintenance remain underrepresented. This suggests that existing evaluation frameworks prioritise material transformation over life extension approaches despite the latter’s potential for sustainability and impact reduction. This aligns with the findings of Jerome et al. (2022), who emphasised the need for indicators tailored to the purpose of evaluation to ensure relevant results. Therefore, it is necessary to develop wind-specific indicators that account for the particularities of WTBs,

including their composite composition and logistics. Integrating these tools with LCA would enhance understanding circularity strategies’ impacts and benefits, facilitating decision-making, improving industrial strategies, and supporting the transition toward more circular models in the wind sector.

4.4. Limitations of the study and future research

The primary limitations of this study concern the scope of the literature review and the methodological approach used for filtering the indicators. This review was limited to the Scopus database, which, although widely recognised for its comprehensive coverage, may not capture all relevant studies indexed in other databases such as Web of Science. As such, some relevant publications may have been excluded. Future studies should aim to extend the database coverage to validate the consistency of the findings and to determine whether additional circularity indicators emerge from broader literature screening. This would support the consolidation of indicator sets and improve the robustness of selection frameworks.

Furthermore, the qualitative approach and the screening criteria of circularity indicators introduced additional limitations. The RACER evaluation was conducted by the authors of the study themselves, which, despite the measures taken to reduce bias (independent scoring, cross-checking, and consensus building) (Section 3.2.2), inevitably introduces a degree of subjectivity. This limitation might be relevant considering the potential cascading effect of the RACER results on subsequent stages of the analysis. To enhance robustness, future research should involve the engagement of external expert panels to validate and refine the evaluation. In addition, the composite design and wind energy criteria (section 3.2.2) are overly general and may not align completely with the developed WTB-LCM pathway diagram. Moreover, their interpretation can vary depending on the specific process within the diagram, highlighting their generic nature and the need for more specific criteria tailored to the different stages of the WTB value chain.

Future research should prioritise the development of circularity indicators tailored to the wind industry, grounded in process-specific criteria that reflect the complexity of the entire value chain. This would overcome the limitations of generic filtering approaches and improve the alignment between assessment tools and the WTB-LCM framework. In addition, since recycling technologies are not yet fully implemented, there is an opportunity to design indicators that anticipate their potential performance before large-scale deployment, thereby ensuring the sustainability of future EoL management systems.

Furthermore, future studies should implement integrated methodologies that combine circularity indicators with supplementary assessment instruments, such as LCA. This approach would facilitate a more

rigorous evaluation of trade-offs and synergies among material circularity, energy consumption, and environmental impacts. The incorporation of these methodologies would strengthen the consistency and relevance of sustainability assessment while supporting more informed decision-making in the development of CE strategies.

Building on the identification of the most suitable indicators for different stages of WTB-LCM, future research should focus on assessing the maximum circularity potential that can realistically be achieved in the wind sector. This requires moving beyond indicator selection towards the development of technically-economically plausible scenarios in which circularity is optimised across WTB-LCM pathways, considering current technological capabilities and foreseeable advancements. Such scenarios would allow for the characterisation of the key factors influencing the highest achievable levels of circularity—whether related to material composition, processing technologies, product design, or regulatory and operational conditions—and help identify the main barriers currently limiting circular performance, as well as areas where innovation is most needed.

In this regard, it is important to acknowledge the challenges associated with the thermal or chemical recycling of sandwich panel sections containing foam materials (such as PVC foam) due to the reaction products generated (Yousef et al., 2024). Addressing these challenges requires that manufacturers of WTBs consider, from early design stages, the cost, mechanical performance, aerodynamics, sustainable LCM, applicable recycling technologies, and recyclable materials in future development processes (Jensen and Skelton, 2018). Grounding circularity assessments in realistic performance thresholds would help refine existing indicators and improve their applicability in decision-making. This, in turn, would enable more effective and sector-specific CE strategies for the sustainable management of composite materials in the wind energy sector.

5. Conclusion

This study systematically assessed circularity indicators to determine their scope and applicability across WTB-LCM, from design to EoL management. The analysis included multiple circular strategies such as reuse, repowering, mechanical, thermal, and chemical recycling, as well as co-processing. The research characterised resource flows at each stage and applied a set of pre-selected circularity indicators based on RACER, composite materials and the wind energy sector criteria.

The paper confirms significant variability in the applicability of circularity indicators across different life cycle stages of WTBs. No single indicator fully captures their circularity, as existing metrics primarily address specific stages while overlooking key aspects such as transportation, installation, and decommissioning. Most indicators were designed for broader industrial applications and do not reflect the specific characteristics of WTBs, including their large size, material composition, and complex logistics.

These limitations underscore the need for a more comprehensive assessment framework that integrates environmental, energy, and material efficiency metrics. In addition, the observed misalignment between commonly used design criteria and WTB-LCM strategies points to a broader gap in the literature. This underscores the importance of developing more integrated approaches that connect design decisions with EoL and circularity pathways.

This study contributes to the field by identifying three priority areas for developing new circularity indicators tailored to the wind industry. First, incorporating logistics and transportation criteria will improve assessments of environmental and operational impacts related to WTB mobility and EoL management. Second, developing metrics for the operational phase will allow for a better assessment of maintenance, and lifetime extension strategies, supporting the transition to advanced CE models. Third, adapting recycling methodologies for composite materials will ensure that indicators capture the technical, economic, and environmental feasibility of different valorisation pathways, including

mechanical recycling and emerging technologies such as solvolysis.

A system-level perspective remains essential to understanding the circularity of WTBs at different implementation scales, from localised EoL solutions to regional and global recycling networks. Future research should focus on harmonising circularity indicators to enhance comparability across studies and evaluate new recycling technologies' role in industrial applications. The alignment of regulatory frameworks, technical and safety standards, green certifications, and industrial incentives will also be necessary to drive innovation and investment in circular strategies. Addressing these challenges will contribute to a more resource-efficient and sustainable wind energy sector.

CRedit authorship contribution statement

Marta Diez-Viera: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation. **Eva Sevigné-Itoiz:** Writing – review & editing, Supervision. **Joan Manuel F. Mendoza:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them. Agreement No 101096425 - EoLO-HUBS - HORIZON-CL5-2022-D3-01.

Appendix A. Supplementary data

Further information and data is presented in the supplementary file of the paper, including S1) definition of WTB-LCM pathways and associated stages, S2) identification of circularity indicators, the list of keywords used in the literature review, S3) the list of used criteria for screening and evaluation of circularity indicators, S4) characterisation of WTB-LCM stages and processes, S5) the characterisation of circularity indicators according different sustainability dimensions, S6) detailed scope assessment of circularity indicators in WTB-LCM stages. Supplementary data to this article can be found online at <https://doi.org/10.1016/j.spc.2025.09.010>.

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