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The lifespan problem: Why EU circular economy indicators understate progress

Jonas Grafström

Luleå University of Technology, Luleå, 97187 Sweden
The Ratio Institute, Sweden

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ABSTRACT

The European Union circularity rate increased by only 1 %age point between 2013 and 2024 despite sustained regulatory effort. Aggregate circularity indicators combine sectors with fundamentally different material lifespans into a single metric, systematically understating progress in sectors dominated by long-lived material stocks. A stock-flow framework formalizes the mechanism: recovered material flows within any observation window are determined by the lifespan distribution of accumulated stock rather than by current recovery effort alone. The framework is illustrated using nineteen European industries spanning packaging, textiles, electronics, vehicles, construction, and energy infrastructure. The analysis develops three reform options within the existing EU statistical architecture. Class-disaggregated reporting could be piloted within the Circular Economy Monitoring Framework, a quality-adjusted construction and demolition waste indicator would require revised Eurostat reporting, and forward-looking credits depend on mandatory digital product passport infrastructure. Improving circularity measurement is necessary for directing policy attention and investment toward sectors that dominate future material use.

1. Introduction

The European Commission's Circular Economy Action Plan of 2020 committed the European Union to ambitious targets for material recovery, recycling, and secondary material use across a broad range of sectors (European Commission, 2020a). The underlying logic is straightforward: if materials remain in use longer and recovery systems improve, primary extraction declines, emissions fall, and resource security strengthens. The empirical record is difficult to reconcile with that expectation. Eurostat data show that the EU circular material use rate increased only marginally between 2013 and 2024, rising from 11 to 12% (Eurostat, 2025; see Fig. 1). To policymakers, the result may suggest limited progress despite extensive regulatory intervention. To critics, it may indicate that the circular economy (CE) agenda has generated more rhetoric than structural change. Both interpretations are incomplete because aggregate circularity indicators do not account for differences in material lifespans across sectors.

Recent industrial ecology research suggests that circularity at any moment reflects historical material inflows as much as current recovery effort (Richter et al., 2024; Krych et al., 2025). Sazdovski et al. (2022) distinguished between high-frequency, low-mass loops such as packaging and low-frequency, high-mass loops such as buildings and infrastructure, arguing that the two require fundamentally different analytical perspectives. Timmers et al. (2024) similarly found that the age distribution of building stock shaped material availability for recovery more strongly than individual policy interventions. The implication from that literature is that the temporal structure of material stock may itself generate stagnant aggregate indicators even when recovery systems improve.

The dominant CE barrier literature has approached the problem differently. Existing frameworks emphasize technological, market, institutional, and social barriers to circular transitions (de Jesus and Mendonça, 2018; Kirchherr et al., 2018). Empirical studies identify fragmented supply chains, weak market incentives, and insufficient recovery infrastructure as persistent constraints on circularity (Rizos et al., 2015; Masi et al., 2018; Tura et al., 2019). Those explanations clarify why circular markets fail to emerge in particular sectors but say less about why aggregate indicators stagnate even where collection systems, recycling technologies, and regulatory frameworks have improved.

A complementary perspective emerges from intertemporal economics. Environmental and resource economics has long shown that delayed benefits are systematically undervalued when return horizons

E-mail address: jonas.grafstrom@ltu.se.

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are long and uncertain (Ramsey, 1928; Hotelling, 1931; Stern, 2007). Recent CE research applies that logic to durability, repairability, and recovery systems. Fullerton and He (2024) argue that market incentives tend to produce products that are too short-lived relative to the social optimum because future recovery benefits are discounted by producers and consumers. Tessitore et al. (2023) identify a similar mismatch between private incentives and socially desirable circular outcomes, particularly in sectors with long payback horizons. The literature therefore points to a common structural problem: the mismatch between material return horizons and the short observation windows used in circular economy monitoring.

The gap in the literature is therefore not empirical but diagnostic. Prior research has established that material return flows depend on the lifespan distribution of accumulated stock rather than on current recovery effort alone (Timmers et al., 2024; Richter et al., 2024; Krych et al., 2025). The present paper applies that stock-flow logic to the interpretation of the EU circular material use rate and to the design of improved indicators within the existing EU statistical architecture.

The purpose of the paper is to explain why aggregate EU circularity indicators are structurally biased toward stagnation and to develop concrete options for reducing that bias. The analysis proceeds in two steps. First, a stock-flow framework formalizes how product lifespan distributions shape observed circularity outcomes across sectors. Second, the framework is illustrated using nineteen European industries spanning packaging, textiles, electronics, vehicles, construction, and energy infrastructure. The paper then three indicator reform options within existing EU reporting systems.

The paper does not seek to estimate the precise magnitude of circularity bias across the European economy or to provide a statistically representative sector comparison. The objective is diagnostic: to identify and formalize a structural mechanism linking product lifespan distributions to observed circularity outcomes. The nineteen-industry sample is therefore constructed for illustrative rather than probabilistic purposes, spanning sectors with widely different material return horizons and covering the major material-intensive domains prioritized in the EU Circular Economy Action Plan. Cross-sector comparisons are used to demonstrate the implications of the stock-flow framework rather than to support causal inference. The paper contributes an analytical explanation of temporal indicator bias and its implications for circular economy measurement and policy design.

2. Background

2.1. Barriers to a circular economy and material lifespans

Research on CE barriers has converged on four recurring categories: technological, market, institutional, and social (de Jesus and Mendonça, 2018; Kirchherr et al., 2018). Empirical studies identify fragmented supply chains, weak market incentives, limited consumer awareness, and insufficient recovery infrastructure as persistent constraints on circular transitions (Rizos et al., 2015; Masi et al., 2018; Tura et al., 2019). Most of the literature treats time indirectly, typically as a planning horizon over which costs and benefits emerge, rather than as a structural property of the material system itself.

Industrial ecology research has approached the problem differently by modelling material stocks and product lifespans explicitly (Richter et al., 2024). Dynamic material flow analysis describes recovery flows as functions of historical inflows and lifespan distributions, implying that material available for recovery today largely reflect production and design decisions made years or decades earlier (Krych et al., 2025). Circularity therefore depends not only on current recovery effort but also on the age structure of accumulated material stock.

Empirical lifespan estimates vary substantially across sectors. Packaging materials and paper circulate rapidly, often within months or a few years (Sazdovski et al., 2022). Passenger vehicles typically remain in use for twelve to eighteen years depending on national fleet characteristics and scrappage patterns (Held et al., 2021). Buildings and infrastructure operate on much longer horizons. Residential structures in European and US cities have an average lifespan of more than seventy years (Berglund-Brown et al., 2025). The built environment consequently dominates total material stock by mass despite generating relatively limited annual recovery flows.

The lifespan structure of material stock has direct implications for observed circularity performance. Short-lived goods generate frequent return flows that become visible within ordinary policy and reporting cycles. Long-lived goods keep material embedded in use for decades, delaying the appearance of recoverable flows even when products are designed for future recovery. Aggregate circularity indicators therefore combine sectors operating on fundamentally different temporal horizons.

The EU circular material use rate is defined by Eurostat as the ratio of secondary material input to total material use. The numerator covers waste recovered in domestic recovery plants, adjusted for net trade in waste destined for recovery, and explicitly excludes energy recovery and

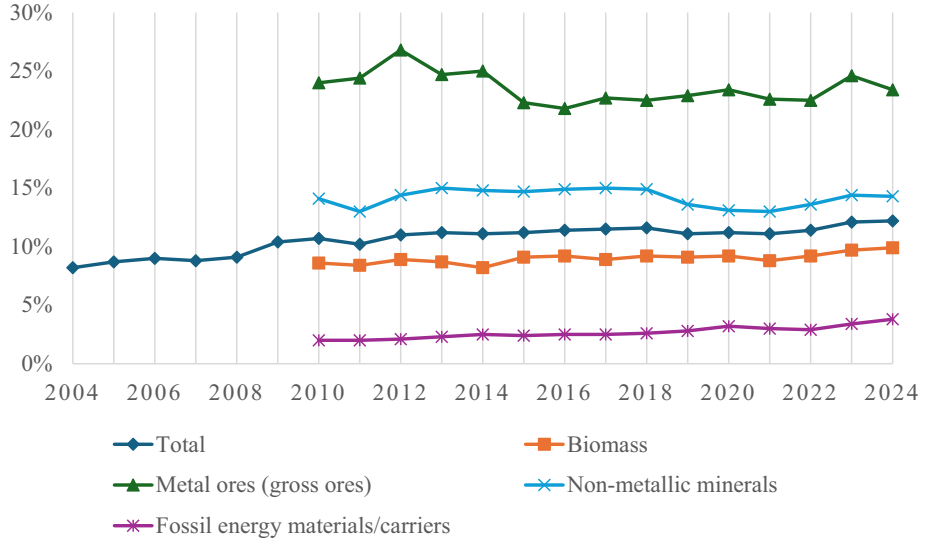


Fig. 1. Circularity rate by material categories, EU, 2004–2024. Source: Eurostat (2025).

backfilling. The denominator is the sum of domestic material consumption and the secondary material input. The indicator is an economy-wide flow ratio reported annually at member-state and EU aggregate levels (Eurostat, 2018). It is distinct from sector-level recycling rates, which measure waste recovery relative to waste generated within a defined industry or material stream. It also differs from collection rates, which measure the share of end-of-life products entering collection systems, and from technical recyclability assessments, which evaluate material properties independently of actual recovery flows. Where sector-level rates appear in the analysis, they refer to industry-specific recycling or recovery ratios as reported by Eurostat or sectoral monitoring bodies, not to the circular material use rate. The lifespan bias identified in the paper operates at the level of the circular material use rate: because the indicator measures secondary material flows within an annual observation window, it systematically underrepresents sectors with long material return horizons, regardless of what sector-level recycling rates show.

2.2. Intertemporal economics and the time barrier

The economic analysis of intertemporal resource allocation provides a theoretical foundation for why delayed circularity benefits are systematically undervalued. A long tradition in environmental and resource economics has shown that future benefits receive lower weight when return horizons are long and uncertain (Ramsey, 1928; Hotelling, 1931; Stern, 2007). The same logic applies to circular investments whose material recovery benefits emerge only after long periods of use.

Recent CE research has applied intertemporal reasoning to durability, repairability, and recovery systems. Fullerton and He (2024) shows that market incentives tend to produce products that are too short-lived relative to the social optimum because future recovery benefits are discounted by producers and consumers. Tessitore et al. (2023) identify a similar mismatch between private incentives and socially desirable circular outcomes, particularly in sectors with long payback horizons.

The temporal dimension becomes especially important when circularity is measured through short-term material flows. Circularity indicators are generally constructed as ratios of recovered material to total material use during a given observation period. Let circularity at time $t$be defined as:

$$C_t = \frac{R_t}{M_t} \tag{1}$$

where R_t denotes recovered material and M_t denotes total material use. The recovered flow is determined not only by current recovery efficiency but also by historical inflows and the lifespan distribution of goods in use. Recoverable material at time $t$can therefore be written as:

$$R_t = \int_0^{\infty} I_{t-\tau} f(\tau) d\tau \tag{2}$$

where $I_{t-\tau}$ represents past material inflows and $f(\tau)$ denotes the lifespan distribution governing when materials return to the recovery system.

The implication is straightforward. In sectors dominated by short-lived goods, improvements in recovery systems become visible rapidly because materials re-enter the recovery stream within a few years. In sectors dominated by long-lived material stock, most material remains embedded in buildings, infrastructure, and durable equipment for decades. Aggregate circularity indicators therefore respond slowly even when recovery efficiency improves. The result is a structural bias toward sectors with short return horizons and against sectors where circular gains materialize over much longer periods.

2.3. A stylized illustration of temporal indicator bias

The stock-flow framework implies that observed circularity responds faster in sectors with short material return horizons than in sectors with long return horizons, even when recovery efficiency improves by the same amount. Let annual material inflow be constant and normalized to one. Let recovery efficiency be denoted by ρ_t, and let the lifespan distribution determine the share of past inflows returning to the recovery system in period t. Observed circularity can then be written as:

$$C_t = \rho_t \int_0^{\infty} I_{t-\tau} f(\tau) d\tau \tag{3}$$

where $I_{t-\tau}$ is historical material inflow and $f(\tau)$ is the lifespan distribution. Under constant inflows, differences in observed circularity arise from differences in $f(\tau)$, not from differences in current recovery effort. Consider two sectors with identical material inflows and identical improvements in recovery efficiency. The sector with the shorter average lifespan will show a faster increase in observed circularity.

The intuition is straightforward. A recovery-efficiency improvement affects only materials that return to the recovery system. In short-lived sectors, a large share of the material stock returns within a single policy cycle, so improved recovery efficiency is quickly visible in circularity indicators. In long-lived sectors, most material remains embedded in use, so the same improvement affects only a small return flow. Observed circularity therefore changes slowly even when current design, sorting, and recovery systems improve.

A simple numerical example illustrates the mechanism. Consider two sectors with identical annual inflows and the same improvement in recovery efficiency from 40% to 60%. Sector A has a mean lifespan of two years. Sector B has a mean lifespan of fifty years. After ten years, most materials placed on the market in Sector A have already returned to the recovery system, so the higher recovery efficiency is visible in measured circularity. In Sector B, most materials remain embedded in buildings, infrastructure, or durable equipment. The indicator records little change because the relevant material flows have not yet occurred.

The difference reflects the observation window rather than weaker circular performance in the long-lived sector. A five-to-ten-year policy horizon is long enough to observe circularity gains in packaging or paper, but too short to observe gains in buildings, infrastructure, or energy systems. Aggregate indicators therefore overweight short-lived material loops and understate progress in long-lived sectors. The bias increases as the mass share of long-lived stock increases.

This result explains why aggregate EU circularity indicators can remain nearly flat despite improvements in selected recovery systems. Stagnation in the aggregate rate is compatible with real progress when a large share of material stock is unavailable for recovery within the measurement period. The implication is that current circularity indicators measure realized return flows rather than circular capacity created by current investment.

Fig. 2 illustrates the core mechanism developed in the paper. Both sectors experience the same increase in recovery efficiency following a policy intervention at year 0, but the observed circularity trajectories because of differences in the lifespan structure of the underlying material stock. In the short-lived sector, materials return rapidly to the recovery system, allowing improved recovery performance to become visible within a single policy cycle. In the long-lived sector, most material stock remains embedded in use for decades, so observed circularity changes only gradually even when recovery systems improve. The shaded area represents a typical EU policy horizon of five to ten years. The figure therefore illustrates why aggregate circularity indicators structurally understate progress in sectors dominated by long-lived material stocks.

3. Data and industry sample

3.1. Industry selection and data sources

The industry sample is intended to illustrate variation in material

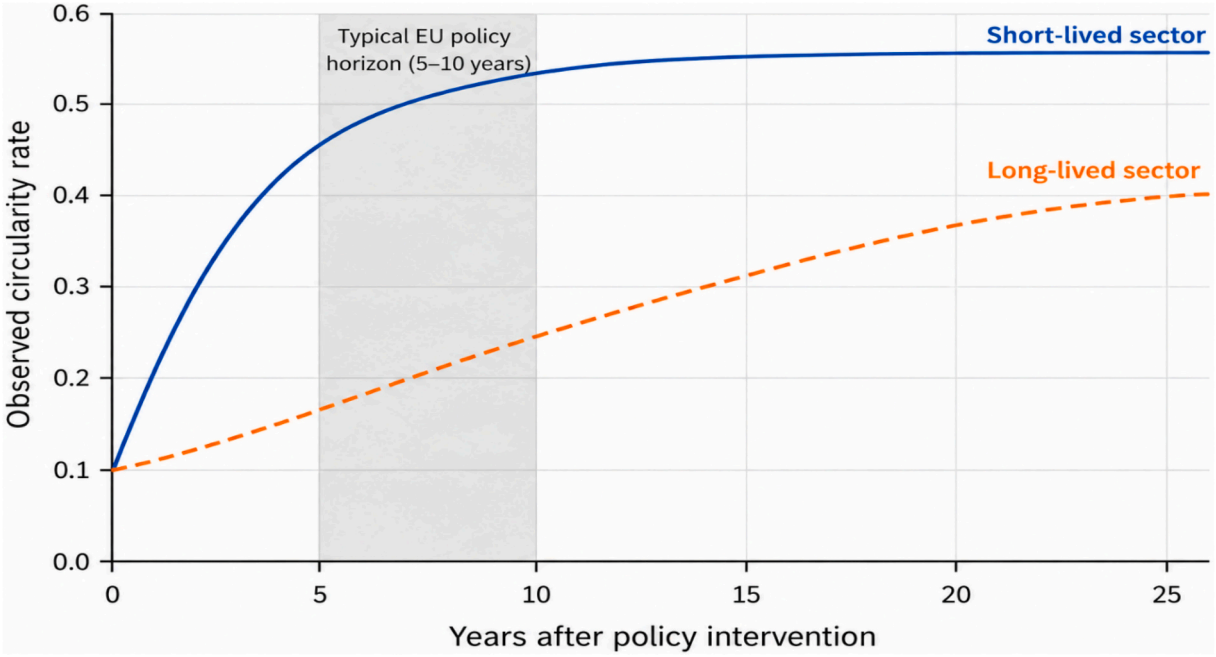


Fig. 2. Stylized evolution of observed circularity under identical recovery-efficiency improvements for sectors with different average product lifespans.

return horizons rather than to provide exhaustive coverage of the European economy. The sample consists of nineteen European industries spanning the full range of product lifespans, from days in packaging materials to a century or more in water and utility infrastructure.

Industries were selected to achieve broad coverage of three lifespan classes defined in Grafström (2026): Class *S* covers goods with typical lifespans of up to three years; Class *M* covers three to twenty years; Class *L* covers goods with lifespans exceeding twenty years. Within each class, industries were chosen to represent the major material-intensive sectors identified as priorities in the EU Circular Economy Action Plan (European Commission, 2020a) and to ensure that at least partial EU-level circularity or recycling data exist for each sector. Fig. 3 presents the three-stage selection procedure:

Data are drawn from three primary European institutional sources. Eurostat sector-specific waste databases provide recycling rates for packaging, waste electrical and electronic equipment (WEEE), and construction and demolition waste (CDW). The EEA publishes sector briefings on electronics (EEA, 2020), textiles (EEA, 2024), and product lifespans (EEA, 2024) containing cross-sector estimates at the EU level. European Commission sector reports, regulations, and impact assessments provide complementary data, particularly for end-of-life vehicles, tyres, and batteries, where dedicated regulatory frameworks generate monitoring data. Lifespan data are drawn from published academic literature. All figures are EU-level averages; performance varies substantially across member states. Fig. 4 shows the decision logic used to assign the policy maturity rating for each industry.

Circularity rate definitions differ across sectors, and cross-sector comparisons should be read as indicative rather than precise. Data are

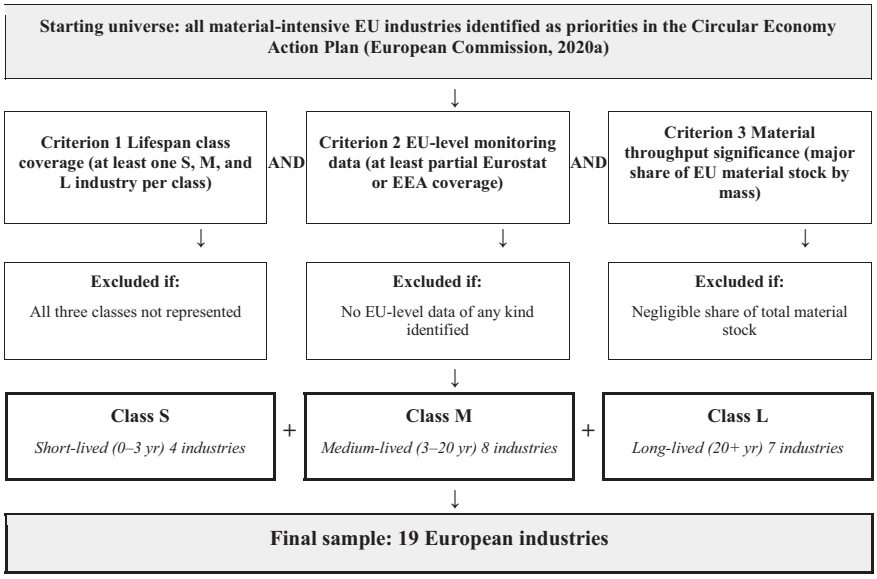
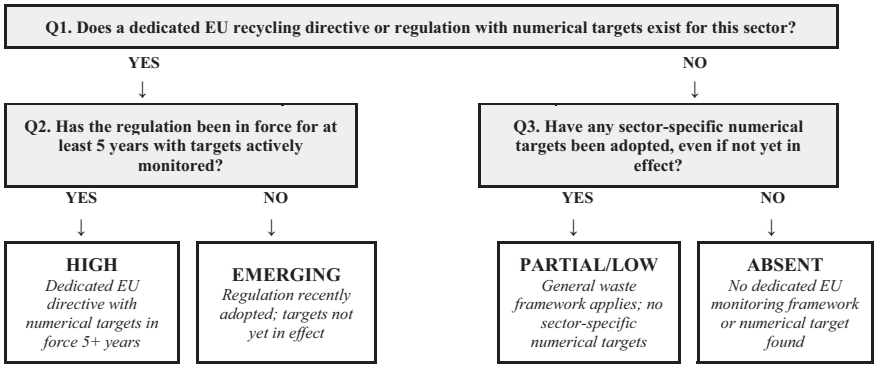


Fig. 3. Industry selection and classification procedure. The sample was constructed in two steps: first, candidate industries were assessed against three criteria applied simultaneously; second, passing industries were assigned to lifespan classes S, M, or L.



Rating	Industries	Regulatory basis
High	6	Packaging (PPWR), paper, vehicles (ELV Directive 2000/53/EC), tyres (producer responsibility), consumer electronics (WEEE Directive 2012/19/EU)
Emerging	1	EV batteries (EU Batteries Regulation 2023/1542; recycled content targets effective 2030)
Partial	4	Residential, commercial, industrial buildings, road infrastructure (general CDW provisions under Waste Framework Directive 2008/98/EC; no sector-specific numerical targets)
Absent	3	Furniture and interiors, rail infrastructure, water and utility infrastructure (no dedicated EU monitoring framework identified)
Low	5	Fast fashion, single-use plastics, technical textiles, solar PV, wind turbines (mandatory collection only from Jan 2025 or coverage under WEEE without sector-specific targets)

Fig. 4. Policy maturity assessment decision tree.

drawn from Eurostat waste statistics, EEA sector reports, European Commission regulatory documents, and published lifespan estimates from the industrial ecology literature. Eurostat provides sector-level recycling and waste treatment statistics for packaging, WEEE, and construction and demolition waste, whereas EEA and Commission sources provide complementary evidence for sectors where harmonized monitoring remains limited.

3.2. Limitations

The nineteen-industry sample, while broad, is not exhaustive. Sectors such as chemicals, pharmaceuticals, and aerospace are absent, partly because of limited EU-level circularity monitoring and partly because their material flows are difficult to classify within the S/M/L taxonomy without additional research. The selection criteria favor sectors with some monitoring data, which may systematically exclude sectors where the circularity gap is largest precisely because they have not attracted regulatory attention.

Circularity measures are not fully comparable across sectors because EU monitoring frameworks differ in scope and definition. The construction and demolition waste rate includes low-grade backfilling operations, whereas packaging rates measure verified material recycling. WEEE collection rates are benchmarked against historical market inflows, introducing a built-in temporal lag. None of the sector-level rates reported in Table 1 is equivalent to the EU circular material use rate, which measures secondary material input as a share of total material use across the entire economy. The reported values should therefore be interpreted as indicative cross-sector comparisons rather than harmonized measures of circular performance. A weighted material flow analysis using age-cohort stock data would allow future research to quantify the aggregate magnitude of the temporal bias identified here.

A further boundary condition concerns the relationship between lifespan distributions and actual disposal behavior. The stock-flow framework assumes that materials return to the recovery system in accordance with the lifespan distribution of accumulated stock. In practice, return flows also depend on consumer behavior that the model does not capture: product hoarding delays returns beyond expected horizons, premature disposal in fast-fashion and electronics shortens effective lifespans below designed values, and informal disposal or export channels remove materials from monitored recovery streams entirely. Cross-country variation in collection infrastructure, consumer norms, and regulatory enforcement means that harmonized EU-level indicators would reflect an aggregate that masks substantial member state heterogeneity.

Streamlining toward a single reporting framework carries the risk of obscuring variation that is diagnostically valuable at the national level. The class-disaggregated rates proposed here are therefore most useful as macro-level guidance instruments rather than templates for uniform national implementation.

4. Descriptive patterns across lifespan classes

4.1. Cross-industry overview

Table 1 presents the full industry sample with lifespan class, typical lifespan range, observed EU recycling or recovery rate (sector-level), and policy maturity rating. The data illustrate where the structural condition identified in Section 2 is most plausibly consequential within the illustrative sample. Three broad patterns emerge. Short-lived sectors achieve the highest sector-level recycling rates but represent a small share of total material stock by mass. Medium-lived sectors show wide internal variation, driven largely by regulatory history rather than lifespan alone. Long-lived sectors dominate material stock by mass but show the lowest genuine recovery rates and the weakest monitoring coverage. Each class is discussed in turn below.

4.2. Class S: Short-lived industries

The four Class S industries display the highest observed sector-level recycling rates in the sample, although performance varies substantially across sectors. Glass packaging achieves recycling rates close to 80% across Europe, and paper and cardboard exceed 70% under long-

Table 1
Industry sample: lifespan classes, circularity performance, and policy maturity.

Industry	Class	Typical Lifespan	EU recycling or recovery rate (sector-level, approx.)	Policy Maturity
Food and beverage packaging	*S*	Days – 2 yr	Glass 80%; Paper 74%; Plastic 40%	High
Fast fashion and apparel	*S*	1–3 yr	<1% fibre-to-fibre; ~30% collected	Low
Single-use plastics	*S*	Days – months	~13% recycled into new plastics	Low
Paper and cardboard	*S*	Days – 1 yr	~74% (2020); target 76% by 2030	High
Consumer electronics	*M*	3–7 yr	37.5% WEEE collection (2023)	High
White goods and appliances	*M*	7–15 yr	Under WEEE; lifespan +2% (2019–23)	High
Automotive and vehicles	*M*	10–20 yr	~85% recycling by weight	High
Furniture and interiors	*M*	7–20 yr	No dedicated EU tracking; low	Absent
Tyres and rubber	*M*	3–6 yr	95% ELT collection and treatment	High
Technical textiles	*M*	3–10 yr	Mandatory collection from Jan 2025	Low
Electric vehicle batteries	*M*	8–15 yr	Recycled content targets from 2030	Emerging
Solar photovoltaic panels	*M/L*	25–30 yr	Under WEEE; infrastructure immature	Low
Residential buildings	*L*	50–100 yr	CDW recovery 89% but mostly low-grade	Partial
Commercial buildings	*L*	40–80 yr	CDW ~89%; component reuse marginal	Partial
Industrial buildings	*L*	30–60 yr	CDW profile; modular can shorten loops	Partial
Road infrastructure	*L*	20–50 yr	CDW varies 10–90% across member states	Partial
Rail infrastructure	*L*	30–60 yr	Steel recyclable; no sector-level tracking	Absent
Wind turbines	*L*	20–30 yr	85–90% recyclable; blades mostly landfilled	Low
Water and utility infrastructure	*L*	50–100 yr	Steel pipes recyclable; no EU tracking	Absent

Notes: S = short-lived (0–3 yr); M = medium-lived (3–20 yr); L = long-lived (20+ yr). CDW = construction and demolition waste. WEEE = waste electrical and electronic equipment. ELT = end-of-life tyres. Policy maturity: High = dedicated EU directive or regulation with numerical targets in force for 5+ years; Emerging = recent regulation with targets not yet effective; Partial = general waste framework applies, no sector-specific targets; Absent = no dedicated EU monitoring framework. Recycling rates (sector-level rates) are the best available EU-level estimates for approximately 2021–2023 and are not fully comparable across sectors owing to differences in monitoring frameworks and definitions. Sources: Eurostat env_waspacr, env_waselee; European Environment Agency (EEA) (2020, 2024); European Commission ELV and CDW statistics; Tyres Europe (2025); Held et al. (2021); Niinimäki et al. (2020); Sazdovski et al. (2022); Berglund-Brown et al. (2025).

established producer responsibility systems (European Paper Recycling Council, 2024). The rapid circulation of packaging materials allows improvements in collection and recovery systems to become visible within ordinary policy cycles.

Fast fashion and apparel differ sharply from other short-lived sectors. Fibre-to-fibre recycling remains below one percent despite collection rates of approximately 30% (European Environment Agency (EEA), 2025). Mandatory separate textile collection entered into force only in 2025, several decades after comparable packaging systems were introduced. Single-use plastics also perform poorly relative to other short-lived materials, with recycling rates near 13% (European Commission, 2026). The contrast within Class S indicates that short return horizons facilitate observable circularity gains but do not guarantee them. Regulatory maturity and recovery infrastructure remain important conditioning factors.

4.3. Class M: Medium-lived industries

Class M industries display wider variation in observed circularity performance. Vehicles and tyres achieve some of the highest recovery rates in the sample under mature producer responsibility systems and long-standing EU regulation. End-of-life vehicles reach approximately 85% recycling by weight, and end-of-life tyre collection exceeds 90% in most member states (ACEA, 2023; Tyres Europe, 2025).

Consumer electronics present a different pattern. Despite two decades of WEEE regulation, collection rates remain below EU targets, reaching approximately 37.5% in 2023 (Eurostat, 2024). Actual product lifespans in electronics have also shortened relative to designed lifetimes, increasing waste generation and placing additional pressure on recovery systems (EEA, 2020). White goods have shown modest lifespan increases following recent repairability initiatives, although recovery performance remains uneven across member states.

Emerging sectors reveal a further temporal dimension. Electric vehicle batteries are only beginning to enter end-of-life flows at scale, and large volumes of solar photovoltaic panels are not expected to reach end of life until the 2040s and 2050s. Recovery infrastructure for both sectors therefore remains limited relative to projected future material flows (CISL, 2025). The variation across Class M industries reflects regulatory history, infrastructure development, and product lifespan.

4.4. Class L: Long-lived industries

Long-lived sectors dominate European material stock by mass but remain weakly represented in existing circularity indicators. The sector-level CDW recovery rate reported in EU policy documents reaches approximately 89%. Construction and demolition waste has high aggregate recovery rates at the EU level, although much of the reported recovery consists of low-grade backfilling and road sub-base applications rather than material-to-material reuse (Caro et al., 2024). High-grade recovery of structural components and building materials remains limited across most member states.

The long lifespan of buildings and infrastructure further constrains observable recovery flows. Much of the European building stock approaching demolition was constructed under material and design regimes that did not prioritize recoverability, limiting the quality and separability of demolition outputs. Similar conditions apply to rail infrastructure, utility networks, and industrial facilities, where material recovery depends on replacement cycles extending across several decades.

Energy infrastructure presents related challenges. Wind turbines have high recyclability across their metallic components, but composite rotor blades remain difficult to recover at commercial scale and are frequently landfilled or incinerated (Spini and Bettini, 2024). Solar photovoltaic systems face a different problem: most installed capacity has not yet reached end of life, delaying the emergence of economically viable recycling systems. Across Class L sectors, long replacement cycles and limited monitoring coverage reduce the visibility of circular progress within conventional policy horizons.

Long material lifespans create governance challenges that go beyond measurement. Circular investments made today, including design for disassembly, material documentation, and component standardization, will not generate recovery flows for decades. The policy conditions, market structures, and technologies governing recovery at that point cannot be reliably anticipated, and products documented as recyclable today may not be recovered if collection infrastructure or material markets shift. Conventional policy cycles are too short not only to observe circularity gains in long-lived sectors but also to manage the material commitments those sectors create.

4.5. The policy horizon mismatch

EU circular economy policy combines long-term strategic objectives with shorter operational monitoring cycles. Although the European Green Deal and related climate frameworks extend to 2050, most circular economy targets, reporting systems, and policy evaluations operate on horizons of approximately five to ten years. The relationship between product lifespan and policy monitoring windows therefore differs substantially across lifespan classes.

Table 2 quantifies the mismatch between median material return horizons and typical EU policy cycles. In short-lived sectors, material returns within a single monitoring period, allowing improvements in collection and recovery systems to appear rapidly in observed circularity rates. Medium-lived sectors generate observable gains more gradually across multiple policy cycles. In long-lived sectors, most material stock remains embedded in use far beyond the period captured by current reporting systems.

The mismatch has direct implications for aggregate circularity indicators. Improvements in short-lived sectors become visible rapidly because materials circulate through recovery systems within ordinary reporting periods. Improvements in long-lived sectors emerge much more slowly because recovery flows depend on replacement and demolition cycles extending across several decades. The illustrative sample is consistent with the expectation that aggregate indicators overweight sectors with rapid material turnover and understate progress in sectors where circular investments produce delayed recovery flows, although the magnitude of the effect across the full EU economy cannot be quantified from the present sample.

5. Discussion: Options for indicator reform

5.1. Sources of bias in current circularity indicators

Three distinct sources of bias follow directly from the temporal structure of material stocks. An aggregation bias arises because a single indicator combines sectors with fundamentally different return horizons: short-lived sectors generate frequent return flows and dominate observed circularity rates, whereas long-lived sectors dominate material stock by mass but contribute little to measured flows within the observation window. A truncation bias arises because circularity indicators measure flows within a limited time horizon, typically aligned with five-to-ten-year policy cycles, leaving materials embedded in long-lived goods outside the measurement window even when recovery is technically feasible and planned. A quality misclassification bias arises in sectors such as CDW, where low-grade uses including backfilling are counted alongside material-to-material recovery, inflating measured circularity in long-lived sectors and obscuring the true gap in high-grade recovery.

Indicator reform can be understood as a set of targeted corrections to each of these biases. Three concrete options are assessed in Table 3. Each corresponds directly to one of the biases identified above and is evaluated against three criteria: the degree to which it removes temporal bias from reported performance, the data infrastructure required, and institutional feasibility within current EU statistical frameworks.

Table 2
Policy horizon mismatch by lifespan class.

Class	Median return horizon (years)	EU policy horizon (years)	Mismatch ratio	Interpretation
Short (S)	1	5–10	0.1–0.2	Materials return within a single policy cycle. Progress is observable and attributable.
Medium (M)	10	5–10	1.0–2.0	Materials return across one to two policy cycles. Attribution is difficult; gains are delayed.
Long (L)	50	5–10	5.0–10.0	Materials will not return for five to ten policy cycles. Current indicators cannot capture progress.

Notes: The mismatch ratio is calculated as the median return horizon divided by the midpoint of the EU policy horizon range (7.5 years). Median return horizons are illustrative central estimates derived from the sectoral evidence summarized in Table 1.

5.2. Constructing lifespan-adjusted indicators

Three indicator reforms follow from the bias sources identified in Section 5.1. Each is specified below with a formal definition, required data inputs, and an illustrative comparison with the existing EU circular material use rate.

Applying the definition established in Section 2 to each lifespan class separately yields the class-disaggregated rate. Let U_t denote total domestic material use in period $t$and S_t denote the secondary material component in the same period. The aggregate rate is:

$$CMU_t = \frac{S_t}{U_t} \tag{4}$$

The class-disaggregated analogue partitions both numerator and denominator by lifespan class:

$$CMU_{x,t} = \frac{S_{x,t}}{U_{x,t}}, \quad x \in \{S, M, L\} \tag{5}$$

where S_t and U_t denote secondary material input and total material use observed during calendar year t, corresponding to the annual Eurostat reporting window. $S_{x,t}$ and $U_{x,t}$ denote the corresponding secondary material input and total material use within lifespan class x during the same period. The class-disaggregated measure therefore preserves the same annual observation window as the aggregate circular material use rate but reports flows separately for short-, medium-, and long-lived material classes. The technical requirement is a mapping between existing Eurostat waste categories and the S/M/L taxonomy defined in Section 3. Such a mapping does not currently exist in Eurostat's formal classification system but could be established through a methodological protocol within the Circular Economy Monitoring Framework.

Table 1 provides the basis for an illustrative calculation. Packaging glass reaches recycling rates near 80%, paper and cardboard exceed 74%, and single-use plastics are near 13%. Together, they produce a weighted Class S rate in the range of 50 to 60% depending on relative material volumes. Medium-lived sectors show wider dispersion: vehicles at 85% and tyres at 95% pull the average upward, whereas consumer electronics at 37.5% and furniture and technical textiles near zero pull it downward. The resulting Class M rate is in the range of 20 to 40% once unmonitored sectors are included. Long-lived sectors report a nominal construction and demolition waste recovery rate of 89%, but that figure is dominated by low-grade backfilling rather than material-to-material recovery. Excluding backfilling operations reduces the effective Class L rate to an estimated 15 to 45% across member states (Caro et al., 2024). The contrast with the aggregate circular material use rate of 12% reflects a composition effect: the aggregate is depressed by the mass of long-lived stock relative to total material use, not by weak recovery performance in the short-lived sectors where policy has had the most effect.

A rising Class S rate accompanied by a stable Class L rate would be interpreted as evidence that policy is working where it can rather than as evidence of partial failure. A rising Class L rate, when it eventually occurs, would signal genuine progress in the sectors that dominate total material stock by mass.

The current EU construction and demolition waste recovery rate of

Table 3
Options for circularity indicator reform: mechanisms, advantages, and limitations.

Reform option	Mechanism	Advantage	Limitation
Class-disaggregated reporting	Report separate circularity rates for S, M, and L industries rather than a single aggregate	Removes lifespan bias from aggregate; makes cross-sector comparison meaningful	Requires harmonization of sector classification across Eurostat frameworks
Quality-adjusted CDW rate	Separate high-grade material-to-material recovery from low-grade backfilling in construction and demolition waste reporting	Removes the statistical artefact that inflates long-lived sector performance	Requires revised reporting definitions and additional monitoring at treatment facilities
Forward-looking credit indicator	Credit present design decisions for expected future recovery flows, using material passport data	Captures circular investment before material returns; aligns incentives	Requires reliable material passport infrastructure not yet in place at scale

Notes: Assessment is qualitative and based on current EU data availability, existing Eurostat reporting frameworks, and the institutional requirements of each option. All three options could in principle be implemented in parallel rather than as alternatives.

approximately 89% combines recycling with lower-grade recovery operations, including backfilling. Under Annex II of Directive 2008/98/EC, R3 covers the recycling or reclamation of organic substances not used as solvents, R4 covers metals and metal compounds, and R5 covers other inorganic materials. Construction and demolition waste is therefore primarily associated with R4 and R5 depending on material composition, although organic fractions may also fall under R3. Eurostat distinguishes recycling from backfilling as separate waste-treatment categories even though backfilling may formally fall within R3 or R5. Backfilling refers to the use of suitable waste for reclamation in excavated areas or for engineering purposes in landscaping and is excluded from the EU definition of recycling. A quality-adjusted construction and demolition waste indicator should therefore distinguish recycling from backfilling rather than exclude a particular R-code:

$$QACDW_t = \frac{CDW_t^{REC}}{CDW_t^{TOT}} \tag{6}$$

where CDW_t^{REC} denotes construction and demolition waste classified as recycling, excluding backfilling, and CDW_t^{TOT} denotes total construction and demolition waste generated in period t. The adjustment therefore retains genuine recycling under relevant R3, R4, and R5 operations but excludes quantities reported as backfilling. The distinction is between treatment outcomes rather than between R-codes: an R5 operation may represent genuine recycling of inorganic material or backfilling depending on the specific treatment. Applying the adjustment to existing Eurostat waste-treatment data reduces the effective EU construction and demolition waste recovery rate from 89% to an estimated 15 to 45% across member states, with the lower end applying in countries that rely most heavily on backfilling (Caro et al., 2024 Implementation would require harmonized reporting of recycling and backfilling within construction and demolition waste statistics across member states. The two treatment outcomes could then be reported separately in the proposed quality-adjusted indicator.

In contrast to the annual flow measures in Eqs. 4 and 5, the forward-looking indicator attributes a present-period credit to material entering use in period t based on its expected recovery at a later date. Let $M_{new,t}$ denote the mass of material entering new products or structures in period t, let r_{exp} denote the expected recovery rate at end of life based on material passport documentation, and let d denote a discount factor reflecting uncertainty about whether designed recyclability will translate into actual recovery. A provisional credit in period t takes the form:

$$FLC_t = d \cdot r_{exp} \cdot M_{new,t} \tag{7}$$

where FLC_t represents the forward-looking circularity contribution attributed to material entering use in period t. The discount factor d is necessary because designed recyclability does not guarantee actual future recovery: materials documented as recyclable today may not be recovered owing to changes in technology, markets, or regulatory frameworks. Without an explicit discount, forward-looking credits risk rewarding theoretical recyclability rather than genuine circular outcomes. The indicator requires standardized material passport records, which the Ecodesign for Sustainable Products Regulation and the revised Energy Performance of Buildings Directive are beginning to establish but have not yet mandated at scale (Markou et al., 2025). The forward-looking credit indicator should therefore be treated as a medium-term reform that depends on mandatory digital product passport infrastructure across member states.

The three proposed indicators differ from the existing circular material use rate in both scope and interpretive function. The existing rate is an economy-wide flow ratio: secondary material input as a share of total material use, reported annually for the EU as a whole. The class-disaggregated rate applies the same formula within each lifespan class, making it directly comparable in construction but interpretively distinct. A rising Class S rate signals policy effectiveness, whereas a rising Class L rate signals structural stock turnover. The two cannot be averaged into a meaningful aggregate without reintroducing the conflation the disaggregation is designed to remove. The quality-adjusted construction and demolition waste rate applies to a single sector and is not intended as an economy-wide measure; its function is to replace a systematically inflated sectoral figure with one that reflects genuine material-to-material recovery.

The forward-looking credit indicator differs most fundamentally: it does not measure realized recovery flows but anticipated future contributions, and is therefore not directly comparable to the existing rate. Its appropriate use is as a complement to flow-based indicators rather than a substitute, capturing circular investment that current monitoring cannot register. The three reforms are not alternative versions of the same indicator. They address different layers of the measurement problem identified in Section 5.1 and would ideally be reported alongside the existing aggregate rather than instead of it.

Three verification challenges accompany the forward-looking credit indicator. First, material passport records must be independently audited rather than self-reported, because credits based on unverified recyclability claims would reproduce the quality misclassification problem the indicator is designed to correct. Second, the discount factor d should be calibrated against observed gaps between designed recyclability and actual recovery rates in sectors where both data exist, rather than set administratively without empirical grounding. Third, credits should lapse or be revised downward if material passport documentation is not updated at key product life-cycle stages, such as renovation or change of ownership for buildings, to prevent credits from persisting beyond the conditions that justified them. Without these safeguards, forward-looking credits risk becoming a mechanism for reporting circular progress that never materialises.

5.3. Sector-specific and economy-wide indicators: complementarity and limits

Economy-wide and sector-specific circularity indicators share the same logical structure but apply the measurement boundary at different levels. The EU circular material use rate aggregates across all sectors into a single suited to tracking aggregate resource productivity and supporting cross-country comparison. Sector-specific rates provide the

diagnostic resolution needed to identify where progress is occurring, but they measure different things under different regulatory definitions and cannot be summed into a meaningful aggregate.

The class-disaggregated rates proposed in Section 5.2 sit between the two levels. Grouping sectors by material return horizon rather than by industry classification produces rates that are internally comparable within each class and jointly interpretable across classes. A rising Class S rate alongside a stable Class L rate helps identify where progress is occurring within the material system in a way that neither the aggregate rate nor individual sector rates allow on their own. The three measurement levels are most useful in combination: the aggregate rate as a headline indicator, class rates for temporal diagnosis, and sector rates for intervention design.

Three implications follow for EU circular economy governance. First, class-disaggregated reporting could be piloted within the existing Circular Economy Monitoring Framework without new legislation, requiring only a methodological protocol to map current Eurostat waste categories to the S/M/L taxonomy. The European Environment Agency, which already produces the monitoring framework's indicator reports, is the natural institutional home for that work. Second, the quality-adjusted construction and demolition waste rate could be implemented by harmonizing the distinction between recycling and backfilling in construction and demolition waste reporting across member states.

6. Concluding remarks

The apparent stagnation of EU circularity indicators is partly a consequence of how circularity is measured rather than evidence of uniformly weak circular economy performance. The resulting structural bias favors sectors with rapid material turnover and disadvantages sectors where recovery gains emerge slowly over time. Short-lived sectors such as packaging and paper show relatively rapid and visible improvements in recycling performance. Long-lived sectors dominate material stock by mass but remain weakly represented in conventional indicators because much of the stock has not yet returned to the recovery system. Aggregate circularity measures are likely to understate progress in sectors where circular investments operate over long time horizons.

The analysis is conceptual and diagnostic rather than inferential, and several extensions remain open for future research. Dynamic material flow models using age-cohort stock data could quantify the aggregate magnitude of the temporal bias identified here. Further work is also needed to develop operational classification systems linking Eurostat waste categories to lifespan-based circularity reporting.

The central implication remains straightforward: circular economy indicators built around short observation windows cannot fully capture progress in sectors where material recovery depends on long-lived stocks. Improving measurement is therefore not only a statistical exercise but also a condition for directing policy attention and investment toward the sectors likely to dominate future material use.

CRediT authorship contribution statement

Jonas Grafström: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author used ChatGPT and Claude to improve the language and gather potential sources that were then expanded and amended by the author. After using this tool/service, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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Appendix A. Policy maturity assessment: Primary sources and direct links

The policy maturity variable is assessed at four levels — High, Emerging, Partial, and Absent — as documented in the notes to Table 1 and in Fig. 2. Because this assessment involves individual judgement about the scope and status of EU legislation, this appendix provides a direct link to every primary source consulted for each rating. Readers can click each link to verify the rating independently. All links were active as of submission.

Rating: HIGH — *Dedicated EU directive or regulation with numerical targets in force for 5+ years*		
Industries: Food and beverage packaging, paper and cardboard, consumer electronics, white goods and appliances, automotive and vehicles, tyres and rubber		
Document / source	What it establishes	Direct link
Packaging and Packaging Waste Regulation (EU) 2025/40	Mandatory recycling targets by material type; replaces Directive 94/62/EC	EUR-Lex — PPWR 2025/40
European Paper Recycling Council (2024)	EU paper recycling rates 2021–2030; 74% achieved; 76% target	EPRC Declaration 2021–2030
WEEE Directive 2012/19/EU (recast)	65% collection target for electronics; monitoring framework in force since 2014	EUR-Lex — WEEE Directive
Eurostat WEEE statistics	Annual collection rate data by member state; 37.5% EU average 2023	Eurostat env_waselee
End-of-Life Vehicles Directive 2000/53/EC	85% recycling target by weight; in force since 2002; monitoring via Eurostat	EUR-Lex — ELV Directive
Eurostat ELV statistics	Annual ELV recycling rates by member state	Eurostat env_waselvt
Tyres Europe (2025)	95% end-of-life tyre collection and treatment rate under producer responsibility	Tyres Europe — Circularity and end-of-life
Rating: PARTIAL — *General waste framework applies; no sector-specific numerical targets*		
Industries: Residential buildings, commercial buildings, industrial buildings, road infrastructure, rail infrastructure		
Document / source	What it establishes	Direct link

(*continued on next page*)

(*continued*)

Rating: PARTIAL — *General waste framework applies; no sector-specific numerical targets*		
Industries: Residential buildings, commercial buildings, industrial buildings, road infrastructure, rail infrastructure		
Document / source	What it establishes	Direct link
Waste Framework Directive 2008/98/EC (amended by 2018/851)	General 70% CDW recovery target; no sector-specific building or infrastructure targets	EUR-Lex — Waste Framework Directive
European Commission CDW statistics	EU CDW recovery rate ~ 89%; includes backfilling; no building-type breakdown	EC — Waste statistics
Caro et al. (2024)	Environmental and socio-economic effects of CDW recycling in the EU; quality-adjusted rates	Science of the Total Environment — Caro et al.
Energy Performance of Buildings Directive (recast) 2024/1275	Encourages material passports for new construction; no mandatory CDW numerical targets	EUR-Lex — EPBD recast
European Commission Renovation Wave (2020)	Policy ambition for building stock renovation; no sector-specific recycling targets	EC — Renovation Wave
EU Batteries Regulation 2023/1542	Mandatory recycled content targets for EV batteries effective from 2030; collection targets from 2025	EUR-Lex — Batteries Regulation
Rating: ABSENT — *No dedicated EU monitoring framework or numerical target found*		
Industries: Furniture and interiors, rail infrastructure, water and utility infrastructure		
Document / source	What it establishes	Direct link
Eurostat waste statistics browser	Search confirms no dedicated waste code or monitoring series for furniture, rail, or utility sectors	Eurostat — waste statistics browser
EU Circular Economy Action Plan (2020)	Furniture identified as a priority value chain but no targets or monitoring framework established	EC — Circular Economy Action Plan
Waste Framework Directive 2008/98/EC	General framework applies by default; no sector-specific provisions for these sectors	EUR-Lex — Waste Framework Directive
Rating: LOW — *Mandatory collection framework recently introduced or coverage under WEEE without sector-specific targets*		
Industries: Fast fashion and apparel, single-use plastics, technical textiles, solar PV panels, wind turbines		
Document / source	What it establishes	Direct link
EU Textile Strategy (2022)	Policy framework for textiles; mandatory separate collection from January 2025 under revised WFD; no numerical recycling targets	EC — EU Strategy for Sustainable Textiles
European Parliament — Fast fashion (2025)	Overview of EU legislative measures for sustainable textile consumption	EP — Fast fashion EU laws
EEA (2025) — EU textiles circularity	Circularity of the EU textiles value chain in numbers; <1% fibre-to-fibre recycling	EEA — Textiles circularity report
Single-Use Plastics Directive 2019/904	Bans certain SUP items; no recycling rate target for plastics as a category	EUR-Lex — SUP Directive
European Commission (2026) — Plastics circularity package	Questions and answers on the circularity plastics package; ~13% recycling rate	EC — Plastics circularity Q&A
WEEE Directive 2012/19/EU — Solar PV coverage	Solar PV panels covered under WEEE Annex I from 2014; no sector-specific volume target	EUR-Lex — WEEE Directive (Annex I)
CISL (2025) — Circular Solar report	Infrastructure for PV recycling immature; major end-of-life wave expected post-2040	CISL — Circular Solar Industry report
Jasińska and Dutkiewicz (2025)	Wind turbine blade waste management; landfilling banned in DE, AT, FI, NL; no EU target	Jasinska and Dutkiewicz
Spini and Bettini (2024)	End-of-life wind turbine blades; review of recycling strategies; no commercial-scale solution	Composites Part B — Spini and Bettini

General sources used across all ratings.

Document / source	What it establishes	Direct link
Eurostat circular economy indicators	Aggregate EU material circularity rate 2013–2024; stagnation at 11–12%	Eurostat — Circular economy material flows
EU Circular Economy Action Plan (2020)	Priority sectors, targets, and legislative roadmap	EC — CEAP 2020
EEA (2024): Product lifespans	Monitoring trends in product lifespans across sectors; actual vs designed lifetimes	EEA — Product lifespans report
Berglund-Brown et al. (2025)	Average residential building lifespan 71 years across European and US cities	Buildings and Cities — Berglund-Brown et al.

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