



Circular Economy Principles in Energy Transitions: Relationship Directions, Evidence Bases, and Trade-offs in a Systematic Review

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ABSTRACT

Energy transitions are increasingly constrained by material demand, end-of-life flows, and resource governance, yet the role of circular-economy (CE) principles remains fragmented across the literature. This systematic review examines how CE and energy transitions (ET) are related, what evidence supports these relationships, and which trade-offs are reported. Peer-reviewed publications indexed in Scopus and Web of Science between 2015 and 25 February 2025 were screened in accordance with PRISMA 2020, yielding a final corpus of 55 studies. Fifteen circularity principles were identified. Thirty studies framed CE as influencing ET, eight framed ET as influencing CE, and 17 described a synergistic relationship. Only six studies provided direct empirical evidence; the remaining 49 relied on inference or theoretical reflection. Reuse/repurposing and recycling were the most frequently identified principles. Trade-offs appeared in 25 studies, mainly involving materials and resource flows, waste and emissions, energy-economic performance and supply security, and social, territorial, and justice-related impacts. The review proposes an analytical framework that distinguishes relationship direction, evidence basis, circularity principles, and trade-offs, enabling more transparent comparison across heterogeneous CE-ET studies.

Keywords: Circular Economy, Energy Transition, Sociotechnical Transitions, Circular Energy Systems, Resource Governance

JEL Classifications: Q42, Q56, Q57

1. INTRODUCTION

Global dependence on fossil fuels and the persistence of linear production systems—based on extracting, producing, using, and discarding resources—connect two central sustainability challenges: Greenhouse-gas emissions and increasing pressure on materials, ecosystems, and resource stocks (Geissdoerfer et al., 2017; Rockström et al., 2009; Steffen et al., 2015). These pressures make it difficult to discuss energy transitions separately from the extraction, use, circulation, and end-of-life management of the resources required by energy systems (Falcone, 2018; Okafor et al., 2021).

Circular economy (CE) is commonly discussed as an alternative to linear production and consumption and as an approach for

operationalizing sustainability through narrower, slower, and more regenerative material cycles (Ellen MacArthur Foundation, n.d.; Prieto-Sandoval et al., 2018; Ramos et al., 2020). In this review, CE is operationalized through circularity principles such as reducing resource demand, extending product and infrastructure lifetimes, reusing and repurposing assets, recovering materials and components, recycling, circular design, reverse logistics, industrial symbiosis, and regeneration of natural systems.

Energy transition (ET) refers to changes in primary energy sources and in the systems that produce, distribute, regulate, and use energy (Smil, 2017). Contemporary transitions therefore extend beyond substituting one source for another. They involve infrastructures, institutions, policies, industrial structures, material supply chains,

and socio-environmental relations (Millot and Maïzi, 2021; Pavanelli et al., 2023). As low-carbon technologies scale, their dependence on minerals, components, grids, storage, and new end-of-life streams becomes increasingly important.

This material dimension creates a direct conceptual link between CE and ET. Low-carbon technologies can reduce operational emissions while simultaneously increasing demand for minerals and creating future waste flows. Circular strategies may reduce part of these pressures by preserving material value, extending asset lifetimes, improving resource productivity, and structuring recovery chains. At the same time, the expansion of low-carbon systems can itself create incentives for recycling, remanufacturing, reverse logistics, and critical-mineral governance. The relationship may therefore run from CE to ET, from ET to CE, or operate through reciprocal and synergistic mechanisms.

Previous research has identified points of convergence between the two fields. Chen and Kim (2019) linked circularity and energy transition through resource-demand reduction, emissions mitigation, material-loop closure, and the integration of material and energy efficiency. Kalchenko et al. (2019) similarly treated CE as an approach capable of optimizing resource use, reducing waste, and supporting renewable-energy development. Despite this progress, the literature remains fragmented. Circularity is frequently invoked at a broad level without systematically identifying which principles are mobilized, what direction of influence is proposed, how closely that relationship is supported by the study's own evidence, or which countervailing outcomes accompany it (Calisto Friant et al., 2020; 2021).

This review addresses that gap through the following research question: How are circular-economy principles mobilized in the literature on energy transitions, what types of CE-ET relationship are identified, what evidence supports those relationships, and what trade-offs are associated with them? The study identifies and systematizes circularity principles, classifies the direction of the CE-ET relationship, distinguishes the evidentiary basis supporting each relationship, and examines trade-offs as an independent cross-cutting analytical dimension. The resulting framework separates dimensions that are often aggregated and enables more transparent comparison across heterogeneous studies.

2. THEORETICAL FRAMING

2.1. Circular Economy as Material-System Transformation

CE is not treated here as synonymous with recycling. The analytical scope includes strategies that reduce resource demand and waste generation, retain the value of products and components, recover materials after use, reorganize inter-firm flows, and—where relevant—support ecological regeneration. This broader interpretation is important for energy systems because a narrow end-of-pipe focus can overlook upstream extraction and the material intensity embedded in infrastructures.

Material cycles also cannot be closed completely. Quality losses, dispersion, thermodynamic constraints, collection inefficiencies,

and energy requirements mean that recycling and remanufacturing can reduce but not eliminate primary extraction (Valero and Valero, 2019). Circularity should therefore be evaluated in relation to both the quantity and quality of retained material value and the energy required to maintain those loops.

2.2. Energy Transitions as Material, Institutional, and Territorial Transformations

Energy transitions reorganize more than the energy mix. They modify infrastructures, investment patterns, industrial supply chains, land and mineral requirements, governance arrangements, and the spatial distribution of environmental burdens. Renewable and low-carbon systems consequently need to be examined across their full life cycles rather than only through operational emissions (Hu et al., 2024). These transformations also have distributive and justice dimensions because transition costs, benefits, and environmental pressures can be unevenly allocated across groups and territories (Arias et al., 2023).

Critical-mineral supply illustrates this point. The geographic concentration of mineral resources, long development times for new mines, environmental constraints, and limited secondary supply can generate new vulnerabilities even as dependence on fossil fuels declines (International Energy Agency, 2021; International Renewable Energy Agency, 2023; Jowitt, 2024; Overland, 2019). These dynamics create a material-governance agenda within ET and make circularity potentially relevant to resource security as well as environmental performance.

2.3. Linking Circular Economy and Energy Transitions

The CE-ET nexus can be conceptualized through three relationship directions. First, CE may influence ET when circular strategies reduce primary-material demand, extend infrastructure lifetimes, lower life-cycle burdens, or improve the resilience of low-carbon supply chains. Second, ET may influence CE when the deployment of renewable-energy technologies, batteries, grids, and electrified mobility creates new material streams and therefore new incentives for recovery, recycling, reverse logistics, redesign, or resource governance. Third, CE and ET may operate synergistically when material and energy strategies reinforce one another through coordinated policy, infrastructure, technology, or institutional change.

These relationship directions should not be conflated with the strength of the evidence supporting them. A conceptual argument about synergy is analytically different from a study that directly models how circular strategies alter material demand or emissions. The framework used in this review therefore separates relationship type from evidence basis and treats trade-offs as a third, independent dimension.

3. METHODS

3.1. Review Design and Protocol

A systematic literature review was conducted to identify, select, and compare peer-reviewed studies addressing the relationship between circular economy and energy transition. A systematic

approach was chosen to consolidate a fragmented literature using explicit and reproducible selection and synthesis procedures (Littell et al., 2008; Randles and Finnegan, 2023). The review design and reporting of identification, screening, eligibility, and inclusion were guided by PRISMA 2020 (Page et al., 2021). The protocol was specified before study selection, although it was not registered in a public repository. The main elements of the systematic-review protocol are summarized in Table 1.

Scopus and Web of Science were selected because of their multidisciplinary coverage and structured metadata. The review deliberately focused on studies that explicitly connected CE and ET rather than on the entire literature on decarbonization, renewable energy, or energy technologies. This narrower strategy was intended to preserve conceptual relevance to the review question.

3.2. Screening and Study Selection

The database searches retrieved 383 records. Duplicates were identified by comparing DOI, title, authors, and publication year and then manually checking complete or partial matches. Seven duplicates were removed, leaving 376 records. Exclusion by document type reduced the set to 300 records; restricting the corpus to English-language publications resulted in 295 records for title and abstract screening.

Title and abstract screening retained 113 studies for full-text assessment. Fifty-eight full texts were excluded: 18 because the

CE-ET relationship was only marginal; 16 because the energy dimension was not substantively examined; five because no circularity principle could be identified explicitly or inferred from objectives, methods, results, or discussion; and 19 because they focused on a specific technology or process without analyzing energy transition as a systemic, institutional, material, or sociotechnical process. When more than one exclusion reason applied, only the primary reason was recorded. The final corpus comprised 55 studies. The complete screening and eligibility process is summarized in Table 2.

Title/abstract screening and full-text assessment were conducted by the primary researcher; no independent second-reviewer validation was completed for the corpus analyzed in this manuscript.

3.3. Content Analysis and Coding

The coding matrix was organized around two main analytical axes and one cross-cutting axis: (i) The evidence basis supporting the CE-ET interaction; (ii) the direction of the CE-ET relationship; and (iii) the presence and nature of trade-offs. Each study was the unit of analysis. Relevant passages in objectives, methods, results, and discussions were recorded and linked to coding decisions.

The evidence basis was classified as E1, direct empirical evidence, when the CE-ET relationship itself was examined by the study design and supported by data, estimates, modeling, simulation, or case results; E2, inference from results or discussion, when findings relevant to CE and ET were available but the direction or synergy was analytically constructed rather than directly tested; or E3, theoretical reflection, when the relationship was proposed through conceptual argument, frameworks, narrative synthesis, or recommendations without a directly related result. These categories indicate proximity of evidence to the coded relationship; they are not methodological-quality or risk-of-bias scores.

Relationship type was coded into three mutually exclusive categories: R1, CE influences ET (CE → ET); R2, ET influences CE (ET → CE); and R3, a synergistic relationship. Trade-offs were coded independently as T0, no identifiable trade-off; T1, explicit trade-off; or T2, inferred trade-off. Four non-exclusive trade-off dimensions were refined during the analysis: TD1, materials, resources, and circularity of flows; TD2, waste, emissions, and pollution; TD3, energy/economic performance and security of supply; and TD4, social, territorial, and justice impacts.

Fifteen circularity principles were identified inductively from the full-text corpus: Resource-use efficiency (P01), reduction

Table 1: Systematic-review protocol

Protocol element	Specification
Research question	How are CE principles mobilized in studies of energy transitions, what CE-ET relationship types are identified, what evidence supports them, and what trade-offs are associated with them?
Databases	Scopus and Web of Science
Search date	February 25, 2025
Coverage	January 01, 2015-February 25, 2025
Search string	("Circular economy" OR circularity) AND ("Energy transition" OR "Energy transformation")
Fields	Title, abstract, and keywords
Included document types	Peer-reviewed articles, reviews, and book chapters
Excluded document types	Conference abstracts, editorials, errata, technical notes, and editorial material
Language	English
Record management	Microsoft Excel
Analysis	Content analysis using a structured coding matrix and codebook
Unit of analysis	Each peer-reviewed study included after full-text eligibility assessment
Unit of record	Textual or analytical meaning units in objectives, methods, results, and discussions related to CE-ET relationships, circularity principles, and trade-offs
Analytical categories	CE-ET relationship type; evidence basis; trade-off status and dimensions; circularity principles; form of principle identification; sector; and geographic scope

Table 2: Study-selection flow

Stage	Records (n)
Records identified in Scopus and Web of Science	383
Duplicates removed	7
Records after deduplication	376
Records after document-type filtering	300
Records after English-language filtering	295
Records excluded during title/Abstract screening	182
Full texts assessed for eligibility	113
Full texts excluded	58
Studies included in the final corpus	55

(P02), lifetime extension (P03), reuse and repurposing (P04), remanufacturing and refurbishment (P05), recycling (P06), recovery of materials and components (P07), waste valorization (P08), circular design (P09), reverse logistics (P10), industrial symbiosis (P11), circular governance of critical minerals (P12), regeneration of natural systems (P13), circular decommissioning (P14), and renewable energy for circular processes (P15). Principles were non-exclusive. Their identification was also coded as PI1, explicitly mentioned by the authors; PI2, inferred from a described practice or result; or PI3, suggested only in the discussion without a corresponding analyzed practice or result.

The 55 studies were coded by the primary researcher using codebook version 1.2, finalized on April 01, 2026. Ambiguous cases were re-examined against operational definitions, inclusion and exclusion criteria, and decision rules. The complete codebook and study-level matrices can be provided upon request from the corresponding author.

4. RESULTS

4.1. Corpus Profile, Relationship Directions, and Evidence Base

Of the 55 studies, 25 were classified as E3 (theoretical reflection), 24 as E2 (inference from results or discussion), and only six as E1 (direct empirical evidence). The CE-ET nexus therefore remains dominated by conceptual arguments and analytical inference rather than by studies designed to directly test the relationship.

Twenty-four studies had a global scope and three combined a global perspective with specific geographic cases. The energy sector appeared in 49 studies, followed by industry (29), government and public policy (25), materials and critical minerals (23), and waste (21). Mining and transport/mobility each appeared in 12 studies, economy/macroeconomics in 11, and agriculture/bioeconomy in six. Sector coding was non-exclusive.

Thirty studies were classified as R1 (CE → ET), eight as R2 (ET → CE), and 17 as R3 (synergistic relationship). The distribution suggests that the literature has focused more heavily on how circularity may support energy transition than on how the expansion of low-carbon systems itself reshapes circular practices and institutions. The cross-classification of evidence basis and CE-ET relationship type is presented in Table 3.

4.2. Circularity Principles in the Corpus

Reuse and repurposing (P04) was the most frequent principle, identified in 44 studies (80.0%), followed by recycling (P06) in

39 (70.9%). Resource-use efficiency (P01) appeared in 26 studies (47.3%), reduction (P02) in 24 (43.6%), and circular design (P09) in 23 (41.8%). Waste valorization (P08) was identified in 20 studies, recovery of materials and components (P07) in 18, lifetime extension (P03) in 17, and remanufacturing/refurbishment (P05) in 14.

Principles related to institutional, ecological, and system-level arrangements were less frequent: Regeneration of natural systems (P13) occurred in nine studies; renewable energy for circular processes (P15) in eight; reverse logistics (P10) and circular decommissioning (P14) in seven each; industrial symbiosis (P11) in six; and circular governance of critical minerals (P12) in four. The pattern indicates that CE-ET research remains concentrated on technical-material strategies for retaining value in materials and assets, while governance, reverse-flow coordination, ecological regeneration, and inter-sectoral arrangements are comparatively underexplored. The frequency of the 15 circularity principles identified in the corpus is reported in Table 4.

4.3. Circular Economy Influences Energy Transition (R1)

In the 30 R1 studies, circularity was primarily framed as a way to reduce the material intensity and life-cycle impacts associated with low-carbon deployment. Among the E1 studies, empirical evidence indicates that circular strategies can alter outcomes relevant to energy transition through demand reduction, reuse, recycling, lifetime extension, remanufacturing, and waste valorization (Hu et al., 2024; Ishaq et al., 2022; Ramakrishna et al., 2022).

Material efficiency was especially prominent where studies considered renewable-generation infrastructure, transmission systems, and critical-mineral inputs. Without circular strategies, low-carbon deployment can shift environmental burdens toward mining, industrial processing, and end-of-life management (Hu et al., 2024). The solar-PV case analyzed by Hu et al. (2024), for example, directly modeled how demand reduction, reuse, and recycling affect material demand and impacts in photovoltaic

Table 4: Frequency of circularity principles in the corpus

Code	Circularity principle	Studies (n)	Percentage of corpus
P04	Reuse and repurposing	44	80.0
P06	Recycling	39	70.9
P01	Resource-use efficiency	26	47.3
P02	Reduction	24	43.6
P09	Circular design	23	41.8
P08	Waste valorization	20	36.4
P07	Recovery of materials and components	18	32.7
P03	Lifetime extension	17	30.9
P05	Remanufacturing and refurbishment	14	25.5
P13	Regeneration of natural systems	9	16.4
P15	Renewable energy for circular processes	8	14.5
P10	Reverse logistics	7	12.7
P14	Circular decommissioning	7	12.7
P11	Industrial symbiosis	6	10.9
P12	Circular governance of critical minerals	4	7.3

Principle coding was non-exclusive; therefore, frequencies and percentages sum to more than 55 studies and 100%

Table 3: Evidence basis by CE-ET relationship type (n=55)

Evidence basis	R1: CE→ET	R2: ET→CE	R3: Synergy	Total
E1: Direct empirical evidence	3	1	2	6
E2: Inference from results/discussion	9	3	12	24
E3: Theoretical reflection	18	4	3	25
Total	30	8	17	55

expansion. This is one of the clearest empirical examples in the corpus of CE strategies affecting ET-related outcomes.

Among inferential studies, infrastructure reuse (Holwerda et al., 2024), reduced dependence on critical raw materials and mining-sector circular integration (Cusenza et al., 2024; Krause and Kretschmann, 2023), recovery and lifetime extension (Prabhu et al., 2022; Revinova et al., 2024), waste valorization (Szewczyk-Świątek et al., 2024), resource-efficiency strategies (Niwalkar et al., 2023), and integration of renewable energy with productive chains (Mutezo and Mulopo, 2021) were associated with lower material intensity or improved environmental performance.

The theoretical literature similarly positions circularity as a response to material pressure, waste generation, and supply risks created by low-carbon technologies (Ghisellini et al., 2025; Goddin, 2020; Groves et al., 2025; Jowitt, 2024; Khalifa et al., 2022; Stille et al., 2025). However, recycling and remanufacturing do not remove the need for primary extraction, and recovery processes continue to require energy inputs (Valero and Valero, 2019). The contribution of CE to ET is therefore better understood as reducing material intensity and retaining value rather than as fully closing material and energy loops.

4.4. Energy Transition Influences Circular Economy (R2)

Eight studies were classified as R2. Only one provided direct empirical evidence, but the group indicates that low-carbon deployment can itself generate demand for circular systems. Mittal and Kushwaha (2024) associated the production of biogas and biofuels from biowaste with circular practices that link renewable-energy production, waste valorization, and nutrient recovery.

The deployment of electric vehicles, batteries, solar panels, wind turbines, and other low-carbon technologies increases flows of copper, nickel, lithium, cobalt, rare earths, and other materials. Several studies suggest that these flows create practical and strategic incentives for reverse logistics, recycling, remanufacturing, component recovery, and design for disassembly (Mendoza and Pigosso, 2023; Van Oorschot et al., 2022; Watari et al., 2021). In this relationship direction, ET is not simply a beneficiary of circularity; it becomes a driver of new circular requirements.

The R2 literature is also ambivalent. The same technologies that stimulate recovery chains may increase upstream resource pressure and social-environmental burdens. Mulvaney et al. (2021), Thomassen et al. (2024), and Velenturf (2021) therefore emphasize resource governance and intergenerational considerations alongside technical circularity. This suggests that the institutional response to new material flows is as important as the existence of recyclable technologies.

4.5. Synergistic Relationships (R3)

Seventeen studies were classified as R3. Synergy appeared through complementarity between material and energy flows, integration of policy agendas, and institutional coordination. Derouez et al. (2024) jointly analyzed CE and renewable-energy indicators

in relation to emissions and poverty, while Schwartzman and Schwartzman (2021) embedded circularity within broader modeled pathways toward renewable-energy systems. The theoretical E3 subset also framed synergy through scenarios and conceptual models, including photovoltaic deployment, circular building envelopes, and port-city regeneration (Azcarate-Aguerre, 2023; De Martino, 2022; Mirlletz et al., 2024).

Among E2 studies, three recurring mechanisms were visible. First, CE can reduce resource use and waste while renewable energy lowers the energy-related emissions of recovery and production processes (Cerqueti et al., 2025; Chishti et al., 2023; Gallo et al., 2022). Second, coordinated circular, energy, and environmental policies were associated with improved efficiency, energy security, or emissions outcomes, although policy fragmentation remained important (Ha et al., 2025; Nunes et al., 2023; Shobande et al., 2025; Tiwari et al., 2024). Third, the relationship depended on institutional capacity and cross-policy coordination rather than on the simple co-presence of CE and ET objectives.

The synergistic category therefore does not imply automatic mutual benefit. It identifies studies in which CE and ET are analytically linked as complementary processes. The relatively small number of E1 studies in this category reinforces the need to distinguish conceptual integration from demonstrated joint effects.

4.6. Trade-offs Across CE-ET Relationships

Thirty studies (54.5%) had no identifiable trade-off and were coded T0. Twenty-five studies (45.5%) contained a countervailing outcome: 23 explicit (T1) and two inferred (T2). Among these 25 studies, TD1—materials, resources, and circularity of flows—was most frequent (19 studies), followed by TD2—waste, emissions, and pollution (12), TD3—energy/economic performance and security of supply (10), and TD4—social, territorial, and justice impacts (four). Dimensions were non-exclusive. Table 5 summarizes the status and dimensions of the trade-offs identified in the reviewed studies.

Material trade-offs included increasing demand for critical minerals, continued primary extraction, limited recycling capacity, and timing gaps before secondary materials become available (Jowitt, 2024; Van Oorschot et al., 2022; Watari et al., 2021). Waste and pollution trade-offs included future end-of-life liabilities from offshore wind and photovoltaic systems and the coexistence of

Table 5: Trade-off status and dimensions

Indicator	Studies (n)	Share/note
T0 — No trade-off identified	30	54.5% of corpus
T1 — Explicit trade-off	23	41.8% of corpus
T2 — Inferred trade-off	2	3.6% of corpus
TD1 — Materials/Resources/Flow circularity	19	Among 25 studies with trade-offs
TD2 — Waste/Emissions/Pollution	12	Among 25 studies with trade-offs
TD3 — Energy/Economic performance/Supply security	10	Among 25 studies with trade-offs
TD4 — Social/Territorial/Justice impacts	4	Among 25 studies with trade-offs

lower operational climate impacts with mining, water, radiation, and long-lived-waste burdens elsewhere in the life cycle (Erat and Telli, 2020; Ghisellini et al., 2025; Velenturf, 2021).

Energy-economic and supply-security tensions included short-term increases in energy demand for circular processing, cost and technological-readiness differences among hydrogen options, and divergences between short- and long-term energy-security outcomes (Ha et al., 2025; Mirlatz et al., 2024; Revinova et al., 2024). Social and territorial trade-offs included mining-related impacts in contexts of weaker governance, competition among food, energy, and material uses of biomass, and the transfer of long-lived waste burdens to future generations (Ghisellini et al., 2025; Järnefelt et al., 2021; Watari et al., 2021).

These patterns show that circularity is not an automatic property of low-carbon technologies. Lower operational emissions can coexist with greater mineral demand, complex waste streams, and impacts displaced to other life-cycle stages or territories. Circular energy transitions therefore require governance mechanisms able to identify, evaluate, and manage these transfers.

5. DISCUSSION

5.1. An Asymmetric and Still Weakly Empirical CE-ET Evidence Base

The review reveals a clear asymmetry in both relationship direction and evidentiary strength. More than half of the corpus frames CE as supporting ET, whereas comparatively few studies analyze how ET generates circular requirements. At the same time, only six studies provide direct empirical evidence for the coded CE-ET relationship. The field therefore appears conceptually active but empirically underdeveloped.

This distinction matters because the language of “synergy” can otherwise overstate what the literature actually demonstrates. Many studies plausibly connect resource efficiency, recycling, renewable energy, and emissions outcomes, but a plausible link is not equivalent to a directly tested mechanism. Separating R1-R3 from E1-E3 makes that distinction visible and creates a basis for future cumulative evidence.

5.2. Circularity as Material Governance for Energy Transitions

The frequency distribution of principles further clarifies how the literature currently understands circularity. Reuse, repurposing, recycling, efficiency, reduction, and circular design dominate. These strategies are technically tangible and relatively easy to connect to energy technologies and infrastructure. By contrast, critical-mineral governance, industrial symbiosis, reverse logistics, ecological regeneration, and circular decommissioning appear less often.

This imbalance suggests that the CE-ET agenda is still more developed at the level of material and asset strategies than at the level of institutions. Yet several of the strongest trade-offs arise precisely where institutional coordination is required: Mineral supply, end-of-life responsibility, cross-sector resource

competition, and distribution of environmental burdens. A more mature circular-energy-transition agenda therefore needs to connect engineering strategies with governance of material flows, liabilities, territories, and value chains.

5.3. Why Low-Carbon Does Not Automatically Mean Circular

The trade-off analysis challenges any assumption that low-carbon deployment is inherently circular. Renewable-energy systems can reduce direct fossil-fuel use while increasing demand for metals, land, processing, and future end-of-life capacity. Circular strategies can mitigate these pressures, but they also face physical, temporal, technological, and economic limits.

The policy implication is not that circularity weakens the case for energy transition. Rather, circularity changes the criteria by which transition quality is assessed. A transition can be evaluated not only by operational decarbonization but also by whether it reduces primary-resource intensity, preserves material value, manages end-of-life streams, limits displacement of environmental burdens, and distributes costs and benefits more equitably.

6. CONCLUSION, IMPLICATIONS, LIMITATIONS AND FUTURE AGENDA

The relationship between circular economy and energy transition is neither singular nor automatically synergistic. Across 55 studies, CE most often appears as an enabling condition for ET, but ET can also generate new circular requirements, while a smaller group of studies frames the two agendas as mutually reinforcing. The evidence supporting these claims remains uneven: only six studies directly examine the coded CE-ET relationship, while most rely on inference or theoretical reflection.

The review further shows that circularity in energy transitions is currently understood predominantly through reuse, recycling, resource efficiency, reduction, and circular design. Governance-oriented and system-level principles are less developed even though many identified trade-offs concern mineral supply, waste responsibility, security of supply, and distributional impacts.

The proposed analytical framework separates circularity principles, relationship direction, evidence basis, and trade-offs. This separation provides a more disciplined way to compare heterogeneous studies and distinguish conceptual claims from directly supported mechanisms. A circular energy transition requires more than expanding renewable energy or increasing recycling: it also requires life-cycle planning, governance of material flows, reverse infrastructure, and explicit management of environmental and social burden shifting. Taken together, these findings have several implications for energy, environmental, and resource-governance policies.

First, energy-transition policy should incorporate material-flow and end-of-life requirements during planning rather than treating them as downstream waste issues. Procurement standards, licensing, industrial policy, and infrastructure planning can include

durability, repairability, modularity, disassembly, recoverability, and secondary-material targets where technically appropriate.

Second, critical-mineral policy should connect supply security with circular strategies. Primary extraction is likely to remain necessary in the near term, but recovery, reuse, recycling, lifetime extension, and substitution can reduce exposure to concentrated supply and delay part of the need for new extraction. These measures require reliable data on stocks, flows, product composition, ownership, and future end-of-life volumes.

Third, reverse infrastructure must scale alongside low-carbon deployment. Rapid growth of photovoltaic panels, wind turbines, batteries, and electrical equipment without parallel collection, sorting, testing, remanufacturing, and recycling capacity can create future liabilities. Extended producer responsibility, take-back systems, technical standards, and market development for secondary materials are therefore relevant to transition planning.

Fourth, circularity metrics should be linked to transition metrics. Emissions reductions alone do not capture material intensity, waste creation, recovery performance, or territorial burden shifting. Integrated monitoring can help public agencies and firms distinguish apparent circularity from verified reductions in resource and life-cycle pressures.

Finally, policy coordination matters. The R3 studies suggest that CE and ET outcomes improve when energy, industrial, waste, mineral, and environmental policies are aligned (Chen and Kim, 2019; Kalchenko et al., 2019; Nunes et al., 2023; Okafor et al., 2021). Fragmented governance can undermine otherwise technically viable circular solutions by creating inconsistent incentives, uncertain responsibilities, and missing infrastructure.

These implications should, however, be interpreted in light of five limitations. First, it was restricted to Scopus and Web of Science and to English-language publications. Relevant studies in regional journals, other databases, grey literature, or other languages may therefore have been excluded. Second, the search string was intentionally narrow in order to retain studies explicitly articulating CE and ET; this improves conceptual specificity but can exclude relevant work framed through adjacent terms such as decarbonization, resource transition, industrial ecology, or low-carbon systems.

Third, the database search was completed on February 25, 2025; consequently, studies published after this date are not represented in the corpus.

Fourth, title/abstract screening, full-text assessment, and coding were conducted by the primary researcher. The use of a detailed codebook and documented rationales supports traceability, but no independent second-reviewer validation was completed for the present corpus. Independent validation would strengthen reliability, particularly for inferred principles, evidence levels, and T2 trade-offs.

Fifth, the E1-E3 classification was designed to classify how directly a CE-ET relationship is supported by each study's evidence; it is

not a formal risk-of-bias or methodological-quality assessment. The review therefore does not weight findings by study quality.

These limitations, together with the evidence gaps identified above, suggest five priorities for future research. First, more studies should directly test CE-ET mechanisms rather than infer them from parallel trends. Material-flow analysis, life-cycle assessment, techno-economic modeling, longitudinal case studies, and quasi-experimental policy evaluation can strengthen causal and mechanism-based understanding.

Second, comparative research is needed across sectors and territories. The corpus contains substantial European and global framing, but circular-energy-transition mechanisms may differ in regions where mineral extraction, infrastructure deficits, informal recovery systems, or environmental-justice concerns are more pronounced.

Third, the underrepresented principles deserve specific attention. Circular governance of critical minerals, reverse logistics, industrial symbiosis, regeneration, and circular decommissioning are likely to become more important as low-carbon assets mature and larger end-of-life flows emerge.

Fourth, future research should treat trade-offs as explicit analytical objects rather than incidental limitations. This includes quantifying when emission reductions shift burdens to materials, land, water, waste, energy use, or vulnerable territories and identifying governance arrangements that reduce those transfers.

Fifth, longitudinal studies should examine co-evolution. The R2 and R3 categories imply that ET can reshape CE institutions and that CE can alter transition pathways over time. Capturing these feedbacks requires research designs that follow technologies, policies, markets, and material stocks beyond single-point assessments.

Addressing these gaps would help move the CE-ET literature from predominantly conceptual associations toward more robust empirical evidence on mechanisms, outcomes, and trade-offs.

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