

Circular Economy and Carbon Neutrality: Synergies, Pathways, and Policy Implications

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ABSTRACT

Global climate change, driven by industrialization and dependence on non-renewable energy, has made carbon neutrality an urgent international objective. This paper examines the role of the circular economy as a systemic complement to conventional decarbonization strategies. It argues that renewable energy deployment, carbon capture, and efficiency gains, while necessary, are insufficient without transforming how materials and products are produced, used, and recovered. Drawing on the concept of carbon as both an energy carrier and a material, the paper analyzes the mechanisms through which circular strategies resource efficiency, product life extension, waste valorization, recycling, and industrial symbiosis reduce greenhouse gas emissions across the waste, industrial, agricultural, urban, and energy sectors. A dedicated empirical case study section presents facility, cluster, and economy-level evidence, including an industrial symbiosis network in China that reduced CO₂ emissions by 1.09 Mt per year, equivalent to 3.63% of a city's total carbon footprint under a business-as-usual scenario. Life cycle assessment of municipal solid waste indicates average global emissions of 89.7 kg CO₂e per tonne in 2023, with open dumping contributing almost 70%, and modelling shows that circular economy implementation could achieve net-zero emissions from global municipal solid waste management by 2050. The paper concludes by discussing policy frameworks in the European Union and China, implementation barriers, and key challenges such as land-use trade-offs of bio-based materials and the high cost of carbon removal technologies, which range from \$100 to \$1,200 per ton of CO₂.

Keywords: circular economy, carbon neutrality, net-zero emissions, waste management, industrial symbiosis, climate policy

INTRODUCTION

Global industrialization and the over-exploitation of fossil fuels have driven an unprecedented release of greenhouse gases, raising global temperatures and destabilizing environmental systems (Chen et al., 2022). The response of the international community is anchored in the Paris Agreement, adopted by 196 parties at the 21st Conference of the Parties, which commits to limiting global warming to below 1.5 °C relative to pre-industrial levels, reducing carbon emissions by 45% by 2030, and achieving carbon neutrality by 2050 (Yang et al., 2022). Yet the trajectory of current efforts is discouraging rather than declining by 45%, global greenhouse gas emissions are forecast to increase by 14% by 2030, and the burden of these emissions is highly concentrated, with the top ten emitters accounting for over 68% of global greenhouse gas emissions while fewer than one hundred countries contribute just 3% (Chen et al., 2022). Moreover, only 4.5% of countries have so far achieved carbon neutrality, with most planning to do so between 2050 and 2070 (Chen et al., 2022).

Conventional mitigation measures renewable energy adoption, carbon capture, and efficiency improvements are vital but insufficient on their own (Oni et al., 2025). Achieving carbon neutrality requires systemic transformation across economic and industrial sectors (Oni et al., 2025). The circular economy, a model that is "restorative or regenerative by intention and design," offers a complementary and increasingly recognized pathway (Bassi & Dias, 2020). This paper synthesizes the conceptual foundations of the circular economy and

carbon neutrality, examines the mechanisms linking the two, reviews sectoral strategies, presents dedicated empirical case-study evidence, and assesses the policy and institutional landscape shaping the transition.

Conceptual Foundations

The Circular Economy

The circular economy has its intellectual roots in industrial ecology and in German and Swedish environmental policies that emphasized loop-closing (Gautam et al., 2025). It emerged as a development strategy to resolve the conflict between rapid economic growth and the scarcity of raw materials and energy resources (Gautam et al., 2025). Although there is no universally accepted definition, the essence of the circular economy lies in the circular flow of materials and the use of raw materials and energy across multiple phases (Gautam et al., 2025). The Ellen MacArthur Foundation, the most influential advocate of the concept, defines the circular economy as "an industrial economy that is restorative or regenerative by intention and design," incorporating the principles of designing out waste and pollution, keeping products and materials in use, and regenerating natural systems (Bassi & Dias, 2020).

Three foundational principles underpin the model: preserving and enhancing natural capital by controlling finite stocks and balancing renewable resource flows; optimizing resource use by circulating products, components, and materials at their highest utility in both biological and technical cycles; and fostering system effectiveness by designing out waste and negative externalities (Kara et al., 2022; Upadhyay et al., 2021). Operational guidance is provided by the ReSOLVE framework regeneration, sharing, optimization, looping, virtualization, and exchange which translates circular principles into business and policy action (Urbinati et al., 2017). In practice, the concept is commonly implemented through the "3R" principles of reduction, reuse, and recycling, expanded to include recovery, remanufacturing, repair, and rethink (Marco-Fondevila et al., 2020). In biological cycles, biodegradable materials feed back into the system through composting and anaerobic digestion, while technical cycles recover and restore products and components through reuse, repair, remanufacturing, and recycling (Kara et al., 2022).

Business models are central to implementation. Circular business models emphasize product-life extension designing durable, long-lifetime products and shifting toward leasing and service-based revenue as well as redistribution and reuse, since "the most sustainable product is often one we already own" (Urbinati et al., 2017). The environmental promise of circularity rests on this transformation of production consumption systems away from the linear take-make-dispose model (Jesús & Mendonça, 2017).

Carbon Neutrality

Carbon neutrality is defined as a state of zero net CO₂-equivalent emissions, attained by balancing the emission of CO₂ with its removal so as to halt its accumulation in the atmosphere (Zeng, 2022). In the twenty-first century, carbon neutrality has become the new industry paradigm worldwide, with some scholars describing it as a potential "fifth industrial revolution" (Chen et al., 2022). Momentum is substantial: as of February 2021, 124 countries had pledged to achieve carbon neutrality by 2050 or 2060, propelled by the Copenhagen Accord and the Paris Agreement (Chen et al., 2022).

A crucial insight linking carbon neutrality to the circular economy is that carbon plays a dual role: it functions as an energy carrier through combustion and simultaneously as a material embedded in products (Murakami et al., 2022). CO₂ is a waste product of burning carbon for energy, yet carbon itself is also a raw material; therefore, promoting the carbon cycle requires harmonizing carbon's material function with its role as an energy carrier (Murakami et al., 2022). On this view, the further introduction of renewable energy and a societal shift toward circularity contribute to carbon neutrality and more resource-efficient use in a mutually complementary manner (Murakami et al., 2022).

The Nexus: How the Circular Economy Contributes to Carbon Neutrality

The claim that the circular economy supports carbon neutrality rests on a systemic insight: traditional mitigation measures such as renewable energy, carbon capture, and efficiency improvements remain insufficient without

transformation across economic and industrial sectors, whereas circular practices resource efficiency, waste valorization, product life extension, and recycling decouple economic growth from environmental degradation (Oni et al., 2025). Integration of the circular economy enhances the effectiveness of renewable energy systems, industrial decarbonization, and waste reduction, yielding reductions in greenhouse gas emissions, improvements in resource productivity, and strengthened socio-economic resilience (Oni et al., 2025).

The mechanisms are direct. Extending product lifetimes through reuse, repair, and refurbishment delays the need for new production, avoiding the embedded emissions of manufacturing and assembly; products that cannot be reused are recycled efficiently, reducing the demand for virgin materials (Kara et al., 2022). Simultaneously, strategies such as shifting away from fossil fuels toward renewable energy, electrifying energy services, and raising energy efficiency reduce emissions at the point of energy use (Chen et al., 2022). The two agendas reinforce each other: a more circular economy reduces the material and energy intensity of production, lowering the scale of the decarbonization challenge, while renewable energy supplies the low-carbon power that makes recycling and remanufacturing genuinely low-emission (Murakami et al., 2022).

Quantitative evidence supports this synergy. Analyzing annual data for a panel of 29 European countries from 2000 to 2020 with an identification strategy addressing endogeneity, Hailemariam and Erdiaw-Kwasie find that progress toward a circular economy significantly improves environmental quality via reduced CO₂ emissions, suggesting that business strategies promoting recycling and circular practices play an important role in emission reduction and environmental sustainability (Hailemariam & Erdiaw-Kwasie, 2022).

Sectoral Pathways

Waste Management

The waste sector is a major anthropogenic source of global greenhouse gas emissions (Oo et al., 2024). Life cycle assessment of municipal solid waste treatment systems shows that average global GHG emissions from one tonne of municipal solid waste in 2023 were approximately 89.7 kg CO₂e, with open dumping the dominant contributor at almost 70% of emissions (Oo et al., 2024). The global municipal solid waste management sector emitted a total of 173.2 Mt CO₂e in 2023, a figure projected to rise to 203.4 Mt CO₂e by 2030 and 289.5 Mt CO₂e by 2050 if no improvements are made (Oo et al., 2024). Critically, the same analysis finds that implementing the circular economy in the waste sector has the potential to achieve net-zero emissions from global municipal solid waste management by 2030 and 2050 (Oo et al., 2024). Priority actions include upgrading open dumps, standardizing household-level waste separation, minimizing food waste, establishing national recycling targets, and promoting a zero-waste approach (Oo et al., 2024).

The climate stakes extend beyond the sector's current footprint. With global solid waste generation estimated at 2.56 to 3.33 billion tonnes by 2050, abrupt technical and behavioral changes could produce a net-zero warming solid waste system relative to 2020, avoiding 11 to 27 billion tonnes of CO₂ warming-equivalent emissions under the Paris temperature limits — but only if accelerated adoption occurs within 9 to 17 years, i.e., by 2033 to 2041, in alignment with the Global Methane Pledge (Hoy et al., 2023).

Industry and Industrial Symbiosis

Industry offers some of the most mature circular economy applications. Industrial symbiosis, a key concept of the circular economy that mimics ecological systems, engages traditionally separate entities in the exchange of materials, energy, and by-products (Daddi et al., 2017; Neves et al., 2019). Eco-industrial parks, which concentrate such exchanges, have been shown to reduce overall carbon emissions and increase resource utilization efficiency; analysis of China's Shenyang Economic and Technological Development Zone using life cycle and input-output methods found that deeply bound industrial parks confer collective competitive advantages in energy procurement, raw materials, waste treatment, and by-product exchange, making the circular economy more cost-effective (Huan & Han, 2022).

Case-level quantification confirms the magnitude of these benefits. In a Chinese coal-aluminum-electricity-steel industrial system, eight designed synergies centered on the aluminum, electricity, and steel plants were found to reduce CO₂ by 1.09 Mt per year, equivalent to 3.63% of the city's total carbon footprints in a business-as-usual

scenario in 2012 a second mitigation effect beyond technological efficiency change (Huan & Han, 2022). Such synergies can also generate materials needed by other technologies, creating cascading benefits across industrial networks (Xie et al., 2024). However, realizing these gains requires rigorous assessment: life cycle assessment is necessary to optimize new circular systems and verify their environmental advantages (Daddi et al., 2017), and LCA studies of industrial symbiosis initiatives confirm positive contributions across impact categories including climate change (Daddi et al., 2017).

Agriculture and Food

The circular economy also reshapes the emissions profile of agriculture and food systems. Strategies for reducing emissions in this sector include shifting toward more vegetarian diets with less meat and food waste, pasture restoration, integrated crop-livestock-forestry systems, no-till agriculture, afforestation, biological nitrogen fixation, and organic waste recycling (Yang et al., 2022). Valorizing food and agricultural waste adds further value: food and agro-waste can be converted into pharmaceuticals, phytochemicals, enzyme immobilization substrates, wastewater treatment agents, and biodiesel from waste cooking oil, though such applications must be scaled up from the laboratory to realize their benefits (Yang et al., 2022). Low-carbon agriculture, altered consumer behavior, and raising the value of food and agricultural waste are essential steps toward net-zero carbon emissions (Yang et al., 2022). Households are pivotal here as well a typical European urban household's carbon footprint is 6.93 t CO₂e per year, equivalent to the annual carbon absorbed by 0.51 hectares of forest (Murakami et al., 2022).

Buildings, Cities, and Energy

Cities concentrate both resource flows and emissions, making them critical arenas for circularity. The circular economy strategy offers an innovative pathway for sustainable urban development in terms of resource saving and waste mitigation (Möslinger et al., 2023). Buildings should be designed to be resilient to natural hazards while minimizing disruption to the natural environment, and cities with decentralized energy systems and technologies such as electric vehicles, the Internet of Things, and big data can significantly contribute to climate change mitigation (Yang et al., 2022). The salience of these measures is reflected in the Horizon Europe 100 Climate-Neutral and Smart Cities Mission, within which 362 interested cities have articulated roadmaps to zero emissions, with circular actions envisioned as supporting climate neutrality by 2030 (Möslinger et al., 2023). Across the 362 cities, circularity is seen as having particularly high mitigation potential in specific urban sectors and metabolic flows, although the translation of circular imaginaries into local governance remains uneven (Möslinger et al., 2023).

Empirical Case Studies

Case 1: A Coal-Aluminum-Electricity-Steel Industrial Symbiosis System

The most granular facility-level evidence comes from a local coal-aluminum-electricity-steel industrial system in China, analyzed under a business-as-usual scenario for 2012 (Huan & Han, 2022). Eight designed synergies centered on the aluminum, electricity, and steel plants exchanged energy, water, and by-products among traditionally separate firms. The assessment found that these synergies reduced CO₂ emissions by 1.09 Mt per year, equivalent to 3.63% of the city's total carbon footprint under business-as-usual conditions (Huan & Han, 2022). Importantly, the study characterized this as a second mitigation effect, operating alongside and distinct from conventional technological efficiency improvements (Huan & Han, 2022). The case demonstrates that industrial symbiosis delivers measurable carbon reductions even in resource and carbon-intensive industrial systems, precisely where decarbonization is hardest.

Case 2: Life Cycle Assessment of Industrial Symbiosis in an SME Cluster

At the cluster level, a life cycle assessment of an industrial symbiosis initiative among small and medium-sized enterprises documented positive contributions across environmental impact categories, including climate change (Daddi et al., 2017). The study's central methodological lesson is that LCA is indispensable for validating symbiotic exchanges: without it, circular reconfigurations cannot be verified as environmentally superior, and

new circular systems cannot be optimized (Daddi et al., 2017). This positions rigorous assessment rather than intuitive assumptions of circular benefit as a precondition for credible circular carbon reductions.

Case 3: Regional Low-Carbon Transition Optimization

At the regional systems level, an integrated optimization modelling framework for resource-based industrial symbiosis showed that symbiotic exchanges can generate materials needed by other technologies, creating cascading benefits across industrial networks (Xie et al., 2024). The same line of work sounded a cautionary note: simulation of low-carbon regional transitions indicates that reliance on carbon capture, utilization, and storage may be financially untenable under stringent zero-emission policy scenarios (Xie et al., 2024). The combined implication is that circular, symbiotic restructuring of regional industry may be more financially viable than removal-dependent pathways.

Case 4: Global Waste System Modeling

The broadest empirical evidence concerns the global waste system. Life cycle-based assessment of global waste management found that average emissions were 89.7 kg CO_{2e} per tonne of municipal solid waste in 2023, with open dumping contributing almost 70%, and that the sector emitted 173.2 Mt CO_{2e} in 2023, rising to a projected 289.5 Mt CO_{2e} by 2050 without intervention (Oo et al., 2024). The decisive finding is that circular economy implementation could achieve net-zero emissions from global municipal solid waste management by 2030 and 2050, with waste management goals reducing GHG emissions by approximately 1% to more than 160% depending on the goal and baseline (Oo et al., 2024). A complementary global study estimated that circular waste-system transformation could avoid 11 to 27 billion tonnes of CO₂ warming-equivalent emissions but only if adoption accelerates within 9 to 17 years, by 2033 to 2041 (Hoy et al., 2023).

Case 5: Macro-Level Panel Evidence

Finally, at the economy wide scale, panel analysis of 29 European countries over 2000 - 2020, using an instrumental variable strategy to address endogeneity, established that progress toward the circular economy significantly reduces CO₂ emissions and improves environmental quality (Hailemariam & Erdiaw-Kwasie, 2022). Together, these five cases span the full range of scales from single industrial parks, through enterprise clusters and regions, to the global waste system and national economies and consistently point in the same direction: circular strategies produce real, quantifiable emission reductions at every level.

Policy Landscape and Barriers

Circular economy policy has advanced most prominently in China and the European Union, which adopted the concept nearly simultaneously as a foundation for economically and environmentally effective policy (Ranta et al., 2017). The circular economy entered formal public policy in China with the Cleaner Production Promotion Law of 2002 and the Circular Economy Promotion Law of 2009 (Liu et al., 2021), driven by government agencies such as the National Development and Reform Commission and the Ministry of Environmental Protection (Liu et al., 2021). However, China's progress in circular economy implementation has been modest due to persistent barriers (Liu et al., 2021).

In Europe, following the 2011 roadmap toward a resource efficient economy, the European Commission adopted its first Circular Economy Action Plan in 2015 to "close the loop" of product life cycles (González-Torres et al., 2026). Although early implementation produced considerably higher recycling rates in the EU than global figures, the overall degree of circularity remains low, because recycling is only one element of a circular economy and circularity cannot be achieved on this basis alone (González-Torres et al., 2026). By 2019 the plan's 54 actions were completed, and policy attention has since shifted toward integrating circularity into product design and extended producer responsibility (González-Torres et al., 2026). Cross-regional comparison reveals that member states vary considerably in their circular economy aspirations and approaches, with only a few countries including Germany, Austria, and Finland maintaining dedicated resource efficiency and circular economy strategies (McDowall et al., 2017).

Despite this policy momentum, significant barriers impede the transition. Institutional drivers and barriers differ markedly across China, the United States, and Europe, reflecting divergent regulatory traditions and stakeholder configurations (Ranta et al., 2017). The circular economy itself remains an underspecified notion spanning sustainable production consumption systems, closed-loop supply chains, and product service systems, which complicates the identification of transition determinants (Jesús & Mendonça, 2017). Barriers are context-specific, as illustrated by analyses of food consumption and production in China (Liu et al., 2021). Moreover, corporate uptake is uneven: politically, only a few companies worldwide have set explicit climate change goals (Chen et al., 2022), and evidence from the largest Spanish companies suggests that even well designed circular economy policies do not automatically reach organizations (Marco-Fondevila et al., 2020).

Challenges and the Road Ahead

Even with strong conceptual and empirical support, the circular economy carbon neutrality agenda faces hard constraints. Carbon removal technologies, essential for offsetting residual emissions, are prohibitively expensive, ranging from \$100 to \$1,200 per ton of CO₂ (Chen et al., 2022). Simulation studies of low-carbon regional transitions likewise indicate that reliance on carbon capture, utilization, and storage may be financially untenable under stringent zero emission policy scenarios (Xie et al., 2024). These cost realities increase the value of avoided emissions through circularity, but they also underscore that circular strategies must be prioritized precisely because removal is costly.

Trade-offs also emerge within circular strategies themselves. Increasing the use of bio-based materials a common circular prescription is challenged by land use and land cover constraints, as biomass production competes with food systems and natural ecosystems (Oni et al., 2025). Rebound effects, measurement complexity, and the fragmentation of circular economy research all demand continued methodological rigor, particularly life cycle assessment, to ensure that circular systems genuinely outperform their linear counterparts (Daddi et al., 2017). Finally, the political economy of transition remains formidable: achieving carbon neutrality requires a unified framework combining technological, economic, and policy measures that prioritize sustainability transitions (Chen et al., 2022).

The way forward is nonetheless clear. Circularity and decarbonization must be pursued as one integrated agenda in which carbon is managed simultaneously as a material and an energy carrier (Murakami et al., 2022). Waste management should be prioritized as an immediate, high-leverage intervention capable of reaching net-zero emissions from the global municipal solid waste sector within decades (Oo et al., 2024). Industrial symbiosis should be scaled through eco-industrial parks and supportive regional policy (Xie et al., 2024). And policy frameworks from the EU's evolving product-focused circularity agenda to China's consolidation of its circular economy laws must be strengthened with explicit indicators, financing mechanisms, and measurable targets (McDowall et al., 2017).

CONCLUSION

This paper has examined the relationship between the circular economy and carbon neutrality, arguing that the two agendas are mutually reinforcing and jointly necessary. Carbon neutrality cannot be achieved through energy transition alone: because carbon is embedded in materials, the decarbonization of production and consumption requires the restorative, regenerative logic of circularity (Murakami et al., 2022). Empirical case evidence from a Chinese industrial symbiosis network cutting 1.09 Mt CO₂ per year (3.63% of a city's footprint), through LCA-validated SME clusters and regional optimization models, to global waste-system modeling showing net-zero potential by 2050 and European panel data confirms that circular strategies measurably reduce CO₂ emissions at every scale (Hailemariam & Erdiaw-Kwasie, 2022; Huan & Han, 2022; Oo et al., 2024). Policy leadership in China and the European Union has established the institutional scaffolding, yet barriers of cost, measurement, institutional capacity, and corporate commitment remain (Marco-Fondevila et al., 2020; Ranta et al., 2017). The central challenge ahead is translational: converting circular principles into default industrial practice and embedding them in the fabric of carbon-neutral economies. As the 2030 and 2050 milestones of the Paris Agreement approach, the circular economy offers one of the most credible and cost-effective routes to meeting them provided the transition is pursued with urgency, rigor, and systemic vision.

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