



Working Paper

Opening Schrödinger's Box: Rethinking Carbon Beyond the Binary in Plastic Recycling

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Executive Summary

The circular carbon economy (CCE) reframes carbon not as an inherent liability, but as a managed resource that should be stewarded across its full lifecycle to ensure it resides in the appropriate reservoirs for suitable durations under effective governance.¹ Rather than viewing carbon primarily as waste to be eliminated, CCE treats it as an economic asset that can be captured, reused, valorized, and cycled into productive applications.² The framework focuses on managing carbon flows to minimize uncontrolled atmospheric accumulation and unmanaged physical waste streams while maximizing productive use in durable, value-creating forms. This process optimizes where carbon comes from, where it flows, and how it circulates across interconnected geologic, biogenic, atmospheric, aquatic, and anthropogenic systems.

This CCE systems-based approach moves beyond current, scientifically inconsistent framings of decarbonization and zero carbon, which can emphasize narrow tests of definitional purity – for example, whether a given pathway counts as recycling – and toward a focus on system-level optimization. The central question becomes how carbon flows can be improved across the system to reduce net emissions and net impacts across the entire carbon cycle.

In the plastics recycling debate, circularity is often defined narrowly by polymer reconstitution alone, or by isolating individual outputs without regard to the broader carbon system. Yet if the objective of a sustainable circular economy is to retain economic value, improve resource efficiency, reduce waste, and balance environmental, economic, and social outcomes, the relevant metric cannot be whether every output returns to polymer. More meaningful measures include whether carbon remains within managed, value-creating systems, reduces reliance on higher-impact virgin extraction and associated impacts, prevents landfilling, and achieves a balance of net lifecycle benefits and burdens.

From a CCE perspective, fuel pathways produced through advanced recycling may not meet traditional definitions of material recycling, but they can function within a managed carbon system that, under certain conditions, reduces net atmospheric accumulation and landfilling while maximizing carbon's productive use within a defined carbon budget.

The discussion surrounding advanced recycling, therefore, illustrates a broader challenge in sustainability governance: Policy discussions often focus on categorical

definitions rather than system performance. A narrow insistence that circularity requires polymer-to-polymer reconstitution risks overlooking how carbon actually flows through industrial and geologic systems and may unintentionally constrain viable pathways that reduce waste and improve carbon efficiency.

A systems-level approach shifts attention from product-level purity to carbon stewardship across the full lifecycle. The central policy question is not whether carbon exists in the economy, but where it resides, how long it remains there, and whether its circulation reduces impacts while preserving economic value.

Viewed through this lens, the CCE is not a defense of carbon-intensive systems but a governance framework for managing carbon across reservoirs and time horizons. Success is measured not by categorical labels, but by whether carbon remains productive within the system – reducing waste, limiting reliance on virgin extraction, and improving overall lifecycle performance.

While this working paper draws heavily on examples from plastics and advanced recycling, these systems are used as illustrative cases within a broader carbon management framework. The underlying principles apply across carbon-intensive sectors, including fuels, chemicals, and biogenic systems, where similar trade-offs between material form, emissions, and value retention are present.

I. Reframing Carbon: From Enemy to Managed Asset

Carbon occupies a conceptual superposition in modern policy dialogue: It is both indispensable to economic development and treated as a systemic threat.³ Carbon policy discussions have often been framed as binary: Carbon is either villain or virtue, liability or lifeblood. Like Schrödinger's cat, it is rhetorically declared dead in climate discourse while remaining very much alive as the backbone of existence and industrial civilization.

Plastics preserve food and medical sterility; hydrocarbons provide energy density unmatched by alternatives in aviation and heavy industry. For example, carbon chemistry enables pharmaceuticals and semiconductors. Yet prevailing climate and plastics frameworks often treat carbon primarily as an existential threat, an externality to be eliminated rather than as a resource to be governed. This framing obscures the deeper systems question: not whether carbon should exist in the economy, but how it should be stewarded across reservoirs and time horizons.

The CCE moves beyond this limited binary framing. It begins from three interrelated premises:

1. Carbon is foundational to modern economies.
2. Uncontrolled atmospheric accumulation of CO₂ and unmanaged physical waste streams present material climate and physical risks.

3. The core policy challenge is not carbon's existence, but its management across the full system.

Carbon resides in multiple interconnected reservoirs: geologic stocks (fossil resources); the atmosphere (CO₂); terrestrial biogenic systems (forests, soils, biomass); oceanic and other aquatic systems (oceans, coastal waters, freshwater bodies); and anthropogenic stocks (plastics, fuels, buildings, materials, and other durable goods). Carbon dioxide itself, often framed exclusively as a waste or liability, is also the foundational feedstock of the biogenic carbon cycle. Through photosynthesis, atmospheric CO₂ is continuously fixed into biomass, forming the basis of terrestrial ecosystems, agricultural systems, and forest carbon stocks. In this context, CO₂ is not the nemesis but a necessary input into life-supporting systems, with its impact determined by concentration, flux, and the capacity of natural systems to assimilate and store it.

However, this balance is increasingly disrupted by land-use change, particularly deforestation, which introduces an uncontrolled perturbation to both carbon stocks and flows. Forest clearing not only releases stored carbon into the atmosphere but also reduces the system's capacity for future carbon uptake, effectively weakening one of the primary natural mechanisms for regulating atmospheric CO₂. From a systems perspective, this represents a dual breakdown of carbon management: the loss of a stable biogenic reservoir and the acceleration of atmospheric accumulation. In this sense, deforestation is to the biogenic carbon system what landfilling and uncontrolled emissions are to the anthropogenic system: a failure to retain carbon within managed, value-stable reservoirs.

Carbon is the constant; CO₂, plastics, fuels, and biomass are its forms.

The policy objective is therefore not carbon eradication, but carbon optimization — determining where carbon should reside, how long it should remain there, and under what governance mechanisms it should circulate. This reframing helps clarify the paradox of carbon. Carbon is neither inherently an enemy nor inherently benign. Unmanaged carbon released and accumulated in the environment or discarded as waste is the problem. Managed carbon that is retained in durable materials, cycled productively into value-added uses, displaces higher-impact extraction pathways, and accounted for within a carbon budget can function as an asset within an economic system.

CCE centers on managing carbon flows to minimize uncontrolled atmospheric accumulation and physical waste streams while maximizing productive use in durable, value-creating forms. This is a systems management framework grounded in lifecycle insights, designed to enhance carbon's economic utility within material system realities.

To avoid ambiguity, this working paper distinguishes between carbon as an element and its various molecular and material forms. Carbon refers to the elemental substance as it moves across interconnected systems. CO₂ refers specifically to carbon in its oxidized

atmospheric form, which functions both as a climate-relevant emission and as a feedstock in biogenic systems. References to plastics, fuels, and other materials describe specific anthropogenic forms in which carbon is embodied. Unless otherwise specified, the analysis focuses on how carbon moves between these forms and reservoirs, rather than privileging any single material category.

II. Managing Carbon Across the Full Carbon Cycle

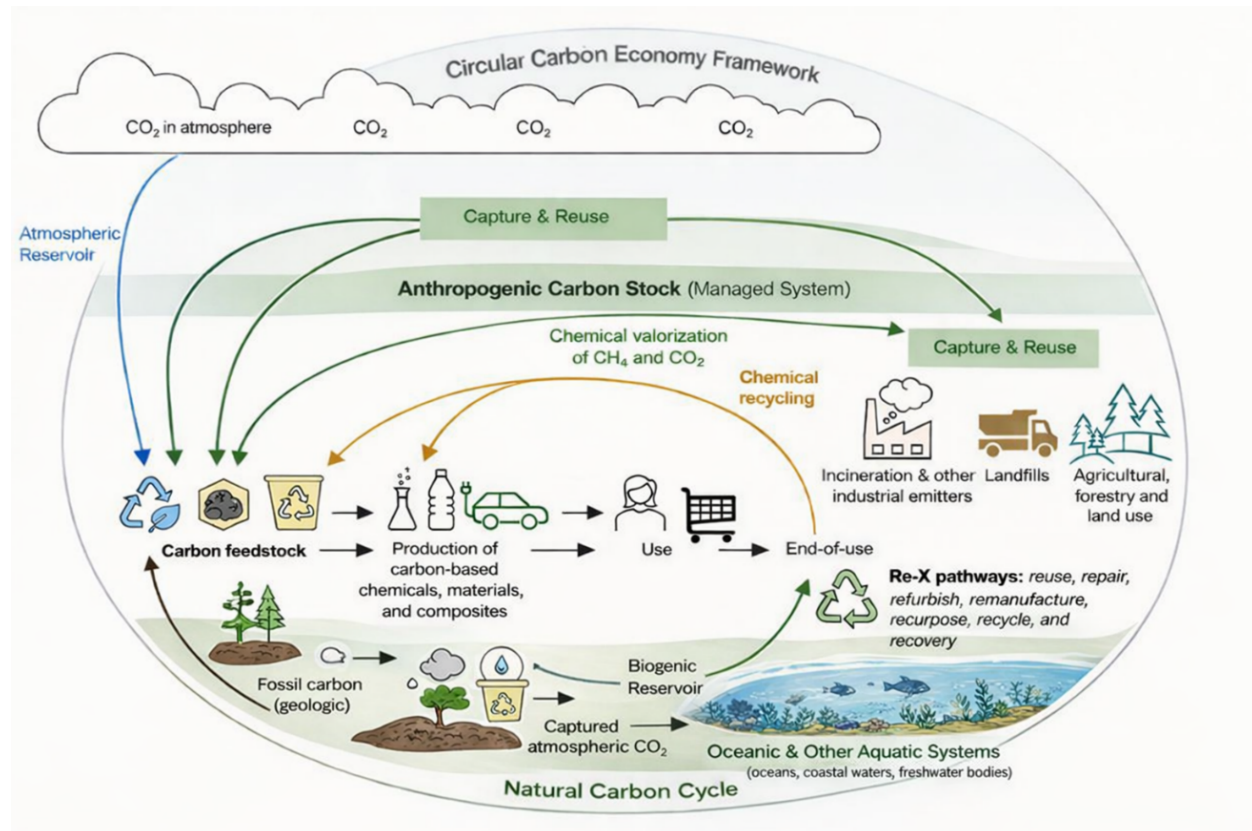
The CCE illustrates carbon management as a continuous system rather than a series of disconnected interventions (Figure 1). Carbon embedded in nonfuel products enters the economy through multiple feedstocks (fossil resources, biogenic sources, and captured CO₂) and moves through the production of chemicals, materials, and composites into use-phase applications. At the end of use, it does not simply disappear; it flows into a range of pathways, including reuse, repair, refurbishment, remanufacturing, repurposing, recycling, energy recovery, landfilling, incineration, industrial capture, and even agricultural or land-based sinks. The central insight is that each of these nodes represents a decision point about where carbon resides and how it continues to circulate. Biogenic systems play a parallel and equally critical role in this framework. Forests, soils, and biomass function as dynamic carbon reservoirs, continuously cycling CO₂ between the atmosphere and terrestrial stocks. Maintaining the integrity of these systems is essential for maximum carbon utility, as disruptions such as deforestation or soil degradation alter both the magnitude and direction of carbon flows, shifting carbon from managed, long-duration reservoirs into the atmosphere.

A critical, and often underemphasized, function within this system is the diversion of carbon from terminal pathways such as landfilling and incineration. These pathways represent effective exit points from managed anthropogenic carbon systems. Landfilling sequesters carbon in a largely inaccessible form with limited future value recovery and potential for fugitive emissions over time, while incineration converts embedded carbon directly into atmospheric CO₂. From a circular carbon economy perspective, both pathways constitute forms of carbon loss from the managed system. Technologies and strategies that intercept material flows prior to these endpoints – by redirecting them into reuse, recycling, or other recovery pathways – preserve carbon within value-creating systems and maintain optionality for future utilization.

CCE, therefore, requires deliberate management both upstream and downstream. Upstream (encompassing feedstock sourcing, preparation, and industrial production prior to product use) the focus would be on feedstock strategy and production efficiency: reducing virgin extraction where feasible, integrating recycled and bio-based inputs, capturing and utilizing CO₂ and other emissions, improving process efficiency, and chemically valorizing methane and CO₂ streams. The objective is not theoretical idealism but pragmatic improvement – reducing high-impact extraction of feedstocks and aligning carbon sourcing with technological, market, and infrastructure realities.

Downstream (encompassing the post-use phase beyond initial production, including collection, sorting, waste management, and recovery pathways such as reuse, recycling, and energy recovery), the emphasis shifts to preserving value and reducing terminal single-use outcomes. Extending product life, enabling reuse and repair, and recovering embedded carbon from discarded materials all keep carbon within managed anthropogenic systems. Avoiding waste where carbon becomes permanently lost value is central to the framework.

Figure 1 – Circular Carbon Economy Framework



Source: Author.

This downstream re-entry point, where post-use carbon either recirculates or exits managed systems, provides the context for the controversy surrounding advanced recycling, also referred to as chemical or molecular recycling. Advanced recycling technologies are not conceptually separate from the CCE; they are one of the mechanisms through which post-use carbon can be redirected away from landfills and unmanaged release. In this context, one of the central contributions of advanced recycling is its ability to intercept carbon that would otherwise be lost to landfill or incineration and reintroduce it into managed industrial systems. This diversion function is foundational from a systems perspective, even where output pathways differ in form or end use.

It is at this downstream stage that advanced recycling debates often collapse into a single question: Does the output return to polymer? From a CCE point of view, that framing is incomplete. The more relevant inquiry is how each pathway affects carbon retention, value preservation, and net system impacts compared to virgin extraction or single-use – balancing emissions, resource efficiency, economic viability, and societal outcomes across the full carbon cycle. Sustainability is multidimensional, and focusing on only one element of a full carbon cycle may lead to less net improvement across those dimensions.⁴

III. Moving Beyond Definitional Purity in Advanced Recycling

The advanced recycling debate is best understood not as a plastics-specific issue, but as a case study in how carbon is managed when materials reach the end of their initial use phase. Advanced recycling dialogues have become preoccupied with definitional boundaries: For instance, whether the outputs from plastic pyrolysis⁵ qualify as recycled, whether fuel production disqualifies circularity, and whether mass balance accounting should permit allocation to fuel streams. These questions are relevant for regulatory clarity and market transparency. However, they should not eclipse the larger objective of improved system performance.

Circularity is too often defined exclusively by polymer reconstitution, the idea that plastic is circular only if it becomes plastic again. This reflects a material-loop lens, which is important but incomplete. It assumes that the only legitimate form of circularity is product-level closure within the same material class. The CCE expands that lens and distinguishes between two levels of circularity. The first is material-loop circularity, in which carbon remains bound within polymers and cycles multiple times through material applications. The second is elemental carbon circularity, in which carbon atoms remain within managed anthropogenic or biogenic systems and displace higher emission virgin extraction, even if they enter fuel or other non-polymer pathways.

Fuel pathways do not meet the traditional but narrow definition of material recycling, which focuses on returning polymers back into material use. Yet under certain conditions, they displace virgin fossil inputs, reduce upstream extraction and environmental impacts, prevent uncontrolled waste accumulation in landfills, and operate within a managed carbon budget. In a CCE, this constitutes carbon recycling in the broader carbon management system rather than material recycling within the physical polymer loop.

The distinction is not semantic; it is structural. By excluding pathways that effectively divert material from landfill and incineration, definitional constraints risk privileging theoretical material purity over practical carbon retention. In doing so, they may inadvertently accelerate the loss of carbon from managed systems, undermining one of the primary objectives of a circular carbon economy. From a systems standpoint, the first-order question is not whether carbon returns to polymer, but whether it avoids becoming unrecoverable waste or immediate atmospheric emissions. Rejecting all non-

polymer outputs as inherently noncircular overlooks the broader management of carbon flows across the system. In doing so, it risks narrowing the solution space and, paradoxically, increasing reliance on virgin extraction by constraining viable pathways for retaining carbon within productive use.

This dynamic presents an economic trade-off: Confining output pathways also restricts the economies of scale of waste collection, sorting, preprocessing, and chemical recycling infrastructure needed to reduce overall system costs, thereby undermining the economic viability and cost competitiveness of and investment in polymer-to-polymer recycling itself.

IV. The Mass Balance Debate and Systems-Level Thinking

The mass balance debate illustrates how circularity discussions can drift from systems analysis toward debates centered on strict definitional criteria. Critics argue that where outputs are not physically distinguished or directly traceable, recycled-content claims may lack credibility or environmental integrity, particularly when recycled content is allocated through chain-of-custody or mass balance accounting frameworks. Yet in other sectors, environmental legitimacy is not determined by physical segregation. Mass balance accounting has been widely accepted precisely because physical segregation is impractical.⁶ Once renewable electricity enters the grid, its electrons are indistinguishable from conventional ones; similarly, sustainable aviation fuel and biofuels are processed in integrated refining systems where molecules cannot be separated after commingling. In those contexts, credibility rests on verified accounting systems and lifecycle performance metrics rather than molecular traceability. The standard applied in those sectors focuses on fossil displacement and lifecycle emissions reduction, rather than physical isolation of molecules.

The more consequential issue, therefore, is system value. What is the highest-value state carbon can realistically occupy given technological constraints, yield variability, cost, market demand, infrastructure limitations, policy frameworks, and lifecycle emissions profiles? These factors shape what is feasible at economies of scale and what delivers measurable carbon management outcomes.

An exclusive focus on returning all outputs to polymer form may narrow the solution set in ways that undermine economic viability and system performance. Such constraints can reduce facility utilization, limit economies of scale, increase per-unit costs, discourage capital formation, and ultimately slow decarbonization, or, conversely, increase carbon emissions. The CCE shifts the focus from product-level circular perfection to system-level performance: whether a pathway improves overall carbon efficiency, reduces reliance on virgin extraction, and manages carbon flows across the full system. That is the essence of systems thinking.

This perspective does not imply that advanced recycling pathways are impact-free. Advanced recycling and related processes can generate residual streams that require

responsible management and may carry environmental, economic, and social burdens of their own. A systems-oriented evaluation should account for these outputs alongside product yields, lifecycle emissions, and displacement effects, weighing whether, on balance, the pathway delivers net carbon and systems benefits relative to higher-impact alternatives.

V. Keeping Carbon in Its Highest-Value State

A central principle of the CCE is value retention, keeping carbon in its highest-value state for as long as possible within managed systems. Carbon embedded in durable goods, such as construction materials, long-lived polymers, and infrastructure, typically represents a more stable and valuable reservoir than in short-lived or single-use applications. In these contexts, material recirculation is often the theoretically preferred pathway.

Yet value in practice is inherently context-dependent. When carbon embedded in discarded plastic cannot be mechanically recycled due to degradation, contamination, mixed resin streams, or lack of viable end-market demand, insisting on polymer-to-polymer reconstitution may not represent the highest-value or lowest-impact outcome. Under real-world technological and market constraints, certain advanced recycling pathways, including those yielding fuel-range outputs, may prevent landfill accumulation, avoid incineration without energy recovery, displace virgin fossil inputs, and support the economic viability of broader recycling infrastructure. In practice, recycling pathways frequently face higher per-unit costs than virgin production, due in part to fragmented and deficient collection and sorting systems, contamination challenges, limited aggregation preprocessing, and homogenization of usable feedstocks to achieve consistent quality and volume, transportation logistics, and subscale processing infrastructure. Achieving cost parity requires sufficient throughput across the value chain. Restricting certain output pathways may unintentionally limit the economies of scale necessary to reduce costs, even for polymer-to-polymer recycling.

VI. Policy Considerations

A CCE framework implies a set of policy shifts that gravitate from definitional, single-focused debates and toward measurable multidimensional system performance.

First, policymakers should prioritize system outcomes over labels. This means statutory or regulatory definitions that include pathways based on lifecycle emissions, displacement effects, resource efficiency, and broader sustainability considerations rather than relying solely on whether an activity satisfies a narrow definition of recycling. This includes explicitly recognizing the value of diverting material from landfill and incineration as a measurable system benefit, particularly where such diversion preserves carbon within managed value chains.

Second, metrics should be aligned with virgin displacement. The central question is not simply whether carbon is reprocessed, but whether a given pathway materially reduces reliance on upstream fossil extraction and associated lifecycle impacts. This provides a more accurate indicator of system-level benefit than product-level classification alone.

Third, policy frameworks should incorporate carbon budget accounting. Pathways should be assessed within the context of managed carbon budgets aligned with emission targets, ensuring that carbon flows remain consistent with long-term goals rather than being evaluated in isolation.

Fourth, policy should enable infrastructure scale and recognize multiple circular pathways. Economies of scale are central to cost reduction across the recycling value chain. Collection, sorting, preprocessing, transport, and advanced recycling facilities depend on sufficient throughput to lower per-unit costs and attract sustained investment. A circular carbon system cannot mature without coordinated scaling across these nodes.

Importantly, achieving that scale may require recognizing multiple output pathways. Limiting advanced recycling to polymer-to-polymer outcomes alone may constrain facility utilization and restrict the volume necessary to drive down system-wide costs. Excluding fuel pathways may unintentionally increase the cost of polymer-to-polymer recycling by constraining the throughput required to achieve economies of scale across the recycling value chain. Allowing both material recycling and managed carbon pathways, including fuel displacement where lifecycle benefits are demonstrated, can support the throughput required to make higher-value recycling pathways economically viable. The objective is not to privilege one output category over another, but to develop a resilient, expanding recycling ecosystem capable of reducing reliance on virgin extraction.

Regulatory systems should explicitly acknowledge multiple circular pathways. Material recycling and broader carbon recycling serve distinct functions within the system and should be differentiated without being conflated. A polymer-to-polymer loop is not equivalent to carbon cycling through other managed pathways, but neither is it the only legitimate form of circularity. A thriving circular carbon system requires volume, market stability, and policy clarity.

Regulatory coherence is therefore essential. The United States currently functions within a fragmented, state-by-state regulatory landscape characterized by divergent definitions of recycling, uneven extended producer responsibility regimes, inconsistent classification of advanced recycling facilities, varying recycled-content requirements, and, in some states, the absence of a comprehensive recycling framework altogether. This heterogeneity increases compliance costs, complicates interstate feedstock movement, discourages capital formation, and fragments markets. Greater national alignment, particularly around definitions of recycling that recognize both polymer-to-polymer pathways and managed carbon pathways, including fuel displacement where lifecycle benefits are demonstrated, would reduce uncertainty and support

infrastructure scaling. Narrow regulatory definitions that exclude certain output pathways may unintentionally constrain facility utilization, limiting the very scale efficiencies required to make polymer-to-polymer recycling more competitive. This fragmented regulatory environment increases system-wide costs and undermines economies of scale, making national scaling of recycling infrastructure more expensive and less predictable than under a harmonized framework.

Fifth, transitional incentives may be necessary to overcome structural cost barriers during scale-up. Recycling systems face embedded economic disadvantages relative to virgin production, particularly when fossil feedstock prices are low, and collection and sorting infrastructure remains fragmented. Targeted tax incentives, accelerated depreciation, production-based credits tied to lifecycle performance, and infrastructure support for feedstock aggregation can help reduce early-stage capital and operating constraints.

Equally important, downstream market signals and consumer-facing incentives are often overlooked. Procurement preferences, recycled-content standards, tax credits for manufacturers incorporating recycled inputs, and mechanisms that influence consumer purchasing behavior can help stabilize demand and create predictable offtake markets. Without coordinated supply-side and demand-side incentives, recycling systems struggle to achieve the throughput necessary for economies of scale. Absent early-stage market formation policies, recycling risks remaining subscale and structurally disadvantaged relative to virgin extraction.

Finally, innovation should be enabled through flexible accounting structures that reflect scientific and economic realities. Overly rigid frameworks risk penalizing scalable pathways that reduce lifecycle intensity and improve carbon efficiency simply because they do not conform to traditional classifications. A systems-oriented approach allows policy to support carbon optimization rather than constrain it. A CCE requires not only technological innovation, but regulatory alignment and economic architecture capable of supporting system-wide scale.

Conclusion

From the perspective of Schrödinger's cat paradox, depending on how and where it is observed, carbon occupies a conceptual box, simultaneously treated as both villain and indispensable foundation of modern civilization. Climate and plastics debates often oscillate between these extremes, portraying carbon either as something to be eliminated or something to be defended. CCE opens that box and reframes the question, not as a binary enemy versus non-enemy, but as a managed economic asset whose impacts depend on how intelligently we govern its flows. The issue is not whether carbon should exist in the economy, but how it is managed across reservoirs, time horizons, and industrial systems.

Viewed through this lens, the debate over advanced recycling reveals a broader challenge in sustainability governance. Too often, policy discussions prioritize categorical definitions and distinctions over system performance. Yet industrial systems do not operate within neat definitional boundaries. Carbon moves continuously through materials, fuels, infrastructure, and natural reservoirs. Managing those flows effectively requires evaluating pathways based on lifecycle performance, resource efficiency, and their ability to reduce reliance on new extraction while preventing waste accumulation.

A systems-oriented CCE framework shifts the focus from product-level purity to a discipline of carbon stewardship. Different pathways may retain carbon in different forms, sometimes as materials, sometimes as energy carriers, but the underlying objective remains the same: to keep carbon productively managed within the economy for as long as possible while creating net lifecycle value.

This principle applies equally across anthropogenic and biogenic systems. While industrial debates often focus on plastics and fossil carbon, unmanaged carbon in the form of deforestation and land-use change represents one of the largest uncontrolled releases in the global carbon cycle. Conversely, the role of CO₂ as a biogenic feedstock underscores that carbon, when properly governed, underpins both natural and industrial systems. The challenge is not elimination, but alignment — ensuring that carbon remains within managed reservoirs, whether in ecosystems or engineered systems, rather than contributing to uncontrolled atmospheric accumulation. Carbon itself was never the problem. Unmanaged carbon is.

Notes

¹ Eric Williams, Adam Sieminski, and Abdulaziz al Tuwaijri, *CCE Guide Overview: A Guide to the Circular Carbon Economy* (King Abdullah Petroleum Studies and Research Center [KAPSARC], 2020), <https://www.cceguide.org/wp-content/uploads/2020/08/00-CCE-Guide-Overview.pdf>.

² The circular carbon economy concept gained prominence through energy-sector policy frameworks and was endorsed by the G20 in 2020. However, its intellectual roots extend deeper into industrial ecology, circular economy theory, and carbon cycle science. This paper advances that lineage by reframing CCE as a reservoir-governance framework centered on managed carbon flows rather than material-loop purity.

³ Rachel A. Meidl, “Schrödinger’s Cat Paradox: Carbon Is the Enemy. Carbon Is Not the Enemy,” Rice University’s Baker Institute for Public Policy, August 9, 2023, <https://doi.org/10.25613/5ED9-S212>.

⁴ Meidl and Kenneth B. Medlock III, “The Pride and Prejudice of Sustainability: Rethinking Sustainability from a Systems Perspective,” Rice University’s Baker Institute for Public Policy, November 8, 2023, <https://doi.org/10.25613/20CH-3Z48>.

⁵ Jiayang Wu et al., *Pyrolysis of Plastic Waste: Recycling Hard-to-Recycle Plastics*,

Chemical Upcycling of Waste Plastics, 2023, https://cuwp.org/wp-content/uploads/2024/01/2_PYROLYSIS_112023.pdf.

⁶ Zero Waste Europe, *Chemical Recycling: Plastic Waste or Plastic Solution?* (2020); Global Alliance for Incinerator Alternatives (GAIA), *Chemical Recycling: A False Solution to the Plastic Crisis* (2020); NGO coalition statements during EU Packaging and Packaging Waste Regulation (PPWR) negotiations (2022–24); Oregon Department of Environmental Quality (DEQ) rulemaking commentary on advanced recycling; California S.B. 54 regulatory discussions; and European Commission Joint Research Centre commentary on chemical recycling allocation methods.