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Reducing Primary Carbon Demand – How circularity reshapes the role of carbon in a net-zero economy

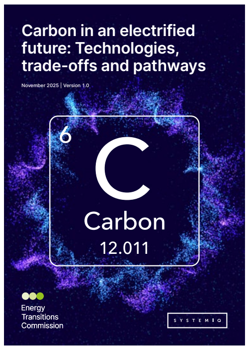
Why circularity matters for the way we use carbon

"Circular Carbon" strategies enable us to decouple from fossil-derived carbon by keeping carbon molecules in the economy for longer, rather than using them once and discarding them to the ground or releasing them into the atmosphere.

Even in a highly electrified economy, some carbon remains essential for materials, products and selected energy uses, with total demand estimated at around 5 Gt of carbon by 2050. While electrification can help us to shift away from fossil fuel combustion for energy, and clean hydrogen can extend the reach of clean power where direct electrification is not technically feasible, even the most ambitious scenarios still leave a residual role for carbon molecules. In materials, carbon remains an essential chemical building block for products like plastics, industrial chemicals, solvents, and synthetic fuels such as e-methanol. In energy uses, carbon-based fuels remain necessary for applications requiring high energy density, notable long-distance aviation and shipping, where direct electrification is not easily feasible. Residual carbon demand therefore persists even after electrification and hydrogen are pushed close to their limits.

Today's system is overwhelmingly linear, with just 2% of carbon recycled. Innovation and large-scale deployment could change this dramatically, increasing circularity fifteenfold so that by 2050, circular sources supply around 30% of residual carbon demand (~1.5 Gt C). At present across the energy and materials systems, the equivalent of 11.5 Gt of carbon is used each year, with 85% sourced from fossil fuels and 88% ultimately emitted to the atmosphere (Exhibit 1). The small share that is cycled back into productive use – around 2% – comes primarily from wood, pulp and paper. Circular performance varies widely by sector: fibre-based systems such as paper achieve relatively high recovery rates (around two-thirds recycled globally), whereas plastics lag far behind, with only around 9% recycled. Circularity is not limited to solid materials. Gaseous waste streams, including CO_2 and CO from industrial processes, can also be captured and reused as inputs, but these pathways remain at an early stage, with deployment largely confined to pilots and demonstration projects today.

The scale and cost of residual carbon management in 2050 will ultimately depend on how effectively carbon demand is reduced upstream. A system that maximises reuse, product longevity and material recovery requires less reliance on large-scale carbon



The ETC's and Systemiq's *Carbon in an Electrified Future: Technologies, Trade-offs and Pathways* report, from which this summary is based, analyses how carbon can be sourced, used and reduced in a net-zero global economy. It focuses on the role of electrification, hydrogen, circularity, and carbon sourcing and management technologies that together can enable the sustainable supply, reuse and permanent storage of carbon molecules. The report also examines the key system trade-offs and innovation priorities needed to achieve deep decarbonisation while balancing cost, resource use and technological readiness. This summary is one of a series drawn from this report and focuses on the role of the potential to reduce primary demand.

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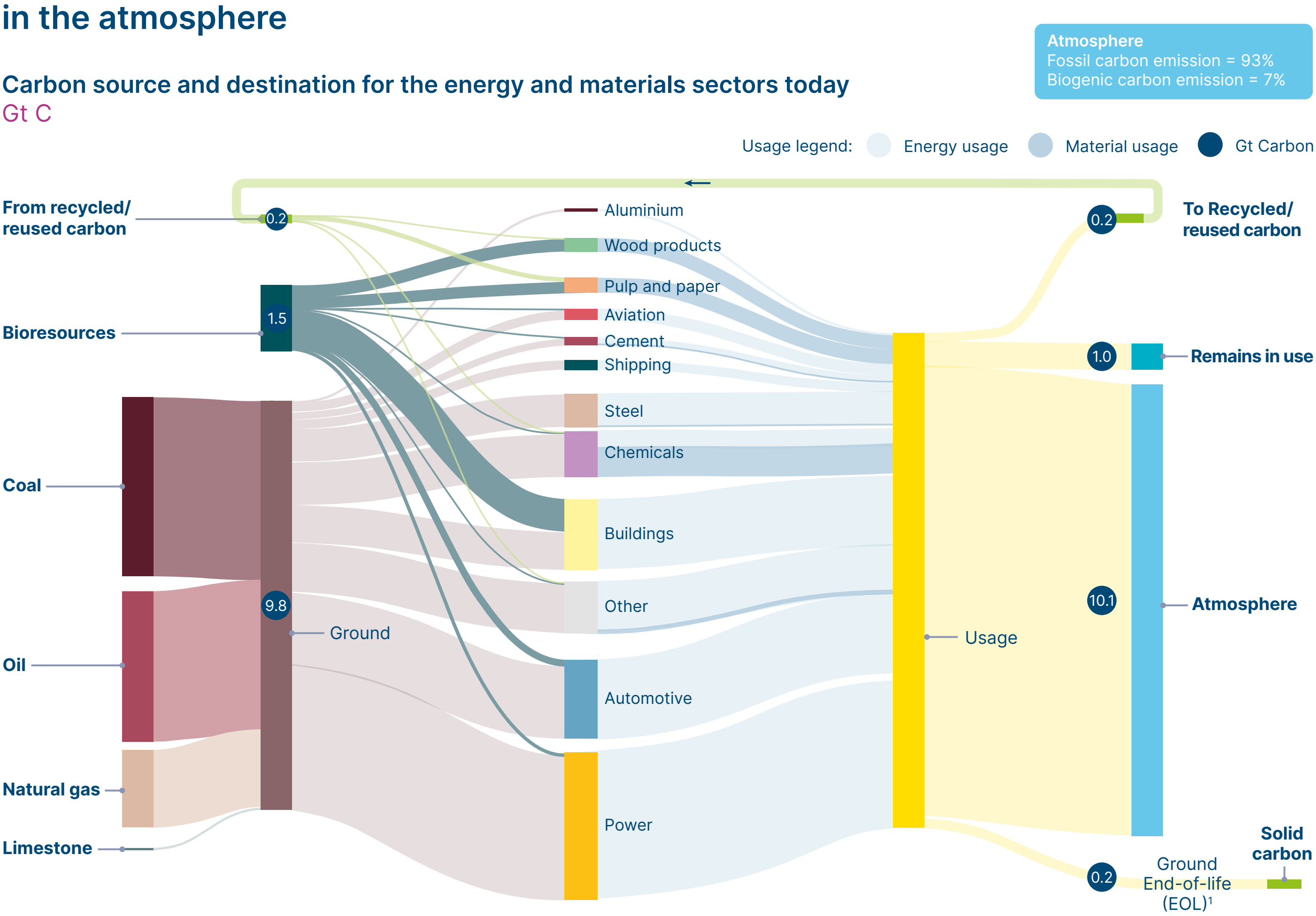
capture, durable removals and land-intensive biomass expansion. In shrinking the volume of primary carbon that must be sourced and permanently managed, circularity lowers exposure to infrastructure bottlenecks, storage capacity constraints and clean energy trade-offs. In this sense, circularity functions as a risk-reduction strategy for net-zero, easing pressure on complex and capital-intensive parts of the carbon system. Industries and countries that embrace circular carbon strategies can unlock unique opportunities to build innovative domestic industries while reducing reliance on fossil fuels, strengthening jobs, competitiveness, and economic resilience.

Exhibit 1

The majority of carbon today comes from fossil sources and ends up in the atmosphere

Carbon source and destination for the energy and materials sectors today

Gt C



NOTE: [1] This includes unmanaged solid carbon that goes to ground and eventually ends in oceans.

SOURCE: Systemiq analysis for the ETC; ETC (2023), *Fossil Fuels in Transition*.

Innovations for a circular system

Core technologies that 1) reduce demand, 2) enable material recycling, and 3) recycle carbon (Exhibit 2), are already available and proven today and could allow circular carbon strategies to scale rapidly, but achieving a fifteenfold increase in circularity by 2050 requires holistic system overhaul. Our analysis focuses on key technologies within these three pathways; new re-use technologies and delivery models, mechanical recycling, recycling through chemical and thermo conversion pathways such as pyrolysis, gasification and depolymerisation and carbon utilisation from waste streams including technologies like hydrogenation to methane or methanol and biocatalysis. Today, scaling these technologies is primarily a challenge of behaviour, economics, and system design, requiring incentives for reuse over disposability, strong end-market demand and internalised externalities to support viable business models, and credible mass-balancing and harmonised standards to unlock scale. Governments play a central role in enabling these conditions.

Exhibit 2

To understand how much of carbon demand can be circular, we deep-dive on key re-use and recycling technologies

Material and carbon circularity solution set; technology–deep–dives

Lever	Actions	Technologies in focus	Most applicable sectors
1 Reduce demand	Eliminate, Reuse, Substitute	• New re-use technology & delivery models	• Plastic and packaging • Building and construction • Automotive • Fashion
2 Recycle material	Physical or mechanical recycling of material	• Mechanical recycling	• Plastic and packaging • Wood pulp and paper • Building and construction
3 Recycle carbon	Chemical recycling of material and thermo conversion	• Depolymerisation • Pyrolysis • Gasification	• Chemicals • Aviation and fuels
	Utilise waste CO and CO_2	• Hydrogenation to methane or methanol • Electrochemical reduction • Reverse Water Gas shift • Biocatalysis	• Chemicals • Aviation and shipping fuels • Road transport • Heating

SOURCE: Systemiq analysis for the ETC (2025).

1. New re-use technology and delivery models

Reuse business models extend the life of carbon within the system and, once scaled, could reduce overall system costs[1] versus today by around 20%. Reuse and lifetime-extension models, including refill and return systems, remanufacturing, repair, modular design, and service-based business models, can reduce demand for new material production by keeping products and materials in use for longer. Examples include TerraCycle's Loop reusable packaging platform, IKEA's furniture take-back and resale programmes, and wider remanufacturing, repair and service-based business models across automotive, electronics and industrial sectors. Growing attention to the climate impacts of consumer products, rising resource-efficiency pressures, and improvements in logistics and digital tracking have made these models increasingly viable.

However, their ability to reach full potential is constrained by the need for deeper and more extensive system-wide change. In carbon-intensive product categories such as packaging and consumer goods, reuse at scale can substantially reduce material demand and deliver significant emissions reductions, while also lowering system costs relative to single-use models. Yet scaling reuse requires a holistic operational overhaul across the value chain, including product and packaging redesign, new logistics and reverse supply systems, changes to brand and retailer operating models, and sustained shifts in consumer behaviour, all of which must be supported by coherent, integrated policy to compete with cheap single-use alternatives.

1 Includes all costs, from production, conversion and filling, to collection and sorting, recycling and disposal

2. Mechanical recycling

Mechanical recycling is a mature and widely deployed technology, but has not reached its full potential, due to competition with low-cost virgin fossil feedstocks and the low quality feedstock produced by the system today. Mechanical recycling involves the collection, sorting, washing and the processing of material feedstocks which often comprise highly diverse, contaminated and mixed plastic waste streams. It is important to note that as a technology it can lead to recycling into lower grade applications, for example, some recyclate becomes unsuitable for higher performance markets such as food contact, cosmetics or automotive. Today mechanical recycling is most effective for uncontaminated waste streams such as PET[2] bottles, which account for a limited share of total plastic waste and face strong competition across recycling markets.

Mechanical recycling will only scale if policy makes the business case viable, since without vastly stronger economics it is difficult to justify investment in resolving feedstock quality challenges. Governments are increasingly using tools such as recycled-content mandates, extended producer responsibility schemes, and restrictions on landfill or incineration to improve the competitiveness of recycled materials. Emerging technologies, including AI-enabled sortation, digital watermarking and improved collection systems, can raise yields and feedstock quality, but they cannot overcome the deeper structural barriers created by poor product design and weak market incentives. In practice, a large share of plastic waste cannot be mechanically recycled without upstream interventions to reduce contamination and material complexity. As a result, progress remains constrained by mixed waste streams, uneven infrastructure, and price signals that continue to favour low-cost virgin fossil feedstocks over recycled content.

3. Chemical recycling and thermo-conversion

Chemical recycling and thermo-conversion[3] expand the range of materials that can be returned to productive use by converting waste into virgin-quality outputs. However, these technologies, which are still scaling commercially, are more energy and emissions intensive (Exhibit 3) than mechanical recycling, so are best suited as residual solutions for hard-to-recycle materials. Depolymerisation, pyrolysis and gasification are chemical recycling and thermo-conversion technologies that breakdown waste into chemical building blocks that can substitute for fossil feedstocks, helping to recover carbon from contaminated, composite and mixed materials. These technologies can process mixed and contaminated waste streams, but in practice perform most reliably on the higher-quality waste streams similar to those used by mechanical recycling. As a result, these technologies risk competing directly with mechanical recycling for feedstocks, but as shown in Exhibit 2, avoid as little as 1.4tCO_2 from plastic waste input to product output, versus mechanical recycling which can avoid as much as 4.8tCO_2. These are net emissions, incorporating credits for avoided incineration of plastic waste that is instead used as feedstock in the process.

For chemical recycling and thermo-conversion, continued improvements in reactor design and process integration are strengthening technical performance and improving the reliability of processing mixed and contaminated waste streams. Producing refinery- or cracker-ready outputs can, however, require additional upgrading steps (e.g., hydrotreatment), increasing energy demand, complexity and overall costs. Creating a viable business case for these pathways will depend on clearer and more stable policy and market frameworks, including robust mass-balance accounting rules, the development of compliance criteria under instruments such as the EU Packaging and Packaging Waste Regulation, and stronger demand signals for high-quality secondary materials.

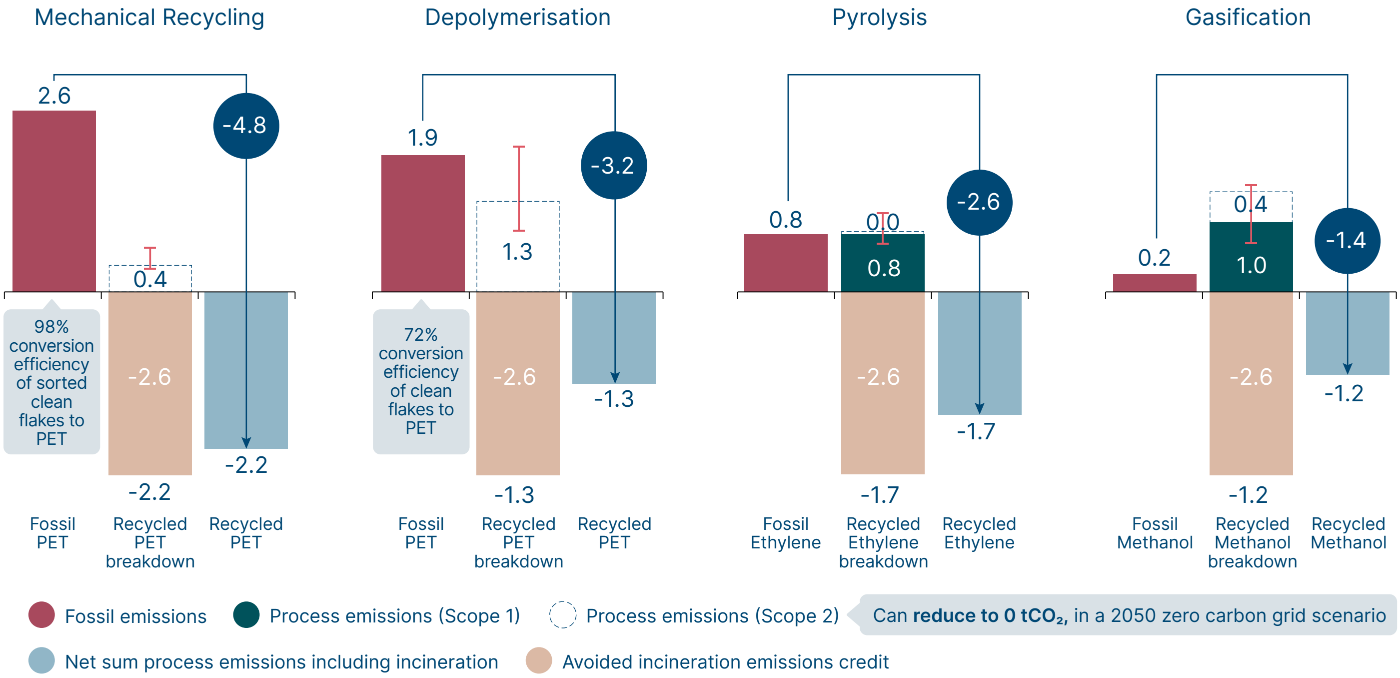
2 PET = Polyethylene Terephthalate. This type of plastic is the most commonly used for beverage bottles.

3 Chemical recycling and thermo-conversion describe processes that break plastics into chemical intermediates. Chemical recycling typically returns monomers to material production, while thermo-conversion produces oils or syngas that may be routed to materials or fuels depending on end use.

Exhibit 3

Pyrolysis and gasification are more emission intensive than mechanical recycling, but can provide emission savings with avoided CO_2 emissions from incineration

Net CO_2 emissions for recycling processes, compared with fossil production
tCO_2 / tonne of waste input



NOTE: 98% conversion of clean flakes in mechanical recycling. 72% overall yield of clean flakes to PET via depolymerisation. Assumptions for conversion yields for gasification and pyrolysis are 43% and 41%, however yields can vary largely depending on real world operations.

SOURCE: 1) CE Delft (2019) 2) Uekert et al. (2022) 3) Uekert et al. (2023). Carbon footprint of fossil methanol based on Methanol institute (2023) *Carbon Footprint of Methanol. Fossil Ethylene based on Chemical and Engineering news* (2021) *The search for greener ethylene and University of Illinois* (2022) *A breakthrough discovery in carbon capture conversion for ethylene production.* Incineration emissions factor based on *Reshaping Plastic* Systemiq (2022). Fossil emissions for PET based on Eco-profiles produced for Plastic Europe; LCI Assessment for Cradle-to-Gate (Raw Materials/Energy, Precursos production, Polymer production). Gasification based on NREL (2022) *Techno-Economic Analysis of Waste Plastic gasification to Methanol Process.* Pyrolysis emissions based on Energy and Environmental Science (2023) *Techno-economic analysis and life cycle assessment for catalytic fast pyrolysis of mixed plastic waste*

4. Carbon utilisation

Carbon utilisation expands the reuse of carbon beyond solids into captured gaseous molecules, but its energy intensity and cost of feedstock, particularly where green hydrogen is used, means it remains 2-4x more expensive than fossil alternatives today, limiting its role to targeted applications. Carbon utilisation technologies convert captured CO_2 or CO into fuels, chemicals or intermediates through pathways such as hydrogenation (e.g., methanol synthesis), reverse water–gas shift (RWGS) to produce syngas, electrochemical reduction, and biocatalysis. Advances in catalysts and electrochemical systems are improving technical performance, alongside growing interest in e-fuels.

Carbon utilisation must nevertheless be positioned within a clear mitigation hierarchy, as it is less efficient than direct electrification or permanent storage. As a result, carbon utilisation is best suited to targeted applications where carbon molecules are intrinsically required and alternatives are limited, such as e-fuels for aviation and shipping, or specific chemical feedstocks. The case for carbon utilisation is strongest where direct electrification cannot be applied, where a carbon-based product is still functionally required, and where permanent sequestration is not preferable or feasible. It could be particularly attractive where capture offers additionality through relatively concentrated biogenic or industrial point source CO_2 streams, as capture costs for high-purity sources above 90% CO_2 can be below $50 per tonne, compared with well over $150 per tonne for dilute streams such as gas power flue gas, making concentration a critical determinant of viability.

In most cases, energy efficiency and direct electrification are more energy-efficient and cost-effective than converting CO_2 back into fuels. For example, while synthetic fuels produced via carbon utilisation may offer transitional advantages in regions with extensive legacy gas or fuel infrastructure, their higher electricity requirements mean they are generally less system-efficient than direct electrification in applications such as building heat and passenger road transport. Where emissions cannot be avoided and no carbon-based product is required, permanent storage (CCS) is typically cheaper and more system-efficient than utilisation, for example for cement kiln process emissions.

The cumulative impact of ‘circular’ technologies

In a maximum circularity scenario, around 30% of residual carbon demand (equals ~1.5Gt C out of ~5.0Gt C in 2050) is met through circular pathways. This circular supply is driven by:

- **Mechanical recycling (570 MtC, ~39% of total circular carbon supply)** (Exhibit 4), the single largest lever, driven by further scale-up of pulp and paper recycling and significant expansion in plastics. Realising this potential depends on an unprecedented scaling of the technology, involving upstream product design improvements, higher-quality feedstocks, and policy frameworks that strengthen demand for recycled materials.

- **Carbon utilisation (490 MtC, ~33% of circular carbon supply),** the second-largest lever, reusing captured CO_2 and CO as inputs into fuels and chemical intermediates. Its role is concentrated in applications where carbon molecules are intrinsically required and where utilisation fits within a clear mitigation hierarchy.

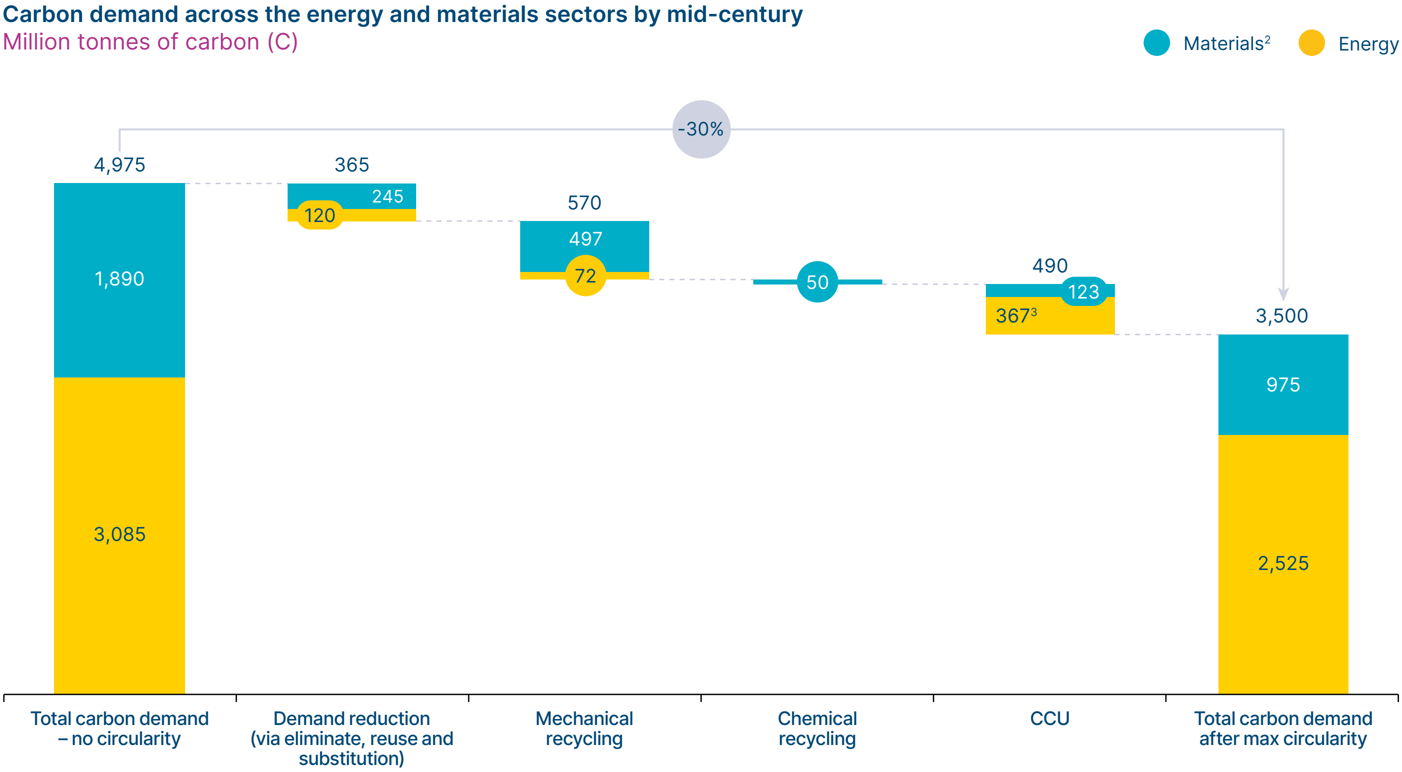
- **Reuse and upstream demand reduction (370 MtC, ~25% of circular carbon supply),** delivering system-wide benefits by avoiding new material production altogether through reuse, elimination and substitution. As an upstream intervention, it reduces pressure on recycling systems and long-term carbon management, but scaling requires operational change across brands and retailers and sustained behavioural shifts.

- **Chemical recycling and thermo-conversion (50 MtC, ~3[4]% of circular carbon supply)** expand the range of materials that can be returned to productive use by converting residual and contaminated waste streams into virgin-quality outputs. While still scaling commercially, their contribution remains targeted given their higher energy and emissions intensity and the need for stable policy and market frameworks to support deployment. This also highlights an innovation gap, where breakthroughs in recycling truly mixed and complex waste streams could open up more disruptive circular production routes over time.

Exhibit 4

Circularity levers could reduce primary carbon demand by 30% by mid-century

Carbon demand across the energy and materials sectors by mid-century
Million tonnes of carbon (C)



NOTE: [a]Chemicals and steel include the feedstock from the energy system that has remained in material, i.e. plastic, in order to show the circularity levers. [b]Other includes carbon ash, biochar, carbon fibre, charcoal. [c]Total carbon demand is shown without applying the circularity levers included in ACF. [d]Excludes Enhanced Oil Recovery as it does not reduce the carbon demand.

SOURCE: Energy: Systemiq analysis for the ETC; ETC (2023), based on *Fossil Fuels in Transition*; Chemicals: Systemiq (2022), *Planet Positive Chemicals* (BAU Net-Zero scenario); Biomass: ETC (2021), *Bioresources within a Net-Zero Emissions Economy*; Steel: MPP (2022), Making net-zero steel possible.; MPP (2022), Making net-zero aviation possible; Cement: MPP (2023), Making net-zero concrete and cement possible. Cotton, Bitumen and Soda Ash: Systemiq analysis (2025).

4 This value equates to 20% of all plastic waste being chemically recycling, which represents an ambitious assumption across literature

Reaching around 30% circular carbon by 2050 would already represent a major system transformation. While a fifteen-fold increase in circular carbon supply is technically possible, achieving this would require coordinated changes across materials, waste, energy and policy systems, making it a highly ambitious outcome rather than a conservative one. For example, even under this scenario, global plastics recycling would need to rise to around 40% of waste, compared with ~9% today, and well above current best-practice levels in leading countries (e.g., 14% in Finland). This would require a step change in collection, sorting and processing infrastructure, alongside stronger policy frameworks and sustained market demand for recycled materials.

Similarly, scaling carbon utilisation is constrained not only by the pace of carbon capture deployment, but by limited end-use demand. CO_2 and CO-derived fuels and chemicals can only expand in sectors where carbon molecules remain intrinsically necessary such as aviation, shipping and parts of the chemical industry and where policy support can sustain higher-cost low-carbon alternatives. **Taken together, these constraints mean that achieving ~30% circular carbon would already signal substantial progress,** even though higher theoretical potentials exist.

From circular technologies to enabling circular systems

Circularity technologies and models face a major barrier in that they mostly do not offer discrete, drop-in solutions to existing infrastructure and modes of consumption, and often lack investable business models under today's market conditions. They must therefore be supported by policy that incentivses behaviour change (e.g., from single use, towards recycling and reuse), improve the economics for circular technologies and support system design that allows these technologies to scale. Importantly, the transformative potential of circularity does not lie primarily in individual technologies themselves, but in the orchestration of the wider system in which they operate. As circular solutions often deliver only incremental gains within entrenched linear structures, their full benefits can only be realised through holistic change across operations, policy, markets, and behaviour. The real innovation required is therefore systemic, not technological. It lies in embedding clear lifecycle responsibility for carbon, from production through use to end of life, so that waste and emissions are no longer externalised but actively managed.

Behaviour change

1. Single-use and disposability are convenient and incentivised options in todays' system. Until reuse and recycling are just as easy and accessible for consumers, they will not scale. Both reuse and recycling depend on sustained behaviour change: reuse requires consumers to return and refill, while recycling relies on consistent sorting and participation. Driving this shift will require simple systems, clear incentives and visible signals that make circular actions intuitive, without adding meaningful cost or complexity.

Economics

2. Demand certainty is critical to unlock investment in recycling, carbon utilisation, and the supporting infrastructure needed for circularity. First-of-a-kind circular projects often face high capital costs, limited operating track records, and uncertain markets for their outputs. Creating stable, predictable demand for circular materials and business models is therefore essential to mobilise private investment and accelerate deployment.

3. Levelling the playing field between linear fossil and circular materials and models is essential to unlock investment and scale circular infrastructure. Fossil-based materials retain a structural cost advantage due to cheap feedstocks and largely unpriced environmental externalities, which continue to distort markets against recycled and low-carbon alternatives. Closing this gap requires effective carbon pricing, recycled-content mandates, and strengthened extended producer responsibility to ensure circular solutions can compete on fair economic terms.

System design

4. Ensuring that higher-quality waste enters recycling facilities begins upstream, through better product design. Early design choices determine whether materials can be recovered at high value, or lost after first use, meaning design and reuse interventions are often more powerful than downstream fixes. Enforceable product design rules are needed to reduce material complexity, problematic additives, and contamination, while design-for-recycling approaches expand the range of applications for recycled outputs and improve overall economics.

5. Scaling collection, sorting, and pre-treatment infrastructure is essential to make circular systems viable. Today, only around 9% of global plastic waste reaches recycling facilities, highlighting the scale of the challenge. Advanced sortation technologies can increase recovery rates by roughly 25% and significantly improve recyclate quality, but these benefits will only be realised if collection systems and downstream recycling capacity expand in parallel. Table 1 details the system shifts and key actions from stakeholders.

Table 1: Who needs to do what?

System Shift	Governments	Chemical producers	Brand owners and manufacturers
1. Enable consumer reuse and recycling behaviours	**Implement deposit-return and take-back systems** that incentivise product return **De-risk first movers** through public co-investment and support for shared return/logistics infrastructure **Standardise labelling and collection rules** to reduce consumer confusion across regions. **Align fiscal incentives so single-use is not structurally favoured,** e.g., through instruments such as EPR	**Adapt polymer and additive formulations** to meet durability and washability requirements where policy creates re-use demand	**Redesign products for durability, modularity and repairability** where incentives reward lifetime performance **Standardise packaging formats** where feasible to enable shared return, refill and collection systems. **Provide clear, consistent labelling** that makes reuse, return and correct sorting for recycling easy to understand
2. Create demand certainty for circular materials and models	**Set minimum recycled-content requirements** for selected materials and products **Use public procurement** to create early bankable demand for circular products **Define credible product standards** and disclosure rules so buyers can trust circular claims **Introduce product-based contracts-for-difference** or similar revenue-stabilisation tools for circular materials in early markets	**Adapt product specifications** to accept certified recycled feedstocks once standards are in place **Invest in recycling and circular feedstock capacity** once mandates and standards provide long-term visibility	**Commit to long-term offtake agreements** for recycled materials once regulatory frameworks and standards reduce competitive and reputational risk.
3. Level the cost advantage	**Enforce modulated EPR schemes** with fees linked to end of life outcomes and material quality **Extend carbon pricing** to virgin production and incineration **Align trade and product rules** to prevent leakage and undercutting by high-carbon imports	**Rebalance capital allocation toward circular capacity** as carbon pricing and regulatory costs narrow the virgin cost advantage	**Increase uptake of circular materials** where compliance or price parity is established
4. Prioritise upstream interventions to improve feedstock quality	**Mandate design-for-recycling requirements** (material simplification, additive restrictions) **Harmonise labelling, material definitions** and recyclability standards across markets **Restrict problematic combinations** that structurally degrade recycling yields	**Specify feedstock quality needs** clearly so sorting systems can deliver usable streams	**Reduce unnecessary material complexity** in packaging and products **Align product design** with recovery system capabilities
5. Scale collection, sorting and pre-treatment infrastructure	**Invest in collection, and sorting systems** designed for recovery, not disposal **Coordinate infrastructure build-out** across regions to unlock scale economics	**Invest in upgrading and recycling capacity** once policy frameworks ensure reliable, quality feedstock supply	**Invest in pre-treatment facilities** to ensure high quality feedstock enter recycling facilities **Meet EPR obligations** and take-back requirements as they are strengthened **Support traceability and sorting** through improved labelling and reporting

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