Chapter Summary

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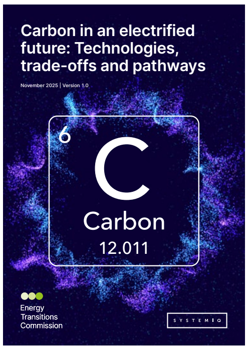
Residual Carbon in Net-Zero: Sources and End of Life Pathways

Carbon sourcing and stewardship in a net-zero economy

Even after maximising carbon reduction through electrification and hydrogen, and minimising primary demand through circularity, a net-zero energy and materials system still requires both new carbon entering the system and robust management of carbon exiting the system.

Even in the most optimistic scenario of electrification, hydrogen and circularity, a minimum of ~2.3Gt of primary carbon, equivalent to approximately 20% of today's total demand (11.5 Gt C), will still be required in 2050. This residual carbon demand will persist in sectors such as long-distance aviation, which requires high energy density fuels, as well as wood, pulp, paper and chemicals where carbon remains an essential building block.

Net-zero is not emissions-free; continued use of fossil-based carbon makes end-of-life management and carbon removals unavoidable, and today's sourcing choices lock in the scale of removals and storage needed later this century. Greater reliance on recycled, biogenic and atmospheric carbon reduces fossil dependence and lowers long-term permanence obligations. They can also lead to net emission reductions when stored as durable storage prevents the re-release of carbon drawn from the atmosphere. Exhibit 1 shows an example of carbon usage and capture pathways that can lead to different end of life outcomes for emissions depending on the carbon source.



Carbon in an electrified future: Technologies, trade-offs and pathways

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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 carbon supply and end of life management.

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Exhibit 1

Eventual CO_2 emission impact, depends on the source of carbon used, and end of life treatment – biogenic and atmospheric/oceanic carbon can lead to neutral or negative emissions versus dependence on removals

Carbon source	End of life pathways and CO_2 emission impact	
	No end of life carbon management (Combusted to atmosphere)	**Managed end of life**[2] Carbon capture Saline aquifers / Depleted oil and gas fields Mineralisation Landfill[3,4]
Atmosphere/Ocean Bioresources	**2** **Emissions ~Neutral**[1] *e.g. sustainable aviation biofuel* Carbon originally sourced from the atmosphere can return to the atmosphere with limited net impact	**4** **Atmospheric carbon removals** *e.g. DACCS, BECCS or nature-based pathways* Residual emissions from fossil drive greater dependence upon scaling removals.
Fossil or mineral carbon	**1** **High emissions** *e.g. gas power generation* Fossil carbon is extracted, used and released to the atmosphere, driving climate change	**3** **Emissions reductions** *e.g. Carbon capture and storage* Extracted fossil carbon must be managed at end of life in a net zero system, but leave unavoidable residual emissions[5]

NOTE: 1. Net impact from use of these carbon sources can be limited; however, this is dependent on accounting for total life-cycle emissions. 2. Includes incineration + CCS for solid carbon. 3. Outcomes for landfill depend on the quality and durability of the landfill. Durable storage that prevents re-release of CO_2 over timescales of 100 years+ can lead to carbon removals for atmospheric/ocean and bioresource carbon, while non-durable storage would see the same carbon re-released to the atmosphere over shorter timescales. 4. Non-durable biogenic storage may generate non-CO_2 greenhouse gases. 5. Results in some emissions due to upstream fossil production and carbon capture rates not being 100%.

SOURCE: Systemiq analysis for the ETC (2026).

Sourcing carbon, innovations and trade-offs

Innovations are improving the cost and effectiveness of how carbon is sourced whether from fossil sources coupled with point-source capture technologies and permanent storage, direct air capture (DAC), ocean-based capture, or from sustainable biomass.

Fossil and limestone

Industrial point-source capture paired with permanent geological storage can make targeted fossil-based carbon use more compatible with net-zero, with capture rates now reaching around 90–95% in advanced and well-designed systems. However, it comes with significant considerations around capture performance, storage integrity and residual emissions. Most capture approaches today rely on solvent-based absorption, while emerging options such as calcium looping for high-temperature industries and process-integrated cycles like the Allam-Fetvedt configuration are improving capture in specific applications. Scaling these pathways remains constrained by high first-of-a-kind costs, retrofit complexity, and the need for large-scale CO_2 transport and storage networks to ensure permanent management of captured CO_2.

More broadly, there is a fundamental trade-off between pursuing a deeply transformed net-zero system built on electrification, circularity and sustainable carbon sources versus maintaining a largely linear fossil-based system abated by CCS and carbon removals. The former requires greater upfront structural change and system redesign, while the latter limits disruption but depends heavily on the large-scale, reliable deployment of capture, transport and permanent storage infrastructure. Achieving net-zero alignment under a fossil-plus-CCS pathway would require consistently high capture rates, near-zero leakage, long-term liability and clarity and rapid build-out of CO_2 networks. Even then, durable carbon removals would still be needed to balance residual emissions that cannot be fully captured.

Direct air and ocean capture

Alternatives sources to fossil-based carbon paired with point-source capture include atmospheric carbon capture approaches such as direct air capture (DAC) and emerging ocean-based carbon dioxide removal (O-CDR). Ocean-based approaches similarly target CO_2 that originates from the atmosphere, as dissolved carbon in seawater is in continuous exchange with atmospheric CO_2. If durably stored, atmospheric carbon can deliver negative emissions; if re-released, it does not increase atmospheric CO_2 provided the removal process and subsequent use are powered without additional fossil emissions. These technologies can serve a dual role: as sources of carbon molecules for fuels and materials when CO_2 is used, or as carbon dioxide removal (CDR) pathways when paired with permanent storage. Unlike point-source capture, which prevents new emissions from entering the atmosphere, DAC and O-CDR directly reduce atmospheric CO_2 concentrations when used with storage.

While theoretically highly scalable, DAC remains costly, with expected cost reductions and learning rates yet to materialise at pace. DAC removes CO_2 from ambient air using engineered sorbents or solvents, creating a scalable pathway for carbon sourcing and removals independent of industrial point sources. Technology progress is improving capture materials, system integration and modular plant design, increasing operational feasibility beyond early pilots. Recent commercial and pilot project experience suggests DAC costs are likely to remain higher for longer than previously expected, with current costs around ~\$800–1000/tCO_2 and 2030 estimates now closer to ~\$480/tCO_2. High energy intensity remains a barrier to scaling, in addition to high capital costs, and uncertain long-term revenue frameworks.

Critically, in a transition where clean electricity and renewable hydrogen are likely to remain constrained for the medium term, deploying large volumes of DAC also carries an opportunity cost. Scarce zero-carbon energy may deliver greater near-term abatement when directed toward electrification and demand reduction rather than extracting CO_2 from ambient air. This reinforces the importance of optimising the use of existing carbon already available today through electrification, circularity and efficiency measures before relying on energy-intensive atmospheric removal pathways.

Ocean-based carbon capture is an emerging complement to DAC, with the potential to co-produce clean hydrogen as a by-product and thereby improve cost of production by ~60%. However, these approaches remain at an early stage of development and deployment. Ocean-based capture removes CO_2 indirectly by extracting it from seawater or shifting ocean chemistry so that the ocean draws additional CO_2 from the atmosphere. The approach is gaining interest as a potential complement to DAC because of high concentrations of dissolved carbon in seawater. However, it remains at an earlier stage of development, with limited operational experience today and barriers such as cost uncertainty, environmental impacts and unresolved governance and monitoring challenges still to be addressed, meaning it is unlikely to make a material impact before the 2030s.

Biogenic carbon

Biogenic carbon is a potentially low-emission carbon source because it originates from the active carbon cycle rather than fossil stocks. However, its climate benefit depends on sustained regrowth and full lifecycle accounting, and its availability is inherently constrained by land, ecosystems, and competing uses. If durably stored, biogenic carbon can deliver negative emissions; if re-released, it does not increase atmospheric CO_2 provided biomass regrows and lifecycle emissions are accounted for.

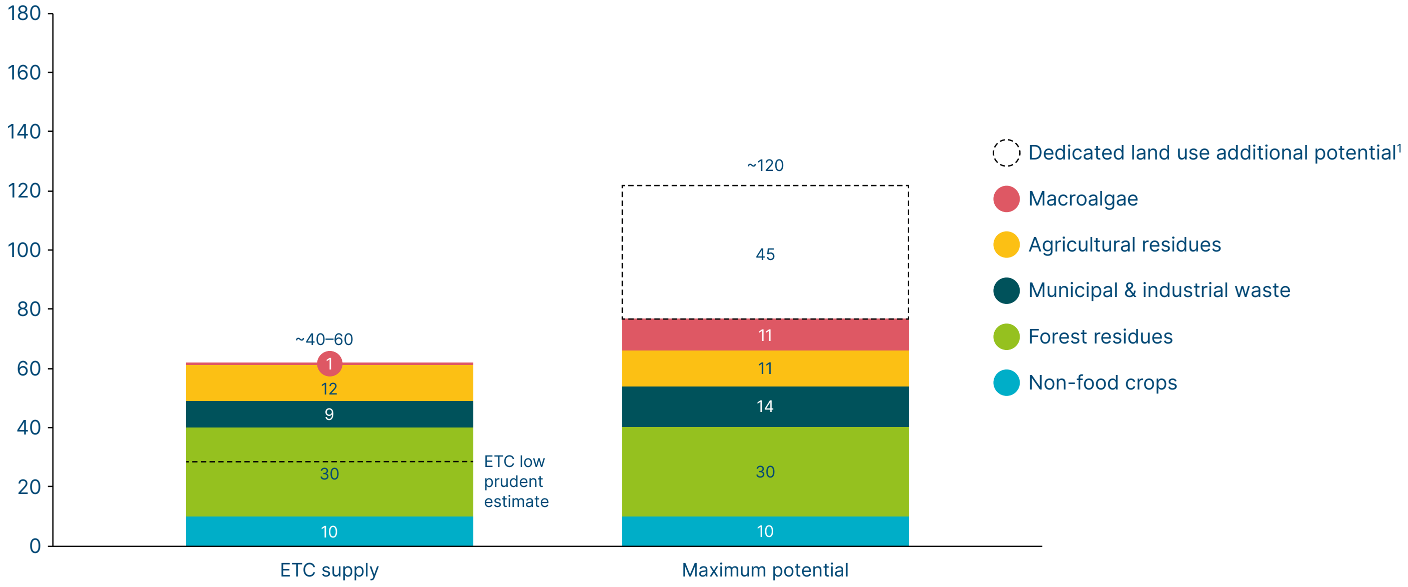
Given the lack of readily available, affordable, and renewable carbon sources, biogenic carbon sources are confronted by an intense over-demand versus available supply. To reconcile this disconnect to some degree, scaling biogenic carbon sustainably could be achieved through a portfolio of carefully scaled efficiency improvements and new sourcing technologies. These include i) reduced land demand via alternative proteins and dietary shifts, ii) improved biomass conversion catalysts, iii) higher-yielding energy crops, and iv) emerging new sources such as macroalgae. However, land availability remains the binding constraint, meaning any expansion must be carefully governed to avoid compromising food security and biodiversity.

Shifting diets and scaling alternative proteins offers one of the largest opportunities to reduce land demand and free up sustainable biomass supply. The ETC has previously estimated sustainable biomass prudent supply to be 40-60EJ (Exhibit 2). A high scenario of 120EJ might be possible with additional dedicated land, driven by dietary shifts, agricultural productivity and reduced food waste. Dietary shifts are key in this estimate, and technologies like plant-based and fermentation-derived proteins are becoming more cost-competitive and gaining market share across multiple regions. However, uptake will depend on consumer acceptance, affordability, supportive policy, and broader food-system transitions.

Exhibit 2

Additional dedicated land-use potential is expected to be driven by agricultural productivity improvements and dietary changes, enabled by alternative protein technologies

Biomass supply potential
EJ primary biomass



NOTE: 1) Significantly higher levels of biomass supply from dedicated land would only be possible if land is freed up from agricultural production through system shifts including major dietary changes, agricultural productivity improvements, and reductions in food loss and waste. These could be enabled by breakthrough biotechnologies.

SOURCES: Systemiq Analysis (2025), ETC analysis; ETC (2021), *Bioresources Within a Net-Zero Emissions Economy: Making a Sustainable Approach Possible.*

Given that land availability is a constraint upon production, improving the efficiency of biomass conversion is a critical lever for scaling biogenic carbon within sustainable limits. Advances in catalysts are increasing yields from existing feedstocks and enabling higher-value outputs such as sustainable aviation fuels and chemical intermediates. For example, catalyst and reactor innovations across key bio sustainable aviation fuels could reduce the primary biomass required by 30%. However, these gains depend on continued innovation and investment, the deployment of first-of-a-kind facilities, and the ability to manage feedstock variability and capital intensity.

New higher-yield energy crops, such as energy cane, could represent a significant opportunity to expand biomass supply by increasing output per hectare or increasing productive land use on degraded land or freed-up land. However dedicated energy crop scale-up carries substantial land-use risks must be undertaken with strong safeguards and proof-points on net-environmental gains. Advances in crop genetics, agronomic practices and region-specific varieties are improving yields and resilience, increasing the theoretical supply potential from suitable areas. However, without strict governance, certification standards and monitoring to prevent indirect land-use change and biodiversity loss, expanded deployment could undermine net climate and ecological outcomes. Additionally, while there is broader alignment on degraded land estimates globally (1,500-2,000 Mha), there is less so on degraded land suitable for energy crops, with estimates ranging from less than 100 to over 1,000 Mha. The reality will be highly region-specific, depending on local soil and climatic conditions and the extent of land degradation, including whether food crops are truly no longer feasible.

Novel biomass sources such as macro- and micro-algae could expand biogenic carbon supply without directly competing for cropland. Progress in cultivation systems, strain development and downstream processing is improving productivity and product yields. However, high costs, processing complexity and the need for scalable infrastructure mean these pathways remain longer-term options.

In a scenario that minimises fossil carbon use across the materials and energy system, biomass could supply approximately 65% of total carbon demand (equivalent to 2.5 Gt of Carbon), and remain within the estimated upper supply limit of around 120 EJ of sustainable biomass. However, achieving this level of deployment would depend critically on expanding the availability of dedicated land for biomass, enabled for example, by the uptake of alternative proteins that reduce pressure on agricultural land, and on scaling novel biomass sources such as algae. At the same time, strong guardrails on land governance, certification, and social acceptance would be essential. Under these conditions, biomass could underpin a transition pathway in which large-scale carbon storage is infeasible or prohibitively costly.

Two innovations for managing carbon at end-of-life

If not recycled, continued use of fossil carbon requires end-of-life capture and permanent storage to avoid adding new CO_2 to the atmosphere. By contrast, biogenic and atmospheric (including ocean-derived) carbon originate from the active carbon cycle. When durably stored, they can deliver net removals. If instead they are released without capture, they do not increase atmospheric CO_2 in the same way as fossil carbon, provided biomass regrows and lifecycle emissions, including energy inputs, are controlled.

Today the major options for storage of carbon at end of life are geological storage of CO_2 in saline aquifers or depleted oil and gas fields, and landfill or incineration for solid carbon in materials. However, two emerging technologies offer complementary options that allow for safer and more diversified storage.

Mineralisation

Conventional geological storage in saline aquifers and depleted oil and gas fields remains the primary end-of-life pathway for CO_2, with estimated capacity of around 51,000 $GtCO_2$. The bottleneck for storage is not a volume constraint, but a scaling rate constraint. As operational experience, monitoring and regulation improve, confidence in storage performance is rising; the central challenge is shifting from whether storage can work to whether it can scale fast enough, given injection-rate constraints, long-term liability and the need for shared CO_2 transport-and-storage networks.

Mineralisation offers a potential alternative end-of-life pathway for CO_2, providing enhanced permanence and additional capacity by converting injected CO_2 into stable solid carbonates in reactive basaltic or ultramafic rocks. Advances in in-situ approaches and early pilots are improving feasibility, but it remains at lower maturity than conventional geological storage. The storage potential of mineralisation adds to what is already available, with pathway specific capacities ranging from 100,000 Gt to 600,000 $GtCO_2$. Achievable scale depends on suitable geology, material availability and deployment progress this decade. Suitable geology is uneven and often far from major CO_2 sources, infrastructure and regulation are less mature than for sedimentary storage and costs are still higher (with onland basalt estimated ~50% above conventional onshore sedimentary storage today).

Advanced landfill

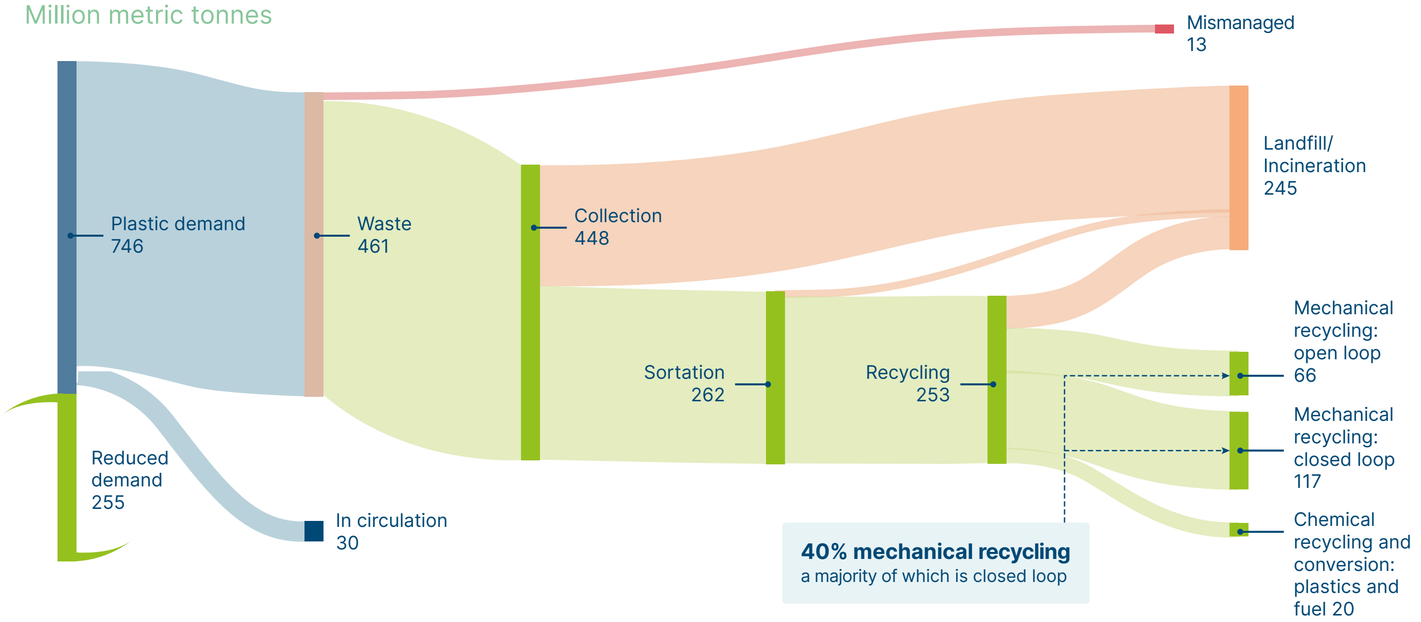
For solid carbon waste, advanced landfill combines waste pre-treatment, engineered containment and methane capture to minimise emissions from unavoidable residual disposal. It is lower cost and effective compared to other linear abatement options, like incineration with CCS, but must be rigorously executed and not used as an incentive to avoid circularity. End-of-life choices are strongly shaped by geography and policy, with measures such as the EU Landfill Directive shifting waste flows toward thermal treatment and increasing demand for abated disposal options. Incineration with CCS is emerging but remains at pilot stage, with projects beginning to test CO_2 capture from waste streams, but not yet delivering widespread commercial deployment. Landfill continues to carry social and environmental trade-offs, including land-use conflicts and long-term stewardship obligations, but remain structurally embedded in the waste system. Even with stronger circularity, ~40% of global plastic waste could still go to landfill by 2040 (Exhibit 3), meaning advanced landfill is a significant "backstop" pathway for large residual volumes. Potential constraints to scaling advanced landfill include uneven global standards, risk of methane leakage without strict enforcement, and the need to avoid disincentives for circular pathways.

Exhibit 3

Even in the most optimistic scenario with circular economy solutions, nearly 40% of all global plastic waste is expected to go to landfills by 2040

Fate of global plastic waste, 2040

Million metric tonnes



40% mechanical recycling
a majority of which is closed loop

SOURCE: Systemiq (2024), Plastic Treaty Futures, Global rules scenario

Implications and actions: moving from carbon sources to accountable carbon systems

Even in the most optimistic transition, primary carbon still flows through the system in 2050, meaning sustainable sourcing and credible end-of-life management become defining system conditions. Delivering this requires coordinated system shifts to optimise remaining fossil use to be aligned with net-zero, scale biomass supply and support other forms of sustainable carbon sourcing.

If fossil carbon continues to be used, it must be optimised selectively and governed with strict performance and integrity requirements. Ensuring residual fossil carbon is aligned with net-zero outcomes requires coordinated demand, infrastructure and monitoring and verification. Without predictable demand signals, investment in CO_2 storage falls short of what is needed, while long-term monitoring and liability obligations create uncertainty that slows deployment. CO_2 transport and storage networks are unlikely to emerge organically, given high early costs, fragmented volumes and unclear responsibility, which is why continued reliance on fossil carbon remains problematic without strong systems to ensure permanence and accountability.

Efficiency gains are critical to expand the supply of genuinely low-carbon biogenic carbon without increasing land pressure or ecological trade-offs. Scaling alternative proteins and improved conversion catalysts are promising measures with relatively limited sustainability downsides, but they require a shift from R&D-led innovation to deployment-led scale-up, supported by clear regulatory pathways, demand signals, and investment in large-scale production and processing capacity. In both cases, coordinated action is needed to de-risk first commercial deployments, integrate new technologies into existing systems, and accelerate cost reduction through learning-by-doing.

Scaling energy crops and aquatic biomass will require more than selectivity on land type; it depends on proving commercially viable models that operate within robust sustainability and monitoring frameworks. Expansion of terrestrial energy crops should be limited to marginal or genuinely freed-up land, but determining where this is genuinely the case requires region-specific land-use assessment and clarity on how freed land is allocated between biodiversity restoration, managed forestry and biomass production. Aquatic biomass pathways, including macro- and microalgae, may reduce direct competition for cropland, but are not impact-free: large-scale cultivation will require environmental safeguards, monitoring of indirect land-use effects from feed substitution, and continued cost and infrastructure scale-up to demonstrate viability. Strong governance is therefore necessary not only to manage trade-offs, but to ensure that any expansion of biomass supply delivers net climate and ecological value. Demonstrating that these models work at pilot and regional scale is a prerequisite before broader deployment.

Scaling direct air and ocean-based carbon capture will require supportive demand and market frameworks to enable deployment at scale, allowing these technologies to serve as a high-integrity backstop both for carbon sourcing and for durable removals when paired with permanent storage. If fossil carbon continues to be used, durable removals become unavoidable to balance residual emissions; similarly, achieving net-negative emissions requires technologies capable of drawing CO_2 directly from the atmosphere. Direct air capture remains among the most energy- and cost-intensive options today, while ocean-based approaches are earlier-stage with significant uncertainty around costs, scalability and environmental governance. Their role is therefore likely to be limited in the near term, but could grow over time as reliance on fossil-based inputs is minimised and scarce biogenic sources drive higher market prices. If longevity and accounting robustness are appropriately valued, synthetic capture could become increasingly competitive, particularly with policy support and continued cost reductions through technological learning. Table 1 details the system shifts and key actions from stakeholders.

Table 1: Who needs to do what?

System shift / key action priority	Governments & public finance	Infrastructure planners & regulators	Industry & project developers
Create demand for storage, infrastructure and integrity for residual fossil system	**Use carbon pricing, performance standards and procurement** to ensure capture and storage is applied, especially where it is more likely needed, e.g., chemical industry legacy production, cement **Set clear long-term liability rules and establish centralised authorities** to monitor storage integrity and oversee stewardship over decades	**Set detailed monitoring, reporting and verification rules** to ensure storage performance and manage leakage risk over time **Establish government infrastructure coordination entities** to de-risk and oversee large-scale CO_2 transport and storage networks	**Commit to storage-backed value chains** through long-term contracts and hub participation where policy support and disposal infrastructure make projects bankable **Form partnerships to share capital risk** and accelerate learning across early capture-and-storage projects
Scale alternative proteins and more efficient biomass conversion for more sustainable biomass availability	**Streamline novel-food approval processes** and use public procurement, dietary guidelines and fiscal measures to support alternative protein adoption	**Streamline permitting and infrastructure access** (power, water, waste handling) for fermentation and biomass processing hubs	**Invest in scaling production platforms** where there is clear market pull from retailers and food service **Integrate improved biomass conversion technologies** and catalysts into existing assets to increase output from available feedstocks
Investigate trade-offs and ensure safeguards for sustainable biomass expansion	**Build land-suitability and certification frameworks for biomass expansion,** with monitoring, biodiversity net-gain targets, and incentive-and-penalty mechanisms to prevent harm to food systems and ecosystems **Establish clear regional biomass expansion pathways** that define how freed land and suitable aquatic zones are allocated between restoration, food production and energy crops before scaling	**Monitor indirect land-use impacts and enforce certification frameworks** that protect ecosystems and community acceptance **Align regional land and marine planning** with biodiversity and food security priorities, enabling required infrastructure development	**Partner with producers and regulators** to pilot and prove replicable biomass sourcing models, supported by staged financing that enables scale-out from first projects to commercial deployment
Create demand and support cost reductions in early-stage direct air and ocean-based carbon capture	**Create early, bankable demand for DAC and ocean-based capture** through advance purchase commitments, procurement of durable removals, and contracts-for-difference that reward verified cost reductions over time **Establish integrity and accounting rules that certify and valorise durable removals, and link demand to compliance obligations** (e.g., fossil producers addressing residual lifecycle emissions) so early markets are investable and scalable	**Enable transport, use and storage frameworks** that recognise and govern sourcing and durable removals of DAC and ocean based capture at scale	**Advance pilots and modular scale-up** where long-term demand provides a viable route to replication

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This summary should be cited as: ETC and Systemiq (2026), *Residual Carbon in Net Zero: Sources and End of Life Pathways*

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