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

November 2025 | Version 1.0

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Energy Transitions Commission

SYSTEMIQ

The Energy Transitions Commission (ETC) is a global coalition of leaders from across the energy landscape committed to achieving net-zero emissions by mid-century, in line with the Paris climate objective of limiting global warming to well below 2°C and ideally to 1.5°C.

This report was developed by ETC and Systemiq. Systemiq is a system-change B-Corp certified company founded in 2016 to transform markets and business models in five key systems: nature and food, materials and circularity, energy, urban areas, and sustainable finance. Systemiq combines strategic advisory with high-impact, on-the-ground work, and partners with business, finance, policymakers and civil society to deliver system change.

The ETC Commissioners come from a range of organisations – energy producers, energy-intensive industries, technology providers, finance players and environmental NGOs – that operate across developed and developing countries and play different roles in the energy transition. This diversity of viewpoints informs this work: our analyses are developed with a systems perspective through extensive exchanges with experts and practitioners. The ETC is chaired by Lord Adair Turner who works with the ETC team.

The ETC Commissioners not only agree on the importance of reaching net-zero carbon emissions from the energy and industrial systems by mid-century but also share a broad vision of how the transition can be achieved. The fact that this agreement is possible between leaders from companies and organisations with different perspectives on and interests in the energy system should give decision-makers across the world confidence that it is possible simultaneously to grow the global economy and to limit global warming to well below 2°C. Many of the key actions to achieve these goals are clear and can be pursued without delay.

The ETC's and Systemiq's report *Carbon in an Electrified Future: Technologies, Trade-offs and Pathways* analyses how carbon can be reduced, used, sourced and disposed of at end-of-life in a net-zero global economy. It focuses on the role of electrification, hydrogen, circularity, carbon sourcing and management technologies, including the key system trade-offs and scenarios illustrating their impact.

This report was developed in consultation with ETC Members, but it should not be taken as members agreeing with every finding or recommendation. The ETC team would like to thank the ETC members, member experts and the ETC's broader network of external contributors for their active participation in developing this work, and Systemiq for its analytical and coordination support. This work has been made possible through the generous support of the Quadrature Climate Foundation.

This report should be cited as: ETC and Systemiq (2025), *Carbon in an electrified future: Technologies, trade-offs and pathways*.

Energy Transitions Commission

SYSTEMIQ

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Major ETC reports and working papers

To download all ETC reports, papers, explainers and factsheets visit www.energy-transitions.org

Global Reports

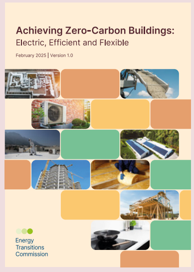
Mission Possible (2018) outlines pathways to reach net-zero emissions from the harder-to-abate sectors in heavy industry (cement, steel, plastics) and heavy-duty transport (trucking, shipping, aviation).

Making Mission Possible (2020) shows that a net-zero global economy is technically and economically possible by mid-century and will require a profound transformation of the global energy system.

Making Mission Possible Series (2021-2022) outlines how to scale up clean energy provision to achieve a net-zero emissions economy by mid-century.

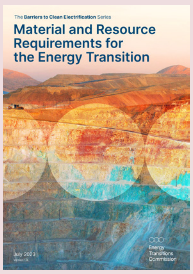
Barriers to Clean Electrification Series (2022-2025) recommends actions to overcome key obstacles to clean electrification scale-up, including planning and permitting, supply chains and power grids.

Financing the Transition (2023–2024) quantifies the finance needed to achieve a net-zero global economy and identifies policies needed to unleash investment on the scale required.

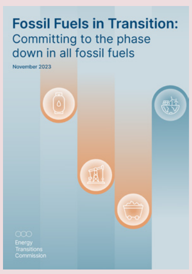


Achieving Zero-Carbon Buildings (2025) draws a complete picture of the buildings sector's emissions and energy use and describes how a combination of electric, efficient, and flexible solutions can decarbonise buildings, improve standards of living, and reduce energy bills if supported by ambitious policy.

COP-focused



Material and Resource Requirements for the Energy Transition (2023) dives into the natural resources and materials required to meet the needs of the transition by mid-century, and recommends actions to expand supply rapidly and sustainably.



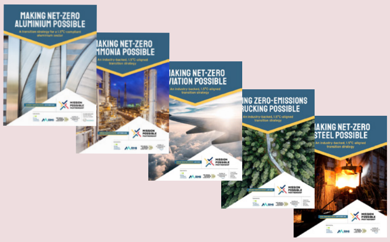
Fossil Fuels in Transition (2023) describes the technically and economically feasible phase-down of coal, oil and gas that is required to limit global warming to well below 2°C as outlined in the Paris Agreement.

Nationally Determined Contributions (2024) calls for industry and government collaboration to raise ambition in the next round of Nationally Determined Contributions by COP30 to limit the impact of climate change.

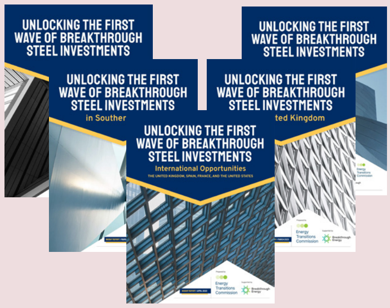
Sectoral and cross-sectoral focuses

Sectoral focuses provided detailed decarbonisation analyses on six of the harder-to-abate sectors after the publication of the **Mission Possible** report (2019).

As a core partner of the MPP, the ETC also completes analysis to support a range of sectorial decarbonisation initiatives:

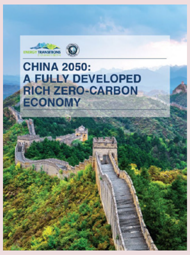


MPP Sector Transition Strategies (2022-2023) a series of reports that guide the decarbonisation of seven of the hardest-to-abate sectors. Of these, four are from the materials industries: aluminium, chemicals, concrete, and steel, and three are from the mobility and transport sectors – aviation, shipping, and trucking.



Unlocking the First Wave of Breakthrough Steel Investments (2023) This ETC series of reports looks at how to scale up near-zero emissions primary (ore-based) steelmaking this decade within specific regional contexts: the UK, Southern Europe, France and USA.

Regional Focus



China 2050: A Fully Developed Rich Zero-carbon Economy (2019) Analyses China's energy sources, technologies and policy interventions required to reach net-zero carbon emissions by 2050.

A series of reports on the Indian power system, outlining decarbonisation roadmaps for India's electricity supply and heavy industry.

Canada's Building Heating Decarbonization - Jurisdictional Scan (2024) provides an in-depth look at how governments across Canada and the globe are using policy to transition building heating away from fossil fuels.

Setting up industrial regions for net zero (2021-2023) explore the state of play in Australia, and identifies opportunities for transitioning to net-zero emissions in five hard-to-abate supply chains.

Pathways to Net-Zero for the US Energy Transition (2022-2023) examines the trendlines, challenges, and opportunities for meeting the US net-zero objective.

A Path Across the Rift (2023) reviews an analysis of African energy transitions and pinpoints critical questions we need to answer to foster science-based policymaking to enable decisions informed by clear and objective country-specific analysis.

Glossary

Accelerated but Feasible (ACF): A decarbonisation scenario defined by the ETC that assumes rapid but technically and economically feasible action to achieve net-zero emissions.

Advanced sortation: Automated waste sorting using sensors, AI and robotics to improve accuracy and increase recycling rates.

Allam-Fetvedt Cycle (AFC): A high-efficiency, low-emission power cycle that uses supercritical CO_2 as the working fluid and inherently captures CO_2 for storage or utilisation.

Alternative proteins: Non-animal protein sources such as cultured meat, fermentation-based, or plant-derived products that can reduce land use and emissions.

Autothermal Reforming (ATR): A hydrogen production process that combines partial oxidation and steam reforming in a single reactor using oxygen and steam to convert natural gas into hydrogen-rich synthesis gas, well suited to integration with CO_2 capture.

Alcohol-to-Jet (AtJ): A biofuel pathway converting ethanol or other alcohols into synthetic jet fuel via catalytic processes.

Bioenergy with Carbon Capture and Storage (BECCS): Generation of energy from biomass with subsequent capture and permanent storage of the resulting CO_2.

Bioresources: Renewable carbon sources derived from biological material such as crops, residues, or algae, used to replace fossil carbon inputs.

Calcium Looping (CaL): A carbon capture process using calcium oxide (CaO) to absorb CO_2 from flue gases and regenerate calcium carbonate ($CaCO_3$), enabling repeated capture cycles.

Capital Expenditure (CAPEX): The upfront cost of constructing or installing a piece of infrastructure or equipment.

Carbon capture and utilisation or carbon capture and storage (CCU or CCS or CCUS): The term "carbon capture" refers to the process of capturing CO_2 on the back of energy and industrial processes. Unless specified otherwise, we do not include direct air capture (DAC) when using this term. The term Carbon Capture and Storage refers to the combination of carbon capture with underground carbon storage while Carbon Capture and Use refers to the use of carbon in carbon-based products in which CO_2 is sequestered over the long term (e.g., in concrete, aggregates, carbon fibre). Carbon-based products that only delay emissions in the short-term (e.g., synfuels) are excluded when using this terminology.

Carbon emissions/CO_2 emissions: We use these terms interchangeably to describe anthropogenic emissions of carbon dioxide in the atmosphere.

Contract for Difference (CfD): A government policy instrument that guarantees a fixed price for electricity generation, paying the difference if market prices fall below that level.

Chemical recycling: Conversion of plastic waste into chemical feedstocks or fuels through processes such as pyrolysis or gasification, restoring material value.

Clean electrification: The substitution of electricity for fossil fuels in end-uses such as transport, buildings, and industry, combined with the decarbonisation of electricity generation.

CO_2 mineralisation (in situ): Permanent carbon storage by injecting CO_2 into suitable rock formations where it reacts to form solid carbonates.

Direct Air Capture (DAC): DAC technologies extract CO_2 directly from the atmosphere at any location, unlike carbon capture which is generally carried out at the point of emissions, such as a steel plant. The CO_2 can be permanently stored in deep geological formations or used for a variety of applications.

Direct Air Carbon Capture and Storage (DACCS): A carbon dioxide removal technology building on DAC, in which CO_2 captured directly from the atmosphere is permanently stored in geological formations rather than reused.

Demand reduction: Strategies to reduce the need for primary carbon by eliminating unnecessary use, reusing materials, or substituting with lower-carbon alternatives.

E-cracking: Electrified steam-cracking process in petrochemical production that replaces fossil-fuel heat with renewable electricity.

E-fuels: Synthetic fuels such as e-methane, e-methanol or e-kerosene produced from green hydrogen and captured CO_2, used in sectors hard to electrify.

Electrowinning: Electrochemical process extracting metals such as iron or copper using electricity instead of carbon-based reduction agents.

Engineering, Procurement and Construction (EPC): A common project delivery model in infrastructure whereby one contractor delivers all aspects of design, procurement and construction. This report discusses EPC in terms of costs and how that contributes to total storage costs.

Extended Producer Responsibility (EPR): Policy approach requiring producers to manage the environmental impact of their products, including end-of-life collection and recycling.

Emissions Trading System (ETS): Market mechanism that caps total emissions and allows trading of allowances between emitters to reduce costs.

Geological hydrogen: Naturally occurring hydrogen extracted from subsurface formations; a potential low-carbon energy source at early development stage.

Greenhouse gases (GHGs): Gases that trap heat in the atmosphere. Global GHG emission contributions by gas include CO_2 (76%), methane (16%), nitrous oxide (6%) and fluorinated gases (2%).

Green hydrogen: Refers to fuels produced using electricity from low-carbon sources (i.e. variable renewables such as wind and solar).

Hydroprocessed Esters and Fatty Acids (HEFA): A biofuel production pathway converting waste oils and fats into sustainable aviation fuel or diesel through hydrogenation.

High-temperature electrification: Replacement of fossil fuels with electric technologies such as resistive or plasma heating for industrial high-temperature processes.

Indirect use of fossil fuels: The use of fossil fuels to generate electricity.

Levelised Cost of Abatement (LCOA): Average cost per tonne of CO_2 avoided over the lifetime of a mitigation technology.

Levelised Cost of Electricity (LCOE): Average lifetime cost per unit of electricity generated, including capital and operating costs.

Levelised Cost of Production (LCOP): Average lifetime cost per unit of output for fuels or materials, incorporating capital and operational expenses.

Molten Oxide Electrolysis (MOE): Electrochemical process producing iron and oxygen from metal oxides using renewable electricity, eliminating carbon emissions.

Ocean-based Carbon Dioxide Removal (o-CDR): A group of approaches that enhance or directly harness the ocean's capacity to remove and store CO_2, including ocean alkalinity enhancement, biomass sinking, and direct ocean capture.

Operational Expenditures (OPEX): Ongoing costs associated with the operation and maintenance of an asset or system.

Possible but Stretching (PBS): A decarbonisation scenario defined by the ETC assuming fast technological progress and broader deployment of low-carbon solutions.

Polyethylene Terephthalate (PET): A widely used thermoplastic polymer, commonly employed in packaging, textiles and bottles, and recyclable through mechanical or chemical processes.

Point-source capture: Capture of CO_2 from concentrated industrial or power-plant emissions before they reach the atmosphere.

Power-to-X: Broad term for converting electricity into other energy carriers or products (e.g., hydrogen, fuels).

Purchasing Power Agreement (PPA): A long-term contract between an electricity generator and a buyer, guaranteeing a price for the electricity produced.

Recycling (mechanical): Physical reprocessing of materials such as plastics into new products without altering their chemical composition.

Reverse Water–Gas Shift (RWGS): Chemical process converting CO_2 and hydrogen into CO, which can be used to synthesise fuels or chemicals.

Scope 2 emissions: Emissions that a company causes indirectly when the electricity it purchases and uses is produced. For example, emissions caused when generating the electricity used in the company's office buildings.

Solid carbon storage: Long-term containment of carbon-rich solids, such as mineralised carbon or durable plastic waste, to prevent re-emission.

Steam Methane Reforming (SMR): A hydrogen production process that reacts natural gas with steam at high temperatures to produce hydrogen and CO_2, often combined with carbon capture in low-carbon pathways.

Sortation (advanced): Use of automated systems, sensors and robotics to separate materials efficiently and increase recycling rates.

Technology Readiness Level (TRL): Standard scale (1–9) measuring how close a technology is to commercial deployment.

Unconstrained: A decarbonisation scenario defined by the ETC assuming maximum electrification and an unconstrained supply of clean power.

Contents

Introduction: the use of carbon in the current and future system

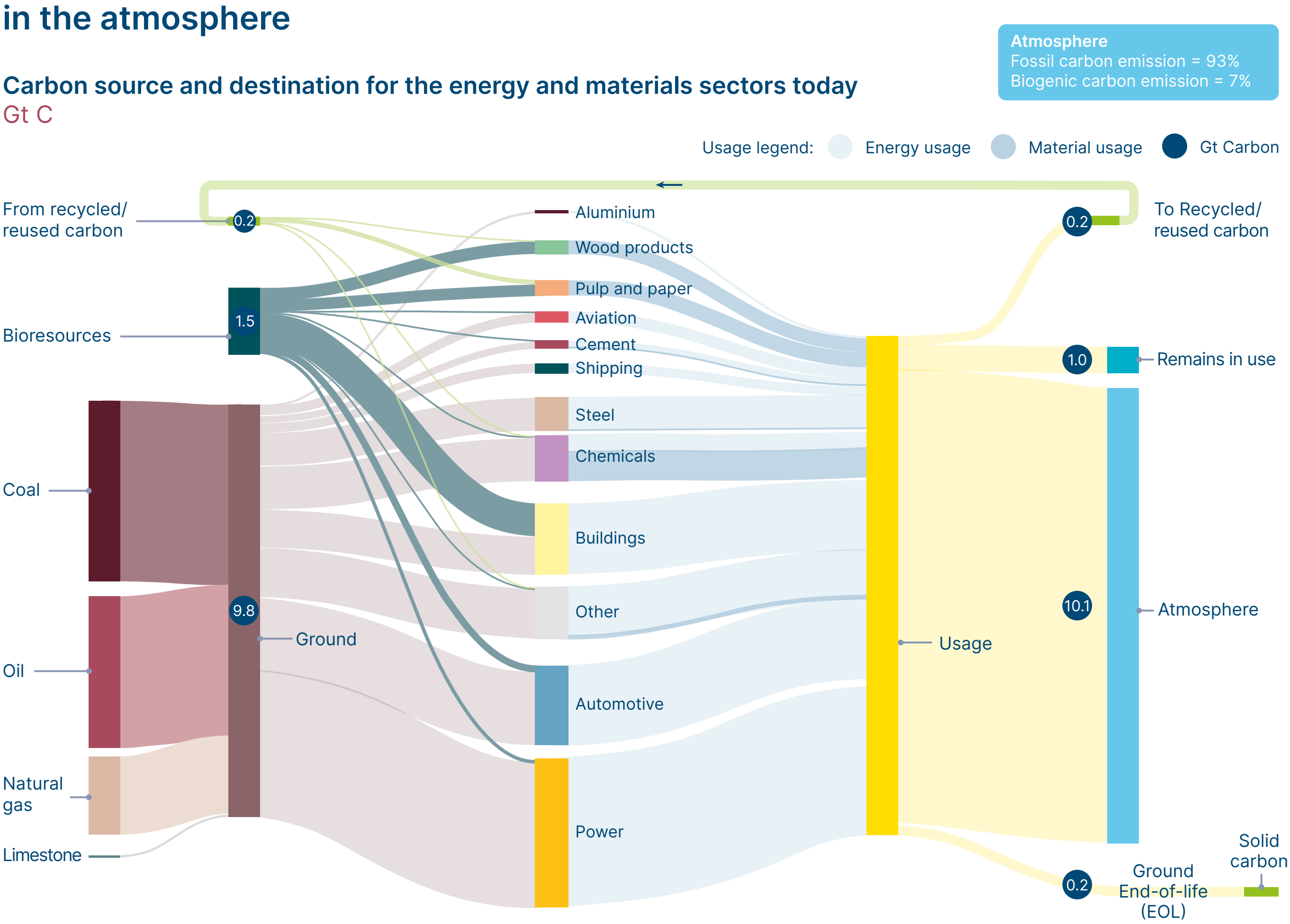
Carbon is one of the most common elements on the planet, a crucial building block of nature and a foundation of human biology, technology and economic activity. Over millions of years, carbon-based molecules derived from plant and animal life were transformed through heat and pressure into fossil fuels. These fuels enabled the Industrial Revolution and have powered dramatic increases in human living standards over the last 200 years. However, the impact of this carbon use upon the climate has not yet been sufficiently accounted for in the design of the global economy.

Human use of carbon-based molecules today in the energy and materials sectors amounts to around 11.5 Gt carbon per year. This excludes carbon flows that circulate naturally within biological systems such as food and agriculture. The vast majority, 9.8 Gt (85%), comes from fossil sources including coal, oil and gas. These are primarily used as fuels for electricity generation, transportation and heating, and as feedstocks for the production of chemicals and materials such as fertilisers and plastics respectively. This generates around 37.1Gt of CO_2 emissions each year. An additional 1.5 Gt of carbon (13%) is sourced from bioresources, while 0.2 Gt (<2%) is provided by recycled or reused carbon[1] [Exhibit 0.1] and [Table 1].

Exhibit 0.1

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



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

1 ETC (2023), *Fossil fuels in transition.*

Table 1: Current sourcing and end-of-life for carbon today

SOURCE			END-OF-LIFE		
Source type	Mt C	% share	End-of-life type	Mt C	% share
Recycled or reused	175	2	Recycled or reused	175	1
Bioresources	1,495	13	Atmosphere	10,115	88 (7% is biogenic)
Ground	9,795	85	Ground	190	2

At the end-of-life, the 0.2 Gt of recycled or reused carbon is joined by 1.0 Gt that remains in long-term use and 0.2 Gt that is stored in solid form.

These emissions are driving a relentless rise in the concentration of CO_2 in the atmosphere, leading to global warming that threatens severe harm to human welfare. To limit temperature increases to well below 2°C, and ideally to 1.5°C, it is essential to reduce CO_2 emissions to net-zero by mid-century.

Electrification and power sector decarbonisation will be the primary levers to achieve this emissions reduction and all major net-zero scenarios project a dramatic increase in electricity's share of final energy demand, reaching for example, 54% and 59% in the 1.5°C-aligned pathways published by the IEA and IRENA respectively [Exhibit 0.2]. Analysis by the ETC in the *Fossil Fuels in Transition* report suggested even higher levels, with electricity reaching 62% in the Accelerated but Feasible (ACF) scenario and 71% in the Possible but Stretching (PBS) scenario.

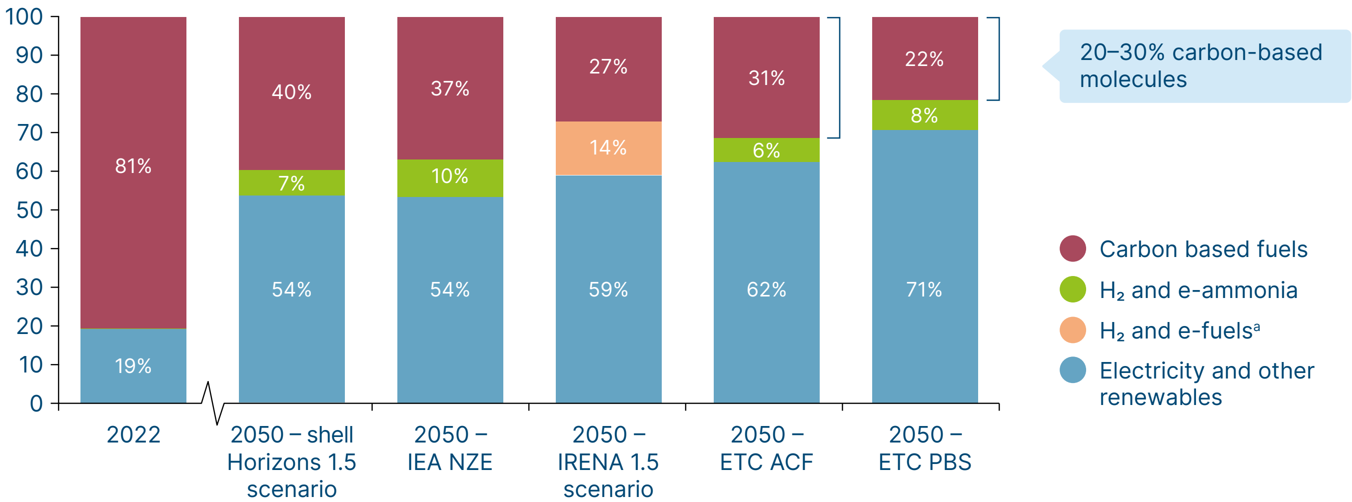
However, electricity cannot fully substitute for carbon-based fuels and feedstocks in all applications. In aviation and shipping, for instance, batteries will not be light enough to enable electric flight except over very short distances at least for several decades, and in plastics, carbon molecules are essential building blocks of the material whatever the energy source.

Hydrogen and its derivatives will therefore play a critical complementary role, filling the gaps where direct electrification is not technically or economically viable. Key sectors include high-temperature industrial processes, long-distance shipping and aviation, fertiliser production and seasonal energy storage within power systems.

Exhibit 0.2

Electrification dominates global final energy demand, but still relies 20–30% on carbon molecules

Global final energy demand by energy source and scenario
% 2050



NOTE: ACF = Accelerated but Clearly Feasible Scenario; PBS = Possible but Stretching Scenario; [a] IRENA combines e-fuels and direct use of H_2.

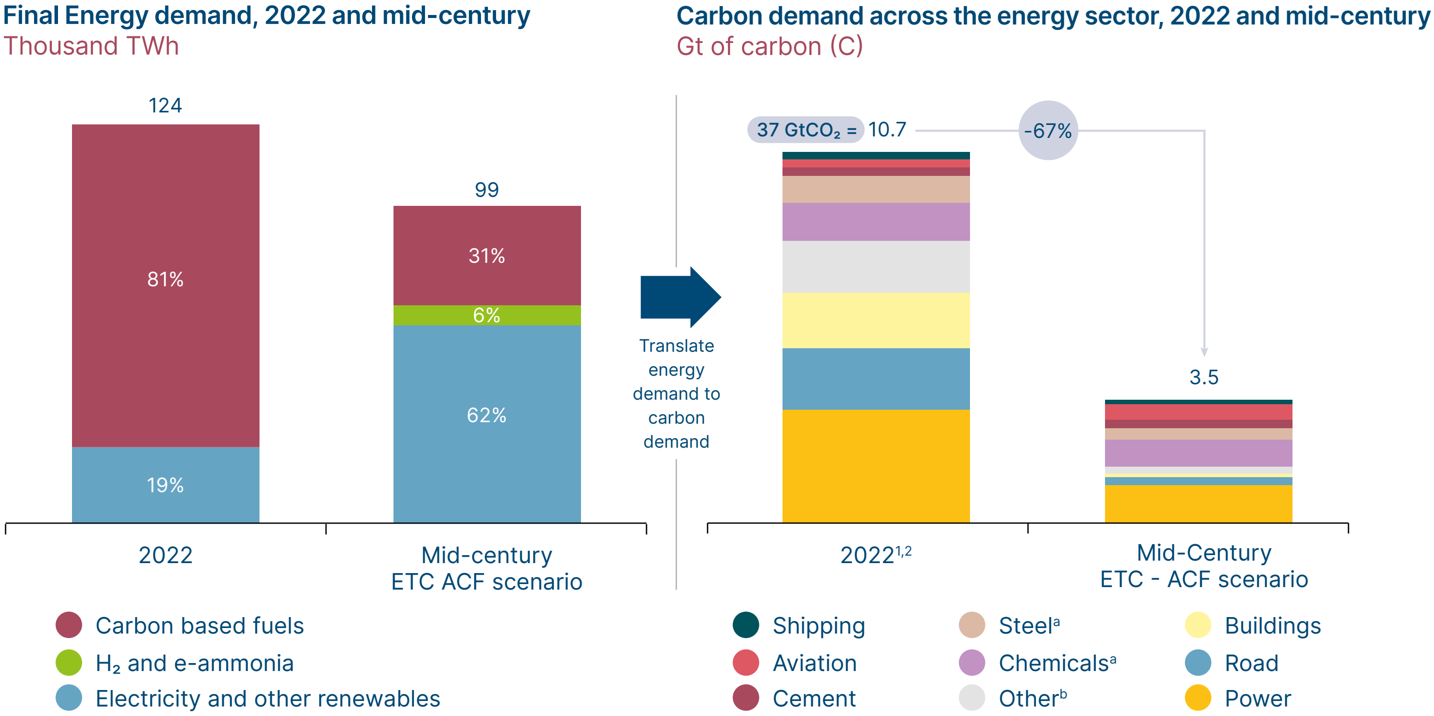
SOURCE: 2022, ACF and PBS scenarios from ETC (2023) *Fossil Fuels in Transition*; IEA NZE: IEA (2023) *World Energy Outlook 2023*; IEA NZE: IRENA (2024) *World Energy Transition Outlook*; Minor updates from ETC (2023), *Fossil Fuels in Transition*.

Building on the ETC's Fossil Fuels in Transition analysis, this report uses the ACF scenario as a reference point to explore the role of carbon molecules in a decarbonised energy system. In this scenario, 31% of total energy demand in 2050 is still expected to rely on the use of carbon molecules. In the more ambitious PBS scenario, this figure drops to 22%. As a result in the ACF scenario:

- Though total demand for carbon in the energy system is projected to decline by 68% by mid-century, this would still imply a need for 3.5 Gt of carbon input [Exhibit 0.3].
- Material demand for non-energy uses, excluding plastics (which are included in the energy analysis), could grow from 0.8 Gt to 1.2 Gt [Exhibit 0.4].

Exhibit 0.3

The need for carbon molecules in the global energy and materials sectors will decline by mid-century, but up to 4.7 Gt will still be required

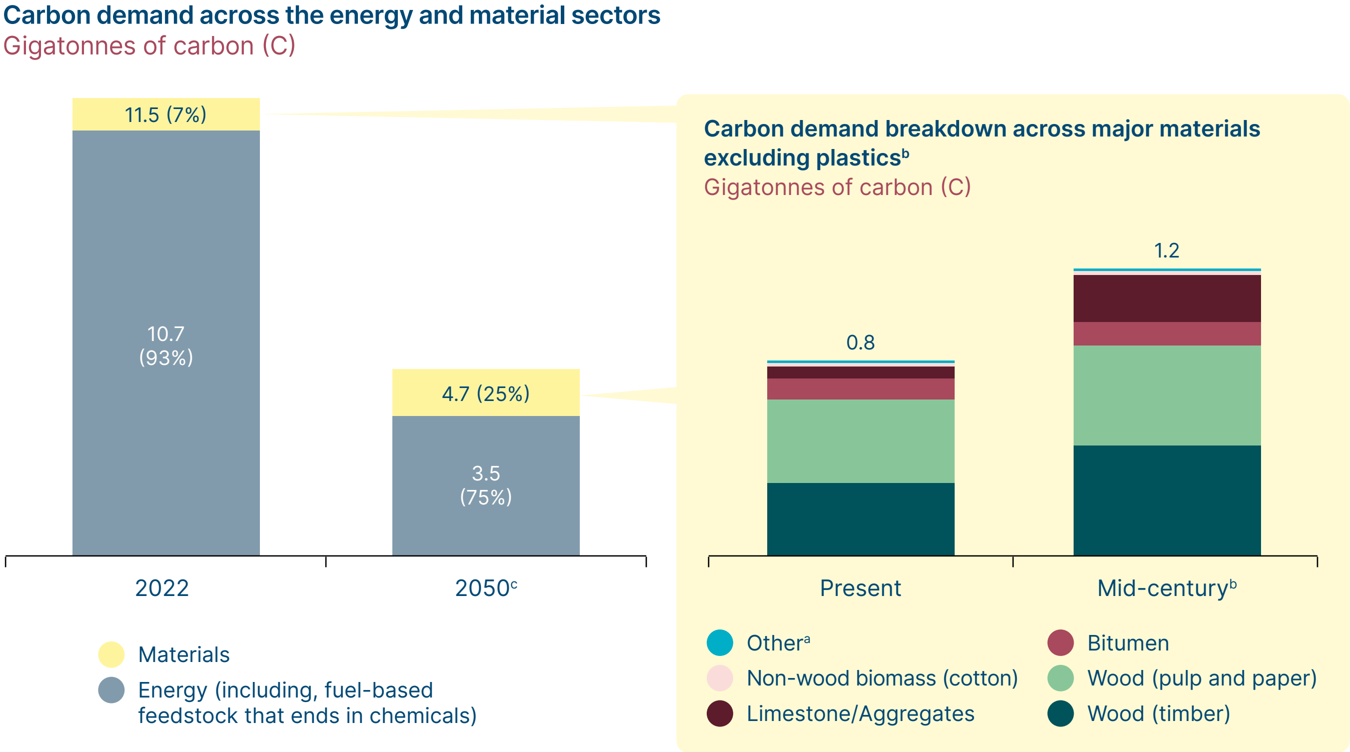


NOTE: Carbon-based fuels include those fuels that also require carbon sources, e.g,. e-methanol and synthetic aviation fuels; ACF = Accelerated but Clearly Feasible scenario, based on ETC (2023), *Fossil Fuels in Transition* with minor updates; [a]Includes energy-based carbon feedstocks (e,g,. oil, gas), a proportion of which end in the final products (e.g,. chemicals for plastics and steel), and others end in process emissions; [b]Includes remaining sectors, primarily other industry and other transport; [c]A majority made up of wood products for timer and pulp and paper.

SOURCE: 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).

Exhibit 0.4

Total carbon demand is dominated by the energy sector, but the materials sector could drive 25% of demand by mid-century



NOTE: [a] Includes carbon ash, biochar, carbon fibre and charcoal. [b] Energy-based carbon feedstocks (e,g,. oil, gas), a proportion of which end in the final products (e.g,. chemicals for plastics and steel) are included in the energy sector. [c] Assumes BAU growth, with limited circularity.

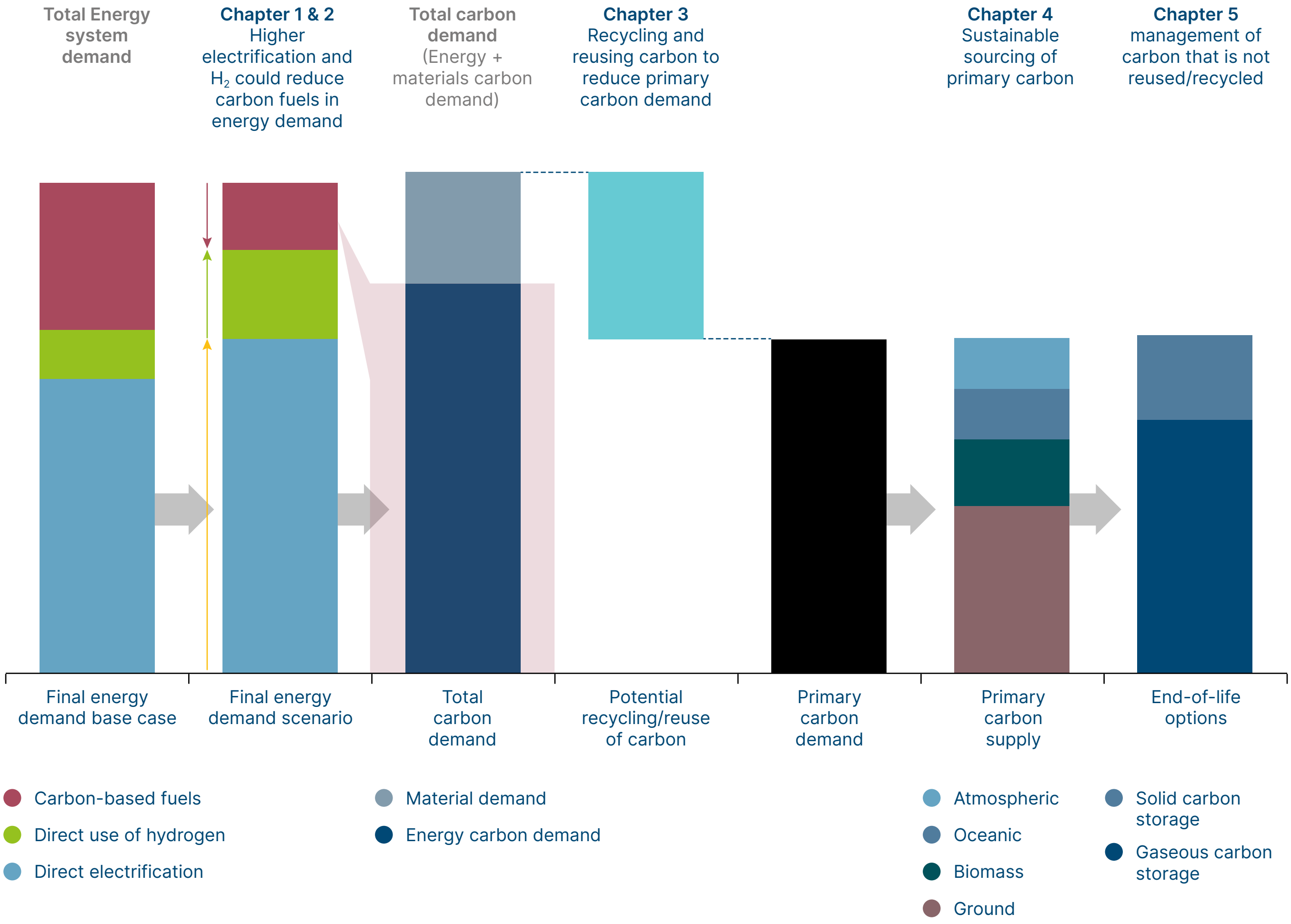
SOURCE: Energy: Systemiq analysis (2025), based on Fossil Fuels in Transition (ETC, 2023); Chemicals: Planet Positive Chemicals Report (Systemiq, 2022, BAU Net-Zero scenario); Biomass: ETC Bioresources report (2021); Steel: MPP STS (2022); Cotton, Bitumen and Soda Ash: Systemiq analysis (2025)

It is essential that all of this carbon is sourced and used in a way that results in net-zero emissions. This can be achieved if carbon is recycled or reused, sourced from sustainable bioresources, or derived from fossil fuels with the resultant emissions neutralised; either by point-source Carbon Capture and Storage (CCS) or by balancing unabated fossil use with equivalent carbon removals. This report analyses the options for sourcing and using the required carbon in a sustainable, zero-emissions fashion [Exhibit 0.5]. It focuses on the role of technological developments which could either further reduce the need for carbon molecules, or enable its sustainable supply and use.

Exhibit 0.5

Framework for analysing demand and sourcing options for carbon in a sustainable, zero-emissions fashion

Illustrative



SOURCE: Systemiq analysis for the ETC.

The objective of this report is to clarify how carbon can be sustainably sourced, used, and stored within a net-zero energy and materials system, identifying the technologies, policy enablers and trade-offs required to achieve this transition. This report covers in turn:

1. The maximum potential role of direct electrification in a zero-emissions global economy.
2. The contribution of hydrogen and non-carbon hydrogen derivatives.
3. The potential to cycle and reuse carbon molecules, whether via plastic recycling, carbon capture and utilisation or other means.
4. The potential to scale sustainable sources of primary carbon, covering:
   - Direct carbon capture from the atmosphere.
   - Point source carbon capture to enable continued fossil fuel use at net-zero emissions.
   - Sustainable bioresource supply.
5. Options for storing carbon in gaseous or solid form at the end-of-life.
6. A comparison of the options: trade-offs between alternative approaches in terms of natural resource use, technological availability and cost.
7. Scenarios for the future pattern of carbon sourcing, utilisation and final destination.

Exhibit 0.6 shows one of the four scenarios which are set out in Chapter 7. In this scenario total carbon demand would be in line with those set out in Exhibit 0.3 and Exhibit 0.4 – with 3.5 Gt for energy use and 1.2 Gt for use as material. This implies a dramatic reduction in the total need for carbon by mid-century, but also a dramatic change in the sources and destination compared with those shown on Exhibit 0.1.

- **Sources**: 57% rather than 85% now derives from fossil fuel sources, 30% rather than 13% from bioresources, while the share of carbon supply deriving from recycling or reuse has grown from 2% to 13%.
- **Destinations:** Only 10% of carbon is emitted to the atmosphere without capture. 47% is stored in gaseous form, 8% in solid form, 20% remains in ongoing use and 13% is recycled.

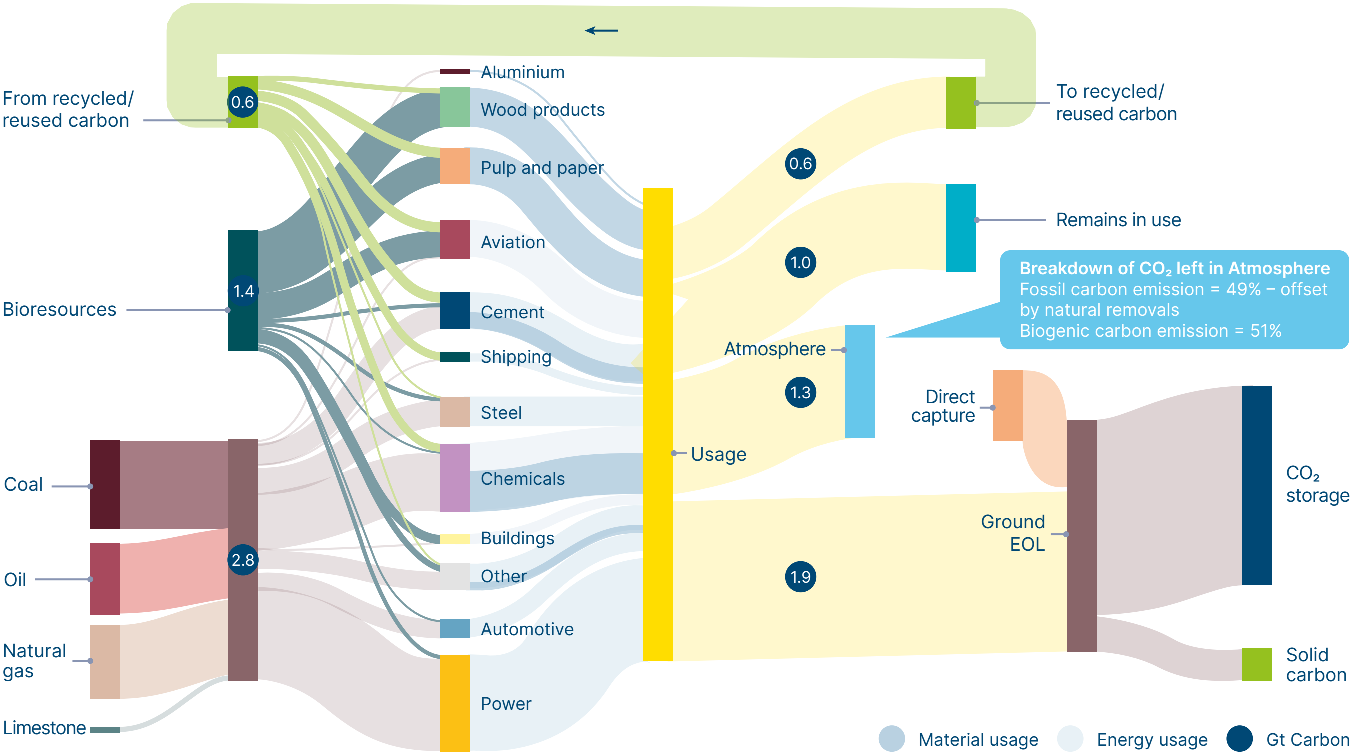
Other scenarios presented in Chapter 7 explore how this pattern would change if the objective were either to maximise recycling and reuse, to minimise fossil fuel use via maximum bio resource supply, or to expand CO_2 storage to allow a large ongoing role for fossil fuels.

Exhibit 0.6

In a baseline decarbonisation scenario, 57% of carbon supply still derives from fossil fuels extracted from the ground

ACF, carbon source and destination for the energy and materials sectors by mid-century

Gt C



SOURCE: Systemiq analysis for the ETC (2025).

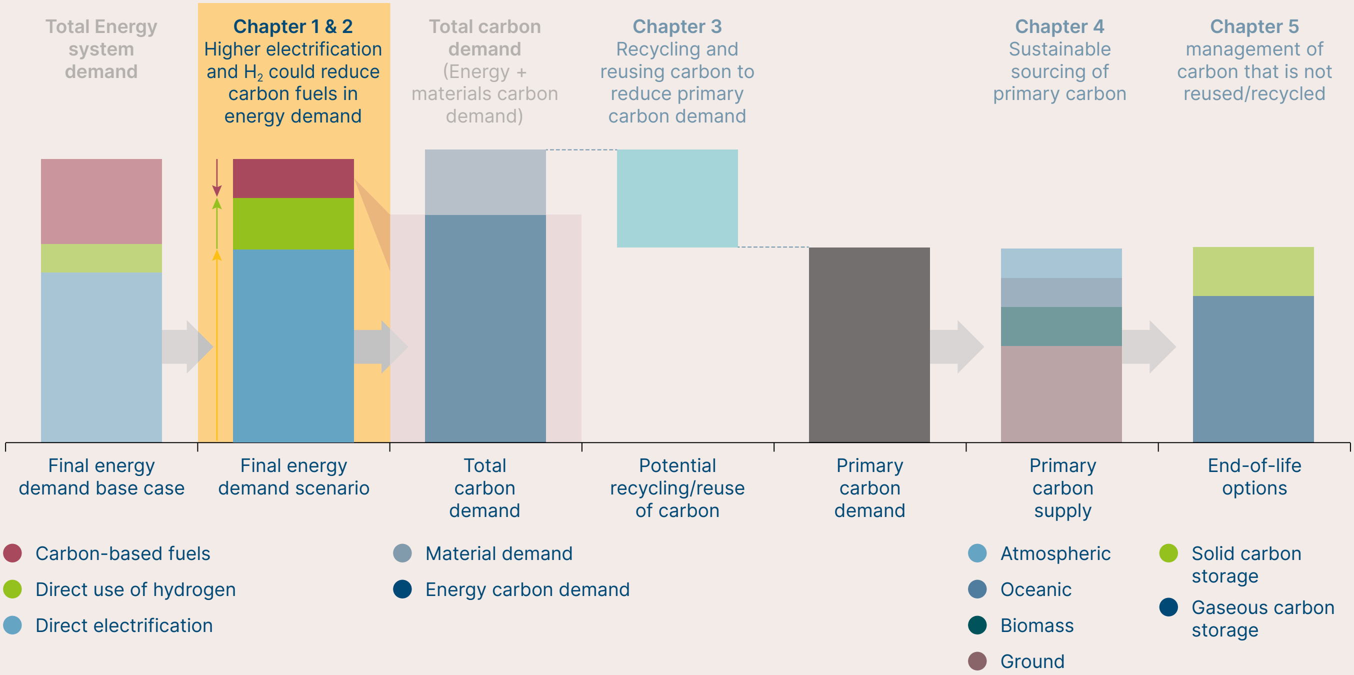
The role of electrification

1

Exhibit 1.0

Framework for analysing demand and sourcing options for carbon in a sustainable, zero-emissions fashion

Illustrative



SOURCE: Systemiq analysis for the ETC.

As shown in Exhibit 0.2, the ETC's previously published scenarios suggest that the direct use of electricity could account for 62–71% of final energy demand by mid-century. In this chapter, we assess whether emerging technological developments could enable even higher levels of electrification and examine the resulting implications for carbon molecule demand. Recent analysis by Ember reinforces this outlook, highlighting that cement, iron and steel, and chemicals hold the greatest remaining potential for industrial electrification. High-temperature heat processes, historically difficult to electrify, are now increasingly within reach, expanding the technical ceiling across heavy industry.[2]

We investigate three high potential opportunities for further electrification beyond the levels shown in Exhibit 0.2:

- **Electrification of high temperature industrial heat**, particularly in cement and petrochemicals.
- **Electrification of primary iron production via electrolysis or electrowinning** as alternatives to using hydrogen as a reduction agent.
- **Advacements in battery chemistry** which might enable greater electrification of shipping and aviation.

We also consider the potential for new technologies such as sodium-ion batteries to lower storage costs and make it easier to decarbonise electricity supply.

2 Ember (2025), *The Long March of Electrification*.

Building on this analysis, we present a scenario of "maximum electrification and unconstrained power supply", which if achievable, would see electrification rise to as much as 77% of final energy demand. This would reduce the demand for carbon molecules by 24% relative to the levels shown in Exhibit 0.3.

1.1 Electrification of high temperature industrial heat

Overview

Electrification of high temperature heat has the potential to further electrify industrial processes above 400°C, reducing reliance on fossil fuels and CCU/S. Over 60 EJ of energy is required annually for industrial heat above 400°C, with cement (~1400°C), steel (~1600°C) and chemicals (~800°C) being the primary sectors [See Exhibit 1.1]. Today, nearly all of the energy used for high-temperature industrial heat is fossil-fuel based.[3] Heat pumps cannot meet the demand for high-temperature heat as they are limited to temperatures below 400°C, making them unsuitable for high-temperature applications. Electrifying high-temperature heat, if made cost-effective, could significantly reduce the dependence on fossil fuels (even with CCS) while driving a substantial increase in electricity demand.

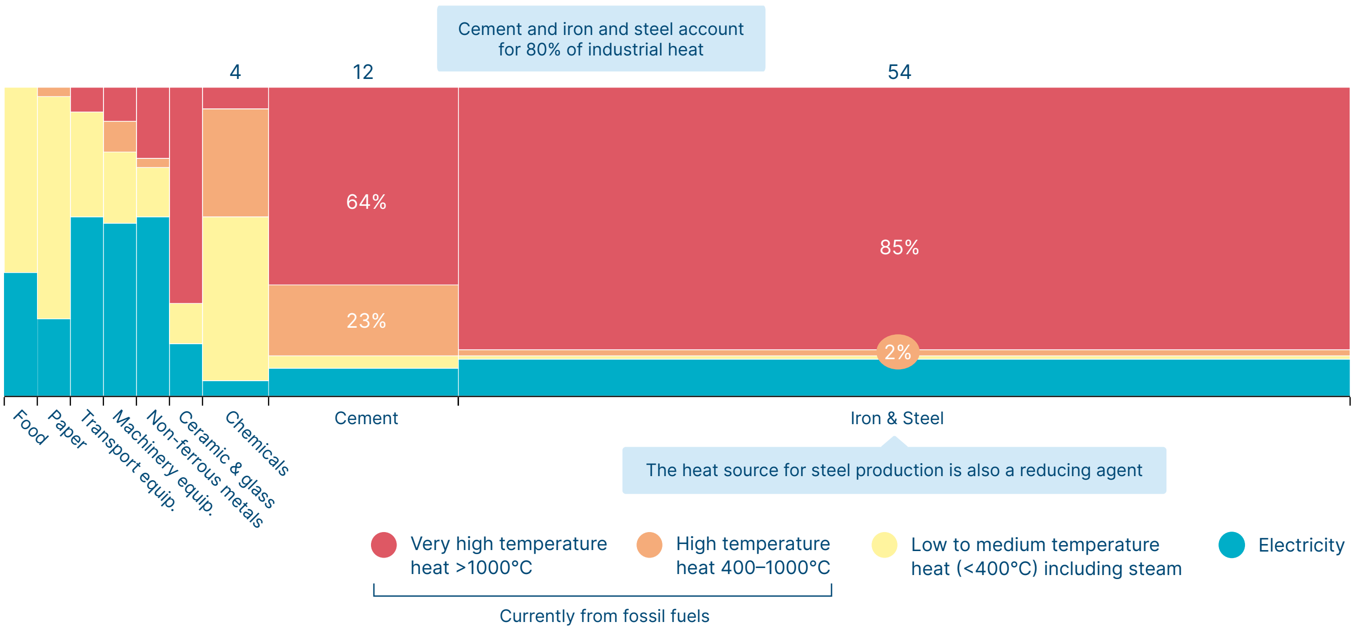
New electrification technologies are advancing, enabling heat electrification through shockwave, electric and plasmas, and resistance heating. Energy efficiency for electrified heat ranges from 50% to 95%, generally outperforming fossil fuels due to lower conversion losses.[4] Large industrial companies, including BASF, Technip Energies, Algoma, Cementa and Siemens, are exploring further electrification of their processes, alongside new innovators like SaltX and Coolbrook entering the space. There are various ways to generate heat with electricity, [Exhibit 1.2], **shockwave, plasma technology and resistance heating** are showing, amongst others, significant advancements in recent years.

Exhibit 1.1

High temperature industrial heat: demand for high temperature heat in steel and cement present a large electrification opportunity

Energy use by temperature and industry sector[a] in 2050

EJ and % of in sector energy use; Illustrative as energy use by temperature and industry is based on European values in 2020



NOTE: [a] Data representing energy split by temperature in EU across the sectors applied to a global level based on a study from Madeddu (20220) with adaptions for the chemical sector to include plastics from Coolbrook (2024).

SOURCE: Final energy demand in 2050 is based on Systemiq analysis (2024) from ETC (2023), *Fossil Fuels in Transition*; Silvia Madeddu (2020), *The CO_2 reduction potential for the European industry via direct electrification of heat supply;* Coolbrook (2024), *Electric cracking: RotoDynamic Reactor cuts 100% of CO_2 in steam cracking.*

3 Future Cleantech architects (2024), *Decarbonizing High-Temperature Heat in Industry*.

4 Some energy is lost to surrounding materials, equipment or the environment via radiation and convection.

Exhibit 1.2

New technologies currently under development could electrify industrial energy demand at high temperatures (over 400°C)

Technology[a]	Process	Sectors[b]	TRL[c]	Energy efficiency	Company Non-exhaustive examples
Shock-wave heating	**Rotation turbines** employ an **electric motor** to spin **blades** and **gas**, where **supersonic speed** and **rapid deceleration** creates a shockwave and turbulent gas, which generates high temperature heat.	Cement, chemicals, steel, aluminum, other industry (glass)	6–7	50–95%	Coolbrook, Siemens, T.EN Technip Energies
Arc and plasma heating	Two electrodes connected to a high-voltage power supply create an **electric field that ionises the air, forming a plasma with electrons and positively charged particles**. The applied electric field causes the ionized gas molecules to oscillate to generate heat.	Cement, Steel, other industry (machinery, transport equipment)	3–9	50–90%	Algoma Steel Inc., Cementa Heidelberg Cement Group, SaltX Technology, PyroGenesis
Resistance	An electric current passes through resistive elements, causing electrons to collide with the atoms of the material, converting electrical energy into heat, the heat is then transferred by gas through convection or through radiation.	Steel, aluminum, chemicals, other industry (glass, machinery, transport equipment)	6–9	50–95%	Linde, BASF, T.EN Technip Energies, Chevron, سابك sabic
Microwave	Electricity powers a **microwave generator**, producing **microwaves** that cause molecules (especially water or other polar materials) to **oscillate**, generating collisions and with that heat.	Steel (sintering), other industry (e.g., ceramics)	Unclear	50–85%	Ferrite Microwave Technologies
Induction	**High-frequency current passes** through an induction col (e.g., copper), creating a **magnetic field**. This process generates induced force and produces heat because of the electrical collisions in the material.	Steel, aluminum, other industry (machinery, glass, minerals, transport)	7–9	50–90%	GH induction

NOTES: [a] Only includes the sectors where a technology can electrify a high temperature processes; [b] Other technologies can be implemented for industry electrification e.g., ultraviolet (UV), infrared, thermoelectric cooling, electron beam, and laser heating but have a narrow field of application; [c] TRL stands for Technology Readiness Level.

SOURCE: Silvia Madeddu (2020) *The CO_2 reduction potential for the European industry via direct electrification of heat supply;* Fraunhofer ISI (2024), *Direct electrification of industrial process heat. An assessment of technologies, potentials and future prospects for the EU. Study on behalf of Agora Industry.*

Costs

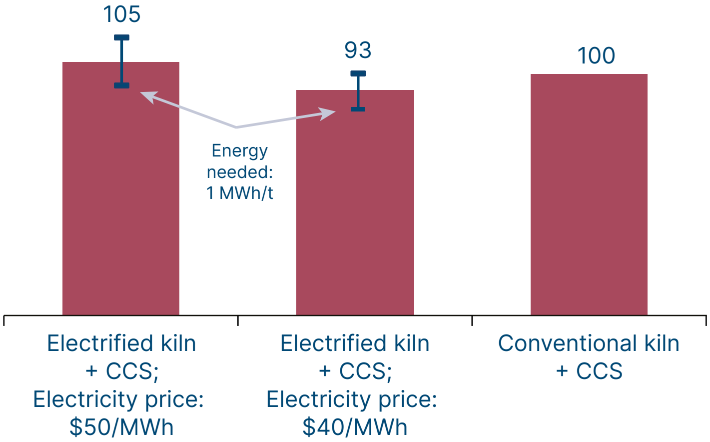
The key advantages that high-temperature heat electrification might offer over other decarbonisation technologies stem from its more efficient use of energy. Depending on the technology and application, energy consumption is typically reduced up to 10–15%, though in some cases reductions up to 40%[5] have been reported compared to fossil fuel-based systems, primarily due to lower conversion losses enabled by direct electrification. This could be more economical than other low-carbon alternatives as higher capital expenditures (CAPEX) of the emerging technologies are offset by this efficiency. Exhibit 1.3 shows a case study of how an electrified cement kiln could be cost competitive with a conventional cement kiln into the future. Cement production involves heating limestone, which releases CO_2. While that CO_2 still needs to be captured, the fossil fuel used for heating can be replaced with electricity. The cost of electricity is key to competitiveness, particularly this cost of electricity relative to a fossil alternative energy price, which can vary highly across regions. This comparison is for projected economics; for example shock-wave heating, a type of high temperature heat technology suited to the cement sectors is currently at technology readiness level (TRL) 6–7, thus not commercially deployed. The realisation of these economics ultimately depends on whether such technologies can successfully reach market readiness, and there remains significant uncertainty around their scalability, cost trajectory and commercial deployment timelines.

5 Based on shockwave technology compared against conventional gas burners for e-crackers. Center for Global Commons & Systemiq (2022), *Planet Positive Chemicals.*

Exhibit 1.3

Case study: switching to electric cement kilns could be cost competitive with conventional kilns at an electricity price of $40/MWh

Levelised cost of heat for cement production by 2050
($/t cement)[a]



Key inputs	Electrified + CCS	Conventional + CCS
CAPEX[a]	$300/t	$280/t
Energy requirements	1-1.4 MWh/t	1.0 MWh/t
Energy price	$40-$50/MWh (electricity)	$17/MWh (coal)
CCS cost	$60/t$CO_2$	$100/t$CO_2$

NOTE: [a] Greenfield plant. Includes CO_2 capture plant capex and opex for both electrified and conventional kiln. For electrified kiln, some CO_2 capture will still be needed to capture residual process emissions. Plasma heater-based electric kiln with efficiency ~70% can have energy requirements of 1.4 MWh/t. Resistance and shockwave heating with efficiency of >90% can drop energy requirements to 1 MWh/t. CCS: Carbon Capture Storage.

SOURCE: Mission Possible Partnership (2023), *Making Net-Zero Concrete and Cement Possible*.

Barriers and enablers

Besides the economic challenge, a reliable, low-cost supply of clean electricity would greatly benefit high-temperature heat technologies.[6] A firm and near-constant energy supply is needed, as these systems struggle to ramp up and down due to high temperatures. This could pose challenges given the intermittency of renewables and the growing demands on the power system, such as the electrification of passenger road transport and data centres.

Achieving and maintaining high temperatures requires materials that can endure extreme conditions over long lifetimes. For example, electrifying cement kilns poses durability challenges because electric heating methods like plasma torches and induction create different heat patterns than traditional fuels, which can stress kiln materials in new ways.[7] Materials to line high-temperate industrial equipment like cement kilns, furnaces and reactors must withstand intense heat, chemical reaction from raw materials and frequent temperature changes, all of which can reduce their lifespan.[8] Ensuring even heat distribution and material resilience remains a key hurdle.

1.2 Molten Oxide Electrolysis (MOE) and Electrowinning – electrifying the iron-making process

Overview

Alongside more established low-carbon iron and steel-making pathways like hydrogen-based reduction, natural gas DRI with CCS, and Electric Arc Furnaces (EAF) with scrap steel, novel electrochemical technologies such as MOE and Electrowinning are being explored as potential longer-term solutions. These are two novel electrified processes for converting iron ore into iron using electrochemistry rather than fossil fuel-based reduction. They could reduce reliance on hydrogen and CCU/S as alternate decarbonisation pathways for iron/steel, while increasing overall electricity demand.

6 Future Clean Architects (2024), *Decarbonizing high-temperature heat in industry*.

7 Burman T et al. (2021), *Evaluation of usage of plasma torches in cement production*.

8 Tatič M et al. (2022), *New Generation of Refractories for Rotary Cement Kiln, Advance in Thermal Processes and Energy Transformation* Volume 5, No.4, p. 69-77, ISSN 2585-9102.

MOE operates by immersing iron ore in a molten oxide bath heated to approximately 1600°C. The bath typically contains a mixture of oxides, such as CaO-Al_2O_3-MgO-SiO_2, which act as a solvent for iron oxide. When an electric current is applied, it breaks down Fe_2O_3 into molten iron and oxygen gas. Electrowinning, by contrast, suspends iron ore in an alkaline solution (typically NaOH or KOH) at around 100–110°C, where electricity reduces the ore to solid or powder iron.

Key operational advantages include:

- **MOE modules are bus-sized**, making the technology modular and scalable by simply adding more units. The molten iron product can be cast or used directly, removing the need for an EAF.
- **Electrowinning runs at lower temperatures**, which enables better compatibility with intermittent renewables, potentially lowering energy costs.

Several large-scale iron and steel companies are exploring MOE and electrowinning, both currently at TRL 4–6, with pilot plants producing up to 40–80 kt of iron per year. For comparison, a typical commercial steel plant produces around one Mt of steel annually, meaning these pilots are at 5–8% of full industrial scale.

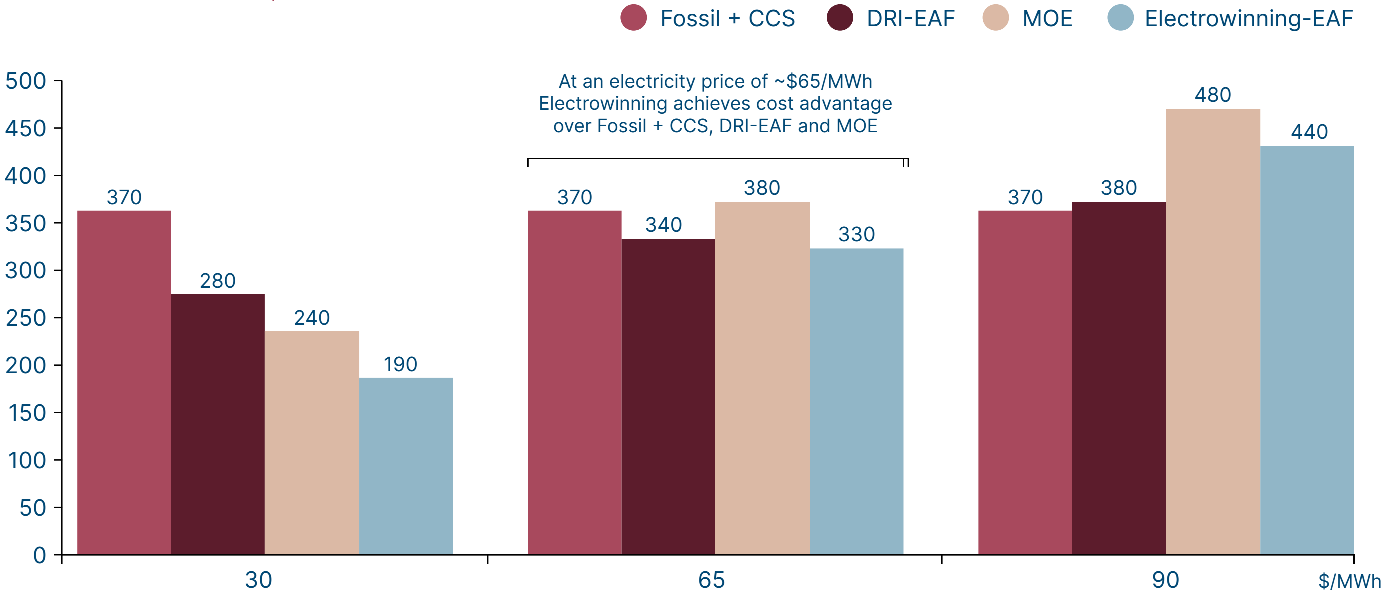
Costs of electrifying iron-making

With electricity prices below $65 per MWh, MOE and electrowinning could become more cost-effective than other low-carbon steelmaking alternatives [Exhibit 1.4]. Their expected higher capital costs may be offset by lower energy consumption, making them competitive under favourable electricity pricing. Capital expenditures for MOE and electrowinning are expected to be comparable in scale to those of direct reduced iron with electric arc furnaces (DRI-EAF). Additionally, these technologies could offer around 6% lower energy use compared to hydrogen-based steelmaking routes. However, given their early stage, cost-competitiveness is still highly uncertain and will depend on technology learning rates as well as regional power prices.

Exhibit 1.4

Electrowinning could outcompete other decarbonisation options if electricity costs fall below ~$65/MWh

Sensitivity analysis of electricity price ($/MWh) on the levelised cost of heat ($/t steel)
Levelised cost of heat, $/t steel



NOTE: Assumed over 10 years, average over different electrification technologies and average BF-BOF CAPEX assumed; for energy consumption 11.7 GJ/t steel for coking coal and 6.8 GJ/steel for lower-grade steel assumed; for CCU/S cost emissivity for best available technology assumed 1.8 tCO_2/t steel and a capture price of $100/t CO_2. 5. $3/kg H_2. The $65/MWh represents the electricity cost to the factory gate. Capex for MOE is $795 per t/steel, with energy demand of 4 MWh/t steel. CAPEX for electrowinning is $825 per t/steel, with energy demand of 4.2 MWh/t steel; EAF = electric arc furnace; DRI-EAF = direct reduced iron with electric arc furnace; MOE = Molten oxide electrolysis.

SOURCE: Systemiq analysis based on Mission Possible Partnership MPP (2022), *Making Net-Zero Steel Possible.*

Barriers and enablers

Despite their potential, MOE and electrowinning face some barriers to commercial deployment. While potentially more energy-efficient, they must still compete with lower-cost fossil-based steelmaking with CCS and H_2 DRI, which are more commercially ready today. Operational expenditures (OPEX) are also uncertain, particularly due to anode degradation at extreme temperatures (~1,600°C).[9] Similar to high temperature industrial heat electrification, MOE requires close to constant clean power supply due to high temperature needs (1,600°C). In contrast, electrowinning and other electrochemical processes, such as direct electrochemical reduction or oxygen-decoupled electrolysis, operate at much lower temperatures (60°C–300°C). These systems have lower thermal inertia and can pause and restart more easily without significant energy losses or material stress. As a result, they can better accommodate intermittent renewable power without requiring constant provision. A systemic challenge is the timing of investment: the steel sector must decide whether to accelerate deployment of green H_2-DRI today despite cost uncertainties, or hold back in the hope that next-generation electrified routes such as MOE and electrowinning become viable at scale by the mid-2030s. The latter may be commercially attractive, but risks locking in a decade of additional CO_2 emissions in the meantime.

1.3 Advancements in battery chemistries

1.3.1 Batteries for mobility

Overview

The rapid scale-up of battery manufacturing, driven by surging global demand, is creating a dynamic landscape where multiple battery chemistries can coexist and evolve in parallel. Global battery production capacity is projected to grow from three TWh per year in 2023 to nine TWh per year by 2030, exceeding the anticipated six TWh per year demand from electric vehicles (EVs) and stationary storage.[10] This expansion is expected to drive continued improvements in energy density, cost reductions and broader adoption, particularly in emerging markets.

A major area of innovation lies in next-generation battery technologies designed to overcome the limitations of conventional lithium-ion systems. Among these, solid-state batteries are gaining attention for their potential to significantly enhance energy density, safety and charging speed. Such developments have the potential to further accelerate electrification in mobility due to the high energy density levels they can possibly achieve [see Exhibit 1.5].[11] Battery densities of liquid li-ion batteries have been advancing rapidly and by now achieve gravimetric energy densities of ~500 Wh per kg (CATL). Solid-state batteries, currently pre-mass production, get to similar levels today[12] and are being explored by major developers including Toyota, Samsung SDI, LGES, SK On, CATL and BYD. However, they represent just one pathway among many. Advances in anode and cathode materials—such as silicon-based anodes and lithium-metal anodes—are also contributing to performance gains across various battery types.

9 Wiencke et al. (2018), *Electrolysis of iron in a molten oxide electrolyte*, *Journal of Applied Electrochemistry*.

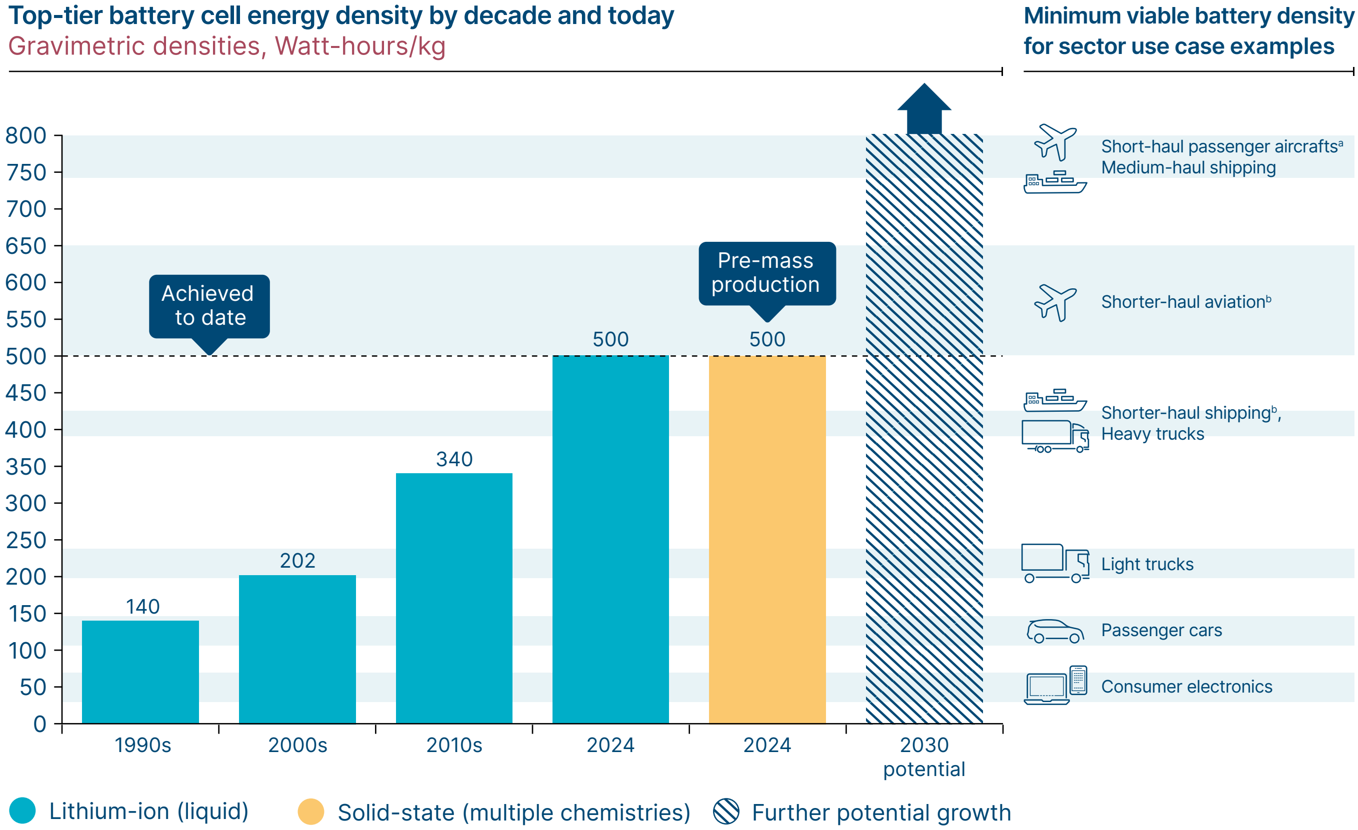
10 ETC analysis based on IEA (2024); Global EV Outlook 2024 and BNEF (2024); China Already Makes as Many Batteries as the Entire World Wants.

11 Exhibit 2.5 based on RMI, (2023), *X-Change: Batteries;* The Battery Domino Effect. Available at: *https://rmi.org/insight/x-change-batteries/*.

12 Wang et al. (2023), *Advances in solid-state batteries: Materials, interfaces, characterizations, and devices*. MRS Bulletin 48.

Exhibit 1.5

Solid-state batteries enhance energy density, increasing electrification potential in aviation and shipping



NOTE: Currently dominant lithium-ion batteries use liquid electrolytes, current solid-state batteries predominantly use lithium, other ions (e.g,. sodium) can be used; Minimum density at which first full battery-electric models are feasible, [a] Typical twin-engine narrowbody aircraft with a range of 600 miles would require 800 Wh/kg, larger models 1,000 Wh/kg, [b] Uptake in niche, shorter haul segments. At an energy density of 1,000 Wh/kg, most regional (~1,000 nautical miles) aviation can turn full electric.

SOURCE: ETC analysis based on RMI (2023) X-Change. Systemiq analysis for the ETC; RMI (2023), X- Change.

Such developments are expected to enable steady performance improvements across all battery chemistries, with historical learning rates for battery technologies typically ranging between 7-9% annually.[13] For instance, semi-solid-state advancements, such as CATL's (a benchmark battery provider) developments, demonstrate incremental gains in energy density and efficiency. Top of Form Ultimately, the evolution of battery technology is not about a single breakthrough, but rather a portfolio of innovations that collectively enhance the viability of electrification across sectors—but particularly in transportation.

Costs

Rapid declines in battery costs could make electrification for some transportations segments economic, potentially accelerating beyond anticipated levels [see Exhibit 1.6].[14] For example in shipping, at battery prices of $100 per kWh; battery-electric ships could be competitive with fuel oil ships (<1,500 km), another halving of the price would make ships up to 3,000 km competitive. With liquid Li-ion batteries already within this threshold, the electrification of all intra-regional shipping appears increasingly feasible.[15] However, cost reductions alone are not sufficient. Energy density is also critical, especially in weight- and space-constrained applications like shipping, where both low cost and high density are needed to achieve viable range without compromising vessel capacity.

13 Nykvist and Nilsson (2015) Rapidly falling costs of battery packs for electric vehilces; Barwick et al (2025) Drive Down the Cost: Learning by Doing and Government POlicies in the Global EV Battery Industry

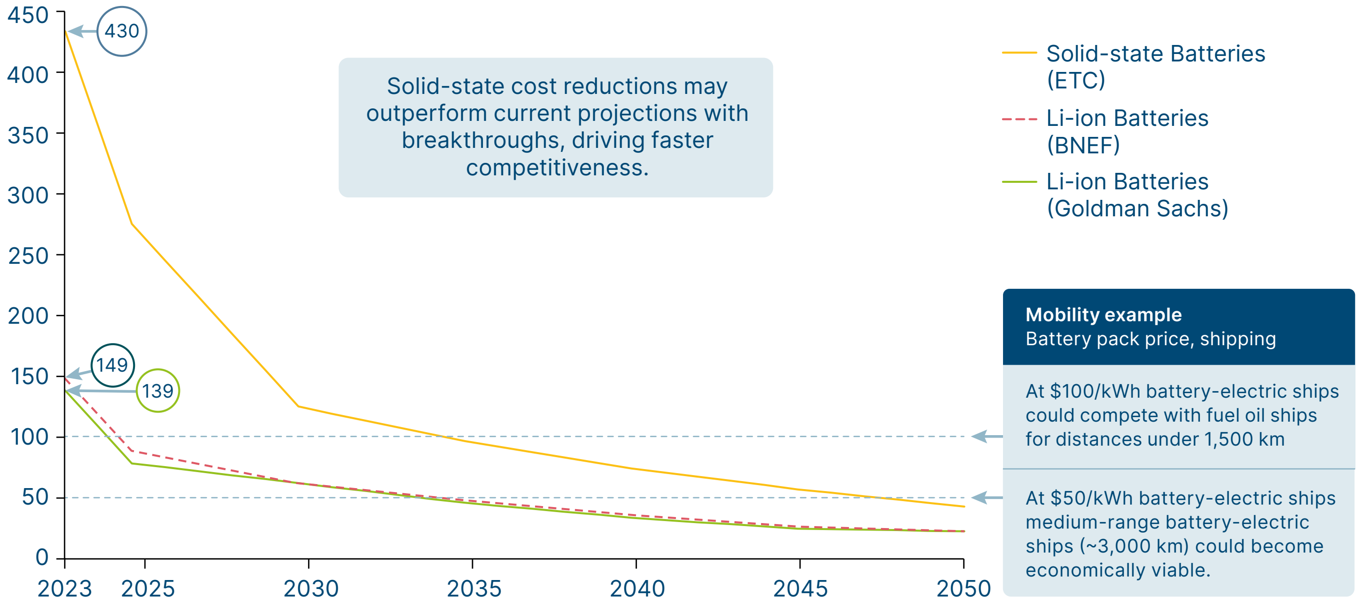
14 Goldman Sachs (2024), Electric vehicle battery prices are expected to fall almost 50% by 2026, based on company data, Wood Mackenzie, SNE Research, Goldman Sachs; BNEF (2024) 2023 Lithium-Ion Battery Price survey; BNEF (2024) New Energy Outlook; Fraunhofer ISI (2024) Solid-state batteries roadmap 2035+; Alkahidli et al. (2024), *Solid-state batteries, their future in the energy storage and electric vehicles market.*

15 Kersey et al. (2022*) Rapid battery cost declines accelerate the prospects of all-electric interregional container shipping.*

Exhibit 1.6

Rapid declines in battery costs could open a range of electrification pathways for mobility, potentially accelerating beyond anticipated levels

Average battery pack price
$/kWh, Actuals and projections[a]



NOTES: [a] Methodology for price projections: For solid-state based on Alkahidli et al (2024) projected cost improvement rate of 20% applied up to 2028, then 5% cost improvement rate applied up to 2050, for Li-ion price projections based on BNEF, price projection has been adapted from BNEF up to 2035 and 6% cost improvement rate applied to years up to 2050; for Li-ion price projections from Goldman Sachs (GS), price projection has been adapted from GS up to 2030, there after 6% cost improvement rate has been applied to years up to 2050.

SOURCE: Systemiq analysis for the ETC; Goldman Sachs (2024), *Electric vehicle battery prices are expected to fall almost 50% by 2026*; BNEF (2024), *Lithium-Ion Battery Pack Prices See Largest Drop Since 2017*; Fraunhofer ISI (2024), *Solid-state batteries roadmap 2035+*; Alkahidli et al. (2024), *Solid-state batteries, their future in the energy storage and electric vehicles market*; RMI (2023), *Xchange: Batteries The Battery Domino Effect*; Kersey, J. et al. (2022), *Rapid battery cost declines accelerate the prospects of all-electric interregional container shipping.* Nat Energy 7, 664–674.

Battery-electric aviation faces economic and technical hurdles, but progress is accelerating. While battery costs are declining, no clear threshold has been established as the tipping point for economic viability in aviation and energy density remains a major constraint.[16] Some first-generation electric aircraft, suitable for short-range flights, are targeting entry into service before 2030,[17] with companies such as Heart Aerospace, Eviation and Joby Aviation already advancing prototypes and certification programs. Wider deployment for flights of several hundred kilometers may take longer, but momentum across the sector indicates faster progress than once assumed. In the near term, “hybrid-electric aircraft,[18] where small electric motors are placed alongside fossil engines, may serve as a transitional solution, enabling incremental emissions reductions while technologies mature.

Barriers and enablers

The key challenge in advancing next-generation batteries lies in commercialising new chemistries at scale and at competitive cost, particularly for transport applications. Many emerging battery types face higher production costs than mature lithium-ion chemistries like lithium iron phosphate (LFP), largely due to low manufacturing volumes and the need for novel production processes. At the same time, the parallel development of multiple chemistries stretches R&D budgets across competing approaches, potentially slowing progress for each.

Manufacturing complexity is a common barrier: for example, solid-state batteries require precise control over materials and interfaces, making high-quality, consistent production difficult. While full solid-state designs

16 Segal S (2021), *The viability of electric aircraft.*

17 Clements K (2025), *Electrifying Flight: Electric Aircraft Technology Takes Off—And Lands*; Garay, E (2022), *Electric Planes Are Coming Sooner Than You Think.*

18 ZeroAvia and others are developing hybrid propulsion systems that combine electric motors with hydrogen or conventional engines to reduce emissions and fuel consumption in regional aviation.

continue to face delays, semi-solid-state variants, which partially replace liquid electrolytes with more stable gel or paste-like materials, are progressing steadily. These designs offer improved safety and energy density while being easier to manufacture than fully solid-state cells. Several OEMs—including Toyota, BMW, Ford, Mercedes and Nio—have announced plans to integrate solid-state technologies by 2030. However, these are just one part of a broader innovation landscape, where incremental improvements across a range of chemistries will be critical to meeting the diverse performance, cost and safety needs of future electric mobility.

Beyond chemistry, sector-specific constraints also loom large in shipping: the immense total power demand of long voyages, multi-day charge times with untested large-scale battery swap concepts and the need for extensive port infrastructure upgrades compared with conventional bunkering.

1.3.2 Batteries for power systems

Decarbonising the power system requires full electrification and low-emission power from variable renewable energy. As wind and solar energy increases, so do balancing needs.[19] Sodium based batteries are explored as an emerging option, with the potential to be a disruptive technology for grid storage markets, providing clean, firm and scalable storage capacity.

Next-generation sodium-ion batteries have made significant strides in recent years, entering low-volume commercial production and are being deployed in stationary applications such as data centres and telecoms, indicating near-commercial readiness.[20] These batteries are particularly well-suited for stationary energy storage, offering advantages such as low-temperature tolerance, long cycle life and enhanced safety [Exhibit 1.7]. While early sodium-ion batteries had energy densities around 160 Wh per kg, CATL announced its second-generation sodium-ion battery, known as Naxtra, with improvements in energy density and cycle life over the first generation that makes it approach LFP batteries.[21]

Sodium-ion batteries offer a potential cost advantage over LFP due to the abundance of sodium and the use of simpler, less expensive materials, such as iron-based cathodes and aluminium current collectors.[22] However, these cost benefits are contingent on achieving manufacturing scale comparable to lithium-ion technologies. At present, low production volumes result in higher per-unit costs. Additionally, sodium-ion batteries still face limitations in energy density, which restricts their use in electric vehicles. Nonetheless, techno-economic models suggest that sodium-ion batteries could become cost-competitive with low-cost lithium-ion variants by the 2030s, especially as energy density and performance continue to improve.[23] Rather than competing directly, sodium-ion and lithium-ion technologies are increasingly seen as complementary, with potential convergence in scalability and technical performance.

19 The ETC's Power Systems Transformation: Delivering Competitive, Resilient Electricity in High-Renewable Systems (2025) demonstrates that power systems with very high shares of renewables can be designed and operated reliably.

20 Patel, P (2024), *Sodium-Ion Batteries Poised to Pick Off Large-Scale Lithium-Ion Applications.*

21 CATL (2025), *Naxtra Battery Breakthrough & Dual-Power Architecture: CATL Pioneers the Multi-Power Era.*

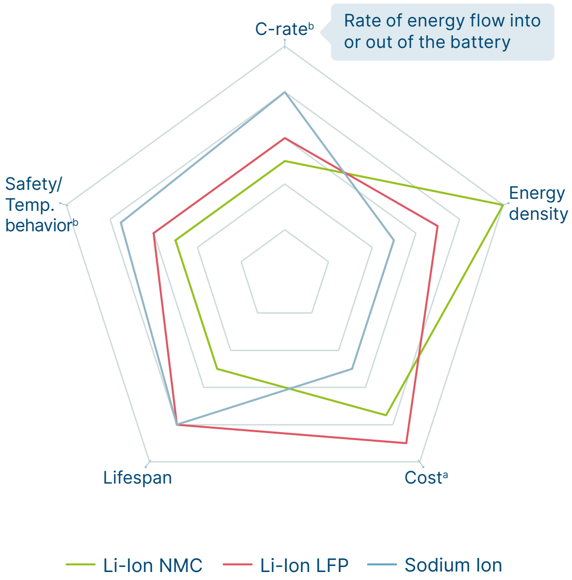
22 Vaalma C, et al. (2018), *A cost and resource analysis of sodium-ion batteries.*

23 Yao A, et al. (2024), *Critically assessing sodium-ion technology roadmaps and scenarios for techno-economic competitiveness against lithium-ion batteries.*

Exhibit 1.7

There are trade-offs between battery chemistries, but recent advancements are narrowing the energy density gap between sodium-ion and lithium-ion batteries

Radar chart of relevant dimensions of SIBs compared to LIBs



Category	Sodium-ion batteries (SIBs)	Lithium-ion batteries (LIBs)
C-rate	2–4 C	4–6 C
Gravimetric energy density	~200 Wh/kg announced by CATL in 2024	~500 Wh/kg via condensed battery cell announced by CATL
Volumetric energy density	~400 Wh/l	600-750 Wh/l
Raw-material cost	Sodium hydroxide is \$300-\$800 per mt	Lithium hydroxide is \$15,000 per mt
Lifespan	Cycle-life similar to LIBs	Steady performance over a high number of cycles

Key technical challenges for SIBs in stationary storage:

- Boost energy density and cycle life to rival lithium-ion batteries.
- Optimise stable, non-toxic materials to minimize capacity fade and extend lifespan

NOTE: Li-ion NMC = Nickel Manganese Cobalt lithium-ion battery; Li-ion LFP = Lithium Iron Phosphate lithium-ion battery [a] Cost of Sodium expected to be 20–30% lower compared to LFP once technology is scaled; [b] C-rate and safety being less of a concern for stationary applications compared to mobile application

SOURCE: ETC analysis based on Systemiq analysis for the ETC; Fraunhofer ISI (2023), *Battery technology advancements 2030+ roadmap*, Volta Foundation (2024), IRENA (2024), *Critical materials: batteries for electric vehicles*.

1.4 An Unconstrained power supply scenario with maximum electrification

Exhibit 1.8 presents an assessment of the potential impact of the electrification technologies considered under a scenario of maximum electrification and unconstrained clean power supply. The combination of the technologies assessed could eventually lift electricity to 77% (from today's 19%) of final energy demand, the share of hydrogen would decline from 8% to 6%, while the contribution of carbon-based energy carriers would fall from 22% to 17%, compared to ETC's ACF scenario.

Exhibit 1.9 illustrates the implications for demand for carbon molecules and hydrogen, expressed in terms of the final energy they supply. Carbon-based final energy demand falls from 18,600 TWh in the PBS scenario to 14,300 TWh. This would imply a reduction in carbon use for energy uses from 2.2 Gt to 1.9 Gt. The two largest potential drivers of reduced demand are a transition within steel-making to electrowinning or MOE and the electrification of heat input to cement making.

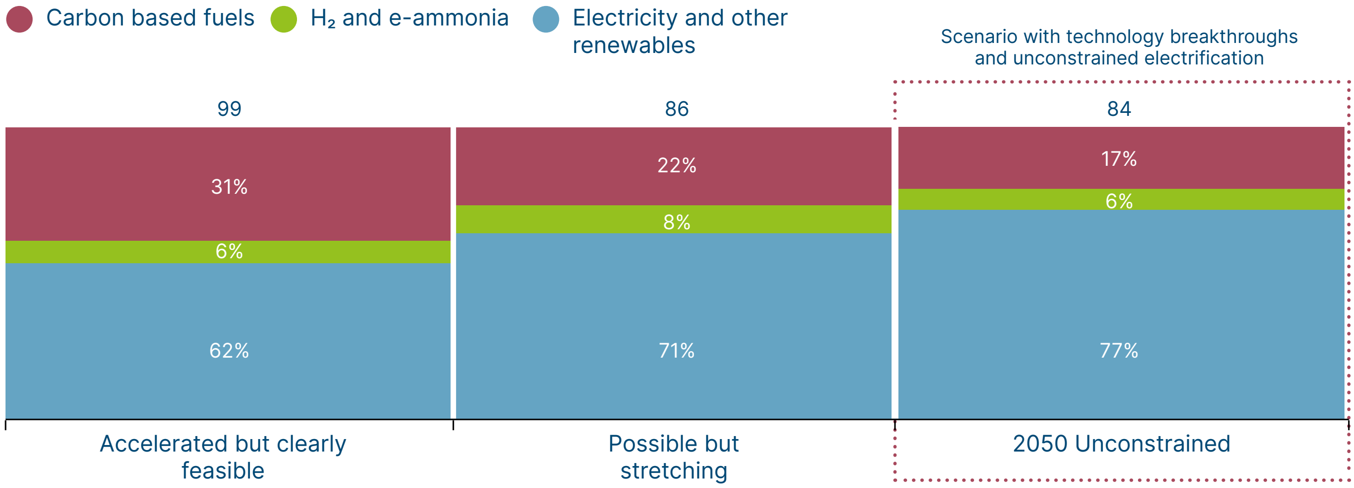
The analysis illustrates the significant long-term potential for even greater electrification than assumed in our ACF and PBS scenarios. But it also shows that even in the most extreme electrification scenarios, and even in the very long term, there will be an irreducible demand for significant carbon inputs into the energy system.

There are an additional 9,300 TWh of final energy consumption from carbon molecules in the power sector that could be displaced by additional clean power deployment, squeezing out any remaining gas and coal from the power system in 2050. The ETC's recent 2025 *Power Systems Transformation* report outlined how, in most geographies, a mix of solar, wind and battery storage is able to meet >90% of hourly demand at lower levelised cost than current power systems. The implications of this, if scaled globally, could reduce coal and gas consumption in the power sector to levels below those assessed by the ETC in 2023 *Fossil Fuels in Transition* report PBS scenario—removing 8,300 TWh of demand for carbon molecules. Alternatively, this reduction in coal and gas demand in the power sector could come from breakthroughs in advanced geothermal or nuclear – topics that the ETC intends to dive into in 2026.

Exhibit 1.8

An Unconstrained electrification scenario with technology disruptions can reduce the share of carbon molecules to ~17% of final energy demand

Global final energy demand by energy source and scenario
Thousand TWh, (%), 2050

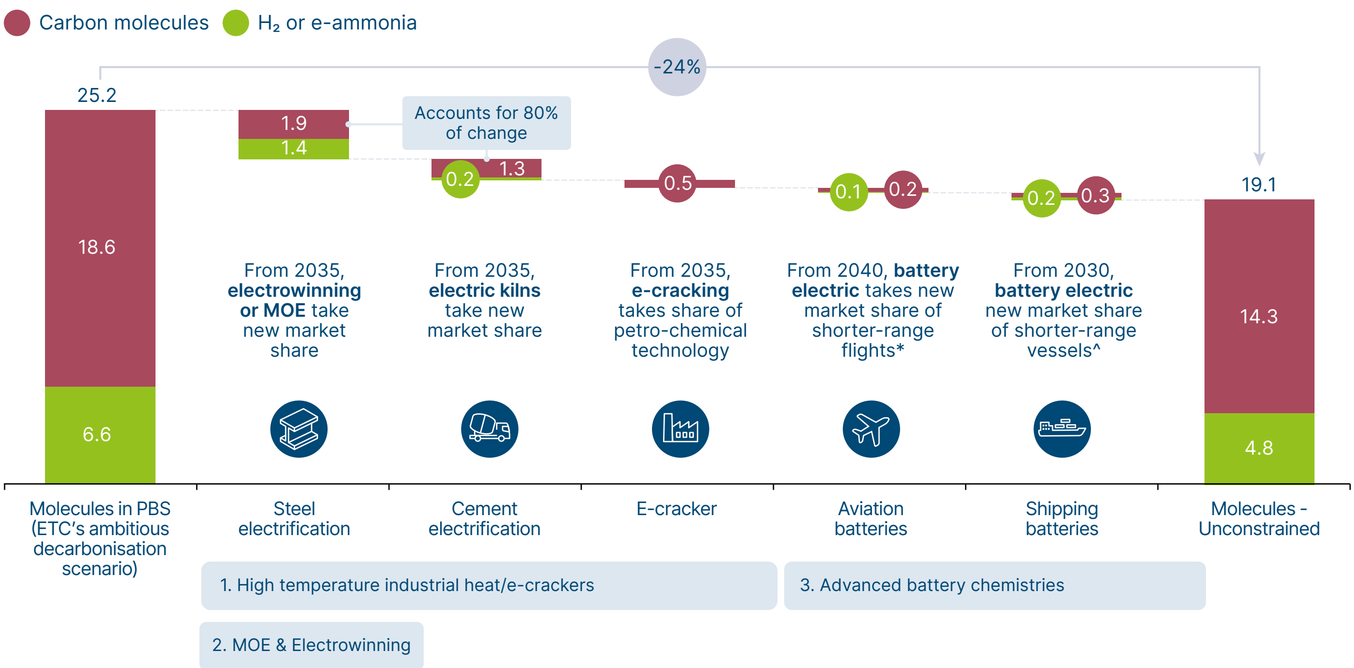


SOURCE: ACF scenario and PBS scenario based on ETC (2023), *Fossil Fuels in Transition*.

Exhibit 1.9

With 1) high-temperature industrial heat, 2) iron/steel electrification and 3) battery chemistries, demand for molecules can be reduced by ~24% compared with the ETC's PBS scenario

Molecules in the energy system – Possible But Stretching (PBS) to Unconstrained share mid-century
Final energy consumption, thousand TWh



NOTE: PBS = Possible But Stretching ETC decarbonisation scenario. *estimated at 15% of all nautical miles travelled, ^estimated at 20% of energy demanded

SOURCE: Systemiq analysis for ETC on (2023), ETC *Fossil Fuels in Transition*, Systemiq (2022), *Planet Positive Chemicals* (BAU Net-Zero scenario); Steel: Mission Possible Partnership (2022) Making Net-Zero Steel Possible Aviation: Mission Possible Partnership (2022) Making Net-Zero Aviation Possible.

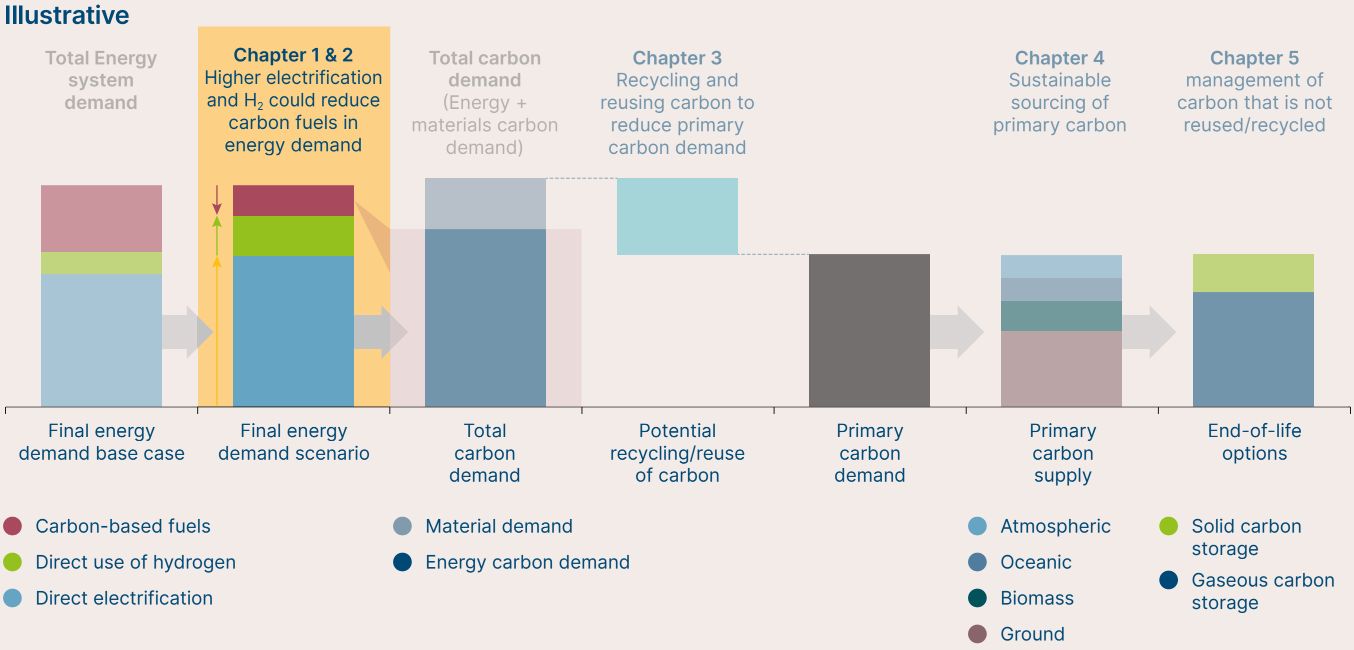
The role of hydrogen

2

Exhibit 2.0

Framework for analysing demand and sourcing options for carbon in a sustainable, zero-emissions fashion

Illustrative



SOURCE: Systemiq analysis for the ETC.

Many projections of the role that hydrogen and non-carbon hydrogen derivatives (e.g., e-ammonia) will play in the energy transition have been revised down over the last five years. The IEA and the Hydrogen Council have all reduced their projections for global hydrogen demand in 2030 and 2050.[24] At the ETC, our 2021 report *Making the hydrogen economy possible* estimated potential global demand in 2050 at up to 800 Mt. However, by 2023, in our *Fossil Fuels in Transition* report and in subsequent revisions, we have reduced this estimate down to between 350 Mt under the ACF scenario and 430 Mt under *PBS*.

These revised projections reflect:

- More rapid progress than anticipated in battery and other technologies which enable direct electrification.
- Slower progress than anticipated in reducing the cost of green hydrogen, primarily because of higher than predicted electrolyser capital and electricity costs.
- Improved understanding and recategorisation of sectoral end-use.

In the *Unconstrained Electrification* scenario shown in Exhibit 1.8, the use of hydrogen, either directly or embedded in non-carbon molecules (e.g., e-ammonia) could be reduced from 8% to 6% of 2050 final energy demand. The reduction

24 IEA (2023), World Energy Outlook 2023; IEA (2021), World Energy Outlook 2021; Hydrogen insights (2024), 'Getting to net zero will need nearly a quarter less clean hydrogen than we initially predicted': BNEF; Hydrogen insights (2023), Half of all clean hydrogen produced globally could be transported long-distance by 2030, says Hydrogen Council

reflects, in large part, greater electrification in the steel sector reducing hydrogen's role. This would imply around 365 MtH_2 used per annum in 2050 (downwards revision), of which 150 MtH_2 would be used directly for energy in the steel, fertiliser, shipping and trucking sectors [Exhibit 2.1]. There would in addition be hydrogen used as an input to power-to-liquid hydrocarbon fuels, petrochemicals and as a storage mechanism with the power system.

In this report we do not re-evaluate the application landscape for hydrogen. The potential end uses of hydrogen have been assessed extensively in recent years and the overall picture has remained stable: hydrogen demand is not expanding into new sectors, nor have compelling new applications emerged that would substantially increase its role. Instead, the critical uncertainty lies on the cost side. For hydrogen to fulfil its role in hard-to-electrify sectors, production costs must decline sharply through cheaper renewable power, falling electrolyser costs and innovation in storage and transport.[25]

Accordingly, this chapter focuses on the economics of hydrogen supply and the pathways by which it can become competitive. We assess whether two categories of technological and cost development might imply higher use of hydrogen shown in Exhibit 2.1:

- The exploitation of geological hydrogen.
- More rapid progress in electrolyser technology and cost reductions, including reflecting developments in China.

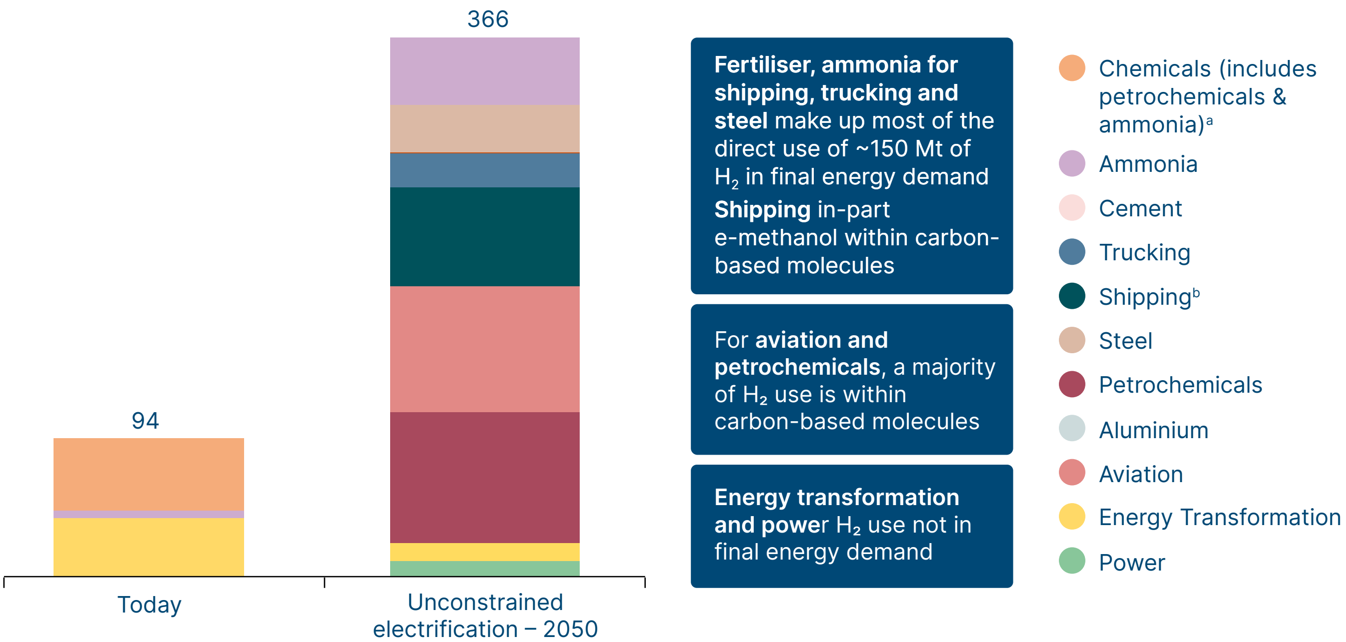
2.1 Hydrogen applications by sector

Exhibit 2.1 depicts how hydrogen demand across sectors in a deeply electrified energy system. Current hydrogen use is around 95 Mt per year, largely concentrated in ammonia and refining. By 2050, even under an Unconstrained electrification pathway, total demand rises more than fourfold to 365 Mt per year, with sectoral patterns reflecting where direct electricity cannot easily substitute

Exhibit 2.1

Hydrogen demand by sector

Direct and indirect Hydrogen demand by sector
Million tonnes of hydrogen (MtH_2) per annum



NOTE: [a] Based on historical data that does not include split between chemical types. [b] Ammonia does not include ammonia/hydrogen used in shipping, which is accounted for separately under "Shipping", Energy transformation = energy consumed in processing raw fossil fuels into useable energy products, mostly to convert crude oil to refined oil products.

SOURCE: Systemiq analysis for the ETC (2025).

25 ETC (2021), *Making the Hydrogen Economy Possible.*

- Chemicals and Ammonia: Fertilisers and chemical feedstocks remain the single largest source of hydrogen demand, making up over one-third of the total.
- Steel: Hydrogen-based direct reduced iron (H_2-DRI) could emerge a key decarbonisation route, particularly where cheap green hydrogen is available.
- Cement and Aluminium: Both sectors show more limited hydrogen uptake. In cement, hydrogen can substitute fossil fuels for high-temperature kiln heat, though carbon capture is often more cost-effective. Aluminium may use hydrogen for certain process heat needs, but electricity dominates elsewhere.
- Shipping: International shipping is one of the largest new demand centres, with hydrogen mostly used indirectly via e-fuels such as e-methanol or ammonia. These molecules provide energy-dense, transportable fuels that electricity cannot match for long-distance voyages.
- Trucking and Aviation: Hydrogen plays a niche but important role. For heavy-duty trucking, fuel-cell vehicles may compete with batteries on certain long-haul routes. In aviation, hydrogen appears mainly through derivatives like e-kerosene, rather than direct use.
- Petrochemicals: Hydrogen provides a low-carbon substitute feedstock, though much of the sector will still rely on carbon-based molecules even in 2050.
- Energy Transformation and Power: A share of demand appears in energy transformation, for example, using hydrogen in power systems for seasonal balancing or backup generation.[26] While a small share of total hydrogen demand, it underlines hydrogen's role as a system-balancing vector rather than a primary energy carrier.

Taken together, the exhibit shows how hydrogen fills critical niches left open by electrification: fertilisers, feedstocks and long-distance transport dominate future demand. This pattern reinforces the view that hydrogen will not replace electricity at scale, but rather serve as the essential complement where no direct electric alternative exists.

2.2 Geological hydrogen

Overview and costs

The Earth contains very large resources of naturally occurring geological hydrogen; but the range of estimates is very wide. A recent review of available data and studies suggests a most probable value of 5.6 trillion tonnes but with a lowest estimate of just one billion and an upper estimate of 10,000 trillion tonnes.[27]

This resource is however widely dispersed and only a small fraction of it is likely to be economically recoverable. The same study suggests that feasible global generation of natural hydrogen might be 15–30 Mt per annum: versus our ETC projection of total 2050 hydrogen demand of ~400 Mt. If this volume were available at a competitive cost, it would increase the likelihood that hydrogen would be competitive versus other decarbonisation options in several of the applications assumed in that scenario.

26 Discussed further in the ETC's 2025 Power Systems Transformation report.

27 Geoffrey Ellis and Sarah Gelman (2024), *Model predictions of global geological hydrogen resources*. Available at: https://www.science.org/doi/10.1126/sciadv.ado0955

Geological hydrogen involves drilling through geological layers to find naturally trapped accumulations of hydrogen or migration pathways of the gas, in a manner identical to practices in the oil and gas sector. The exact model to yield a commercial operation has yet to be proven. A number of exploration projects are ongoing for this resource, with drilling activity focussed on the US and Australia, however no commercial scale production has been discovered. Only one geological hydrogen resource has been developed to date, which is a small volume in Mali since 2023 and is used for power in a nearby village.[28] The targeted costs of geological hydrogen for the few companies that are looking to become commercial are in the range of $0.5–1 per kg H_2 by 2030. [29,30] However, little is known about detailed breakdowns of these costs and how achievable they are.

Barriers to the scale up of geological hydrogen

Geological hydrogen costs are relatively unknown, but there could be challenges with high exploration and capital costs challenges in drilling for the resource. Key technical challenges include, successfully finding commercial quantities of hydrogen in trapped and/or migrating form, accurately measuring subsurface hydrogen concentrations, identifying viable extraction methods and handling likely associated gasses (such as nitrogen, helium, carbon dioxide, methane). Given the embryonic nature of the sector, a high failure rate for exploration wells should be expected (high EXPEX) before a reliable predictive model can be developed akin to the oil and gas sector today. These factors could drive up the cost of early-stage projects. In addition, geological hydrogen may face unique logistical hurdles compared to other forms of low-carbon hydrogen. Because natural hydrogen deposits are geologically constrained, they may be located far from demand centres, potentially incurring high transportation costs. This geographic inflexibility could limit its competitiveness relative to green or blue hydrogen, which can often be produced closer to end-use sites by design.

Infrastructure limits are another barrier. Many prospective production areas are remote and distant from markets, while only about 1,700 km of hydrogen pipelines currently exist worldwide. Expanding this network faces shortages of skilled workforce and suitable materials, as pipelines require special seals and alloys to avoid hydrogen embrittlement and leakage. In addition, geopolitical risk looms large, since many projected reserves are located in central Russia. Finally, hydrogen leakage poses both technical and environmental challenges. Hydrogen is an indirect greenhouse gas with an estimated 20-year global warming potential ($GWP_{(20)}$) of around 11, largely due to its effects on methane and ozone chemistry. Given that hydrogen molecules are small and prone to leakage at higher rates than methane, robust containment, monitoring, and regulatory oversight will be essential to ensure that geological hydrogen delivers genuine climate benefits. However despite the higher potential leakage rate, overall volumes of production, at the 300–400 MtH_2 level indicated in this report, would produce around 500 $MtCO_2e$ of emissions – around 15% of the methane related warming from natural gas production and processing today.

2.3 Electrolyser system and balance of plant costs

Overview and costs

Advances in electrolyser technology and manufacturing, along with improvements in the balance of plant and design optimisation, are expected to reduce capital costs of green hydrogen over time. There are four primary electrolyser technologies in the market today. Alkaline and PEM (polymer electrolyte membrane) based technology are already at TRL 9. Less developed technologies AEM (Anion Exchange membrane) and SOEC (solid oxide electrolyser cell) are at TRL 6 and 8 respectively.[31] Advancements continue to be made in higher efficiency electrolysers (such as SOEC) and trade-offs are explored between costs and other dimensions (e.g., efficiency, stack lifetimes) to develop electrolysers with less reliance on expensive materials such as platinum-group catalysts and high-performance membranes used in AEM technology.

Aside from electricity costs, which are expected to account for over 50% of LCOH in alkaline electrolysers by 2030, the levelised cost of electrolysis-based hydrogen is largely driven by electrolyser capital costs.[32] The capital costs vary according to the types of electrolysers and are expected to reduce over time [Exhibit 2.2]. Costs are expected by 2030 to fall in the range of 30–45%, just based off of advancements in manufacturing technology, learning rates and balance of plant improvements. If fully optimised, a further 10–25% cost reduction is reported to be possible,[33] driven by maximising learning rates through successive project build outs, procuring at large volumes and rigorous design simplification. However, a large portion of total installed cost comes from Engineering, Procurement and Construction (EPC)-related expenses—such as civil works, installation, and permitting—which have historically shown low learning rates. As a result, even if electrolyser equipment costs decline significantly, the overall system CAPEX is likely to fall more modestly unless full project delivery is also optimised.

28 Hydrogen insight (2023), US offers $20m in funding for technology to improve natural-hydrogen exploration and extraction.

29 Natural gas producers earn only $0.2–0.4/MMBTU at $2.5/MMBTU prices, equivalent to about $2/kg for hydrogen when adjusted for gathering, processing and transport.

30 Hydrogen insight (2024), A new gold rush | There are now 40 companies searching for natural hydrogen deposits — up from ten in 2020..

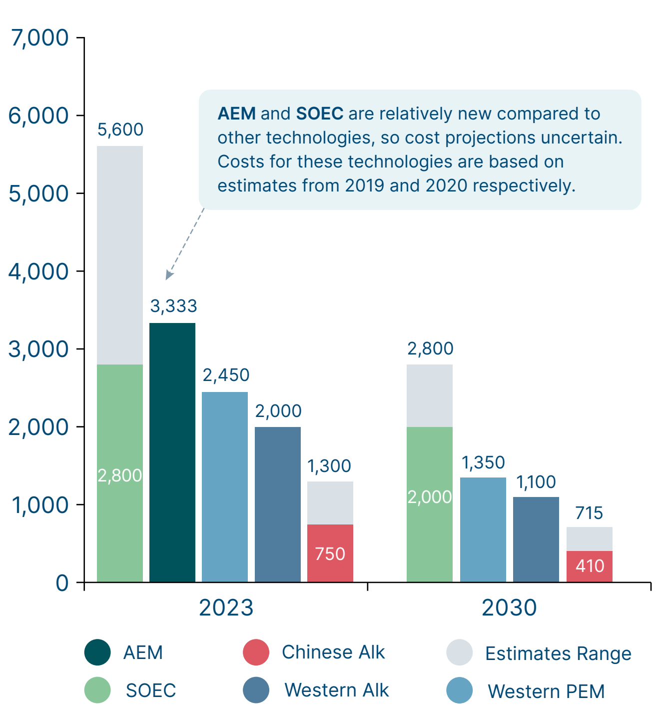
31 IEA (2024), *ETP Clean Energy Technology Guide*.

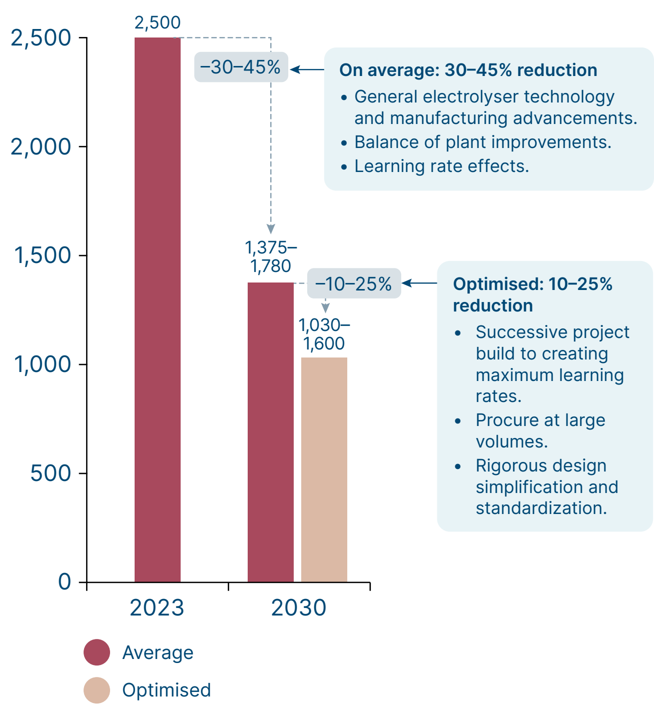
32 IEA (2024), *Hydrogen Review 2024*.

33 Hydrogen Council (2023), *Hydrogen Insights December 2023*.

Exhibit 2.2

Estimates for highly optimised electrolyser costs suggest a reduction potential of 45% cost reduction from today's levels





SOURCE: [a] Hydrogen insight (2024) Cost of electrolysers for green hydrogen production is rising instead of falling: BNEF: [b] IEA (2024), *Global Hydrogen review*; and [c] Hydrogeninsight (2024), *Capital cost of installed hydrogen electrolyzers could fall by 50% by 2030 due to economies of scale*; [d] SOEC ranges based on IEA (2023), *Electrolyzers* and HydrotechWorld (2023), *The role of solid oxide electrolyzers in the green hydrogen landscape*; AEM based on Clean Air Task Force (2023), *Solide Oxide Electrolysis: A Tecyhnology Status Assessment;* [e] Potential cost reductions in electrolyzers based on Hydrogen Council (2023), *Hydrogen Insights December 2023*.

Barriers

Electrolyser systems face challenges with reaching cost competitiveness with fossil based technologies (with and without CCS). While capital costs of electrolysers are expected to decline, the cost of electricity remains a dominant factor in the levelised cost of hydrogen. This makes access to low-cost renewable power essential. In addition, the intermittency of renewable energy poses a major challenge for green hydrogen. It affects not only the design and sizing of electrolyser systems but also increases the required capacity for renewable generation and storage to maintain a steady hydrogen output. This adds to overall system costs and complexity.

Technical barriers also persist. Stack degradation and replacement remain cost drivers. Extending stack lifetimes is still a key technical hurdle.[34] Proton exchange membrane (PEM) electrolysers also face cost barriers due to their reliance on scarce materials, more so than technologies like alkaline or AEM systems.[34] Finally, infrastructure requirements for hydrogen production at scale, such as storage, pipelines and transport, mirror those of current hydrogen routes and will require significant investment and planning.

2.4 Possible future costs of zero carbon hydrogen

Over the last five years, and in the major developed countries in particular, the cost of green hydrogen production has not fallen as fast as was initially projected. This reflects a far slower pace of reduction of electrolyser CAPEX costs than anticipated. But hydrogen developers in China and India continue to be confident of achieving low-cost green hydrogen production – e.g., below $2 per kg sometime in the 2030s. This reflects both very low renewable electricity costs in India and low electrolyser CAPEX costs in China.

34 Clean Air Task Force (2023), *Solide Oxide Electrolysis: A Technology Status Assessment*.

As a result, latest IEA estimates of the cost of producing green hydrogen suggest very wide ranges, with the estimated 2030 of green H_2 produced with solar PV ranging from $2 to $11 per kg [Exhibit 2.3].

Costs of producing grey hydrogen from natural gas, or blue hydrogen with CCS added, also show a very large range due to regional variations in the price of gas.

Overall, the IEA analysis suggests that up to 2030, green hydrogen will only be cost competitive versus grey or even blue in the most favourable locations. But developments discussed above are likely to improve the cost competitiveness of both natural and green hydrogen over time. In particular:

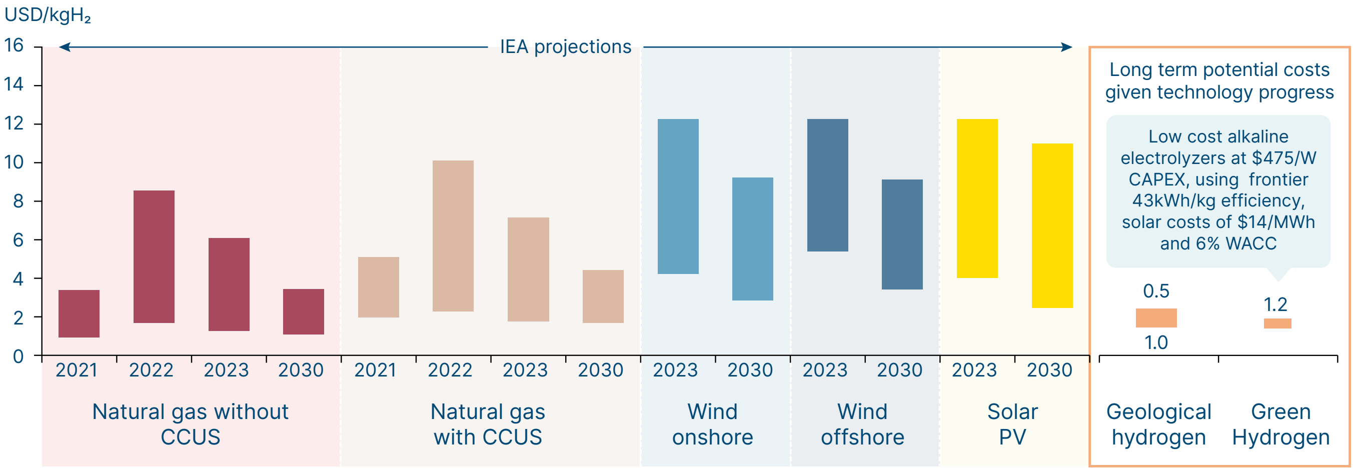
- In favourable geological settings, geological hydrogen could in principle be available at costs in the range of $0.5–1 per kg, which would be competitive with grey hydrogen in most locations. However, these estimates remain highly uncertain, as the scale of accessible reserves and the costs of extraction are still unproven.
- Green hydrogen production will eventually fall below $2 per kg in favourable locations such as China or India, given future trends in both electrolyser and renewable electricity costs. This is in line with initial estimates but at a later date than initially anticipated.

Exhibit 2.3

Potential hydrogen costs in 2030 and over the long term

Hydrogen costs[a]
$ per kg (2023)

Hydrogen production cost by pathway, 2023, and in the Net-Zero Emissions by 2050 Scenario, 2030



NOTE: CCUS = Carbon Capture Utilisation and Storage [a] There is limited evidence of the breakdown of current levelized costs and how existing projects will achieve this cost reduction for white hydrogen. Dashed area represents the CO_2 price impact, based on USD 15–140 t/CO_2 for the NZE Scenario.

SOURCE: Hydrogen insight (2024), *A new gold rush | There are now 40 companies searching for natural hydrogen deposits — up from 10 in 2020*; IEA (2024), *Global Hydrogen review 2024.*

2.5 Conclusions about the role of hydrogen

The two possible cost trends considered above, seem likely to deliver significant reductions in the cost of zero carbon hydrogen over the long-term, supporting the economic application of hydrogen and ammonia in several of the sectors shown in Exhibit 2.1, including for instance shipping and iron making as well as the main existing use in fertiliser production.

But progress in direct electrification technologies will likely continue to squeeze hydrogen out of some applications where a significant role was previously assumed e.g., heavy goods vehicle road transport. Additionally, we have not identified major opportunities to extend the role of pure hydrogen or ammonia at the expense of hydrocarbon fuel uses (e.g., in aviation).

As a result, while hydrogen will play a significant role in some sectors, including iron making and shipping, we do not assess it likely that further progress in the economics of hydrogen production or use will reduce the requirements for carbon molecules below the absolute minimum of 17% of total energy supply shown in Exhibit 1.8.

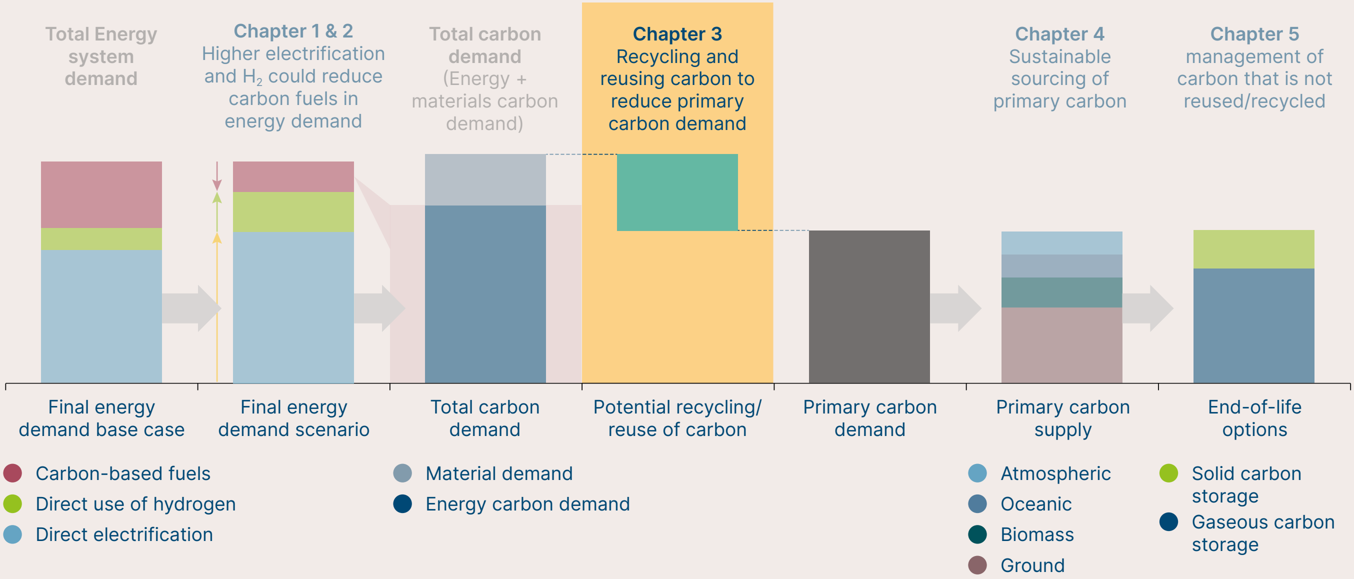
Reducing the amount of “primary” carbon in the system – carbon circularity levers that reuse, reallocate or recycle carbon

3

Exhibit 3.0

Framework for analysing demand and sourcing options for carbon in a sustainable, zero-emissions fashion

Illustrative



SOURCE: Systemiq analysis for the ETC.

Chapters 1 and 2 assessed the maximum potential to reduce the need for carbon inputs via the direct use of electricity and the use of hydrogen and non-carbon hydrogen derivatives. This demand for carbon could be met either with carbon reused and recycled within the economy, or with “primary” carbon sourced from fossil fuels, bio sources, the atmosphere or the oceans. Chapters 4 analyses the potential to source primary carbon in a truly sustainable fashion. This chapter analyses the maximum potential to reduce primary carbon demand through reuse and recycling within the economy, which is critical since fossil feedstocks have been the main driver of rising oil, gas and overall fossil fuel demand over the past 5–10 years.[35] As outlined in Exhibit 3.1, this chapter covers:

1. **The potential to reduce demand via elimination, reuse and substitution.** We focus primarily on the potential in plastics but also assess the more limited potential for other materials.
2. **The role of advanced sortation technology.** This is not in itself a recycling technology but a key enabler of both mechanical and chemical recycling.
3. **The maximum potential for mechanical recycling of plastics**, which involves physically processing waste materials into new products without altering their chemical structure.
4. **The potential for increased chemical recycling and thermo conversion,** which converts waste (in particular plastics) into chemical building blocks.
5. **The potential role for various forms of carbon capture and utilisation**, which can reduce the demand for primary carbon by using the same carbon molecules for more than one economic activity.

A “maximum circularity” scenario is generated and its implications and potential impact for total primary carbon demand are assessed.

35 IEA (2025) Oil 2025 - *Analysis and Forecast to 2030.*

Exhibit 3.1

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

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

Lever	Actions	Relevant technologies	Enablers
Reduce demand	Eliminate, Reuse, Substitute	• AI lightweighting and optimisation tech. • New re-use technology & delivery models.	
Recycle material	Physical or mechanical recycling of material	• Mechanical recycling. • Solvent-based recycling.	Actions: Design for recycling, sortation, collection.
Recycle carbon	Chemical recycling of material and thermo conversion	• Depolymerisation. • Pyrolysis. • Gasification.	Technologies: • Track and trace, material passports. • Advanced AI and robotics sorting.
	Utilise waste CO_2	• Hydrogenation to methane or methanol. • Electrochemical reduction. • Reverse Water Gas shift. • Biocatalysis. • Plasma-catalytic treatment.	

NOTE: Biocatalysis includes enzyme catalysis and whole-cell bioconversions, including gas fermentation, within the broader scope of biomanufacturing.

SOURCE: Systemiq analysis for the ETC (2025).

3.1 Demand reduction: elimination, reuse and substitution

Overview

Before recycling, demand reduction measures can directly reduce the volumes of carbon-intensive materials needed to deliver the same functions. These are upstream circularity strategies, targeting the design and consumption phases of products rather than post-consumer waste management.

Demand reduction can be categorised into three levers:

- **Elimination**: removing excess materials or resources in products when they are unnecessary (e.g., in automotive and construction, where safety margins often lead to overuse).
- **Substitution**: Replacing single-use materials with either lower-carbon density alternatives (e.g., cardboard) or more durable materials (e.g., changing single use plastic cutlery to stainless steel).
- **Reuse**: Extending the lifespan of materials without changing their composition (e.g., replacing single use items with more durable products of similar carbon content).

Together, these measures have the potential to reduce demand for primary carbon molecules in the materials sector. Among them, as shown in Exhibit 3.2, reuse is likely to be the most significant demand reduction lever. This is especially true in the packaging sector, which is the largest driver of demand for chemicals.[36]

Reuse of materials can be classified into three broad modalities:

- **Recommerce:** Extending product lifespans by enabling multiple ownership cycles (e.g., second-hand markets). This model is expected to scale most notably in textiles, reaching up to 25% market share of the fashion industry by mid-century.[37] This only represents a small proportion of total demand.

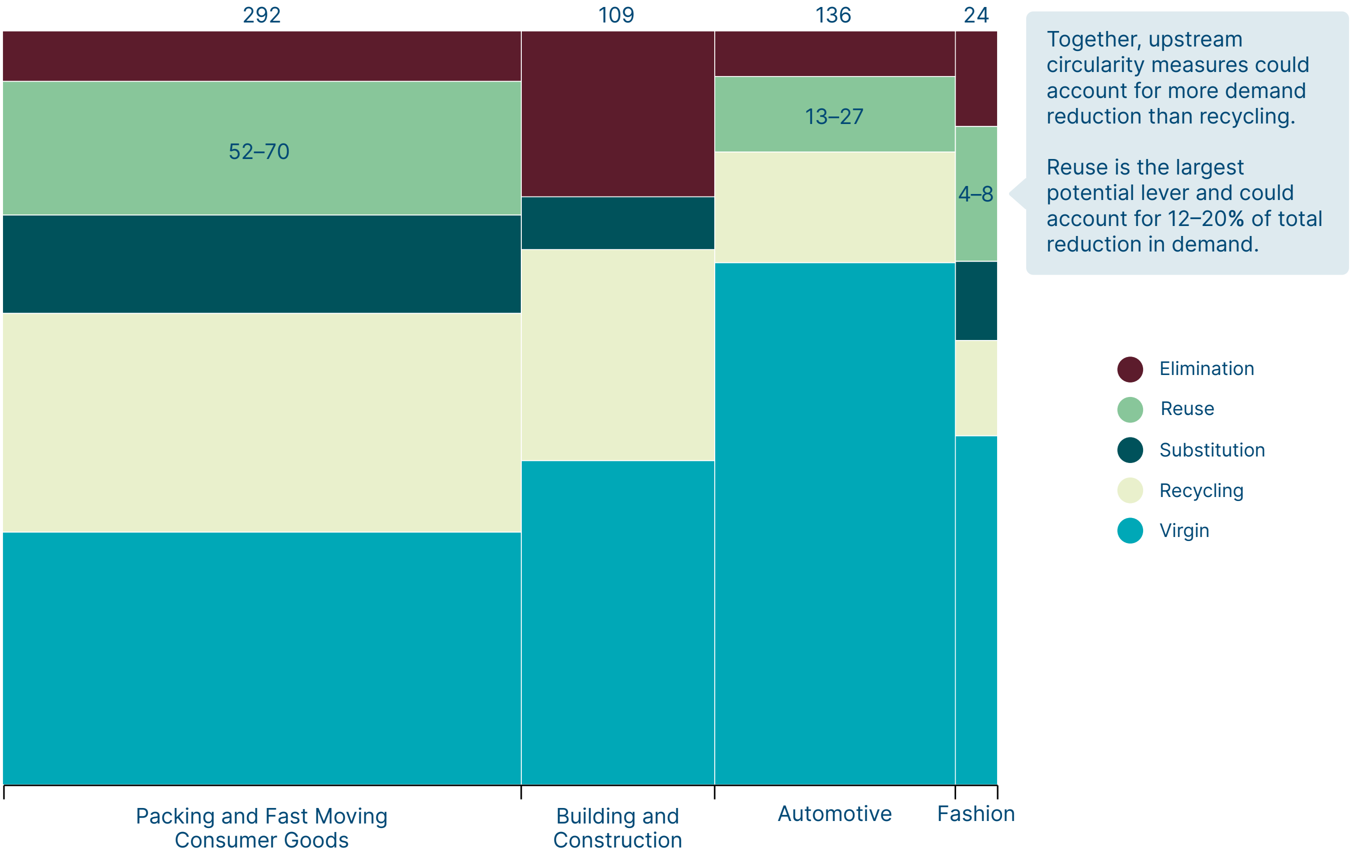
36 Systemiq analysis for the ETC (2022), *Planet Positive Chemicals.*

37 Thredup (2023), *Resale Market and Consumer Trend Report.*

Exhibit 3.2

Reuse models could reduce mid-century chemicals demand in three of the top plastic using sectors

Potential for chemical demand to be met through circularity across key downstream industries, 2050
Mt petrochemical intermediates



NOTE: Reuse is defined as "where a product's utility is still valued but its delivery through a new business model requires less material for the same output."

SOURCE: Systemiq (2022), Planet Positive Chemicals; ETC (2025), Achieving Zero carbon Buildings.

- **X-as-a-Service (XaaS):** Shared-use business models that replace individual ownerships (e.g., Uber for cars, WeWork for buildings, laundromats for white goods). XaaS has a large potential coverage, as it is applicable across most industries. Although we are seeing shifts to rental and sharing economies, notably in the transport sector, it is assumed that XaaS faces a scalability "ceiling" due to behavioural inertia in the short to mid-term. Consumers are likely to replace single-use plastic bags more readily than giving up ownership of homes, clothes or cars.
- **Reuse of packaging:** Services and business which provide the utilities previously furnished by single-use items, while using the same materials. This includes refill and return systems in the consumer and business-to-business sectors.

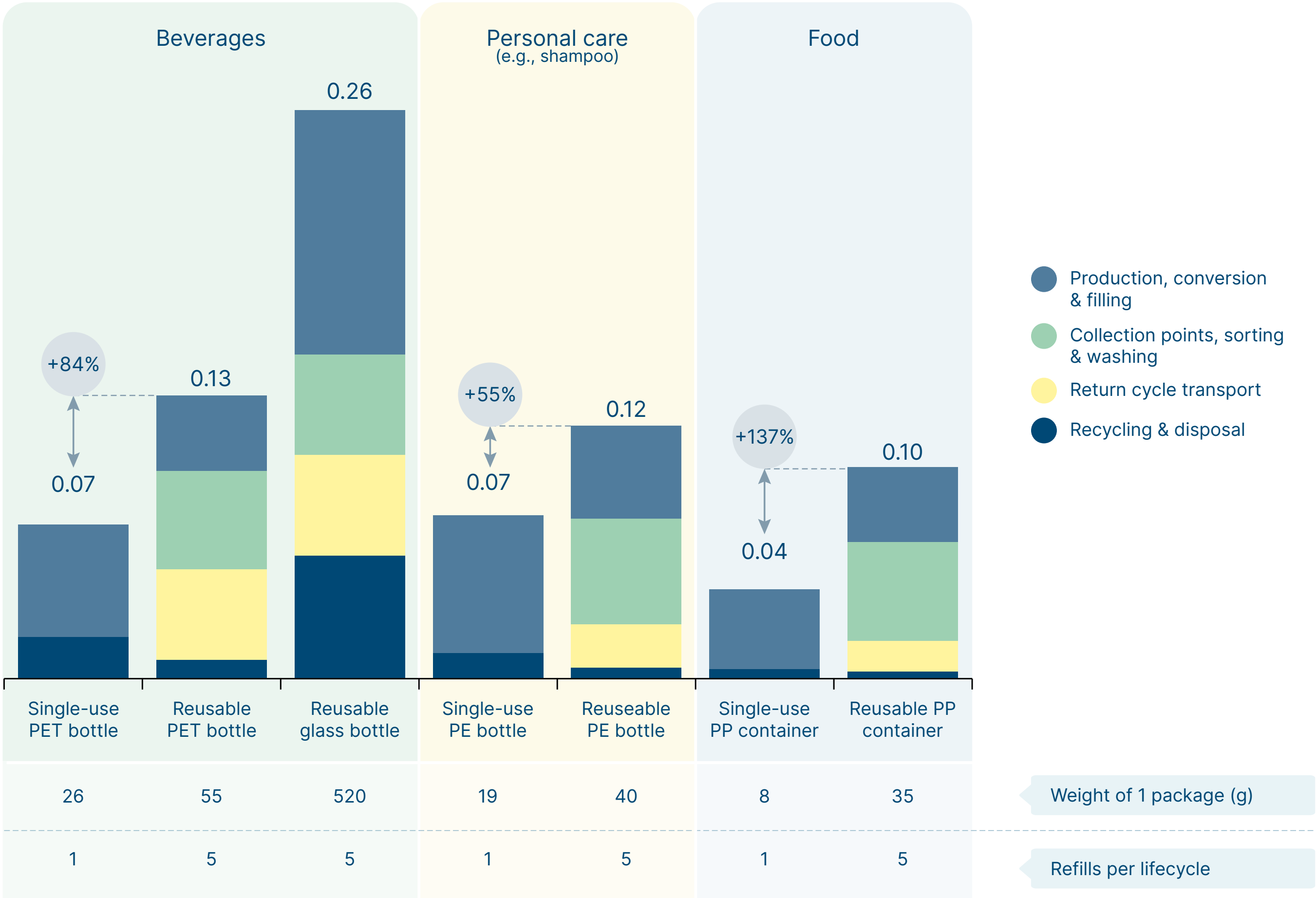
While reuse covers a wide range of use models, the reuse and refill of packaging has the largest potential for demand reduction. Packaging reuse is not new. Many examples, such as refilling pantry items from a dispensary, have only been displaced by single-use packaging in the last 50 years. In general, reuse models have been (re) emerging across consumer goods sectors.

Costs of reuse business models

Brands are beginning to experiment with new "reuse" business models. These require rethinking, adding complexity to supply chains and additional operational expenses for the collection, transport, cleaning and refill of packaging. Reuse also implies changes for the specifications for the packaging itself, which must be able to withstand and facilitate multiple refill and return cycles while remaining visually and chemically unaltered. Exhibit 3.3 shows a total system cost-per-use analysis of the economic impact of shifting from single-use to reusable packaging. Despite the

Exhibit 3.3

Cost of new delivery models vary between materials and uses, but transport and reprocessing costs lead to a 55–137% increase above cost of single use



NOTE: Reuse model assumes return rates of 80%, and lifecycle of 5 uses for reusable items. Costs for entire system, based on EU data. PE = Polyethylene. PET= Polyethylene Terephthalate, PP = Polypropylene

SOURCE: Ellen MacArthur Foundation(2023), *Unlocking a reuse revolution: scaling returnable packaging (2023)*.

averaging of production and disposal costs across successive uses, the additional operations trigger cost increases ranging from 55–135% [Exhibit 3.3]. The difference in cost deltas across sectors is driven primarily by the new requirements for durability and washability of packaging.[38] The cost increase is greater for heavier materials (e.g., food packaging vs. personal care), with extreme cases like switching from plastic to glass showing a significant cost rise.

Despite initial cost challenges, economies of scale can drive significant cost reductions [Exhibit 3.4]. The high barriers to entry – needed to establish new supply chains, cleaning and refill technologies – could be mitigated via economies of scale. This includes:

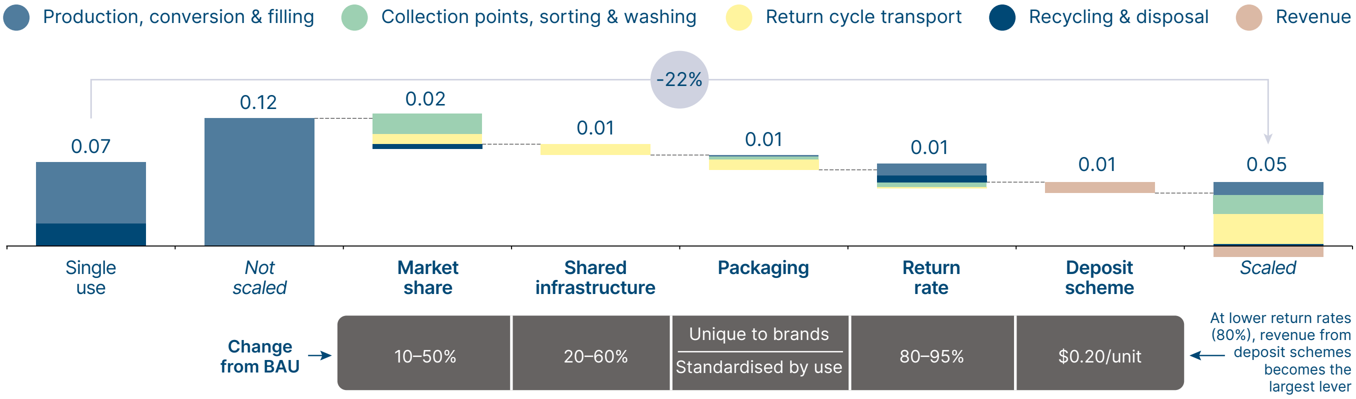
- **Market share expansion:** More companies participating in reuse increases efficiencies.
- **Shared infrastructure:** Shifting from company-specific supply chains and cleaning and refill infrastructure to collectivised infrastructure shortens supply chains, as trucks are able to travel to the nearest available processing plant.
- **Standardised packaging:** Using common formats for beverage bottles or food packaging enables centralised cleaning and refilling across brands, optimising operational costs. While this may seem like an ambitious measure, there is precedent. For example, all beverage bottles have the same size of neck opening to be able to use standardised refill equipment.

38 Ellen MacArthur Foundation (2023), *Unlocking a reuse revolution.*

Exhibit 3.4

High collection and processing costs drop with scale and consumer incentives, resulting in ~22% cost savings vs single use when at scale

Levers for cost reduction, new delivery models for beverage bottles
USD/use



NOTE: % changes in levers based on stretch scenario from source.

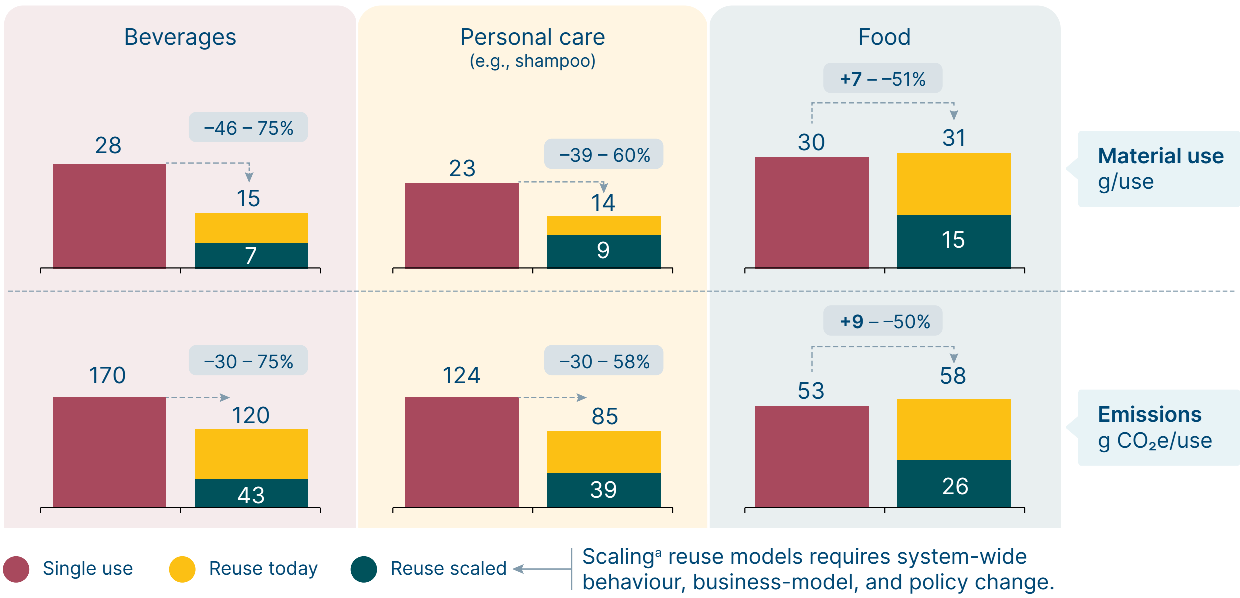
SOURCE: Ellen MacArthur Foundation (2023), *Unlocking a reuse revolution: scaling returnable packaging*.

Impact

Similar to costs, the carbon-reduction potential of reuse models also depends on the scaling of the system. Exhibit 3.5 shows that reuse has a substantial impact on emissions reduction and material demand; when it is done at scale, this is true across all sectors. However, fragmented adoption limits impact—especially in food packaging. Reuse systems reduce emissions from both production and end-of-life disposal, as these are spread across several uses. Additional emissions from increased transportation, cleaning and refill are minimal, and could be close to zero in a clean grid, electrified mid-century future.[39] Taken together, scaled reuse offers a dual benefit: it cuts emissions and reduces overall costs, making it a compelling option for sustainable, cost-effective systems change.

Exhibit 3.5

Reuse can offer material and emissions savings for packaging in all sectors, at costs that are cheaper than or equivalent to single use systems – but only at scale



NOTE: [a] Lowest cost = result of all levers on previous slide being applied.

SOURCE: Ellen MacArthur Foundation (2023), *Unlocking a reuse revolution: scaling returnable packaging*.

39 Ellen MacArthur (2019) *Reuse – Rethinking Packaging*

Barriers and Enablers

Despite promising economics and emissions reduction potential, regulatory and behavioural inertia remains a significant barrier to scaling reuse. Reuse models are not unattractive to business: subscription models offer businesses a captive consumer base and valuable data insights on product usage.[40] However, being a first mover in a fragmented system, is costly and requires betting on customer buy-in and long-term revenue models, rather than immediate returns on investment. Without coordinated policy, action from Fast Moving Consumer Goods, and brands and retailers, consumer-driven change will be slow and incremental. However, implementing these changes for businesses are not operationally simple.

Some policy efforts to encourage reuse exist such as the EU Packaging and Packaging Waste Regulation, setting mandatory reuse targets for specific sectors. Some countries, like Germany and the Netherlands, have implemented sector-wide deposit return schemes for beverage containers—with great success. The UK has implemented charges for single-use carrier bags in supermarkets. These policies are very localised, mostly in the EU and limited in scope. Despite this, they may remain best-in-class examples, since most other consumer-facing policies tend to be unpopular with voters. Scaling reuse, therefore, presents a system-change quandary: without behaviour change and direct consumer demand, it relies on ambitious policy. Passing more ambitious reuse policy, however, may require both political and social will to shift over time.

3.2 Advanced sortation

Overview

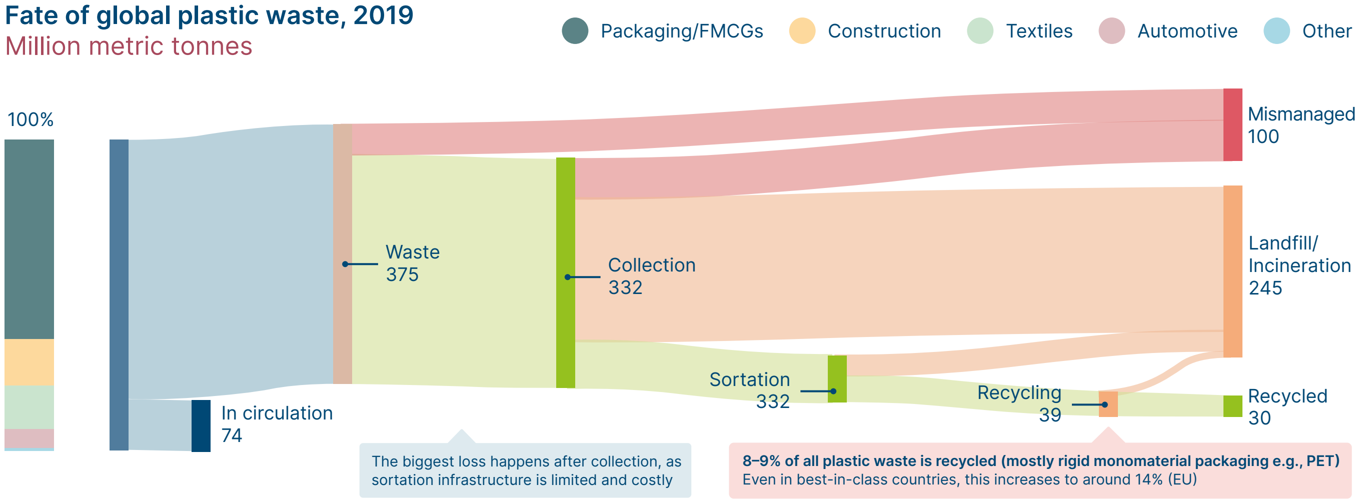
Currently, only 9% of plastic waste even reaches a recycling facility, and in the best-performing countries, this figure is still just 14%.[41] As shown in Exhibit 3.6 sortation is currently a system bottleneck in the plastics system. The biggest loss of material that could be recycled occurs after collection, primarily due to limited economic demand for sorted waste, limited segregation of waste at the collection stage, and insufficient sortation infrastructure. The 43% of the sorted waste is getting landfilled or incinerated. Material Recovery Facilities (MRFs) are few, small-scale and not operating at full capacity due to complex economics.[42]

In a complex sector with "traditional" MRF set-ups ranging from fully-manual sortation line to sensors able to identify clear plastic bottles, untangling the innovations that could transform the system is difficult. "Advanced sortation" encompasses a range of technologies across the value chain, as shown in Exhibit 3.7.

Exhibit 3.6

A majority of plastic waste does not get sorted for recycling – only 8–9% of all plastic waste is recycled

Fate of global plastic waste, 2019
Million metric tonnes



SOURCE: Systemiq (2024), *Plastic Treaty Futures*; Systemiq analysis for the ETC; Systemiq (2022), ReShaping Plastics, Systemiq (2020), Breaking the Plastic Wave; and Systemiq (2022), Plastic IQ, Geyer R, Jambeck JR, Law KL. Production, use, and fate of all plastics ever made. Sci Adv. 2017 Jul 19;3(7), Our World in Data (2024), *Plastic recycling rates are increasing, but slowly, in many regions.*

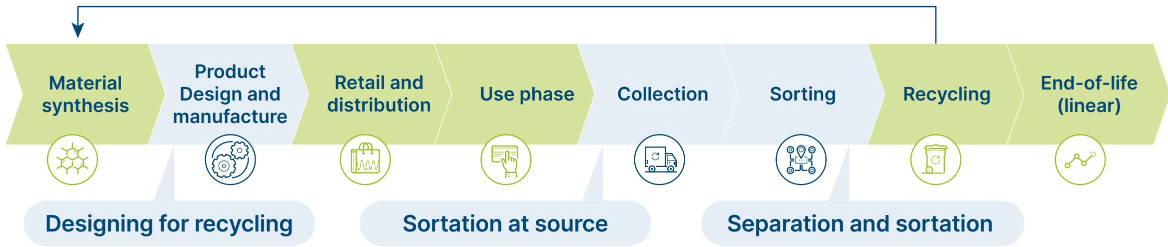
40 Ellen MacArthur (2019), *Reuse – Rethinking Packaging.*

41 Systemiq (2024), Plastic Treaty Futures.

42 TOMRA (2022), *Breaking the bottlenecks of recycled plastic content.*

Exhibit 3.7

Digitalisation, advanced sensors, and artificial intelligence are driving a new technology wave in sortation



	Designing for recycling	Sortation at source	Separation and sortation
Current system	• Single-material items	• Manual waste segregation	• Mechanical sortation • Manual sortation
Digitalisation and AI-enabled technologies	• Digital sorting watermarks • Photonic markers • Blockchain technology	• Smart bins	• High-tech sensors • Robotic sorting • Optimising process per load of feedstock

Examples
Not exhaustive

SOEX GLACIER greyparrot AMP ROBOTICS TOMRA

Costs and Impact

Industry analysis[43] show that final yield (recovery rate) of recyclable product can increase by 25% in advanced facilities versus an average existing facility. This increase in yield applies only to waste that already reaches sortation facilities. In today's system—where relatively low volumes are collected and sorted—this would increase global recycling rates from around 9% to 12% in the future.[44] However, in a future system where downstream infrastructure is scaled and a greater share of waste reaches advanced sorting, the impact could be significantly larger—both in absolute terms and as a share of total plastic waste.

This hypothetical increase in yield is driven by a series of small improvements:

- Fewer losses of valuable materials due to advanced sensors and rapid sortation technology.
- Better sortation of difficult plastics, including: coloured plastics, flexible plastics, contact-sensitive plastics.
- Lower rates of contamination due to faster response rates (AI-enabled systems are capable of reaching speed of 140 picks per minute, 200% of current system speeds).[45]
- Higher purity and therefore grade of recyclate bales (compressed blocks of sorted plastic ready to be sold to recycling plants). This limits need for further sortation at recycling plants and is the largest potential yield increase.

Potentially more important than the incremental improvements in efficiency and accuracy of sortation, advanced sortation may improve the economic viability of the sortation sector. Currently, sortation facilities operate most often at a loss.[46] The sector is heavily subsidised, and MRFs are often running below capacity due to the combined pressures of high labour costs and the low, fluctuating value of recyclate. As Exhibit 3.8 shows, advanced sortation can improve the revenue of the sector with limited impact on costs. Although these technologies involve higher capital and energy expenditure, such costs can be offset by decreased labour requirements, improved efficiency and savings on disposal fees. Additionally, improved recyclate quality and yield can generate higher revenues in the commodity market. While these improvements can significantly strengthen the business case for MRFs, some level of subsidy is likely to remain necessary elsewhere in the value chain, such as during collection or recycling stages, as recognised in policies like Extended Producer Responsibility (EPR). [47]

43 Recycleye (2024), *How AI robots reduce costs of waste sorting*, Eunomia (2024) *Advanced Sortation for Circularity*.
44 Systemiq analysis for the ETC.
45 AMP robotics (2022), *AMP Robotics Achieves Data Milestones and Recycling Automation Breakthrough.*
46 PWC (2022), *Plastic Pathways.*
47 Recycleye (2024) *How AI robots reduce costs of waste sorting*

Exhibit 3.8

Despite higher energy and capex costs, advanced sortation systems unlock operational efficiencies and drive revenue growth

Cost of waste processing in an Material Recovery Facilities
$/t waste

NOTE: Based on 70,000t MRF in Michigan 2023). CAPEX: Included cost of building and machinery, amortised over 20 years. Advanced MRF assumes addition of two sensor + robot machinery, costing $12,000,000 each. Energy: Assumes increase of 20–70%. Electricity cost: Low: ~$40/MWh, High: ~$80/MWh. Residual disposal fees: Assumed $80/t gate fee. Revenue: Assumes 25% higher yield and 20% higher value in AI MRF.

SOURCE: Michigan State (2023); *MoA Material Recovery Facility Feasibility Study*; Recleye (2024), *How AI Robots help reduce the cost of waste sorting in MRFs*; Systemiq (2022); *ReShaping Plastics*; Bradshaw SL, et al. (2025). *Material Recovery Facilities (MRFs) in the United States: Operations, revenue, and the impact of scale.*

Barriers and enablers

The main barrier to scaling advanced sortation is the widespread absence or underdevelopment of basic sortation infrastructure. In many regions, recyclable waste is collected through co-mingled systems and often sent directly to disposal. In these cases, there is limited value in applying advanced technologies when the foundational systems are missing or ineffective. Scaling sortation will require significant policy support, including direct investment in infrastructure and indirect measures such as mandates for separate collection and improved waste segregation.

These include:

- Direct policy interventions—setting clear targets and subsidising the sector, mandating separate collection streams (e.g., plastic vs. organic waste) and providing capital grants or tax credits for facility upgrades.
- Indirect policy interventions to improve economics: EPR—shifting financial and operational accountability for waste to producers and carbon pricing mechanisms that internalise the climate cost of incineration and landfilling.

Advanced sortation may enable system change beyond costs as it fits into the broader waste management picture.

- Provides greater system visibility—enabling better product design, infrastructure planning and collection optimisation.
- Most importantly, supports policy and system changes needed to scale sortation in the first place.

3.3 Mechanical recycling

Overview

Physical and mechanical recycling encompasses two primary technologies: mechanical recycling and solvent-based recycling. Mechanical recycling involves physically processing waste materials into new products without altering their chemical structure. This process typically includes sorting, cleaning, shredding and/or melting the materials. Solvent-based recycling, on the other hand, uses chemical solvents to dissolve and separate the components of waste materials, allowing for the recovery of pure polymers that can be reprocessed into high-quality products. One practical example of this is the recycling of end-of-life vehicles, where shredded material is treated with solvents to separate plastic fractions from complex residue streams. This approach allows for the extraction of relatively pure polymers from otherwise hard-to-sort mixtures. Mechanical recycling remains the most advanced technology in terms of maturity [see Exhibit 3.9], but only for a limited range of plastic feedstock types.

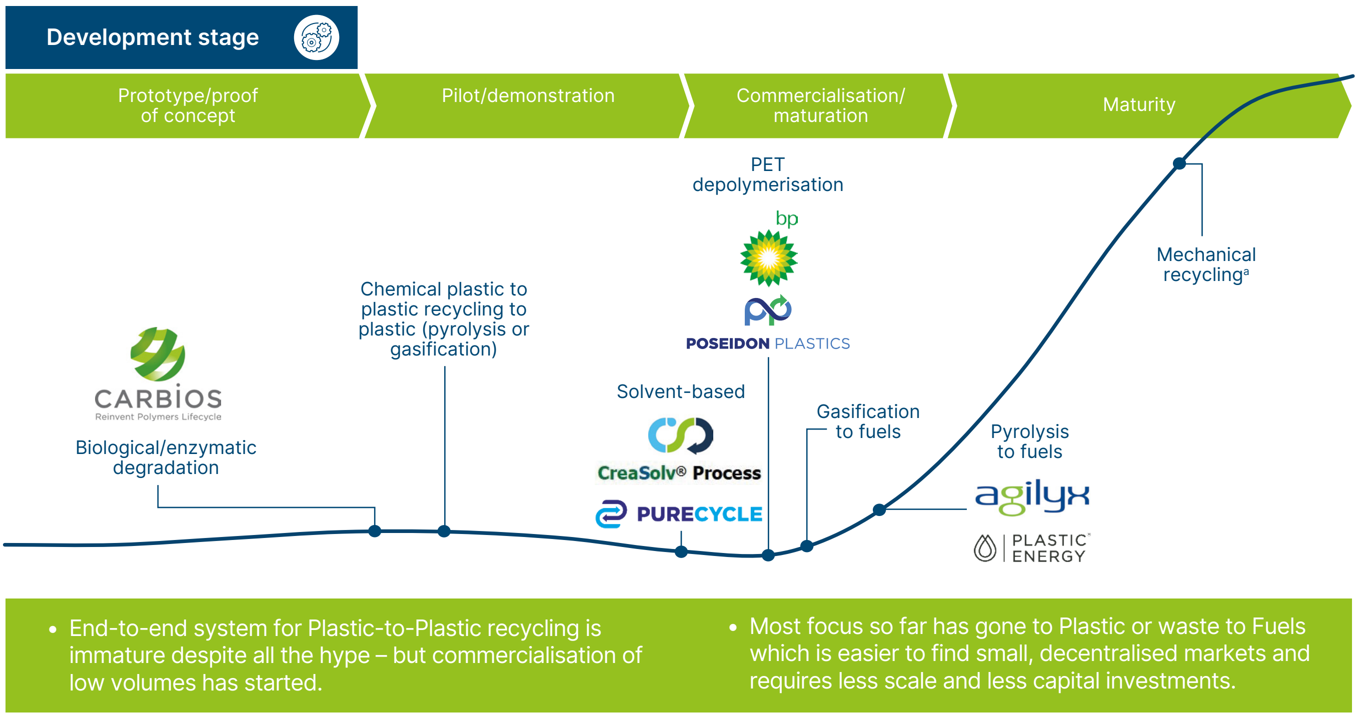
Barriers

Despite mechanical recycling being a well-established technology, it faces several challenges that limit its scalability. One major issue is the degradation of polymer properties due to heat, mechanical stress and oxidation during the recycling process. This degradation can reduce material performance, making recycled plastic less suitable for certain applications. For food-grade mechanical recycling, the primary barrier is contamination risk rather than polymer degradation. This is typically managed through strict input controls, as seen in PET (polyethylene terephthalate, commonly used in beverage bottles and food packaging) recycling. Additionally, since most mechanical recycling today involves only one cycle of previously virgin plastic, it remains uncertain how many times a material can be recycled before losing its essential properties in real-world conditions. In controlled laboratory settings, scientists have managed to recycle an HDPE (high-density polyethylene, widely used in milk jugs, detergent bottles and rigid containers) bottle up to 10 times.[48]

Exhibit 3.9

Different recycling technologies are along the maturity curves, with mechanical recycling the most advanced commercially

Plastic and chemical recovery technologies and their maturity (examples)
Maturity curve for technologies



NOTE: [a] For a limited range of plastic feedstock types.

SOURCE: Systemiq analysis for the ETC (2025)

48 Plastics today (2018), *Scientific tests prove HDPE can be recycled at least 10 times.*

Another majority challenge for mechanical recycling centres around feedstock sensitivity. Mechanical recycling requires high levels of purity and contaminated plastics either cannot be recycled or are recycled into lower-grade applications. Consequently, the output of what is mechanically recycled, is often converted into non-contact sensitive materials,[49] such as polyester for textiles, plastics for furniture or the built environment, or strapping and packaging, in a process known as "open-loop" recycling.[50]

Several cycles of closed-loop[51] recycling collecting and reprocessing waste into the same product at similar quality, so the material stays in a continuous cycle are technically feasible, but they require high levels of advanced sorting and cleaning. Design for recycling will also play a crucial role in scaling mechanical recycling. Bottles and rigid packaging (so-called "rigids"—durable, hard plastics such as bottles, tubs and containers) are more easily recycled in a closed loop than flexible or easily contaminated plastics, such as household goods and construction materials. Multi-layer multi-material (MLMM) products are virtually impossible to mechanically recycle, further complicating the process with many products being a combination of different materials and sometimes as a necessity. By shifting from complex, compound polymer designs to simple mono-material rigids with minimal additives, colourings and plasticisers, the quality of recyclate is increased.

Another significant barrier to mechanical recycling is the business case. While mechanical recycling provides environmental benefits, the economic viability can be challenging. The costs associated with sorting, cleaning and processing plastics can be high, and the market value of recycled plastics is often lower than that of virgin plastics[52] because of the abundance of low-cost naphtha fossil feedstock. However, in a market where fossil feedstock is scarce or its life-cycle carbon impact is priced appropriately, the business case for mechanical recycling could be far more compelling. This disparity can make it difficult for businesses to justify the investment in mechanical recycling infrastructure today. Some investments are being made today, but mostly in easier-to-recycle segments such as PET bottles. Additionally, fluctuations in the price of virgin plastics can impact the competitiveness of recycled plastics, further complicating the business case for mechanical recycling.[53]

Enablers and potential impact

Mechanical recycling can be significantly enabled through a multifaceted approach that addresses the entire material lifecycle. Key enablers include investing and improving more waste collection, and sorting systems and infrastructure to ensure material makes it to recycling facilities. Additionally, coordination among stakeholders in the value chain is needed to ensure best in class recycling infrastructure and policies that incentivise circularity. Key policies would include, but are not limited to:

Policies and targets:[54]

- Reduce virgin plastic volumes.
- Increase collection and recycling in developing countries.
- Ban plastics designed for single use and hard-to-recycle plastics.
- Design rules for safe re-use, repair and recycling (e.g., the EU's packaging and packaging wate directive include requirements for the design of packaging to facilitate re-use and recycling).
- EPR schemes and/or unrecyclable plastic fees (e.g., EU plastics levy).

In a highly ambitious scenario by 2040, Plastic Treaty analysis undertaken by Systemiq estimates that mechanical recycling grow five times, from levels today of ~30 Mt to183 Mt (open and closed loop mechanical recycling) by 2040 [Exhibit 3.10].

49 Non-contact sensitive means materials that are not intended to come into direct contact with products that require high safety and hygiene standards, such as food, beverages, cosmetics and medical products.

50 Systemiq analysis for the ETC (2023), *Circularity of PET/polyester packaging and textiles in Europe.*

51 Closed-loop recycling refers to collecting and reprocessing waste into the same product at similar quality, so the material stays in a continuous cycle.

52 AMTOP (2024), *Difference between virgin plastic and recycled plastic.*

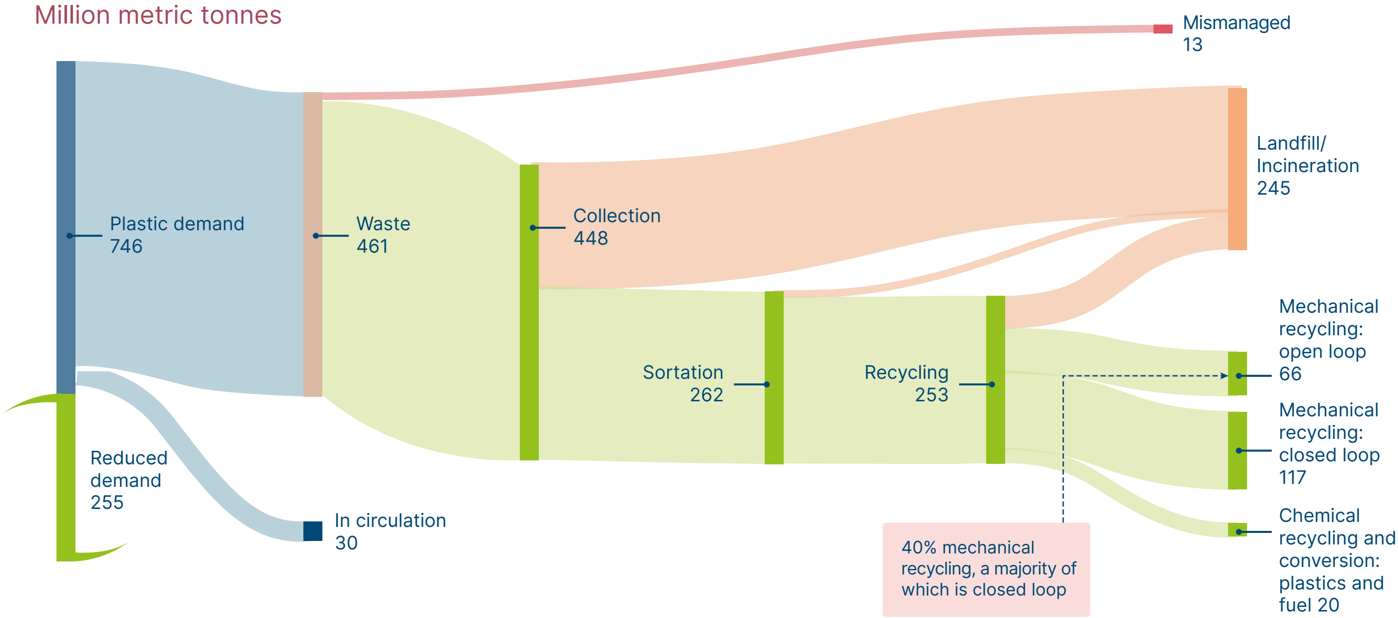
53 IEEF (2024), *Impact on Virgin vs Recycled plastics prices and implications for a production cap.*

54 Systemiq (2024), *Plastic Treaty Futures.*

Exhibit 3.10

In an ambitious scenario, the share of waste ending in mechanical recycled is expected to grow through to 2040, driven by policies

Fate of global plastic waste, 2040
Million metric tonnes



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

3.4 Chemical recycling and thermo conversion

Overview

Chemical recycling and thermo-conversion offer a pathway to reduce reliance on virgin fossil-based feedstocks by converting waste (especially plastic) into virgin materials or valuable chemical building blocks. Unlike mechanical recycling, which degrades plastic quality over successive cycles, these processes break down polymers into their fundamental components. Once in this form, the material can either be chemically recycled back into new plastics and chemicals (closed loop, i.e. material-to-material) or thermo-converted into other products such as fuels, for example, methanol for shipping.[55]

There are some select emerging technologies for chemical recycling/thermo-conversion, with three fundamental approaches that dominate the current landscape: depolymerisation, pyrolysis and gasification. Each process yields different chemical products, as illustrated in Exhibit 3.11. In this analysis:

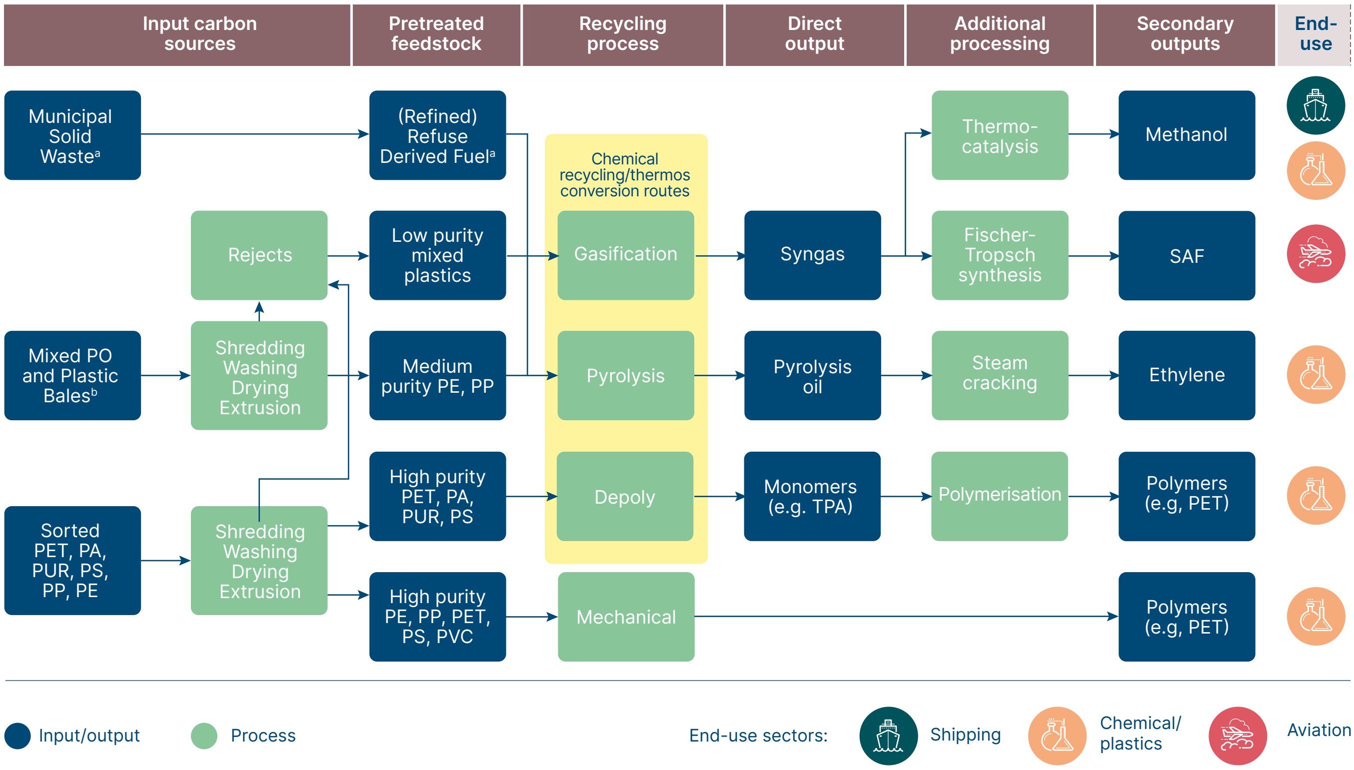
- Depolymerisation is assessed based on PET production. PET depolymerisation holds the highest market potential and is more mature application compared to the lower recycling volumes and more difficult processing of Polyurethane (PUR) and Polystyrene (PS).
- Gasification is evaluated based on methanol production via syngas formation. However, the process offers product versatility: in combination with gas fermentation, ethanol and other high-value products can be produced.
- Pyrolysis is analysed in terms of High-Value Chemicals (HVC), specifically ethylene.

These technologies have the potential to complement mechanical recycling by processing contaminated and mixed plastic waste streams that would otherwise be incinerated or landfilled. The choice of an appropriate chemical recycling/thermo-conversion process depends primarily on the costs, the feedstock characteristics and the desired product. Exhibit 3.12 provides the different advantages and disadvantages of each technology. In practice, the limited availability of uncontaminated or sorted feedstocks, and the demand for recycled content with virgin-like quality, risks placing mechanical and chemical recycling pathways in competition rather than alignment. This dynamic may challenge the optimal allocation of waste streams and the scaling of both technologies simultaneously.

55 Ragaert et al (2023), *Clarifying European terminology in plastics recycling.*

Exhibit 3.11

Chemical recycling and thermo-conversion pathways differ by their outputs and end-use sectors



NOTE: PET = Polyethylene terephthalate, PA = Polyamide, PUR = Polyurethane, PE = polyethylene, PO = Polyolefins, PS = Polystyrene, PVC = Polyvinylchloride SAF = Sustainable Aviation Fuels [a)] Municipal solid waste (MSW) might be used as gasification feedstock but with low efficiency. Upgrading to Refuse Derived Fuel (RDF) is a better feedstock, especially if refined for high PO contents for pyrolysis. [b)] Includes PE, PP, PET, traces PS, multilayer flexibles (i.e. originated from different plastic-based aluminum and paper layers) and clogged materials (i.e; plastic items inside or tied up with others).

SOURCE: Systemiq analysis for the ETC (2025)

Exhibit 3.12

Overview of primary chemical recycling/thermo-conversion technologies, including key advantages and disadvantages

	Depolymerisation	Pyrolysis	Gasification
Description	Breaks plastics into monomers for reuse in polymerisation; enables closed-loop recycling.	Thermally breaks down plastics without oxygen to produce oil and gas that can be refined into valuable chemical feedstocks, including plastics.	Converts plastics into syngas (H_2 + CO) for use in chemical and polymer production.
Advantages	• Enables high-quality closed-loop recycling. • Integrates well with PET production lines.	• Handles mixed plastics and minor non-plastics (<7 wt%)[b]. • Can link to existing steam crackers in petrochemical setups.	• Accepts mixed and contaminated waste streams. • Produces versatile syngas for industrial use.[d]
Challenges	• Can't handle mixed or contaminated waste.[a] • Feedstock preparation can be energy intensive for certain plastic types and technologies.	• Needs <0.3 wt% PVC, requiring heavy pre-treatment.[c] • Difficult to scale. • Energy and GHG intensity can be high.	• Needs high waste volumes to be viable. • High technical risk and costly to build and operate. • Energy and GHG intensity can be high.

SOURCE: Bohre et al. (2023), *Chemical Recycling Processes of Waste Polyethylene Terephthalate Using Solid Catalysts*; Adam Gendell and Vera Lahme (2022), Feedstock Quality Guidelines for Pyrolysis of Plastic Waste; Eunomia (2020), *Chemical Recycling: State of Play*; Bashir et al. (2025), Plastic waste gasification for low-carbon hydrogen production: a comprehensive review.

Costs

While the levelised cost of production for these technologies varies significantly, all face a significant premium when compared with their fossil based-alternative. Key cost drivers include capital and operational expenditures, feedstock and pre-treatment requirements, energy use and the potential revenue from by-products. Exhibit 3.13 compares the levelised cost of production of each process with its fossil-based alternative.

Feedstock costs are one of the major cost drivers in chemical recycling and thermo-conversion, with significant differences between the three technologies:

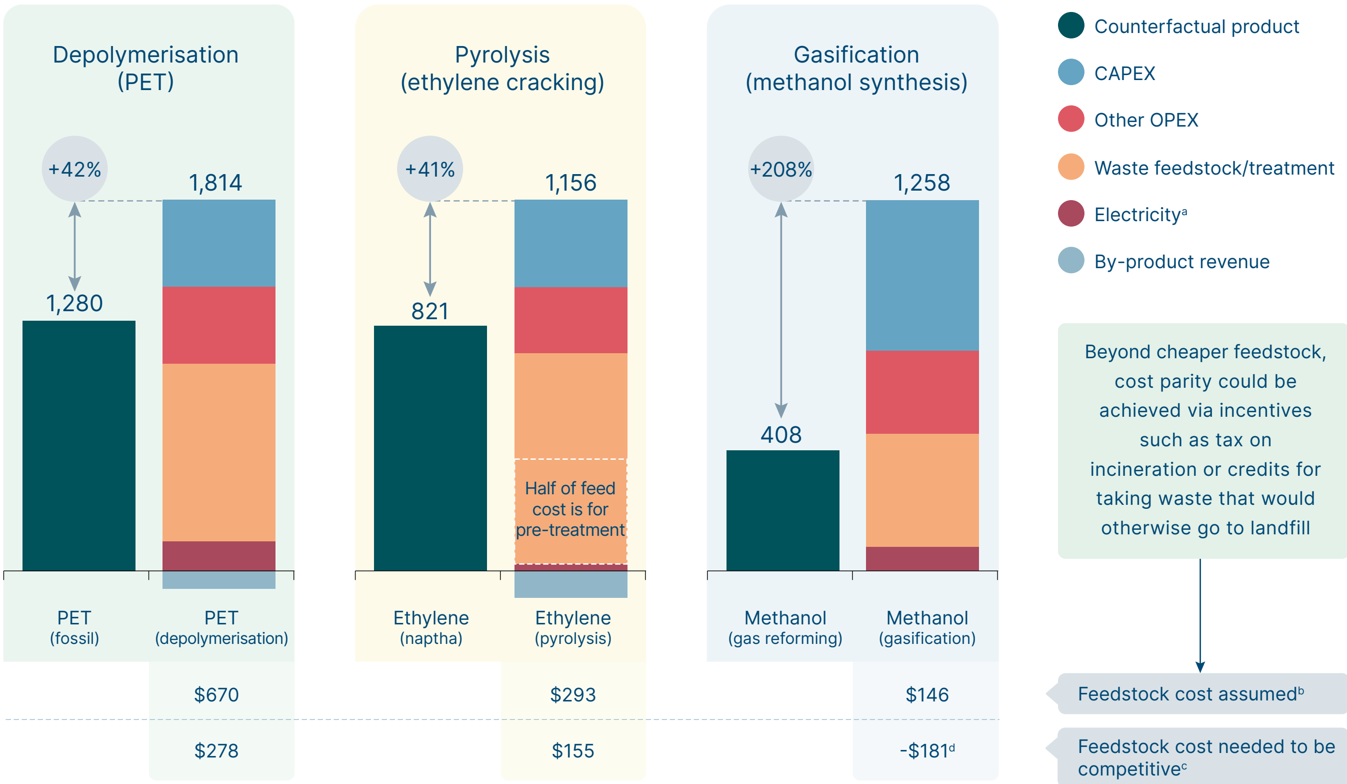
- Depolymerisation: Requires high-purity PET flakes, often introducing additional purification steps and making it more expensive. Treatment costs are significant but necessary to ensure high efficiency and reliable operation.
- Pyrolysis: Feedstock costs fall in the middle range, but pre-treatment is substantial, contributing around half of total costs.
- Gasification: Can process highly contaminated waste, resulting in the lowest feedstock cost. However, this advantage is offset by much higher CAPEX and OPEX as a share of total costs.

In a scenario where regulations prohibit the burning of waste for energy recovery, the purchase cost of certain feedstocks could fall due to the lack of alternative disposal options.

Exhibit 3.13

What you need to believe: Chemical recycling is complementary to mechanical, but will need to overcome business case and feedstock challenges

Levelised cost of production
$/tonne (2025)



NOTE: [a] Assumes baseload PPA power (~$60/MWh). Midpoint of lower bound (~$40/MWh) for low-cost H_2 production region (Spain) and upper bound (~$80/MWh) for high-cost region (Germany). [b] Gasification can take a variety of feedstocks from Municipal solid waste, mixed plastics are feedstocks for pyrolysis, cleaned PET flakes are feedstocks for depolymerisation. [c] Includes feedstock treatment costs. [d] Negative feedstock cost required to make gasification competitive, as the main cost component with is capital costs.

SOURCE: Singh et al. (2021), *Depolymerisation estimation is based on published data*; Gasification and pyrolysis based on BEIS, NREL and Systemiq PCC model.

Impact

The CO_2 emissions of chemical recycling and thermo-conversion processes are challenging to estimate due to the multiple process pathways that can influence emissions, efficiency, product range and overall economics. To provide a meaningful comparison across technologies, the environmental footprint evaluation focuses on the most common pathways, enabling a consistent assessment of their relative impacts.

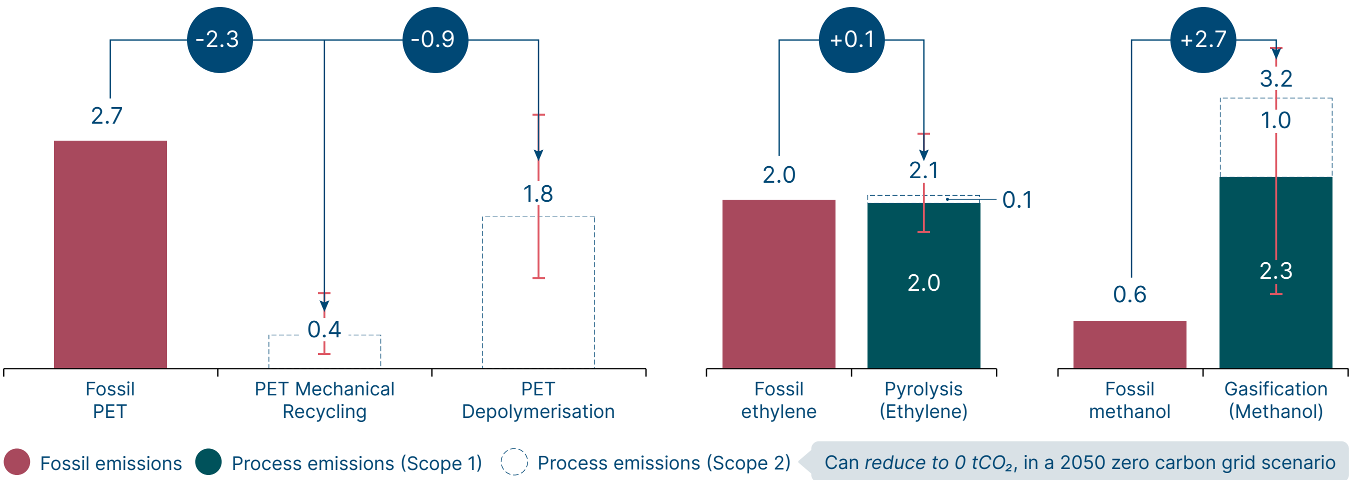
Gasification and pyrolysis currently emit more CO_2 than virgin fossil production from methanol and ethylene [Exhibit 3.14], when not accounting for avoided incineration credits.[56] A potential improvement is hydrogen (H_2) injection, which could lower CO_2 emissions but would increase operational costs, reducing economic feasibility. Pyrolysis emissions could also be improved by electrification of the pyrolysis unit and/or the steam cracker, but this would require redirecting off-gases to alternative applications to maintain process efficiency. In contrast, chemical PET depolymerisation and mechanical recycling have lower CO_2 emissions than fossil PET production. Additionally, both of them could be fully electrified, as they primarily involve low-temperature operations, allowing for net-zero CO_2 emissions when powered by renewable energy.[57]

Exhibit 3.14

Mechanical recycling and depolymerisation reduce CO_2 emissions output, but gasification and pyrolysis do not

Emissions within each recycling process vs. avoided emissions of fossil route
tCO_2/tonne of product output

1. Emissions shown for direct output of process, but pyrolysis and gasification products can be turned back into plastic.
2. These are not lifecycle emissions, so incineration credits are not included.



NOTE: PET depolymerisation shows a wide range of CO_2 emissions depending on the technological path that is followed.

SOURCE: 1) CE Delft (2019), exploratory study on chemical recycling: update 2019; 2) Uekert et al. (2022) Life cycle assessment of enzymatic poly(ethylene terephthalate) recycling. Green Chemistry; 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. 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 LCA varies, values here reflect Energy and Environmental Science (2023) *Techno-economic analysis and life cycle assessment for catalytic fast pyrolysis of mixed plastic waste.*

Across the different chemical recycling and thermo-conversion technologies, yields from feedstocks vary significantly depending on the process and operating conditions. This is an important factor when comparing emissions, since lower conversion rates mean a greater share of the original plastic is not retained in the final material. However, they also lead to higher incineration emission savings per tonne of product, since more of the non-converted material is diverted from incineration. To accurately compare the net CO_2 impact of each process—factoring in the avoided emissions from incinerating waste plastic—it is preferable to normalise emissions data based on one tonne of plastic waste input. Exhibit 3.15 illustrates the overall CO_2 emission savings achieved by each process when processing one tonne of waste plastic.

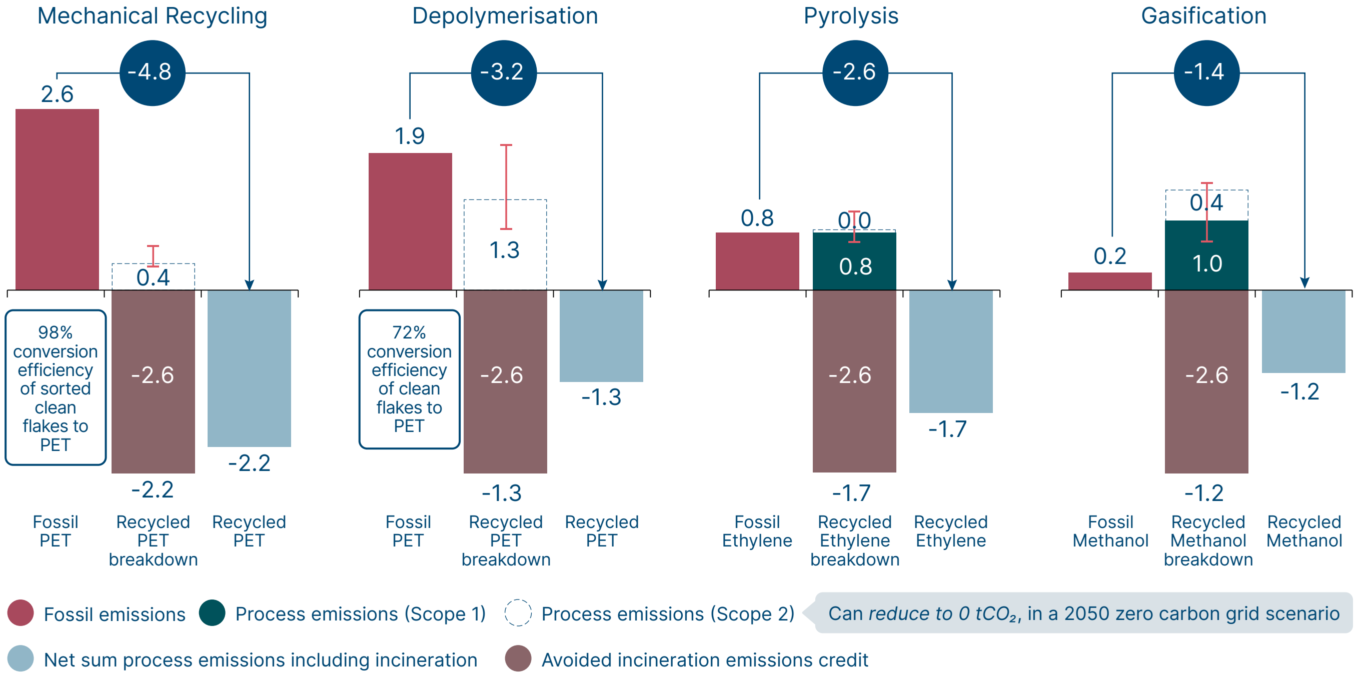
56 By diverting waste to chemical recycling routes (such as gasification or pyrolysis), the baseline emissions from conventional incineration are avoided, and this difference can be accounted for as a credit in lifecycle assessments.

57 Yadav et al. (2023), *Natural fiber reinforced rPET/polyester composites: a review on development, mechanical performance, and sustainable management.*

Exhibit 3.15

In full chain analysis pyrolysis and gasification provide emissions savings, because CO_2 emissions from incineration are avoided

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: ;CE Delft (2019), Exploratory study on chemical recycling: update 2019. Uekert et al. (2023), Technical, Economic, and Environmental Comparison of Closed-Loop Recycling Technologies for Common Plastics, Carbon footprint of fossil methanol based on Methanol institute (2023), Carbon Footprint of Methanol. Fossil Ethylene based on Chemical and Engineering news (2021), 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.*

The main GHG impact of chemical recycling and thermo-conversion is from avoided alternative end-of-life emissions, like unabated incineration emissions.[58] When accounting for incineration, all processes offer net CO_2 savings. Mechanical recycling delivers the highest reductions—up to 3.5x more than gasification—followed by depolymerisation, pyrolysis and gasification in descending order. From both an economic and environmental perspective, the most effective approach to reducing carbon demand in the chemical sector follows a hierarchical strategy.

1. Demand reduction and reuse should be prioritised, as they offer the highest carbon savings with minimal energy input.
2. Mechanical recycling is the next best option, as it allows for the recovery of plastic waste with lower emissions than chemical recycling.
3. Chemical recycling and thermo-conversion should be considered only for the plastic waste that cannot be processed by other means, given its higher energy consumption and economic constraints.

Applying this hierarchy, the balance between mechanical and chemical recycling remains uncertain and will ultimately depend on system change, strong policy support and improved business cases.

Exhibit 3.16 therefore represents an idealised stretch scenario, where the majority of waste could be managed via demand reduction, reuse and mechanical recycling, and a remaining ~20% addressed by chemical recycling

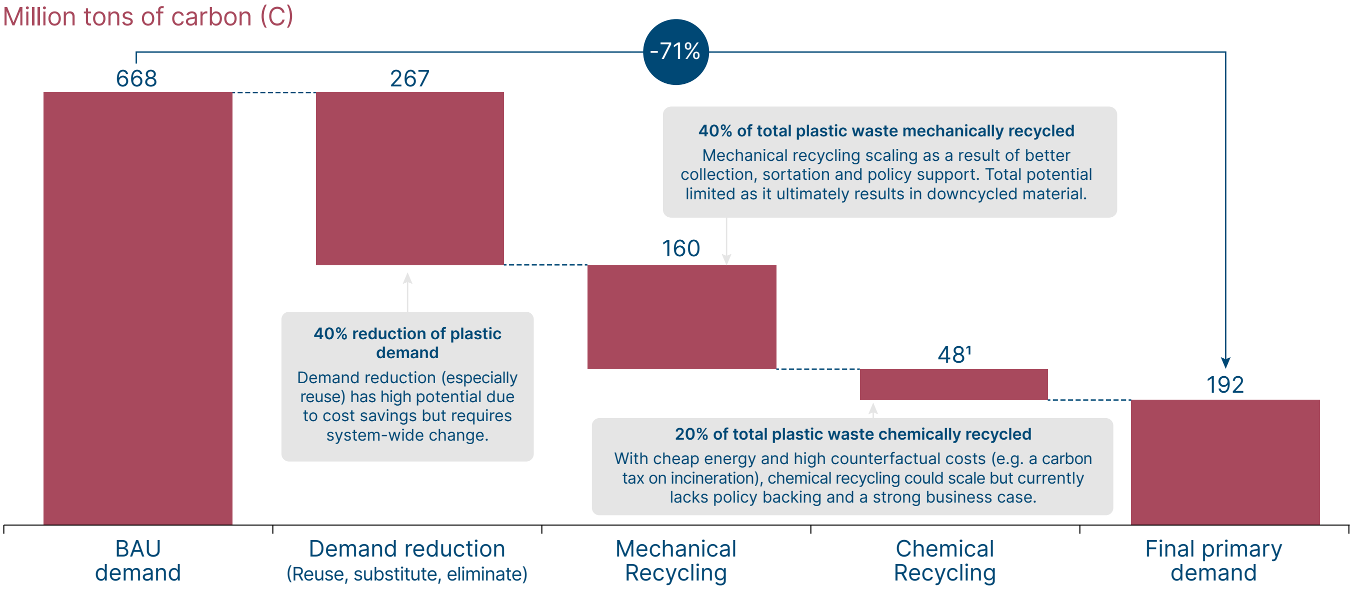
58 Incineration coupled with CCS is not assessed here, as advanced landfilling currently offers a more cost-competitive and technologically mature option for managing residual waste. A fuller explanation is provided in Chapter 5.

and thermo-conversion. If these conditions are not met, chemical recycling is likely to play a greater role. Circularity solutions have the potential to reduce carbon demand in the chemicals sector by over two-thirds—an important consideration given the limited availability of truly sustainable carbon sources. Despite its limited role in volume, chemical recycling/thermo-conversion is essential to process hard-to-recycle waste and support the 2050 sustainability goals.

Exhibit 3.16

Stretch scenario: Primary carbon demand for plastic can be reduced by 70%, but requires system change, policy support and improved business cases.

Primary carbon demand reduction potential in the chemicals sector, 2050
Million tons of carbon (C)



SOURCE: Energy: ETC (2023), Fossil Fuels in Transition; Chemicals: Planet Positive Chemicals Report (Systemiq (2022), BAU Net-Zero scenario) and Systemiq (2024), Plastic Treaty Futures; Freek van Eijk et a. (2023), Chemical Recycling in a circular perspective.

Barriers and enablers

While chemical recycling and thermo-conversion has the potential to address plastic waste challenges, several barriers limit its widespread adoption. However, with strategic investments, supportive policies and technological advancements, it could become a key component of a more sustainable plastic value chain. Key barriers and enablers are as follows:

Technology maturity and efficiency

Barriers: Chemical recycling and thermo-conversion technologies, while based on processes that have in some cases been used for decades, have not yet been proven at scale as end-to-end solutions within real-world waste management systems. Their integration into existing value chains remains limited, particularly when dealing with heterogeneous, contaminated waste streams. Scaling up will require improvements in conversion rates, energy efficiency and overall process stability, all of which carry significant technological risk. Process efficiency remains a challenge, as highly variable feedstock makes it difficult to retain high-quality output production.

Enablers: Electrification and catalyst improvements could enhance efficiency but require further R&D and infrastructure investments.

Economic competitiveness:

Barriers: Chemical recycling and thermo-conversion is currently more expensive than fossil-based plastic production and mechanical recycling due to:

- High CAPEX and pre-treatment costs.
- Lack of economies of scale, making it difficult to compete with established fossil-based processes.

Enablers: Financial mechanisms can improve the economic viability of chemical recycling and thermo-conversion. EPR schemes place the burden of waste management on producers, incentivising the use of recyclable and recycled materials. Carbon pricing makes fossil-based inputs less attractive by internalising their environmental costs, while landfill taxes discourage the disposal of plastic waste that could be recovered. In addition, standardised policies on feedstock classification and product quality would reduce uncertainty, encouraging investment and supporting market growth.[59]

Feedstock availability and quality:

Barriers: Chemical recycling and thermo-conversion require a steady supply of suitable feedstock, but:

- Plastic collection and sorting systems remain inadequate, leading to inconsistent material streams.
- Contaminants such as PVC can cause operational challenges, increasing processing costs.

Enablers: Advanced sorting and pre-treatment technologies need to be scaled to ensure high-quality input materials. Improving waste management infrastructure is necessary to establish a more reliable feedstock supply.

Criticism of their circularity of chemical recycling:

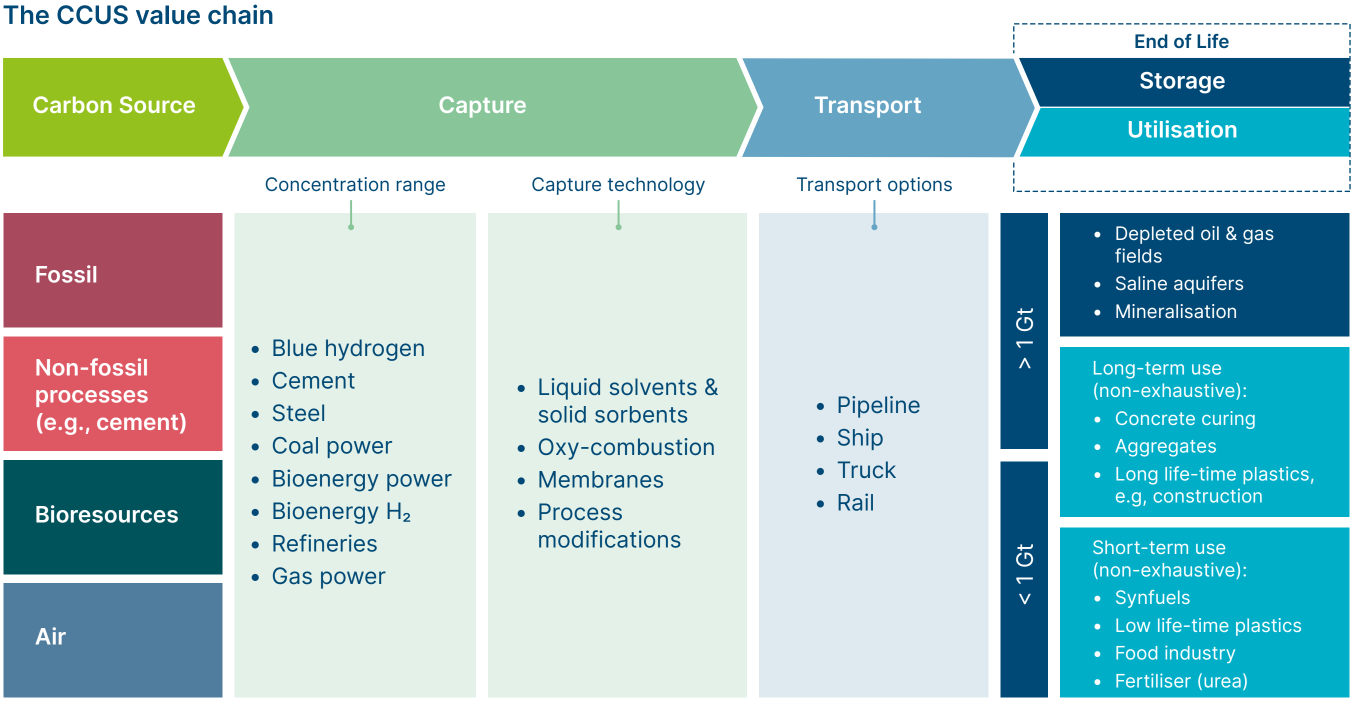
Barrier: Although chemical recycling has the potential to support circularity by converting waste plastics back into monomers or polymers, stakeholder trust remains limited. Many fear that in practice, technologies marketed as chemical recycling may operate as material-to-fuel processes, prioritising energy recovery over true circularity. This conflicts with the waste hierarchy, which favors prevention, reuse, and mechanical recycling. Additional concerns include greenhouse gas emissions, toxic by-products, health impacts from large-scale facilities and environmental justice for nearby communities. There is also broader unease that these technologies could enable continued growth in virgin plastic production without addressing systemic climate and sustainability goals.

Enabler: Building broad stakeholder support will require clear evidence that chemical recycling delivers material-to-material outcomes, along with strong climate and health safeguards. Transparent standards and third-party verification will be essential to build trust and ensure alignment with circular economy principles.

Exhibit 3.17

The CCUS value chain can be split into four distinct stages

The CCUS value chain



SOURCE: ETC (2022), *Carbon Capture, Utilisation and Storage in the Energy Transition.*

59 (OECD, 2024) *Plastic recycled content requirements*

3.5 Carbon capture and utilisation

Overview

As industries seek to decarbonise and transition to a circular economy, CCU has emerged as a viable solution to reduce CO_2 emissions while generating valuable products. The Carbon management pathway consists of four key stages, as shown in Exhibit 3.17, capture, transport and end-of-life.

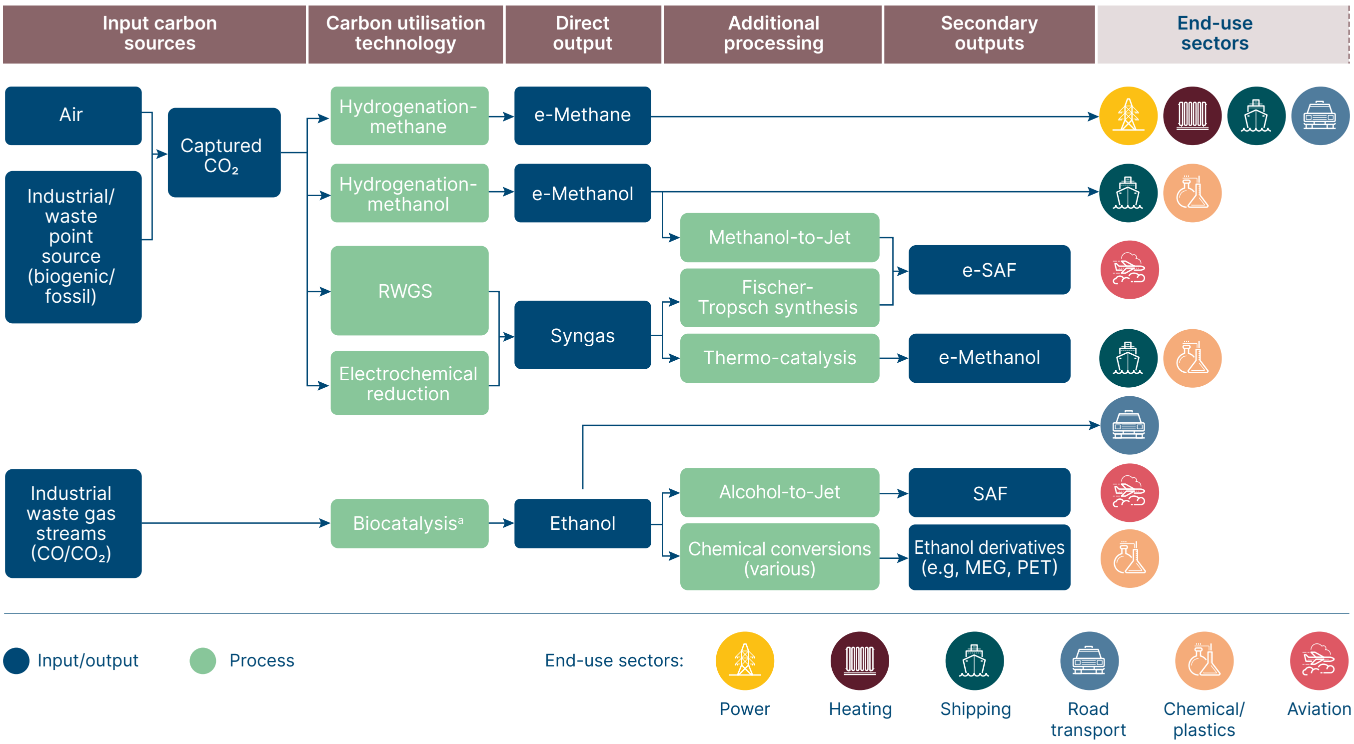
Unlike CCS, which focuses solely on sequestration, CCU repurposes CO_2 into chemicals, fuels and materials, providing economic incentives for carbon reduction while supporting circular carbon cycles. Final emissions from these technologies depend on the CO_2 source that is recycled, such as whether it originates from biogenic, atmospheric or fossil-based processes, and the end use of the resulting product, for example whether it is embedded in materials like plastics or later released through combustion. This analysis focuses on four key CCU technologies that convert CO and/or CO_2 into fuels (including e-fuels) and fuel precursors: Hydrogenation, Reverse Water-Gas Shift (RWGS), Electrochemical Reduction and Biocatalysis.[60] These technologies primarily produce methane, methanol, syngas and ethanol, which can be further upgraded into sustainable aviation fuel (SAF) and chemical feedstocks**. Their core processes are as follows:**

- **Hydrogenation**: Combines CO_2 with green hydrogen to produce synthetic molecules such as e-methane or e-methanol; the latter can be further upgraded into fuels or chemicals.
- **RWGS**: Transforms CO_2 into syngas (a mix of CO and H_2) and other carbon-based intermediates using heat or electricity.
- **Electrochemical reduction:** Uses renewable electricity to directly convert CO_2 into syngas or other reduced products at the electrode surface.
- **Biocatalysis:** Leverages microbes to convert CO or CO_2 and hydrogen via fermentation into ethanol (which can be further processed into chemical derivatives or SAF) or directly to other chemicals or proteins.[61]

Exhibit 3.18 illustrates the conversion pathways and their end uses and Exhibit 3.19 presents the key advantages and disadvantages of these processes.

Exhibit 3.18

Carbon utilisation pathways differ by their outputs and end-use sectors



NOTE: ª Biocatalysis can utilise varied carbon sources, including CO_2, agricultural residues and municipal solid waste, and in principle convert them into diverse products such as methane, methanol, or higher-value chemicals.

SOURCE: Systemiq analysis for the ETC (2025)

60 Refers to the broader scope of biomanufacturing process, including enzyme catalysis and microbial conversion pathways such as gas fermentation.

61 Liew F et al. (2022), *Carbon-negative production of acetone and isopropanol by gas fermentation at industrial pilot scale*.

Exhibit 3.19

Comparison of key advantages and disadvantages of carbon utilisation processes

	Hydrogenation to Methane / Hydrogenation to Methanol	RWGS (Syngas)	Electrochemical Reduction (CO/Syngas)	Biocatalysis (Ethanol)
Ease of adoption	Scalable from modular to large-scale due to established reactors	Numerous downstream uses for syngas	Syngas production using only electricity input	Flexibility to work with a variety of gas streams, H_2 input can be avoided
Ease of operation	Proven technology and few process steps	Fewer losses due to higher conversion efficiency	Ambient operation without need for thermal integration	Minimal treatment needed if CO-rich feedstock
Input requirements	High costs – need for high H_2 input per tonne of product	High temperature heat use	High energy requirements	Customised microbes needed for specific products
Deployment bottlenecks	Narrow operating windows for catalysts	Further development necessary for stable catalysts	Rigorous removal of contaminants is necessary	Energy intensive purification of aqueous product

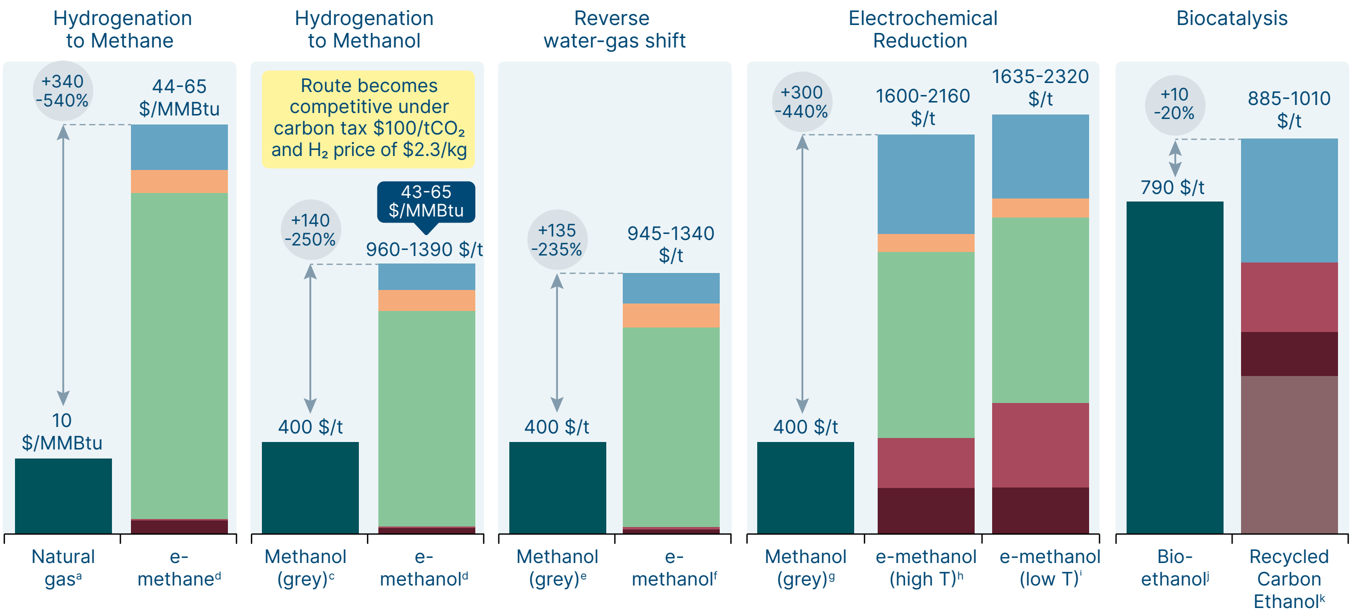
Most favourable   Least favourable

SOURCE: Systemiq analysis for the ETC; Lee et al. (2024), *Techno-economic and life cycle analysis of synthetic natural gas production from low-carbon H_2 and point-source or atmospheric CO_2 in the United States*; MPP (2024), *EU PtX modelling*; Systemiq (2022), *Planet Positive Chemicals*; Zang et al. (2021), *Performance and Cost Analysis of Liquid Fuel Production from H_2 and CO_2 Based on the Fischer-Tropsch Process*; Soler et al. (2024), *E-Fuels: A techno-economic assessment of European domestic production and imports towards 2050*; Carbontech (2023), *Life cycle assessment of ethanol production from BOF gas*; Carbontech, (2024), *Life cycle assessment of ethanol production from silicomanganese alloy off-gas*; Scown et al. (2022), *Sustainable manufacturing with synthetic biology*; Kopke M and Simpson SD (2020), *Pollution to products: recycling of 'above ground' carbon by gas fermentation.*

Exhibit 3.20

What you need to believe – CCU technologies become competitive through the reduction of green H_2 prices and penalties for fossil

Levelised cost of production
$/unit output (2030)



Key inputs

CO_2 cost	$60/tCO₂	
Green H_2 cost	Low: ~$3/kg	High: ~$5/kg
Electricity cost	Low: ~$40/MWh	High: ~$80/MWh

Counterfactual product · Electricity · CAPEX · H_2 feed · Other OPEX · Syngas feed · CO_2 feed

NOTE & SOURCE: [a] Ten-year historical mean of EU Natural Gas TTF; [b] 20-year historical mean (Methanex): [c] MPP (2024), *EU PtX modelling*; [d] IEA (2024), *E-methane: a new gas for a net-zero future?*; [e] Lee et al. (2024), *Techno-economic and life cycle analysis of synthetic natural gas production from low-carbon H_2 and point-source or atmospheric CO_2 in the United States*; [f] Detz et al. (2023), *Electrochemical CO_2 conversion technologies: state-of-the-art and future perspectives*; [g] CIT Renergy (2024), *Electrochemical reduction of CO_2*; Osorio-Tejada et al. (2024), *CO_2 conversion to CO via plasma and electrolysis: a techno-economic and energy cost analysis*; [h] Cost of CO_2 capture from an industrial point source; [i] Assumes baseload PPA power; Lower: ES, upper: DE; [j] Anicic et al. (2014); IRENA, *Conventional ethanol from corn*; [k] CAPEX from LanzaTech from EIC presentation (2022); IEA Bioenergy, (2020) *Annual Report*.

Costs

The levelised cost of production for carbon utilisation technologies varies significantly depending on CAPEX, OPEX, H_2 costs and energy consumption. To improve comparability between pathways, RWGS and Electrochemical Reduction were modelled for syngas conversion to methanol, allowing for direct benchmarking against hydrogenation-based methanol production. The levelised cost of production of each route is compared to its fossil-based alternative, as shown in Exhibit 3.21.

Across the board, most carbon utilisation pathways remain substantially more expensive than fossil-based alternatives—often by more than double. Key cost drivers and differences include:

- **Hydrogenation and RWGS**: Highly dependent on hydrogen input, with hydrogen feedstock making up 72–87% of production costs. RWGS requires slightly less hydrogen than direct CO_2 hydrogenation due to more efficient CO-to-methanol conversion, but both remain cost-intensive.
- **Electrochemical reduction**: Less reliant on external hydrogen but remains the least cost-competitive pathway. It produces CO-rich syngas that reduces recycling during methanol synthesis, yet high CAPEX and electricity demand push costs up.[62]
- **Biocatalysis**: The most cost-competitive option, with only a 10–20% premium over bioethanol. Its independence from hydrogen makes it less sensitive to H_2 price fluctuations, though scalability is constrained by limited availability of industrial CO streams. Biocatalytic systems can also use CO_2 and H_2, though this increases their reliance on green H_2.

For a pathway like hydrogenation to methanol to become competitive with grey methanol, it would take green H_2 prices to be in the range of $2.5 per kg, couple with a carbon price of $100 per t CO_2 penalising the fossil alternative.[63]

Impact

By 2050, CCU is projected to account for ~27% of captured CO_2, with the rest permanently stored via CCS. According to ETC's ACF scenario, total CO_2 capture reaches ~8.8 Gt per year, of which 2.3 Gt is utilised—primarily for synthetic fuels and chemicals—while 6.5 Gt is sequestered. This reflects the consensus that CCU improves carbon efficiency enabling the reuse of captured CO2, while permanent storage is essential for net-zero—though for some chemical products, recapture at end-of-life can create a closed carbon loop that also supports net-zero pathways.[64]

The volume of CCU in the system will be dependent on the demand from key end-use sectors:

- **Aviation:** e-SAF can be produced through several pathways: methanol-to-jet (using e-methanol), RWGS + Fischer–Tropsch (using syngas), or ethanol-to-jet, where syngas is first converted to ethanol via biocatalysis. These drop-in fuels are well-suited for long-haul flights. The MPP Aviation Transition Strategy estimates e-SAF could meet 36% of 2050 demand.
- **Shipping:** e-methanol is expected to supply 28% of 2050 energy demand. Methanol-powered vessels are already in use, signalling strong traction. E-methane may play a smaller role, especially where LNG infrastructure is retained.
- **Chemicals and plastics:** e-methanol and e-ethanol provide fossil-free feedstocks. E-methanol could meet ~36% of he sector's high-value chemical demand, while ethanol-based derivatives (e.g., PET) may cover ~3% of 2050 needs.[65]
- **Power and industry:** e-methane use will likely be limited, except in countries such as Japan, which targets 90% city gas substitution by 2050.
- **Other CCU applications:** cement, aggregates and EOR remain niche due to high costs, limited volumes, or lack of standards. Aggregates in particular often lack market value, while CO_2 streams remain inconsistent or uncertified.

Barriers and Enablers

Widespread adoption of CCU technologies faces both sector-specific barriers and broader system-level challenges.

- **Aviation:** e-SAF faces high production costs and strong competition from biofuels, limiting large-scale deployment except where mandates require its use. Without substantial cost reductions or policy incentives, HEFA based SAF (which is unable to fulfil future demand due to feedstock limitations) remains the preferred alternative, slowing the uptake of CCU-based fuels in the short-term. Although in the UK, there is a high buyout price for both recycled carbon SAF and e-SAF which will support uptake as HEFA based fuels face a sustainability and feedstock limitations to 2030.

62 Anicic et al (2014), *Comparison between two methods of methanol production from carbon dioxide.*

63 Systemiq analysis for the ETC (2025)

64 Liew et al. (2025), Addendum: Carbon-negative production of acetone and isopropanol by gas fermentation at industrial pilot scale.

65 Systemiq and Center for Global Commons (2022), *Planet positive chemicals.*

- **Shipping:** e-Methanol presents a promising decarbonisation pathway, but higher costs compared to fossil fuels, supply chain constraints and competition from ammonia and biofuels delay market growth. Although methanol-powered ships are increasing, ensuring affordable, scalable supply remains a key challenge.
- **Chemicals and Plastics:** e-Methanol and ethanol (including e-ethanol from CO_2) could replace fossil-based feedstocks, but currently lack cost competitiveness. Without strong policy support, such as carbon pricing or incentives for low-carbon chemicals, fossil methanol or fossil derived ethylene continues to dominate the market.
- **Power and Industry:** e-Methane struggles to compete with lower-cost electrification, making it a less viable large-scale option. Similarly, carbon-based materials like cement and aggregates face high infrastructure costs and limited market potential, constraining their role in CCU deployment.

Across all sectors, scaling CCU technologies will require both cost reduction and strong demand signals from the market. The economic viability of many pathways, particularly hydrogen-based routes, relies on access to low-cost green hydrogen and CO_2. On the demand side, strong policy support, including blending mandates and carbon pricing, will be essential to create viable markets. While biocatalysis offers a more cost-competitive entry point, its long-term scalability will be limited by the availability of suitable feedstocks.[66]

3.6 A maximum circularity scenario

Exhibit 3.21 illustrates the maximum potential reduction in primary carbon demand achievable through circular economy strategies, as previously discussed.

The analysis suggests that primary carbon demand could be reduced from 5 Gt (adjusting for circularity levers already applied to the ACF scenario of ~0.2 Gt) to 3.5 Gt, through a combination of the following levers:

- Demand reduction through elimination, reuse and substitution which could reduce demand related to material use by ~140 Mt and energy demand by 120 Mt. Substitution includes shifting from plastic to paper in packaging, which can reduce overall primary demand.
- Recycling of plastics enabled by improved sortation which in total could cut primary carbon demand by around 420 Mt. Mechanical recycling (including plastic, but also wood, pulp and paper, which have relatively high recycling rates today) accounts for around 90% of this reduction, lowering both material and energy demand. By contrast, chemical recycling reduces material demand but offers little or no energy savings, since the process essentially replicates primary production pathways.
- Various forms of CCU which could reduce primary carbon to meet energy demands by 490 Mt.

In total, this would amount to a 30% reduction in primary carbon demand. However, this is a maximum potential scenario which could only be achieved in practice with very strong supporting policies.

In the case of demand reductions and recycling these would need to involve

- Policies to require/encourage producers to eliminate unnecessary plastic packaging and facilitate reuse.
- Regulations to require/encourage improved sortation.
- Policies to reduce the role of end-of-life incineration, including via carbon pricing and regulatory constraints.

In the case of CCU, it would require blending mandates and carbon pricing, together with cost reduction achieved through scale, technological progress and the development of low-cost hydrogen supply.

The optimal extent of demand reduction and circularity actually achieved will depend on the relative cost of options considered in this chapter versus the costs of sustainable primary carbon supply – which are considered in Chapter 4.

This balance cannot and does not need to be specified precisely in advance. But the analysis in this chapter shows that:

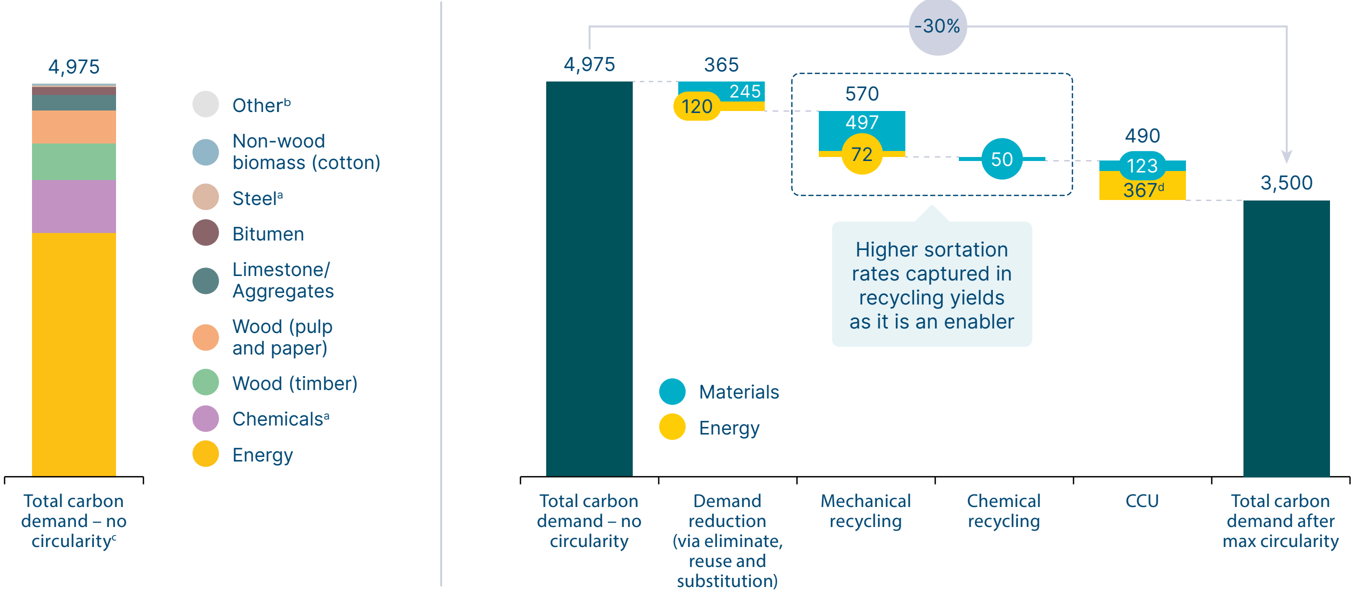
- There is a very significant maximum potential for reuse and recycling – a 30% reduction. This indicates the potential prize if well designed policies plus technology developments can enable cost-effective implementation. Beyond carbon savings, greater reuse and recycling can also reduce resource extraction, energy use, and land use, while enhancing material security and supporting economic resilience by lowering dependence on volatile global commodity markets and increasing the stability of domestic supply chains.
- Even this maximum potential reduction would leave a need for 3.5 Gt of sustainable primary carbon supply.

66 Systemiq analysis for the ETC (2022), *Carbon Capture, Utilisation & Storage in the Energy Transition: Vital but Limited.*

Exhibit 3.21

Circularity levers could reduce 30% primary carbon demand 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] Enhance Oil Recovery (EOR) 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).

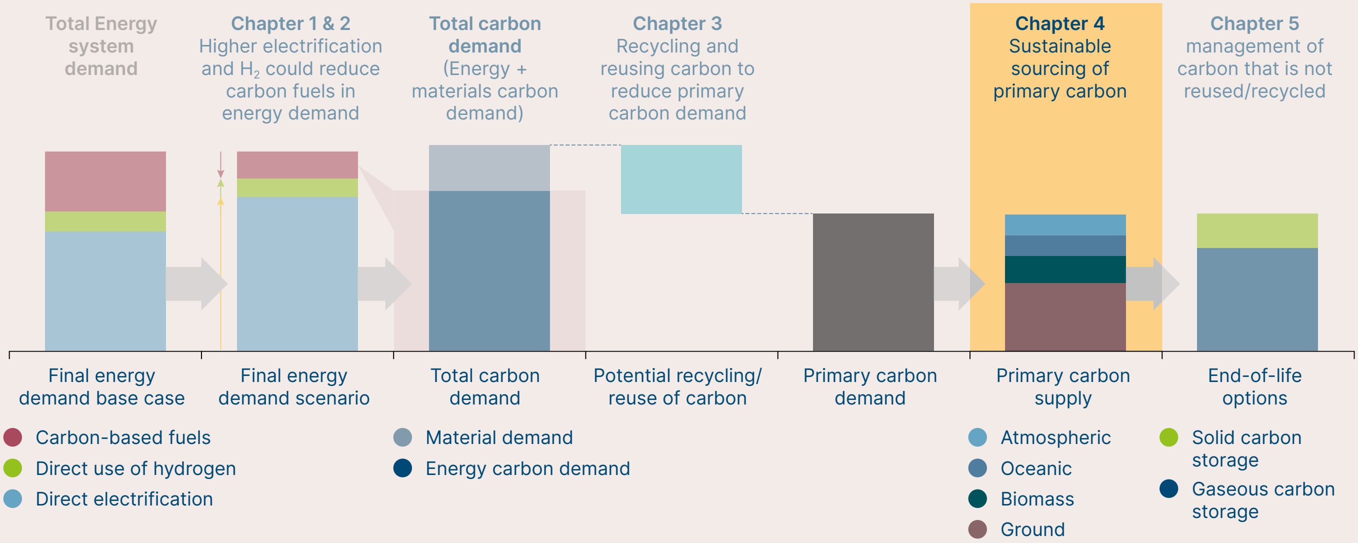
Sustainable sourcing of primary carbon

4

Exhibit 4.0

Framework for analysing demand and sourcing options for carbon in a sustainable, zero-emissions fashion

Illustrative



SOURCE: Systemiq analysis for the ETC (2025).

Primary carbon supplies could be sourced from the atmosphere, the ocean, the biomass or the ground [Exhibit 4.1]. The challenges of ensuring sustainability differ by source:

- Sourcing carbon from the atmosphere or the ocean directly or indirectly reduces greenhouse gas concentrations and can be inherently sustainable. The key issues relate to cost-effectiveness and sustainable availability of key feedstocks.
- Biomass sources can be sustainable if the bioresource is extracted in ways that limit harmful land use change, protect biodiversity and maintain carbon stocks.
- Using fossil for carbon from the ground is only sustainable if there is some combination of (i) capture and storage of any CO_2 produced in combustion, (ii) safe and clean in ground of solid products at end-of-life, and (iii) carbon removals elsewhere in the economy to offset any residual emissions.

This Chapter therefore considers:

- Technologies for capturing carbon, including:
  - Direct capture from the atmosphere or the ocean.
  - Point source carbon capture at the end of industrial processes.
- Biomass related technologies including:
  - Technologies to extract more biomass sustainably from land not currently devoted to food production.
  - New technologies such as alternative proteins which could reduce the need for land for food production.

- Potential new sources of biomass – macro and microalgae.
- Technologies to improve biomass conversion efficiency.

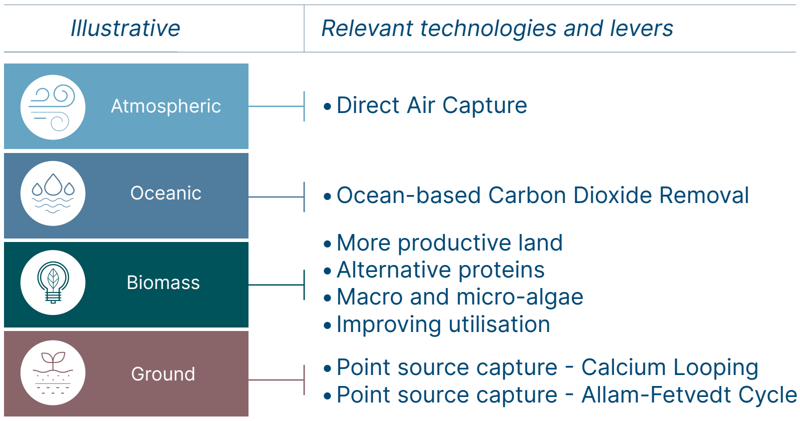
- Conclusions on the possible and optimal balance between different sources of sustainable carbon supply.

Chapter 5 considers the storage technologies which will also be required to ensure that any use of fossil carbon is compatible with achieving net-zero emissions.

Exhibit 4.1

Sustainable pathways for primary carbon

Sources of primary carbon supply



SOURCE: Systemiq analysis for the ETC (2025).

4.1 Categories of carbon capture systems

Capturing carbon dioxide[67] from different sources is central to both reducing emissions and creating a circular carbon supply. There are two principal capture pathways:

- **Direct capture** refers to the removal of CO_2 directly from the ambient environment, either from the air or the ocean.
- **Point-source capture** involves capturing CO_2 at the location of emission, such as industrial facilities or bioenergy plants.

As shown in Table 2, these technologies operate across different concentrations of CO_2 and serve different purposes. Point-source capture is focused on emission avoidance,[68] while direct capture supports carbon removal. The technology landscape includes a range of systems tailored to specific concentrations, temperatures and industrial settings.

Table 2

Overview of Carbon Capture Types[68]

Capture Type	Application Example	Typical CO_2 Concentration (vol%)
Industrial point-source capture	Cement, steel, refinery furnaces	5–30%
Industrial point-source capture	Ammonia, hydrogen (SMR/ATR), ethanol	50–99%
Bioenergy point-source capture	Biomass conversion with CCS	5–15%
Direct air capture	Atmospheric removal	0.04%
Ocean-based capture	Electrochemical or alkalinity-based CDR	0.01%

SOURCE: Systemiq analysis for the ETC (2025).

67 CO_2 is used as a shorthand term, consistent with conventions such as the US 45Q tax code, which defines it broadly to include carbon oxides.

68 In the case of biomass feedstocks, this is also considered CO_2 removal due to atmospheric drawdown via biomass.

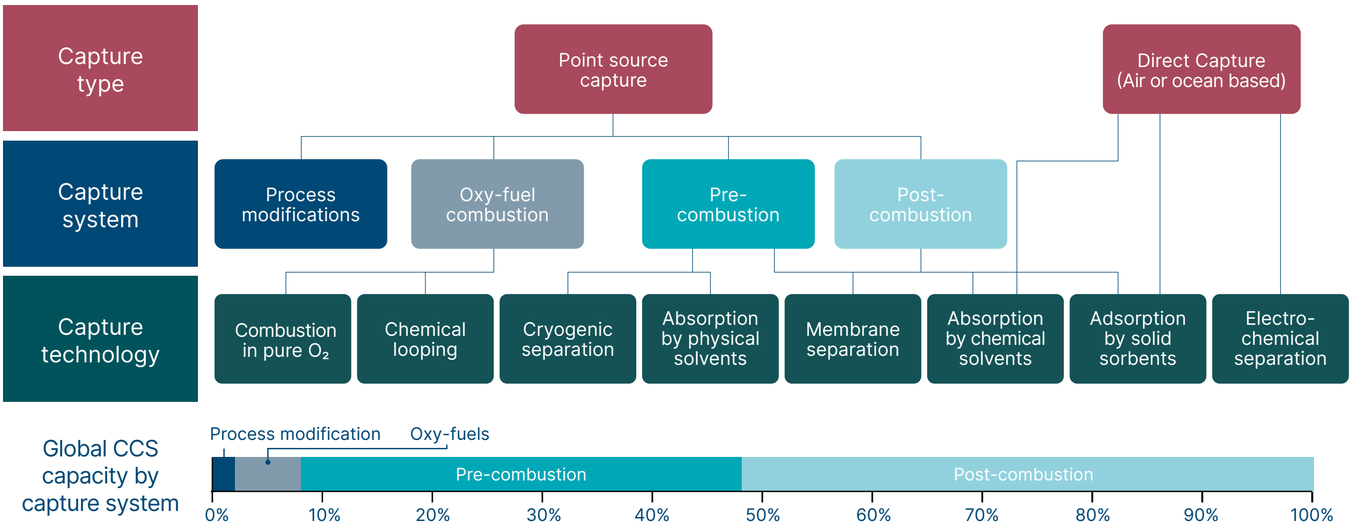
69 Leung, D Y.C. et al. (2014), *An overview of current status of carbon dioxide capture and storage technologies.*

Carbon capture systems are typically categorised by capture type (point-source or direct), **system configuration** (e.g., process-integrated, end-of-pipe, combustion stage), **and separation technology** (e.g., solvent-based absorption, membranes, adsorption, or electrochemical methods). Point-source capture accounts for the vast majority of global CCS capacity, though the specific breakdown between pre-combustion, post-combustion and process separation routes varies by sector and geography [see Exhibit 4.2 for an indicative capacity distribution]. While post-combustion systems constitute the largest single category by installed capacity, most operational projects today target high-purity CO_2 streams — such as those from natural gas processing, ammonia production or hydrogen reforming — where CO_2 is more concentrated and separation is less energy-intensive. Direct capture methods, such as air- or ocean-based systems, represent a growing class of distributed removal technologies, but still comprise a small share of total installed capacity.[68]

Exhibit 4.2

Despite a broad technology landscape, global carbon capture is dominated by pre- and post-combustion systems

Standard carbon capture technologies



SOURCE: Systemiq analysis for the ETC (2022); Cancawe (2018), *Technology scouting – carbon capture.*

Each capture approach presents specific trade-offs in energy intensity, cost, selectivity and ease of integration:[70,71]

- Allam–Fetvedt Cycle: Achieves high capture rates with low operational energy penalties, but requires entirely new-build infrastructure and carries high capital costs, limiting near-term scalability.
- Oxy-fuel combustion: Simplifies downstream capture by producing a nearly pure CO_2 stream, reducing mechanical complexity. However, it requires oxygen supply systems and costly retrofits.
- Pre-combustion capture: Captures CO_2 before fuel is burned (e.g., via gasification or reforming). Most effective in new, integrated plants such as hydrogen or power facilities.
- Post-combustion absorption: Uses chemical solvents. Well-established and effective, but energy-intensive and susceptible to degradation from SO_X and NO_X impurities.
- Adsorption: Operates at lower regeneration temperatures, lowering thermal energy demand. However, CO_2 purity can be reduced due to residual gases, and performance is affected by acid gases.
- Membranes: Modular and less maintenance than solvent based systems, but less effective at low CO_2 partial pressures and often require gas recycling.
- Cryogenic separation: Delivers nearly complete CO_2 recovery, but is highly energy-intensive and prone to process blockages.

70 Global CCS Institute (2025), *Advancements in CCS technologies and costs.*

71 Wang, X. et al. (2020), *Carbon capture from flue gas and the atmosphere: A perspective.*

- Electrochemical methods: Offer fully electrified, low-energy and highly selective capture, especially promising for ocean-based systems. Still at early TRLs and difficult to scale.

Our analysis focuses on technologies at TRL 5 or above, where integrated system components have been validated in relevant environments. As shown in Exhibit 4.3, we prioritise pathways with medium-term deployment potential, recognising the importance of balancing innovation with technological maturity.

Exhibit 4.3

Emerging CO_2 capture technologies with the greatest potential to cut costs and accelerate deployment

Emerging technologies

Category			Technology	Process	TRL	Companies Non-exhaustive examples
Direct capture	Absorption/ adsorption	1	DAC (liquid and solid sorbents)	Liquid DAC uses a strong hydroxide solution to capture CO_2. Solid DAC uses fans to pass air over chemicals on a solid surface that bind CO_2.	5–9	
Direct capture	Electro-chemical	2	Ocean-based CDR	Electrochemical processes or contactors to extract CO_2 directly from seawater.	5–6	
Point source capture	Post-combustion	3	Liquid absorption/ solid adsorption	Liquid chemical solvents to absorb CO_2 from flue gas, or solid materials like metal-organic frameworks (MOFs) or activated carbon to capture CO_2.	7–9	
Point source capture	Oxy-fuel	4	Calcium looping	Transformative techniques capturing CO_2 with lime by forming $CaCO_3$, then regenerated by burning fuel in pure oxygen.	6–7	
Point source capture	Process modification	5	Allam-Fetvedt Cycle	CO_2 is separated from gases using selective permeable membranes.	7	

SOURCES: Systemiq analysis for the ETC; Global CCS Institute (2025), *Advancements in CCS technologies and costs*; Global CCS Institute (2021), *Technology Readiness and costs.*

4.1.1 Direct capture (atmospheric and oceanic)

This chapter explores direct CO_2 capture pathways from both atmospheric and oceanic sources.

Atmospheric

As global attention turns to large-scale carbon dioxide removal, Direct Air Capture (DAC) stands out as a leading technology. Its ability to extract CO_2 directly from ambient air makes it vital for offsetting residual emissions and supporting carbon circularity in hard-to-abate sectors. However, DAC faces notable technical and economic hurdles. This chapter explores DAC configurations, cost trajectories and the potential rise of ocean-based CDR (o-CDR) as a viable alternative.

DAC aims to capture CO_2 from the atmosphere, where concentrations are low and diffuse. These systems use engineered materials or chemical processes to extract CO_2 and then regenerate the capture medium. While conceptually simple, implementation is energy-intensive and requires careful optimisation for cost and scale. DAC is commonly classified into three types: solid sorbent, liquid solvent, and electrochemical which differ in maturity and on-going developments, as shown in Exhibit 4.4:[72]

72 Bisotti, F. et al. "Direct Air capture (DAC) deployment: A review of the industrial deployment." *Chemical Engineering Science* 283 (2024): 119416.

Exhibit 4.4

Solid sorbent DAC is leading in maturity, liquid solvent DAC is scaling rapidly, and electrochemical approaches may offer long-term disruption

Type of DAC	Technological innovations	Deployment examples	Companies and TRL	
Solid sorbent *Low temperature heat*	• Novel sorbent materials with improved stability and reaction kinetics. • Improve absorbent conductivity and heating efficiency.	• Climeworks has 12 DAC pilot plants in operation, among which the largest DAC facility in Iceland (36 kt CO_2/y). • Plans for scaling up to **100 ktCO_2/y until 2035.**	climeworks	7–8
			Global Thermostat	7–8
			Heirloom	6
			Sirona Technologies	4
			skytree	4
Liquid solvent *High capture rate*	• Improve configuration for better flow pattern to improve performance and energy consumption. • Novel solvents (ionic liquids, phase change). • Limit corrosion in amine capture plants.	• Carbon engineering project in Texas aiming to capture up to **1 MtCO_2/y in late 2025.**[a,b]	1PointFive	7–8
			Capture6	4
Electro-chemical *Electrified*	• Development of ion-selective membranes that can drop the costs due to weaker bonding of the CO_2 on the capturing material. • Development of continuous process.	• Start-ups developments using electro-swing adsorption or ion-selective membranes show potential of 3–4x reduction in energy consumption. • The technology has only been tested at **laboratory scale**.	RepAir	4
			Phlair	4
			Bi-Polar Membrane Electro-Dialysis technology	2–3

NOTE: BPMED=Bi-Polar Membrane Electro-Dialysis technology

SOURCE: [a] 1PointFive & Carbon Engineering announce Direct Air Capture deployment approach to enable global build-out of plants (2022); [b] STRATOS nears completion as Direct Air Capture moves forward (2025); Filippo Bisotti et al. (2024), *Direct Air capture (DAC) deployment: A review of the industrial deployment.*

Initial DAC cost projections were optimistic driven by expectations around capital costs. The 2021 ETC report 'Carbon Capture Utilisation and Storage' anticipated rapid cost reductions to $100–200 per tonne by mid-century. However, new data from early commercial projects prompted significant upward revisions which underlines the need for technology-specific data in cost models rather than generalised analogues. As DAC limitations become clearer, o-CDR is gaining attention as a complementary or alternative approach. As illustrated in Exhibit 4.5, these systems enhance the ocean's carbon uptake using electrochemical processes that manipulate seawater chemistry.

Oceanic

Ocean-based electrochemical carbon removal can involve one of **two primary processes: electrodialysis** or **electrolysis**, each resulting in a different carbon removal pathway and chemical outcome. In both approaches, seawater is split into two distinct streams — acidic and alkaline — through the application of electric current.[73]

CO_2 removal is possible to occur in both streams, but the actual mechanism depends on the technology used:[74]

- **Electrodialysis-based systems**: In this configuration, seawater is separated into an acidic stream and an alkaline stream. In the acidic stream, the reduction in pH shifts the carbonate equilibrium toward gaseous CO_2 release, as dissolved bicarbonate and carbonate ions convert back to CO_2 gas. This evolved CO_2 is captured, typically through vacuum stripping, a process where pressure is reduced to encourage the release and collection of dissolved gases. The acidic and alkaline streams are subsequently recombined, yielding seawater with slightly higher pH and enhanced capacity to reabsorb atmospheric CO_2 upon discharge. Thus, the net removal occurs at the point of CO_2 gas evolution, with indirect drawdown from the atmosphere occurring as the ocean re-equilibrates over time.
- **Electrolysis-based systems**: In this configuration, water electrolysis produces an alkaline stream capable of absorbing CO_2 directly from the atmosphere. This absorbed CO_2 reacts with naturally occurring calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions in seawater to form solid carbonate minerals (precipitation). This represents atmospheric CO_2 removal via mineralisation, rather than extraction from seawater. In parallel, an acidic stream is also generated from the anode compartment and must be neutralised to avoid ecological harm, which typically involves adding alkaline minerals (ground rock). The solid form of the captured CO_2 makes it unable to be utilised as a gas, but it could hold small value as a mineral making it a potential by-product. Additionally, H_2 is generated as a useful by-product.

73 Prince Aleta (2024), *Direct ocean capture: the emergence of electrochemical processes for oceanic carbon removal.*

74 The process of Captura is used as a reference for electrodialysis-based systems. The process of Equatic is used as reference for electrolysis-based systems.

Exhibit 4.5

Ocean-based CDR (o-CDR): removes dissolved carbon directly from seawater using a range of electrochemical processes

Overview of production process

1 Electrodialysis or electrolysis

Electrochemical process

Electricity splits seawater into two streams:

Acidic stream: low pH, releases CO_2

Alkaline stream: high pH, absorbs atmospheric CO_2

The process can be done in two ways: **Electrodialysis** or **Electrolysis.**

2 CO_2 capture or precipitation

CO_2 capture

Electrodialysis: Captures CO_2 gas released in the acidic stream. Then alkaline stream reabsorbs CO_2 from the air.

Electrolysis: Alkaline stream absorbs atmospheric CO_2 and turns it into solid minerals (carbonates). Also produces hydrogen as a by-product.

3 Neutralisation and disposal of water

Return to Ocean

Before discharge, the streams are neutralised to prevent harm to marine ecosystems. This makes the process safe and reversible, restoring balance to the ocean.

NOTE & SOURCE: 1) Absorption: CO_2 binds with solvent/sorbent (like MEA) in a reactor. Desorption: The CO_2-rich solvent/sorbent is heated to release CO_2 and regenerate the solvent Yafiee et al. (2024) Direct air capture (DAC) vs. Direct ocean capture (DOC)–A perspective on scale-up demonstrations and environmental relevance to sustain decarbonization ; Prince Aleta et al. (2023) *direct ocean capture: the emergence of electrochemical process for oceanic carbon removals.*

Though o-CDR shares the objective of atmospheric CO_2 removal with DAC, it operates through a different medium and mechanism, skipping the DAC step and reducing energy demand. Properly designed systems may also help combat ocean acidification. However, o-CDR remains early-stage, and key assumptions — especially that CO_2 removed from seawater will be fully replaced by atmospheric drawdown — are still under investigation. Re-equilibration rates vary by location and can take days to months, posing challenges for carbon accounting and certification. Its future success depends on site-specific deployment, access to clean electricity, and robust MRV frameworks. Until those are in place, o-CDR should be seen as a promising but emerging complement to more mature CO_2 removal pathways like DAC.[75,76]

Table 3: Comparison of key characteristics of o-CDR and DAC

Parameter	o-CDR	DAC
CO_2 source medium	Seawater	Ambient air
Mechanism	Only desorption or precipitation	Absorption and desorption
Temperature	Ambient or low	80–900°C
System type	Near-shore	Modular, decentralised
By-product potential	Hydrogen (if electrolysis is used)	None

Costs

Atmospheric

A major challenge in projecting DAC costs is the limited installed capacity and lack of historical deployment data. Most models rely on assumptions and analogies from mature sectors like solar PV or wind, which may not apply to DAC. Learning rate assumptions vary widely:[77,78,79]

75 Eisaman (2024), *Pathways for marine carbon dioxide removal using electrochemical acid-base generation.*

76 La Plante et al. (2021), *Saline Water-Based Mineralization Pathway for Gigatonne-Scale CO_2 Management.*

77 Sievert et al. *"Considering technology characteristics to project future costs of direct air capture." Joule* 8.4 (2024): 979-999.

78 Abegg, et al. *"Expert insights into future trajectories: assessing cost reductions and scalability of carbon dioxide removal technologies." Frontiers in Climate* 6 (2024): 1331901.

79 Nancy W. Stauffer (November 2024), *Reality check on technologies to remove carbon dioxide from the air.* Available at: https://news.mit.edu/2024/reality-check-tech-to-remove-carbon-dioxide-from-air-1120

- **CAPEX:** Assumed learning rates range from 10% to 20%.
- **OPEX:** Learning rates range from 2% to 10%.

Moreover, many studies use **single-component learning curves**, which carry two critical limitations:

- They assume uniform learning across all system components, ignoring that many parts (e.g., compressors, heat exchangers) are already mature and will not benefit from deployment scale.
- Even for novel components, learning rates can vary from 11% to 27%, depending on design, integration and manufacturing scale, making simple curve-based extrapolations unreliable.

As shown in Exhibit 4.6, recent 2024 literature from ETH Zurich and MIT estimates DAC costs may exceed $400/ tCO_2 by 2050. These studies derived their estimates using expert interviews to assess the cost of individual system components, multi-component learning curves, or a combination of both approaches.

In light of updated data, the ETC has revised its internal projections for DAC costs in 2025 and beyond. These revisions are informed by actual project experience, notably from Climeworks' plant in Iceland, and reflect a more grounded outlook on technology learning and system design.

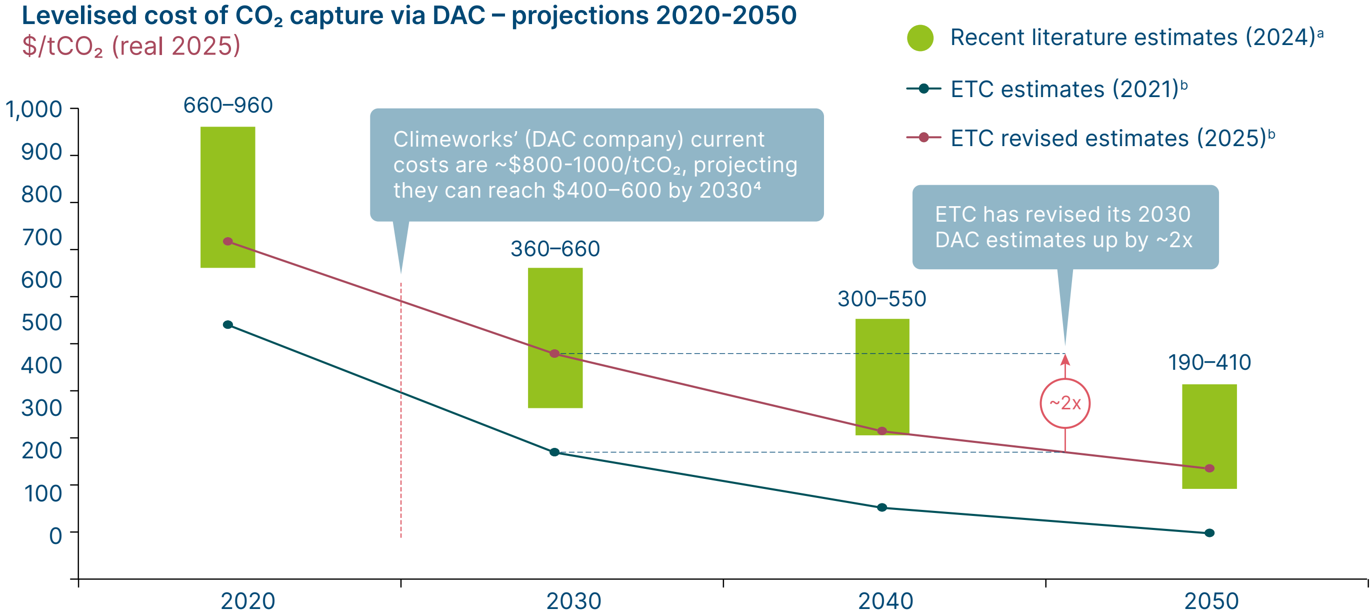
Key updates include:

- **CAPEX revision:** Upward adjustment from $1470 to $2500 per t CO_2 per year capacity, based on Climeworks' recent deployment.
- **Learning rate:** Reduced from 12% to 6%, reflecting the slower-than-expected cost decline across major DAC components.
- **Electricity consumption:** Increased from 250 to 370 kWh per tCO_2, aligned with new research and more realistic system configurations.
- **OPEX implications:** Higher base costs and a flatter learning curve translate into more conservative future cost reductions.

Exhibit 4.6

Recent estimates of levelised cost of DAC are higher than previously predicted, which could hinder the technology's scale-up in the long-term

Levelised cost of CO_2 capture via DAC – projections 2020-2050
$/$tCO_2$ (real 2025)

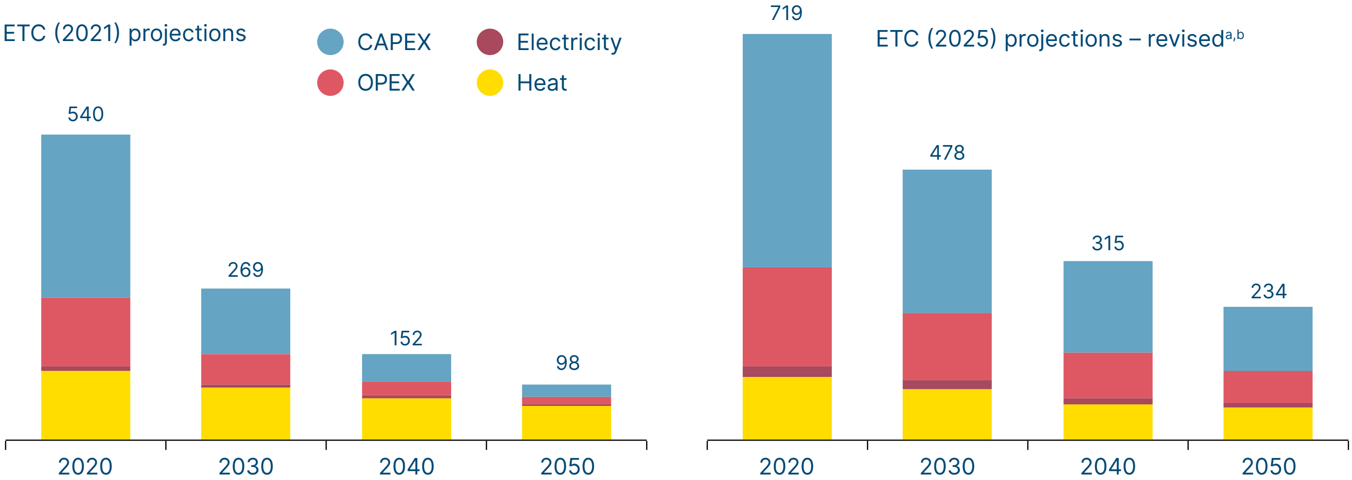


NOTE & SOURCE: Systemiq analysis for the ETC; [a] 2020 and 2030 estimates: Sani, L. (2024). *Bridging the gap between the UK's CCUS targets and reality*; 2040 and 2050 estimates: Sievert, K. et al. (2024), *Considering technology characteristics to project future costs of direct air capture*; Abegg M., et al. (2024), *Expert insights into future trajectories: assessing cost reductions and scalability of carbon dioxide removal technologies*; [b] Levelised cost of DAC refers to a fully electrified DAC system for 5,000 full load hours per annum. Assumes weighted average cost of capital of 7% and plant lifetime of 20 years, growing to 30 years by 2050; [c] MIT Energy Initiative (2024), *Reality check on technologies to remove carbon dioxide from the air*; [d] Bloomberg (2024), *Carbon Removal' s Holy Grail Cost Cut Is Further Away Than It Seems*; [e] Adjusted for inflation to 2025 real US dollars (19% between 2021–2025).

Exhibit 4.7

ETC estimates for the cost of DAC, factor in real-world project CAPEX

Estimated levelised cost of direct air capture by cost driver
$/t$CO_2$ (real 2025)



NOTES & SOURCE: Systemiq analysis for the ETC; [a] Reuters (2021), *Climeworks opens the world's largest carbon-capture facility in Iceland*; Ozkan (2024), *Atmospheric alchemy: The energy and cost dynamics ofdirect air carbon capture*); [b] Previously applied learning rates vary widely and often refer to other low-carbon technologies such as solar and wind, due to limited historical data. Using single component learning rates has its limitations, e.g., assuming learning across all components, overlooking that somecomponents are already widely used. Electricity/heat price forecasts are also updated to align with comparisons across other capture technologies.

These changes result in a projected cost of $480 per t$CO_2$ in 2030, compared to earlier forecasts of around $270. Even under optimistic deployment scenarios, the new ETC trajectory forecasts costs falling to around $235 per t$CO_2$ by 2050. The revised estimates emphasise that while DAC remains a crucial tool for net-zero transitions, its scalability and economic viability depend heavily on continued innovation, policy support and the integration of low-cost, renewable energy infrastructure. A detailed breakdown of the updated levelised cost components is provided in the accompanying Exhibit 4.7.

These revised cost projections are primarily based on high-TRL liquid and solid sorbent DAC systems, such as those deployed by Climeworks, which offer real-world performance and cost data. Their maturity allows for grounded assumptions around learning rates and system configuration, albeit within the limits of current deployment experience. At the same time, emerging technologies like electrochemical DAC could represent a step change in cost trajectories. By eliminating thermal regeneration and instead using low-voltage or low-temperature electrochemical separation, they promise lower energy intensity and potentially reduced CAPEX. Companies like Heimdal, RepAir, and Phlair are pursuing novel architectures and business models, with cost targets below $150 per t$CO_2$ by 2035. However, these technologies remain at significantly lower TRLs, with limited validation at pilot or integrated system level. Demonstrating durable, scalable, and cost-effective performance across real-world operating conditions will be essential to confirm their disruptive potential.

Oceanic

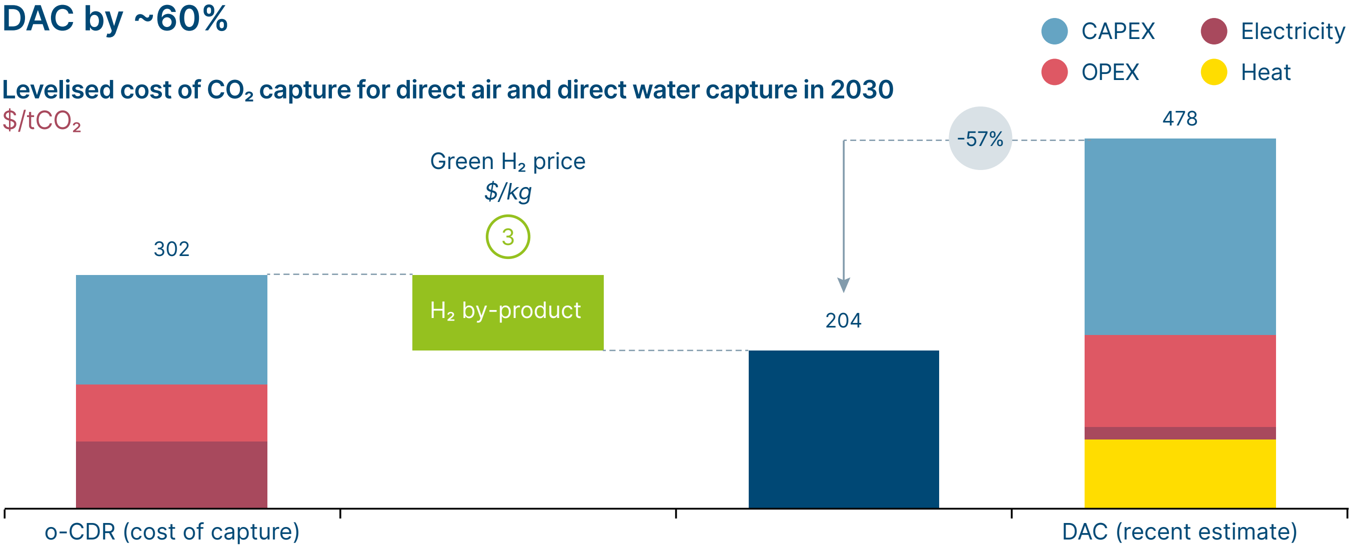
To assess ocean-based carbon removal pathways, we highlight the Equatic process, which employs seawater electrolysis. Functioning similarly to an alkaline electrolyser, the system uses ion-selective membranes to separate seawater into acidic and alkaline streams. Within this configuration, the alkaline stream absorbs atmospheric CO_2 and facilitates its precipitation into stable carbonate minerals, while the process simultaneously produces hydrogen gas as a valuable co-product. The acidic stream is subsequently neutralised using low-cost crushed rock, allowing for environmentally safe discharge back into the ocean.

Cost estimates for this system are anchored to benchmarks for alkaline electrolysers, albeit adjusted upward to account for the dual-function nature of the Equatic design. Mineral by-products, while generated during the process, are currently not monetised due to limited market maturity, although they may offer modest additional value in the future. A further cost advantage arises from the system's ability to bypass desalination, significantly reducing overall operating expenses.

Exhibit 4.8

o-CDR net cost with hydrogen by-product could become more economical than DAC by ~60%

Levelised cost of CO_2 capture for direct air and direct water capture in 2030
$/t$CO_2$



NOTE: Electricity cost: 50$/MWh. Electrolyser utilisation: 50%. Plant capacity: 110,000 tonnes CO_2/y.

SOURCE: Patent US20220040639A1; Globe Newswire (2024), *Equatic to Build North America's First Commercial-Scale Ocean-Based Carbon Removal Facility.*

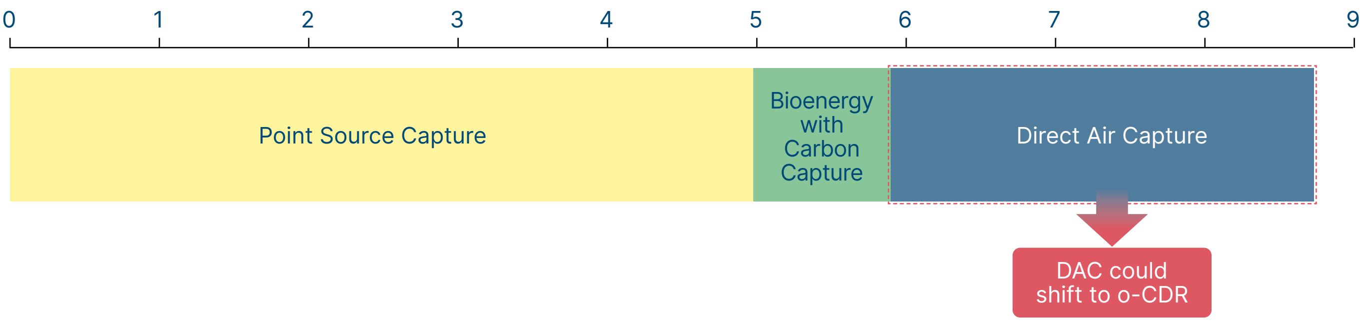
In the cost assessment we evaluate a capture system of 110,000 tonnes CO_2 per year which produces 3,600 tonnes of hydrogen.[80,81] In many cases, this hydrogen is valued at around $3 per kilogram, a price point that reflects expectations for future green hydrogen markets. At that price range, H_2 co-product substantially offsets system costs, reducing the net CO_2 removal cost to an estimated $200 per tonne. This is up to 60% lower than the updated ETC estimate for DAC, which places 2030 DAC costs around $480 per tonne. A detailed breakdown of these cost components is shown in Exhibit 4.8.

If this is realised, ocean-based electrolysis could become one of the most competitive and scalable carbon removal solutions, particularly in coastal regions with abundant renewable energy infrastructure. However, it is important to note that the DAC estimate reflects real-world project experience and commercial-scale learning, whereas the lower cost range projected for Equatic remains theoretical and subject to revision as the technology matures. Additionally, this figure assumes ideal power conditions, including access to very low-cost, reliable electricity.

Exhibit 4.9

If o-CDR proves to be more economical, it could become more promising option than DAC

CCUS volumes in 2050 under Base scenario
GtCO_2/year



SOURCE: Systemiq analysis for the ETC (2023); ETC (2022), *Carbon capture, utilisation and storage in the energy transition.*

80 Equatic announcement (2024), *Equatic to build North America's first commercial-scale ocean-based carbon removal facility*. Available at: https://www.equatic.tech/articles/equatic-to-build-north-americas-first-commercial-scale-ocean-based-carbon-removal-facility

81 According to Equatic's patent: US20220040639A1

Impact

If demonstrated successfully at scale, o-CDR could replace a substantial portion of projected DAC deployment. According to ETC estimates, achieving net-zero by 2050 may require up to 2.9 $GtCO_2$ per year of removals from DAC, as shown in Exhibit 4.9. As o-CDR technologies advance and prove cost-effective, they could capture a meaningful share of this volume, offering a promising alternative pathway for atmospheric CO_2 removal.

Potential:

- Rapidly scalable if economic and environmental barriers are addressed.
- Could help restore marine ecosystems and reduce ocean acidification.

Limitations:

- Operational complexity is significant, particularly around solids precipitation, fouling and equipment maintenance. Exposing electrochemical systems to raw seawater introduces challenges that have proven demanding even in simpler processes like reverse osmosis.
- TRL remains low. Most systems are still at lab or small pilot scale.
- Large-scale deployment could alter local seawater chemistry and impact marine biodiversity. Potential risks include shifts in pH, localised increases in salinity or turbidity, and disturbance of benthic habitats, all of which will require rigorous environmental monitoring and regulatory oversight.

DAC remains a critical carbon removal pathway, especially for hard-to-abate emissions, but faces persistent cost and energy barriers confirmed by recent data. Ocean-based capture has gained momentum as a complementary solution, with potential co-benefits such as hydrogen production and local ecosystem support. However, its success hinges not just on scalability, but on resolving major reliability and process engineering issues. In the near term, DAC may focus on modular, high-purity applications, while larger-scale removal could shift toward ocean-based or hybrid approaches—if these can meet environmental and operational performance thresholds.

Barriers and Enablers

Key barriers to scale-up remain:

- Early technology readiness levels for ocean-based removal systems, with limited large-scale demonstrations.
- High capital and operational costs, particularly for early-stage DAC and o-CDR systems.
- Uncertain long-term revenue streams and limited integration due to the lack of liquid markets and reliable offtakers.
- Potential ecological trade-offs and public opposition in the absence of strong governance; environmental impacts still require further research and validation.
- Operational risk under real-world conditions, including performance variability due to weather, air quality and seawater composition, as seen in cases like Climeworks' Orca plant, where output fell short of expectations.

While technology is advancing rapidly, large-scale deployment of DAC and o-CDR will depend on aligning system innovation, energy infrastructure, market incentives and regulatory safeguards. These systems are uniquely positioned to deliver durable, high-integrity removals if the enabling environment continues to mature in parallel with technical readiness.

For DAC and ocean-based carbon removal to contribute meaningfully to a net-zero future, key technical, economic and policy milestones must be reached. Despite innovation, both remain limited by high costs, energy needs and deployment complexity. **The following enablers are critical for scaling these technologies:**

- **Technology development and system innovation:** Continued progress in sorbents, solvents, membranes and overall system architecture is essential. Modular platforms enhance deployment flexibility, while digital tools such as AI can accelerate material discovery. For ocean-based systems, improving the efficiency and stability of electrochemical processes and mineral precipitation will be particularly important.[82]
- **Access to low-cost, zero-carbon energy:** The viability of both approaches is intrinsically tied to the availability of affordable, clean energy. While some pilots are already leveraging geothermal, nuclear and solar inputs, broader deployment will depend on stable access to renewable power at scale.
- **Site-specific deployment strategies:** Strategic siting near renewable energy hubs, CO_2 infrastructure and suitable marine environments can reduce costs and simplify logistics. For DAC, proximity to storage or utilisation sites is

82 Zentou, H. et al. (2025), *"Recent advances and challenges in solid sorbents for CO_2 capture." Carbon Capture Science & Technology*: 100386.

essential. o-CDR requires coastal access, permitting support and local supplies of alkaline minerals (e.g., crushed rock) for neutralisation. Sites must also enable disposal or reuse of mineralised CO_2, and ideally provide access to hydrogen markets to monetise co-produced H_2.

- **Market frameworks and certification standards:** Clear and credible rules for quantifying net CO_2 removals are foundational. Momentum is building through instruments such as the EU Carbon Removal Certification Framework (CRCF) and RED III. Full integration into compliance and voluntary markets will be critical for long-term investment and scalability.[83,84]
- **Environmental safeguards and public trust:** Maintaining environmental integrity is a prerequisite for social license to operate. DAC systems must mitigate concerns related to solvent use, water consumption and land impact. Ocean-based systems must be designed to avoid ecological disruption through careful pH management and trace metal monitoring. Early pilot projects suggest low environmental impact[85], but long-term monitoring and transparency are essential.

4.1.2 Point-Source carbon capture

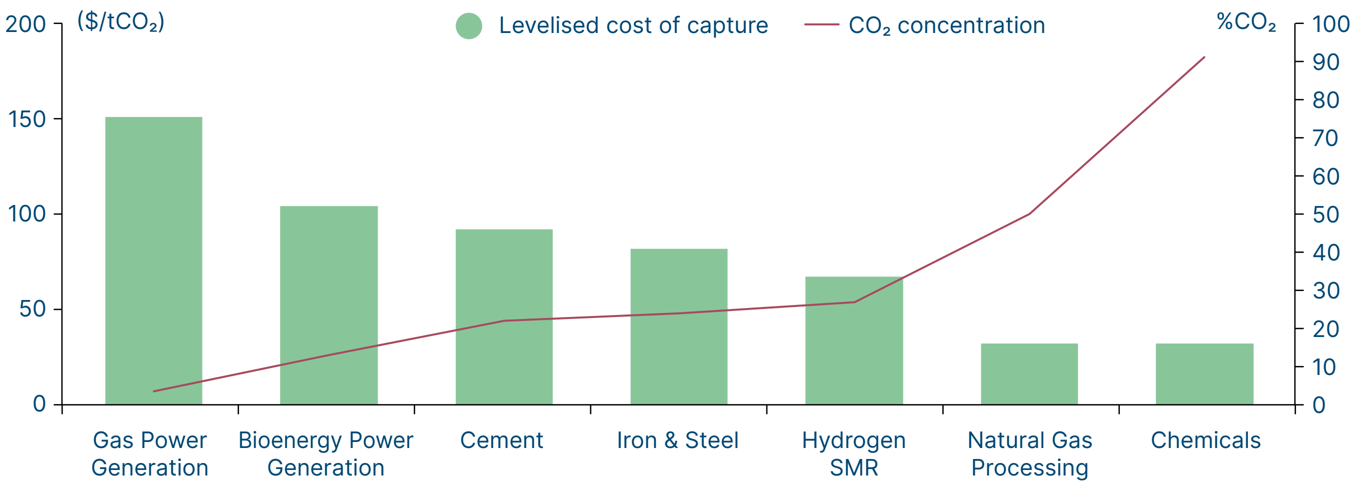
Overview

Point-source carbon capture is essential for reducing emissions from high-volume industrial emitters. Unlike direct capture methods that extract CO_2 from ambient air or water, point-source systems target emissions where they are most concentrated. This makes them well-suited for sectors such as power, cement and heavy industry. However, viability depends on CO_2 concentration in the exhaust stream, thermal integration opportunities and technology maturity.

Exhibit 4.10

There is an inverse correlation between the concentration of CO_2 and the cost of capture in different applications

Levelised cost of capture (left) and CO_2 concentration (right) by application, 2024



SOURCES: 1) ETC (2022) *Carbon Capture, Utilisation and Storage in Energy Transition: Vital but Limited* 2) Carbon tracker (2024) *Curb your Enthusiasm* 3) Bui et al. (2018), Carbon capture and storage (CCS): the way forward.

As shown in Exhibit 4.10, there is a strong inverse relationship between CO_2 concentration in flue gas and the cost of capture.[86,87] The lower the concentration, the more energy and infrastructure is required to separate and purify the CO_2, leading to higher costs.

- Gas power generation is the most expensive application, with typical CO_2 concentrations around 3–4%, pushing capture costs above $150 per tonne.

83 Systemiq (2024),, *Fossil-free Plastics: Driving Clean Industrial Leadership in Europe.*

84 Carbon Removal Certification Framework (CRCF) EU/2024/3012.

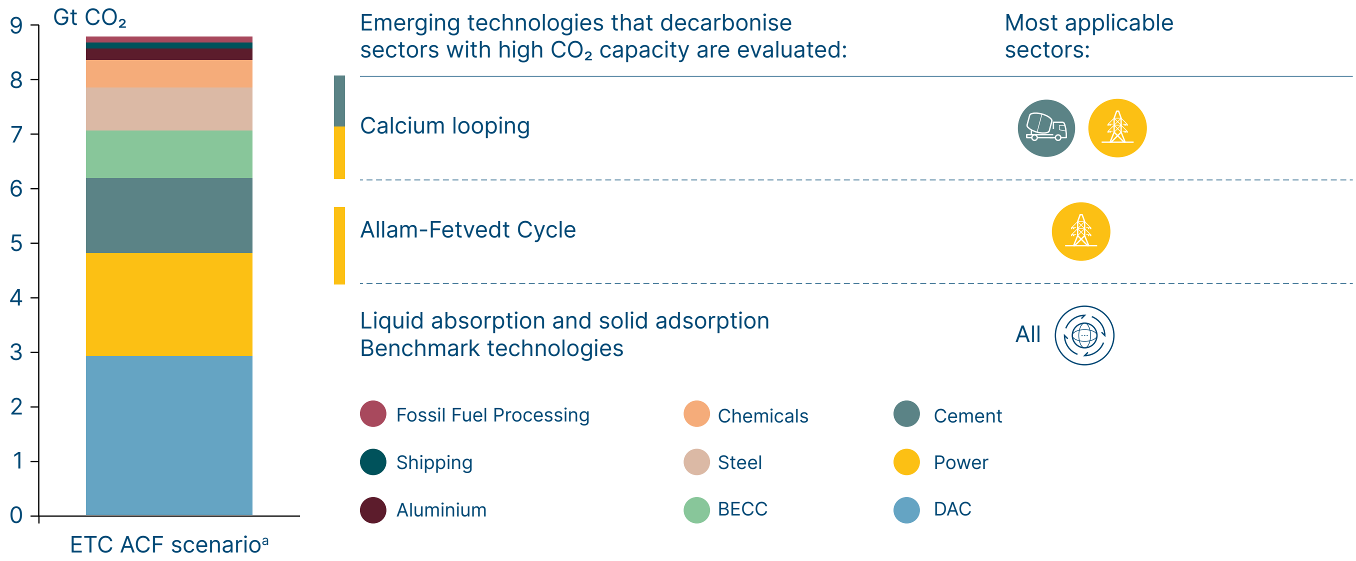
85 ClimateTech IE Research (2025), *Carbon Removal at Sea: The Science, Startups, and Stakes of Ocean-Based Solutions.*

86 ETC (2022), *Carbon Capture, Utilisation and Storage in Energy Transition: Vital but Limited.*

87 Carbon tracker (2024), *Curb Your Enthusiasm: Bridging the gap between the UK's CCUS targets and reality.* Available at: https://carbontracker.org/reports/curb-your-enthusiasm/

Exhibit 4.11

Power and cement sectors have the highest need for emission avoidance via Point Source Capture and are well-suited for emerging technologies



NOTE: [a] Volume shown refer to Accelerated But Clearly Feasible scenario. Fossil Fuel Processing includes natural gas processing, oil products refining and production of high value petrochemicals. The volumes are currently under revision in the latest work of ETC.

SOURCE: Systemiq analysis for the ETC; ETC (2022), *Carbon capture, utilisation and storage in the energy transition;* Ana Amorim et al. (2025), *Analysis of integrated calcium looping alternatives in a cement plant*; Betela et al. (2025), CO_2 *pollution capture and removal from thermal and cement industries through solar energy: a comprehensive review*.

- Cement and bioenergy with carbon capture (BECC) fall in the mid-range, with concentrations between 15–30%, and capture costs typically around $80–130 per tonne.
- Natural gas processing and chemical production offer the lowest capture costs, due to access to high-purity CO_2 streams, typically above 90% in chemical processes.

Sectors with dilute streams require more advanced, integrated technologies. Additionally, as shown in Exhibit 4.11, gas power and cement are also highly emission-intensive and challenging to decarbonise via electrification. These two sectors represent the highest projected CO_2 capture volumes by 2050. While BECC, steel and chemicals are important, they contribute less volume overall.[88] DAC, though significant, is assessed separately. Given the scale and cost challenges, power and cement sectors demand targeted technological solutions.

Benchmark point-source carbon capture technologies today are predominantly post-combustion systems, using either liquid absorption or solid adsorption. These methods remove CO_2 from flue gases after fossil fuel combustion and are already widely deployed at commercial scales. The process involves two key steps:

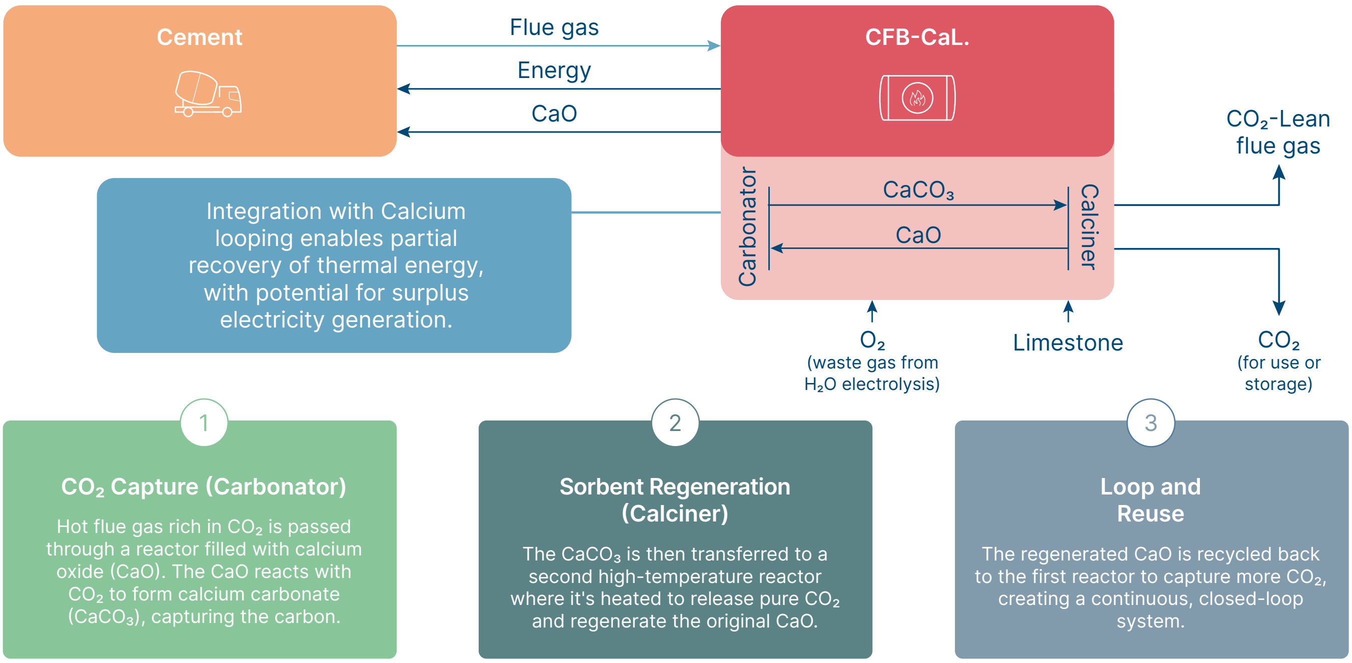
1. **CO_2 Capture:**
    - In **liquid absorption**, flue gas is passed through an absorber column where a liquid solvent (typically an amine-based chemical like monoethanolamine) binds with CO_2.
    - In **solid adsorption**, CO_2 molecules are captured on the surface of solid materials such as amine-functionalised sorbents, zeolites or metal-organic frameworks (MOFs).
2. **Regeneration:**
    - For liquid systems, the solvent is heated in a stripper column to release high-purity CO_2 and regenerate the liquid for reuse.
    - For solids, CO_2 is desorbed via heating, pressure swing, or vacuum swing processes, after which the material is reused.

88 Volume shown refer to the ETC's Accelerated But Clearly Feasible scenario. Fossil Fuel Processing includes natural gas processing, oil products refining and production of high value petrochemicals. The volumes are currently under revision in the latest work of ETC.

Exhibit 4.12

Calcium looping: Captures CO_2 using a looping cycle of limestone-based reactions

Overview of production process



SOURCE: Systemiq analysis for the ETC; Arias et al. (2024), Pilot Testing of Calcium Looping at TRL7 with CO_2 Capture Efficiencies toward 99%; Calby2030 project funded by the EU. Available at: https://www.calby2030.eu/overview-of-the-project.

Advantages:

- Tail-end retrofits are possible with minimal plant modifications, enabling easier integration into existing infrastructure.
- Continuous innovation, especially in solvents (DMX) and sorbents (MOFs), is improving performance.

Disadvantages:

- Both solvents and solid sorbents can degrade in the presence of flue gas impurities (SO_X, NO_X, dust), requiring pretreatment.[89]
- Solid adsorbents may suffer reduced CO_2 capacity due to competition with water vapor, particularly for materials like zeolites, which are highly sensitive to humidity.

Two next-generation capture technologies are now emerging with potential to disrupt the post-combustion paradigm:

- **Calcium Looping (CaL)** for cement: It is the focus of CaLby2030, an EU-funded project with 18 partners working toward commercial deployment by 2030.
- **Allam-Fetvedt Cycle (AFC)** for power generation: It is now being scaled by NET Power, with a 300 MW commercial plant in Odessa, Texas, expected to begin operation by 2029.

These will be compared with post-combustion benchmarks in terms of energy efficiency, scalability and integration potential.

Calcium Looping (CaL) is a promising carbon capture technology tailored for high-temperature industrial sectors such as cement. It operates through a closed-loop reaction between calcium oxide (CaO) and calcium carbonate ($CaCO_3$), using solid materials to chemically bind and release CO_2. As illustrated in Exhibit 4.12, the process includes three key stages: CO_2 capture in a carbonator, regeneration of the sorbent in a calciner and continuous looping of the material. The calciner typically uses natural gas as a fuel in an oxy-fuel configuration, enabling the production of a concentrated CO_2 stream that can be efficiently captured and processed.

89 Neerup et al. (2023), *Solvent degradation and emissions from a CO_2 capture pilot at a waste-to-energy plant.*

CaL is particularly compelling for cement industry integration, where calcination is already a core part of clinker production. While the CaL process requires a separate carbonator-calciner loop, opportunities exist to share infrastructure—raw materials, heat exchange networks, oxygen supply systems and potentially even calciner design and footprint—with existing cement kiln operations. Projects like CLEANKER have demonstrated that partial integration is not only feasible but can offer capital efficiency and energy synergies, especially in new-build or deeply retrofitted facilities.[90]

Advantages:

- High capture rate, typically around 90% and potentially up to 99%.
- Tolerant to flue gas impurities, eliminating the need for gas pretreatment.
- CaL can directly use the plant's existing raw materials as the sorbent for CO_2, improving circularity.
- Electricity generation is enabled through heat integration, as waste heat from the exothermic carbonation reaction and high-temperature calciner can be partially recovered to generate surplus electricity.

Disadvantages:

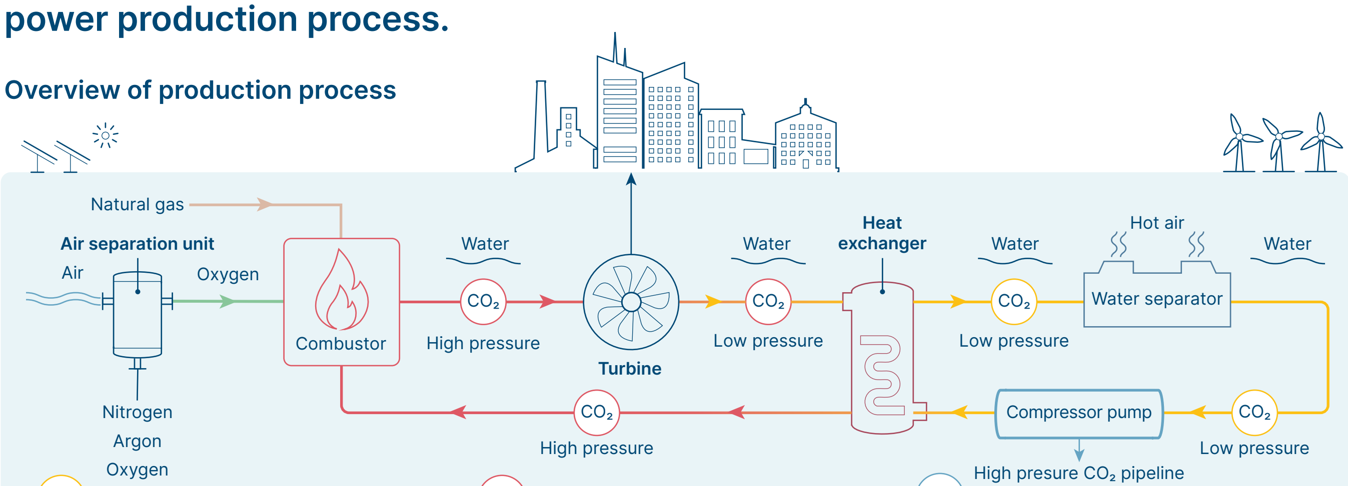
- Requires high-temperature operation, making it less suitable for retrofits in low-temperature systems.
- Medium-to-high CAPEX, depending on the level of integration.
- Needs dedicated oxygen supply and careful material handling to manage solid sorbents, which can slow down deployment.

Overall, CaL presents a promising but technically demanding pathway for cement decarbonisation. It offers opportunities for partial integration with existing plant infrastructure and energy efficiency gains through heat recovery, but its viability depends on careful system design, fuel and oxygen sourcing and management of high-temperature solid flows.[91]

Exhibit 4.13

Process modification: the Allam-Fetvedt Cycle captures CO_2 and utilises it in the power production process.

Overview of production process



1 Combustion in pure O_2

Natural gas is burned with recycled CO_2 and pure oxygen from an air separation unit (ASU), not air. This avoids nitrogen in the combustion process and produces only CO_2 and steam. The high-pressure, high-temperature gas spins a turbine to generate electricity.

2 Heat recovery and water removal

As the hot gas leaves the turbine, heat is recovered for reuse. Then, the gas is cooled and water vapor is removed, leaving behind a stream of nearly pure CO_2.

3 CO_2 Recirculation and export

The captured CO_2 is partly compressed and sent for storage or use. The rest is recycled back into the system to maintain pressure and continue the cycle.

SOURCE: 1) Sonal Patel (2021), *UK's First Gas-Fired Allam Cycle Power Plant Taking Shape*. Available at: *https://www.powermag.com/uks-first-gas-fired-allam-cycle-power-plant-taking-shape; (courtesy: 8Rivers)*; IEAGHG (2015), *Oxy-combustion turbine power plants*; 3) FutureBridge (2022), *Allam-Fetvedt Cycle*.

90 Martina Fantini et al. (2021), *Calcium Looping Technology Demonstration in Industrial Environment: Status of the CLEANKER Pilot Plant.*

91 Calby2030 project. Available at: https://www.calby2030.eu/overview-of-the-project.

The AFC is a novel power generation system that fully integrates CO_2 capture within its core thermodynamic process [illustrated in Exhibit 4.13]. Unlike conventional plants that bolt on capture units after combustion, AFC is designed as a greenfield solution where CO_2 is not a waste product, but a working fluid. As shown in the figure, the cycle begins by combusting natural gas with pure oxygen, eliminating nitrogen from the system and producing a high-pressure stream of CO_2 and water vapor. This gas powers a turbine to produce electricity. Downstream, heat is recovered and water is condensed, leaving a near-pure stream of CO_2. Part of this is sequestered or reused, while the rest is recycled to sustain system pressure.

Advantages:

- Near-total CO_2 capture (~99%) built into the core process.
- No need for chemical solvents like MEA, avoiding solvent degradation and emissions.
- As the working fluid is pure CO_2, non-condensable pollutants (NO_X, SO_X, particulates) are virtually eliminated.

Disadvantages:

- Requires a new plant build (greenfield project)—cannot be added onto existing infrastructure.
- High capital cost, driven by the need for oxygen production and CO_2 handling systems.

AFC provides an integrated, high-performance decarbonisation route for power generation, albeit with significant upfront investment.

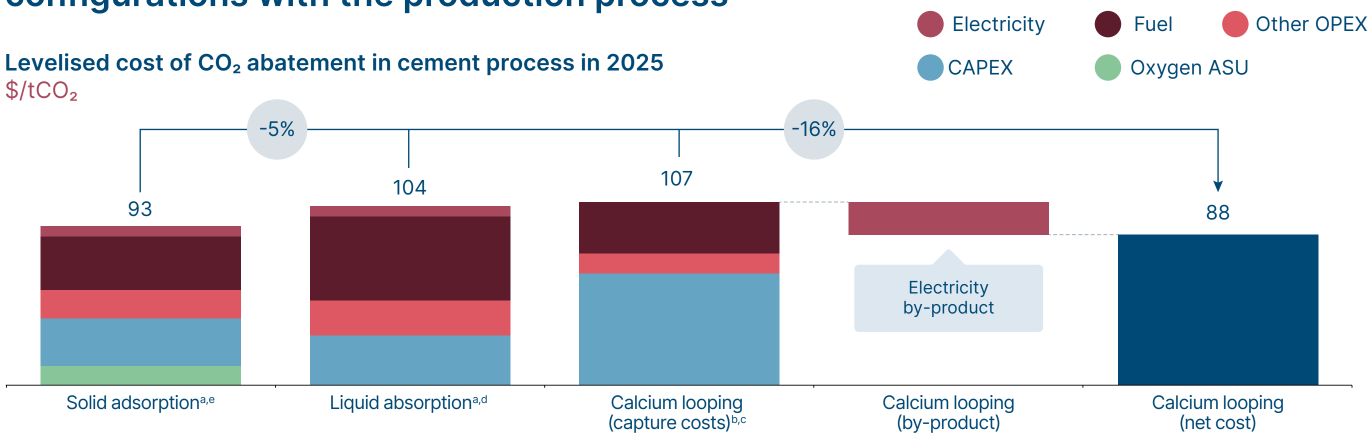
Costs

Exhibit 4.14 shows that among the evaluated technologies for cement decarbonisation, **CaL emerges as the most economical option**, particularly when integrated directly into the production process. A major advantage is the production of electricity as a by-product, which significantly offsets operating costs and enhances overall system economics. In the configuration analysed, the calciner is shared between the cement kiln and the carbon capture system, maximising heat recovery and minimising duplication of equipment. The calciner produces a H_2O/CO_2 stream and a CaO stream that is partly fed to the kiln for clinker production and partly to the carbonator for cyclic CO_2 capture.[92] This configuration requires significant modifications to the existing kiln system and, hence, a high capital cost for retrofitting. Other integration models (e.g., tail-end or downstream) are technically possible and could reduce upfront costs, but may suffer from lower efficiency and higher operational expenditure. The case presented here reflects full integration and provides a representative average estimate of capture cost, at approximately \$88 per tCO_2.

Exhibit 4.14

Calcium looping is promising for the cement industry because of integrated configurations with the production process

Levelised cost of CO_2 abatement in cement process in 2025
$/$tCO_2$



NOTES: Key inputs. Electricity price 60\$/MWh. Cost of Natural gas 12\$/GJ. Plant capacity 2880 t/d clinker. Capture rate: 90%

SOURCE: Systemiq analysis for the ETC; [a] Jaffar, M.M., et al. (2023), *Comparative techno-economic analysis of the integration of MEA-based Scrubbing and silica PEI adsorbent-based CO2 capture processes into cement plants*; [b] Amorim, A., et al. (2025), *Analysis of integrated calcium looping alternatives in cement plant*; [c] Yin J., et al. (2024), *Techno-economic assessment of retrofitting indirect-heated calcium looping using coal and biomass as fuels into an existing cement plant for CO_2 capture*; [d] Hanifa M., et al. (2023), *A review on CO capture and sequestration in the construction industry: Emerging approaches and commercialised technologies*; [e] Thunder said energy, Cryogenic air separation: costs and energy economics, Available at: https://thundersaidenergy.com/downloads/cryogenic-air-separation-the-economics/.

92 Yin, J., et al. (CSIRO 2020), *Retrofitting calcium carbonate looping to an existing cement plant for CO_2 capture: a techno-economic feasibility study.*

Liquid absorption and solid adsorption are also considered valid alternatives, with costs of $104 per tCO_2 and $93 per tCO_2 respectively. However, they face critical limitations in cement applications due to the dusty and chemically complex nature of cement flue gases. These off-gas streams can degrade solvents and adsorbents, requiring intensive pre-treatment or replacement. In contrast, CaL is well-suited to this environment, as it can tolerate impurities such as dust, SO_X, NO_X and trace metals, thereby reducing the need for costly pretreatment and ensuring greater process robustness. While liquid and solid capture systems may work in theory, their practical performance in cement applications remains less certain

Solid adsorption has seen limited deployment, notably in China where it is paired with oxy-fuel combustion to enrich CO_2 concentration and improve capture efficiency. However, the financial and policy context of such deployments—including potential subsidies—is not fully transparent, making cross-comparison difficult. Overall, CaL stands out for its favorable economics, technical compatibility with cement plants, and integrated energy benefits.

Exhibit 4.15 shows that among evaluated technologies for power sector decarbonisation, process modification via the AFC is the most cost-effective option, especially when assessed under a carbon price regime. The AFC achieves a CO_2 capture cost of $90 per tCO_2, which means it would be fully competitive under a $90 per tCO_2 carbon tax. Compared to the benchmark Natural Gas Combined Cycle (NGCC) plant with liquid absorption, AFC delivers 20% lower capital cost and 10% lower levelised cost of electricity (LCOE). This is enabled by its integrated high-pressure oxy-combustion and CO_2 recirculation, which avoids the need for post-combustion capture solvents and enables efficient carbon separation within the cycle itself.

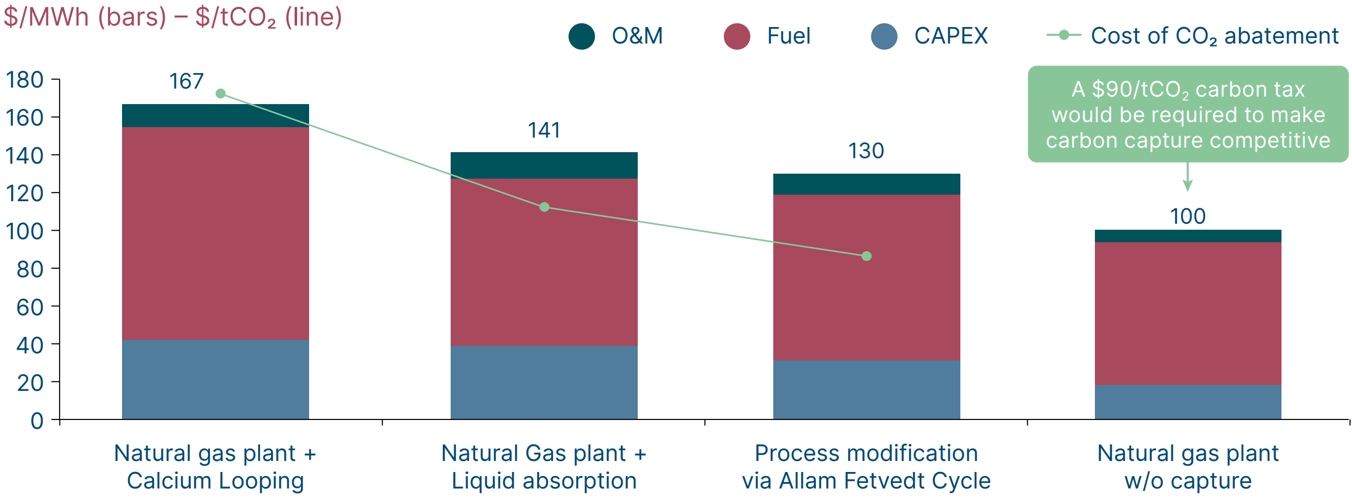
While NGCC coupled with liquid absorption or CaL offers valid alternatives, these configurations are less optimal in power applications.[93] In particular, CaL does not benefit from the same process integration advantages seen in the cement sector, leading to higher capture costs ($175 per tCO_2) due to standalone infrastructure requirements. Liquid absorption achieves moderate costs ($117 per tCO_2), but it still relies on mature solvent-based systems with lower overall efficiencies.

Exhibit 4.15

Process modification via Allam-Fetvedt Cycle (AFC) is the cheapest capture technology for the power sector, being cost-competitive at $90/$tCO_2$ tax

Levelised cost of electricity and cost of CO_2 abatement in 2025

$/MWh (bars) – $/$tCO_2$ (line)



Key takeaways	Natural gas plant + Calcium Looping	Natural Gas plant + Liquid absorption	Process modification via Allam Fetvedt Cycle	Natural gas plant w/o capture
	Less economical	Benchmark, good choice for retrofit	More economical than benchmark but requires greenfield application	Most economical, but unabated.

NOTE: Cost of Natural gas: 12$/GJ. Plant capacities: 650 MW NGCC, 400 MW AFC. Capture rate: 90% NGCC, 99% AFC.

SOURCES: Systemiq analysis for the ETC; European Commission (2021), *Average value of TTF cost in 2021: Market Observatory for Energy* in Quarterly report on European gas markets; Fu, C., et al. (2021), *Techno-Economic Analyses of the CaO/CaCO$_2$ Post-Combustion CO_2 Capture From NGCC Power Plants*; Smitt (NETL 2023), *Cost and performance of retrofitting NGCC units for Carbon capture – Revision* 3. Zheng, Y., et al. (2025), *Impact of energy integration on post-combustion CO_2 capture: A comparative analysis of chemical absorption and calcium looping technologies in coal-fired and natural gas combined cycle power plants*; Martinelli, M., et al. (2025), *Techno-economic assessment of the Allam cycle for different plant sizes, oxygen purities and heat integration with external sources.*

93 Fu, Chao, et al. "*Techno-economic analyses of the CaO/CaCO3 post-combustion CO_2 capture from NGCC power plants.*" *Frontiers in Chemical Engineering* 2 (2021): 596417.

The cost of natural gas is a key variable across all decarbonisation pathways. Nevertheless, the thermal efficiencies of each capture configuration remain broadly comparable, which preserves the relative ranking of options. Despite its favorable performance potential, a key limitation of the AFC is its greenfield nature—it requires the construction of entirely new power plants rather than the retrofit of existing ones. This makes deployment more capital-intensive and slower, even if the system itself is efficient. Moreover, the AFC has not yet been deployed at commercial scale, and its cost estimates rely on engineering models and pilot-scale data. By contrast, NGCC retrofitted with liquid absorption is a proven, commercial technology with known performance under real-world conditions. The future competitiveness of AFC will depend on deployment learning, system reliability and the availability of low-cost oxygen and CO_2 handling infrastructure.

Impact

While point-source carbon capture technologies can achieve capture efficiencies of around 90%, this figure applies only to the CO_2 generated at the point of combustion. A significant share of emissions remains unaddressed in the upstream and downstream segments of the fossil fuel value chain. These include:

- Upstream: Emissions from extraction, flaring and field transport.
- Downstream: Processing, compression and distribution.

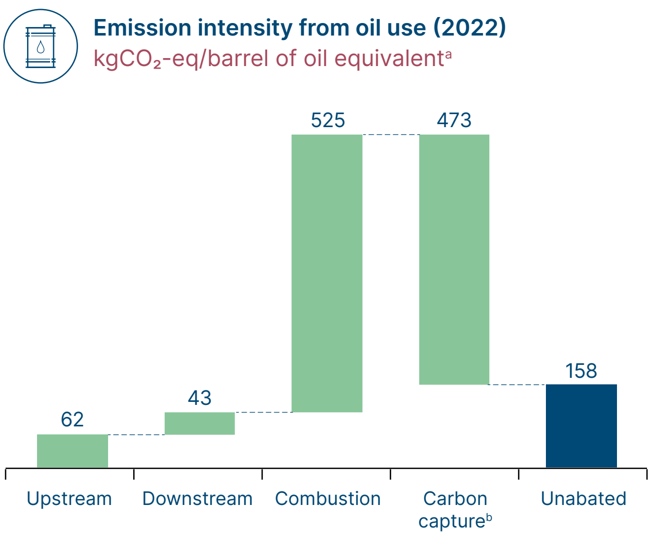
As shown in Exhibit 4.16, oil combustion results in 158 $kgCO_2$-eq of unabated emissions per barrel of oil and natural gas yields 108 $kgCO_2$-eq, even after applying carbon capture.[94,95] This corresponds to an overall emissions gap of 20–25%, which limits the full climate mitigation potential of fossil-based capture solutions.

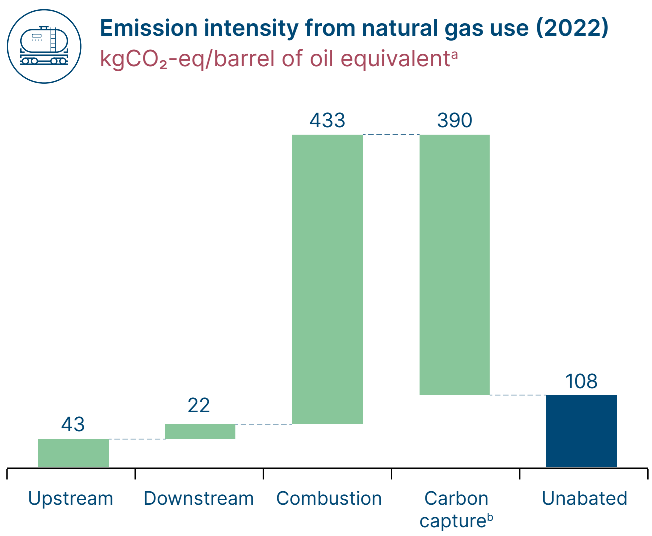
Key levers to address this gap include:

- Reducing methane emissions from upstream oil and gas.
- Electrifying upstream facilities.
- Eliminating non-essential flaring.
- Expanding low-emission hydrogen integration and refining.

Exhibit 4.16

If we rely on fossil carbon sources, we need to address the 20–25% of emissions that could remain unabated under CO_2 capture technologies





NOTE: [a] Barrel of oil equivalent (BOE) is a standardised unit of energy used in the oil and gas industry to compare the energy content of different fuels. One BOE represents the amount of energy released by burning one barrel (159 liters) of crude oil and is approximately equal to 1.7 MWh; [b] Assume 90% capture rate.

SOURCE: IEA (2023), *Emissions from Oil and Gas Operations in Net Zero Transitions: A World Energy Outlook Special Report on the Oil and Gas Industry and COP28.*

94 Barrel of oil equivalent is a standardised unit of energy used in the oil and gas industry to compare the energy content of different fuels. One BOE represents the amount of energy released by burning one barrel (159 litres) of crude oil and is approximately equal to 1.7 MWh.

95 IEA (2023), *Emissions from Oil and Gas Operations in Net Zero Transitions: A World Energy Outlook Special Report on the Oil and Gas Industry and COP28*.

This limitation underscores the importance of targeting the full fossil value chain in parallel with capture solutions. While carbon capture plays a vital role, it must be deployed alongside broader systemic interventions to ensure a pathway to net-zero. Emerging technologies which demonstrate capture efficiencies close to 99% (e.g., AFC), can help reduce the residual emissions at the combustion stage. Although these technologies do not address upstream or downstream emissions, their higher capture rates can contribute to narrowing the overall mitigation gap.

Barriers and Enablers

Key barriers to scale-up remain, particularly in the early stages of deployment. These are:

- **High capital costs**, which affect both retrofit projects and new-build systems like the AFC, especially where integration is complex or site-specific.
- **Regulatory uncertainty** in some regions, particularly regarding long-term storage liability and permitting, which delays investment.
- **Limited access to CO_2 transport and storage infrastructure**, especially outside a few well-characterised hubs such as the US Gulf Coast, restricts project siting and scale.
- **Operational risks under real-world conditions**, including equipment degradation, fluctuating feed conditions and system downtime, remain poorly understood for emerging technologies.
- **Technology-specific limitations constrain adoption**:
    - AFC, though highly efficient and capable of capturing ~99% of CO_2 without chemical solvents, can only be deployed in new-build (greenfield) plants. This limits its suitability for retrofits and near-term relevance mainly to regions where new fossil capacity is still being added—particularly emerging markets that require dispatchable baseload power and lack full renewable penetration. In northern-latitude countries, however, where large gas-CCS fleets may be required to provide mid- to long-term system balancing, the AFC could also play a strategic role. In this sense, it may serve not only as a tactical near-term option but also as a contributor to longer-term balancing capacity within otherwise net-zero-aligned power systems.
    - Calcium Looping is highly promising for cement decarbonisation, thanks to its synergy with kiln infrastructure and tolerance to flue gas impurities. However, it requires high-temperature operation, making it less suitable for industries operating at lower process temperatures. It also entails medium-to-high capital costs and requires dedicated oxygen supply and sorbent handling systems, which can complicate integration in some settings.

Scaling point-source carbon capture to commercially viable levels across industrial and energy systems will require simultaneous progress in technology, infrastructure, policy and financing. Key enablers include:

- **Material and system innovation:** Advances in solvents, sorbents and capture system design are essential for improving efficiency and reducing energy demands. Next-generation materials such as phase-change solvents and metal-organic frameworks (MOFs) are currently undergoing pilot testing and show potential to significantly lower both capital and operational costs.

- **Access to low-cost, zero-carbon energy:** Many point-source capture systems, especially post-combustion, require significant heat or power. Using fossil-derived energy reduces climate benefits and raises costs, whereas renewable or waste heat sources improve efficiency.
- **Process integration:** Embedding capture systems within industrial sites like cement or steel plants can reduce costs by up to 50% compared to non-integrated configurations. For instance, CaL is highly compatible with cement kilns, allowing shared use of calciners, infrastructure and sorbent material.
- **Infrastructure development:** CO_2 transport and storage infrastructure must expand in parallel to support large-scale deployment of capture systems.
- **Policy and finance:** Stable regulatory frameworks, clear carbon pricing and dedicated incentives such as the US 45Q tax credit and EU Innovation Fund are critical to reduce investor risk and unlock new projects.
- **Long-term monitoring:** Proven MRV systems are necessary to ensure transparency and manage long-term liability, such as those demonstrated by Sleipner in Norway.

While post-combustion and looping-based capture technologies are maturing rapidly, their widespread adoption will depend on technology-fit, cost trajectories and the regional energy context. Solutions like CaL offer sector-specific integration advantages, while AFC presents a high-efficiency power solution for niche market–provided the infrastructure and fossil feedstock remain aligned with local development needs. Unlocking full-scale deployment across all sectors will require coordinated action across technology, policy and markets.

4.2 Biomass carbon: harnessing biological productivity

Biomass offers a natural carbon capture pathway through photosynthesis, which serves as a renewable and flexible carbon feedstock if sourced sustainably. It is already used in bioenergy, bioplastics, biochar and a range of low-carbon products, but scaling its use must be managed carefully to avoid land-use conflict and ecological harm. Land dedicated to biomass production faces an opportunity cost, as the same land could otherwise be used for food production, timber, or ecosystem restoration – and current pressures on land, from a growing global population, will limit the amount of sustainable bioenergy available.[96] Biomass can also serve as a carbon dioxide removal pathway if sequestered directly and recent research[97,98] indicates that in carbon-constrained environments, direct burial may deliver greater climate benefits than use as a feedstock. This report does not analyse the pathway further, focusing instead on biomass as a carbon feedstock.[99] Exhibit 4.17 lists the strict criteria necessary for biomass to be considered sustainable. These conditions ensure that biomass does not incur other environmental or social impacts, which may make it even more harmful than fossil resources.

96 World Resources Institute (2018), *Creating a Sustainable Food Future.*

97 World Resources Institute (2023), *Biomass burial as a carbon removal strategy in carbon-constrained scenarios: U.S. modelling results.*

98 Sandalow et al. (2020), *Biomass Carbon Removal and Storage (BiRCS) Roadmap.*

99 Wider ETC work on biomass covers the use of biomass and biochar for carbon dioxide removals, e.g., ETC (2022), Mind the Gap.

BOX A

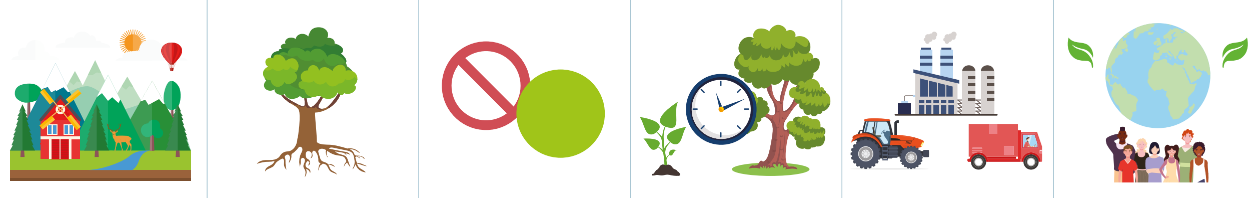
No land is "free". Nearly all land with productive or ecological value is already used for food, feed, timber or ecosystem services such as carbon storage and biodiversity. Dedicating land to biomass for energy or materials therefore carries an opportunity cost–it displaces one or more of these functions. Current trends from WRI's Land & Carbon Lab indicate that cropland and pasture expansion continues globally, while dietary shifts and yield gains remain too slow to free land at the scale assumed in many models. [100] These trends suggest that additional land for bioenergy cannot be taken for granted, reinforcing the need to prioritise residues, wastes and integrated systems over dedicated crops.

Key trade-offs

- **Food security:** Diverting cropland or pasture increases food prices and can shift agricultural expansion into forests or grasslands elsewhere.
- **Carbon opportunity cost:** Even if new biomass is carbon-neutral at harvest, converting land or delaying natural regrowth can release more carbon than is avoided through fossil substitution, creating multi-decade carbon debts.
- **Biodiversity and ecosystem services:** Converting or intensifying natural and semi-natural landscapes for energy crops undermines habitat, soil health and water regulation.
- **Degraded and marginal land:** If land is capable of supporting biomass, it can generally also support food production or ecological restoration. Using it for bioenergy should occur only where neither food production nor restoration is viable in the foreseeable term.
- **Yield growth limits:** Projected improvements in agricultural productivity are uncertain and could be insufficient to meet food demand and restore nature simultaneously. Future land "freed" by diets or yields should consider trade-offs of nature, food or energy use.
- **Governance and equity:** Clear land rights, anti-deforestation enforcement and sustainability certification are essential to prevent land grabbing and ensure that biomass expansion does not harm local communities.

Exhibit 4.17

Biomass can only be considered sustainable if certain conditions are met



No competition with other critical uses of land	No deforestation or peatland conversion	Target degraded land, with little plant growth	Respect growth periods which will delay supply	Close-to-zero emission collection, transportation and processing	No environmental or social harm
Biomass sourcing must not displace essential functions of land, including food production, housing and ecosystem conservation, and restoration.	Biomass sourcing must avoid land-use changes that release stored carbon and destroy natural ecosystems, especially in forests and carbon-rich peatlands.	Biomass sourcing should prioritise using marginal or degraded lands with low ecological value to avoid disruption productive ecosystems and high-carbon landscapes.	Harvesting must align with natural regeneration cycles to maintain long-term productivity and ecosystem health, even if it slows supply.	Biomass supply chains must minimise emissions across logistics and processing to ensure real climate benefits.	Projects must safeguard local environments and communities, delivering benefits without causing displacement or degradation.

SOURCE: ETC (2021), *Bioresources within a Net-Zero Emissions Economy: Making a Sustainable Approach Possible;* World Resources Institute (2018), *Creating a Sustainable Food Future*

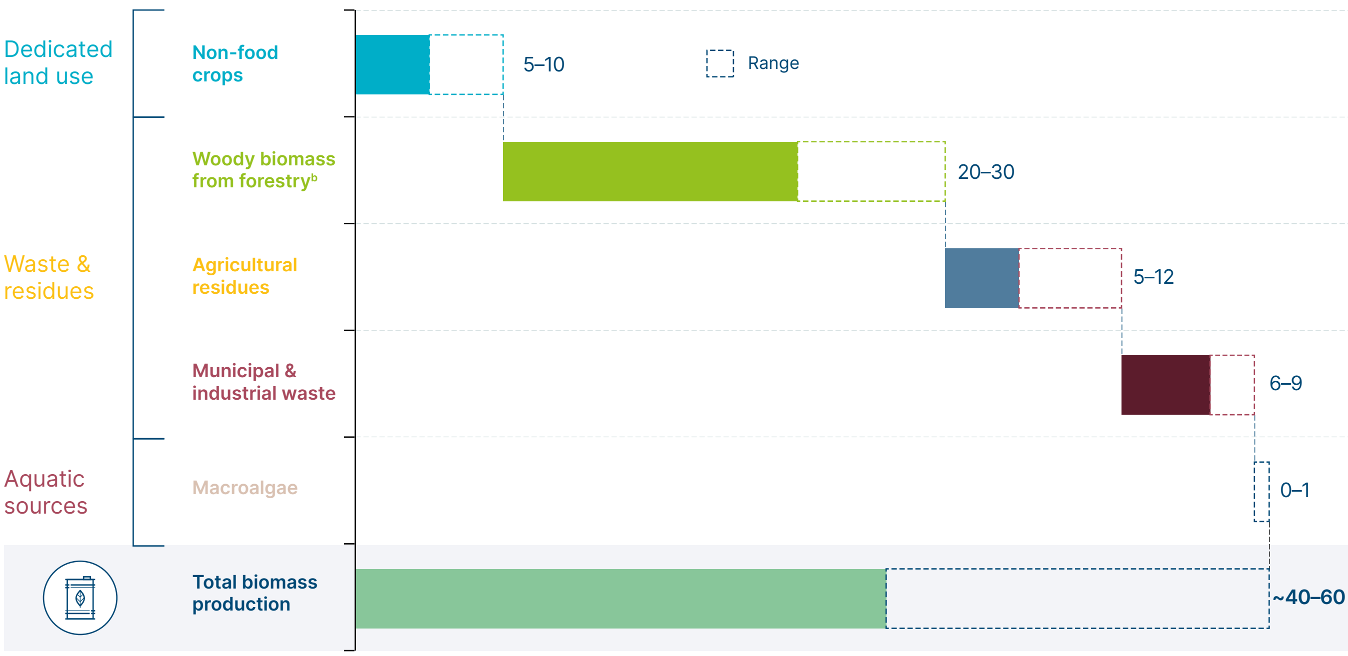
100 World Resources Institute (2023), *The Global Land Squeeze: Managing the Growing Competition for Land.*

Based on these principles, the ETC has previously estimated that ~40–60 EJ of biomass could be sustainably supplied by 2050, as presented in Exhibit 4.18. However, this potential could increase through radical changes, including (1) using more productive land, (2) making additional land available and (3) tapping new sources. This section examines each of these changes in turn as exploratory avenues, noting that any land potentially freed is a viable alternative for food production or ecosystem restoration. Such shifts would depend on a combination of technological advances, cultural change and well-enforced legislation.

Exhibit 4.18

Bioresources – ETC has previously estimated prudent global supply of sustainable biomass at ~40–60 EJ/year, but disruptive innovation could change this

Global sustainable biomass[a] supply (2050), illustrative scenario
EJ/year (primary energy)



NOTES: [a] The term "sustainable biomass" is used to describe organic material that is renewable, has a lifecycle carbon footprint equal or close to zero (including considerations for the opportunity cost of land), and for which the cultivation and harvesting practices used are mindful of ecological considerations such as biodiversity and health of the land and soil; [b] Includes high-quality stemwood from forestry suitable for the timber and pulp & paper sectors (~10 EJ/year today, FAO Industrial Roundwood production less by-products used for energy). This category also includes residues from forestry but excludes traditional fuelwood (~25 EJ/year today, assumed to reduce with modernisation) due to collection and sustainability assurance challenges.

SOURCES: ETC (2021), *Bioresources in a net-zero economy.*

4.2.1 More productive land – degraded land and more productive energy crops

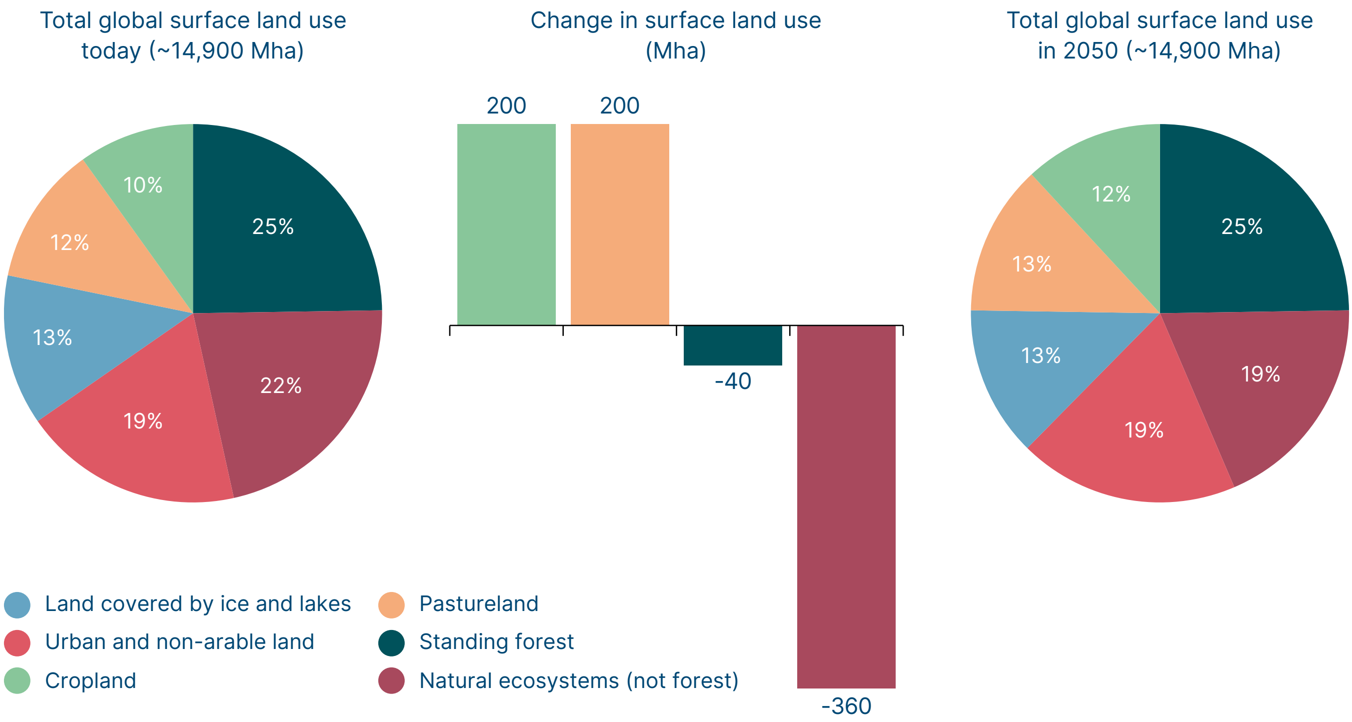
Biomass crops could expand only on land that does not displace food production or critical ecosystem restoration, because land competition can raise food prices and trigger direct and indirect land-use change that increases net greenhouse-gas emissions and harms biodiversity. Suitable crops include high-yielding grasses (e.g., switchgrass), short-rotation woody crops (e.g., willow) and oil-bearing plants (e.g., camelina). Among potential land sources, two are often highlighted: (1) degraded land and (2) farmland that becomes available if diets shift away from animal-based protein. This section examines the first category, while the second will be considered in Chapter 4.2.2.

The International Standards Organisation (ISO) defines degraded land as unable to sustain its economic or ecological function. Degradation has multiple causes; two common ones are industrial sites contaminated with pollutants and farmland degraded by intensive agriculture. Industrial sites often need costly remediation to reduce contaminants before planting, whereas agricultural degradation is a continuum: lightly depleted soils may rebound quickly with organic amendments, cover crops and reduced tillage, while severely eroded or salinised fields demand more intensive restoration. Deploying energy crops on such land can sometimes generate revenue that supports restoration, yet three caveats remain: potential competition with future food supply, loss of existing soil carbon stocks during conversion and the carbon payback time, which varies with crop, yield and prior land cover. Dedicating degraded land to biomass production involves an opportunity cost, as the same land could support other uses such as ecological restoration.

Energy crop expansion must never jeopardise food security, whether the land involved is degraded or not. Exhibit 4.19 demonstrates that increased food demand is expected to cause conversion of natural environments into pasture and cropland by 2050. This can be mitigated by higher yield of food crops and reduced losses in the food supply chain. If this happens, converting unproductive food land for energy production will not contribute to disruptions in food supply. In regions with higher risk of food insecurity, shifting even low land areas from food to energy production may be very impactful and should be avoided, regardless of efficiency gains. For example, in some African countries, shifting land for energy production has already affected local prices.[101]

Exhibit 4.19

Under current trends, need for crop & pastureland will continue to grow at the expense of nature



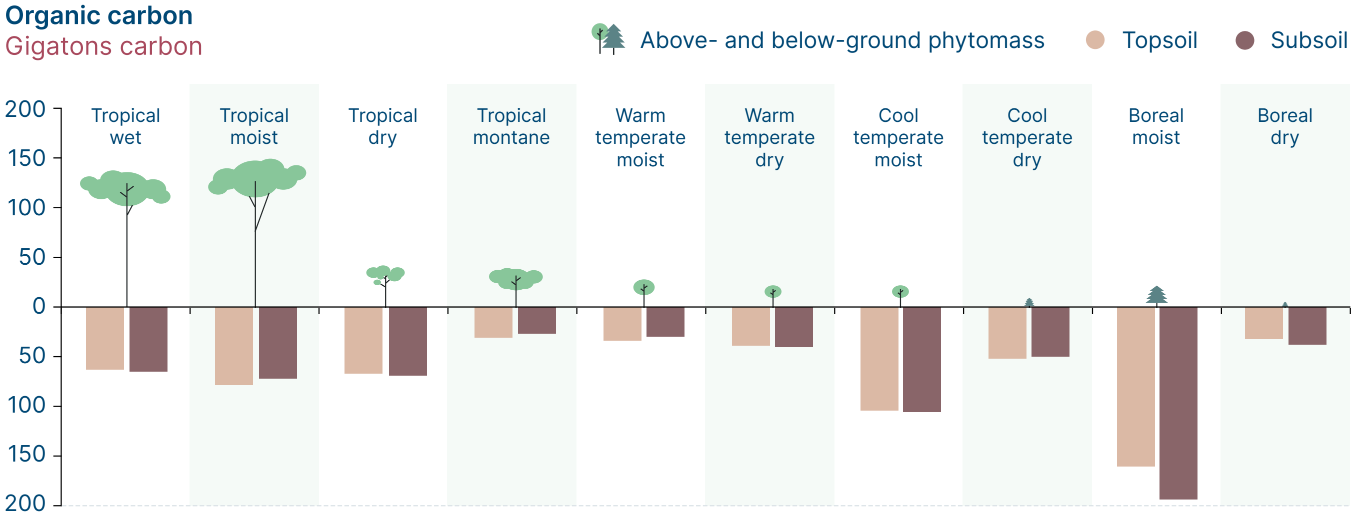
SOURCE: ETC (2021), *Bioresources within a Net-Zero Emissions Economy: Making a Sustainable Approach Possible.*

Natural carbon stocks should be factored into decisions about whether to repurpose degraded land for energy production or prioritise ecosystem restoration. Exhibit 4.20 shows that some vegetation types sequester considerably more carbon than others. In cold climates, slow microbial activity means biomass decomposes slowly, so a large share of carbon accumulates in the soil, as in boreal forests and peat-rich cold temperate zones. By contrast, warm climates provide ample sunlight that fuels rapid plant growth and stores more carbon in living biomass, as in tropical moist and tropical wet forests. Moisture amplifies each trend: wetter cold sites slow decomposition even further, while wetter warm sites accelerate growth. Accordingly, when degraded land originally supported vegetation with high carbon sequestration capacity, restoring that ecosystem should take precedence over energy production, as it is likely to deliver greater long term carbon sink benefits.

101 Waghmode, V,. (2024), *Cassava Prices Soaring in Nigeria Due to Increased Demand from Ethanol Producers.*

Exhibit 4.20

The amount of carbon stored by ecosystems can be significant and varies geographically

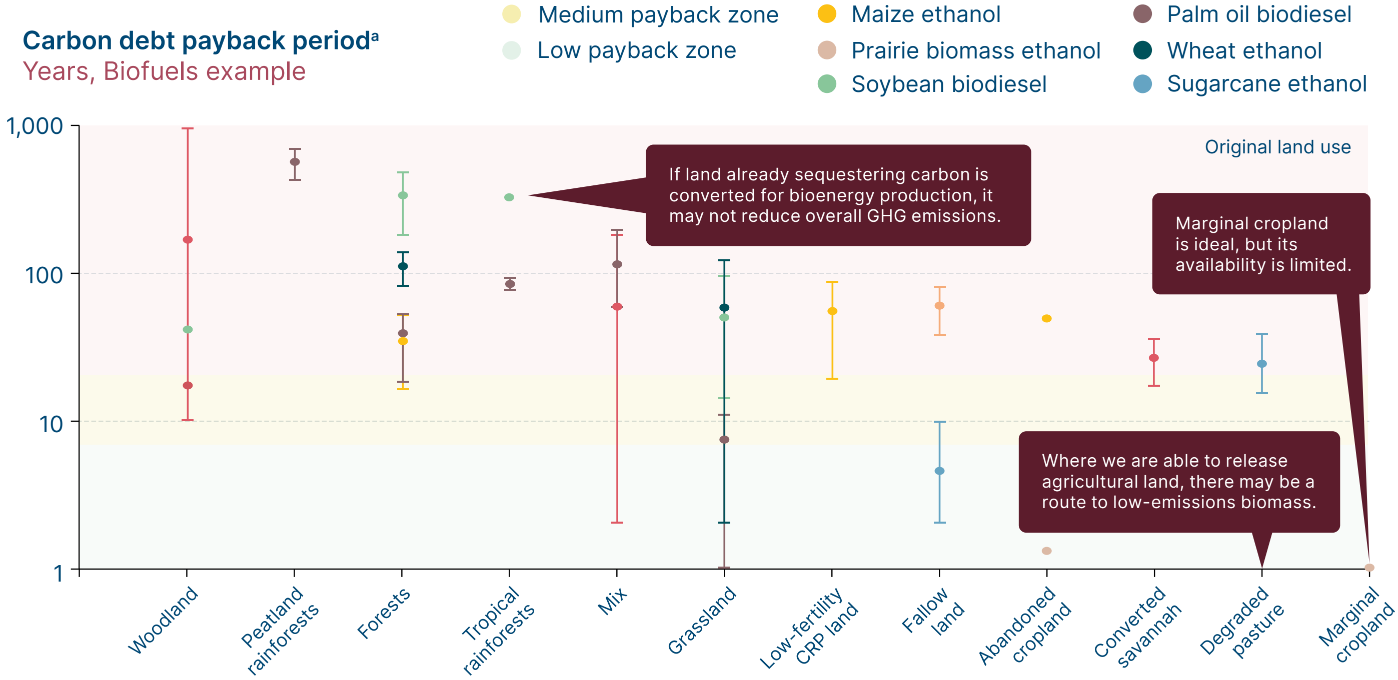


SOURCE: ETC (2021), *Bioresources within a net-zero economy.*

A final consideration is the time required for an energy crop to sequester as much carbon as the vegetation it replaces. Replacing natural ecosystems with energy crops generally involves long carbon payback periods and should therefore be avoided, as demonstrated in Exhibit 4.21. However, certain biofuels can achieve relatively short carbon payback periods when grown on abandoned cropland, degraded pasture, fallow land, grassland or marginal cropland. This spectrum of land types highlights that agricultural degradation is a continuum: soils too depleted for efficient row crop cultivation may still support low intensity grazing. Selecting the right land–crop combination can thus enhance long-term carbon sequestration.

Exhibit 4.21

Conversion of land with high carbon stocks leads to long carbon payback periods



NOTES: GHG: greenhouse gas. [a] Carbon debt payback periods reported were compiled by Gasparatos et al. (2017) from a range of sources in the literature.

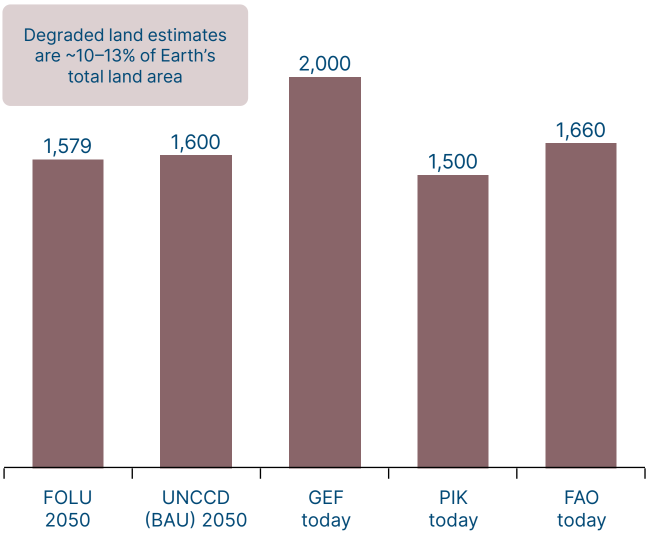
SOURCES: Gasparatos et al. (2017), *Renewable energy and biodiversity: implications for transition to a green economy.*

A review of studies on using degraded land for energy production indicates that the ETC's 30 Mha estimate is conservative. Global degraded land estimates lie around 1,500 Mha, with sources estimating a range of 140–1,411 Mha used for energy production. The upper bound effectively assumes that every hectare of degraded land is converted, an unrealistic scenario that overlooks constraints such as urban degradation, where land within or near cities has been rendered unfit for productive use due to contamination, sealing, or competing social demands. The lower bound is ~5x higher than the ETC estimate, while the average of the lower bounds from the sources, yields ~257 Mha. A summary of the reviewed literature is presented in Exhibit 4.22.

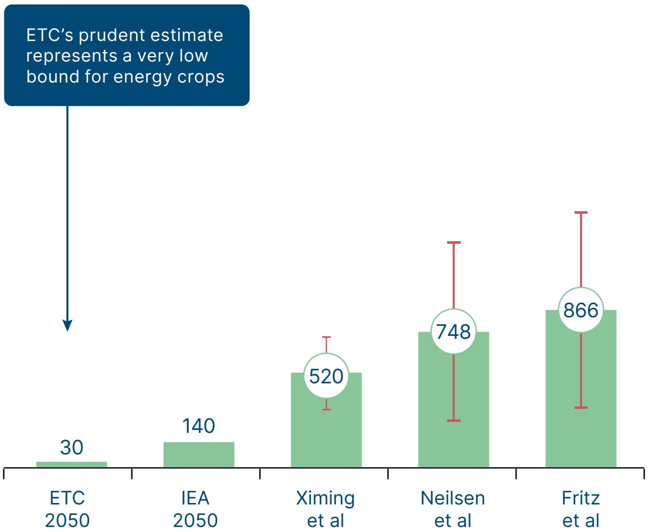
Exhibit 4.22

There is broad agreement around the area of degraded land, but more variance of opinion around the potential to regenerate it for energy crops

Ranges of degraded land estimates
Millions of ha



Range of estimates for energy crops on degraded land
Millions of ha



SOURCE: Systemiq analysis for the ETC; FOLU (2019), *Growing Better*; Global Environmental Facility (2017), GEF-7 *Replenishment Programming Directions*; Potsdam Institute for Climate Impact Research (2024), *Transforming land management within planetary boundaries key to addressing global land use crisis*; PBL Netherlands Environmental Assessment Agency (2022), *The global potential for land restoration: Scenarios for the Global Land Outlook 2*; FAO (2024), *Restoration of degraded agricultural lands*; IPCC (2022); IEA (2024), *Bioenergy, World outlook 2024*.

Literature review is valid for estimating a maximum potential of sustainable biomass growth in degraded land, but cannot account for regional factors. A more accurate assessment would:

i. Map the global distribution of degraded land.

ii. Identify the areas where energy crop cultivation generates the greatest net benefits.

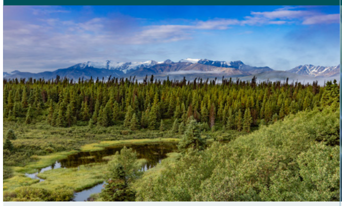
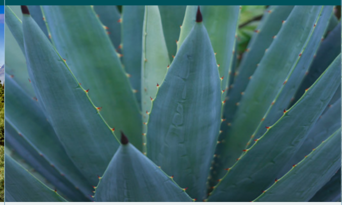
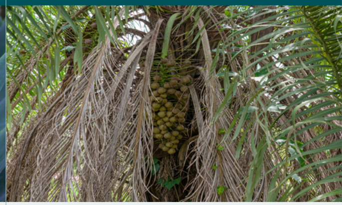
iii. Match suitable energy crops to local soil and climate conditions.

iv. Determine a land restoration plan that specifies the timeframe and inputs required for soil recovery.

In addition to using more degraded land for energy production, introducing novel non-food energy crops could further boost the sustainable biomass supply. Although many of these crops can individually deliver higher yields, prosper on degraded or nutrient poor soils and act as both biomass feedstocks and carbon sinks, realising all three advantages at once often requires substantial synthetic inputs. Exhibit 4.23 summarises the options examined, with energy cane selected for detailed analysis.

Exhibit 4.23

Novel non-food energy crops can thrive on previously untapped soils, increase biomass yields and act as effective carbon sinks

Boreal Forests	Agave	Macaw Palm	Energy Cane
			
• Increasing interest in using logging residues and deadwood from wildfires or pest outbreaks as biomass source • Important carbon sink, but low soil regeneration potential • **Where:** Suitable in cold climates, in regions like Canada, Scandinavia and Russia	• Crops resistant to dry weather and poor soil – able to be cultivated in regions not used for bioenergy/ food • Deep root system helps prevent soil erosion and recover soil structure • **Where:** Thrives in semi-arid soils, low water regions and high solar intensity	• A crop suitable for agroforestry that produces-oil rich fruits and can be combined with food crops on degraded soil • Can be grown on poor soils and regenerate the soil • **Where:** Native to tropical and subtropical regions and resistant to droughts	• High fibre content cane, which have higher yield compared to traditional sugarcane • Moderate potential to recover land, but able to build organic matter • **Where:** Similar conditions to sugar cane, but requires more inputs

● Deep-dive undertaken for Brazil

Exhibit 4.24

Energy-cane is a strain that maximises 2nd generation biofuel production, due to higher productivity and cellulose content

		Sugarcane	Energy-cane
Description		Traditional sugarcane which is designed to produce more TRS[a] (e.g., saccharose)	New strain which is designed to produces more fibers (e.g., bagasse) and less sugar
Yield	**(GJ/ha)** **(ton/ha)**	450–940 Average: 70–100 (max 140)	960–1900 150–200
Technical Specifications	**TRS content (kg/tonne of cane)**	120 – 140	85–95
	Bagasse content[b] (kg/tonne of cane)	~140	250–280
	Straw content[c] (kg/tonne of cane)	~140	140–2803
	Harvests per cycle	~5 cuts before replanting	~10 cuts before replanting
	Plague and disease	Requires intensive management	More resistant to plagues & disease
Projects / Plantations		Commercially planted for centuries, with genetic and operational improvements over time.	GranBio, a company relevant for its R&D work with sugarcane, has announced a 50 kha project in Alagoas for SAF production in 2028.
Costs[d] (initial plantation)		9,900–10,500 BRL/ha (1,800–1900 USD/ha)	11,000–13,000 BRL/ha (2,000–2,350 USD/ha)

● Favourable ● Unfavourable

NOTE: [a] TRS = Total Recoverable Sugar. [b] In terms of dry mass of bagasse and straw [c] No data found online, but straw estimated to be the same as sugar cane or up to 2x more, as the total biomass per hectare may be up to 2x bigger in the Energy-cane as compared to regular sugar cane. [d] Costs based on 2023 values and susceptible to variations due to inputs cost variation. Price for Energy-cane is estimated using a 5–30% cost difference as it is an innovative strain. GranBio sources mention price variations for very small-scale operations. BRL to USD from 30/04/2025 at 0.18.

SOURCE: Systemiq analysis for the ETC; da Silva, F. T. F, et al. (2024), *Analysis of GranBio website*; Ferreira da Silva (2024), *Integrated systems for the production of food, energy and materials as a sustainable strategy for decarbonisation and land use: The case of sugarcane in Brazil*; *Cana Online (2015), Cana-energia produz em média 200 toneladas por hectare*; CONAB website; de Oliveira, V. B., et al. (2025), *A cana energia: tolerante ou suscetível aos herbicidas?*

Energy cane is a high-yield variant of sugarcane bred for cellulosic biomass rather than sucrose production, making it an optimal feedstock for second generation biofuel. Exhibit 4.24 provides a detailed comparison of both strains. Thanks to its higher cellulosic content and superior yields, energy cane can raise the crop's specific energy (energy per kilogram) by as much as 40%. This advantage has attracted companies such as GranBio, which is evaluating the crop as a feedstock for bio derived sustainable aviation fuel (bio SAF).

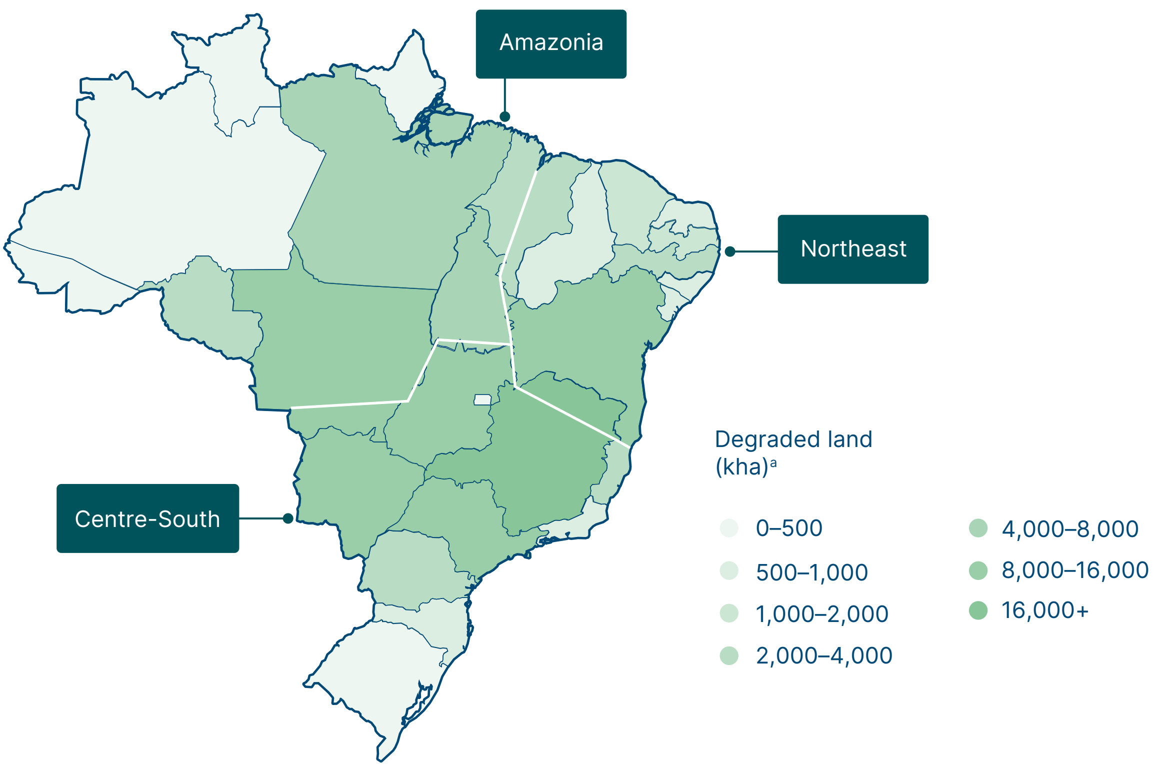
To illustrate the potential of novel energy crops in expanding sustainable biomass supply, an analysis has been conducted of energy cane cultivation on degraded land in Brazil. The country possesses an estimated 112 Mha of degraded land, of which 66 Mha lie within regions already devoted to sugarcane production [Exhibit 4.25]. Restricting energy cane plantations to degraded land in these established sugarcane areas yields several advantages:

1. Expansion into ecologically sensitive biomes—such as the Amazon—is avoided because commercial sugarcane is concentrated in the Centre South.
2. Proximity to existing logistics and processing infrastructure minimises additional capital expenditure.
3. Displacement of food producing land is prevented.
4. Revenue from energy cane cultivation provides a financial incentive that can offset the high cost of soil restoration.
5. Degraded land elsewhere remains available for rehabilitation with food crops or native vegetation, supporting future food security and biodiversity recovery.

Exhibit 4.25

Energy-cane cultivation in degraded land in Brazil has a massive potential to supply sustainable biomass for the energy sector

Brazil has an estimated 112 million hectares of degraded land (~13% of total land)



NOTES: [a] Degraded land categorised as medium and low pasture condition. It has been assumed that 30% of degraded land in Mato Grosso and 80% of degraded land in Minas Gerais is in the Centre-South region; Assumes energy-cane cultivation in degraded lands in established sugarcane regions (Center-South and parts of the Northeast) and considers only bagasse and 50% of TRS available for bioenergy production. Average energy-cane yield of 180 t/ha, 66 million ha of degraded land and 5,512.5 MJ/ton of cane.

SOURCE: MAPBiomas website (Accessed April 2025).

Exhibit 4.26

Robust, well-enforced legislations prevent “made-to-order” land degradation; without regulations, actors will degrade land anyway and profit

Measure	Description	Goal	Examples
Eligibility baseline & definition	• Define “degraded” by clear metrics (e.g., low SOC, NDVI) • Set a fixed cutoff date for land to qualify	Defines degraded land and limits incentive to create degraded land	**US RFS:** feedstocks only from cropland cleared before 19 Dec 2007
Geo-registration & continuous satellite MRV	• Geo-map all eligible parcels with vegetation and soil metrics for audit-ready time-series tracking	Facilitates land identification and monitoring	**EUDR** mandates plot geolocation and proof of no deforestation after 31 Dec 2020
Digital chain of custody & traceability	• End-to-end traceability from field to fuel trader	Limits green washing across supply chain	**US RFS** “RIN” codes track batches through the supply chain
Restoration review & performance linked incentives	• Periodic soil-health audits to track regeneration impact • Credits scaled to regeneration success	Incentivises land restoration as well as biofuel production	**California LCFS** adjusts carbon-intensity scores annually, rewarding better performance
Enforcement, exclusions & transparency	• Blacklist biofuel from any supply-chain actor linked to environmental or social violations • Violations instantly revoke the sustainability seal • Publish land maps MRV alerts, and audit findings	Decreases incentives to disrespect sustainability criteria	**Brazil’s Forest Code** black-lists embargoed properties

NOTE: MRV = Monitoring, Reporting and Verification; SOC = Soil Organic Carbon; NDVI = Normalized Difference Vegetation Index; RFS = Renewable Fuel Standard; EUDR = European Union Deforestation-Free Regulation; RIN = Renewable Identification Number; LCFS = Low; Carbon Fuel Standard.

SOURCE: Systemiq analysis for the ETC (2025).

The analysis indicates a theoretical maximum of 65 EJ of additional biomass, demonstrating the significantly higher specific energy yield of energy cane relative to switchgrass. This estimate, using Brazil as a use case, more than doubles the prudent estimate, 40–60 EJ. The additional value corresponds to a total of ~1.6 Gt of carbon, showing that this use case alone could supply around 34% of the carbon demand in 2050. Although this estimate is more precise than the literature review, a more rigorous assessment of degraded land suitability should be undertaken to identify the specific plots where energy cane plantations are technically, environmentally and economically feasible.

The principle of using degraded land for sustainable biofuel production could create perverse incentives. Greater flexibility in classifying such land may unintentionally reward actors who deliberately degrade it to secure sustainability certification for soil restoration or energy crop cultivation. Existing regulations do not prohibit this practice; therefore, as sustainable biomass becomes more prominent, safeguards should be established to ensure that biofuel supply is not generated at the expense of deliberately degraded land. A further challenge is definitional: it is unclear at what point degraded land that is restored through regenerative agricultural production of bio-feedstocks should no longer be classified as degraded. Exhibit 4.26 outlines five complementary actions that can be used to identify and monitor suitable degraded areas for sustainable biomass production, while discouraging further degradation. Adoption of such policies would enable soil recovery and sustainable carbon sourcing without additional environmental harm.

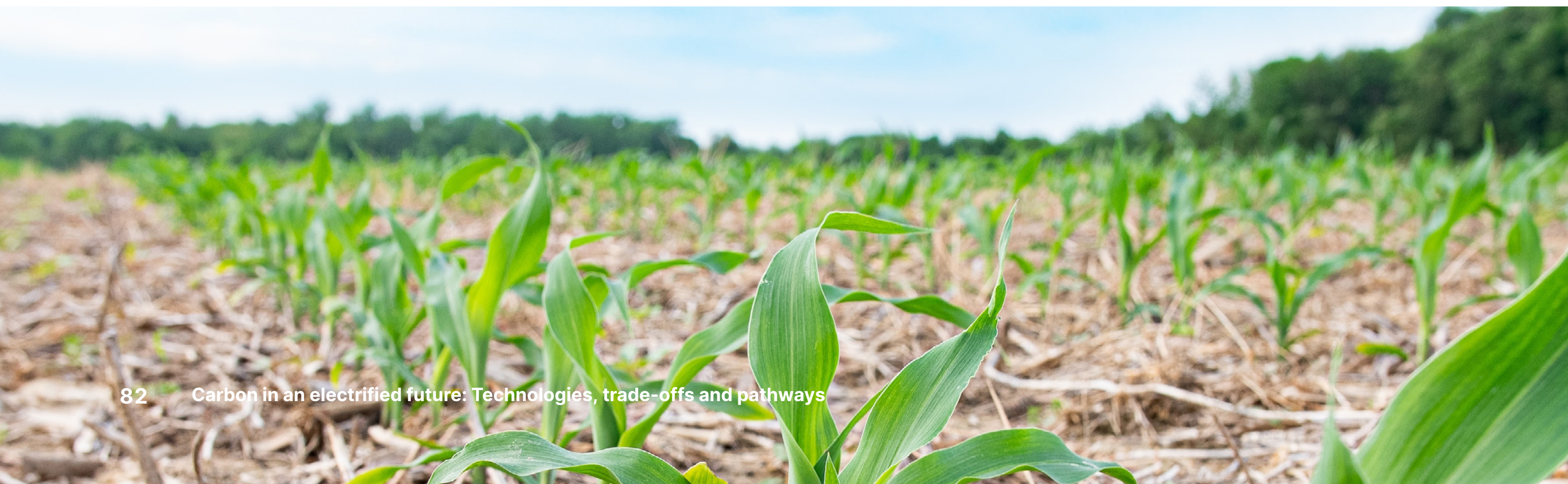


Exhibit 4.27

Within alternative proteins, three key innovations offer the highest potential to reduce land demand for animal feed and grazing

Innovations	Overview					Benefits	
	Goal	Use case	Examples	TRL	Companies	Efficiency potential	Land saving potential
Biomass fermentation (BF)	Produce whole protein-rich biomass	• Base ingredients in meat-like food – e.g., mycoprotein (Quorn), fungal burgers		6–8	Quorn Solar Foods air protein	~13% more energy ~79% less water ~92% less GHGs vs. beef	Very high (up to ~90%) – but products do not fully replicate the look or taste of meat
Precision fermentation (PF)	Make specific molecules for use as ingredients	• Functional ingredients for food production – e.g., egg white for baking, casein, rennet		7	Perfect Day Geltor Every	~15% less energy ~85% less water ~40% less GHGs vs. eggs	Very high (up to ~90%) – but products do not fully replicate the look or taste of meat
Cultivated meat (CM)	Grow real meat tissue from animal cells	• Cuts of meat including muscle, fat and tissue – e.g., beef steaks, chicken breasts		3–5	Mosa Meat Believer Upside Foods	~50% less energy ~88% less water ~88% less GHGs vs. beef	Very high (up to ~90%) – but products do not fully replicate the look or taste of meat

SOURCE: Our World in Data (2022), *Environmental impacts of food production*; Sustainable Nutrition Initiative (2023), *Do the environmental impacts of fermentation-produced protein outweigh those of conventional protein sources?*; Hassan Halawy (2024), *White Paper: Precision Fermentation – A Sustainable; Breakthrough in Food Production*; University of Helsinki (2022), *Biotechnology could provide an environmentally more sustainable alternative to egg white protein production*; Tuomisto & Teixeira de Mattos (2011), *Environmental Impacts of Cultured Meat Production*; Mattick et al. (2015), *Environmental Impacts of Cultured Meat: A cradle-to-gate life cycle assessment*; GFI, (2023) *Environmental benefits of alternative proteins*; Blue Horizon (2020) *Environmental impacts of animal and plant-based food*, Sinke et al (2023) *Ex-ante life cycle assessment of commercial-scale cultivated meat production*; Poore, J., & Nemecek, T., (2018) *Reducing food's environmental impacts through producers and consumers*

4.2.2 More land – alternative proteins

Overview

If diets were to shift away from animal agriculture, alternative proteins can reduce land demand by shifting to plant-based, fermentation-based and cultivated products. These approaches generally require less land and water and can improve conversion efficiency of energy inputs to consumable calories. A potential revolution in food sourcing is therefore offered, although significant technological, cultural and consumer resistance must still be overcome.

Three innovations have been identified as having the greatest potential for land savings: biomass fermentation, precision fermentation and cultivated meat. In general, these technologies involve three steps: (i) microbe selection or cell sourcing (for cultivated meat); (ii) microbe or cell growth in bioreactors; and (iii) product extraction. Exhibit 4.27 summarises the principal features of each technology and the leading industry participants.

Costs

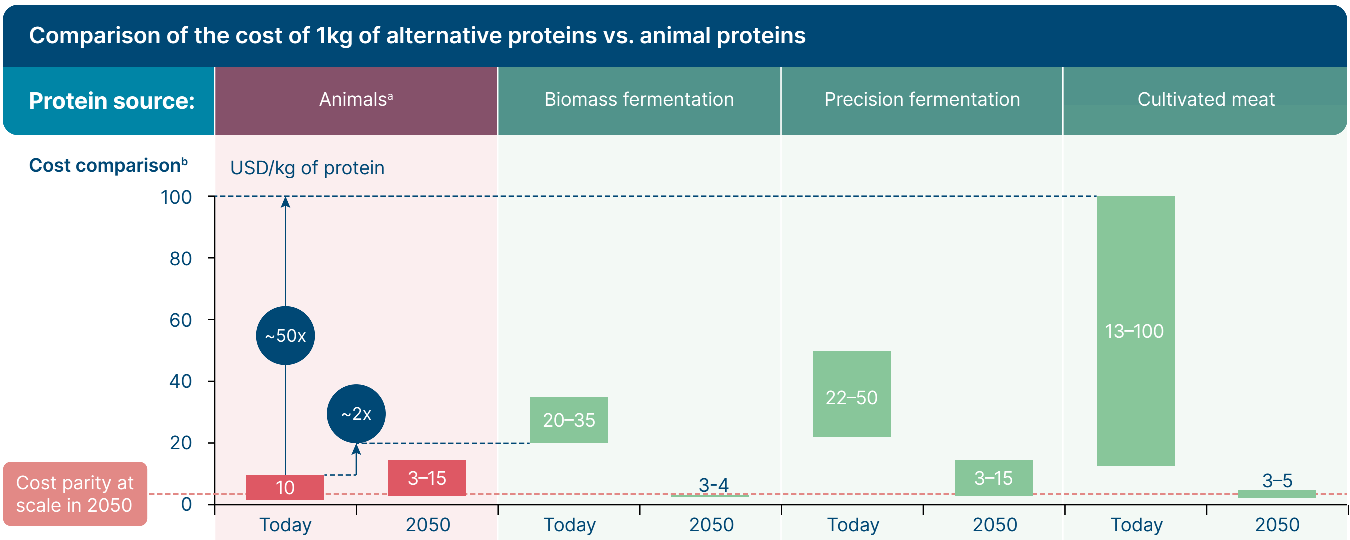
Cost competitiveness with animal based protein has not yet been achieved by these innovations; however, parity could be reached by 2050, or even before, if critical cost reduction levers are applied. An overview of current and projected costs is provided in Exhibit 4.28. At present, mass adoption is constrained by low technological maturity, limited output and complex processing requirements. Targeted strain optimisation can trim operating costs by 10–50 %.[102] Scaling production, through repurposing existing plants, streamlining processes and adopting next generation bioreactors, could then shrink CAPEX by more than 70 %.[103] When these barriers are overcome, the production costs of alternative proteins could fall sufficiently to displace animal based protein and free up land for other agricultural, biomass or ecological uses.

102 GFI, Driving down costs (unpublished)

103 GFI (2023), *Manufacturing capacity landscape and scaling strategies for fermentation-derived proteins; BCG & Synonym* (2024), *Breaking the Cost Barrier on Biomanufacturing.*

Exhibit 4.28

Alternative proteins still 2–50x more expensive than animal proteins, but technological advances and scaling could achieve cost parity by 2050



Cost drivers	Animals	Biomass fermentation / Precision fermentation	Cultivated meat
Drivers of current high costs		• Low cell/microbe density in fermenters resulting in less product per batch • Inefficient feedstock delivery (batch feeding) resulting in long downtime and waste between feeds • Energy-intensive extraction of protein from broth	• Limited cell density of outputs • High cell culture media costs (~50% of total costs) • Limited scale of bioreactors
Levers to achieve cost parity by 2050		• Increase culture density with genetic engineering • Streamline feedstock supply (move from batch to continuous delivery) • Scale up bioreactors (larger units for efficiencies of scale)	• Increasing cell density • Develop food-grade inputs • Increase yields through tech and process improvements

NOTE: [a] Given projections for the cost of animal-based proteins by 2050 are very limited, cost increases of 20–60% are assumed to reflect increased demand from global population growth, resource constraints, and inflation; [b] Ranges reflect cost variations by protein type, geography, and production method, representing global averages.

SOURCE: Systemiq analysis for the ETC; McKinsey & Company (2025), *Ingredients for the future: Bringing the biotech revolution to food*; Green Circle Capital Partners (2023), *Protein Pricing Comparison Summary;* Good Food Initiative (2024), *Precision Fermentation: Communication Guide;* Genetic Engineering & Biotechnology News *(2023), Fermentation Margins and Cost of Goods;* Risner, D. et al. *(2023), A techno-economic model of mycoprotein production: achieving price parity with beef protein, Frontiers in Sustainable Food Systems (7);* Negulescu, P.G. (2022), *Techno-economic modelling and assessment of cultivated meat: Impact of production bioreactor scale, Biotechnology and Bioengineering 120 (4);* Pasitka, L. et al. (2024), *Continuous Manufacturing of Cultivated Meat: Empirical Economic Analysis, Nature Food (5). Knychala, M. M., Boing, L. A., Ienczak, J. L., Trichez, D., & Stambuk, B. U. (2024). Precision Fermentation as an Alternative to Animal Protein, a Review. Fermentation.*

Impact

When cost parity is achieved, we assess that up to 400 Mt of animal based protein could be displaced by alternative proteins, freeing approximately 590 Mha of agricultural land. This represents 40% of global projected 2050 protein demand [Exhibit 4.29], indicating a substantial shift in global protein production. Capturing this market share will require technological progress, supportive policy frameworks and, most critically, increased consumer demand.

These figures were produced with a dedicated forecasting model that quantifies how quickly alternative proteins can gain market share and how much farmland their adoption could release. Annual growth rates for each protein category are projected from assumptions gathered through expert interviews and published studies.[104] After production volumes are calculated, the model translates the resulting decline in animal based protein demand into the equivalent area of agricultural land no longer required for livestock and feed production.

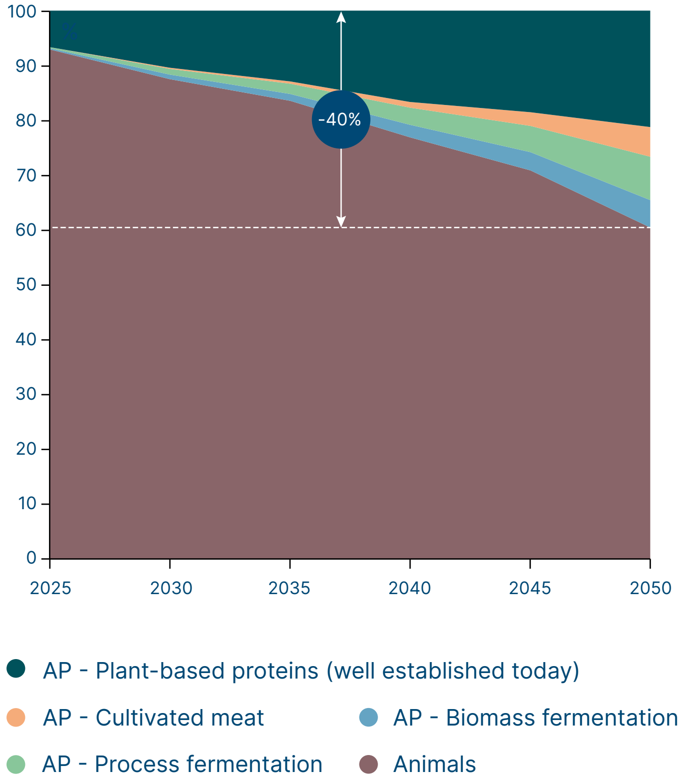
104 Systemiq (2025), *A Taste of Tomorrow*.

Exhibit 4.29

Alternative proteins (AP) adoption and comparative land-use with traditional proteins

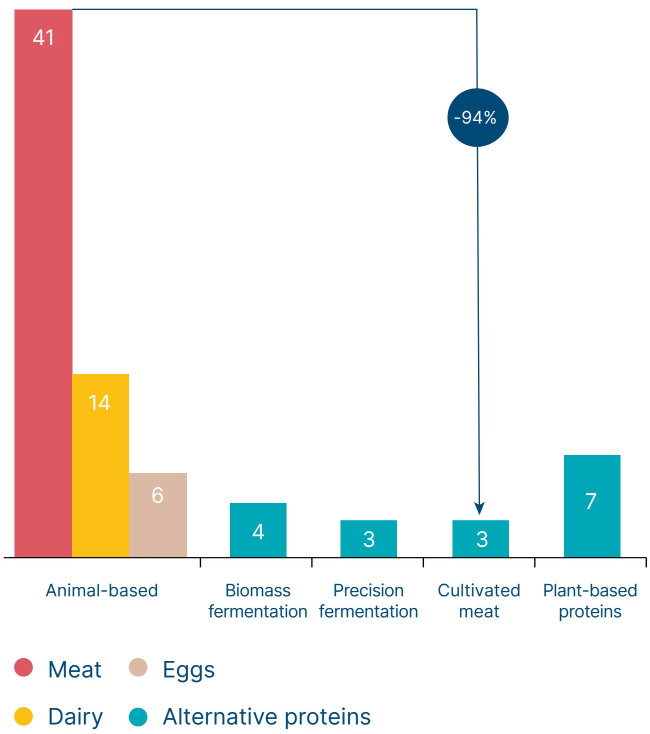
In a high ambition scenario, alternative proteins could capture up to ~40% of the global animal-based protein demand

Breakdown of global protein demand by protein source[a,b]



Cultivated meat could significantly reduce land usage compared to conventional meat in best case scenario

Land-use intensity by protein type and source, m²/kg



NOTE: [a] In alternative proteins made via biomass fermentation, precision fermentation, or cultivation, cell-grown ingredients make up only ~5–20% of total protein weight; the rest comes from plants—driving plant-based proteins' dominant role in meeting 2050 global protein demand [b] Volume of animal protein consumption net of animal carcass weight.

SOURCE: Systemiq analysis for the ETC; Systemiq (2025), *A Taste of Tomorrow: How Protein Diversification Can Strengthen Germany's Economy;* GFI (2023), *Environmental benefits of alternative proteins;* Blue Horizon (2020), *Environmental impacts of animal and plant-based food;* Sinke et al. (2023) *Ex-ante life cycle assessment of commercial-scale cultivated meat production;* Poore, J., & Nemecek, T., (2018), *Reducing food's environmental impacts through producers and consumers; expert interviews.*

The freed land could be allocated to three primary uses: (i) biodiversity restoration; (ii) managed forestry; and (iii) energy crop cultivation, though how this land is allocated between these uses comes with trade-offs that should be analysed in the context of broader land-use priorities. Exhibit 4.30 illustrates the allocation approach for each use, aiming to maximise biodiversity restoration and, where feasible, generate sustainable biomass. Use case selection is guided by region specific land use analyses that consider soil health, native vegetation and other local factors. Under this scenario, an additional 27–28 EJ of sustainable biomass could be supplied.

Exhibit 4.30

587 Mha of land could yield 27-28 EJ of energy and ~1 Gt of carbon per year by 2050, depending on land use

If alternative proteins free up large amounts of land, the key question would be how to allocate it–particularly how much to devote to sustainable energy and carbon supply. Three scenarios illustrate the possible trade-offs.

Scenario	Return to nature	More managed forestry	More energy crops
	100% to nature (587 Mha)	20% to nature (117 Mha) + 80% to managed forests (470 Mha)	75% to nature (441 Mha) + 25% to energy crop plantations (147 Mha)
	Outcome:		
EJ of useful energy	N.A.: land is returned to nature	• 28 EJ of woody biomass including primary products and residues	• 27 EJ of energy crops from for example energy cane or switchgrass
Gt of carbon sequestration		• 1 Gt carbon stored in woody biomass	• 0.95 Gt available carbon in energy crops
Trade-offs	+ Biodiversity + carbon sequestration maximised; restores soil condition & water cycle - No energy output	+ Provides timber & 28 EJ of biomass energy - Moderate biodiversity impact – better than energy-crop monocultures, worse than untouched nature - Decades to reach maturity	+ Fast growing crops that produce yield every year + Large area returned to nature - Small biodiversity impact on planted area

SOURCE: Systemiq for the ETC (2025); ETC (2021), *Bioresources Within a Net-Zero Emissions Economy: Making a Sustainable Approach Possible.*

Barriers and enablers

Alternative proteins will unlock their full land saving and climate benefits only if consumers embrace them. To steer the scale up and measure progress, five development criteria should be tracked:

- **Affordability** – price parity with conventional proteins (target: ≤ US $15 kg^{-1} protein).
- **Attractiveness** – taste, texture and nutrition at least equal to meat, enabling ~40% market share.
- **Accessibility** – adequate scale up finance and early adoption by public institutions, displacing up to 400 Mt of animal protein.
- **Land liberation** – the protein shift releases ~587 Mha of farmland.
- **Land allocation** – freed hectares are steered toward biodiversity recovery and biomass production, supplying an extra 27–28 EJ of sustainable biomass.

Among these metrics, attractiveness is pivotal: once consumers perceive alternative proteins as tasty and healthy, demand surges, investors deploy capital, production scales, costs fall and all other targets become attainable. Without that consumer pull, progress on affordability or capacity alone will not deliver the desired impact.

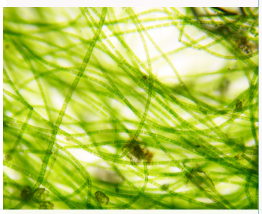
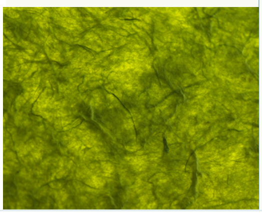
4.2.3 New sources of biomass – macroalgae and microalgae

A further measure for expanding land availability for sustainable biomass production involves shifting food supply from terrestrial to aquatic systems. In this context, macroalgae and microalgae have been identified as promising substitutes for land based food and feed. Macroalgae are fast growing photosynthetic organisms cultivated in coastal waters, whereas microalgae are microscopic photosynthetic organisms grown in open ponds or closed reactor systems. Both groups can supply biomass for food or for third generation biofuels.

Although significant potential exists for food and feed production from these sources, technological maturity remains low. Scaling efforts for macroalgae and microalgae are under way as companies seek optimal use cases. The innovation landscape and the land saving potential of each technology are outlined in Exhibit 4.31.

Exhibit 4.31

Both macro and micro algae offer pathways to increase overall biomass supply and efficiency

	Innovations	Overview			Benefits	
		Use case	TRL	Companies	Efficiency potential	Land saving potential
1	Macroalgae 	• Ruminant feed additive: mixing small amounts of red seaweed into the diet of cows improves feed conversion and reduces methane emissions. • Forage-maize substitution: kelp can be fed to cows in place of a share of their corn feed. • Direct conversion to biofuels	7–8	Atlantic Sea Farms Oceanium	• Zero arable land, freshwater or fertilisers • +14% feed conversion gain in cattle[a]	• Supplementing 0.05% of ruminant feed with red seaweed could save 50 Mha of land by 2050.[a]
2	Microalgae 	• Soybean meal substitution: used as protein supplement in animal feed • Palm and soybean oil (vegetable oil) substitution: used in cooking • Fish-meal substitution: used as feed for aquaculture	8–9	Algama Allmicroalgae	• 7–25× more protein per ha than soy[c]	• 100 algae facilities (111 ha each) in Thailand could replace 10% of world fishmeal on just 11,100 ha.[b]

SOURCE: Systemiq analysis for the ETC; [a] Spillias, et al (2023), *Reducing global land-use pressures with seaweed farming*. Nature Sustainability, 6(4), 380–390.; [b] Beal, et al. (2018), *Marine microalgae commercial production improves sustainability of global fisheries and aquaculture*. Scientific Reports, 8, 3354. [c] Mosibo, et al. (2024), *Microalgae proteins as sustainable ingredients in novel foods: Recent developments and challenges*. Foods, 13(5), 733.

Costs

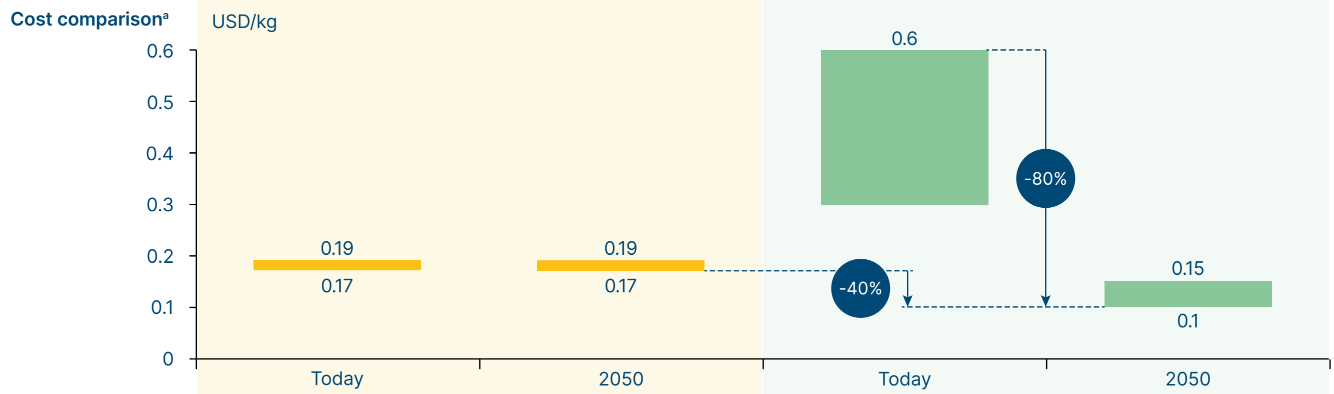
Macroalgae are viewed as a more promising substitute for corn than as a biofuel feedstock. Under favourable cultivation conditions, macroalgae can attain cost competitiveness with corn for food and feed applications, whereas competition with high yield energy crops such as energy cane remains unlikely. Exhibit 4.32 shows that corn is currently far less expensive than macroalgae; however, advances in process automation could reduce macroalgae production costs by up to 80% by 2050. Automation is expected to cut labour and energy requirements while increasing yields, thereby strengthening overall process economics.

Exhibit 4.32

Macroalgae still costs more than maize as a bulk food source for humans and animals, but automated kelp farming could bring costs down by 80%

Cost per kg of dry biomass

Food source:	Maize	Macroalgae



Cost drivers

Levers to achieve cost parity by 2050

- Labour is the top cost driver. Conventional crews and vessels make up ~40% of dry-weight cost. Automation and continuous-harvest systems can cut this by over 80%.
- Drying uses energy, but isn't dominant. Dewatering accounts for 15% of costs. Solar or heat-pump dryers can reduce this by 70%.
- Higher yields cut every cost. Better genetics, tighter line spacing, and nutrient could increase output per metre.
- Cascading increases revenues. Revenue from alginate, pigments, and biostimulants can subsidise OPEX, enabling lower costs per unit of product.

NOTE: [a] Ranges reflect cost variations by biomass type, geography, and production method, representing global averages.

SOURCE: Systemiq analysis for the ETC; Kite-Powell H. L. et al. (JWAS, 2025), *Estimating tingProduction Cost for Large-Scale Seaweed Farms*; US DOE ARPA-E MARINER project; World Bank Commodity Markets Outlook (2023); USDA ERS Feed Grains Market Outlook (2025); DOE BETO Bioenergy Technologies Portfolio (2022); Krause-Jensen, D. et al. (2023), *Global potential of offshore and shallow waters macroalgal biorefineries to provide for food, chemicals and energy: feasibility and sustainability*. Nature Sustainability, 6, 168–179; U.S. Department of Energy, Bioenergy Technologies Office (2023), 2023 Multi-Year Program Plan; National Renewable Energy Laboratory (2022), *Techno-Economic Analysis for Seaweed-Based Biorefineries*; Kim, J. et al. (2017), *A review on the production technologies of marine macroalgae biofuels*. Renewable and Sustainable Energy Reviews, 73, 205–215; ETC (2024), *Bioresources Within a Net-Zero Emissions Economy.*

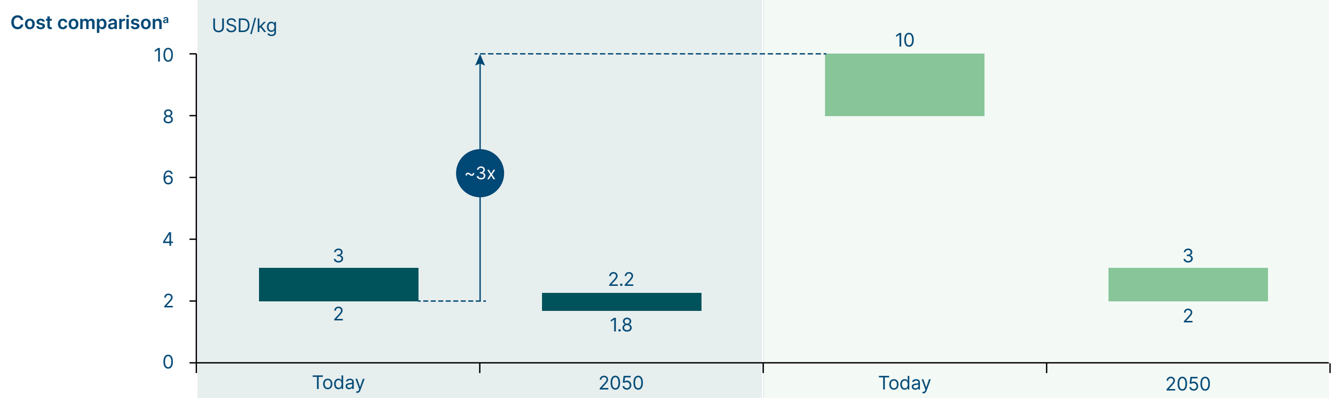
Microalgae are regarded as a potential feed substitute, particularly as a replacement for soy protein isolate. Production costs remain higher than those of soy and are likely to require policy or market incentives to reach cost parity. Scaling is hindered by the need for controlled environment cultivation, like open ponds or closed photobioreactors, whose unit sizes are smaller than those employed for macroalgae. In addition, extensive strain engineering is required to increase cell density, protein concentration and growth rates. Exhibit 4.33 indicates that, even under optimistic assumptions, microalgae are expected to achieve cost competitiveness with soy only in a best case scenario; premium pricing may therefore be needed to offset the remaining cost differential.

Exhibit 4.33

Microalgae costs ~3X more than soy: intensified cultivation may lower costs by 2050, but unlikely to reach parity without additional policy measures

Cost per kg of protein isolate

Food source: Soy | Macroalgae



Cost drivers

Drivers of current high costs

Levers to achieve cost parity by 2050

- **Scale matters most.** Multi-hectare shallow ponds or thin-film photobioreactors spread capital and labour over far more output, trimming those costs by 70–80%.
- **Increase biomass density.** Raising cell density from means far less water to remove, cutting thickening and drying energy by about 70%.
- **Engineer better strains.** Strains that contain over 70% protein and grow faster stretch the same feed, CO_2, and labour over more product, reducing the cost per kilo of protein.
- **Co-products boost revenue.** Pigments and omega-3 oils can contribute to some of the operating bill, reducing the potential cost of bulk protein.

NOTE: [a] Ranges reflect cost variations by biomass type, geography, and production method, representing global averages.

SOURCE: Systemiq analysis for the ETC; Soy isolate costs: Green Circle Capital (2023), *GC Protein Pricing Review Year-End*; Microalgae cost baseline & 2050 targets: National Renewable Energy Laboratory (2022), *Economic, Greenhouse Gas, and Resource Assessment for Fuel and Protein Production from Microalgae: 2022 Harmonization Update*; Cultivation cost model: Davis R. et al. (2016), *Process Design and Economics for the Production of Algal Biomass* (NREL/TP-5100-64772); Intensification levers: Assunção J. & Malcata F.X. (2020), *Enclosed non-conventional photobioreactors for microalga production: A review*. Algal Research 52: 102107; Strain-improvement potential: Huesemann M. et al. (2023), *DISCOVR strain pipeline screening – Part I: Maximum specific growth rate across 38 candidate microalgae. Algal Research 71: 102996.*

Impact

Estimating the true potential of these technologies is challenging. Should cost parity be achieved, a transformation of food and feed production could follow; at present, however, the technologies remain far from competing with incumbent feedstocks. A pragmatic estimate has therefore been prepared for their contribution as food and feed sources. Algal derivatives could supply approximately 2% of global food production Estimation based on Greene, C.H. & Scott-Buechler, C.M. (2022) Algal solutions: Transforming marine aquaculture from the bottom up for a sustainable future; Caporgno & Mathys (2018) rends in Microalgae Incorporation Into Innovative Food Products With Potential Health Benefits and 8% of feed production Estimation based on Makkar et al. (2016) Seaweeds for livestock diets: A review" (Animal Feed Science & Technology 212: 1–17) by 2050, equivalent to 395 Mt. Environmental safeguards are essential, and indirect land-use effects from feed substitution must be closely monitored to prevent unintended trade-offs.

These results were produced with a forecasting model tailored to algal proteins, where growth projections are more uncertain because published estimates diverge. Multiple data sources were reviewed, and a deliberately conservative annual growth rate was adopted. After projected production volumes were established, the model translated the anticipated replacement of conventional food and feed into the corresponding area of farmland released.

Barriers and Enablers

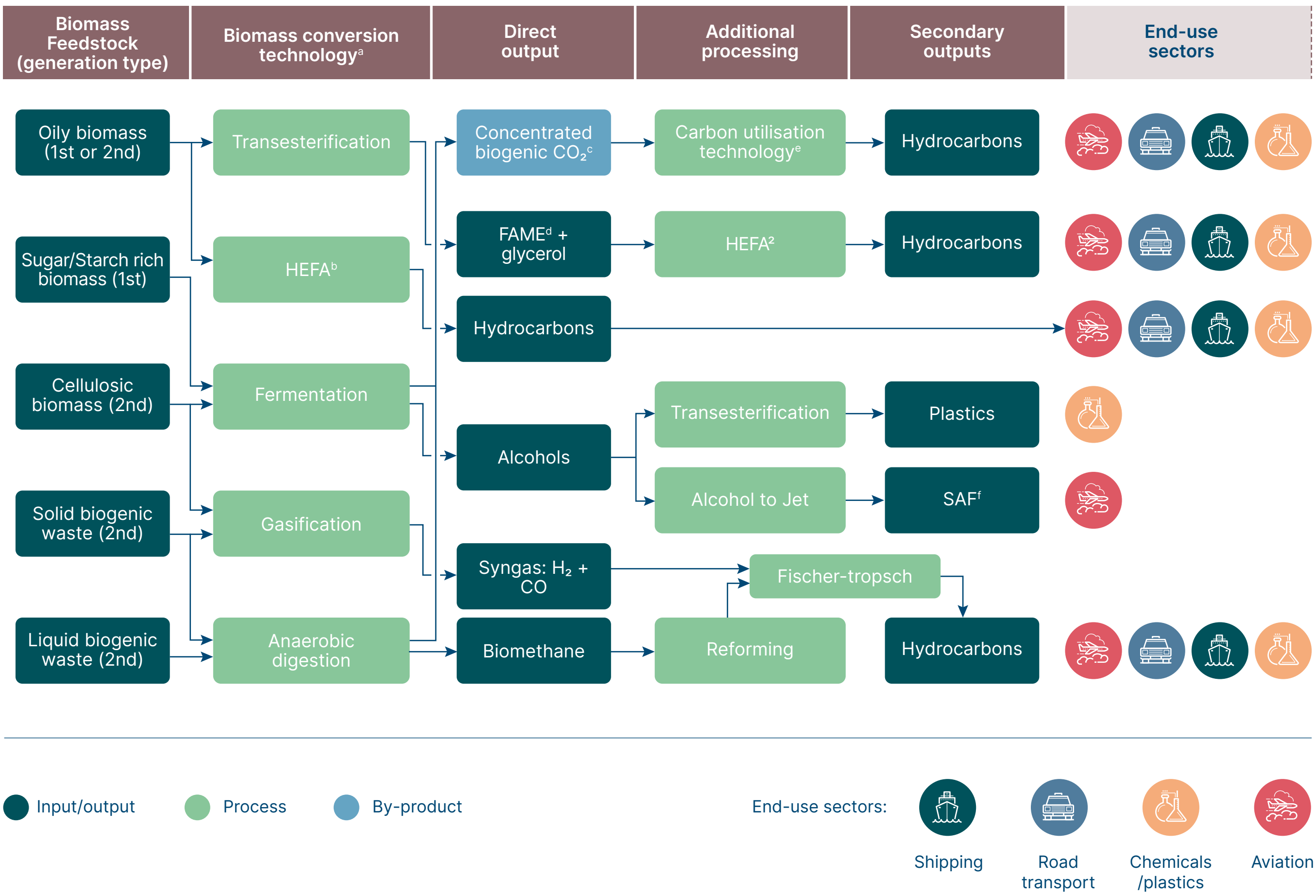
Yield improvements and the facilitation of large scale cultivation are regarded as essential, implying that financing and infrastructure development will be critical. Once these conditions are met, production costs are expected to fall, improving competitiveness with existing feedstocks. The same development criteria as for alternative protein are tracked to ensure impact and measure progress:

- **Affordability** – price parity with conventional feedstocks.
- **Attractiveness** – taste, texture and nutrition match incumbent feedstocks, enabling algae to capture a share in the food and feed market.
- **Accessibility** – infrastructure is mobilised to allow for scale up of ponds and sea farms, displacing 395 Mt of terrestrial crops.
- **Land liberation** – switch to algae-based products free up 81 Mha of agriculture land.
- **Land allocation** – freed hectares are steered toward biodiversity recovery and biomass production, supplying an extra ~10 EJ of sustainable biomass.

Product "attractiveness" (taste, health profile and sourcing perceptions) is considered less decisive than for alternative proteins because algal derivatives are also destined for feed markets and; therefore, face fewer sourcing biases.

Exhibit 4.34

There are several routes to convert biomass into useful molecules which can be used as precursors for other high-end chemicals



NOTE: [a] There are other emerging routes which have not been considered because of limited energetic potential or low maturity, e.g., solid biogenic waste gasification (complex to have heterogenous feedstocks) and cellulosic biomass pyrolysis (good for biochar production, but not so efficient for energy); [b] HEFA = Hydro Processed Esters and Fatty Acids. [c] CO_2 sources with >90% concentration (fermentation) ~ 50% concentration (anaerobic digestion), which is a cheap biogenic CO_2 source. By adding green hydrogen multiple hydrocarbons could by synthetized. [d] FAME = Fatty Acid Methyl Ester. [f] SAF = Sustainable Aviation Fuel.

SOURCE: Systemiq analysis for the ETC (2025).

4.2.4 Biomass conversion: improving utilisation of bio-resources

Overview

In a de-fossilised economy, biomass serves as a feedstock for bio based materials, such as wood and bioplastics, and for biofuels, including bio SAF and biodiesel. The objective is to upgrade primary biomass, a carbon neutral source, into more complex bio based carbon molecules. Primary biomass is highly heterogeneous, originating from oily feedstocks, cellulosic residues, liquid biogenic waste and other sources, which complicates categorisation. The resulting challenge is to devise processes that exploit the specific properties of each feedstock and convert them efficiently into useful products. Exhibit 4.34 maps the principal routes for primary biomass conversion, demonstrating that, regardless of the input, products relevant to the same end use sectors can be synthesised.

Conversion of primary biomass into useful products can be enhanced to reduce overall feedstock needs easing pressure on land systems, and improve process economics. Performance improvements may be achieved by adjusting operating conditions, such as temperature and pressure, or by adopting equipment innovations. Two equipment based advances are particularly important: catalysts and specialised reactors. Catalysts are substances that accelerate reactions by lowering activation energy without being consumed, whereas reactors are vessels engineered to provide an optimal environment that maximises conversion efficiency. Exhibit 4.35 details how these innovations raise conversion efficiency and summarises their deployment in bioenergy projects across the industry.

The two equipment innovations are intended to push reaction conversion toward the theoretical (stoichiometric) limit. For catalysts, research focuses on identifying optimal compositions and physical properties for the target reaction. For reactors, vessels are designed to maximise heat and mass transfer between reactants. The effects of these innovations are more pronounced in low TRL processes than in mature ones; for example, bio SAF production via the HEFA route already operates near its theoretical conversion limit, whereas Alcohol to Jet and Gasification–Fischer Tropsch pathways remain further away, so larger conversion gains are still possible for the latter. The conversion gains are calculated for catalysts to range between 2% and 20% and for reactors between 8% and 20%.

Exhibit 4.35

Novel catalysts and reactors aim to increase conversions, which lower the demand for primary biomass

Type of innovation	Description	Deployment examples[a]	Companies and TRL	
Catalysts	• Novel catalyst aim to improve conversion and yield of desired products, decreasing primary biomass needed and decreasing the activity of competing reactions.	• Innovaturbo yeast for starch feedstocks is used in 60% of U.S. corn-ethanol plants. • Cellic Ctec enzymes dominates cellulosic biomass fermentation (Raizen, GranBio, Beta Renewables).	novozymes	7–9
		• Indonesia's new biorefinery, HydroFlex plant #50, will use Topsoe catalysts to make 6,000 gpd of renewable diesel and SAF.	TOPSOE	9
		• FOAK plant inaugurated in Georgia in 2024, with a capacity of 10 MM gpy of SAF from ethanol at a cost of $ 200 MM.	LANZAJET	7–8
Reactors	• New reactor designs aim to improve reaction kinetics or reduce equipment CAPEX. • Example of new reactors configuration: - Micro-channel reactors - Membrane reactors - Fluidised bed reactors - Modular reactors	• Fluidised bed reactor technology installed in Alberta, which gasifies MSW to produce ~1,000 barrels per day of methanol.	Enerkem	6–8
		• Microchannel FT + Upgrading reactor with two projects in early stage (Shell in the UK and Bayou Fuels in the US) and one small demo plant owned by ENI in the US.	VELOCYS	6–7
		• Memthane AnMBR technology treats diverse industrial effluents. Examples of adoption by a meat processing plant in the US and by a dairy farm in Europe.	VEOLIA	7

NOTE: [a] Innovations are happening on all routes, so list is non-extensive.

SOURCE: Systemiq analysis for the ETC (2025).

Costs

Route specific techno economic assessments are constrained by limited access to proprietary catalyst and reactor data. To compensate for this data gap, cost reductions were estimated indirectly from the feedstock savings associated with higher conversion and product yield factors along each biomass conversion pathway. CAPEX effects were treated as neutral, on the premise that incremental yield gains do not justify an escalation in cost. OPEX impacts related to energy and utility demand were likewise excluded from the baseline calculation. The resulting analysis, summarised in Exhibit 4.36, indicates that feedstock driven cost reductions that advanced catalysts and reactors could deliver are between the range of 4–8%. The reductions alone are insufficient to render bio based pathways cost competitive with their fossil counterparts, but could help enable bio-based products synthesis in locations with expensive feedstocks. Accordingly, additional market incentives (e.g., carbon pricing mechanisms or green premium contracts) will be required to bridge the residual cost gap during initial deployment phases.

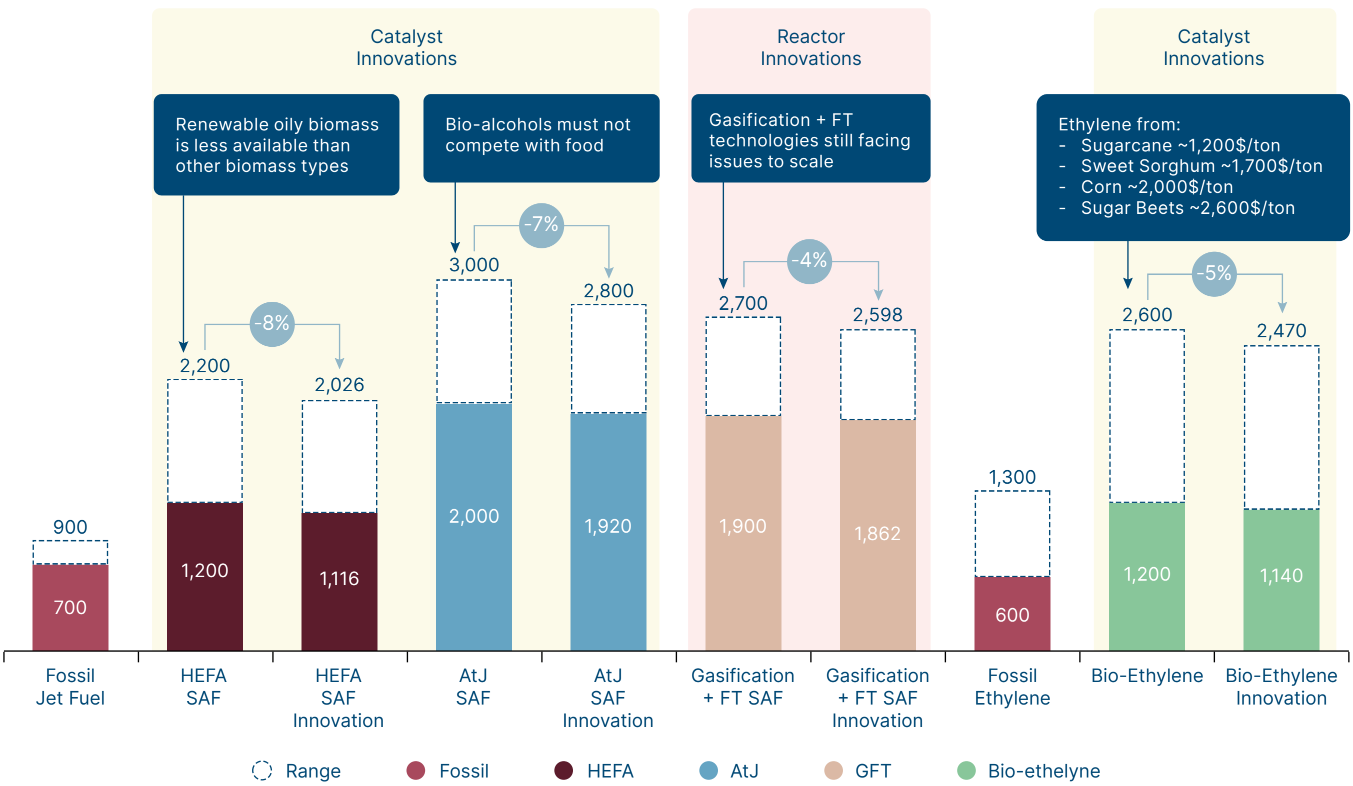
Impact

For the aviation sector, improvements in product yield are estimated to reduce primary biomass demand by approximately 30%. Exhibit 4.37 indicates that yield gains in the Alcohol to Jet (AtJ) and Gasification–Fischer Tropsch (GFT) pathways contribute more to this reduction than gains in the Hydroprocessed Esters and Fatty Acids (HEFA) route. Two factors explain the difference: (i) AtJ and GFT are two step, lower TRL processes, so yield improvements have a larger relative impact; and (ii) HEFA feedstock availability is constrained by the limited global supply of waste lipids, primarily used cooking oil and animal fats. Because of this scarcity, AtJ and GFT pathways, which can use

Exhibit 4.36

Reactors and catalysts can give on average 4–8% cost reduction due to yield increase, but more will be needed to close the gap with fossil

Only bio-ethylene can match fossil costs, and only when prices are at their high end[a]
$/ton of product

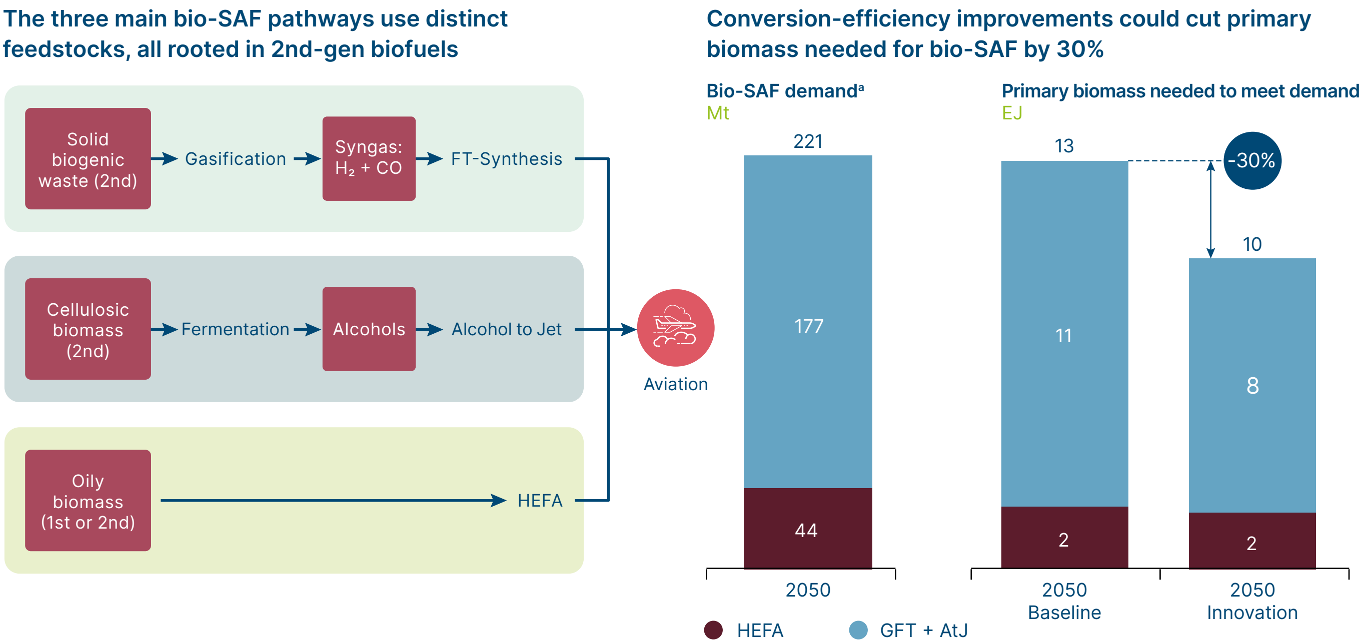


NOTE: [a] Conversion and yield gains due to innovation applied to feedstock percentage of total route cost.

SOURCE: Systemiq analysis for the ETC; Panov, V (2024), *Decarbonizing Air Travel with Sustainable Aviation Fuel*; Mohsenzadeh, A. (2017), *Bioethylene Production from Ethanol: A Review and Techno-economical Evaluation*; Zanon-Zotin, M. et al., (2023), *Unpacking bio-based alternatives to ethylene production in Brazil, Europe, and the United States: A comparative life cycle assessment*; ANRTL (2017), *North Slopes Gas to Liquids (GtL) Plant Proposal Finished Fuels Made on the North Slope – "Again"*; Karimi, M., et al. (2024), *Advanced biofuel production: A comprehensive techno-economic review of pathways and costs.*

Exhibit 4.37

Catalyst and reactor innovations across key bio-SAF routes could cut primary biomass demand by ~30% for key end-use sectors like aviation



SOURCE: [a] According to MPP Prudent decarbonisation scenario; in MPP (2022), *Making Net-Zero Aviation Possible*.

abundant lignocellulosic residues and other organic waste streams, are expected to supply a greater share of total bio-SAF output. In contrast, the HEFA route relies on lipid-rich feedstocks that are in short supply, and increasing use of virgin vegetable oils, particularly palm oil, raises sustainability concerns and underscores the need for stricter regulation to prevent land-use impacts.

Barriers and Enablers

Commercial viability of bio based carbon molecules depends on the continued development of integrated biorefinery systems for sector specific applications, like aviation. Two pillars require coordinated support: feedstock access and demand creation. For feedstock access, three criteria are key:

i. **Uniform biomass regulations that safeguard sustainability without excluding viable resources.** This allows for maximisation of resource utilisation and unification of legislations, avoiding regulatory mismatches.

ii. **Resource mapping coupled with local infrastructure development.** Maximises resource availability and facilitates collection and processing of primary biomass into tradeable products.

iii. **Market mechanisms that promote tradability and commodity homogeneity.** Creation of markets for specific bio-based carbon molecules (e.g., bio-methane, bio-ethanol, syngas, bio-oils), in order to facilitate molecule commercialisation, with policy frameworks that stimulate demand and value across all outputs, since integrated e-/bio-refineries (e.g., BtL/PtL) produce multiple products for multiple sectors.

Demand creation focuses on accelerating deployment to drive cost reductions over time; two criteria are crucial:

i. **Demand side incentives that facilitate long term offtake agreements.** Blending mandates and carbon taxes can push demand for bio-based carbon molecules, reducing commercial risks and enabling more plants to come online.

ii. **Rapid scale up to lower unit costs via economies of scale.** Achieving cost parity with fossil fuels will require steep cost cuts driven by larger scale, learning rates, supply chain growth and product standardisation, all of which require high capacity facilities running for long, sustained periods.

Progress across all criteria will enable the bio-industry to grow organically and reach the scale needed to deliver meaningful impact in a net-zero economy.

4.3 Conclusions about sourcing of primary carbon

As described in this Chapter, there are multiple potential sources of primary carbon which could be used in a way compatible with net-zero emissions. The optimal balance will be determined by future technological and cost development and it is impossible and unnecessary to predict it in advance. Instead, the crucial priority is to introduce technology-neutral regulations and carbon pricing which will help achieve the most efficient solution.

But the key factors which will determine the optimal balance between the different sources are:

- **The cost of direct air capture and ocean-based carbon removal.** Initial estimates of DAC costs reaching below $100 by mid-century have recently been revised up, but further technological progress and cost reductions is possible. Ocean-based CO_2 removal seems to be emerging as a credible and potentially low-cost alternative. If either technology becomes cost-effective versus the alternatives, capture from the atmosphere or ocean could play a useful role both in (i) providing carbon atoms for end use applications and (ii) making it possible to offset emissions resulting from fossil fuel use; in the case of DAC this will also require the storage technologies described in Chapter 5.
- **The technical feasibility and cost of point source carbon capture.** Compared with expectations 10 to 15 years ago, the pace of cost reduction in point source capture and the pace of deployment have been disappointing. This reflects complexities created by sector specific circumstances, the difficulty of applying carbon capture systems to already existing industrial plants and the presence of impurities such as particulate matter, sulphur dioxide and nitrogen oxides. New technologies such as Calcium Looping or the AFC may help overcome these challenges.

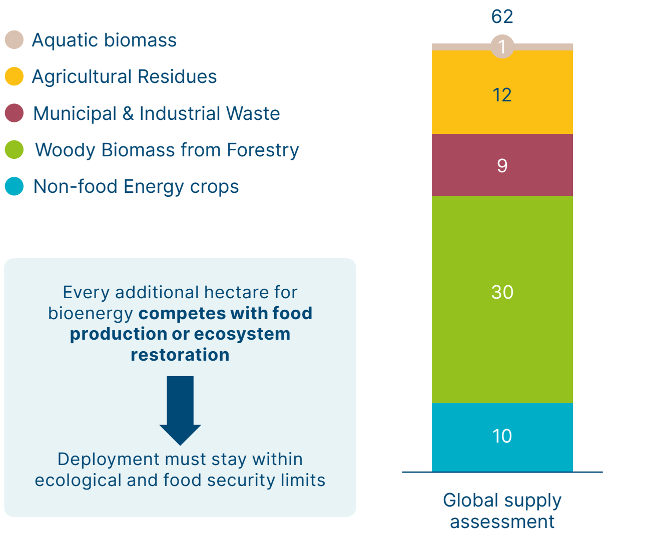
The crucial policy priority to support development and optimal deployment is robust carbon pricing which needs to cover emissions from the production, processing and transport of fossil fuels as well as those which result from end use.

- **The true sustainability of bioresource extraction.** The ETC has previously published a prudent estimate that sustainable biomass extraction might be limited to 40 to 60 EJ (11,000 – 17,000 TWh) primarily deriving from agricultural and forestry residues.[105] This remains the central reference point in this report, reflecting current constraints on land, food and biodiversity, while also framing the exploration of technological and behavioural innovations that could enhance the sustainable use of biomass without assuming additional land availability:

Exhibit 4.38

Technological advances could extend sustainable potential but face inherent trade-offs with food security and nature

Biomass supply potential in 2050
EJ primary biomass



Technological advances that could extend sustainable potential

Agricultural innovation
Improvements in yields and the growth of alternative proteins could reduce land pressure, freeing-up land for biomass supply.

Aquatic biomass
Macroalgae and microalgae could provide low-land, low-carbon feedstocks if developed within strong environmental safeguards.

Residue utilisation
Better harvesting and processing of residues could boost sustainable biomass use, provided they don't harm soil health and fertility.

Marginal land management
Carefully managed use of degraded land could provide limited additional biomass, but only where the land cannot be restored or productively used for food or nature.

SOURCES: Systemiq Analysis (2025) for the ETC; ETC (2021), *Bioresources Within a Net-Zero Emissions Economy.*

105 ETC (2021), *Bioresources within a Net-Zero Emissions Economy. Note that these estimates are for supply at the "primary energy" level, before conversion losses: energy delivered at the "final energy level" would be significant less.*

- Exhibit 4.38 summarises the most important technological advances that could extend sustainable potential. These include improvements in agricultural productivity, more efficient use of residues, development of aquatic biomass. Such innovations could raise the effective supply of sustainable carbon, but only within ecological limits and under strong sustainability safeguards. Achieving any expansion would require broader system changes such as improved land management, responsible use of degraded areas and shifts in production and consumption that ease pressure on land, while avoiding food competition, biodiversity loss and carbon stock depletion.
- Stronger regulations, as described in Exhibit 4.26, are essential to ensure that bioresource production does not compete with food production and to prevent deliberate degradation of land later used for biomass cultivation. Bioresource production should therefore remain guided by principles of food security, ecosystem protection and long-term carbon integrity.

The uncertainties related to each of the possible primary carbon sources make it unhelpful to present one scenario for the future balance of supply. In Chapter 7 we therefore present a range of different scenarios which could result from future trends in technological feasibility, cost and sustainability considerations.

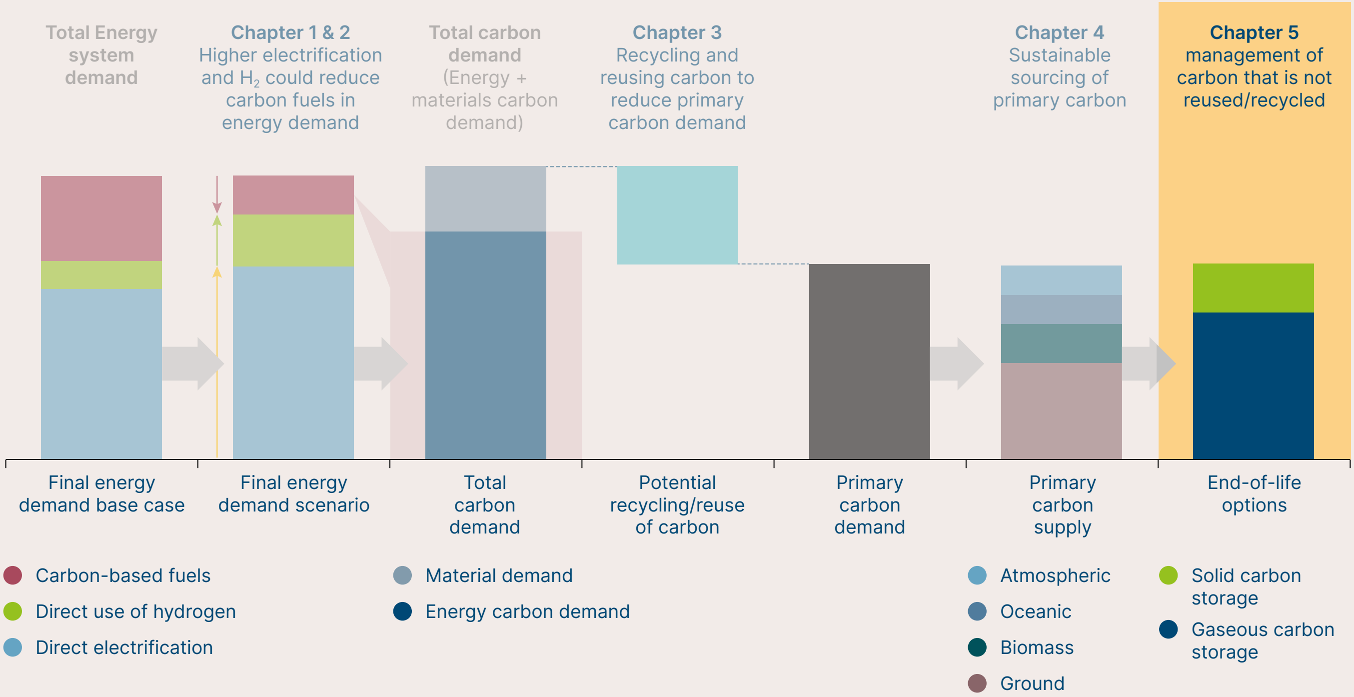
Managing end-of-life carbon

5

Exhibit 5.0

Framework for analysing demand and sourcing options for carbon in a sustainable, zero-emissions fashion

Illustrative



SOURCE: Systemiq analysis for the ETC.

Introduction

Chapter 4 analysed potential sources of primary carbon supply which have different implications for gross and net CO_2 emissions:

- Direct capture from the atmosphere or ocean can result in net-zero emissions if the subsequent use of the carbon (e.g., in aviation fuels) ensures that overall lifecycle emissions remain neutral or negative. Similarly, the use of biomass can be zero carbon over the production and use cycle, with CO_2 emissions in use balanced by CO_2 absorbed during photosynthesis.
- But if fossil fuels are used, CO_2 produced must be not only captured but also stored to deliver net-zero emissions.
- And if carbon storage is applied to CO_2 captured from the atmosphere or ocean, or at the end of an application using biomass, this can result in negative emissions, offsetting any residual emissions from unbated fossil fuel use.

This chapter therefore analyses the technologies available to store carbon at the end-of-life [Exhibit 5.1], considering in turn:

- Storage of CO_2 whether via
    - Sedimentary storage in underground reservoirs or aquifers

- In situ CO_2 mineralisation
- Storage of solid carbon – in particular end of life plastics – considering both
  - Existing solid carbon management practices
  - Advanced landfill technologies
- Overall conclusions on the role of end of life carbon management

5.1 Managing and storing gaseous CO_2

- Past ETC analysis has projected that large scale deployment of gaseous CO_2 storage will be essential to achieve net-zero emissions by mid-century. In our *Fossil Fuels in Transition* report (2023) our ACF scenario projected that 8.8 Gt per annum of CO_2 would have be captured in 2050 (whether from point source applications or direct from the air), and that 6.9 Gt of this will need to be stored.[106] But today CO_2 sequestration in sedimentary formations is currently only 50 Mt (0.05 Gt) p.a.[107]

This section therefore assesses the potential for large scale up of sedimentary storage and the alternative strategy of in situ mineralisation.

Exhibit 5.1

Emerging CO_2 and solid Carbon storage technologies could be cost-competitive and have the greatest potential to prevent leakage

Emerging technologies

	Technology	Process	TRL	Companies Non-exhaustive examples
1	Depleted oil & gas (O&G) reservoirs	These are mature and well-characterised formations originally used for fossil fuel extraction. They offer ready-made infrastructure and known geology, allowing relatively secure CO_2 storage.	9	OXY, PETRONAS
2	Saline aquifers	Deep underground formations containing brine, these are the most abundant and scalable storage option. Their high porosity and wide distribution make them ideal for long-term storage of captured CO_2.	8–9	Shell, Total, equinor
3	Offshore depleted O&G reservoirs and saline aquifers	These combine the geological advantages of depleted O&G reservoirs and saline formations with the benefit of offshore isolation, reducing land use conflicts.	7–9	Shell, equinor, Total, PETRONAS
4	CO_2-to-stone (in situ mineralisation)	This method injects CO_2 into mafic (e.g., basalt) or ultramafic (e.g., peridotite) rocks, which are rich in calcium and magnesium. The CO_2 reacts with the minerals to form stable carbonates which are the most secure and permanent form of storage.	5–7	Carbfix, equinor, aramco
5	CO_2-to-minerals (ex situ mineralisation)	Reacting CO_2 with minerals or alkaline waste outside of the ground, typically in a controlled reactor or manufacturing process, to form solid carbonate products. It can be injected in concrete and strengthen the material.	4–6	CarbonBuilt, Carbon Cure, carbon8
6	Advanced landfill	Adoption of advanced technologies to reduce emissions and environmental impacts of landfilling, e.g., pre-landfill biological waste treatment, methane monitoring and detection, and landfill gas capture and management systems.	7–9	BIANNA, infinis, sniffer

SOURCE: Kelemen, P., et al. (2019), *An overview of the status and challenges of CO_2 Storage in Minerals and Geological Formations*; Kim, K., et al. (2023), *A review of carbon mineralization mechanism during geological CO_2 storage*; Bashir, A., et al. (2024), *Comprehensive review of CO_2 geological storage: Exploring principles, mechanisms, and prospect.*

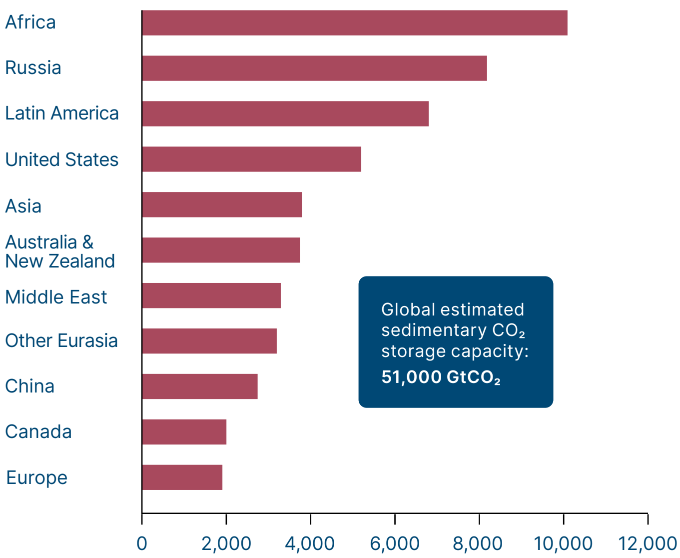
106 ETC (2023), Fossil Fuels in Transition.

107 IEA (2024), *Annual CO_2 capture capacity vs CO_2 storage capacity, current and planned, 2022-2030.*

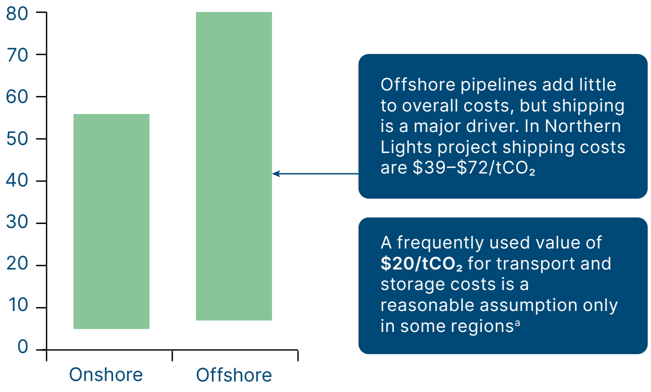
Exhibit 5.2

Established geological options are low cost and sufficient in storage capacity

Range of estimated onshore and offshore sedimentary CO_2 storage capacity
$GtCO_2$



Cost of CO_2 transport and storage in depleted oil & gas reservoirs and saline aquifers, 2025
$\$/tCO_2$ transported and stored



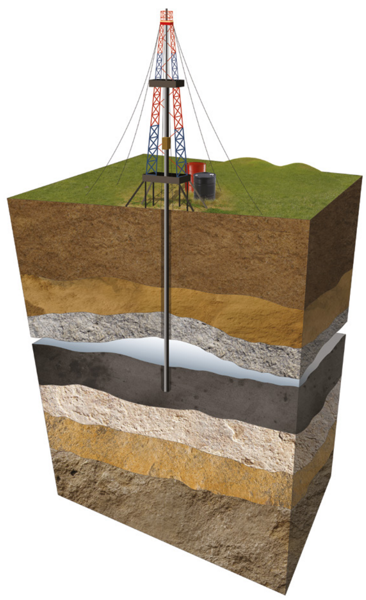
Five key variables affecting the costs:

- Transport distance
- Transport variability (pipeline vs. shipping)
- Scale
- Monitoring required
- Geologic characteristics

SOURCE: Kearns et al. (2017), *Developing a Consistent Database for Regional Geologic CO_2 Storage Capacity Worldwide*; OGCI (2021), *CO_2 storage catalogue*; Barlow, (Global CCS Institute, 2025), *Advancements in CCS Technologies and Costs,* [a] *Smith, E., et al. (2021), The cost of CO_2 transport and storage in global integrated assessment modeling.*

Exhibit 5.3

Depleted oil & gas reservoirs and saline aquifers are mature solutions but limitations may block their scale-up



Potential limitations	Description
Injection rates limits	Annual injection is capped by reservoir pressure, risk of fracturing caprock and potential for induced seismicity, slowing deployment. Some sources indicate this can limit global CO_2 injections up to 2 $GtCO_2$/y.[a]
Leakage risk and monitoring	CO_2 can escape over decades/centuries via faults, fractures, or old wells. Long-term monitoring (50+ years) is required by regulation, creating financial and legal uncertainties.[b]
Environmental and regulatory challenges	Injected CO_2 can push brine into freshwater aquifers or to the surface.[c]
Geological suitability varies	Not all regions have suitable sedimentary formations near CO_2 sources, limiting local deployment.

Lorem ipsum dolor sit amet, consectetuer adipiscing elit, sed diam nonummy nibh euismod tincidunt ut laoreet dolore magna aliquam erat volutpat. Ut wisi enim ad minim veniam,

SOURCE: [a] Keleman, P., et al. (2019), *An Overview of the Status and Challenges of CO_2 Storage in Minerals and Geological Formations*; [b] Wei, Bo., et al. (2023), *CO_2 storage in depleted oil and gas reservoirs: A review*; [c] Mosavata, N., et al. (2024), Brucite: *Revolutionizing CO_2 Mineralization for Sustainable and Permanent Carbon Sequestration.*

5.1.1 Sedimentary CO_2 storage

Established sedimentary options for CO_2 storage have been the solution of focus to date, given their low cost and large theoretical capacities available. As shown on the left-hand side of Exhibit 5.2, global sedimentary CO_2 storage capacity is estimated at 51,000 $GtCO_2$, with regional capacities ranging from ~2,000–10,000 $GtCO_2$. Onshore CO_2 transport and storage networks offer the lowest cost potential (~$5–55 per tCO_2 transported and stored) via pipeline transport and storage in depleted oil and gas reservoirs or saline aquifers. However, not all locations will have access to onshore CO_2 storage options or such locations may be politically unfavourable. An alternative is offshore CO_2 transport and storage, which can be more expensive (typically above $55 per tCO_2 for transport and storage) due to the additional infrastructure needed for CO_2 liquefaction and shipping. However, when CO_2 is transported via subsea pipelines to offshore reservoirs, costs are generally comparable to onshore storage.

Depleted oil and gas reservoirs, along with deep saline aquifers, represent the most mature and well-understood geological options for long-term CO_2 storage. These formations benefit from decades of characterisation through hydrocarbon exploration and production, offering established pathways for injection. However, despite their technical readiness, multiple factors may constrain their ability to scale in line with climate targets. Exhibit 5.3 outlines four key limitations that could hamper the expansion of these conventional CO_2 storage solutions.

One major constraint is the limit on injection rates, which are governed by reservoir pressure, caprock integrity and the risk of induced seismicity. These physical and geological barriers restrict how quickly CO_2 can be injected. This bottleneck highlights a fundamental tension between geological potential and operational feasibility, emphasising potential limitations of global CO_2 injection rates.

Another important consideration is the perceived risk of CO_2 leakage and the burden of long-term monitoring. Well-selected geological formations, such as deep saline aquifers and depleted oil and gas reservoirs, have demonstrated robust containment, with modelling indicating that more than 98% of injected CO_2 remains stored after 10,000 years.[108] Nonetheless, public concern persists about the possibility of CO_2 migrating through legacy wells, faults or fractures over very long periods. To address this, regulatory frameworks typically require monitoring and liability coverage for several decades post-injection (often cited as 50 years), which can introduce financial and legal uncertainties. This makes rigorous site selection, well integrity assurance and transparent monitoring essential not only for technical performance, but also to maintain public trust and support for project deployment.

Environmental and regulatory concerns may also present barriers to deployment. One commonly cited theoretical risk is that injected CO_2 could displace deep saline brines, which might migrate upward and contaminate overlying freshwater aquifers under certain geological conditions.[109,110] While such events have not been observed in commercial-scale projects, they are taken seriously by regulators and have been extensively modelled in academic literature. These perceived risks can trigger regulatory scrutiny and community opposition, particularly in regions with limited experience in subsurface resource management. In addition, regulatory regimes vary significantly across jurisdictions, contributing to uncertainty in permitting timelines and lowering investment confidence.

Lastly, geological suitability is not evenly distributed, with many CO_2 point sources located far from viable storage formations, creating logistical and cost challenges for pipeline or ship transport. This spatial mismatch reduces the economic viability of CCS in key industrial regions and further supports the case for exploring alternative or complementary storage pathways. Emerging CO_2 storage technologies could be critical to bridge this gap and ensure that global CCS infrastructure can meet 2050 capacity targets.

5.1.2 Innovation: in situ CO_2 mineralisation

Overview

A promising alternative to sedimentary CO_2 storage, in situ CO_2 mineralisation (TRL 5–7) offers the potential to permanently store carbon into reactive rock formations. In situ CO_2 mineralisation is a geological carbon storage technique that involves the underground injection of CO_2 into basaltic or ultramafic rocks, where it chemically reacts with naturally occurring minerals to form stable carbonates. Once injected, CO_2 dissolves in formation water and forms carbonic acid (H_2CO_3). This acidic solution reacts with silicate minerals rich in magnesium, calcium and iron, releasing metal cations (e.g., Mg^{2+}, Ca^{2+}, Fe^{2+}) that subsequently bond with carbonate ions (CO_3^{2-}). The result is the formation of solid carbonate minerals such as calcite or magnesite, which permanently lock CO_2 in an immobile and inert form underground.

108 ETC (2022), *Carbon Capture, Utilisation & Storage in the Energy Transition.*

109 Walter, L., et al. (2012), *Brine migration resulting from CO_2 injection into saline aquifers – An approach to risk estimation including various levels of uncertainty.*

110 Gholami, R., et al. (2021), *Leakage risk assessment of a CO_2 storage site: A review.*

In situ mineralisation is being actively pursued by several pioneering companies worldwide. Notably, Carbfix in Iceland has demonstrated the viability of in situ mineralisation at scale (~36,000 tonnes of CO_2 per year[111]), using the country's abundant basaltic rock and renewable geothermal energy to inject and mineralise CO_2. In Canada, Deep Sky is undertaking feasibility studies for similar in situ storage by injecting CO_2 into reactive mafic and ultramafic rocks in Québec. In Kenya, Octavia Carbon is piloting ~1,000 tonnes of CO_2 storage per year[112] via the integration of direct air capture with CO_2 injection into volcanic basalts in the East African Rift, targeting rapid and verifiable mineral storage. These efforts highlight growing momentum behind in situ mineralisation as a commercial CO_2 storage pathway.

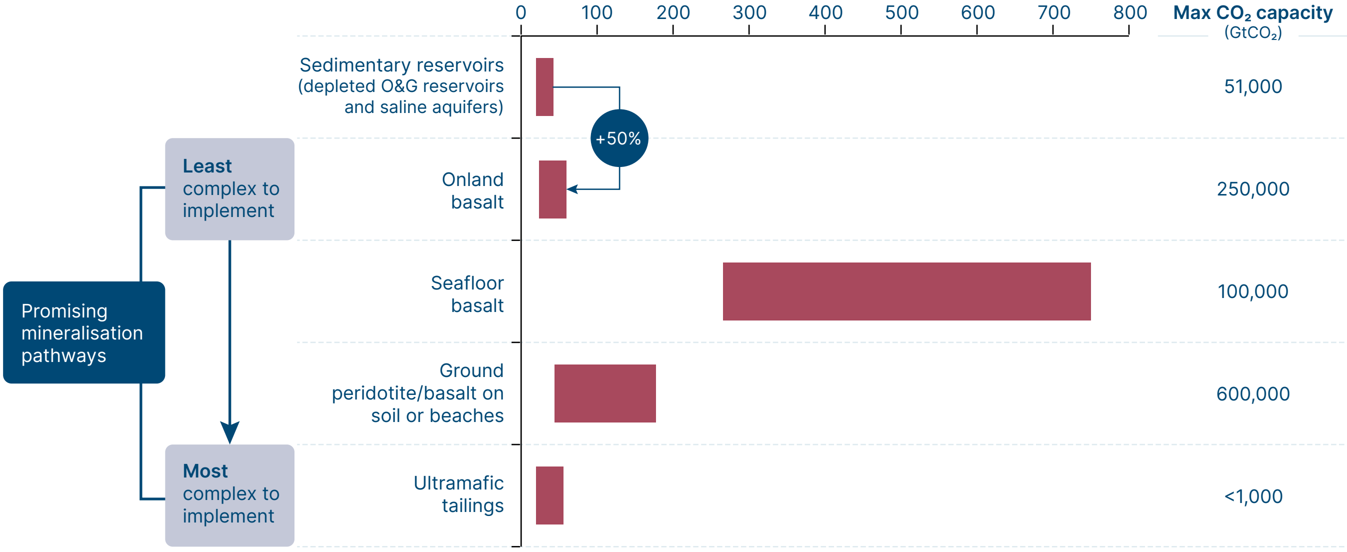
Costs

Despite higher current costs, some mineralisation pathways are approaching cost competitiveness with conventional storage options. As shown in Exhibit 5.4, the least complex pathway (onland basalt) is estimated to currently cost, on average, only 50% greater than storage of CO_2 in conventional onshore sedimentary reservoirs. Conversely, more complex pathways such as seafloor basalt incur significantly higher costs, driven by logistical and technical challenges. Opportunities to deploy mineralisation close to emission sources or captured CO_2 could reduce transportation costs and offset some of the cost differential, particularly in regions with suitable geology.

Exhibit 5.4

Cost of mineralisation today is 50% higher than sedimentary reservoirs, and seafloor mineralisation has significantly higher CO_2 storage capacity

Cost of CO_2 storage for sedimentary reservoirs and most promising mineralisation pathways, 2025
$/t$CO_2$ stored



SOURCE: Systemiq analysis for the ETC; Kelemen, P., et al. (2019), *An overview of the status and challenges of CO_2 Storage in Minerals and Geological Formations*; Smith, E., et al. (2021), *The cost of CO_2 transport and storage in global integrated assessment modelling*; Barlow, H., et al. (Global CCS Institute, 2025), *State of the art: CCS technologies 2025.*

In situ CO_2 mineralisation could offer significantly higher long-term storage potential than traditional sedimentary reservoirs. While formations such as depleted oil and gas fields and saline aquifers are estimated to provide a global maximum capacity of approximately 51,000 GtCO_2, some mineralisation pathways may offer an order of magnitude more. For example, onshore basalt formations, which represent the most cost-effective mineralisation option to date, are estimated to hold up to 250,000 GtCO_2. These formations are often found in different geophysical regions than sedimentary basins, including extensive onland basalt provinces in India, Siberia and the Pacific Northwest of the United States, as well as along seafloor basalt formations such as those in East Africa and the mid-ocean ridges. This geographic distinction means that mineralisation and sedimentary storage can complement each other, expanding the global storage footprint in a regionally additive way. Together, these pathways form a portfolio of CO_2 storage options that improves overall scalability, resilience and availability across diverse geographies.

111 Climeworks, *Mammoth: our newest facility*. Available at: https://climeworks.com/plant-mammoth. [Accessed June 2025].

112 Octavia Carbon, *Accelerating The Path to Net Zero*. Available at: https://www.octaviacarbon.com/technology. [Accessed June 2025].

Impact

One of in situ mineralisation's most significant advantages lies in its permanence: unlike storage in sedimentary reservoirs, mineralised CO_2 becomes chemically stable and immobile within the host rock. This eliminates the risk of long-term leakage and may reduce or remove the need for multi-decade post-injection monitoring and liability management. This level of containment may appeal to industries, regulators, and the public alike, helping build trust in the long-term security of CO_2 storage.

In addition, in situ mineralisation presents no intrinsic environmental limitation on injection rates, making it a potentially high-throughput solution in geologically suitable locations. By contrast, sedimentary storage systems such as saline aquifers or depleted oil and gas fields are constrained by pressure build-up, caprock integrity limits and induced seismicity risks. These factors require complex reservoir modelling and pressure management strategies to avoid leakage or damage. Mineralisation avoids these issues: the CO_2 reacts rapidly with host rock, forming stable carbonates and eliminating pressure buildup, which allows for more continuous and potentially higher injection rates.

However, in situ mineralisation is currently more expensive than sedimentary storage, in part due to limited infrastructure maturity, site development costs and the need for CO_2 pre-conditioning (such as pressurisation or transport to remote basaltic regions). That said, costs may come down over time through process integration with industrial emitters, co-location with renewable energy and scaling of successful demonstration projects. In the longer term, mineralisation's appeal may lie less in near-term cost competitiveness and more in its potential to simplify long-term monitoring, increase geographic storage options and address public acceptance barriers in jurisdictions where traditional storage faces opposition or regulatory inertia.

Barriers and Enablers

The most significant barrier to widespread deployment faced by in situ CO_2 mineralisation is its geological constraint. Suitable rock types are not uniformly distributed across all regions and are often located far from major industrial emission sources. This geographical mismatch raises infrastructure and transport challenges, potentially limiting the number of viable project sites and increasing overall CO_2 transport costs.

Another barrier is the lack of existing infrastructure and regulatory frameworks. Unlike conventional CO_2 storage in depleted oil and gas reservoirs, mineralisation lacks a mature network of pipelines, wells and monitoring systems. Moreover, permitting pathways and standards for this emerging approach are still being defined in many jurisdictions, which may slow project development and final investment decisions. However, there is growing momentum in some regions such as Europe. In 2025, the first permit for large-scale onshore CO_2 mineralisation was awarded to Carbfix under the EU's CCS Directive. While the permitted storage volume is modest (approximately 106 ktCO_2 per year, totalling 3.2 MtCO_2 over three decades) the project represents a significant regulatory milestone. It establishes a permitting pathway for in situ mineralisation in the EU and may pave the way for larger-scale deployments in the future.[113]

Despite these challenges, an important enabler that could accelerate deployment of in situ mineralisation is the growing emphasis on CO_2 storage durability and permanence. Governments and regulators are increasingly embedding long-term durability as a criterion in carbon removal schemes. For instance, the UK is considering integrating carbon removals into its Emissions Trading Scheme,[114] provided permanence of carbon storage can be verifiably measured. Similarly, the Integrity Council for the Voluntary Carbon Market has launched a work programme focused on permanence, proposing industry-wide liability mechanisms to ensure removal permanence over decades.[115] These policy and market shifts may lend preference to CO_2 storage technologies such as in situ mineralisation given its demonstrable permanence of CO_2 in solid form.

Another key enabler could be the co-location of DAC systems with on-land CO_2 mineralisation geological formations. Placing DAC units near basalt or ultramafic rock allows for modular, scalable systems without reliance on offshore infrastructure. However, this model depends not only on suitable geology but also on abundant, low-cost renewable energy, given DAC's high energy requirements. Emerging strategies should focus on coastal locations where onland basalt formations coincide with strong renewable resources. This setup may offer a pathway to low-cost, permanent carbon removal, particularly as o-CDR frameworks evolve. The Carbfix–Climeworks project in Iceland illustrates this model, combining geothermal-powered DAC with nearby basalt storage.

113 Carbfix (2025), *Carbfix Secures Europe's First Storage Permit for Onshore Geological Storage of CO_2*. Available at https://www.carbfix.com/newsmedia/carbfix-secures-europes-first-storage-permit-for-o. [Accessed June 2025].

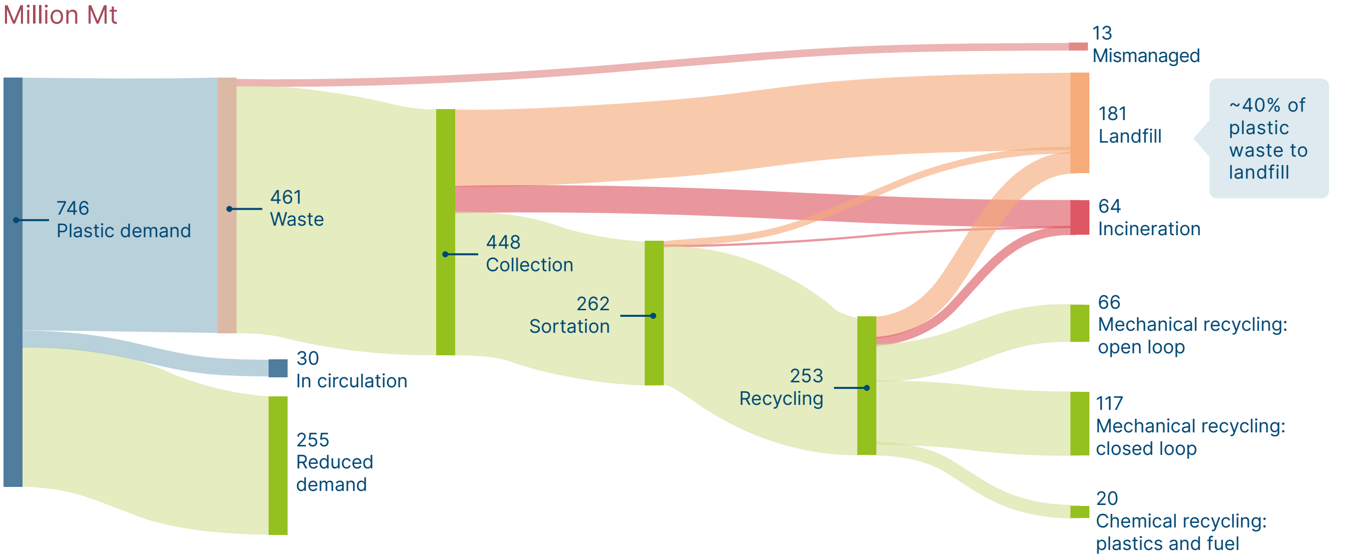
114 UK Government (May 2024), *Integrating greenhouse gas removals in the UK Emissions Trading Scheme*. Available at: https://www.gov.uk/government/consultations/integrating-greenhouse-gas-removals-in-the-uk-emissions-trading-scheme. [Accessed June 2025].

115 Integrity Council for the Voluntary Carbon Market (May 2022), *Integrity Council Releases First Continuous Improvement Work Program Report, Focused on Permanence.* Available at: https://icvcm.org/ciwp-report-on-permanence/. [Accessed June 2025].

Exhibit 5.5

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

Fate of global plastic waste, 2040
Million Mt



SOURCE: Systemiq (2024), *Plastic treaty futures.*

5.2 Managing solid carbon

For the solid carbon contained in physical products, notably plastics, recycling technologies alone will be unable to manage carbon at end-of-life. Exhibit 5.5 showcases a balanced scenario for the end-of-life management of plastic waste in 2040, incorporating circular economy solutions (e.g., reduced demand, recycling) and linear waste management practices (i.e. landfill or incineration). Under this scenario, a significant amount, i.e. 40% of global plastic waste (181 Mt), could still be sent to landfill by 2040.

5.2.1 Existing solid carbon management practices

Landfill and incineration are the dominant commercial technologies for managing plastic waste and broader municipal solid waste (MSW) streams that are not recycled. In developed regions, managed landfills[116] are typically designed with multiple engineered protections to prevent leakage to the environment, such as bottom liners and cover materials or containment and treatment systems for waste by-products (e.g., leachate). However, landfill quality varies widely across the globe. In many low- and middle-income countries, waste is still disposed of in open dumps or poorly managed landfills, which often lack containment and are vulnerable to geological instability, flooding, or coastal erosion, leading to significant environmental risks. At the same time, waste incineration is a well-established and mature industry, particularly in industrialised countries. Many facilities operate under long-term public service contracts and are integrated with waste-to-energy (WtE) systems that recover energy from combustion, typically as electricity, heat or both.

Both landfilling and incineration of plastic waste are significant drivers of climate change, together currently emitting approximately 1.2 $GtCO_2eq$ per year.[117,118] Emissions from landfill are primarily driven by the anaerobic decomposition of organic components of MSW (e.g., food waste) which produces landfill gas, a mixture of methane and CO_2. Given the significant global warming potential of methane, management of landfill gas is becoming an increasing priority for site operators. On the other hand, waste incineration plants emit primarily CO_2 from the combustion of fossil-derived materials such as plastics. Mitigating these emissions will require improved waste management practices, such as the adoption of advanced landfilling technologies or application of CCS on incinerators.

116 Also commonly referred to as engineered or sanitary landfills.

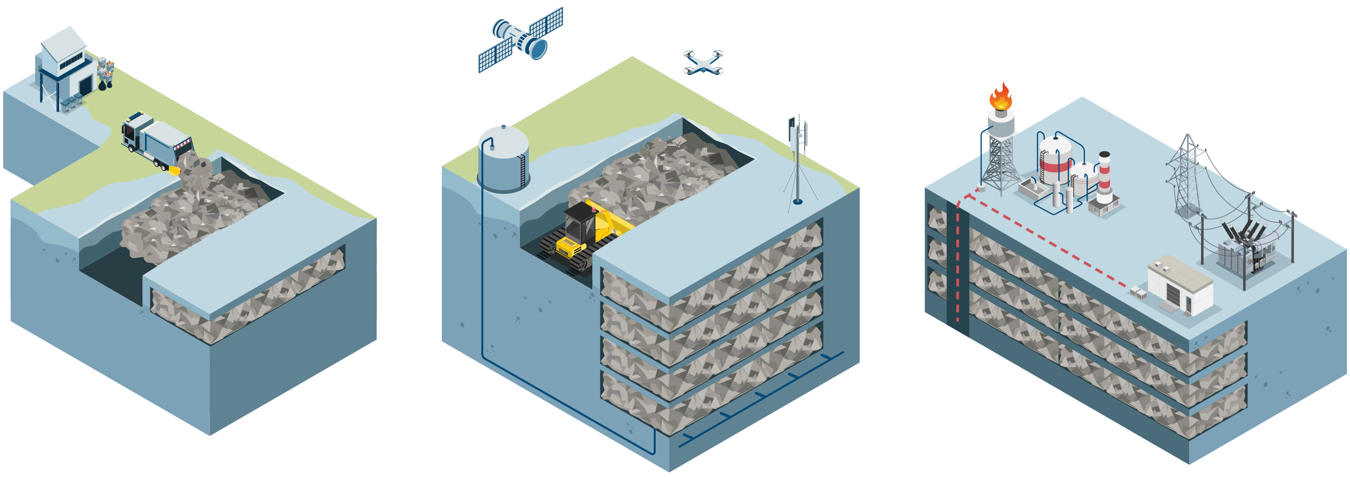
117 Landfill global emissions estimate at ~0.8 $GtCO_2eq$: Pericarbon (2025), *The Methane Crisis: Uncovering the Climate Impact of Landfills.* Available at: https://www.pericarbon.org/post/the-methane-crisis-uncovering-the-climate-impact-of-landfills. [Accessed June 2025].

118 Incineration global emissions estimate at ~0.4 $GtCO_2eq$: Zero Waste Europe (2019), *The impact of Waste-to-Energy incineration on climate.* Available at: https://zerowasteeurope.eu/wp-content/uploads/edd/2019/09/ZWE_Policy-briefing_The-impact-of-Waste-to-Energy-incineration-on-Climate.pdf. [Accessed June 2025].

Exhibit 5.6

Advanced landfilling technologies which can be utilised to reduce the GHG emissions of landfill sites

Overview of advanced landfilling technologies



1

Pre-landfill material recovery and biological treatment (MRBT)[a]

Waste is stabilised via aerobic processing (such as composting) to reduce methane-generating potential before landfilling.

2

Comprehensive methane monitoring and detection[b]

Advanced systems (e.g., drones, satellites, ground sensors) track emissions across the landfill surface to enable leak detection and targeted intervention.

3

Landfill gas capture and management systems[b]

Engineered infrastructure collects methane from buried waste, which can be flared or used for energy production.

NOTE: MSW= municipal solid waste

SOURCES: Zero Waste Europe (2024); *Reducing waste management's contribution to climate change*; RMI (2024), *Deploying Advanced Monitoring Technologies at US Landfills.*

5.2.2 Innovation: advanced landfill technologies

Adoption of advanced landfill technologies will be critical to manage and reduce the GHG emissions of future landfill sites. As shown in Exhibit 5.6, such technologies include:

1. **Pre-landfill material recovery and biological treatment (MRBT):** This technology involves stabilising biogenic MSW through aerobic decomposition before it is landfilled. The aim is to reduce the mass of the input waste by approximately 25–30%, significantly lowering its methane-generating potential once buried. By biologically treating the waste in advance (typically through controlled aerobic composting), the organic content that would typically decompose anaerobically in landfills (and release methane) is largely neutralised. This method is a proactive approach aimed at minimising future emissions at the source, whilst aligning with circular economy principles by enabling the recovery of materials prior to disposal.
2. **Comprehensive methane monitoring and detection:** This category includes advanced systems designed to detect and measure methane leakage from landfills. Tools employed can include aerial infrared imaging, drone-mounted sensors and continuous ground-based analysers. These systems enhance the accuracy and frequency of monitoring, making it easier to detect leaks promptly and take corrective action (e.g., capping leaks). Monitoring technologies can play a vital role in identifying fugitive emissions that are otherwise hard to track and ensuring that landfills mitigate GHG emissions more effectively.
3. **Landfill gas capture and management systems:** These systems focus on capturing landfill gas (methane and CO_2) generated during waste decomposition. The gas is collected at designated wells and routed via pipelines, where it can be processed and upgraded for use as an energy source or fuel. As landfill gas benefits from its biogenic CO_2 content, it is expected to become increasingly marketable in low-carbon energy markets. Additionally, biocover materials may be used on the landfill surface to trap gases and enhance microbial methane oxidation. Together, these systems can help reduce the release of GHG emissions from landfills.

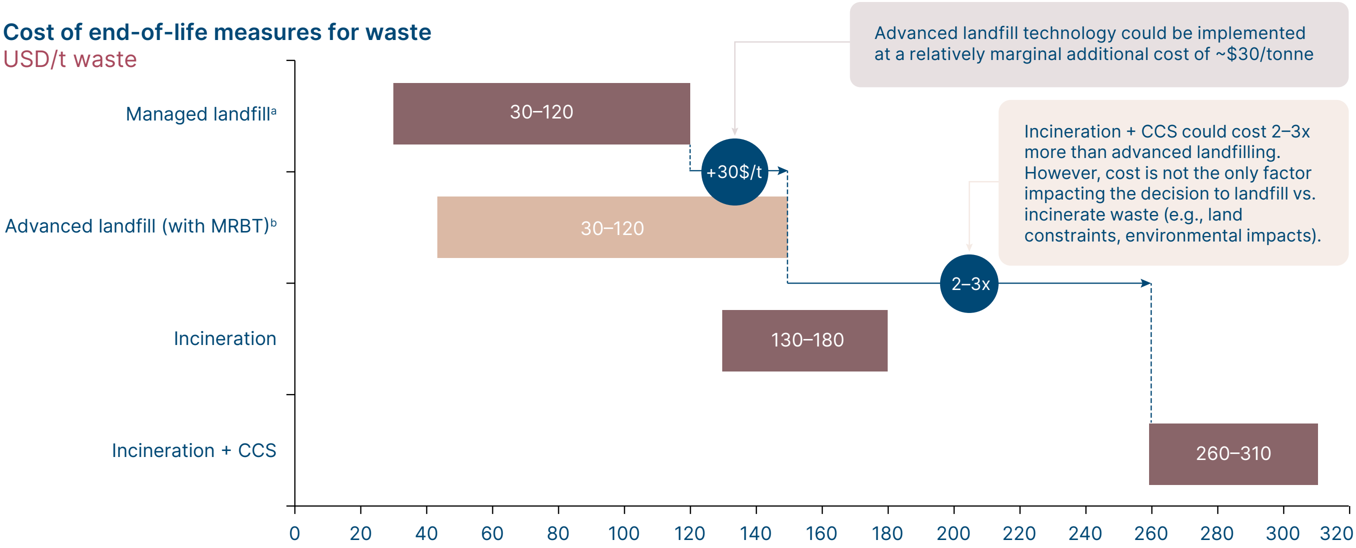
4. Costs

Advanced landfilling with MRBT could be implemented at only a marginally higher cost than conventional managed landfills. As shown in Exhibit 5.7, the cost of a managed landfill typically ranges from $30–120 per tonne of waste, influenced by factors such as land and labour costs or landfill system designs. In comparison, advanced landfill systems incorporating MRBT could have a relatively minor incremental cost of roughly $30 per tonne. Given this small cost increase, adopting advanced landfill systems could offer a cost-effective way to reduce GHG emissions from landfills.

Compared to incineration with CCS, advanced landfilling with MRBT is significantly more cost-competitive and technologically mature. Exhibit 5.7 highlights that incineration with CCS entails a much higher cost between $260–310 per tonne of waste, equating to approximately two to three times the cost of advanced landfilling. Incineration without CCS also remains more expensive, at $130–180 per tonne. This positions advanced landfilling as a highly attractive solution, especially for jurisdictions seeking to balance emissions reductions with financial feasibility. Additionally, advanced landfill technologies are at a higher technology readiness level (TRL 8–9) than incineration with CCS (TRL 7), making them an immediately deployable solution. While managed/advanced landfilling could offer a more cost-effective and market-ready solution, there are other pragmatic considerations (e.g., land use, environmental trade-offs) that influence regional decision-making on waste management strategies and regulations.

Exhibit 5.7

Advanced landfills could cost marginally more than managed landfills today and be highly cost-competitive against incineration with CCS



NOTE: MRBT = Material Recovery and Biological Treatment; [a] Managed landfill (also referred to as sanitary or engineered landfills) refers to where collected waste has been deposited in a central location and where the waste is controlled through daily, intermediate and final cover thus preventing the top layer from escaping into the natural environment through wind and surface water. Lower-cost range for regions with lower land/development (e.g., parts of USA) and high cost range for regions with high land/capital/labour costs (e.g.; parts of Europe); [b] Costs increase shown for advanced landfill using material recovery and biological treatment.

SOURCE: Systemiq analysis for the ETC (2025), based on Gaia (2021), *The High Cost of Waste Incineration*; Zero Waste Europe (2020), *Building a bridge strategy for residual waste*; Eunomia (2021), *CCUS Development Pathway for the EfW Sector*.

Considering project cost and revenue structures, advanced landfill technologies such as MRBT could potentially achieve breakeven with only marginal additional revenue. Exhibit 5.8 (left-hand side) illustrates this cost and revenue structure for the US, a country with greater reliance on landfilling. Due to relatively low baseline landfill costs and the ability to recover revenue (e.g., through waste collection gate fees), the net additional revenue required to breakeven with MRBT is modestly around $10 per tonne. This suggests advanced landfilling could be a financially viable investment in regions that rely heavily on landfill disposal, particularly where regulatory incentives can support cost recovery.

By contrast, the addition of CCS to incineration could significantly increase project costs, particularly in incineration-dependent markets. As shown Exhibit 5.8 (right-hand side), incineration with CCS in the UK could require a steep additional cost of approximately $130 per tonne, translating to an extra $60 per tonne in revenue required to breakeven. Even with electricity and heat revenues factored in, the financial gap is substantial, posing a challenge for widespread CCS deployment without substantial public subsidies or higher gate fees. This contrast underscores the relatively lower economic hurdle associated with scaling advanced landfilling technologies, which may offer a more pragmatic path for emission reduction in certain geographies.

Impact

Advanced landfilling of MSW can reduce GHG emissions by up to 92% compared to managed landfilling, achieving emissions levels comparable to incineration with CCS. As shown in Exhibit 5.9, combining MRBT with gas capture systems can reduce emissions by a factor of ~10, from 2.1 tCO_2e per tonne waste (for conventional managed landfills) down to 0.2 tCO_2e per tonne. This is on par with the emissions from incineration with CCS, which also achieves 0.1–0.2 tCO_2e per tonne waste. Pure plastic waste emits less (0.1 tCO_2e per tonne) than MSW (2.1 tCO_2e per tonne), since plastics do not generate methane in anaerobic conditions. MRBT contributes significantly to this reduction by biologically stabilising organic waste and minimising methane generation. When paired with gas capture infrastructure, the remaining landfill gas emissions can be further contained, delivering significant GHG mitigation potential. As methane represents ~90% of landfill GHG emissions, abatement is particularly important given methane's high global warming potential over a 20-year horizon, where its impact is over 80 times that of CO_2.[119]

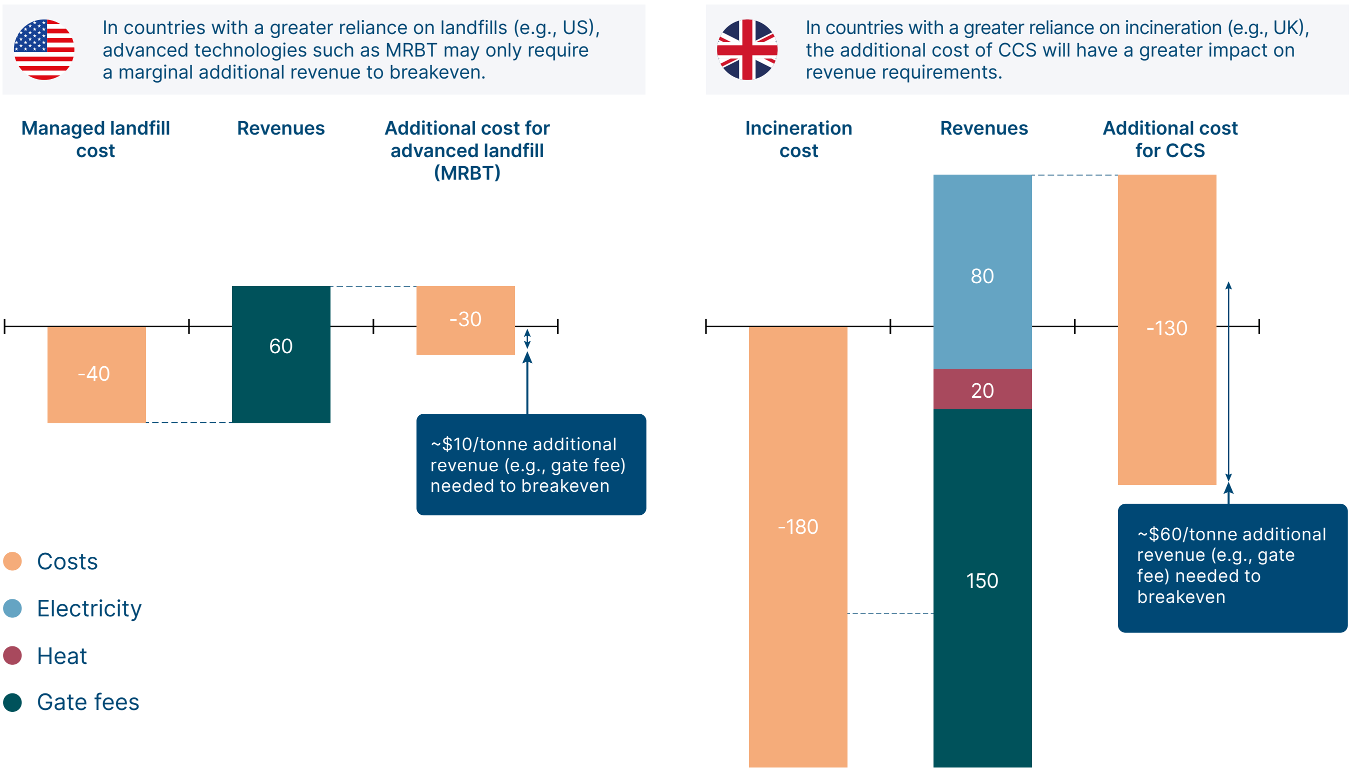
Barriers and enablers

One of the primary barriers to advanced landfilling is the lack of upfront capital and operational funding, especially in low- and middle-income regions. Technologies such as MRBT, comprehensive methane detection and landfill gas capture systems require significant investment in infrastructure and equipment, along with the development of a skilled workforce. Many municipalities still operate under budget-constrained waste management systems, with unsanitary landfills or open dumpsites common in low-income countries. Investments may therefore be difficult to justify without guaranteed returns or proper revenue mechanisms (e.g., sufficient gate fees for waste collection), limiting their attractiveness to both public and private investors.

Exhibit 5.8

Advanced landfilling is significantly less costly than CCS on incineration and has a marginal impact on revenue requirements

Costs and revenues of end-of-life measures for waste,
USD/t waste



NOTE: MRBT = Material Recovery and Biological Treatment.

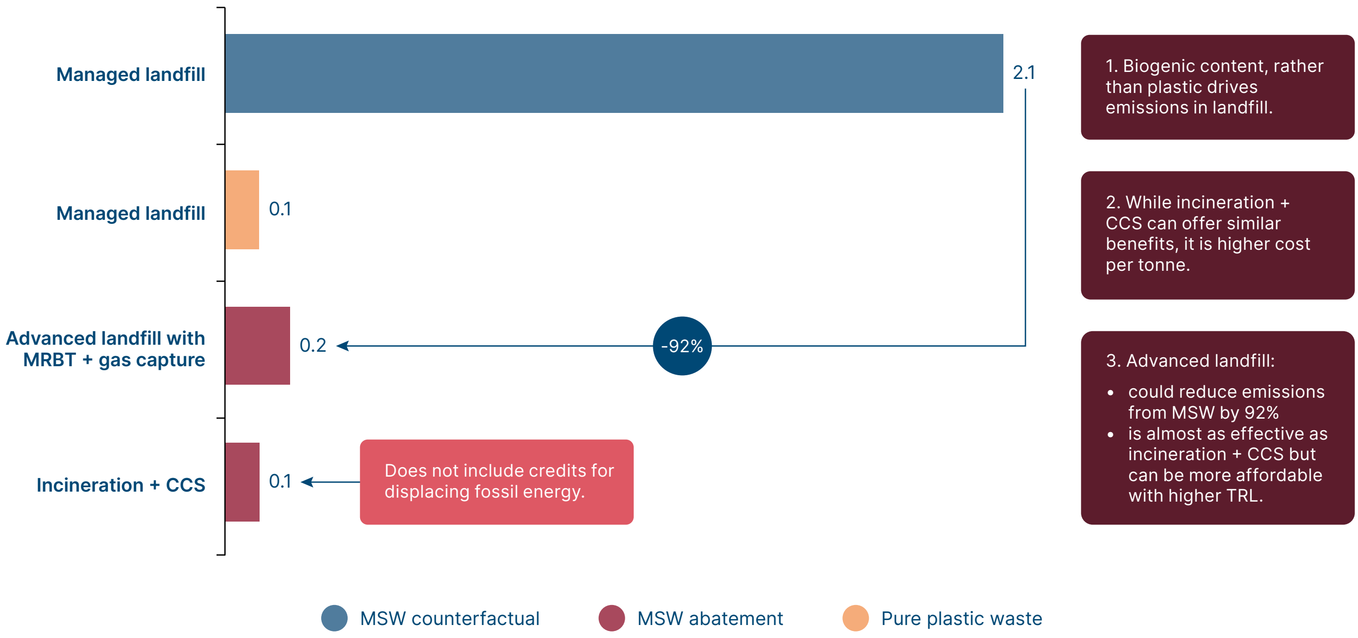
SOURCE: Systemiq analysis for the ETC (2025) based on Gaia (2021), *The High Cost of Waste Incineration*; Zero Waste Europe (2020), *Building a bridge strategy for residual waste*; Eunomia (2021), *CCUS Development Pathway for the EfW Sector*; EREF (2023), *Landfill Tipping Fees*.

119 IEA (2021), *Methane and climate change.* Available at: https://www.iea.org/reports/methane-tracker-2021/methane-and-climate-change. [Accessed June 2025].

Exhibit 5.9

Advanced landfilling of MSW could reduce emissions by ~92%, reaching a similar emissions factor (0.1–0.2 tCO_2e/t waste) to incineration with CCS

End-of-life emissions for landfill and incineration scenarios[a]
tCO_2e/t waste



NOTE: MRBT = Material Recovery and Biological Treatment; MSW managed to advanced landfill abated 1.9 tonnes for incremental $30/t waste; Incineration + CCS abates 1tonne for incremental $130/t waste. This results in cost of abatement equal to $16 per tonne for advanced landfill and $130 per tonne for incineration + CCS.

SOURCE: Systemiq analysis for the ETC; Zero Waste Europe (2020), *Building a bridge strategy for residual waste*, Ecoinvent v 3.11. (Assumes a 90% capture rate).

Another major barrier is access to land. In densely populated or rapidly urbanising areas, securing adequate space for landfill sites is increasingly difficult. Land near population centres is highly competitive, and new landfill proposals often face strong local opposition due to concerns about odour, traffic, health impacts and land value. This spatial constraint can push policymakers toward waste-to-energy incineration, which requires less land and can be co-located with industrial facilities. However, this shift often comes at the cost of higher emissions and lower material recovery. Despite these pressures, the cumulative land required for landfilling all plastic waste generated between now and 2040 is projected to remain minimal, constituting less than 0.001% of Earth's total land area.[120]

A further barrier lies in the lack of strong policy frameworks supporting the adoption of advanced landfilling technologies. In many countries, regulations governing landfilling practices are either outdated or insufficiently enforced, allowing continued reliance on low-cost, high-emission landfill operations. Without clear mandates to reduce biodegradable waste or control methane emissions, there is little regulatory pressure to modernise landfills. Additionally, fragmented jurisdiction between national and local governments can lead to inconsistent implementation (e.g., national government regulations on GHG emissions versus local government management of waste), further hindering technology deployment. In high-income countries, another critical challenge is the existence of long-term waste incineration contracts between municipalities and private operators, creating a strong lock-in effect. These agreements can be expensive to exit and discourage the consideration of alternative solutions such as advanced landfilling. In parallel, incineration of waste to produce power continues to benefit from favourable carbon accounting (e.g., grid electricity emissions offsetting), despite being one of the most carbon-intensive ways to generate electricity.

Social acceptability and broader environmental considerations pose additional barriers to scaling advanced landfilling. Public perception of landfills is often negative**,** given their association with land degradation, environmental contamination risks and unfavourable odours/sights. Hence, local communities are not typically in favour of nearby

120 Global cumulative plastic waste landfilled (2025-2040) estimated at 3.6 Gt. Based on Global rules scenario in Systemiq (2024) Plastic Treaty, Global rules scenario. Systemiq (2024), Plastic treaty futures. Assumes landfill depth of 30m and height of 10m.

landfill sites. Investing in well-managed and state-of-the-art facilities can help build trust and shift social acceptability around modern landfilling. While critics may argue that advanced landfilling could reduce momentum for upstream waste prevention, it is important to recognise their climate benefits. Advanced (methane-mitigated) landfills represent a substantially lower-emission alternative to unabated incineration and offer a pragmatic near-term strategy in landfill-dependent regions.

Policy mandates and regulatory requirements are critical enablers for scaling advanced landfill technologies by creating binding obligations to reduce emissions. The EU Landfill Directive, for example, requires Member States to cut the volume of biodegradable waste sent to landfills by 35% relative to 1995 levels.[121] Complementing this, the EU Waste Framework Directive has mandated the separate recycling and collection of biowaste since end of 2023.[122] These mechanisms pressure municipalities to adopt upstream treatment such as MRBT or invest in biowaste collection and recycling systems. In addition, mandates provide long-term clarity and direction, enabling better planning and investment decisions in waste management infrastructure. Similar regulatory measures can also drive the installation of gas capture systems by requiring landfills above a certain capacity to control and report their methane emissions.

Public and private financial incentives can play a powerful role in accelerating technology deployment, especially when aligned with energy or carbon markets. For example, the US offers corporate tax credits of up to 1.5 cents per kWh for electricity generated from landfill gas,[123] creating a market signal that supports gas capture and utilisation projects. Commercial power purchase agreements (PPAs) for renewable electricity sourced from landfill gas can offer another revenue stream, reducing the payback period for investment. Emerging carbon markets also present a growing opportunity to monetise methane abatement from unmanaged landfills in developing countries. For example, projects can access revenues through Verra's Verified Carbon Standard, with methodologies enabling credits from landfill gas capture or energy use.[124] Overall, a range of incentives can be considered to overcome cost barriers and derisk projects for developers and municipalities.

5.3 Conclusions on end-of-life carbon management

The analysis presented above shows that

- Geological CO_2 storage in reservoirs and aquifers provides safe, permanent sequestration at relatively low cost. Offshore options can expand capacity, though at higher expense. In situ mineralisation offers equivalent permanence with significantly larger potential capacity. While currently more costly, increasing regulatory recognition and successful pilot projects indicate strong long-term prospects.
- Storage in solid carbon form can also be made safe and permanent. Decarbonisation strategies for plastics should therefore consider high-quality in-ground storage alongside recycling and demand reduction. Compared with the high costs of incineration with CCS, advanced landfill with gas capture represents a more cost-effective and near-term solution for reducing emissions.

But it is important to recognise the risks that poorly regulated and monitored storage could be unsafe and impermanent and that extensive reliance on end-of-life storage maintains a major role for fossil fuel extraction, and processing, which in itself is a major source of CO_2 and methane emissions. It is therefore essential that:

- Both gas and solid carbon storage is subject to tight regulations and monitoring.
- Carbon and methane pricing and regulation is applied to upstream fossil fuel production, processing and distribution.

121 European Commission, *Biodegradable waste*. Available at: https://environment.ec.europa.eu/topics/waste-and-recycling/biodegradable-waste_en. [Accessed May 2025].

122 European Parliament, *Resource efficiency and the circular economy*. Available at: https://www.europarl.europa.eu/factsheets/en/sheet/76/waste-management-policy. [Accessed June 2025].

123 US EPA (Dec 2024), *Renewable Electricity Production Tax Credit Information*. Available at: https://www.epa.gov/lmop/renewable-electricity-production-tax-credit-information. [Accessed May 2025].

124 Catalytic Finance Foundation (June 2025), *Whitepaper on Carbon Finance for Municipal Solid Waste in Developing Countries*. Available at: https://www.catalyticfinance.org/news/whitepaper-on-carbon-finance-for-municipal-solid-waste-in-developing-countries. [Accessed June 2025].

Technology trade-offs

6

Chapters 1 to 5 have assessed multiple currently available or emerging technologies which could make it possible to achieve net-zero emissions by mid-century. These technologies make it possible to either (i) provide energy services without any carbon molecule input (ii) reuse or recycle carbon molecules (iii) extract primary carbon supply from non-fossil fuel sources (iv) offset emissions with carbon capture and storage.

The optimal balance over time between these different technologies will reflect technological readiness, costs or tonne of CO_2 reduction, energy input costs now and in the future, natural resource demands and broader environmental impacts. These will all evolve over time, but current comparisons suggest the following broad conclusions.

Technological readiness: In terms of technological readiness (measured by TRL) there is no pattern suggesting that particular categories of technology are likely to dominate [Exhibit 6.1]. Across all of the seven broad categories of possible solutions, there are in most cases multiple technologies in the 5–9 TRL range [Exhibit 6.1]. The major exceptions, and therefore the focus of funding from research and innovation entities, are:

- Electrowinning and metal oxide electrolysis (MOE) are still assessed to be at a TRL of 4–5 and significant technological advancement and fine-tuning is therefore required before commercial rollout.
- Geological hydrogen extraction remains at low technological readiness due to technical challenges (limited field demonstrations, uncertain resources, immature extraction methods and hydrogen purity issues), economic barriers (unproven costs and uncertain yields), regulatory gaps (lack of frameworks and dedicated infrastructure) and environmental concerns (risks of gas leakage, groundwater contamination, and seismicity).[125] However, investors in this industry are confident that these hurdles will be overcome in the coming decades.
- In situ mineralisation of CO_2 remains at a relatively low technological readiness due to technical and cost hurdles including slow reaction rates, subsurface and feedstock uncertainties, high energy and infrastructure requirements, and the need for robust monitoring techniques.[126] These factors have kept costs high and have limited large-scale deployment to date, but some commercial-scale deployment is expected within the next decade.
- Synthetic/cultured meat production is still at a very early stage of technological and commercial deployment. As a result, the feasibility of the large upside for sustainable bioresource extraction, shown on Exhibit 4.30, remains unproven.

Cost per tonne of CO_2 abated: Exhibit 6.2 presents a summary of multiple estimates of the cost of abatement for the different technologies in 2030/2035. There are significant degrees of uncertainty around each specific estimate, but the very wide dispersion between the different technologies suggests some broad conclusions.

- In principle reuse of materials and material recycling of plastics should be able to reduce primary carbon demand at negative cost of abatement. They crucially depend however on the introduction and social acceptance of more disciplined end-of-life recovery and sortation.
- Several direct electrification technologies – in particular electro winning, MOE and e-cracking, seem likely in principle to be low cost options if and when they progress to a higher TRL level.
- Several point source CCS solutions seem likely to be among the more economic options, but estimates of DACCS for 2030 make it still an expensive option at that time.
- The several carbon capture and use options seem expensive, and will need to achieve significant cost reductions to play a major role.

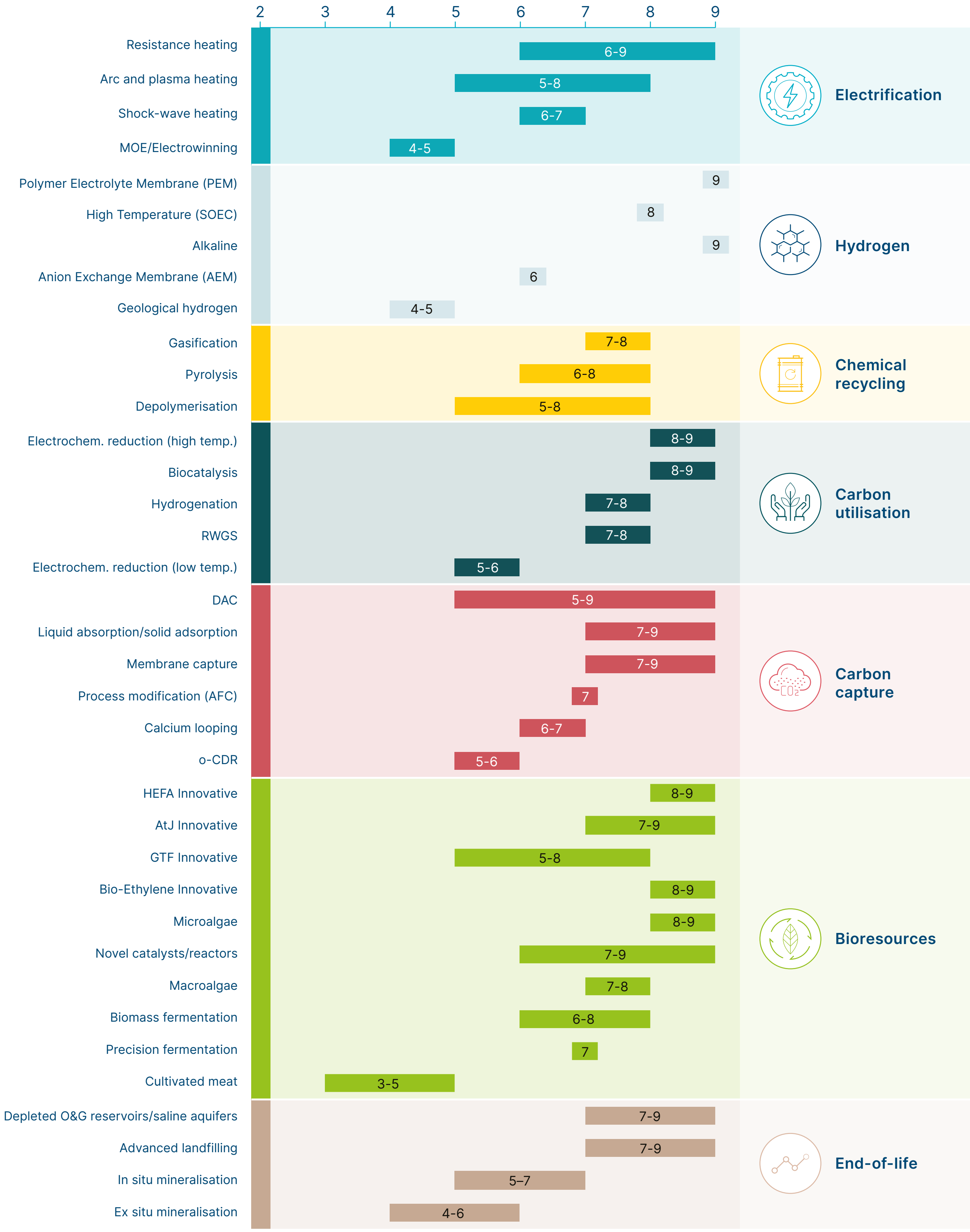
The analysis shows that no single technology can deliver net-zero alone. Mature, lower-cost options like CCS and recycling are essential for rapid emissions cuts, while emerging technologies such as DACCS and electrochemical processes hold the key to long-term system resilience and deep decarbonisation. The real trade-off lies between speed and scalability: deploying what works today while investing in what will be needed tomorrow.

125 Hydrogen Science Coalition (2024), *Everything you need to know about natural or geologic hydrogen.*

126 US Department of Energy (2023), *Pathways to Commercial Liftoff: Carbon Management.*

Exhibit 6.1

Range of Technology Readiness Levels (TRLs) across the technologies explored in this study



NOTE: DAC = Direct Air Capture; AFC = Allam-Fetvedt Cycle; AtJ = Alcohol-to-Jet; HEFA = Hydroprocessed Esters and Fatty Acids; and GFT = Gasification–Fischer-Tropsch. RWGS = Reverse water gas shift; o-CDR = ocean-based carbon dioxide removal.

SOURCE: Systemiq analysis for the ETC (2025).

Exhibit 6.2

Cost of emissions abatement in 2030/2035 vs their counterfactual product, fuel or system

Emissions abatement cost in 2030/2035

$/t$CO_2$e

EOL CCU Electrification CCS Material recycling Bioresources

NOTE: 2030/2035 timeline used due to lower TRL technologies (4-5) unlikely t be commercially ready in 2030. Analysis assumes $50/MWh electricity price. "Material Recycling" technologies include an avoided waste incineration emissions credit; DACCS = Direct Air Carbon Capture and Storage; GFT =Gasification-Fischer-Tropsch; HEFA = Hydroprocessed Esters and Fatty Acids; AtJ = Alcohol-to-Jet; o-CDR = Ocean-based Carbon Dioxide Removal; CCUS = Carbon Capture and Storage; AFC = Allam-Fetvedt Cycle; MOE = Molten Oxide Electrolysis; MRBT = Material Recovery and Biological Treatment; PET; Polyethylene terephthalate; NG = Natural gas, N.A. = Not applicable. Innovative HEFA, AtJ and Bio-ethylene refer to those fuels being produce with advanced and innovative catalysts.

SOURCE: Systemiq analysis for the ETC (2025).

Energy costs now and in the future. One key determinant of the 2030/2035 abatement costs shown in Exhibit 6.2 is the energy intensity of the different processes and the costs of energy inputs. For instance, both DACCS and chemical recycling via gasification have high cost because they are very energy intensive processes; and the high cost of the CCU options are to a significant extent driven by the assumed cost of green hydrogen inputs, which in turn depend on the cost of electricity.

As a result, these technologies would become more competitive if the cost of zero carbon electricity declined significantly, either globally or in specific regions. As the ETC's recent report on *Power Systems Transformation*[127] sets out, this is likely to occur over the medium term in "global sunbelt" countries which enjoy very large solar or wind resources in specific locations therefore some of the technologies – and in particular DACCS – are likely to play a more significant role than their position as Exhibit 6.2 suggests.

Natural resource and local environmental effects. Securing primary carbon supply from either fossil or bio resources could have a significant local environmental impact: these arise from the mining, drilling, transport and refining involved in fossil fuel supply and from the biodiversity losses which may result from biomass if involving land-use. Circularity via reuse or recycling of materials is the most effective lever to reduce this input.[128]

Bio energy by resource supply creates the greatest demand for land: other technology options e.g., for gaseous or solid carbon storage, are trivial by comparison. For example, landfilling all of the world's municipal solid waste (including plastic) from now until 2040 would theoretically occupy 0.85 million hectares,[129] where the freeing up of land via alternative proteins could generate 28 EJ using 585 million hectares [see Exhibit 4.30]. Regulation to minimise the adverse effects on biodiversity, and to avoid bad incentives for land degradation (e.g., as shown on Exhibit 4.26) are therefore essential.

Ultimately, the trade-offs across decarbonisation technologies reflect a balance between speed, scalability, and sustainability. Mature, lower-cost options such as point-source CCS and material recycling enable rapid emissions cuts with known technologies, but their potential is constrained by resources and infrastructure. Emerging solutions like DACCS and electrochemical conversion are slower to scale yet essential for deep, long-term decarbonisation and resilience. The resulting trade-offs are not only economic or technical—they also encompass societal acceptance, land and resource use, and broader environmental impact. For decision-makers, this implies the need to pursue a balanced portfolio: accelerating deployment of mature solutions while investing in innovation that preserves flexibility and strengthens long-term system resilience. Chapter 7 explores how these choices shape alternative pathways to a net-zero carbon system.

127 https://www.energy-transitions.org/publications/power-systems-transformation/

128 These effects can also be reduced by improvements in energy productivity which make it possible to supply useful energy services while reducing final and primary energy demand. See forthcoming ETC Energy Productivity report.

129 Systemiq analysis for the ETC (2025), assuming 41.5 Gt of MSW waste generated between 2025-2040 and compacted landfill depth of 30m and height of 10m.

Technology scenarios 2050

7

Exhibit 0.1 in the report's introduction set out the current pattern of carbon supply, use and end destination in today's energy and material system. In this system, total carbon usage amounts to 11.5 Gt C: 85% originates from fossil sources extracted from the ground and 88% results in emissions to the atmosphere.

The technologies discussed in this report could be combined in multiple different ways to deliver net-zero emissions to the atmosphere. We have therefore developed four scenarios which represent different ways in which this objective could be achieved. Table 4 explains key features of each scenario, Exhibits 7.1–7.4 show the resulting pattern of supply, use and demand, Table 5 shows the quantities of carbon usage and end destination in millions of tons and Table 6 shows the change in quantities from today's system.

Table 4

Description of scenarios developed for carbon flows for materials and energy, 2050

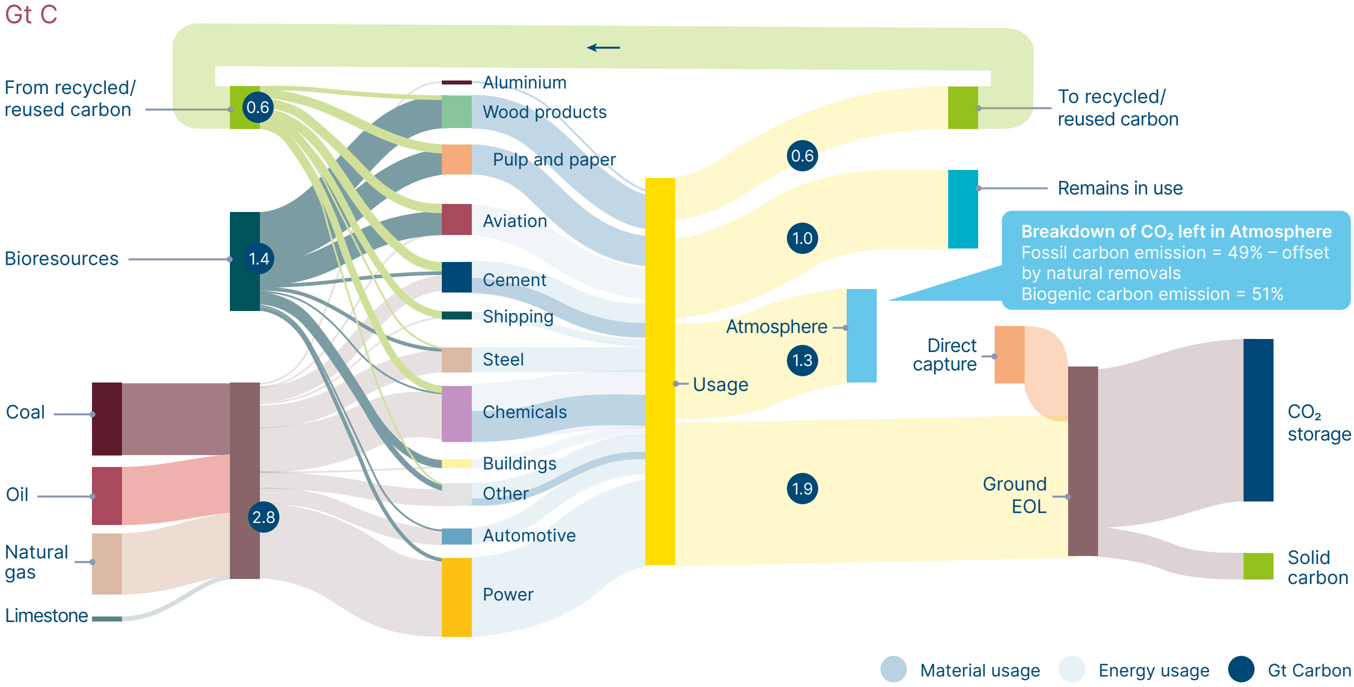
<table>
<tr><th></th><th>Ambitious but clearly feasible (baseline)</th><th>Minimise primary carbon</th><th>Minimise fossil carbon use</th><th>High fossil in perpetuity</th></tr>
<tr><td>Description</td><td rowspan="4">• ETC's baseline decarbonisation scenario
• Clean electrification
• Green H_2, sustainable bio and CCUS for hard-to-abate sectors</td><td>• ETC's more ambitious decarbonisation scenario PBS
Plus
• High circularity
• Cheap unconstrained electricity</td><td>As per scenario Minimise primary carbon, plus
• Maximum available biomass</td><td>• Net-zero with higher fossil
• Baseline circularity
• Limited bio-availability</td></tr>
<tr><td>Relevant explored technologies</td><td>• Re-use models
• Mechanical and chemical recycling
• CCU technologies
• Electrification of steel and, cement
• Advanced battery chemistry</td><td>As per scenario Minimise primary carbon, plus
• Scaling of alternative proteins
• Efficient biomass crops on degraded land</td><td>• Cost-effective DAC
• Ocean based o-CDR
• Point source capture technologies
• Advanced landfill
• CO_2 storage technologies</td></tr>
<tr><td>What you need to believe</td><td>• Widely available renewable firm electricity
• Policy support and deep tech innovation for recycling and reuse
• Waste CO_2 utilised across aviation, chemicals, shipping and cement</td><td>As per scenario Minimise primary carbon, plus
• Cost reductions in alternative proteins and broad consumer uptake
• Land freed from livestock production is used partially for biomass
• Increased availability of sustainable biomass use
• Aviation and shipping cheap bio
• Coal in power, steel and cement switch to biomass</td><td>• Electrification and carbon recycling technologies not scaled due to economic and technical barriers
• High H_2 and carbon utilisation costs are high
• CCS, DACC and removals technologies scale
• Biomass limited
• Aviation and shipping use fossil fuels with removals
• Chemicals sector uses predominantly fossil + CCS</td></tr>
<tr><td>Risks</td><td>• High electrification across sectors strains grid infrastructure, leading to peak demand challenges</td><td>• Freed land faces competing demands
• Carbon accounting complexity of biomass use, means potential hidden overshoot</td><td>• Reduced incentives for cleaner scalable alternatives
• Locked in fossil use without effective abatement risks climate overshoot</td></tr>
</table>

SOURCE: Systemiq analysis for the ETC (2025).

Exhibit 7.1

ACF, carbon source and destination for the energy and materials sectors by mid-century

Gt C



SOURCE: SOURCE: Systemiq analysis for the ETC (2025); ETC (2023), *Fossil Fuels in Transition*.

In all four cases, the total quantity of carbon used in the global energy and material system is dramatically reduced from today 11.5 Gt to between 3.3 Gt to 4.8 Gt depending on scenario. This reflects the impact of electrification which, as Exhibit 0.2 showed, is certain to produce a major reduction in the use of carbon based molecules even before considering the options for increased electrification which were considered in Chapter 1.

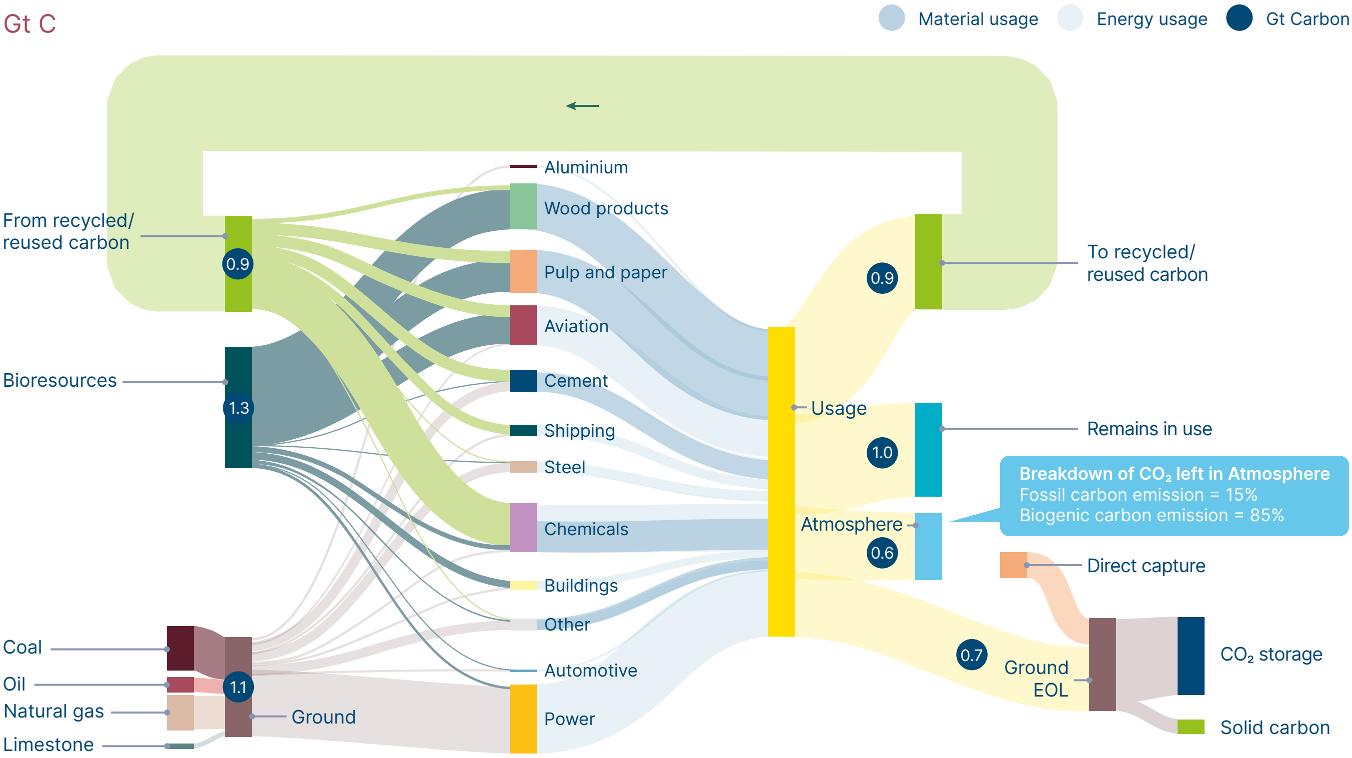
But the balance between different sources and destinations for carbon differs significantly between the four scenarios:

- In our **Baseline** scenario [Exhibit 7.1] which broadly reflects the ETC's Accelerated but clearly feasible (ACF) scenario from our *Fossil Fuels in Transition* report, recycling and reuse has grown from today's 2% of carbon supply to 13% (0.6 Gt C) by 2050: but 58% (2.8 Gt) of carbon supply still derives from fossil fuels extracted from the ground, with 30% deriving from bio resource. At the end of life, 21% of total carbon inputs remain in use, while 56% (2.7 Gt) must be stored in gaseous or solid form. 1.3 Gt of carbon (≈4.8 GtCO_2) is emitted to the atmosphere, but this residual emission is compatible with net-zero due to offsetting 0.8 Gt of carbon removals via direct air capture and 0.7 Gt via nature-based sequestration. This scenario makes conservative assumptions about the progress of both direct electrification and recycling technologies, but as result requires more extensive carbon storage, with gaseous CO_2 storage needing to reach 8.4 Gt of CO_2.
- The **Minimum primary carbon** scenario [Exhibit 7.2] explores the potential impact of maximum progress towards the electrification options considered in Chapter 1, and the reuse/recycling options examined in Chapter 3. In this scenario total demand for carbon is reduced to 3.3 Gt of which a greatly increased 29% is provided via recycling or reuse. Bio resource supply falls to 1.4 Gt versus 1.5 Gt in the Baseline, while fossil carbon supply falls dramatically from 2.7 Gt to 1.1 Gt. Meanwhile at end-of-life, 60% of all carbon used is reused, recycled or stays in use, while the need for gaseous storage falls from 8.4 Gt to 3.2 Gt of CO_2. The feasibility of this scenario depends on the abundant supply of low-cost green power, faster market penetration of electric technologies, and large investments in collection, recycling and carbon utilisation systems.
- The **Minimum Fossil Carbon** scenario [Exhibit 7.3] shows the scale of sustainable bioresource supply needed if large-scale carbon storage were infeasible or too costly, and fossil use had to fall far below the Baseline. Total carbon demand remains low at around 3.6 Gt, supported by ambitious electrification. Under this assumption, total carbon supply from fossil sources would be reduced to just 640 Mt, 16% of the 2050 total, and a 94% reduction from today's 9.8 Gt. In this scenario, the need for end-of-life gaseous would be dramatically reduced to around 480 Mt (about 1.8 Gt of CO_2) since bio energy can be a zero carbon energy source even if CCS is not deployed. This scenario depends on major bioresource expansion and careful land-use management, that goes beyond ETC's prudent supply.

Exhibit 7.2

Minimum primary carbon, carbon source and destination for the energy and materials sectors by mid-century

Gt C

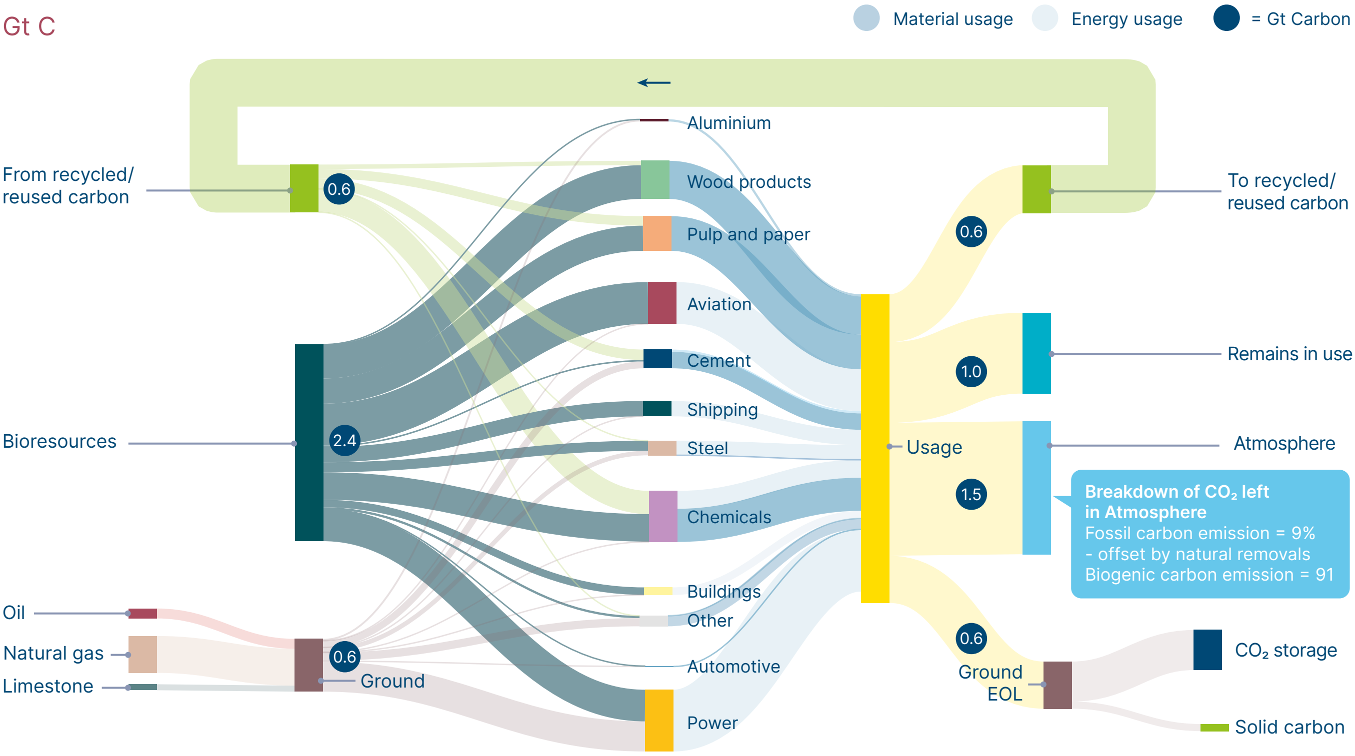


SOURCE: Systemiq analysis for the ETC (2025) based on ETC (2023) *Fossil Fuels in Transition*.

Exhibit 7.3

Minimise fossil carbon use, carbon source and destination for the energy and materials sectors by mid-century

Gt C

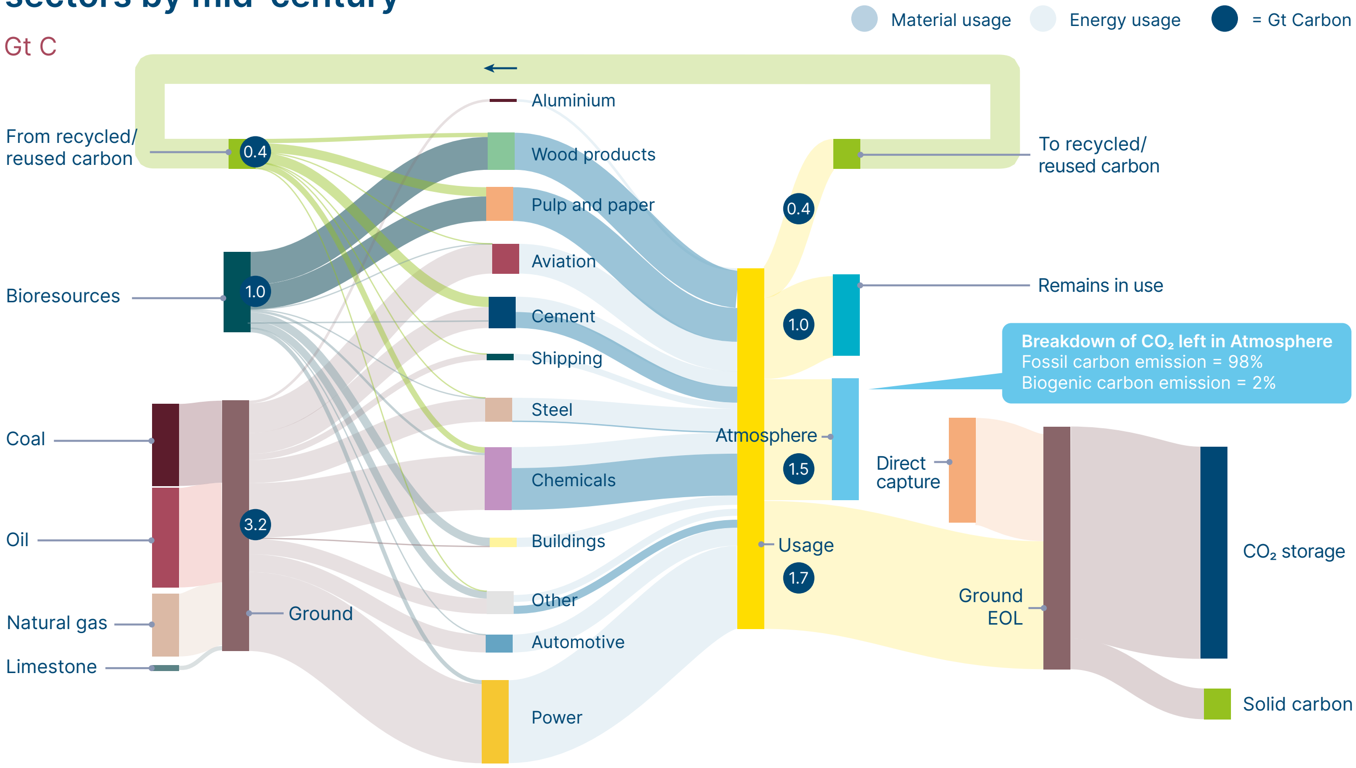


SOURCE: Systemiq analysis for the ETC (2025); ETC (2023), *Fossil Fuels in Transition*.

Exhibit 7.4

Fossil in perpetuity, carbon source and destination for the energy and materials sectors by mid-century

Gt C



SOURCE: Systemiq analysis for the ETC (2025); ETC (2023), *Fossil Fuels in Transition*.

- Finally in the **Fossil fuel in Perpetuity** scenario, [Exhibit 7.4] we explore the implications of accepting a large continuing role for fossil fuels – though one still much reduced from today, with total fossil fuel use of 3.2 Gt C vs. 9.8 Gt C today. This scenario inevitably maximises the need for carbon storage, with a gaseous storage need at about 2.7 Gt of carbon or 9.9 Gt of CO_2 per year. This would require a massive and rapid buildup from today's minimal level of CCS deployment. This 9.9 $GtCO_2$ storage requirement exceeds the IEA's Net-Zero Emissions scenario[130] (7.5 $GtCO_2$ by 2050). It is only comparable to the upper end of the ETC's 2023 *Fossil Fuels in Transition* High scenario (10.1 $GtCO_2$).

Across all scenarios, deep dependency on different technologies shapes both risks and opportunities. The **Fossil-in-Perpetuity** pathway, where roughly 70% of carbon is stored underground, hinges on large-scale deployment of carbon capture and storage (CCS) and direct air capture (DAC)–technologies that remain expensive and largely unscaled. In contrast, the **Minimise-Fossil-Carbon** scenario leans on expanded role of biomass that would only be possible if dietary patterns shift toward lower animal protein consumption and more resource-efficient foods, supported by complementary levers such as biotechnology-driven dietary shifts, high-yield energy crops and utilisation of agricultural and forestry residues. Such shifts are consistent with emerging trends in high-income countries but remain uncertain at global scale, depending on cultural acceptance, affordability, and policy support. Yet biomass-based strategies face critical constraints, from land availability to competing demands for food production and biodiversity. Meanwhile, **electrification** consistently offers the steepest near-term reduction in fossil demand across all scenarios, but cannot fully displace the need for carbon-based molecules. Successfully balancing those molecules with net-zero targets requires active monitoring of technology progress and strategic, diversified investment—avoiding over-reliance on any single pathway and ensuring flexibility to adapt as conditions change.

Looking ahead, an important step will be to assess the relative costs of these pathways. While all four scenarios can deliver net-zero outcomes, their economic implications differ substantially:

- Scenarios with high reliance on CCS and DACCS, such as Fossil-in-Perpetuity, are expected to be more expensive given the high cost and limited maturity of large-scale carbon removal.
- Scenarios that prioritise electrification and recycling tend to reduce both fossil demand and system costs, but depend on rapid buildout of low-cost clean power and enabling infrastructure.

130 IEA (2021), *Net Zero by 2050: A Roadmap for the Global Energy Sector*.

- Biomass-heavy strategies can lower storage requirements but face resource and sustainability constraints that could raise costs in certain regions.

A comparative cost analysis would therefore be critical to assess which combinations of technologies deliver the most affordable and resilient transition. However, outcomes will vary significantly across geographies, depend on the pace of technology deployment, and be shaped by policy design. Uncertainties around learning rates, future fuel prices and the social licence for large-scale infrastructure mean that cost comparisons should be interpreted as indicative—highlighting relative tendencies (e.g., storage-heavy vs electrification-heavy pathways) rather than identifying a single "cheapest" route to net-zero.

Table 5

Volume and share of source per scenario

Metric	Today	ACF	Minimise primary Carbon	Minimise fossil carbon	Fossil in perpetuity
Sourcing - total[3] Mt C	**11,462 Mt C**	**4,770**	**3,305**	**3,587**	**4,613**
Recycled or reused Mt C/% of sourcing	176 Mt C/2%	599	942	577	368
Bioresources Mt C/% of sourcing	1,493 Mt C/13%	1,393	1,260	2,373	997
Ground Mt C[1]/% of sourcing	9,793 Mt C/85%	2,778	1,103	637	3,248
End of life - total Mt C	**11,462 Mt C**	**4,770**	**3,305**	**3,587**	**4,613**
Recycled or reused Mt C/% of end of life	176 Mt C/1%	599	942	577	368
Left in use Mt C/% of end of life	980 Mt C/9%	1,006	975	975	1,006
Atmosphere Mt C/% of end of life	10,116 Mt C/88%	487	355	1,467	141
Ground EOL Mt C[2]/% of end of life	190 Mt C/2%	2,679	1036	569	3,098
Removals Mt C	**0 Mt**	**1,052**	**347**	**137**	**1,481**
Direct capture Mt C/% of removals	0 Mt C/0%	814	294	0	1,392
BECCS Mt C/% of removals	0 Mt C/0%	238	53	137	89
Atmosphere End of life Mt C	**10,116 Mt C**	**487**	**355**	**1,467**	**91**
Fossil Carbon Mt C/% of Atmosphere	9,300 Mt C/92%	238	53	137	89
Biogenic Carbon Mt C/% of Atmosphere	816 Mt C/8%	249	302	1,329	2
Ground End of life Mt C	**190 Mt C**	**2,679**	**1,033**	**548**	**3,107**
Solid Carbon Mt C/% of Ground EOL	190 Mt C/100%	381	156	85	381
Gaseous Carbon Mt C/% of Ground EOL	0 Mt C/0%	2,297	877	483	2,726

NOTES: 1. Includes coal, oil, natural gas and limestone. 2. Includes all carbon capture and storage (DACCS, BECCS and CCS) and solid carbon storage (primarily plastic going to landfill and other terrestrial environment. 3. All values in exhibits are rounded, so in some cases totals in the text and exhibits may differ slightly from the sum of their rounded components.

Table 6

Change in carbon volume flows from today's system

Metric	ACF	Minimise primary Carbon	Minimise fossil carbon	Fossil in perpetuity
Sourcing - change from today Mt C	**-6,692**	**-8,157**	**-7,875**	**-6,849**
Recycled or reused Mt C	423	766	401	192
Bioresources Mt C	-100	-232	880	-496
Ground Mt C[1]	-7,015	-8,690	-9,156	-6,545
End of life - change from today Mt C	**-6,692**	**-8,157**	**-7,875**	**-6,849**
Recycled or reused Mt C	423	766	401	192
Left in use Mt C	26	-5	-5	26
Atmosphere (emissions) Mt C	-9,629	-9,761	-8,649	-9.975
Ground EOL Mt C[2]	2,489	846	379	-2,908

NOTE: 1. Includes coal, oil, natural gas and limestone. 2. Includes all carbon capture and storage (DACCS, BECCS and CCS) and solid carbon storage (primarily plastic going to landfill and other terrestrial environment.

Key conclusions and recommendations

8

A net-zero global economy will remain dependent upon the use of carbon, even after decarbonisation. The challenge in transitioning to a sustainable global carbon economy is not just about reducing carbon use, but about managing the carbon that remains – where it comes from, how it circulates through the economy, and what happens to it at end-of-life.

1 Carbon demand will persist even in a highly electrified world, so it must be actively planned for and managed.

Between 3–5 Gt of carbon will still be needed across energy and materials sectors by mid-century, down from 11.5 Gt today. The transition to net-zero is not a journey to zero carbon use, but to zero carbon emissions. In sectors like aviation, steel and chemicals, i.e. those using carbon for feedstock or industrial processes, carbon is difficult to substitute due to fundamental constraints like energy density and process chemistry. Planning must therefore focus not only on reducing emissions, but also on building a sustainable system to source, use and dispose of carbon in perpetuity.

2 Electrification and re-use are the most efficient tools for reducing carbon usage in the energy and materials sectors.

Direct electrification powered by clean electricity is the most efficient decarbonisation route in many sectors, and can offer low abatement costs relative to scaling many sourcing and circularity technologies. Technologies such as high-temperature electric heating, molten oxide electrolysis and advanced battery chemistries are already displacing fossil carbon and could go further if scaled. Unlocking the full potential of electrification depends on rapid deployment of renewable generation, investment in grids and storage and policies that accelerate clean power buildout.[131] Similarly, reuse also offers a relatively mature and cost-effective upstream measure to reduce carbon molecule demand in the materials sectors.

3 Circularity can play a significant role in reducing primary carbon demand, but requires substantial policy interventions to achieve scale.

A maximum of a third of carbon used in 2050 could be from circular sources. However, circular technologies currently do not offer discrete drop in solutions and require a more holistic and integrated systems approach to scale. Upstream interventions, elimination, reuse and substitution, can significantly reduce total system carbon demand in tandem with cost savings. But reuse for example, would require major behaviour change along the value chain. Mechanical recycling of pulp, paper and plastics is already proven and scalable, but for recycling plastic, scale-up would depend on sufficient quality feedstocks and competition against low-cost virgin fossil production. Other circular technologies further downstream like CCU and chemical recycling face significant business case challenges. Irrespective of potential or constraints, scaling each circularity technology will require a coordinated operational transformation of the value chain, as well as supportive policy interventions. Operational transformation requirements include changes to product design and manufacture, value chain digitisation, brand and retailer operations, consumer behaviour and waste system operations. These changes must be underpinned by robust regulation e.g., carbon accounting and mass balance methodologies, effective carbon pricing to unlock recycling business cases and public support to incentivise first movers. Without this, even the best technologies risk falling short of their potential.

131 A large evidence base on these requirements has been developed in other ETC reports including ETC (2023), *Financing the Transition*, ETC (2025), *Power Systems Transformation*.

4 Linear end-of-life solutions are being advanced and will play a role in a pragmatic and timely transition, especially where circularity solutions are challenged, but should be carefully scaled to avoid giving license to inefficient sourcing and use of carbon.

Not all carbon can be reused or recycled. While every effort should be made to use carbon efficiently first, responsible disposal at scale of end-of-life carbon will be required in 2050. In these cases, linear solutions like geological storage and advanced landfilling provide necessary backstops. New technology advancements such as in-situ CO_2 mineralisation offer high permanence with fewer leakage risks, while methane-stabilising landfill systems can reduce emissions from residual waste. Given the challenges in scaling key end-of-life carbon management technologies in recent decades, a pragmatic, scientific approach should be taken to applying mature, cost-effective and environmentally effective technologies available today. However, these must be scaled with robust governance to ensure storage permanence, avoid negative environmental externalities and avoid incentivising the inefficient use of carbon.

5 Sustainable primary biogenic carbon supply is constrained and direct sourcing technology (DAC, o-CDR) is still emerging, while fossil is abundant. Although there is significant potential to scale sustainable sources of primary carbon, strategic usage of abated fossil and carbon removals will be necessary to deliver a timely transition.

Biomass, DAC and o-CDR represent the most viable sources of sustainable primary carbon, but each comes with trade-offs and thus the available supply of sustainable carbon is constrained. There is a potential upside to biomass sourcing through alternative biotech and utilising degraded land, but sustainable biomass is otherwise largely land-constrained and must be carefully governed to avoid food security and biodiversity risks. DAC is scalable but energy intensive and expensive, while o-CDR offers promise at lower cost but is in an early-stage of technology maturity. Fossil carbon is abundant and affordable, but incompatible with long-term climate goals unless paired with durable removals. Therefore, technologies for abating fossil will be a pragmatic component of the transitioning system. However, their deployment must balance scaling up end-of-life carbon management with scale up of sustainable carbon sourcing to avoid overdependence on a single technology group.

6 While areas of the carbon system have commercially viable abatement solutions, several key gaps still exist in the carbon technology landscape. Further strengthening of the technology acceleration ecosystem is needed where promising technologies are still immature.

Many of the most promising technologies such as high-temperature industrial heat, alternative proteins and o-CDR, are still at low TRLs (4-5) or costly to deploy. However, accelerated commercialisation is critical, even from a low base, given their higher potential to address the hardest parts of the system transition compared to existing solutions. Their success will depend on factors such as access to a robust innovation ecosystem within a mature industrial value chain, abundant clean energy and a willingness to invest in long-term system value over short-term returns. In some select areas, such as chemical recycling, where current business cases are challenging and Greenhouse Gas (GHG) performance is critical, further breakthrough innovation may still be required to achieve significant technology scale up.

7 Flexibility in the solution mix is essential, given the trade-offs across the different technologies, meaning the “optimal” mix will vary significantly by geography, sector and time horizon.

The variance between potential net-zero system-level scenario technology mixes in 2050 is considerable. Reconciling different market characteristics, such as energy availability or industrial structure, with different technology constraints, such as energy intensity or operational complexity, will lead the optimal technology mix to vary significantly by region. For example, biomass-focused strategies can help reduce storage needs, but land availability and sustainability constraints can drive up costs. Electrification and circularity focused technology mixes tend to reduce both fossil demand and overall system costs, although only if supported by rapid buildout of clean power and enabling infrastructure. Fossil-focused technology mixes lean more strongly on removals technologies such as DAC, which is energy intensive, expensive and requires storage.

At this stage in the transition, system decision-makers are empowered to embark on very different technology pathways to reach a net-zero world. The resulting concentration of technology dependence, and thus technology transition risk, is significantly higher in some technology mixes than others. Moreover, they result in very different final net-zero system operating models in 2050. Therefore, consideration must be given not just to reach net-zero, but also to avoiding the creation of new long-term sustainability challenges similar to those faced today following net-zero in 2050. While market forces will help determine which technologies scale, this will be guided by robust regulatory, standardisation and certification frameworks to protect natural and social capital, as well as deliver economic growth. System decision-makers should aim to build diverse, adaptive portfolios that balance cost, technical readiness and resource efficiency, while staying responsive to evolving constraints and opportunities.

8 For a majority of carbon technologies, policy interventions will determine what scales first and how fast; carbon pricing is a critical lever but should be part of a broader policy architecture.

Some key technologies have breakthrough potential and viable business models independent of policy, where industry will likely move first. Others do not, and for these, a pragmatic approach must be taken, using policy to unlock lower-performing but technologically mature solutions now to achieve sufficient scale-up by 2050. Carbon pricing is a critical technology-neutral lever in scaling these key low- emissions technologies. Findings suggest that prices of up to $200 per tCO_2 may be required to bring many essential emerging technologies to cost parity. Projections for the EU ETS point toward steadily rising prices, and the introduction of the European Carbon Border Adjustment Mechanism (CBAM) shows how policy is beginning to expand carbon costs globally.

However, carbon pricing alone is unlikely to be sufficient and must be part of a broader policy architecture focused on the highest impact technologies with the greatest propensity to scale. Policy makers must also identify leading technologies with direct and cross-sectoral abatement potential and with the greatest likelihood of cost reduction to parity e.g., low energy intensity technologies. Equally, policy makers must also identify those technologies facing systemic inertia that require early incentives to catalyse their transition. These objectives can be achieved via instruments such as mandates, EPR schemes, design standards and public procurement. System-level infrastructure investment, tax incentives and certification systems will also be essential to support emerging technologies and safeguard environmental integrity.

Looking forward

This report aims to have several functions in enabling the carbon transition. It seeks to provide a holistic view of the carbon system at a global level coupled with use as a more granular reference document for side-by-side comparison of the best available technologies to transition the system. It aims to provide a common foundation of techno-economics for system decision makers across all systems change levers to chart the most ambitious, feasible and de-risked pathway to a thriving, long-term sustainable global carbon economy by 2050—one in which overall carbon demand is reduced by more than 70% compared to today. Moreover, in this critical decade, it is hoped that this common foundation of insight can be used to incept new or steer existing, multi-stakeholder system initiatives able to directly address key system gaps in carbon efficiencies, sustainable sourcing, technology innovation and end-of-life management. Translating these insights into national, local, policy and corporate contexts will be the next essential step to ensure that the finite economic and natural capital available to deliver the energy transition is deployed to greatest effect in the coming years.

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