



Energy
Transitions
Commission

ETC Expert Workshop: Carbon molecules phase 3 – Sources of primary carbon: costs and sustainability and end-of life carbon management

13 June 2025

Agenda

- Introduction to work program
- Carbon-capture: Direct Capture and Point Source
- Bioresources
- End-of-life management
- Scenarios and next steps



Agenda

- **Introduction to work program**

- Carbon-capture: Direct Capture and Point Source
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Phase 3: Sources of primary carbon: costs and sustainability

Integration in broader carbon molecule project

Having understood how maximum electrification and circularity of carbon to reduce reliance on primary carbon molecules, the last phase of work focuses on how we can meet the remaining demand for carbon molecules and manage end of life carbon

	2024		2025	
	Q4	Q1	Q2	Q3
Workplan	<p>Phase 1A How large can and should the role of direct electrification be in a zero-emission economy</p> <p>Phase 1B The role of hydrogen and derivatives (i.e., ammonia) in a zero-emission economy?</p>	<p>Phase 2 The potential to recycle and reuse carbon molecules</p>	<p>Phase 3 Sources of primary carbon: costs and sustainability and end-of life carbon management</p>	<p>Phase 4 Report production and communication campaign running into COP30</p>
Deliverables	<ul style="list-style-type: none"> A 5-pager published externally A series of short innovation briefs for publication 	<ul style="list-style-type: none"> A 5-pager published externally Report chapter Innovation brief(s) 	<ul style="list-style-type: none"> A 5-pager published externally Report chapter Innovation brief(s) 1-2 workshop with ETC reps/ commissioners 	<ul style="list-style-type: none"> Publication of the ETC report ahead of COP A series of short innovation briefs for publication Workshop Report reviews Report launch at COP
Key interactions	<ul style="list-style-type: none"> 1-2 workshops with ETC Commissioners 	<ul style="list-style-type: none"> 1-2 workshop with ETC reps/ commissioners 		



Outputs of the first two phases of work inform phase 3 analysis

Phase 1
How much can we reduce carbon energy by maximising electrification



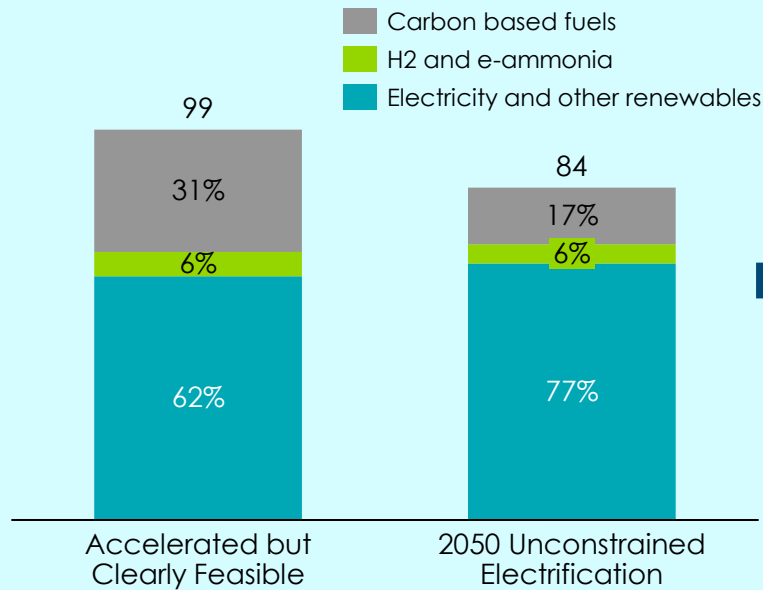
Phase 2
What is total carbon demand and how much of it can be circular



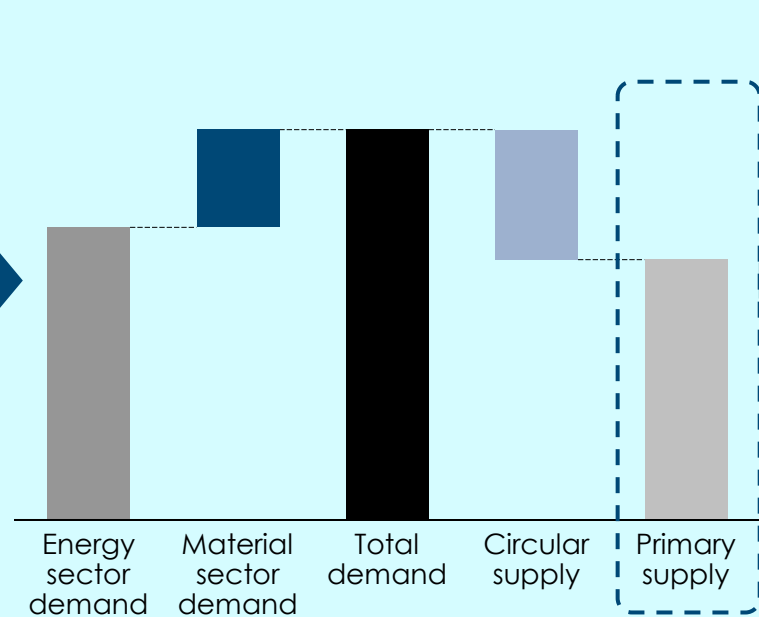
Phase 3
How do we sustainably source primary carbon & manage carbon at end of life



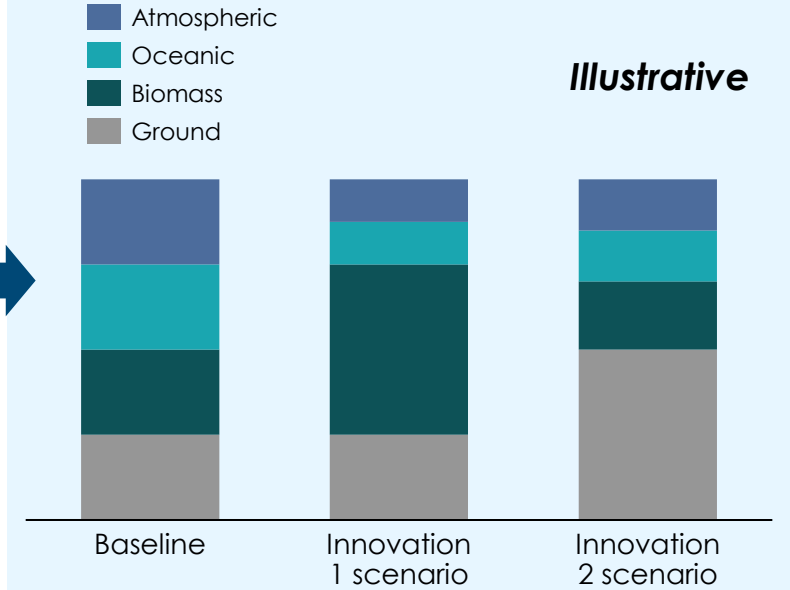
Final Energy Demand for ETC's ACF scenario in 2050
Thousand of TWh



Carbon demand and supply, 2050
Gigatons of carbon (C)



Scenarios for sourcing primary carbon supply
Gigatons of carbon (C)



Cross cutting trade-off analysis

Examples conclusions →

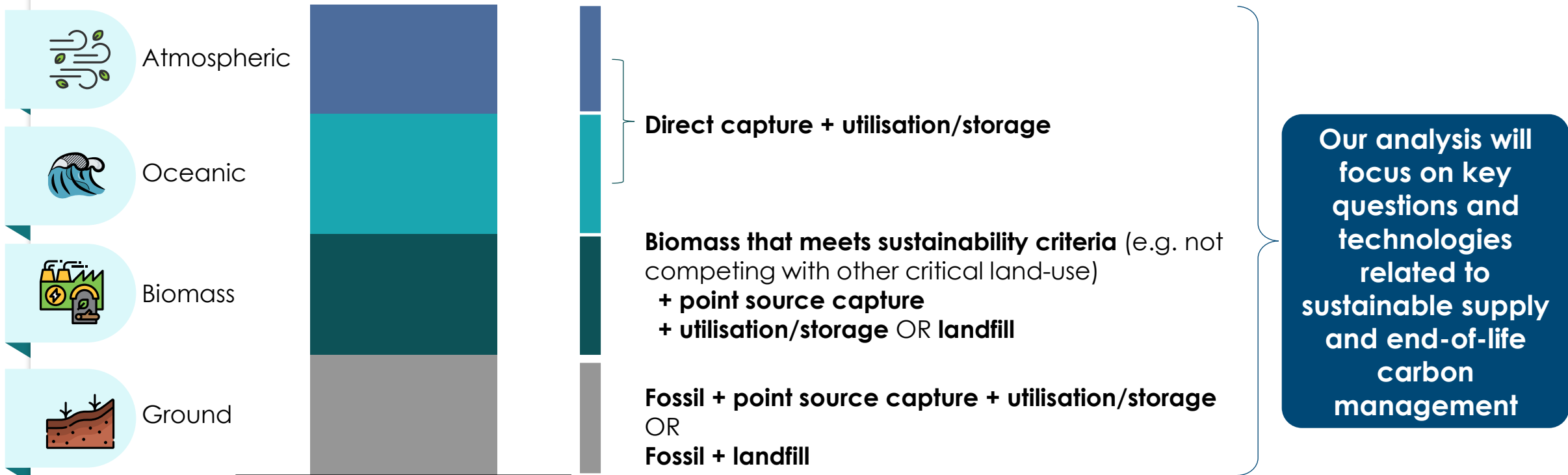
- Pushing circularity as far as we can will saving X million tonnes of primary carbon
- This will save DAC requirements of X tonnes of CO2/y
- Investment requirements for such as system are X







The analysis will focus on sustainable pathways for primary carbon sourcing and end-of-life carbon management

Sources of primary carbon supply

Illustrative



We will focus on key technologies and questions to understand how we best source primary carbon and carbon at end-of-life

	What carbon is available?	How do we improve sourcing of carbon?	How do we optimize our use of carbon?	How do we effectively dispose of carbon?
1. Atmospheric 	910 Gt C¹ But not yet economically accessible	Direct Air Capture Liquid and solid sorbents <i>(benchmark technology)</i>		Cross-cutting carbon sources CO₂ storage <ul style="list-style-type: none"> Depleted oil and gas fields and saline aquifers <i>(benchmark technologies)</i> Sub-sea CO₂ injection CO₂ to stone Advanced landfill
2. Oceanic 	~38,000 Gt C² But not yet economically accessible	Ocean-based CDR Electrochemical separation		
3. Bioresources 	~550 Gt C³ But only an estimated 1.04 Gt sustainable supply⁴ for energy and materials sectors	More productive plants More land New sources of supply	Biomass conversion Advanced reactors Advanced catalysts	
4. Ground 	~5,000-10,000 Gt C⁵ Estimated recoverable		Point Source capture Liquid absorption <i>(benchmark technology)</i> Process modification Calcium Looping	

Notes/sources: 1) Assumes 425 ppm CO₂ in atmosphere and mass of atmosphere of 5.15 x 10¹⁸ kg. 2) "World Ocean Review - A report on the state of the world's oceans" (2010). 3) "The biomass distribution on Earth" (PNAS, 2018). 4) Based on ETC's Prudent scenario. 5) Fossil carbon. "The Carbon Cycle" (NASA Earth Observatory, 2011); "The Global Carbon Cycle" (Penn State University)

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- **Carbon-capture: Direct Capture and Point Source**
- Bioresources
- End-of-life management
- Scenarios and next steps



Carbon capture technologies

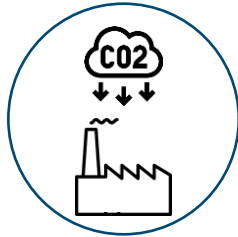


Point-source capture enables carbon avoidance from hard-to-abate emitters, while direct capture removes carbon directly from the atmosphere

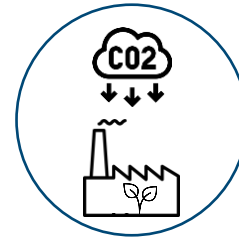
Point source capture

Direct capture

Emission avoidance

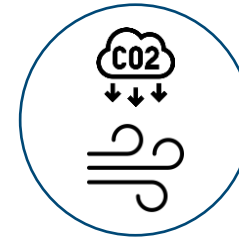


Industrial point source capture

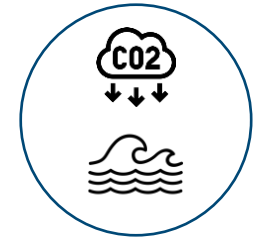


Bioenergy point source capture

Carbon removal



Direct air capture (DAC)

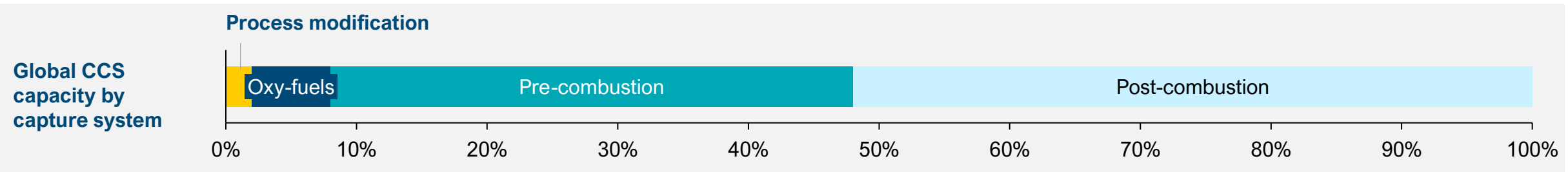
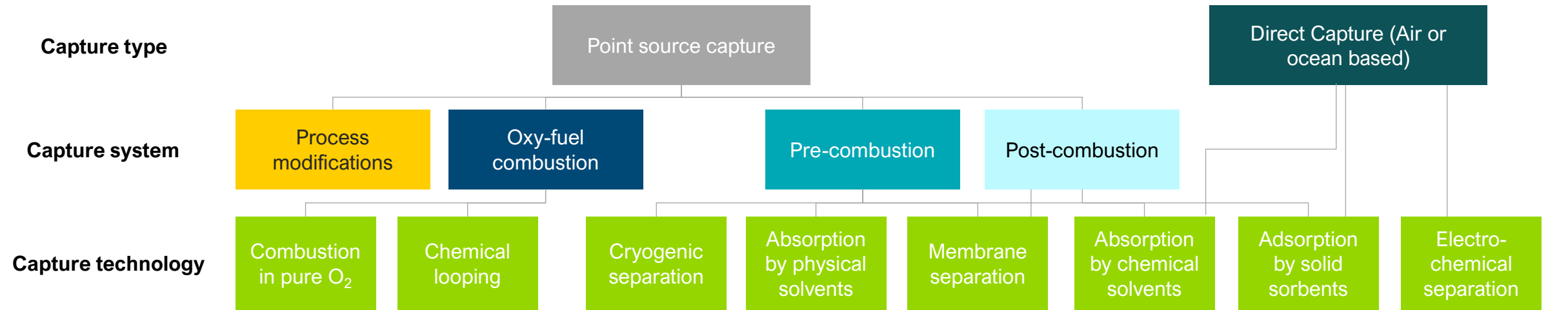


Ocean-based Carbon Dioxide Removal



	Industrial point source capture	Bioenergy point source capture	Direct air capture (DAC)	Ocean-based Carbon Dioxide Removal
Carbon concentration	Medium to very high carbon concentration	Medium to high carbon concentration	Very low carbon concentration	Low carbon concentration
End-users	Demanded by existing industries willing to turn their industrial process carbon neutral	Bioenergy producers with potential to become net-negative when paired with storage or durable utilization	Demanded by governments/ big companies willing to offset residual emissions	Same end-users as DAC, but potentially relevant for coastal energy players
Purpose	Use where electrification or fuel switching is not viable	Further reduce the biomass burning footprint to negative	Balancing net-zero residuals	Balancing net-zero residuals
Advantages	Can leverage existing infrastructure and pipelines	High deployment in regions with established biomass infrastructure	Theoretically unlimited source of sustainable carbon and location-flexible	Unlimited source of carbon and potentially cheaper than DAC

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

Standard carbon capture technologies



Carbon capture systems offer trade-offs between selectivity, cost, energy intensity and easy of integration

	Benefits 	Challenges 
Process modification	<ul style="list-style-type: none"> Low operational cost and maintenance requirement Very high CO₂ capture efficiency 	<ul style="list-style-type: none"> Potentially high CAPEX Limited to new process designs
Oxy-fuel combustion	<ul style="list-style-type: none"> Lowers mechanical failure risk Generates near-pure CO₂ 	<ul style="list-style-type: none"> Sourcing O₂ is expensive if waste streams unavailable Potentially high CAPEX for retrofit
Absorption	<ul style="list-style-type: none"> The most mature technology, widely in operation Can reach high absorption efficiency (> 90% vol. CO₂) 	<ul style="list-style-type: none"> Energy intensive and potentially costly solvent regeneration Solvents easily degraded by contaminants (e.g. SO_x, NO_x)
Adsorption	<ul style="list-style-type: none"> Sorbents can regenerate at lower temperatures meaning lower energy costs and reduced waste 	<ul style="list-style-type: none"> Relatively high material costs (solid amines) Low selectivity of CO₂ over other gases (N₂, CH₄, H₂O)
Membranes	<ul style="list-style-type: none"> Low maintenance requirement, easily installed at any stage Low energy requirement 	<ul style="list-style-type: none"> Low capture efficiency at low partial pressure – requires flue gas recycling or additional membranes
Cryogenic Separation	<ul style="list-style-type: none"> Mature technology, commercially used Extremely high CO₂ recovery rates (99.99%) 	<ul style="list-style-type: none"> Risk of process blockage (due to ice or solid CO₂) High energy requirement due to very low temperature large
Electrochemical	<ul style="list-style-type: none"> Fully electrified operation facilitating renewable operation Potential for high selectivity and very low energy requirements 	<ul style="list-style-type: none"> High capital costs in electrochemical stacks and materials Discontinuous process making scale-up difficult

■ Process modifications
 ■ Oxy-fuel combustion
 ■ Pre-combustion
 ■ Post-combustion

Sources: Wang, X. , Song, C. (2020) Carbon capture from flue gas and the atmosphere: A perspective; Leung, et al. (2014) An overview of current status of carbon dioxide capture and storage technologies, Herzog, et al (2014) Carbon capture and storage from fossil fuel use; Liu et al, (2015) CO₂ adsorption performance of different amine-based siliceous materials; Cheng et al (2021) CO₂ capture from flue gas of a coal-fired power plant using three-bed PSA process; Zanco et al (2021) Postcombustion CO₂ capture: A comparative techno-economic assessment of three technologies using a solvent, an adsorbent, and a membrane

Our deep dives will focus on emerging CO₂ capture technologies which have the greatest potential to cut costs and accelerate deployment

Category	Technology	Process	TRL	Companies <i>Non-exhaustive examples</i>
Direct capture	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	Carbon Engineering, Heirloom, climeworks
	2 Ocean-based CDR	Electrochemical processes or contactors to extract CO ₂ directly from seawater.	5-6	captura, Equatic, SeaQ ₂
Point source capture	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	Shell, Svante, AKER CARBON CAPTURE, INVENTYS, carbon clean
	4 Membrane capture	CO ₂ is separated from gases using selective permeable membranes. This technology can be highly selective but faces challenges at large scale.	7-9	Air Liquide, MTR
	5 Calcium looping	Transformative techniques capturing CO ₂ with lime by forming CaCO ₃ , then regenerated or burning fuel in pure oxygen	6-7	PRODUCTS AIR, ExxonMobil
	6 Process modification (Allam-Fetvet Cycle)	CO ₂ is separated from gases using selective permeable membranes. This technology can be highly selective but faces challenges at large scale.	7	8 RIVERS, NETPOWER







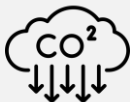


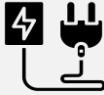




Sources/Notes: 1) Hugh Barlow (Global CCS Institute 2025) Advancements in CCS technologies and costs 2) David Kearns (Global CCS Institute 2021) Technology Readiness and costs

Carbon capture technologies: Direct Capture



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 <i>Low Temperature heat</i> 	<ul style="list-style-type: none"> Novel sorbent materials with improved stability and reaction kinetics Improve absorbent conductivity and heating efficiency 	<ul style="list-style-type: none"> Climeworks has 12 DAC pilot plants in operation, among which the largest DAC facility in Iceland (36 ktonsCO₂/y). Plans for scaling up to 100 ktCO₂/y until 2035. 	 8-9  7-8  7  4  4
Liquid solvent <i>High capture rate</i> 	<ul style="list-style-type: none"> Improve configuration for better flow pattern to improve performance and energy consumption. Novel solvents (ionic liquids, phase change) Limit corrosion in amine capture plants. 	<ul style="list-style-type: none"> Carbon engineering project in Texas aiming to capture up to 1 MtCO₂/y in late 2025.^{1,2} 	 7-9  4
Electrochemical <i>Electrified</i> 	<ul style="list-style-type: none"> Development of ion-selective membranes that can drop the costs due to weaker bonding of the CO₂ on the capturing material. Development of continuous process 	<ul style="list-style-type: none"> 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. 	 4  3-4 Bi-Polar Membrane Electro-Dialysis technology 2-3



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

Sources:1) <https://carbonengineering.com/news-updates/deployment-approach/> 2) <https://decarbonfuse.com/posts/stratos-the-future-of-direct-air-capture-nears-completion> 3) Filippo Bisotti et al. (2024) Direct Air capture (DAC) deployment: A review of the industrial deployment

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 CO₂ capture via DAC – projections 2020-2050

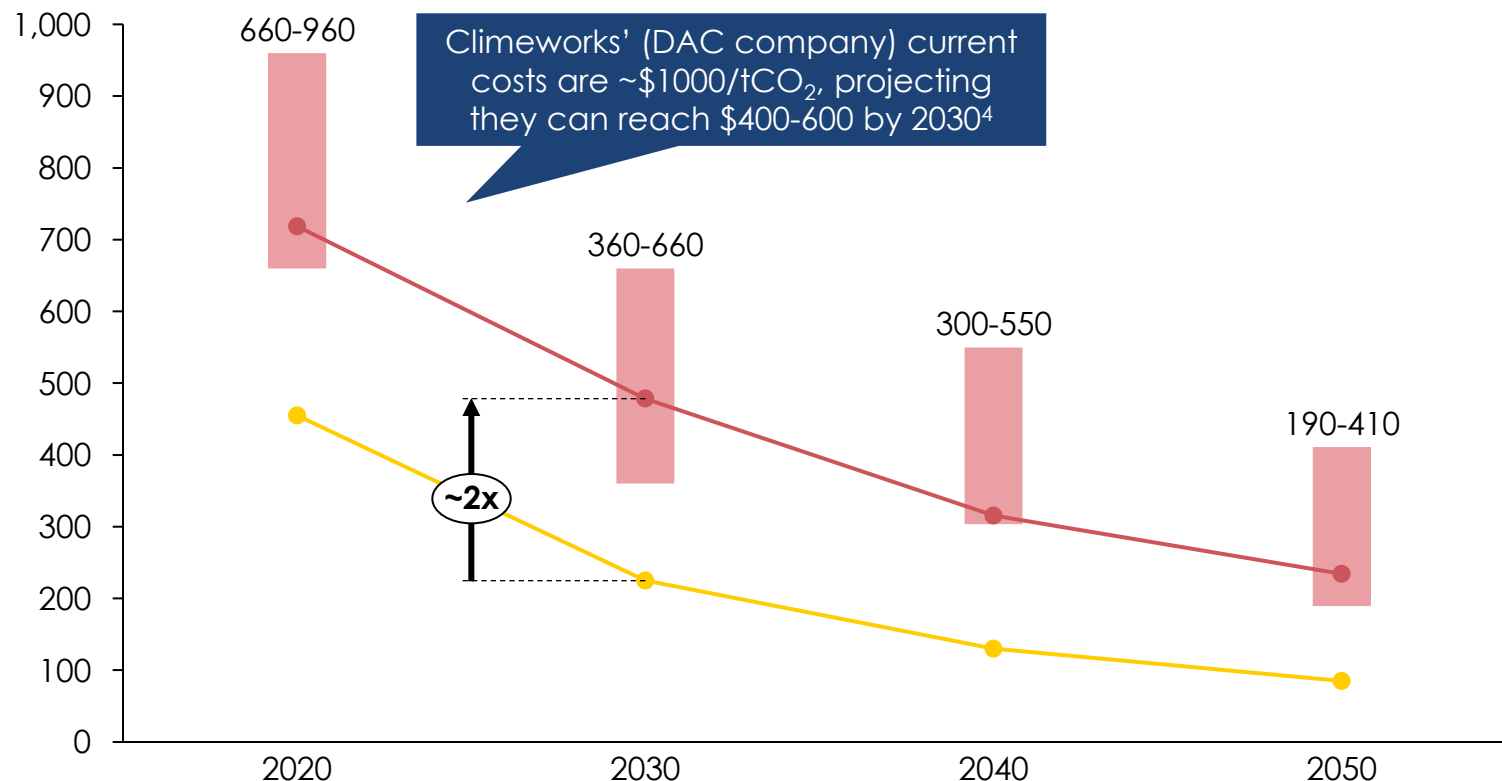
\$/tCO₂

2025 ETC Estimates
Highly Preliminary

- Recent literature estimates (range)¹
- ETC estimates (2021)²
- ETC revised estimates (2025)²

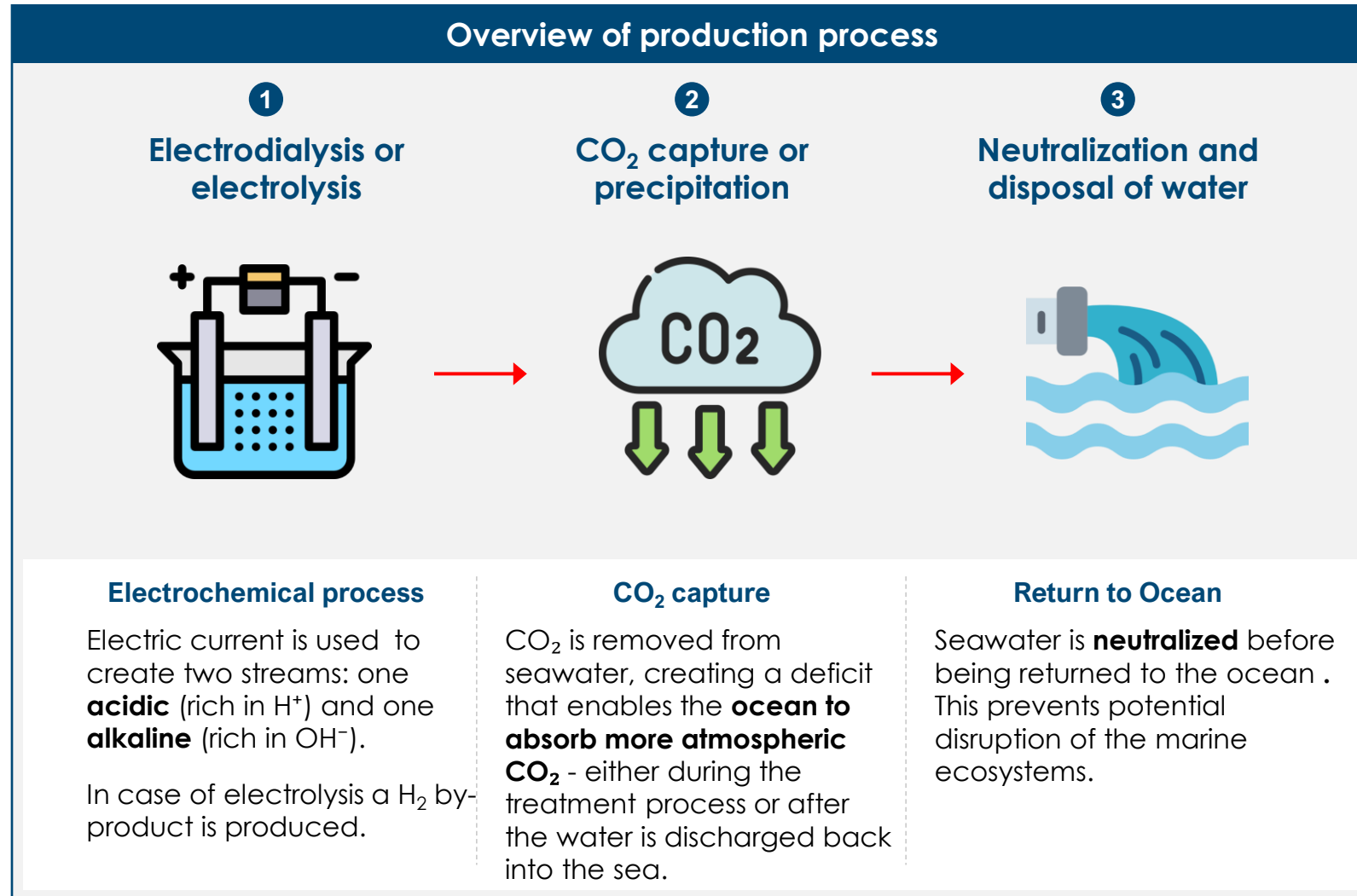
Key take-aways

- Historical DAC cost projections have been optimistic with lower-than-realised capital costs and ongoing energy costs³
- Recent credible publications predict higher costs of DAC until 2050¹, which could hinder the technology's scale-up



Sources/notes: 1) 2020 and 2030 estimates: Lorenzo Sani (2024) Bridging the gap between the UK's CCUS targets and reality. 2040 and 2050 estimates: Katrin Sievert et al. (2024); Manon Abegg et al. (2024); 2) 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. 3) Reality check on technologies to remove carbon dioxide from the air (MIT Energy Initiative, 2024). 4) Carbon Removal's Holy Grail Cost Cut Is Further Away Than It Seems (Bloomberg, 2024)

② Ocean-based CDR (o-CDR): removes dissolved carbon directly from seawater using a range of electrochemical processes



Comparison with DAC

Comparison of Ocean-based CDR with Direct Air Capture process

	o-CDR	DAC
CO ₂ source	100 mg/L	0.7 mg/L
Mechanism ¹	Only desorption	Absorption and desorption
Product form	CO ₂ gas or solid carbonates	CO ₂ gas
Energy requirement	~1.3-1.7 kWh/kg CO ₂	~1.5-2.5 kWh/kg CO ₂
Temperature	Ambient or low Temp	Ambient to high temp - 80-900 °C
Modularity	Decentralized or offshore	Modular units

Notes/Sources: 1) Absorption: CO₂ binds with solvent/sorbent (like MEA) in a reactor. Desorption: The CO₂-rich solvent/sorbent is heated to release CO₂ and regenerate the solvent 2) OmnyaAlYafiee (2024) 3) Prince Aleta et al. (2023)

o-CDR net cost with hydrogen by-product could become more economical than DAC by ~70%

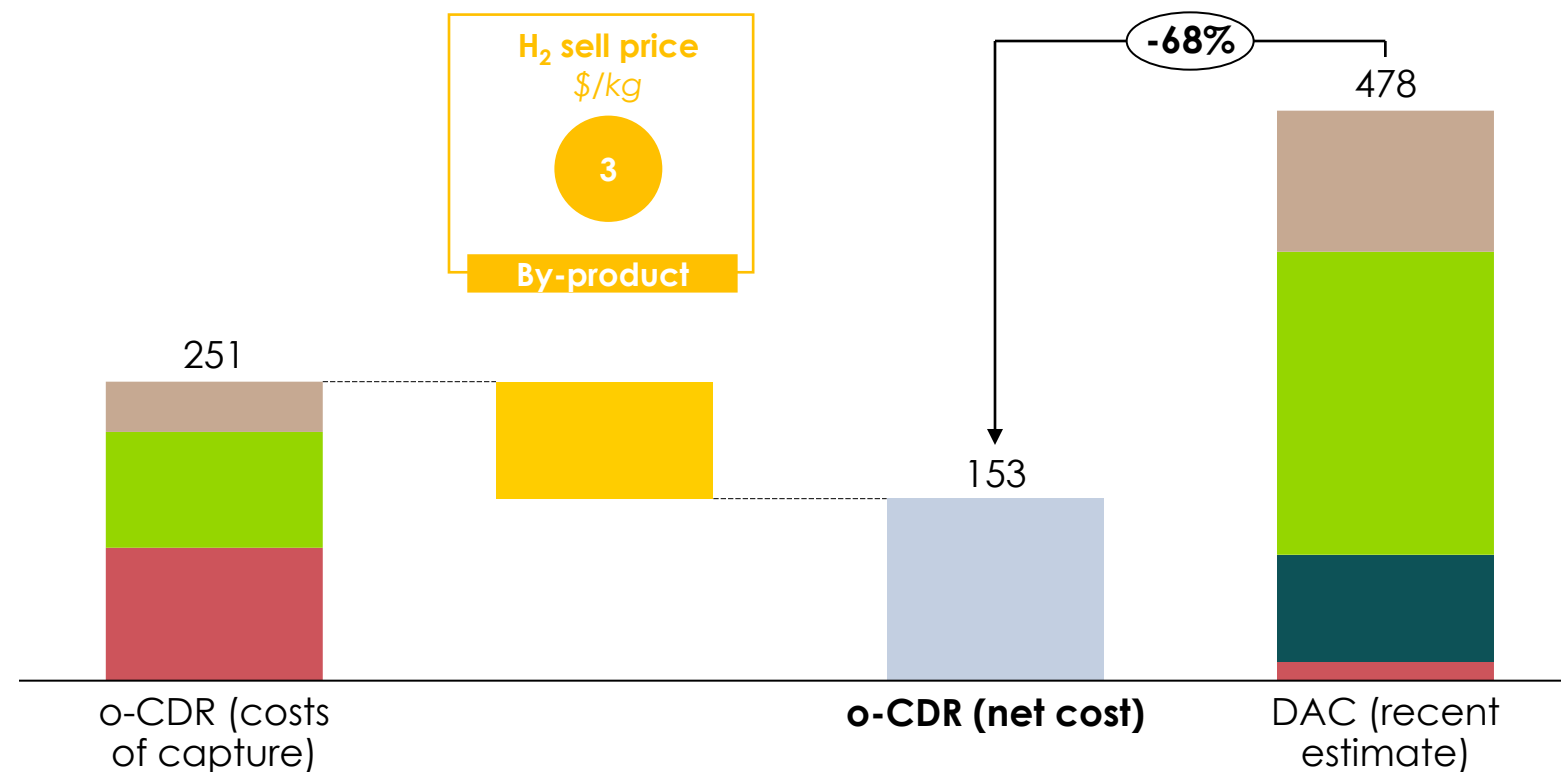
Levelised cost of CO₂ capture for direct air and direct water capture in 2030

\$/tCO₂



Key inputs

Electricity cost ¹⁰	\$50/MWh
Electrolyser utilization	50%
Plant capacity	110,000 tonsCO ₂ /y
H ₂ production	3,600 tonsH ₂ /y



Key takeaways on cost drivers and trends

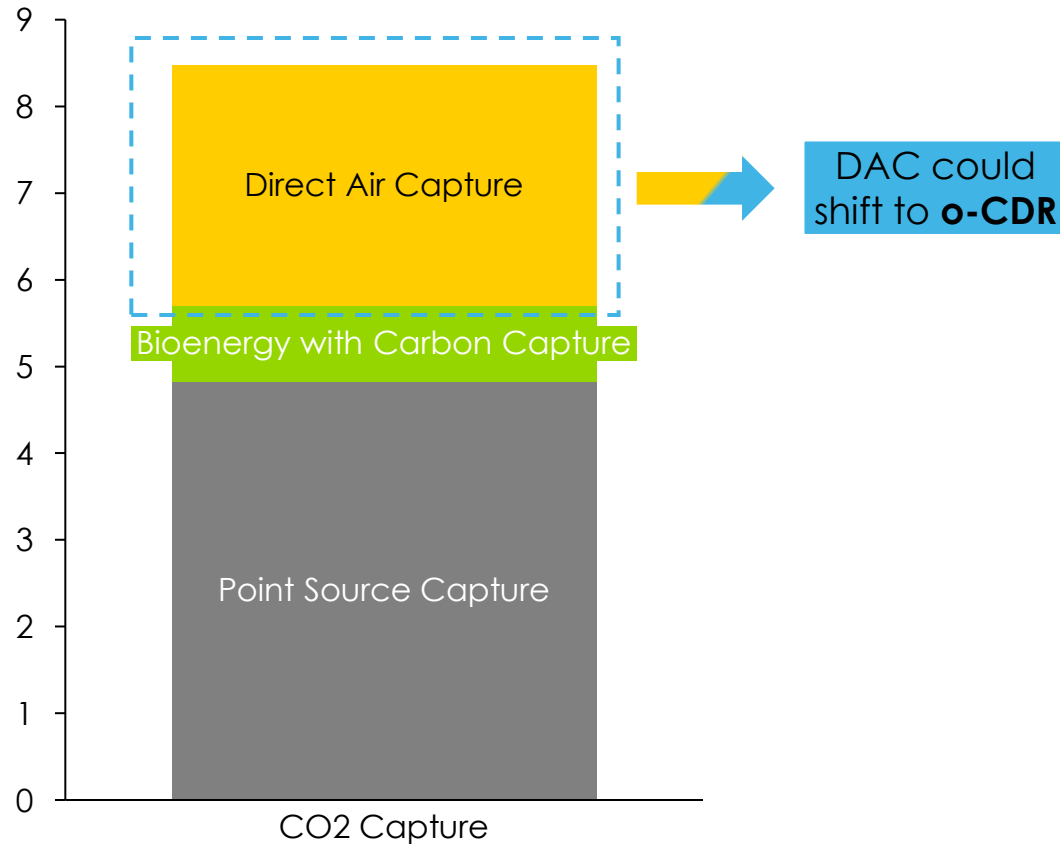
- Lower capex requirements and the valuable H₂ by-product could make o-CDR more economical than DAC. The H₂ is only produced in electrolytic o-CDR routes that involve electrolysis, and not electro dialysis process.
- Both DAC and o-CDR have high cost and scale-up risk, but DAC's stems from sorbent and thermal system uncertainty, while **o-CDR's depends on electrolyser cost** and renewable energy access.

Sources: 1) Patent US20220040639A1, 2) <https://www.equatic.tech/articles/equatic-to-build-north-americas-first-commercial-scale-ocean-based-carbon-removal-facility>

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

CCUS volumes in 2050 under Base scenario

GtCO₂/year



Potential

- **2.8 GtCO₂/y** will need to be removed from the atmosphere by 2050.
- If o-CDR is more economical, it will quickly **take part of this share**.
- In some cases, it could rebalance acidified waters and **restore eco-systems**.

Limitations

- Technology **still needs to be proven** at larger scale.
- Concerns that o-CDR can **disrupt the ocean eco-system** if deployed carelessly.
- o-CDR facilities are more **location dependent** –water with specific temperature/pH/trace metal requirements.¹

What you need to believe for DAC and o-CDR to scale as carbon removal solutions

Goal	We need to believe...	Criteria for success	Evidence of progress
<p>Rapid advancements in adoption, scaling up and cost reduction</p>	<p>Technological advancements will drive cost down and provide incentives</p>	<p>Availability of low-carbon energy Widespread availability of affordable, zero-carbon energy to power DAC/o-CDR facilities</p>	<p>Already deployed DAC pilot projects by Climeworks are powered by geothermal energy¹</p>
	<p>Clear certification, environmental safeguards, and carbon accounting frameworks will reward negative emissions and build market demand for high-integrity carbon.</p>	<p>Technological innovation Breakthroughs in sorbents and electrochemical systems to reduce energy and costs, and modular units accelerate commercialization.</p>	<p>AI developments will boost screening and optimisation of new generation sorbents²</p>
		<p>Deployment Target regions with abundant low-carbon energy but limited biomass, where DAC/o-CDR can unlock new carbon sourcing for local utilization.</p>	<p>Twelve demonstrate integration with CO₂ utilisation, unlocking new markets opportunities³</p>
		<p>Certification & accounting rules DAC/o-CDR must be recognized under RED III, EU ETS, and carbon markets. Lifecycle emissions accounting frameworks which recognize renewable carbon, e.g. -1/+1 methodology for fossil-free plastics.⁵</p>	<p>Continuous efforts to establish durable carbon capture standards and accounting clarity. Most recent the CRCF regulation in 2024⁴</p>
		<p>Environmental safety Concerns of solvent handling could hinder DAC deployment in certain regions. Concerns about disruption of ocean ecosystems could block o-CDR technology. Third party monitoring and transparent reporting is necessary.</p>	<p>o-CDR pilot projects show no significant pH/ecosystem disruptions. Solid sorbent DAC innovations are safer and less water-intensive</p>

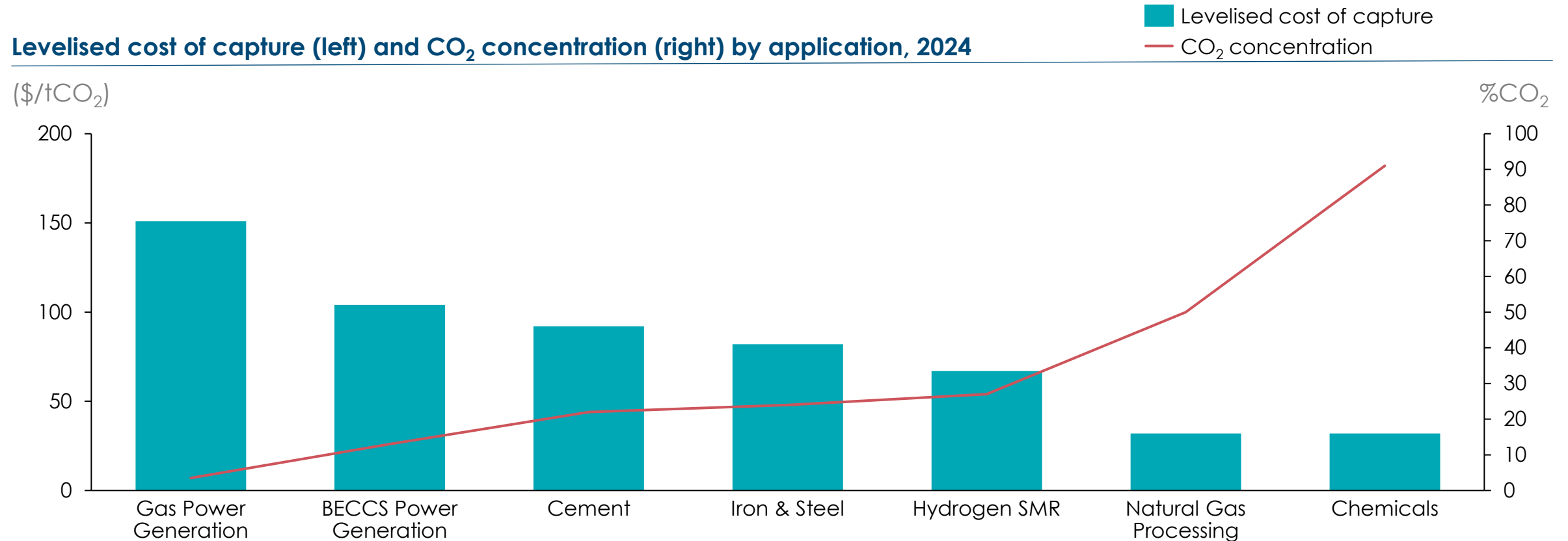


Sources: 1) <https://climeworks.com/plant-orca> 2) Hamid Zentou et al.(2025) Recent advances and challenges in solid sorbents for CO2 capture 3) <https://singularityhub.com/2023/07/31/a-new-us-plant-will-use-captured-co2-to-make-millions-of-gallons-of-jet-fuel> 4) Carbon Removal Certification Framework (CRCF) EU/2024/3012. 5) Fossil-free Plastics: Driving Clean Industrial Leadership in Europe (Systemiq, 2025)

Carbon capture technologies: Point source capture



There is an inverse correlation between the concentration of CO₂ and the cost of capture in different applications

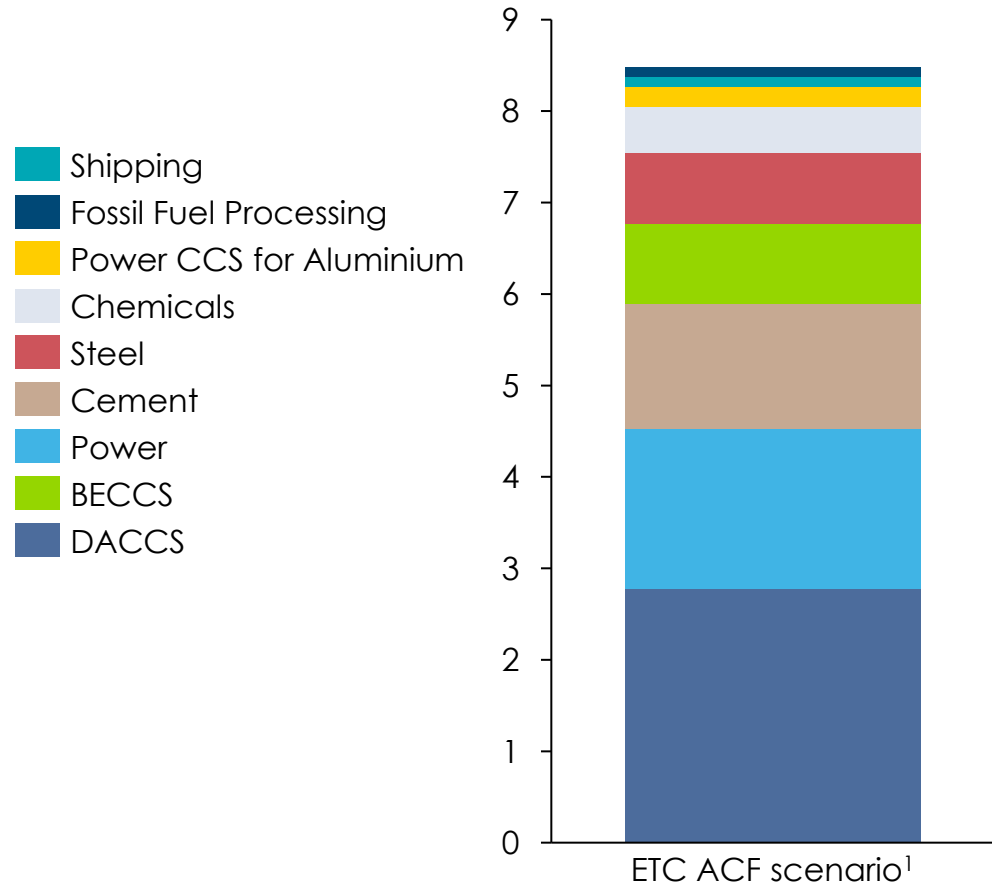


Key takeaways on cost drivers and trends

- Gas Power Generation is the costliest application to decarbonize, and it has the lowest CO₂ concentration in Point-source applications (3-4%)
- Capture costs are higher in applications with low concentrations of CO₂

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

Need for CO₂ emissions avoidance via point source capture by 2050 (GtCO₂ per annum)



Emerging technologies that decarbonize sectors with high CO₂ capacity are evaluated:

Calcium looping

CaLby2030 project, an EU-funded initiative involves 18 partners and aims for **commercial deployment of CaL** by 2030.

Most applicable sectors:

Cement
Power

Process modification

via Allam-Fetvedt Cycle
NET Power's **300 MW commercial-scale plant** in Odessa, Texas, scheduled for operation by 2027.

Power

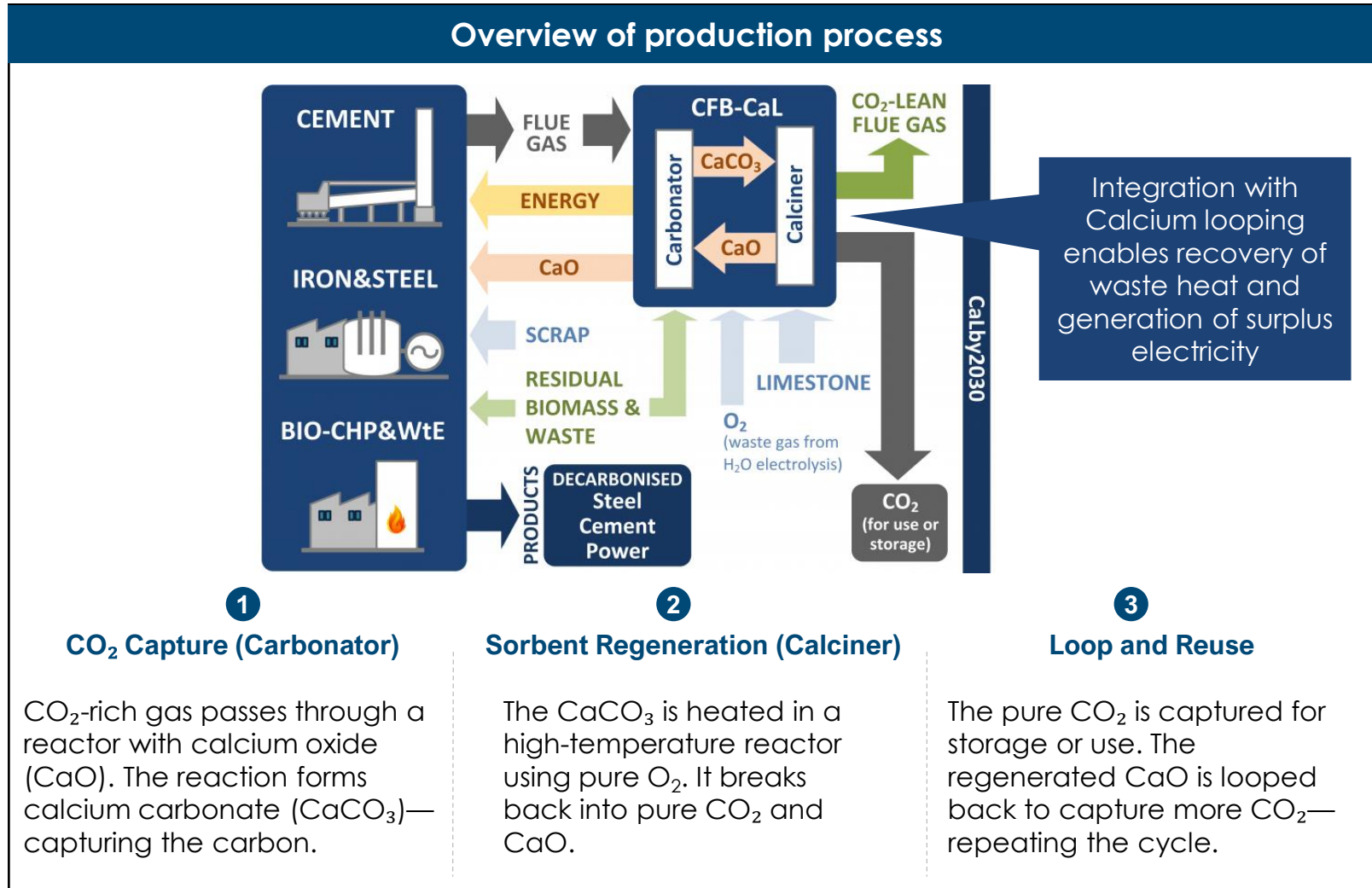
Liquid absorption and solid adsorption

Benchmark technologies that are still evolving. DMX phase-changing solvents and Svante's MOF solid adsorbent are leading the next -gen post-combustion capture and began **semi-industrial demonstration** in 2023.

All

Notes: 1) 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 (2023), ETC (2022), Carbon capture, utilisation and storage in the energy transition

5 Calcium looping: Captures CO₂ using a looping cycle of limestone-based reactions



Comparison with widely used capture

Comparison of Calcium Looping (CaL) with Amine-based Post-Combustion Capture (PCC)

	CaL	PCC
Capture medium	Solid sorbent (CaO)	Liquid solvent (MEA/amine)
CO₂ capture rate¹	Typically ~90% Possible up to 99%	~90%
Other emissions	Spent CaO can replace raw materials in cement production	NOx emissions Methane leak Amine byproducts
Retrofit Flexibility	Needs hot-end integration for optimal efficiency	Tail-end retrofits possible with minimal plant modifications
Tolerance to impurities	Tolerance for contaminants, doesn't require clean gas	Sensitive to degradation
CAPEX	Medium-High (depends on integration)	Lower



Sources: 1) Arias et al. (2024) 2) <https://www.calby2030.eu/overview-of-the-project>

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

Levelised cost of CO₂ abatement in cement process in 2025

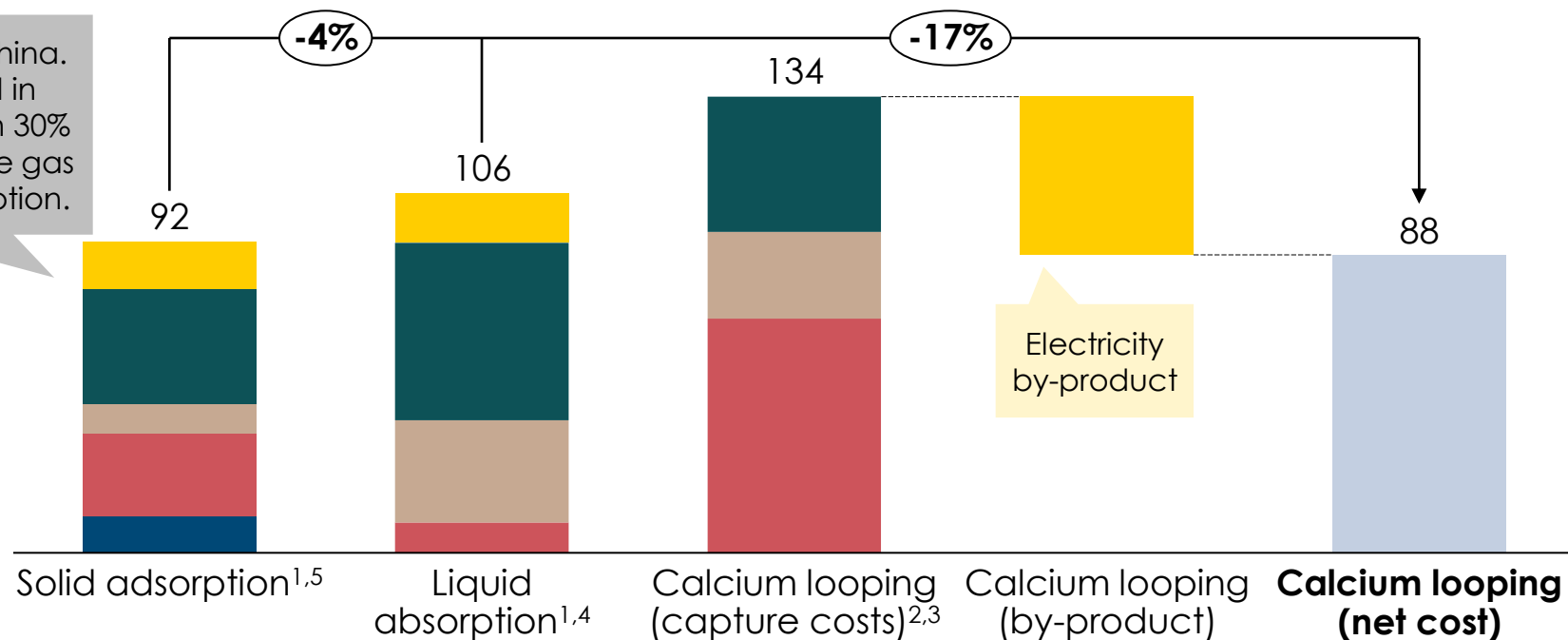
\$/tCO₂

- Electricity
- Fuel
- Other OPEX
- CAPEX
- Oxygen ASU

Currently operating in China. O₂-enriched air is used in cement kiln. This results in 30% CO₂ concentration in flue gas – suitable for solid adsorption.

Key inputs

Electricity price	\$60/tCO ₂
Cost of Natural gas	\$12/GJ
Plant capacity	2880 t/d clinker
Capture rate	90%



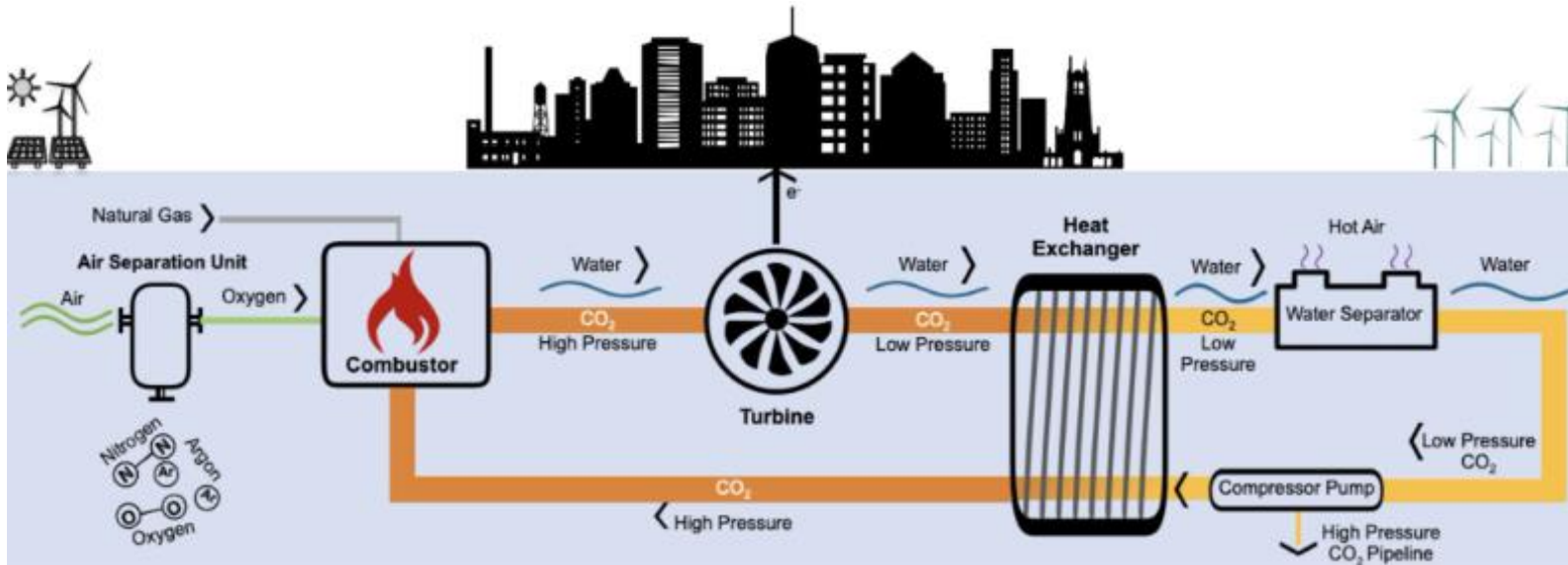
Key takeaways on cost drivers and trends

- Cost of calcium looping varies because of the several integration options with the cement plant which offer OPEX and CAPEX trade-offs.
- Downstream retrofitting of calcium looping without heat integration would result in 106 \$/tCO₂, hence not a suitable option.
- Calcium looping is advantageous for application in cement production because it can tolerate impurities like dust, SO_x, NO_x and trace metals enabling robustness and reducing-pretreatment costs

Sources: 1) M.M. Jaffar 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 2) Ana Amorim et al. (2025) Analysis of integrated calcium looping alternatives in cement plant 3) Junjun Yin et al. (2024) 4) Mohd Hanifa et al. (2023) A review on CO₂ capture and sequestration in the construction industry: Emerging approaches and commercialised technologies 5) Thunder said energy: Cryogenic air separation: costs and energy economics

⑥ Process modification: Captures CO₂ and utilizes it in the power production process via Allam-Fetvedt Cycle

Overview of production process



1

Combustion in pure O₂

Natural gas is combusted with pure oxygen in high-pressure, producing CO₂ and H₂. The high-temperature CO₂-H₂O gas mixture drives a turbine, generating electricity.

2

Heat Recovery and Water Separation

The expanded gas exits the turbine and enters a heat exchanger, where it's cooled. Water vapor condenses and is removed, purifying the CO₂ stream.

3

CO₂ Recirculation and Export

A portion is compressed and utilized/sequestered. The rest is recompressed, reheated, and recycled as a working fluid.

Comparison with conventional plant

Comparison of Allam-Fetvedt Cycle (AFC) with Natural Gas Combined Cycled with amine based post-combustion capture (NGCC+PCC)

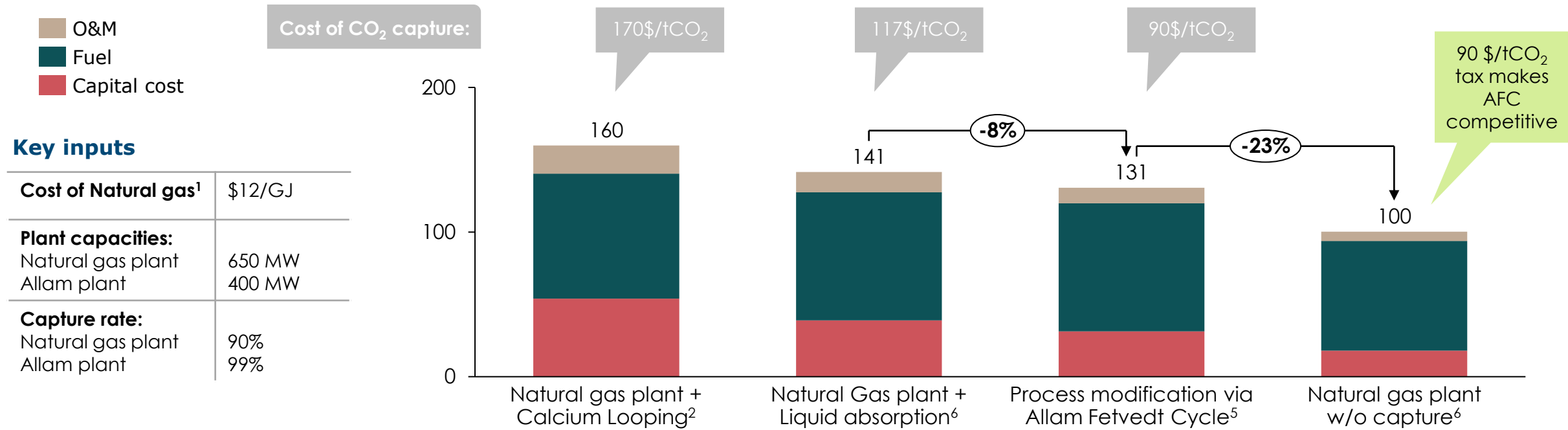
	AFC	NGCC+PCC
Working fluid	Supercritical CO ₂	Steam + Combustion gases
CO₂ capture rate	~99%	~90%
Other emissions	Methane leak	NOx emissions Methane leak Amine byproducts
Electric efficiency	59%	50%
Fuel flexibility	Primarily Natural Gas; adaptable to syngas/H ₂	Natural gas; hydrogen blending in development
CAPEX	High (Air separation unit + CO ₂ handling)	Lower (Mature tech + economies of scale)

Notes/Sources: 1) <https://www.powermag.com/uks-first-gas-fired-allam-cycle-power-plant-taking-shape/> 2) Oxy-combustion turbine power plants (2015) 3) Allam-Fetvedt Cycle (FutureBridge)

Process modification via Allam-Fetvedt Cycle (AFC) is the cheapest capture technology for power sector, being cost-competitive at 90 \$/tCO₂ tax.

Levelised cost of electricity and planned projects for CO₂ capture in 2025

\$/MWh

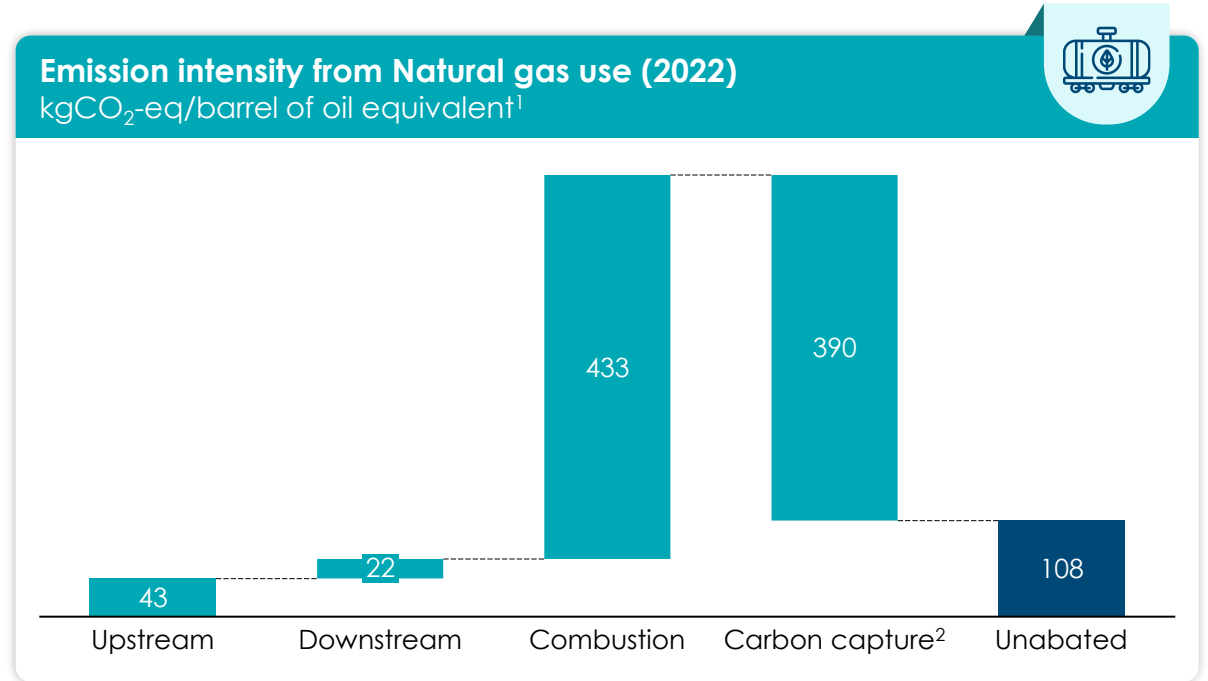
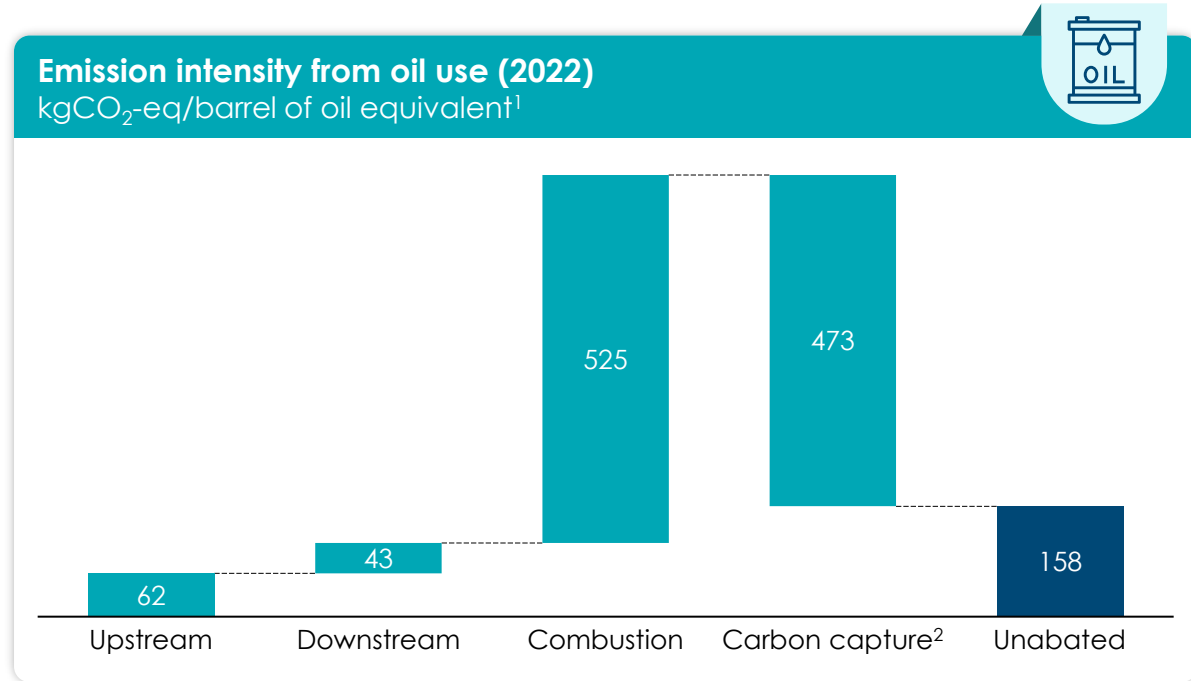


Key takeaways on cost drivers and trends

- Despite smaller plant size, Allam-Fetvedt Cycle results in:
 - 20% lower total capital requirement
 - 10% lower LCOE
- Cost of natural gas can greatly influence the results. However, the thermal efficiencies remain similar across processes, hence the comparison would not differ.
- Calcium looping costs are higher than liquid absorption and Allam cycle. However it can enable decarbonization of sectors where other capture technologies are not applicable

Notes: CO₂ transport & storage costs align with 10\$/ton universal assumption as in ETC (2022), Carbon capture, utilisation and storage in the energy transition. Sources 1) average value of TTF cost in 2021: Market Observatory for Energy, "Quarterly report on European gas markets" 2) Chao Fu (2021) Techno-Economic Analyses of the CaO/CaCO₃ Post-Combustion CO₂ Capture From NGCC Power Plants 3) Dongliang Zhang (2024) 4) Maria Erans (2015) 5) Matteo Martinelli et al. (2025) 6) Smitt (NETL 2023) Cost and performance of retrofitting NGCC units for Carbon capture – Revision 3

If we rely on fossil carbon sources, we need to address the 20-25% of emissions that could remain unabated under CO₂ capture technologies



- #### Upstream emissions of fossil fuels
- Energy used for extraction, mining, drilling rigs
 - Field level transport
 - Flaring, venting and emissions of initial processing (e.g. dehydration, sweetening)
- #### Downstream emissions of fossil fuels
- Energy used for compressing and processing (e.g. oil refining, or liquefaction of Natural gas)
 - Fuel Transport (pipelines, road, marine) and storage

- #### Five key levers to reduce upstream and downstream emissions
- Reduce methane emissions
 - Eliminate all non-emergency flaring
 - Electrify upstream facilities
 - Deploy CCUS in oil and gas processes
 - Expand low-emission hydrogen use in refineries

Notes: 1) Barrel of oil equivalent is a standardized 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. 2) Assume 90% capture rate
 Sources: 1) 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

What do we need to believe for point source capture to be a cost-effective solution

Goal	We need to believe...	Criteria for success	Evidence of progress
<p>Rapid scale-up of Point Source Capture across industrial and energy sectors, enabling near-term emissions reductions and supplying CO₂ for storage or utilization.</p>	<p>Technological advancements will drive cost down and provide incentives</p>	<p>Technological innovation Developments in solvents and sorbents can increase capture rates and reduce energy consumption</p>	<p>New generation solvents and sorbents show great potential²</p>
	<p>Robust Policy, Funding, and Market Support will create a viable market and provide transparency of operation.</p>	<p>Integration with existing infrastructure Integration of capture systems with specific plants (e.g. steel, cement) can yield economic benefits up to 50% compared to non-integrated approaches¹</p>	<p>Pilot projects in Europe and Asia have successfully retrofitted cement and steel plants with carbon capture³</p>
		<p>CO₂ handling infrastructure CO₂ transport and storage networks will scale alongside capture to reduce costs and enable large-scale deployment</p>	<p>The Midwest Carbon Express and Northern Lights projects are scaling CO₂ transport and storage across multiple sites.⁴</p>
		<p>Supportive regulatory and financial frameworks Clear policies around carbon pricing and funding mechanisms drive investment and reduce uncertainty. This is key to enable long-term planning and new plant design.</p>	<p>U.S. 45Q tax credit, EU Innovation Fund, and UK CCS clusters are accelerating PSC deployment.</p>
<p>Long-term liability and monitoring Reliable systems for monitoring, reporting, and verifying (MRV) storage integrity and managing long-term liability.</p>	<p>The Sleipner project in Norway is operational for 25 years and has successfully stored 23 MtCO₂ with MRV⁵</p>		



Sources: 1) Rafael Castro-Amoedo et al. (2023) On the role of system integration of carbon capture and mineralization in achieving net-negative emissions in industrial sectors 2) National Energy Technology Laboratory (2023) Solvent-based carbon capture 3) <https://projects.research-and-innovation.ec.europa.eu/en/projects/success-stories/all/reaching-new-heights-co2-capture-cement-plants> 4) <https://gulfcompanies.com/our-project/project-gallery/midwest-carbon-express-co2-pipeline-system> 5) <https://ccreservoirs.com/the-sleipner-ccs-project-an-active-case-history-for-co2-storage-in-a-saline-aquifer>

Agenda

- Introduction to work program
- Carbon-capture: Direct Capture and Point Source
- **Bioresources**
- End-of-life management
- Scenarios and next steps



Bioresources

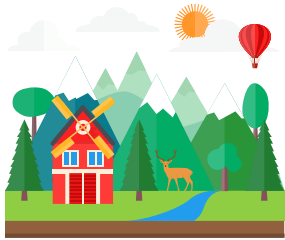


Biomass supply overview



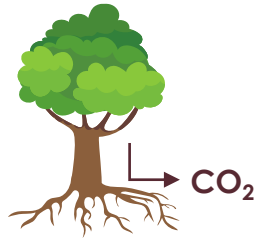
Biomass can only be considered sustainable if certain conditions are met

No competition with other critical uses of land



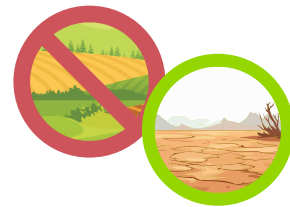
Biomass **sourcing must not displace essential functions of land**, including food production, housing and conservation

No deforestation or peatland conversion



Biomass **sourcing must avoid land-use changes that release stored carbon and destroy natural ecosystems**, especially in forests and carbon-rich peatlands

Target degraded land, with little plant growth



Biomass **sourcing should prioritize using marginal or degraded lands** with low ecological value to avoid disruption productive ecosystems and high-carbon landscapes

Respect growth periods which will delay supply



Harvesting must align with natural regeneration cycles to maintain long-term productivity and ecosystem health, even if it slows supply

Close-to-zero emission collection, transportation and processing



Biomass supply chains must minimize emissions across logistics and processing to **ensure real climate benefits**

No environmental or social harm



Projects must safeguard local environments and communities, delivering benefits without causing displacement or degradation

Given truly sustainable biomass is finite, it should be prioritised for uses with no viable low-carbon alternatives

Constraints on supply mean only ~17% of 2050 global energy and material demand for biomass could be sourced sustainably

Potential biomass 2050

Legend: **Demand** if all energy and material sectors convert current demand to biomass¹
 Supply under ETC's ambitious scenario²



The use of sustainable biomass should therefore be reserved for applications without viable, low-carbon alternatives, including:

Sector	Rationale for biomass use
Materials & feedstocks (e.g., pulp & paper, chemicals)	<ul style="list-style-type: none"> ▪ Cost effectiveness: biomass competitive with fossil materials in many applications (e.g., bioplastics). ▪ Carbon sequestration: biomass stores carbon when used in materials vs. releases carbon when combusted. ▪ Lack of substitutes: limited low-carbon alternatives in some materials (e.g. specialty chemicals).
Aviation	<ul style="list-style-type: none"> • Cost effectiveness: bio-SAFs are far cheaper than synthetic SAFs. • Urgent decarbonisation need: aviation emissions make up large share of total and are growing. • Lack of substitutes: electrification, hydrogen and synthetic sustainable aviation fuels (SAFs) not viable at scale soon.

Notes: [1] Assumes all current end-uses of energy and materials—across transport, heating, electricity, and industrial production—are replaced by biomass-based alternatives (e.g. biofuels, bio-based materials). [2] Assumes major food system changes (e.g. widespread dietary change with reduced meat consumption). [3] Potential supply estimated without major system changes.

Sources: ETC (2021), Bioresources within a Net-Zero Emissions Economy: Making a Sustainable Approach Possible; IEA (2017, 2020), Energy Technology Perspectives

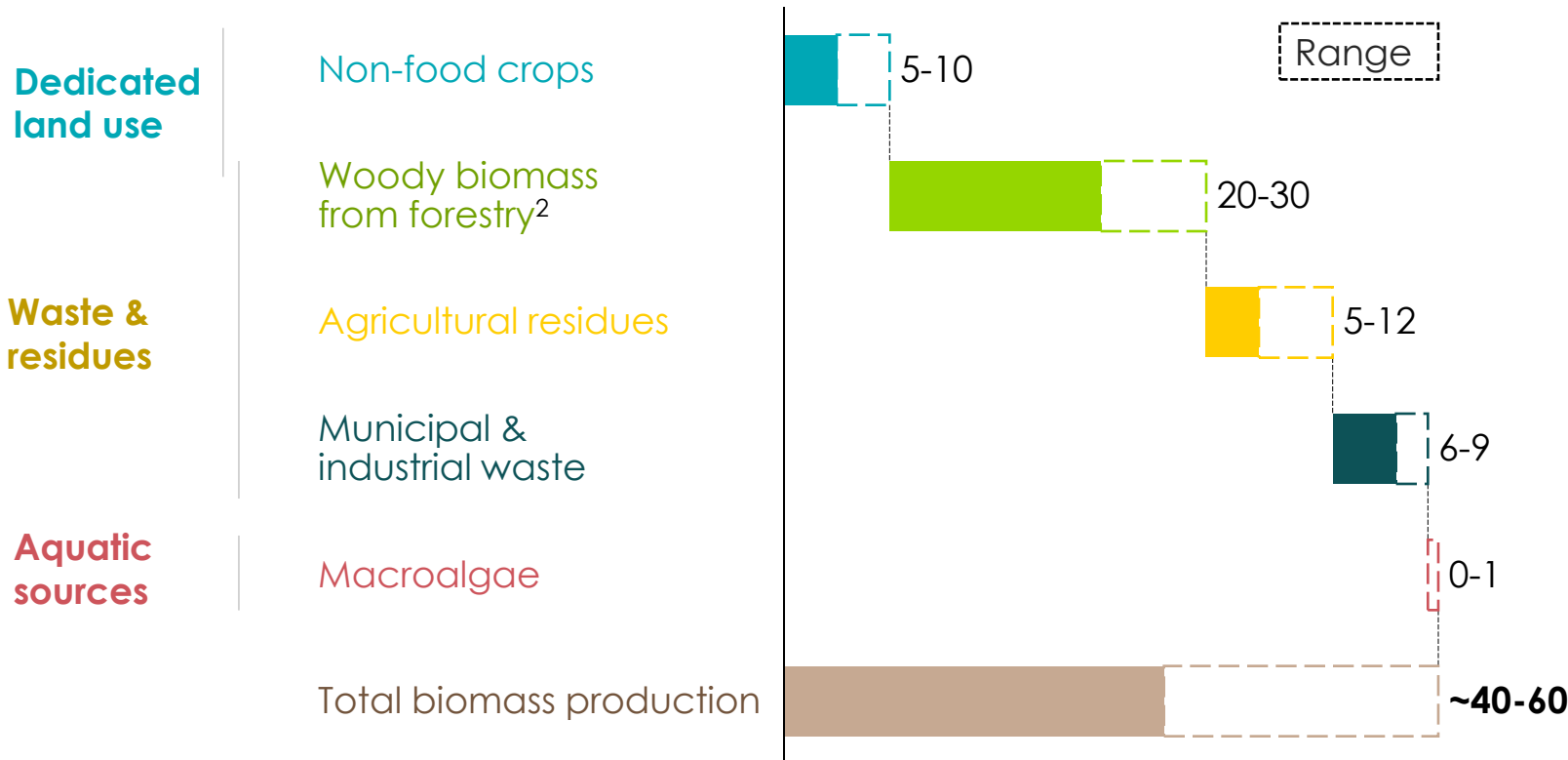


Bioresources – ETC has previously estimated prudent global supply of sustainable biomass at ~40-60 EJ/year, but disruptive innovation could change this

Global sustainable biomass¹ supply (2050) – illustrative scenario
EJ/year (primary energy)



Extra bioresource if radical change can happen



- 1 More productive land**
More productive plants (traditional crops, algae)
- 2 More available land**
Dietary shifts from animal based-protein
Less food waste
- 3 New sources**
Development of macroalgae
Increased collection to organic waste

Notes: 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. (2) 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. (3) E.g., timber, pulp & paper. Based on current harvests from commercial forestry; additional high-quality stemwood could be made available if freed up land were dedicated to forestry. (4) Additional supply from recycled materials (~4 EJ/year today).
Source: SYSTEMIQ analysis for ETC (2021).



When analysing land use for energy production, three concerns need to be considered to determine suitability



Food Supply

If no system change occurs, i.e., improved farming yields, decreased food losses in supply chain and dietary shifts, **land requirements for food supply will increase, which should be prioritized over energy production**



Carbon stocked by natural ecosystems

Different types of vegetation **store carbon in different locations** (roots vs stems). Therefore, depending on the native vegetation, **different plants will have advantages over other in terms of long-term carbon storage**



Carbon payback

Depending on the soil type and the crop used, the carbon payback, or in other words the amount of carbon that the **new crop sequester needs to compensate for the amount of carbon that used to be sequester by the native vegetation**

More productive land



Energy crops have an increased potential if cultivated on degraded or freed land, sparing housing, food, natural habitat, and climate needs



Use of degraded or marginal land for energy crops, and not competing with food requirements



Energy crops cultivated on land which is freed up through system change, including dietary shifts, higher yields and reduction in food losses



- Gives economic purpose to land
- If managed appropriately could restore soil health
- Might not necessarily improve biodiversity

- No potential competition with 'food' land use (due to dietary shift)
- Requires most significant consumer behaviour, e.g. overcoming barriers to 'synthetic' protein uptake



- Degraded land definitions are unclear
- The extent that 'degraded' land can be utilized is dependent on technical and geographical constraints

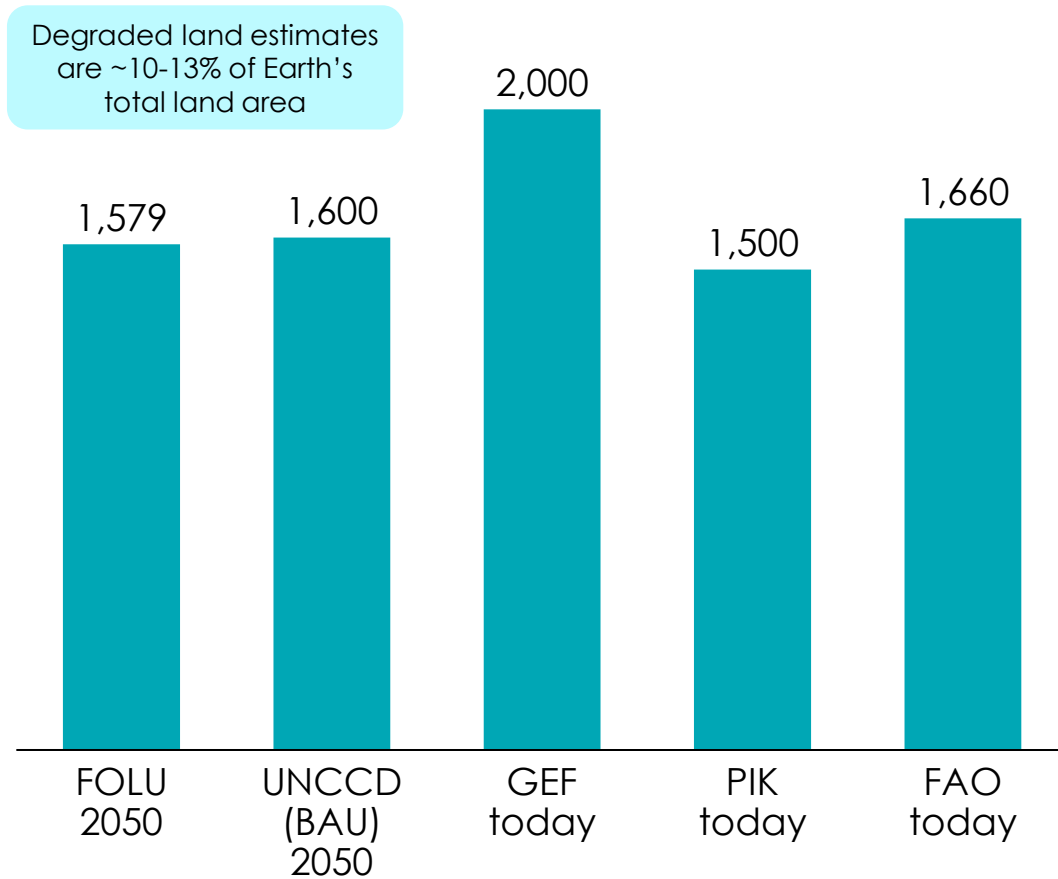
- Returning the land for biodiversity restoration is another option to use free productive land



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

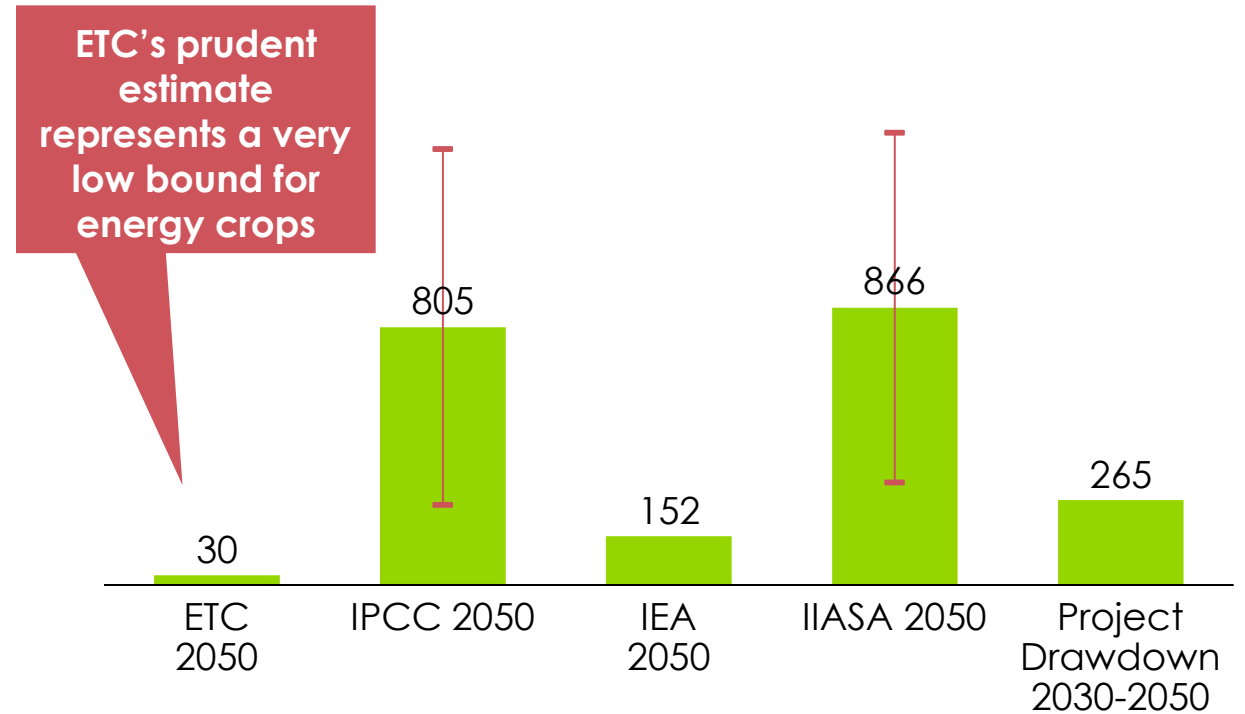
Ranges of degraded land estimates

Millions of ha



Range of estimates for energy crops on degraded land

Millions of ha

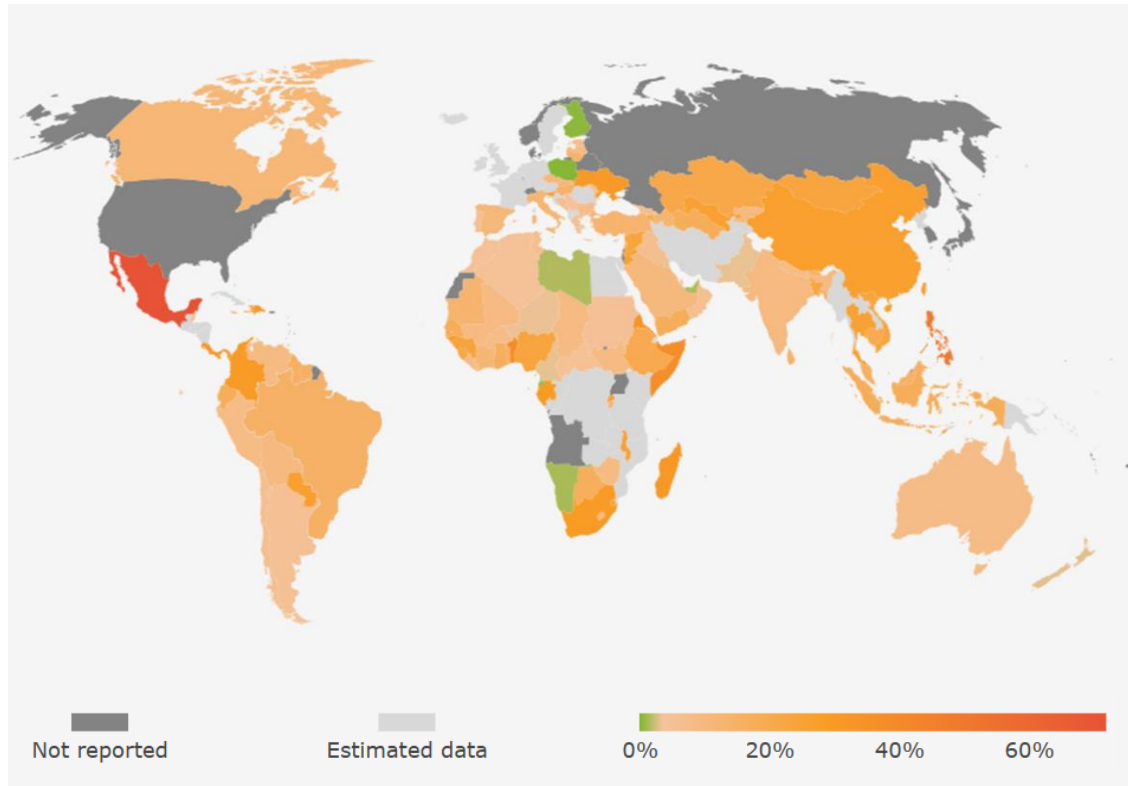


Sources: Food and Land-Use Coalition (FOLU) (2019) Growing Better, Global Environmental Facility (GEF) (2017) GEF-7 Replenishment Programming Directions, Potsdam Institute for Climate Impact Research (PIK) (2024) Transforming land management within planetary boundaries key to addressing global land use crisis, United Nations Convention to Combat Desertification (UNCCD) 2021 by Van der Esch et al The global potential for land restoration: Scenarios for the Global Land Outlook 2. PBL Netherlands Environmental Assessment Agency, The Hague. Food and Land Organization (FAO) 2024 Restoration of degraded agricultural lands.; IPCC (2022) Climate Change 2022: Mitigation of Climate Change; IEA (2024) Bioenergy

Southeast Asia, South America and Africa have the highest overlap of degraded land and crop suitability so are likely regions for planting energy crops

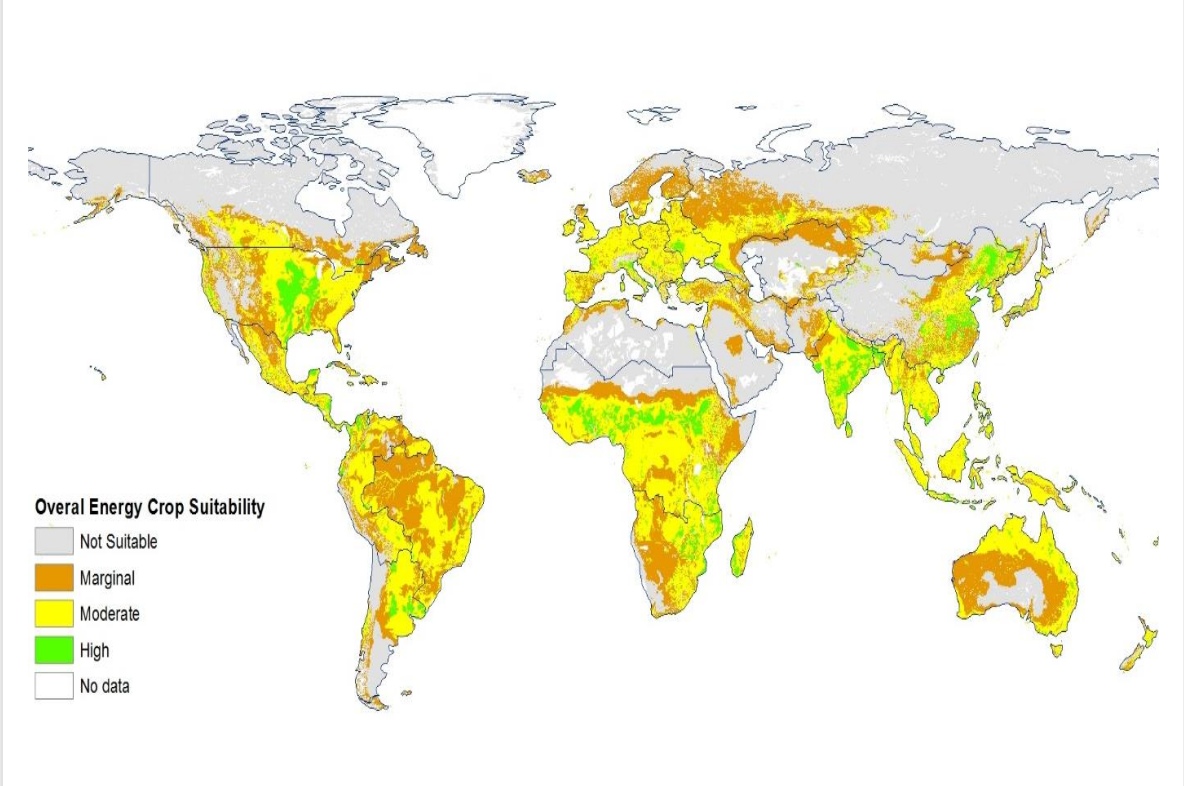
Ranges of degraded land estimates

Proportion of degraded land over total land area



Suitability of energy crops by area

Millions of ha

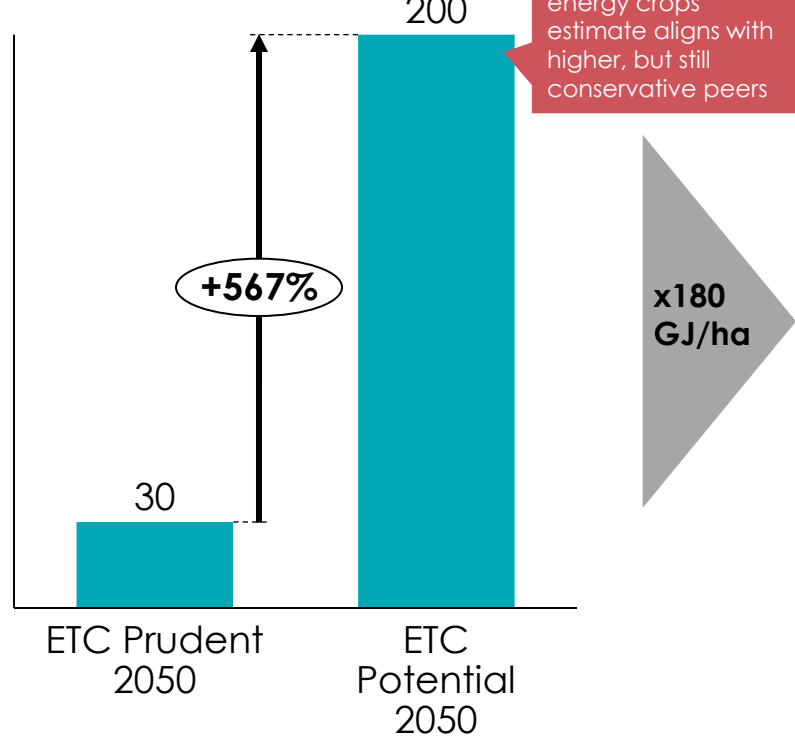


Notes: 1) Degraded land estimates map from United Nations Convention to Combat Desertification (UNCCD) (2022). Suitability of energy crops by area from Cronin et al (2020). Energy crops included in the study include sugar and starch crops, oil crops, grasses and short rotation coppice/forestry crop. Note: Brazil

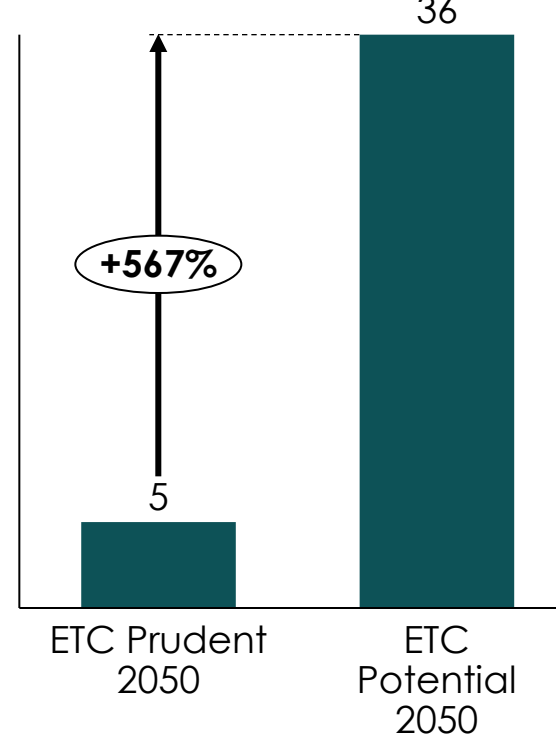
A new upper bound of degraded land available for energy crops is estimated based on other sources, increasing primary biomass supply from non-food energy crops

Revising degraded land availability for energy crops adds 21 EJ to the available sustainable bioenergy from non-food energy crops

Degraded land use for energy crops Mha



Bioenergy from non-food energy crops EJ



Bottom-up allocation of degraded to energy crops is more precise and maximizes benefits

- Revised numbers are based on the many estimates from other sources
- Considers switchgrass as a standardized energy crop, which has an energy density of 180 GJ/ha
- A bottom-up approach would yield a more accurate number while devising a plan for degraded soil recovery world-wide:
 - Map-out lands where energy crop would be the optimal land use
 - Determine climate and soil characteristics of specific land
 - Match crop with highest suitability to soil and climate characteristics
 - Determine time frame and inputs needed for soil recovery



Energy cane in Brazil could offer a new productive alternative to standard sugar cane

Deep-dive undertaken for Brazil

Boreal Forests



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

Agave



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

Macaw Palm



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

Energy Cane



High fibre content cane, which have higher yield compared to traditional sugarcane

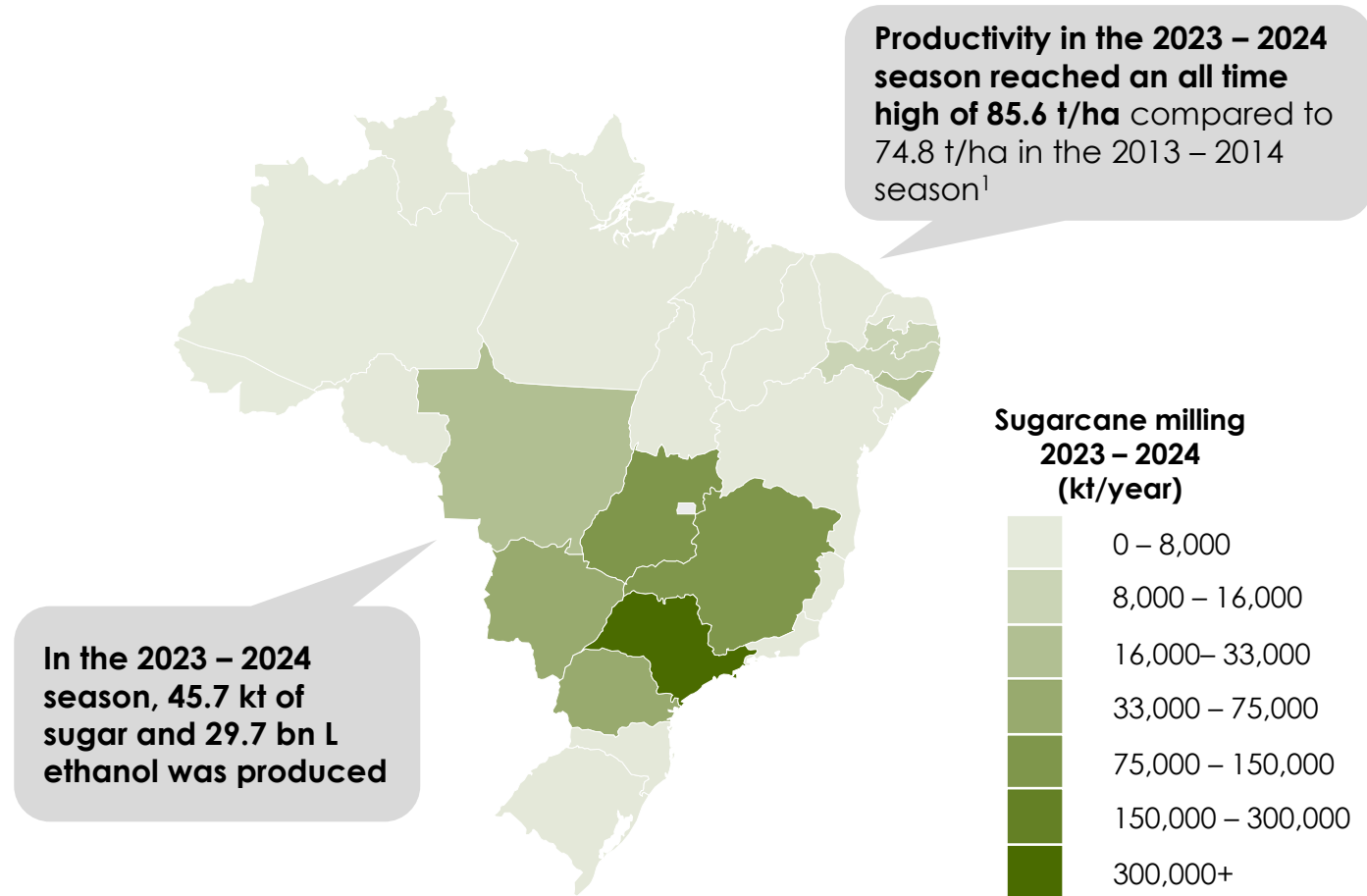
- Moderate potential to recover land, but able to build organic matter

Where: Similar conditions to sugar cane, but requires more inputs



Brazil is a major historical sugarcane producer, but questions arise over sustainability, food security and role in the energy transition

Sugarcane production is highly concentrated in the Center-South region, with 54% of production concentrated in the state of São Paulo



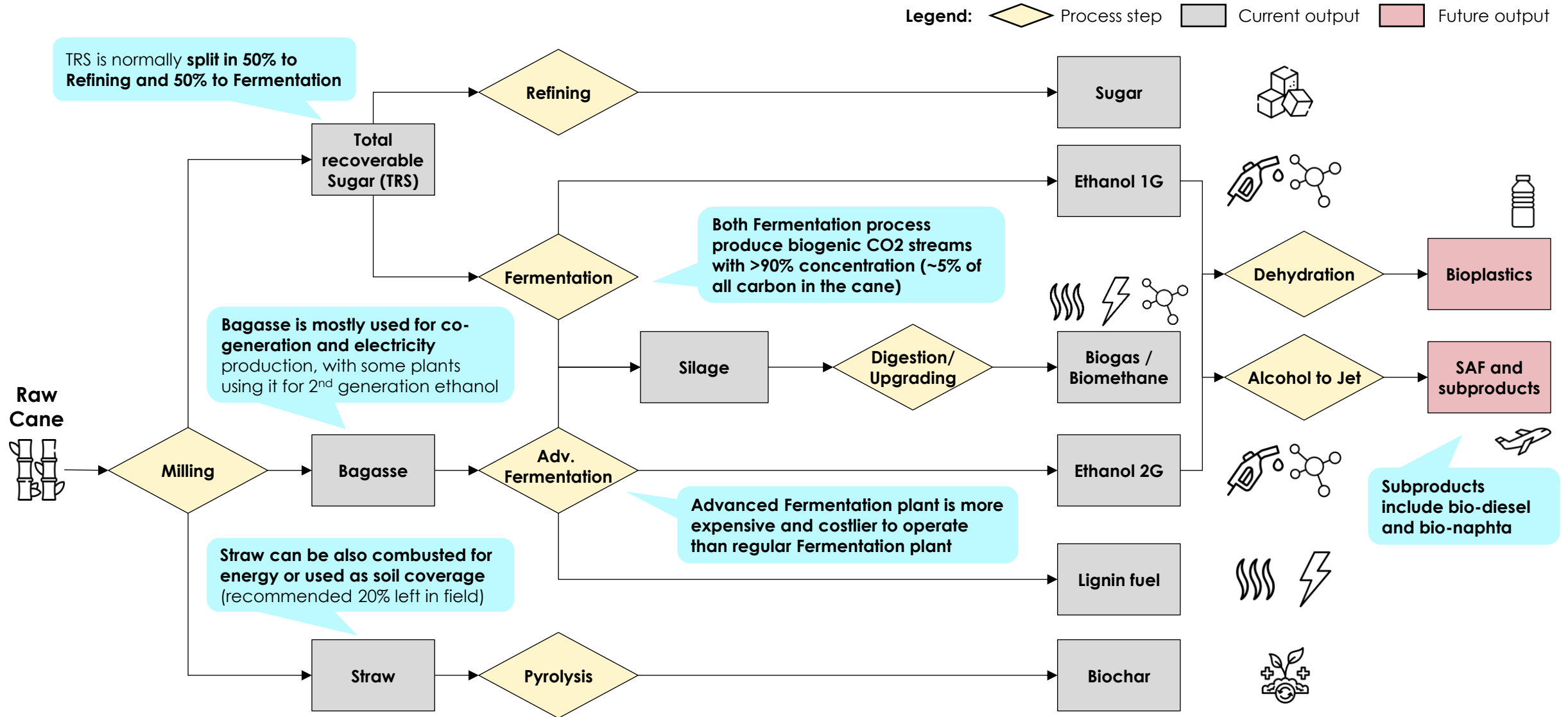
Brazil's Sugarcane: Historic Roots, Modern Debates on Sustainability and Food Security

- **Highly mechanized – refineries typically located within 50 km of the fields.**
- **Ethanol used as a road transportation fuel, but production of Sustainable Aviation Fuel (SAF) from ethanol is emerging.**
- Historical deforestation occurred, **but current policies restrict expansion into sensitive biomes.**
- **Ongoing debate around sustainability, as cultivation may displace primary food crops, despite also producing sugar — a secondary food product.**
- **Major Players:**



Notes: 1) Productivity increase can be linked to higher operation and crop efficiencies, but is also linked to climate aspects
Sources: CONAB website

Sugarcane is a versatile feedstock for multiple products, with potential to enable advanced chemicals critical for decarbonizing hard-to-abate sectors



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 ¹ (e.g., saccharose)	New strain which is designed to produces more fibers (e.g., bagasse) and less sugar
Yield (ton/ha)		Average: 70 – 100 Maximum:140	150 – 200
Technical Specifications	TRS content (kg/ton of cane)	120 – 140	85 – 95
	Bagasse content ² (kg/ton of cane)	~140	250 – 280
	Straw content ² (kg/ton of cane)	~140	140 – 280 ³
	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 ⁴ (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)

Note: 1) TRS = Total Recoverable Sugar. 2) In terms of dry mass of bagasse and straw 3) 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. 4) 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
Sources: da Silva, F. T. F., et al. (2024) Analysis of GranBio website; Integrated systems for the production of food, energy and materials as a sustainable strategy for decarbonization 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?

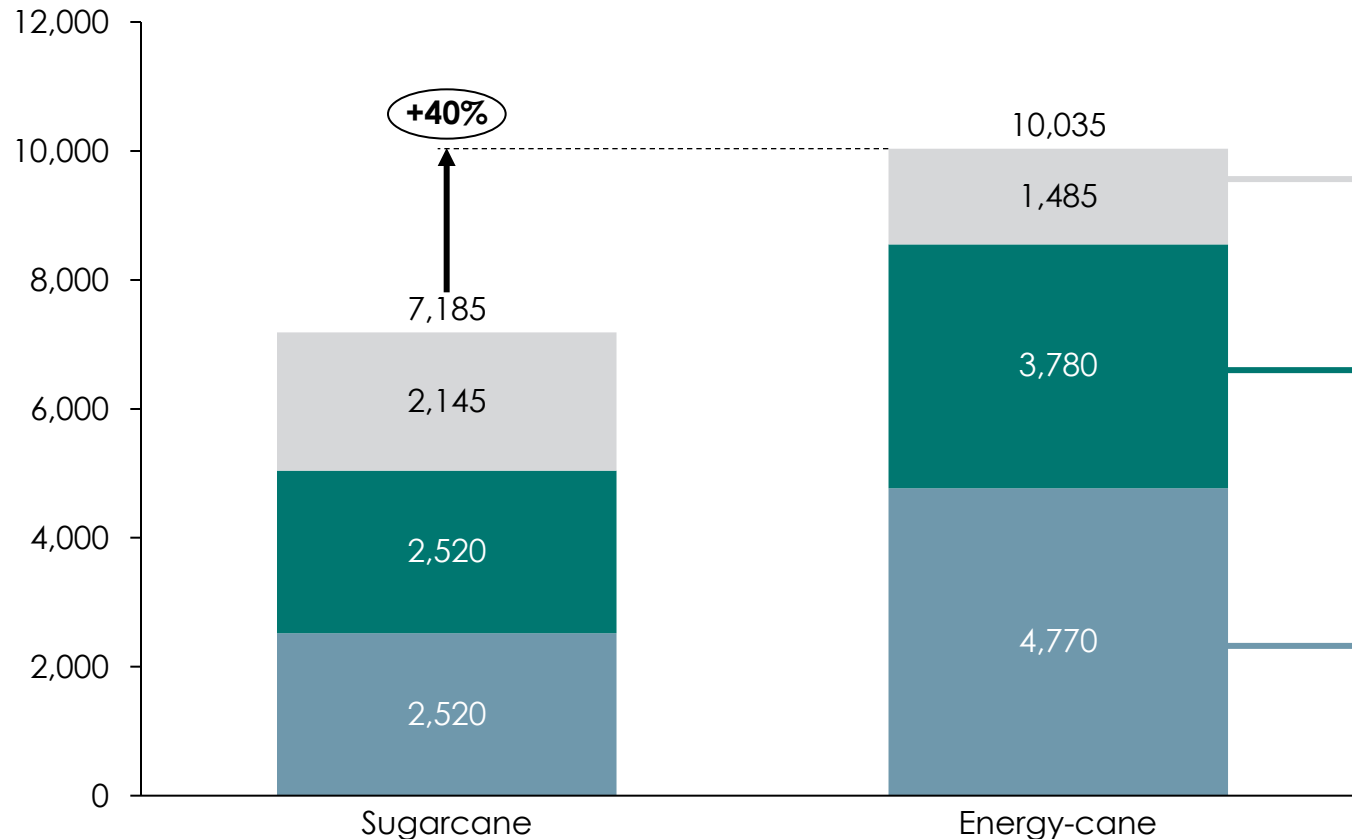
Energy-cane has 40% more energy than traditional sugarcane, but absolute value must consider other factors, such as energy demand by the refinery

Energy-cane boosts primary bioenergy per kg of cane, as the higher energy content components (bagasse and straw) are maximized¹

Technical available biomass must consider market, plantation and refinery demand

Specific bioenergy (MJ/ton of cane)

TRS Straw Bagasse



- All three components could theoretically be used for ethanol production and later upgraded into advanced chemicals.

In industry, 50% of **TRS** is allocated to sugar production for diversification and market trading.

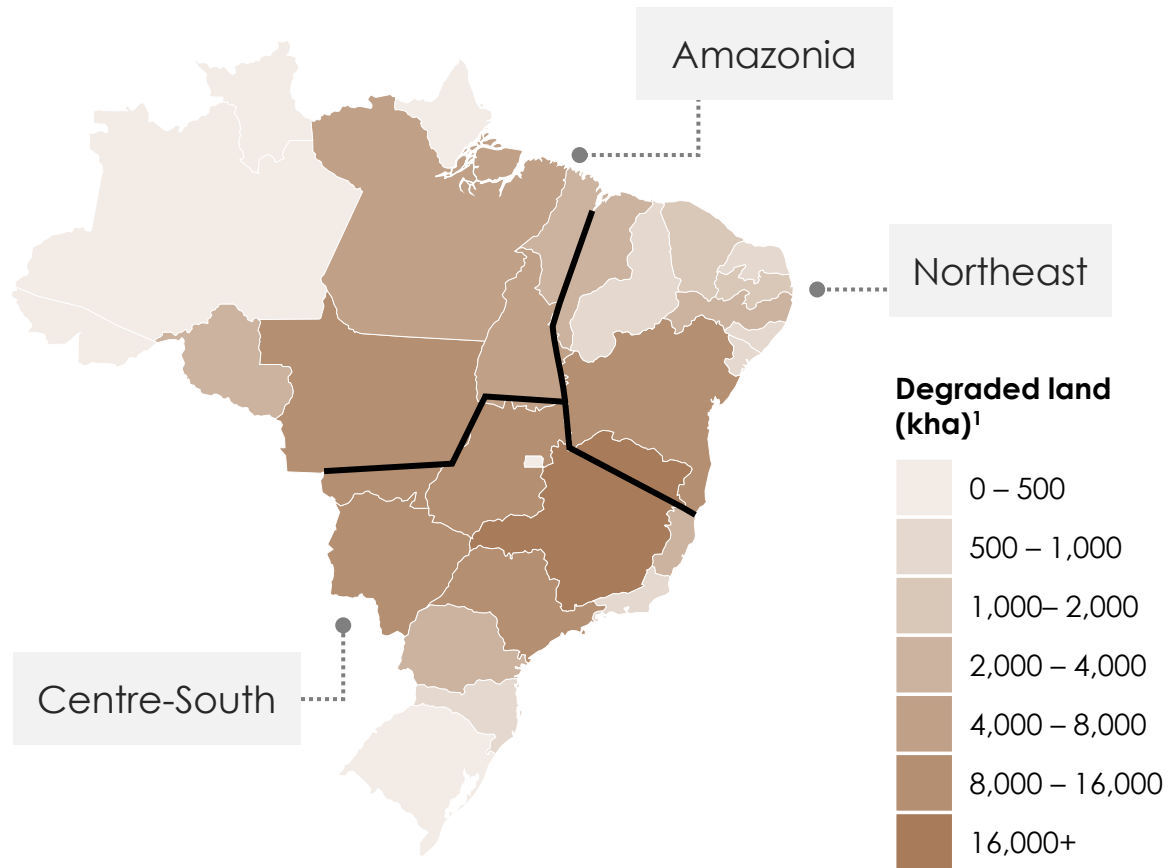
Using all **straw** as primary biomass isn't recommended, as ~20% is needed for soil coverage. Converting it into biochar can enhance soil stabilization and reduce fertilizer use.

Refineries currently use **bagasse** for co-generation (heat and electricity), but other sources like heat electrification and renewable energy could maximize biomass availability

Notes: 1) TRS (Total Recoverable Sugar): energy content = 16.5 MJ/kg (assuming TRS is composed only of saccharose), Bagasse calorific value = ~18 MJ/kg (dry); Straw calorific value = ~18 MJ/kg (dry). Middle values for composition taken from the comparative table
 Sources: Silva, A. C. M. S (2018) Estudo da influência da umidade do bagaço da cana de açúcar na produção de energia em plantas de cogeração; Marques, T.A, Pinto, L. E. V (2013) Biomass energy from sugarcane under influence of hydrogel, vegetation cover and planting depth; Neves, L. C. G (2015) Biomass energy from sugarcane under influence of hydrogel, vegetation cover and planting depth

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)



Restricting land availability and energy-cane allocation reduces biomass availability but ensures sustainability

Theoretical available biomass:

- **65 EJ/year²** – volume available if energy cane is planted on degraded land in established sugarcane regions (66 million ha)

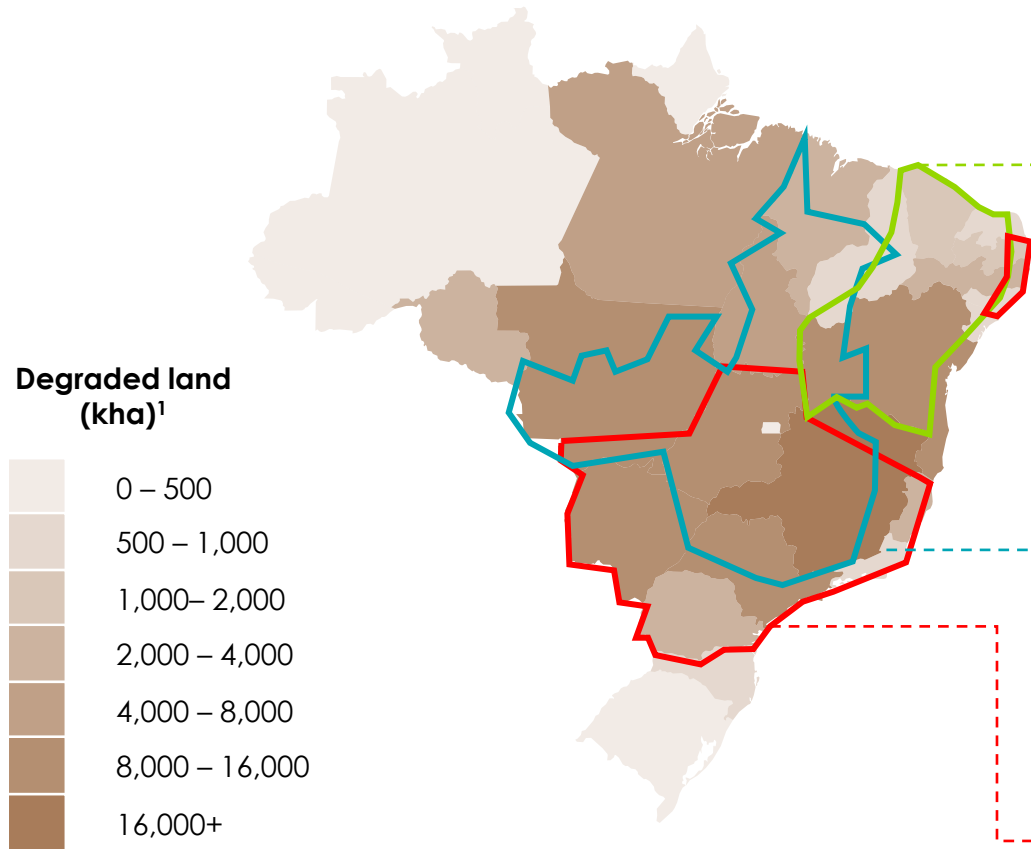
Considerations:

- Limiting energy-cane to sugarcane areas avoids pressure on endangered biomes and reduces infrastructure costs.
- Degraded land use for bioenergy doesn't displace current food production land.
- Energy-cane can restore degraded land, though it needs high initial investment for soil preparation.
- Non-biofuel degraded land can be restored via agroforestry, benefiting food production and biodiversity.

Footer: 1) Degraded land categorized 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. 2) 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: MAPBiomass website.

Brazil has the potential to grow at least three of the innovative energy crops identified and boost degraded land use

To optimize degraded land use with energy crops, the regional suitability of different crops needs to be accounted



The selected crops are attracting interests from different players, keen to develop efficient bioenergy process

Agave



- Focused on the interior of the northeast region, a semi-arid region
- Shell is participating on a program (BRAVE program) to develop agave-based ethanol refineries

Macaw Oil



- Can be planted on multiple biomes as it is mainly focused on degraded land recovery
- Acelen Renovaveis, backed by the Mubadala fund, is investing US\$ 2.5 billion on SAF from Macaw Oil

Energy Cane












- Cultivation focused on regions where traditional sugarcane is planted
- GranBio is interested on developing energy cane plantation, but have struggled with 2nd generation ethanol refinery technology

More available land - Alternative foods



Alternative proteins can ease constraints on sustainable biomass supply by freeing up land used for animal feed and grazing

The production of alternative proteins is far more land-use efficient than that of animal-based proteins
 Comparison of animal vs. alternative protein across three drivers of land-use efficiency

Drivers of land efficiency	Source of protein	Level of efficiency
 Raw inputs-to-feed efficiency	Animal protein	 <u>Low:</u> Animals indirectly rely on large amounts of land, water and energy to grow feed crops
	Alternative protein	 <u>High:</u> Microbes directly convert raw inputs into protein
 Feed-to-protein efficiency	Animal protein	 <u>Low:</u> High feed-to-protein conversion losses occur due to animal metabolism, movement, and bodily functions
	Alternative protein	 <u>High:</u> Microbes achieve high yields due to high biological efficiency and controlled production environments
 Production cycle duration	Animal protein	 <u>Low:</u> Livestock requires months or years to reach maturity
	Alternative protein	 <u>High:</u> Alternative proteins can be produced within days/weeks















Lower land requirements mean increase in alternative protein share of total proteins could free up land for biomass production for energy and materials



Source: ETC analysis

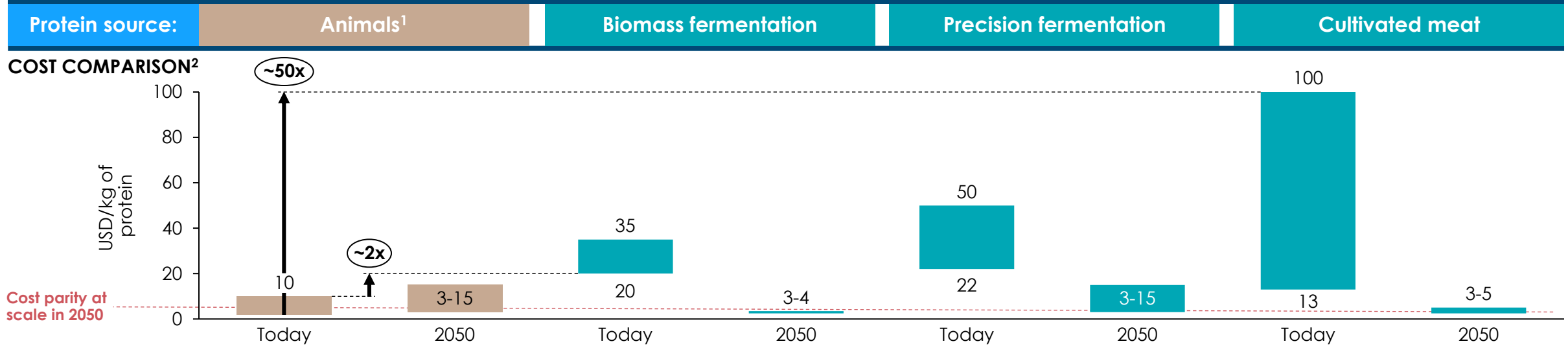
Within alternative proteins, three key innovations offer the highest potential to reduce land demand for animal feed and grazing

Innovations	Overview					Benefits	
	Goal	Use case	Examples	TRL	Companies	Efficiency potential	Land saving potential
1 Biomass fermentation (BF)	Produce whole protein-rich biomass	<ul style="list-style-type: none"> • Base ingredients in meat-like foods • e.g., mycoprotein (Quorn), fungal burgers 		6-8	  	~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
2 Precision fermentation (PF)	Make specific molecules for use as ingredients	<ul style="list-style-type: none"> • Functional ingredients for food production • e.g., egg white for baking, casein, rennet 		7	  	~15% less energy ~85% less water ~40% less GHGs vs. eggs	Very high (up to -60%) – varies by ingredient
3 Cultivated meat (CM)	Grow real meat tissue from animal cells	<ul style="list-style-type: none"> • Cuts of meat including muscle, fat and tissue • e.g., beef steaks, chicken breasts 		3-5	  	~50% less energy ~88% less water ~88% less GHGs vs. beef	Very high (up to -94%) – properties uniquely identical to meat

Sources: 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".

Alternative proteins still 2-50x more expensive than animal proteins, but cost parity possible by 2050 thanks to technology improvements and scale

Comparison of the cost of 1kg of alternative proteins vs. animal proteins



COST DRIVERS

Drivers of current high costs	Levers to achieve cost parity by 2050
<ul style="list-style-type: none"> • 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 	<ul style="list-style-type: none"> • Increased culture density with genetic engineering • Streamline feedstock supply (move from batch to continuous delivery) • Scale up bioreactors (larger units for efficiencies of scale)
<ul style="list-style-type: none"> • Limited cell density of outputs • High cell culture media costs (~50% of total costs) • Limited scale of bioreactors 	<ul style="list-style-type: none"> • Increasing cell density • Develop food-grade inputs • Increase yields through tech and process improvements

Notes: [1] 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. [2] Ranges reflect cost variations by protein type, geography, and production method, representing global averages. Sources: 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*.

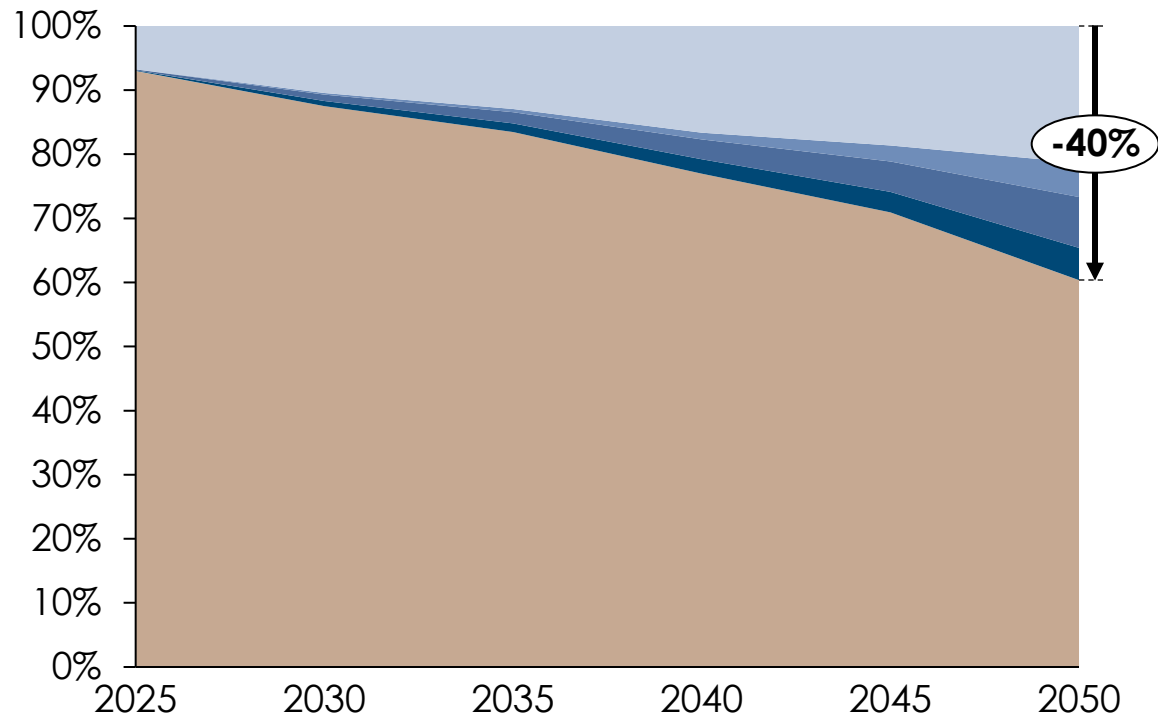


① Alternative protein uptake: the adoption of alternative proteins could displace up to 400 million tonnes of animal-based protein by 2050

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 source¹

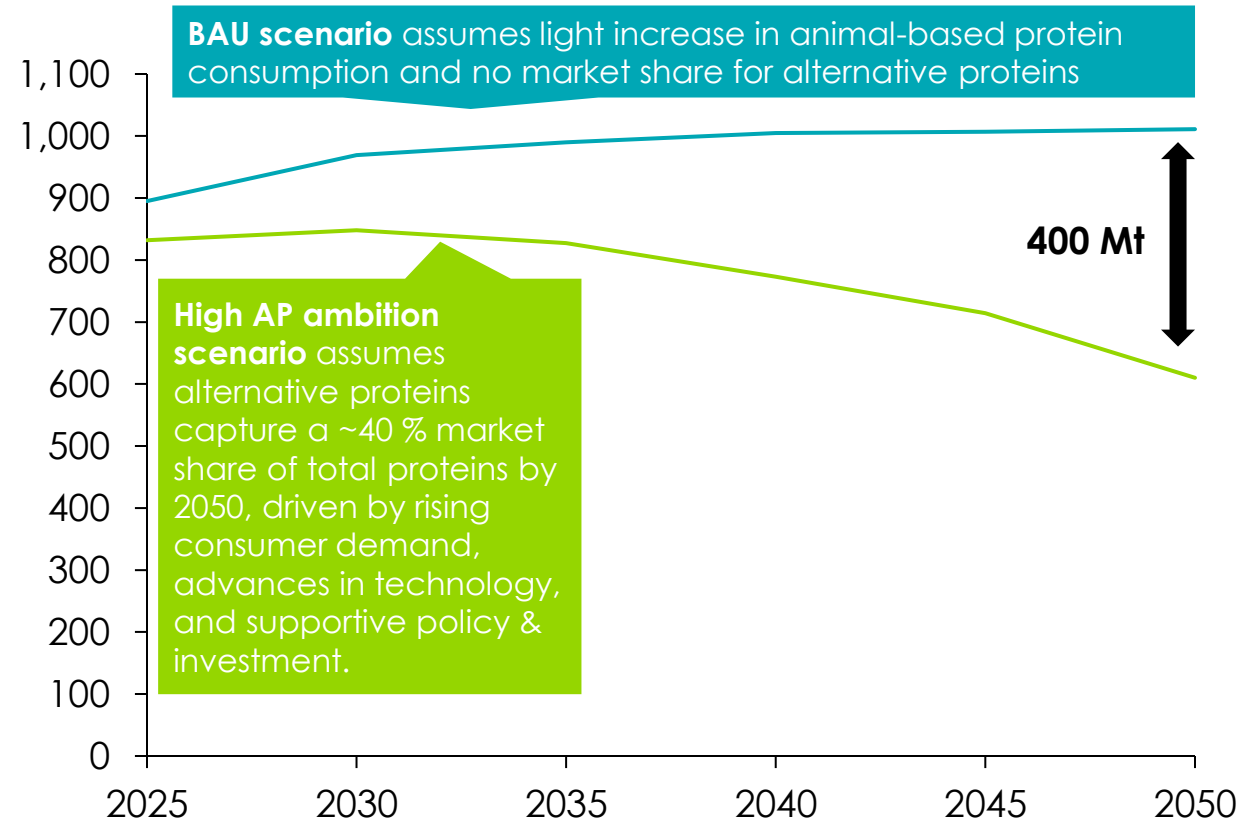
- AP - Plant-based proteins (well established today)
- AP - Cultivated meat
- AP - Process fermentation
- AP - Biomass fermentation
- Animals



This uptake in alternative proteins could displace 400 Mt of animal-based proteins relative to a business-as-usual scenario

Net animal protein consumption², million tonnes

- BAU scenario
- High AP ambition scenario



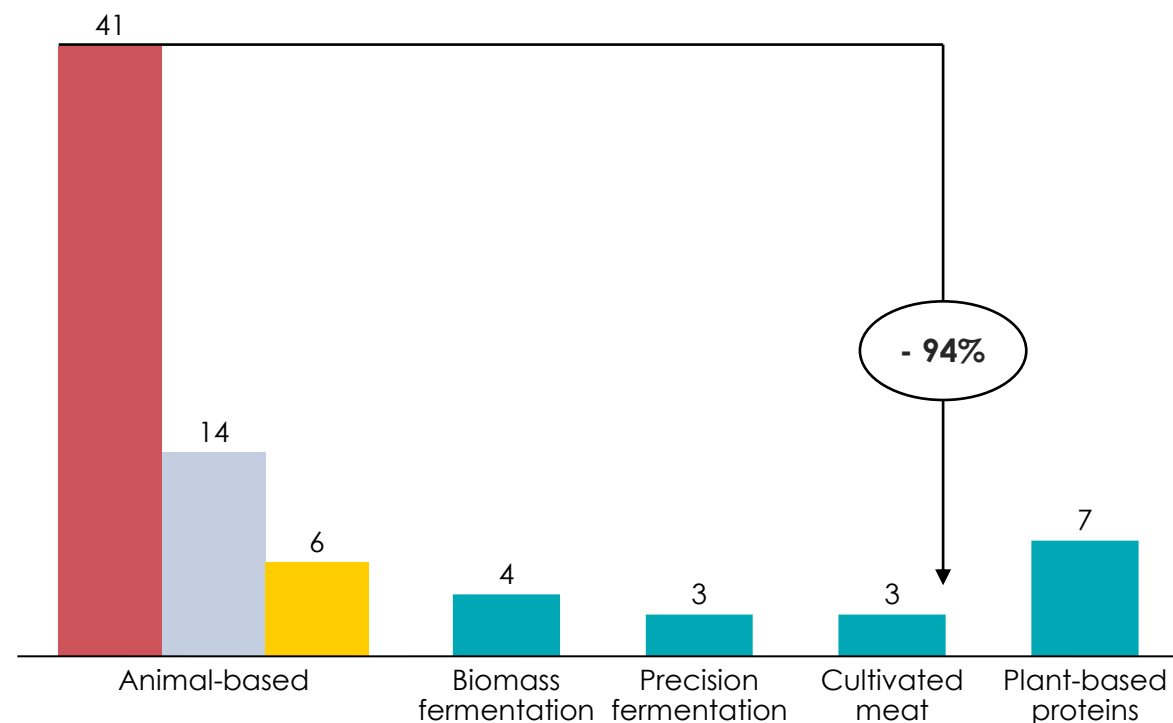
Notes: [1] In alternative proteins made via biomass fermentation, precision fermentation, or cultivation, cell-grown ingredients make up only ~5–20% of total protein weight; the rest comes from plants—driving plant-based proteins' dominant role in meeting 2050 global protein demand [2] Volume of animal protein consumption net of animal carcass weight. Sources: ETC analysis; Systemiq (2025), A Taste of Tomorrow: How Protein Diversification Can Strengthen Germany's Economy; FAOSTAT

② Freed up land: 587 million hectares of land could be freed up by 2050 if alternative proteins displace 400 Mt of animal-based protein

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

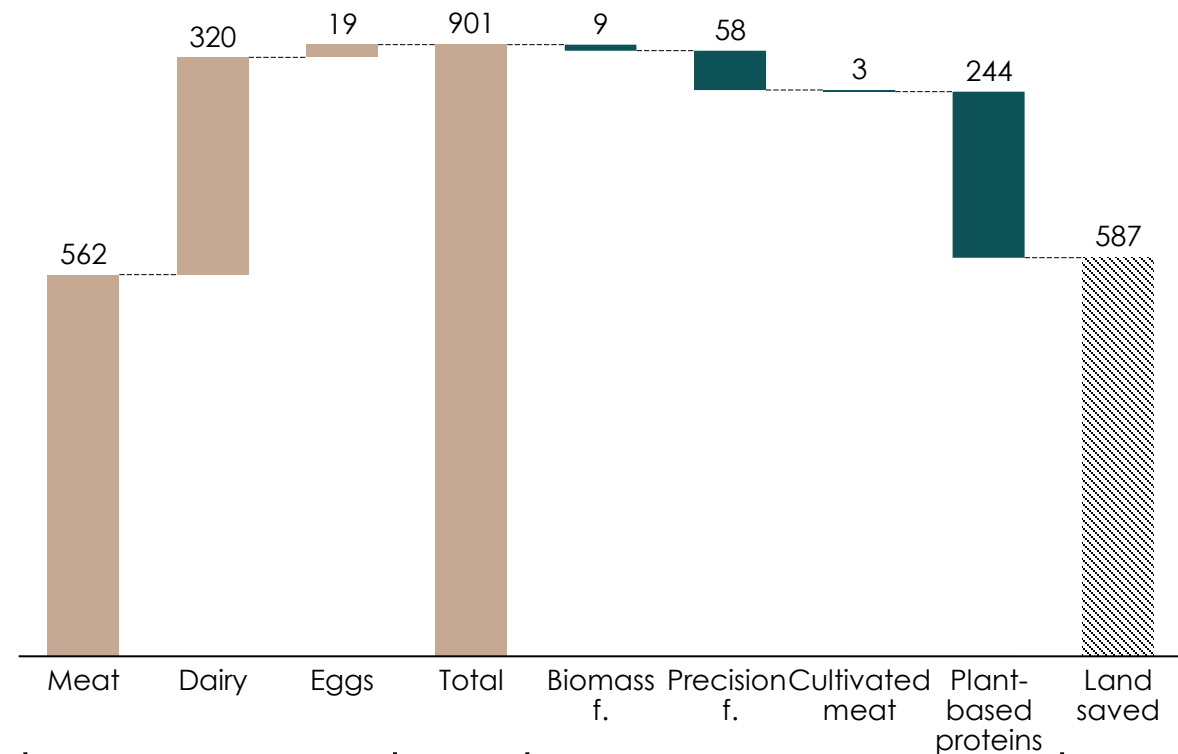
Meat Dairy Eggs All proteins



587 million hectares (Mha) of land would be freed if 400 Mt of protein were sourced from alternative rather than animal-based proteins

Land required for protein production, Mha

Animal-based protein Alternative protein Land saved






Land required to produce 400 Mt of animal-based protein

Land required to produce 400 Mt of alternative protein

Sources: 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.

③ Energy and carbon potential: 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)	75% to nature (441 Mha)
		+	+
		80% to managed forests (470 Mha)	25% to energy crop plantations (147 Mha)
Outcome:			
EJ of useful energy	N.a.: land is returned to nature, energy and carbon potential is not exploited	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	<ul style="list-style-type: none"> ⊕ Biodiversity + carbon sequestration maximised; restores soil condition & water cycle ⊖ No energy output, so other sustainable biomass routes must be scaled 	<ul style="list-style-type: none"> ⊕ Provides timber & 28 EJ of biomass energy ⊖ Moderate biodiversity impact – better than energy-crop monocultures, worse than untouched nature ⊖ Decades to reach maturity 	<ul style="list-style-type: none"> ⊕ Significant biodiversity impact on planted area, but large area returned to nature ⊕ Fast growing crops that produce yield every year

Source: ETC analysis; ETC (2021), Bioresources Within a Net-Zero Emissions Economy: Making a Sustainable Approach Possible.

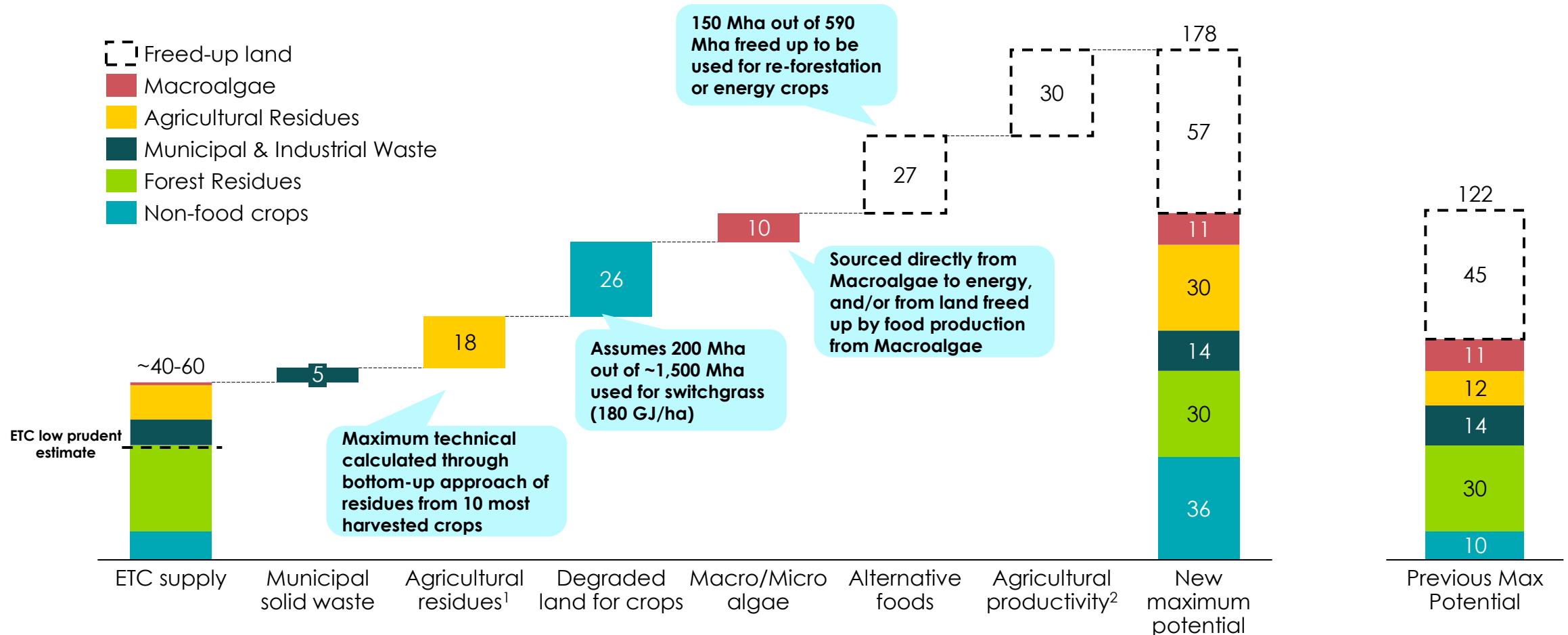
Scaling alternative proteins to free up land for sustainable biomass supply requires several conditions to be met

	We need to believe...	Criteria for success	Measuring success	Evidence of progress
<p>Goal Rapid alternative-protein adoption frees up land, a portion of which is converted to sustainable biomass production.</p>	<p>Alternative proteins are adopted and scaled at pace</p>	<p>Affordability Alt. proteins are cost competitive with conventional proteins.</p>	<p>All alt. proteins fall below 15 USD/kg</p>	<p>Cost of precision fermentation on track to drop below \$10 per kg by 2030.</p>
		<p>Attractiveness Taste, texture & nutrition match or beat animal products.</p>	<p>Alt proteins reach 40% market share</p>	<p>US plant based retail market doubled in size over seven years to be worth \$8.1 billion in 2024</p>
<p>Land returns to nature and converts to biomass production because of declines in animal agriculture</p>		<p>Accessibility Scale-up finance and public institutions becoming early adopters unlock growth.</p>	<p>Displace 400 Mt of animal protein</p>	<p>26 new or expanded alternative protein factories in 2024, including Danone and Lactalis</p>
		<p>Land liberation Land is freed up as result of the shift to alternative proteins.</p>	<p>587 Mha of land liberated</p>	<p>Kozicka et al., estimate that substituting 50% of animal products globally would almost fully halt the reduction in forests and natural land.</p>
		<p>Land allocation Released hectares are reallocated to rewilding and biomass production.</p>	<p>80% to managed forests (470 Mha)</p>	<p>IEA projects total bioenergy supply from short rotation woody crops to rise from 25EJ to 40EJ in 2050.</p>

Notes: [1] These figures are derived from our analysis are intended as indicative call-outs, rather than exhaustive evidence. Sources: GFI & Integration Consulting. "Fermentation manufacturing capacity analysis" (June 2023), Box 2-1 "Capital-learning curves for large-scale food-grade fermenters"; GFI Europe. "Germany plant-based food retail market insights" (Oct 2024) + Smart Protein/ProVeg UK consumer tracker (2024). GFI. "State of Global Policy on Alternative Proteins – 2023" (June 2024); OECD-FAO Agricultural Outlook 2023-2032, "Meat" chapter, Figure 1.3 (per-capita beef trend in OECD). SIQ analysis.

Biomass supply summary – a new possible maximum scenario estimates that sustainable biomass availability around ~180EJ

Biomass supply potential, EJ primary biomass



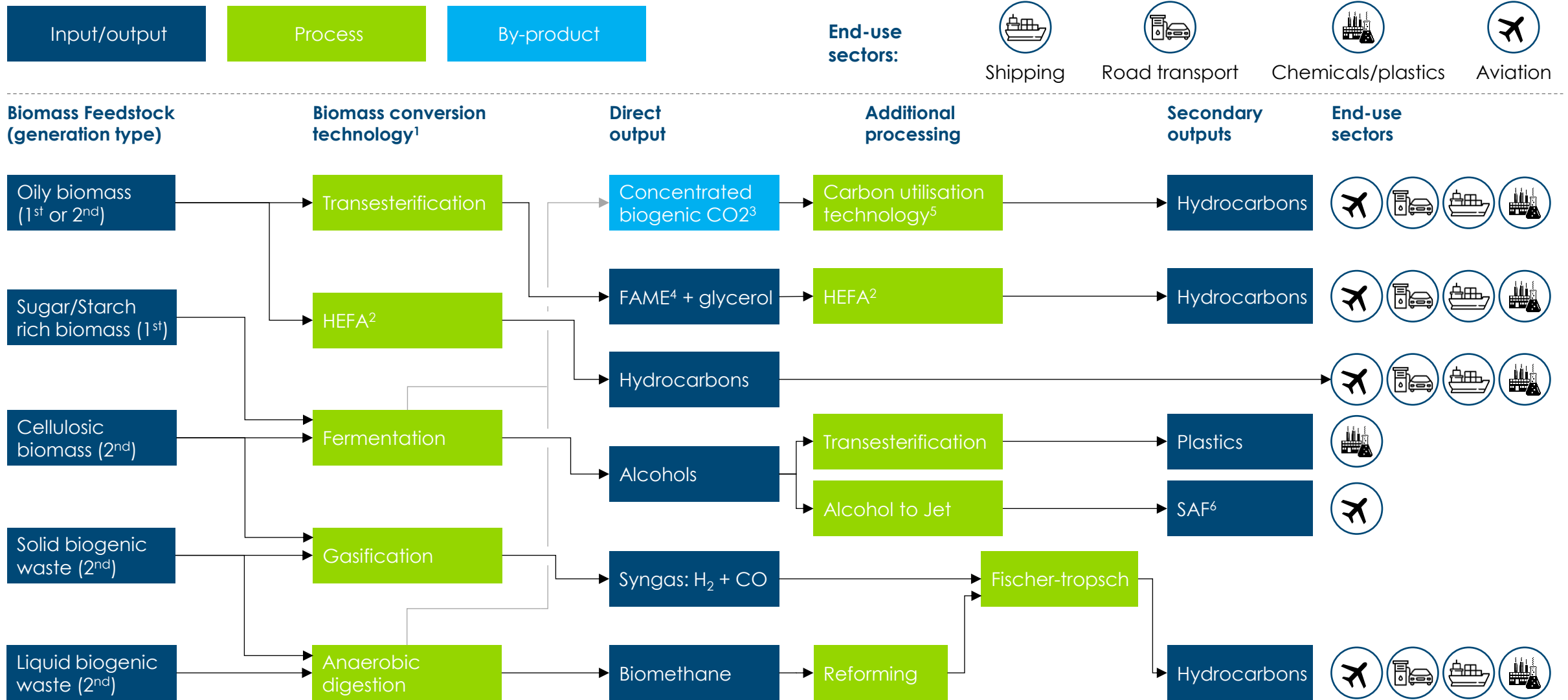
Notes:1) Agricultural residues revised through a numerical approach by analyzing residues from top 10 most harvested crops. From total unprocessed residues, 70% are left on ground and a recoverability of ~50% is assumed. Production from 2023 is taken and extrapolated to 2050 using the same CAGR for the 2003 – 2023 period. 2) 0.9 CAGR taken from 2019 to 2050 plus an additional 12% increase by 2050 due to technological advancements yields a total of 40% increased productivity. This frees up 640 million ha, which is split in the same way as freed land from Alternative Proteins or Macroalgae, yielding additional 30 EJ

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

Biomass conversion efficiency









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



Notes: 1) 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); 2) HEFA = Hydro Processed Esters and Fatty Acids. 3) CO₂ sources with >90% concentration (fermentation) ~ 50% concentration (anaerobic digestion), which is a cheap biogenic CO₂ source. By adding green hydrogen multiple hydrocarbons could be synthesized. 4) FAME = Fatty Acid Methyl Ester. 5) See phase two slide 84 diagram for detailed view of routes. 6) SAF = Sustainable Aviation Fuel

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

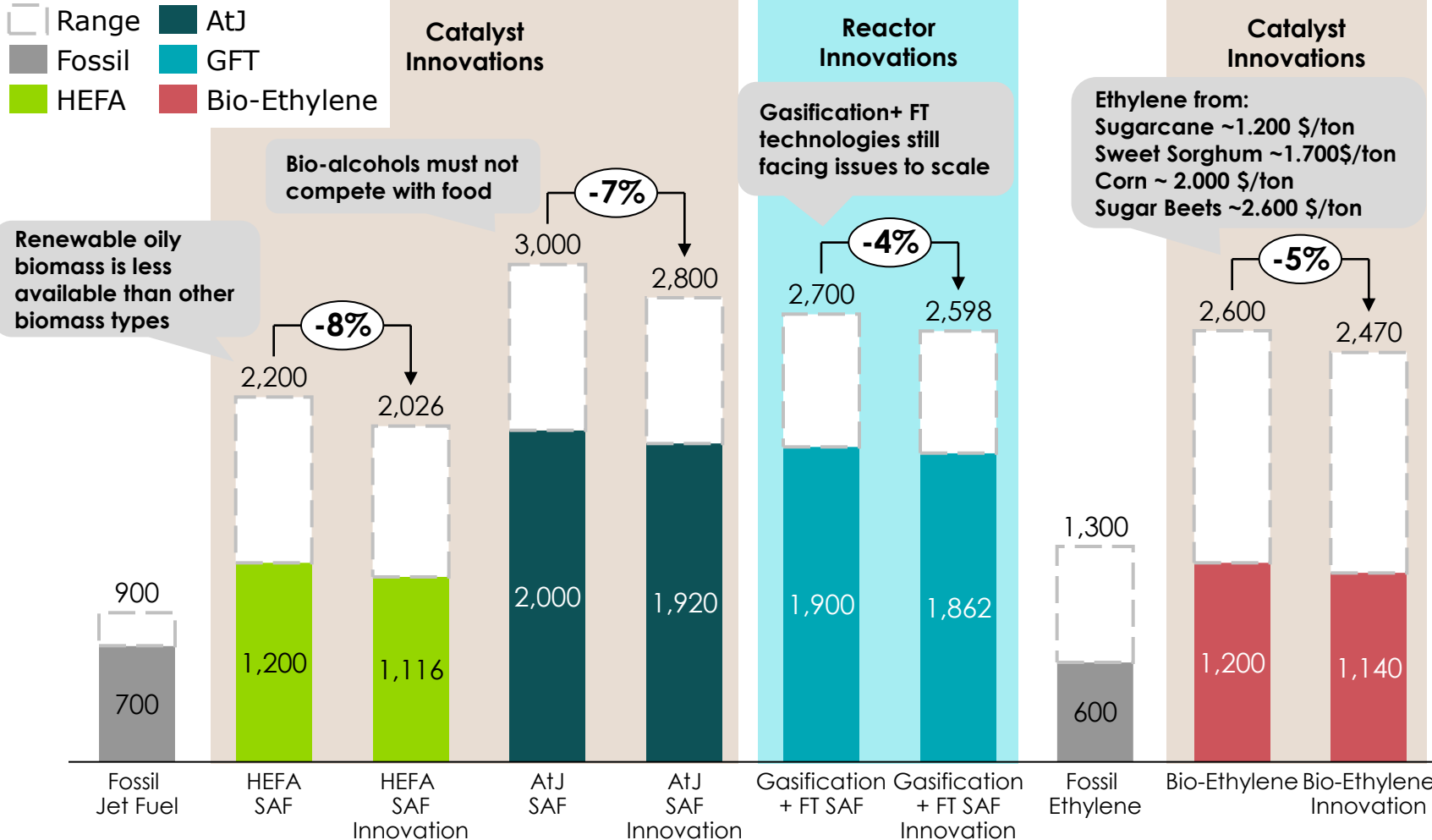
Type of innovation	Description	Deployment examples ¹	Companies and TRL
Catalysts	<ul style="list-style-type: none"> Novel catalyst aim to improve conversion and yield of desired products, decreasing primary biomass needed and decreasing the activity of competing reactions 	<ul style="list-style-type: none"> 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) 	 7 – 9
		<ul style="list-style-type: none"> Indonesia's new biorefinery—HydroFlex plant #50—will use Topsoe catalysts to make 6 000 gpd of renewable diesel and SAF. 	 9
		<ul style="list-style-type: none"> FOAK plant inaugurated in Georgia in 2024, with a capacity of 10 MM gpy of SAF from ethanol at a cost of US\$ 200 MM 	 7 – 8
Reactors	<ul style="list-style-type: none"> New reactor designs aim to improve reaction kinetics or reduce equipment CAPEX Example of new reactors configuration: <ul style="list-style-type: none"> Micro-channel reactors Membrane reactors Fluidized bed reactors Modular reactors 	<ul style="list-style-type: none"> Fluidized bed reactor technology installed in Alberta, which gasifies MSW to produce ~1,000 barrels per day of methanol 	 6 – 8
		<ul style="list-style-type: none"> 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 	 6 – 7
		<ul style="list-style-type: none"> 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 	 7



Notes: 1) Innovations are happening on all routes, so list is non-extensive; 2) Novozymes also develop the first yeasts-based catalyst for oily biomass conversion to FAME

Costs: 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 end¹
\$/ton of product



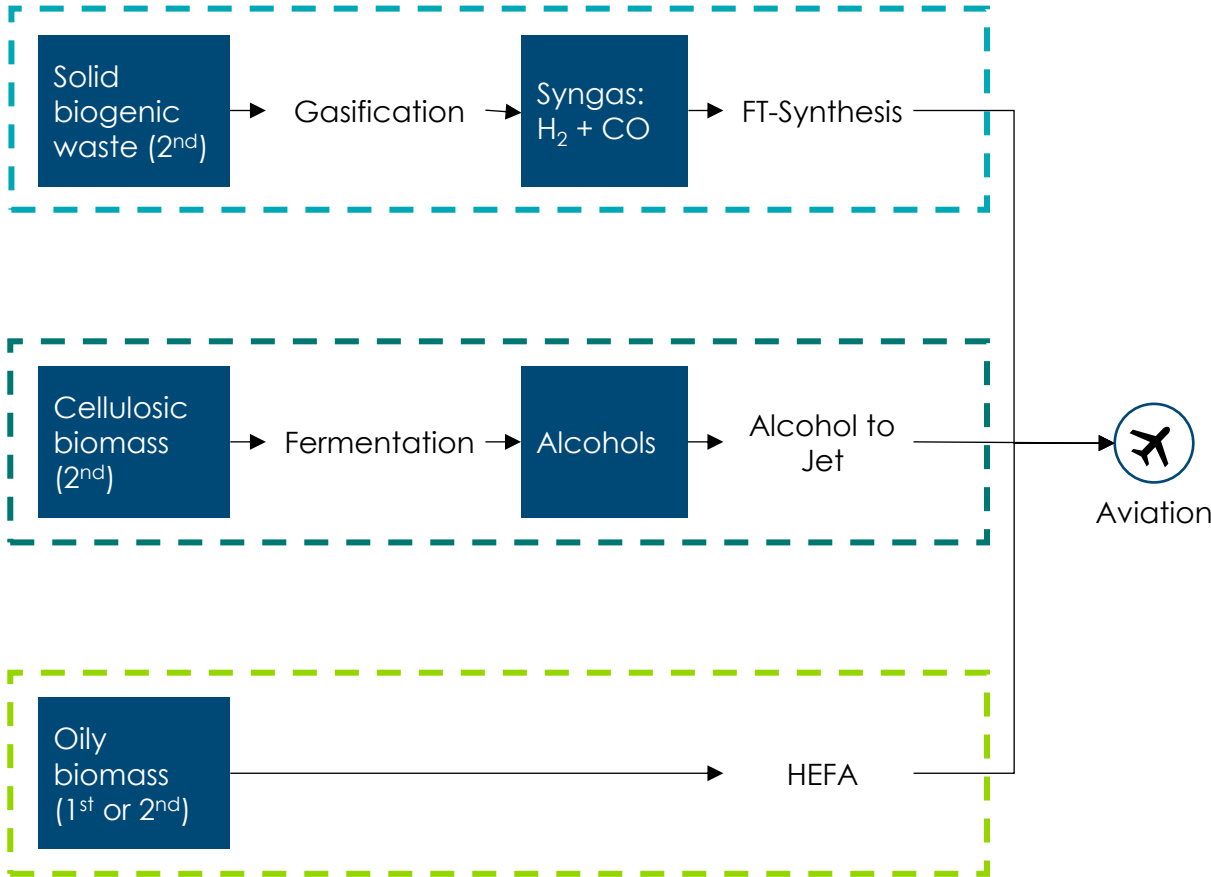
Cost considerations

- Primary cost drivers of biofuel cost:** feedstock prices, plant CAPEX, and other OPEX (heat, electricity, hydrogen, labor...)
- Current cost analysis** assumes savings only from higher conversion, which decreases feedstock needs only (no in-depth analysis on OPEX reduction)
- Catalyst/reactor upgrades are treated as CAPEX-neutral:** yield gains aren't justified if CAPEX spikes. Example: Calumet's micro-channel FT reactor costs ~15% less than incumbent technology.

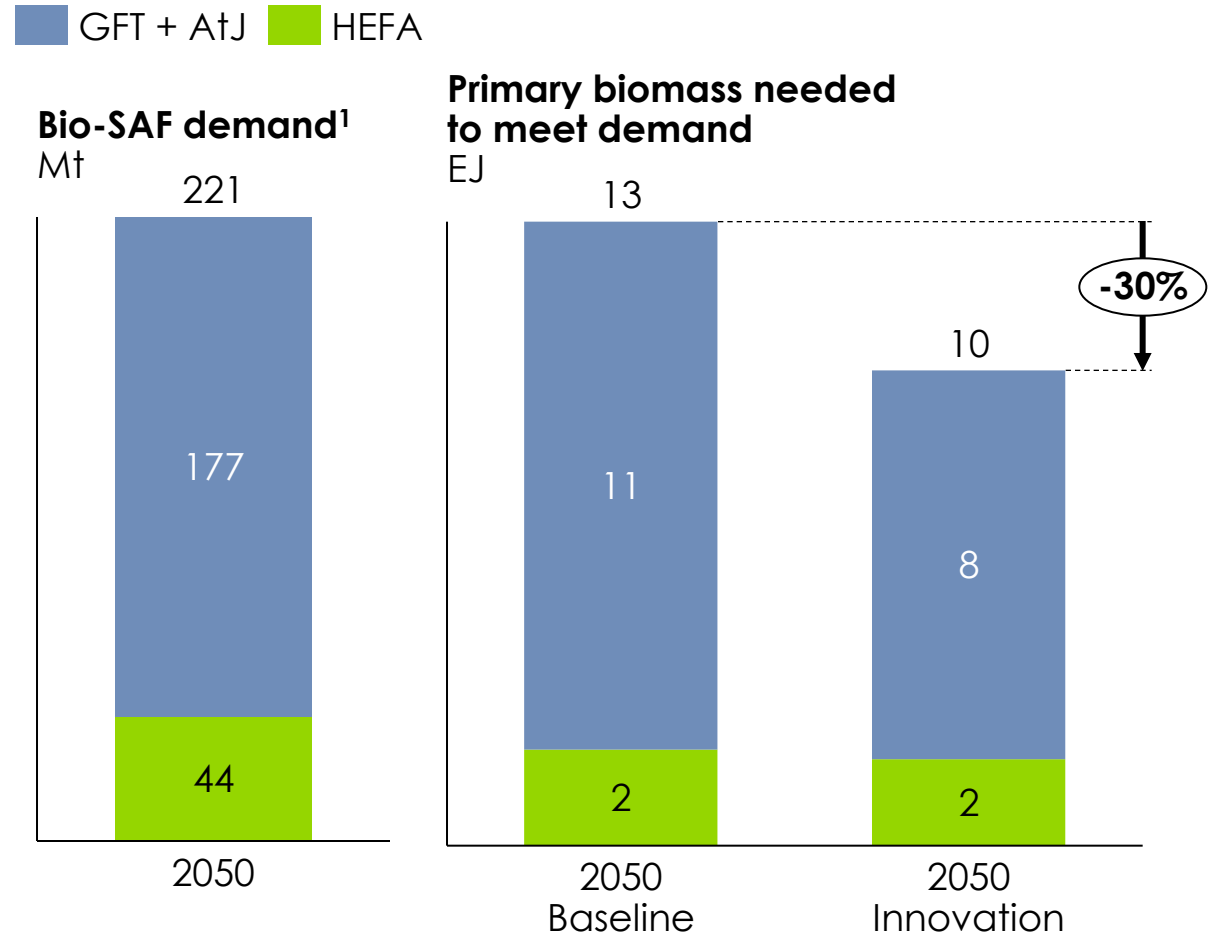
Notes: 1) Conversion and yield gains due to innovation applied to feedstock percentage of total route cost
 Sources: Panov, V. (2024) Decarbonizing Air Travel with Sustainable Aviation Fuel; Mohsenzadeh, A. (2017) Bioethylene Production from Ethanol: A Review and Techno-economical Evaluation; Zanon-Zotin, 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

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

The three main bio-SAF pathways use distinct feedstocks, all rooted in 2nd-gen biofuels



Conversion-efficiency improvements could cut primary biomass needed for bio-SAF by 30%



Sources: Mission Possible Partnership (2022) Making Net-Zero Aviation Possible, Notes: 1) According to Mission Possible Partnership's Prudent decarbonization scenario

Securing feedstock and demand incentives accelerates deployment and cuts costs

	We need to believe...	Criteria for success	Evidence of progress/status
<p>Goal</p> <p>Advanced bio-based carbon molecules become a viable alternative for fossil-based carbon molecules</p>	<p>Feedstock are made more accessible through precise regulation, maximisation of local resource use and commodity pricing</p>	<p>Sustainable biomass regulations Global definition of sustainable biomass, which is inclusive without compromising other areas (e.g., land use)</p>	<p>Currently, divergent definitions of sustainable biomass drive regulatory misalignment.</p>
	<p>Increased demand pushes for faster deployment, which over time reduce the technology costs</p>	<p>Maximisation of local resources Development of local collection or local processing, to concentrate feedstocks</p>	<p>Several studies map regional biomass potential, and small-scale projects are already operating¹</p>
<p>Market creation Creation of commodities markets which make bio-based molecules tradable (e.g., biomethane, biogenic CO₂)</p>		<p>Europe leads, with countries having biomethane, CO₂ and even Syngas markets</p>	
<p>Demand incentives Blending mandates and emission targets, which create a solid demand for bio-based chemicals and materials, facilitating offtake agreements</p>		<p>Many countries enforce blending mandates and sectoral emission caps, yet ambition must rise to spur large-scale projects</p>	
<p>Accelerated deployment As more plants reach FID, costs fall via learning, scale, supply chain growth, and standardization, making bio-based solutions more competitive with fossil fuels</p>	<p>IEA Bioenergy states that 111 bio-SAF facilities² have been announced (~33 Bn L/year), but most are in very early planning stage</p>		

Notes: 1) Some example of projects: GEF-Biogás & Aurora Alimentos in Brazil who have established a multi-stakeholder project to collect pig wastes from farms and slaughterhouse, Sugar-mill cogeneration hubs in India, which collect bagasse from nearby plantations and can generate 94MW excess electricity, Nature Energy Korskro / Sydvestjysk Biogas in Denmark where 100 pig and cattle farmers deliver wastes to a centralized anaerobic digestion plant, which injects biomethane in the gas pipeline; 2) 56 HEFA plants, 21 AtJ, 20 FT, 13 Co-processing and 1 Pyrolysis.
 Sources: IEA Bioenergy (2024) Progress in Commercialization of Bio-jet / Sustainable Aviation Fuels (SAF)

Agenda



















- Introduction to work program
- Carbon-capture: Direct Capture and Point Source
- Bioresources
- **End-of-life management**
- Scenarios and next steps



End-of-life management



Our deep dives will focus on emerging CO₂ and solid C storage technologies which have the greatest potential to cut costs and prevent leakage

Technology	Process	TRL	Companies <i>Non-exhaustive examples</i>
1 Depleted oil & gas (O&G) reservoirs	These are mature and well-characterized formations originally used for fossil fuel extraction. They offer ready-made infrastructure and known geology, allowing relatively secure CO ₂ storage.	9	 
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	  
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	   
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	  
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	  
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	  

Emerging technologies

Notes/Sources: 1) Peter Kelemen et al. (2019) An overview of the status and challenges of CO₂ Storage in Minerals and Geological Formations 2) Kyuhyun Kim et al. (2023) A review of carbon mineralization mechanism during geological CO₂ storage 3) Ahmed Bashir et al. (2024)

End-of-life management: CO₂ storage

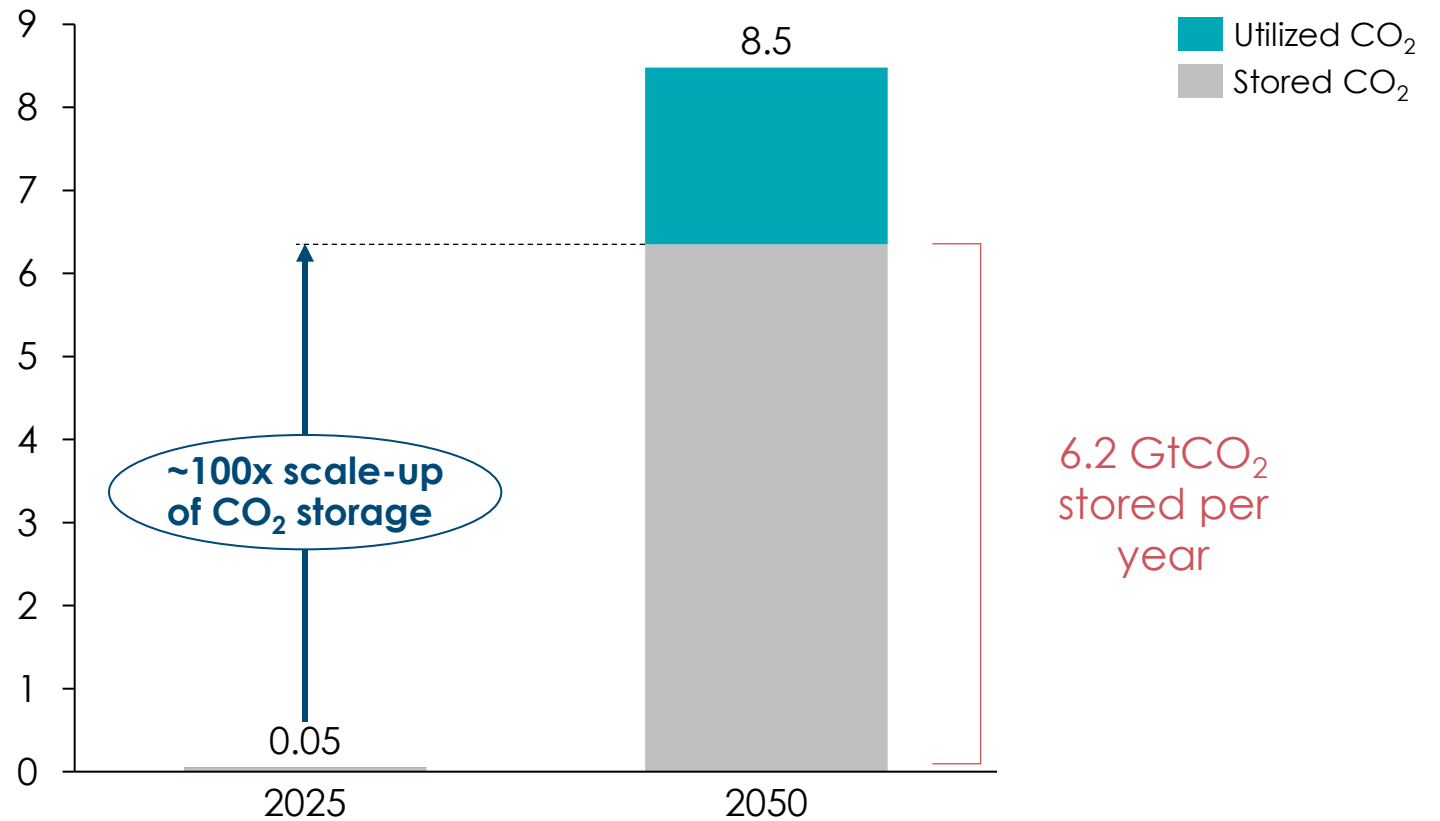


In the following decades, wide-scale deployment of CO₂ storage will be needed to meet net-zero by 2050



- 1 Of the projected 8.5 GtCO₂ per annum of captured CO₂ in 2050, the majority (6.2 GtCO₂) will need to be stored
- 2 Current CO₂ sequestration in sedimentary formations is around 50 MtCO₂ (0.05 GtCO₂) per year — 100-fold scale-up is required by 2050 to meet climate targets²

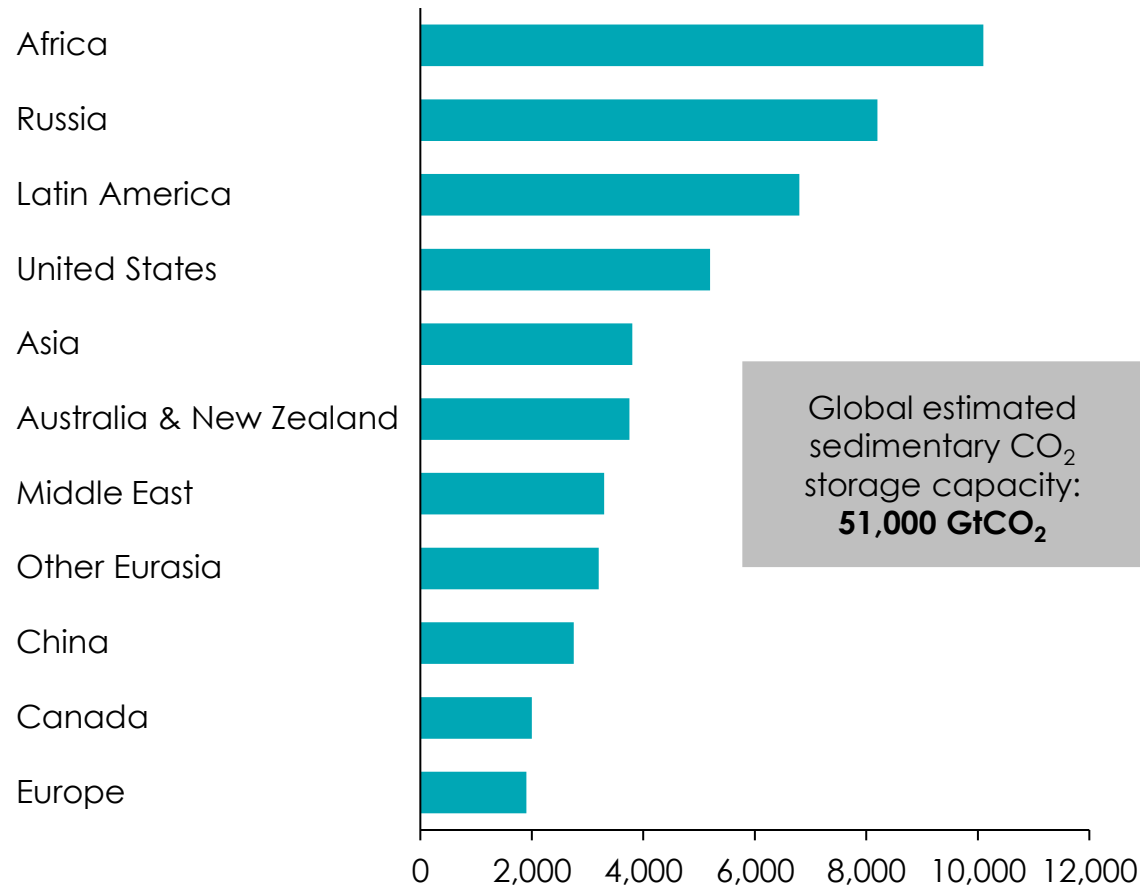
Carbon capture and carbon utilization and storage volumes¹
GtCO₂ p.a.



Established geological options are low cost and sufficient in storage capacity

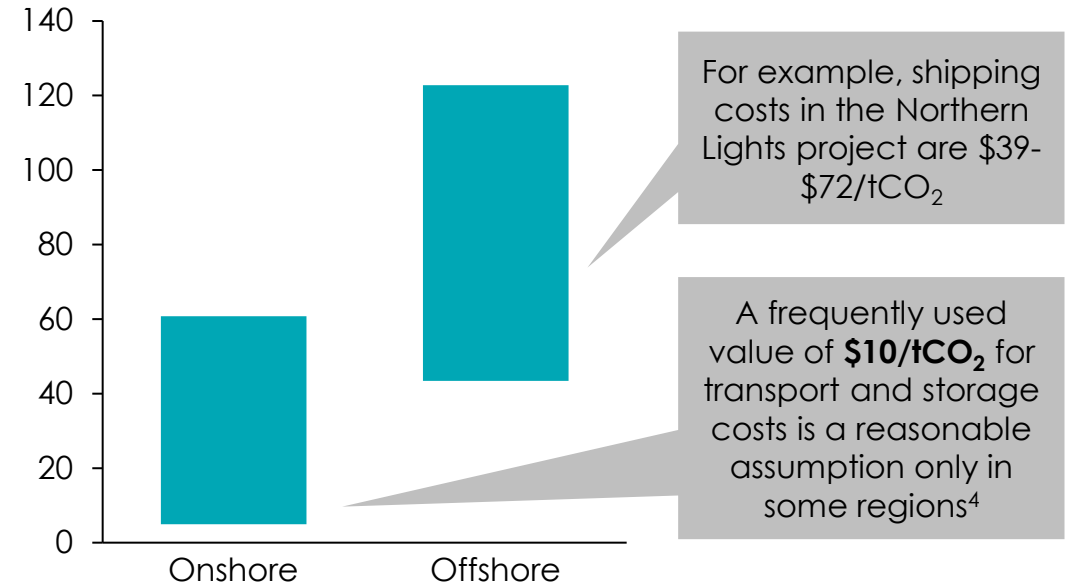
Range of estimated onshore and offshore sedimentary CO₂ storage capacity

GtCO₂



Cost of CO₂ transport and storage in depleted oil & gas reservoirs and saline aquifers, 2025

\$/tCO₂ transported and stored

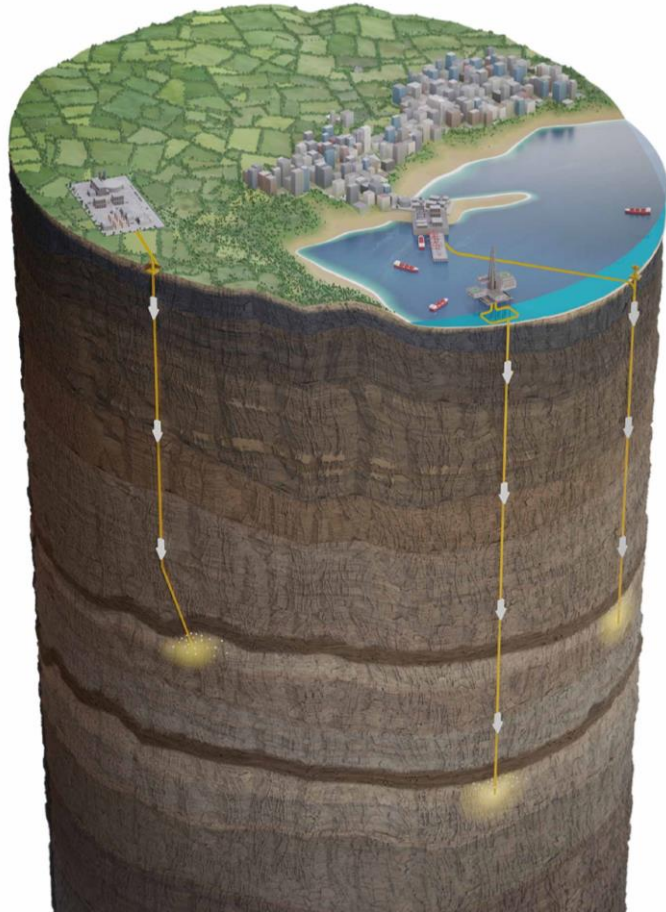


5 key variables affecting the costs:

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

Sources: 1) Kearns et al. (2017) Developing a Consistent Database for Regional Geologic CO₂ Storage Capacity Worldwide 2) OGCI (2021) CO₂ storage catalogue 3) Hugh Barlow (Global CCS Institute 2025) 4) Erin Smith et al. (2021)

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

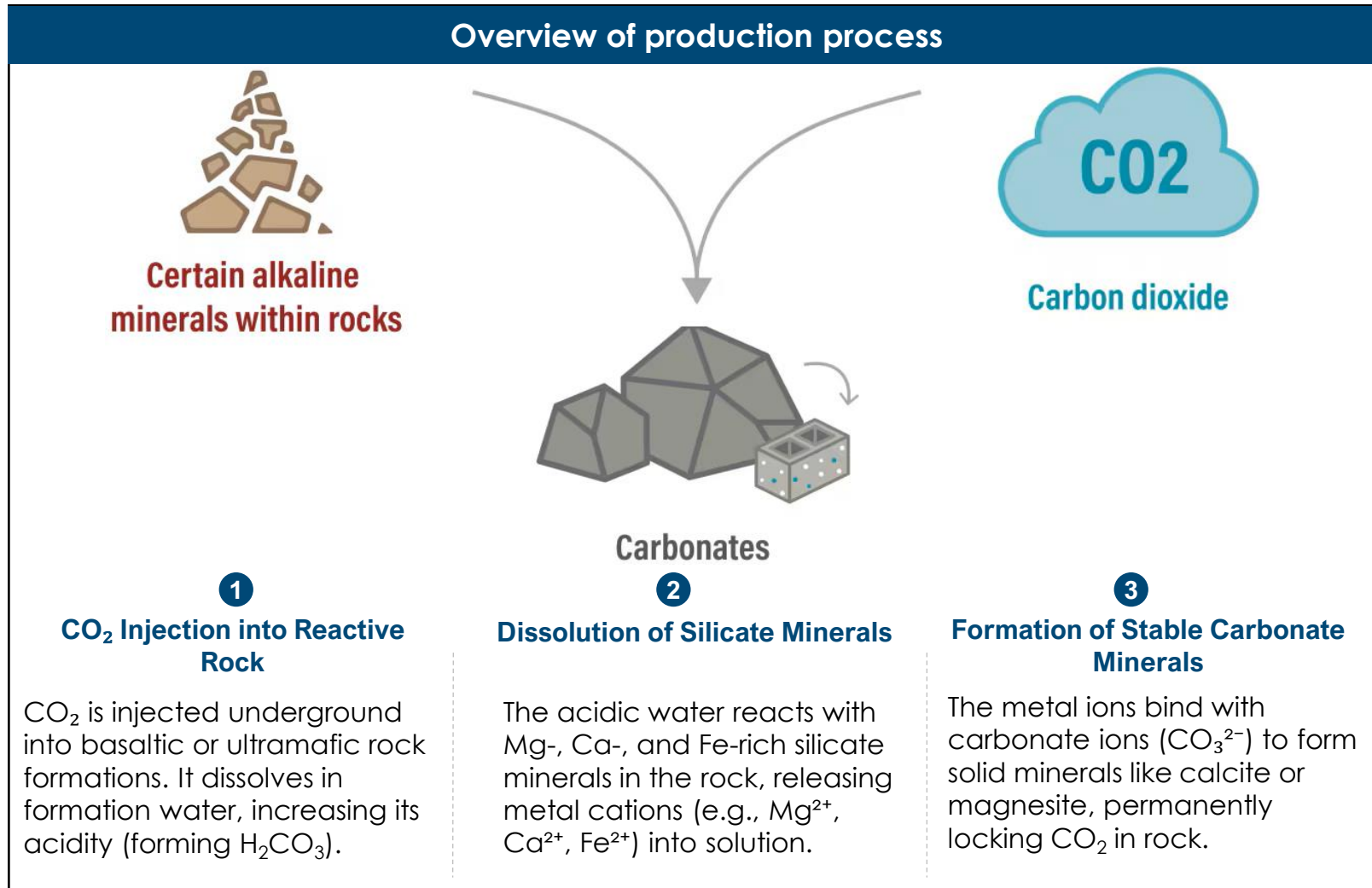


Potential limitations	Description
Injection rates limits	Annual injection is capped by reservoir pressure, risk of fracturing caprock, and potential for induced seismicity, slowing deployment. Some sources indicate this can limit global CO ₂ injections up to 2 GtCO ₂ /y. ¹
Leakage risk and monitoring	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. ²
Environmental and regulatory challenges	Injected CO ₂ can push brine into freshwater aquifers or to the surface. ¹
Geological suitability varies	Not all regions have suitable sedimentary formations near CO ₂ sources, limiting local deployment.
Emerging CO₂ storage technologies	Required to facilitate deployment and meet 2050 capacity targets.



Sources: 1) Peter Kelemen et al. (2019) 2) Bo Wei et al. (2023) CO₂ storage in depleted oil and gas reservoirs: A review 3) Nader Mosavata et al. (2024)

4 CO₂ mineralisation (in situ): Underground injection of CO₂ to form solid carbonates in reactive rocks



Comparison with widely used storage

Comparison of CO₂ mineralisation with CO₂ storage in sedimentary reservoirs

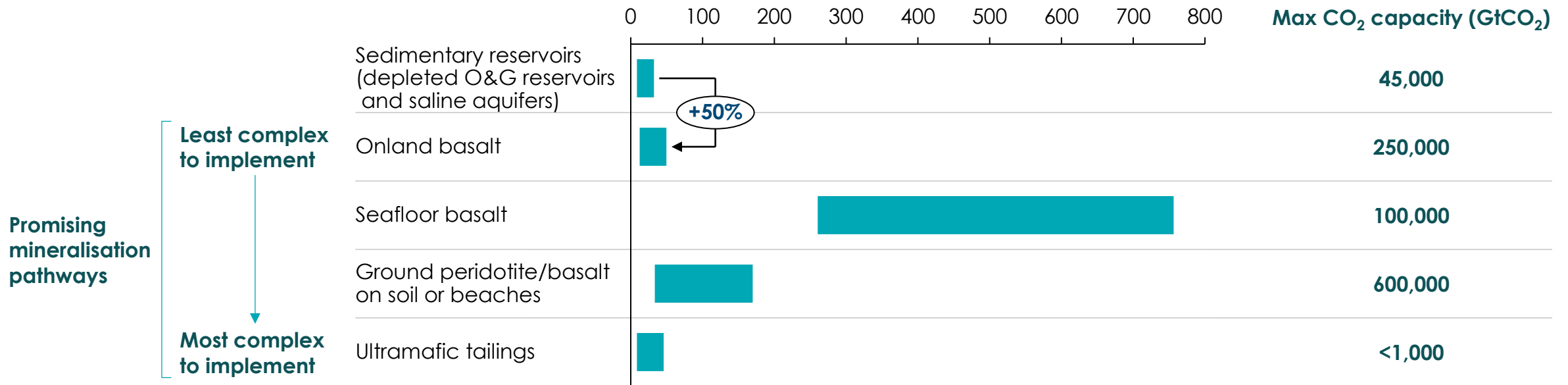
	Mineralisation	Reservoirs
Available capacity	Very high Up to 10 ⁶ GtCO ₂	Enough Up to 5*10 ⁴ GtCO ₂
Injection rate	Very high – no environmental limitations	Lower – pressure build-up limitations
Leakage risk	None - permanent and immobile minerals	Small but possible on long timeframes
Monitoring	No need	Necessary for 50+ years
Scalability	Globally available but geographically constrained	Vast scalability and existing infrastructure
Cost	Cost are competitive but higher	Most cost-effective method

Notes/Sources: 1) Kyuhyun Kim et al. (2023) A review of carbon mineralization mechanism during geological CO₂ storage 2) Erin Smith et al. (2021) 3) Colin D. Hills et al. (2020) 4) Nader Mosavata et al. (2024)

Cost of mineralisation today is 50% higher than depleted oil & gas reservoirs and saline aquifers, but has significantly higher capacity CO₂ storage



Cost of CO₂ storage for sedimentary reservoirs and most promising mineralisation pathways, 2025
\$/tCO₂ stored



Key takeaways on cost drivers and trends



- Sequestration in **on-land basalt** and **ultramafic tailings** could become **competitive** with storage in sedimentary reservoirs, but costs rise significantly for storage in seafloor basalts.
- Different pathways **can complement one another** other as their geological occurrences do not typically overlap geographically.
- Mineralisation significantly **increases available capacity and geographical locations**, cutting down transportation costs.

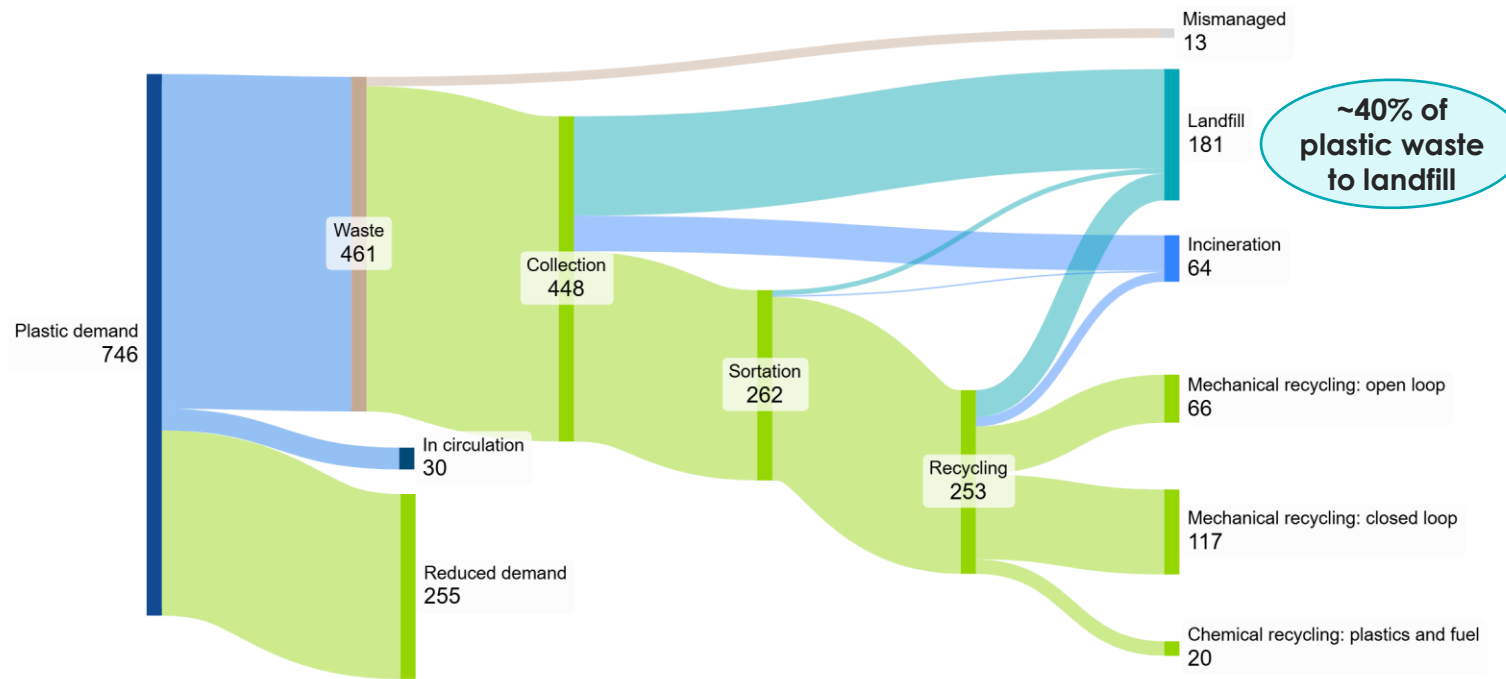


End-of-life management: landfilling



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, 2040¹, million metric tonnes

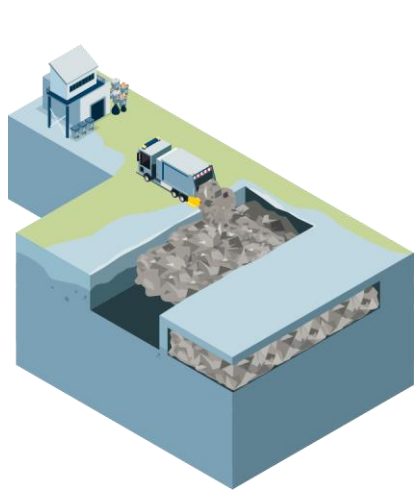


- Current practices of solid carbon waste management via landfill and incineration are significant drivers of climate change, together emitting CO₂-equivalent gases of approximately 1.2 GtCO₂/y today^{2,3}
- Globally, landfill use is expected to remain a significant strategy for waste management over the coming decades, making up nearly 40% of plastic waste's end-of-life destination in 2040
- Advanced technologies will be crucial to reduce the climate and environmental impacts of landfilling (*detailed next slide*)

Sources/notes: 1) Systemiq (2024) Plastic Treaty, Global rules scenario. 2) Pericarbon (2025) The Methane Crisis: Uncovering the Climate Impact of Landfills 3) Zero Waste Europe (2019) The impact of Waste-to-Energy incineration on climate

⑥ Advanced landfilling: Technologies which can be utilised to reduce the GHG emissions of mismanaged landfill sites

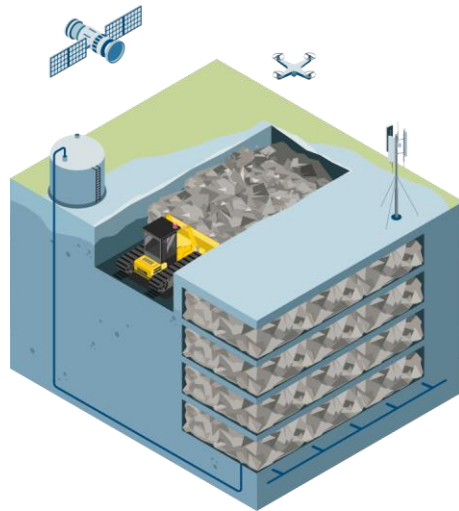
Overview of advanced landfilling technologies



1

Pre-landfill material recovery and biological treatment (MRBT)¹

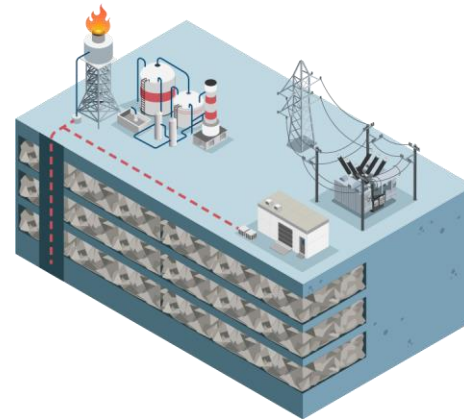
Biological stabilisation of MSW using aerobic decomposition to reduce ~25-30% mass of input waste to ensure material generates less methane when landfilled



2

Comprehensive methane monitoring and detection²

Systems which detect and quantify methane leakage (e.g. aerial infrared imaging, drone-mounted sensors, continuous ground-based analysers)



3

Landfill gas capture and management systems²

Landfill gas (methane, CO₂) is captured at wells and routed via pipework to be upgraded for energy/fuel use; biocover materials can trap gas and improve methane oxidation

Comparison with incineration

Comparison of MSW treatment via advanced landfilling versus incineration

	Advanced landfilling	Incineration
GHG emissions (per t MSW)	~0.2 tCO ₂ e ³	~0.7-1.2 tCO ₂ e ⁴
Land requirement (ha/Mt MSW)	10+	0.1
Non-GHG environment impacts	Potential leachate groundwater contamination	Toxic air pollutants if not properly controlled
Regulatory alignment	Increasing landfill restrictions or bans in some regions	Under scrutiny to recycle/abate emissions (CCUS)
Energy recovery	Capture of landfill gas as fuel for heat or electricity	Combustion of waste to generate heat or electricity

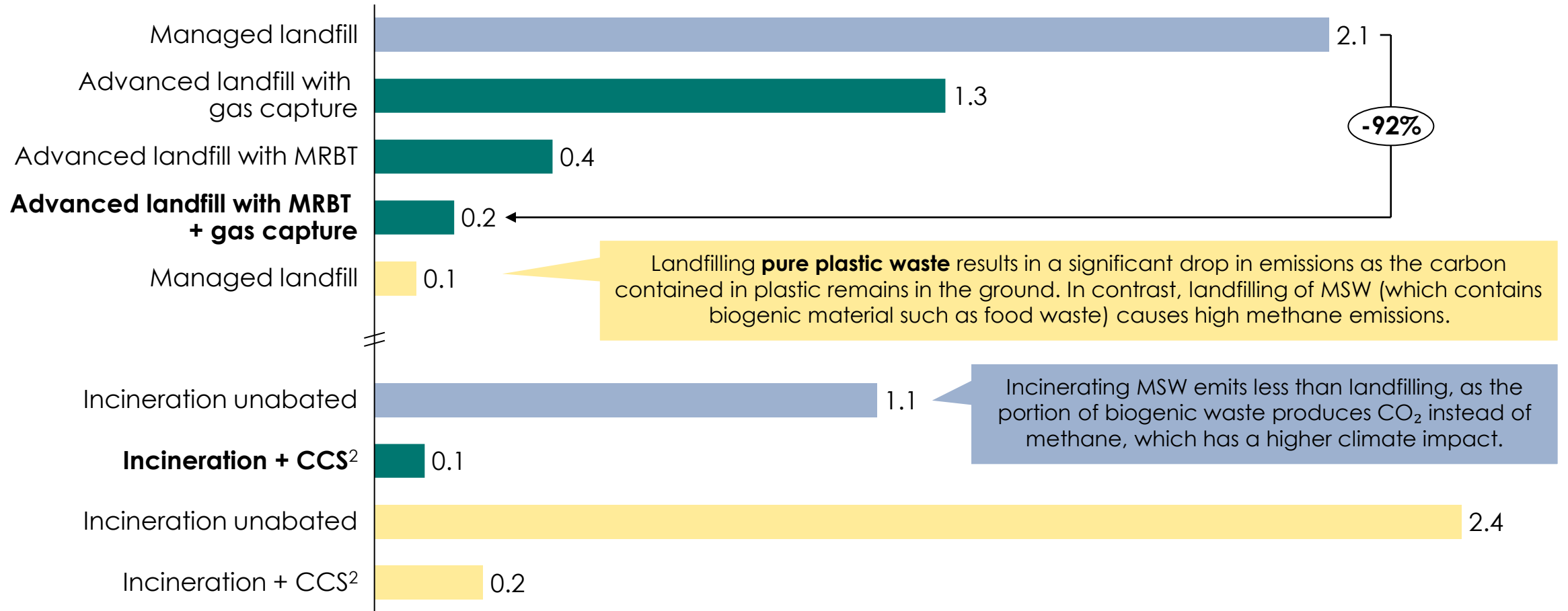
MSW = municipal solid waste

Notes/sources: 1) "Reducing waste management's contribution to climate change" (Zero Waste Europe, 2024). 2) "Deploying Advanced Monitoring Technologies at US Landfills" (RMI, 2024). 3) Includes implementation of mixed waste sorting and biological treatment prior to landfilling and landfill gas capture system. Emissions include biogenic CO₂. "Material Recovery and Biological Treatment to manage residual waste within a circular economy" (Zero Waste Europe, 2021); 4) "Understanding the carbon impacts of Waste to Energy incineration" (Zero Waste Europe, 2020)

Advanced landfilling of MSW could reduce emissions by ~92%, reaching a similar emissions factor (0.1-0.2 tCO₂e/t waste) to incineration with CCS

End-of-life emissions for landfill and incineration scenarios¹,
tCO₂e/t waste

MSW counterfactual MSW abatement Pure plastic waste

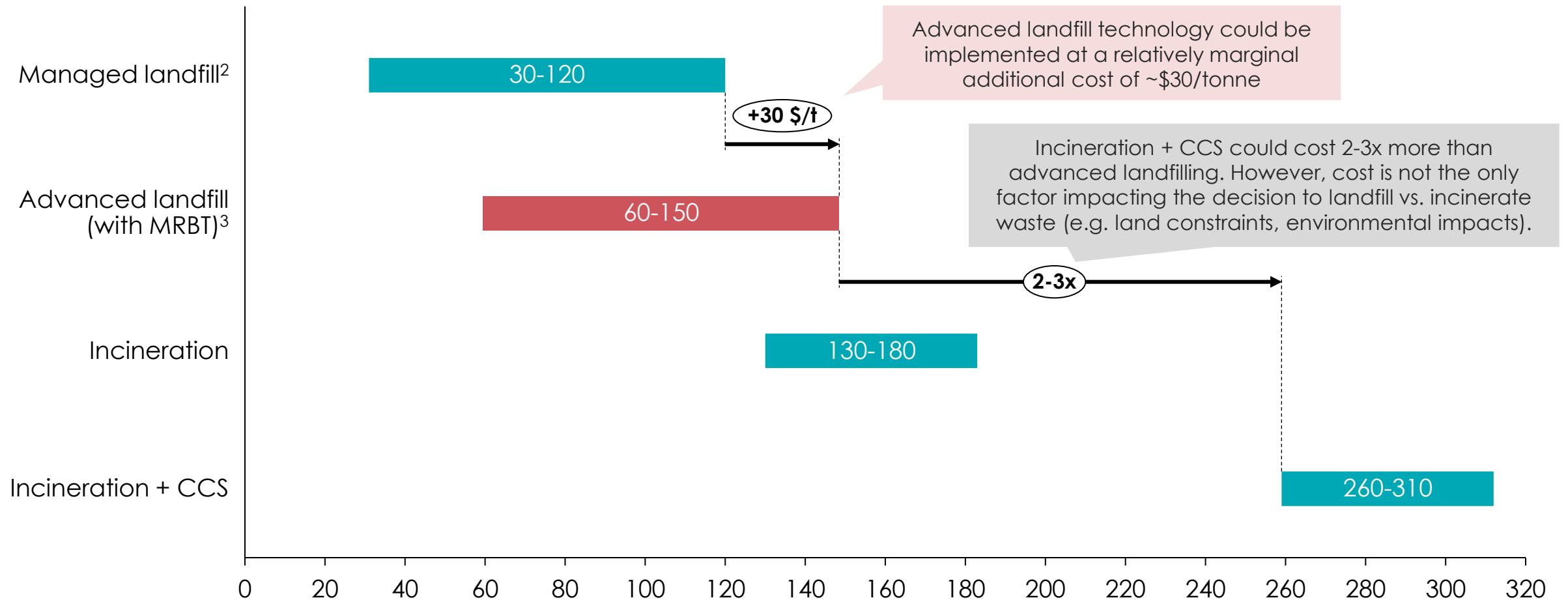


MRBT = Material Recovery and Biological Treatment

Sources/notes: 1) Systemiq analysis (2025), based on: "Building a bridge strategy for residual waste" (Zero Waste Europe, 2020); Ecoinvent v 3.11. 2) Assumes a 90% capture rate.

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

Cost of end-of-life measures for waste¹, USD/t waste



Sources/notes: 1) Systemiq analysis (2025), based on: "The High Cost of Waste Incineration" (gaia, 2021); "Building a bridge strategy for residual waste" (Zero Waste Europe, 2020); "CCUS Development Pathway for the EfW Sector" (eunomia, 2021). 2) 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). 3) Costs increase shown for advanced landfill using material recovery and biological treatment.

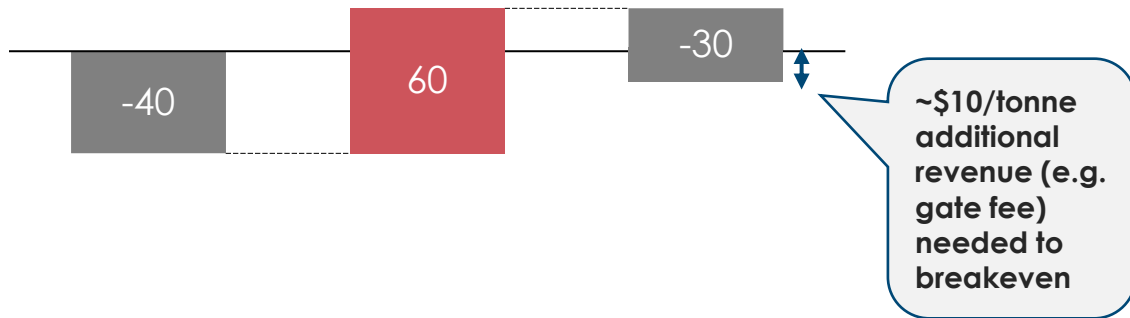


Adoption of advanced landfill technologies could have a marginal impact on project economics compared to scaling CCS on incinerators

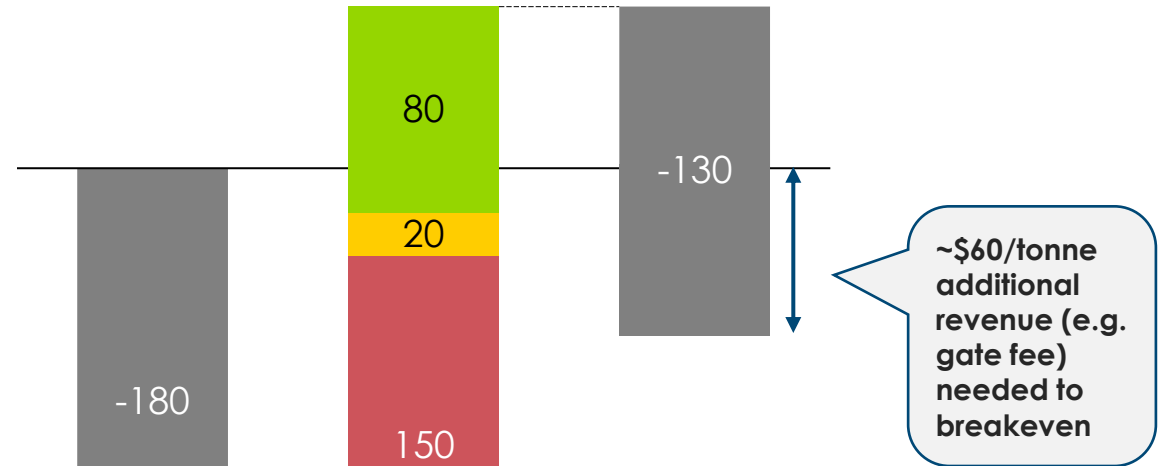
Costs and revenues of end-of-life measures for waste¹, USD/t waste ■ Costs ■ Electricity ■ Heat ■ Gate fees

Case studies below are based on high-level assumptions. Exact cost/revenue structures differ widely from site-to-site.

In countries with a greater reliance on landfills (e.g. US), advanced technologies such as MRBT may only require a marginal additional revenue to breakeven



In countries with a greater reliance on incineration (e.g. UK), the additional cost of CCS will have a greater impact on project economics













Managed landfill cost Revenues Additional cost for advanced landfill (MRBT)

Incineration cost Revenues Additional cost for CCS



MRBT = Material Recovery and Biological Treatment
 Sources/notes: 1) Systemiq analysis (2025), based on: "The High Cost of Waste Incineration" (gaia, 2021); "Building a bridge strategy for residual waste" (Zero Waste Europe, 2020); "CCUS Development Pathway for the EfW Sector" (eunomia, 2021); "2023 Landfill Tipping Fees" (EREF).

What do we need to believe for safe and permanent disposal of carbon

Goal	We need to believe...	Criteria for success	Evidence of progress
Rapid and wide-scale deployment of CO₂ transport and storage (T&S) solutions , enabling permanent disposal of captured CO ₂ from industrial and renewable carbon sources	Technological advancements (e.g., mineralisation) enabling greater storage capacities Business models to support CO ₂ T&S markets	 Technological innovation Developments in CO ₂ mineralisation pathways with high injection rates and low risk of leakage	 New technologies / companies are entering the market (e.g. Carbfix, CarbonCure)
		 Long-term liability and monitoring Reliable systems for monitoring, reporting, and verifying (MRV) storage integrity and managing long-term liability	 The Sleipner project in Norway is operational for 25 years and has successfully stored 23 MtCO₂ with MRV¹
		 Commercial CO₂ market intermediaries CO ₂ T&S networks can reach greater economies of scale with market intermediaries that provide CO ₂ T&S as a service to multiple parties	 Northern Lights has started offering open-access CO₂ offshore T&S services for European industrial emitters
Adoption of advanced technologies to reduce GHG emissions from landfills	Regulatory measures to address the GHG emissions from landfills and incentivise technology adoption	 Policy mandates and requirements Strict policies addressing the management of GHG emissions from landfills (e.g. limits on the amount of biodegradable waste sent to landfills, requirements to install landfill gas capture systems)	 The EU's Landfill Directive obliged Member States to reduce biodegradable waste sent to landfills by 35% (relative to 1995 levels)²
		 Incentives for technology deployment Private or public incentives, e.g. commercial contracts to procure electricity/heat from landfill gas capture projects, tax credits for energy generation	 The US government provides a corporate tax credit up to 1.5 cents/kWh for electricity generated from landfill gas³

Sources/notes: 1) "The Sleipner CCS Project" (C&C Reservoirs, accessed May 2025). 2) "Biodegradable waste" (European Commission, accessed May 2025). 3) "Renewable Electricity Production Tax Credit Information" (US EPA, 2024)

Agenda

- Introduction to work program
- Carbon-capture: Direct Capture and Point Source
- Bioresources
- End-of-life management
- **Scenarios and next steps**

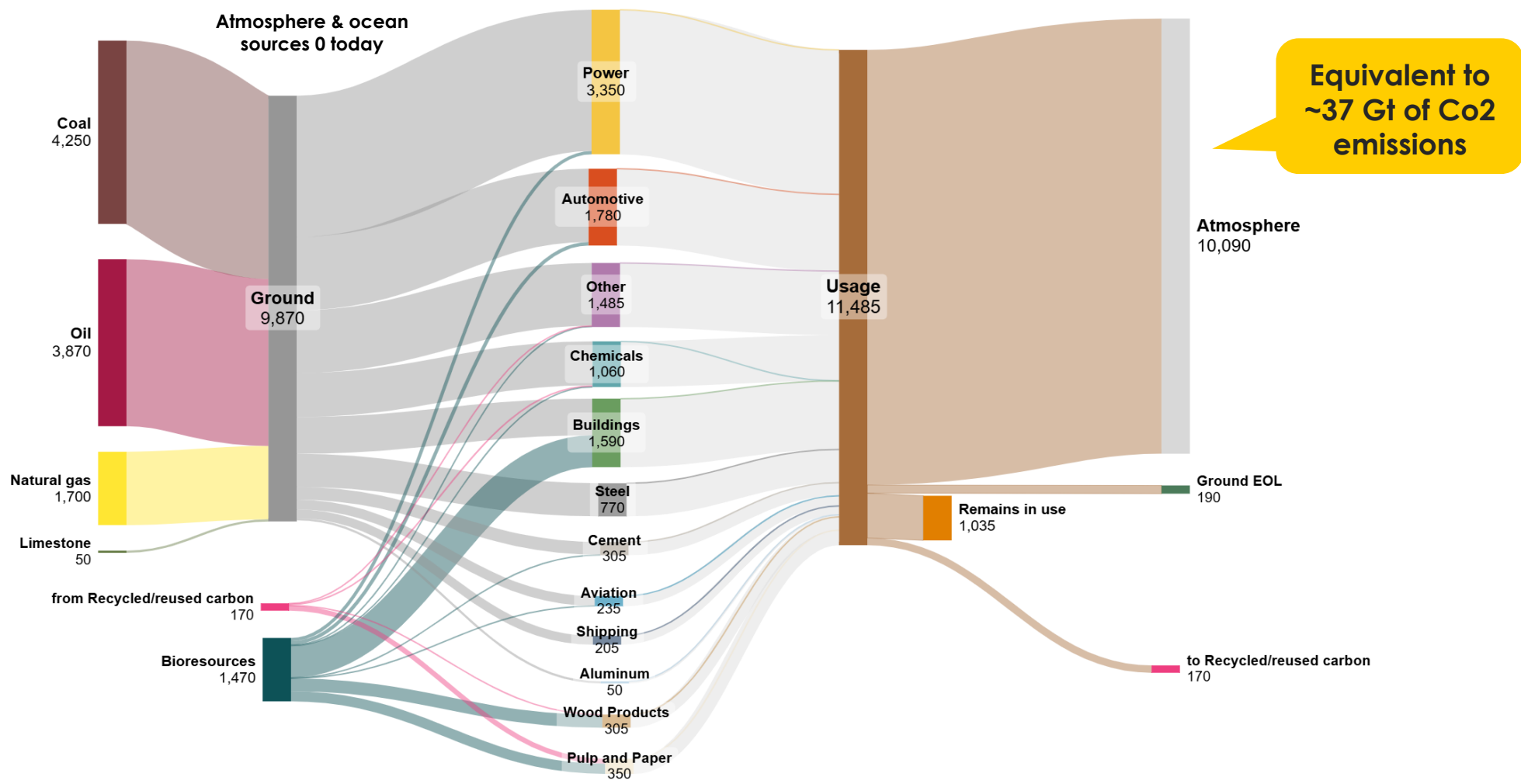


Our starting point today: A majority of our carbon is coming from the ground and ending in the atmosphere

Preliminary

Carbon source and destination for the Energy and Materials Sectors today, Mt C

Today



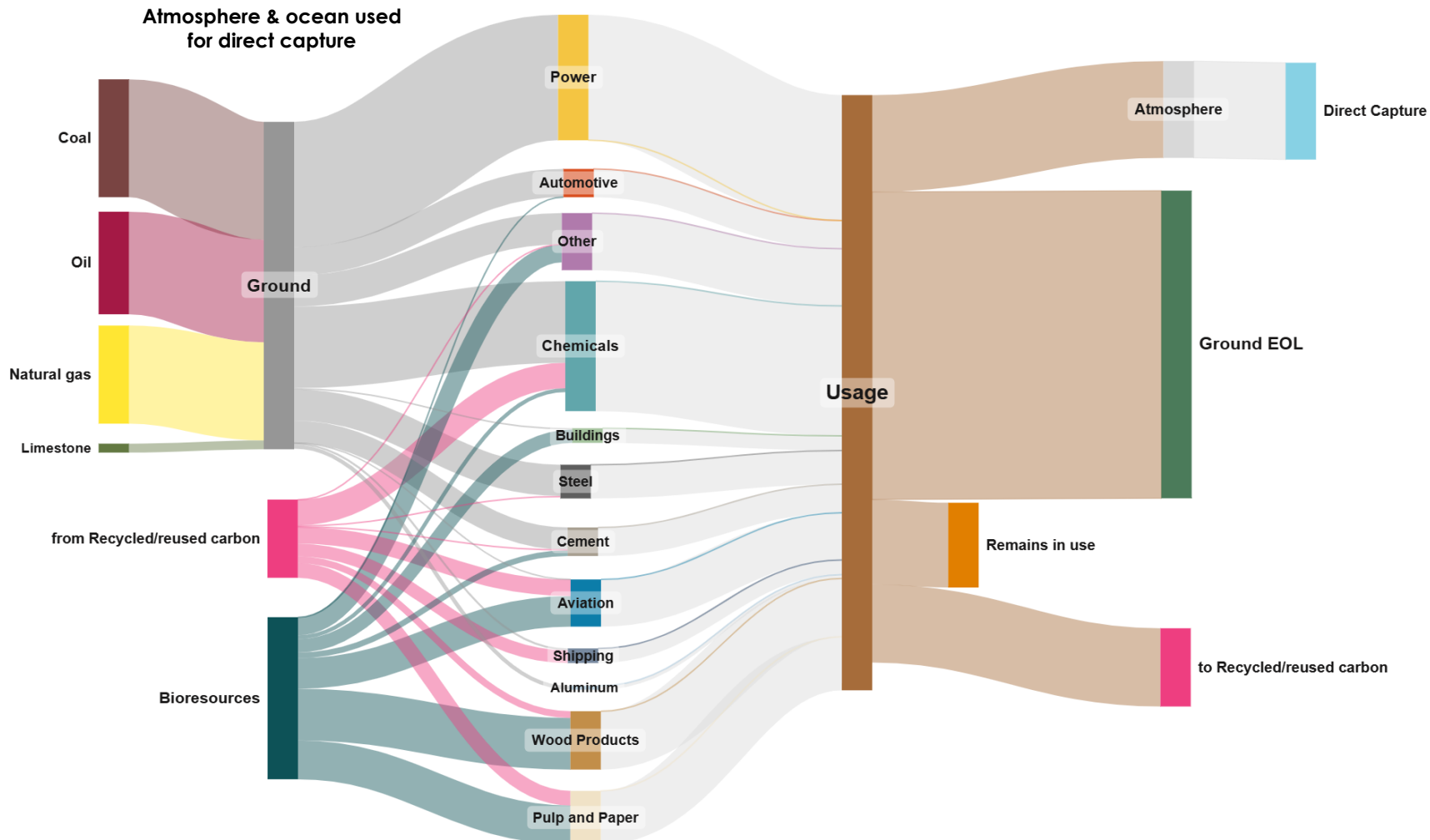
Source: Systemiq analysis for the ETC (2025)

From our exploration of innovations from this program of work, what does the potential system look like?

Preliminary

Carbon source and destination for the Energy and Materials Sectors, ACF mid-century, Mt C

Mid-Century
Illustrative



Scenario analysis will answer

How could different innovation change the way our systems look?

What are the different trade-offs of such systems?, e.g. costs



Source: Systemiq analysis for the ETC (2025)

Scenarios will be combined across the three phases of work

Scenario explored across phases

Phase 1

How much can we reduce carbon energy by maximising electrification



Net Zero Baseline

- Accelerated but Clearly Feasible (ACF)
- ETC's most conservative decarbonization scenario

Unconstrained electrification

- Disruptions reduce carbon molecules in energy mix including
 - High temperature industrial heat
 - Electrification of iron/steel making
 - Solid State batteries

Phase 2

What is total carbon demand and how much of it can be circular



Baseline (more linear system)

- Less ambitious mechanical recycling targets
- Chemical recycling remains niche
- CCU becomes prevalent only in a few sectors (e.g. aviation, shipping, some chemicals)

Stretched circularity

- A global, whole-lifecycle, binding Plastics Treaty is adopted by UNEP
 - Demand reduction up to 30%
 - Globally ~60% of plastic waste sorted
 - Chemical recycling scales up
- Current best-in-class targets for recycling of other materials
- CCU is maximized across all eligible demand sectors

Phase 3

How do we sustainably source primary carbon & manage carbon at end of life



High biomass supply

- Biotech innovations are realised
- Land freed up for energy biomass
- More sectors use biomass vs baseline decarbonizations scenario

Linear system

- Point source + storage remains inexpensive
- CCU routes remain expensive
- Recycling chemicals remains challenging
- Advanced landfill cost-effective

Primary fossil carbon minimization

- Unconstrained electrification + stretched circularity (phase 1 and 2)
- High biomass supply
- Cost effective DAC



Next steps



Calculate and compare a **scenarios** for primary supply sourcing



Explore the **trade-offs** between different scenarios



Develop **innovation briefs** on key technologies



Report draft to members in the summer

