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

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- **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	Q4
Workplan	**Phase 1A** How large can and should the **role of direct electrification** be in a zero-emission economy **Phase 1B** **The role of hydrogen** and **derivatives (i.e., ammonia)** in a zero-emission economy?	**Phase 2** The potential to **recycle** and **reuse carbon molecules**	**Phase 3** **Sources** of **primary carbon: costs** and **sustainability** and **end-of life carbon management**	**Phase 4** **Report production and communication campaign running into COP30**	
Deliverables	• A 5-pager published externally • A series of short innovation briefs for publication	• A 5-pager published externally • Report chapter • Innovation brief(s)	• A 5-pager published externally • Report chapter • Innovation brief(s)	• Publication of the ETC report ahead of COP • A series of short innovation briefs for publication	
Key interactions	• 1-2 workshops with ETC Commissioners	• 1-2 workshop with ETC reps/ commissioners	• 1-2 workshop with ETC reps/ commissioners	• Workshop • Report reviews • Report launch at COP	

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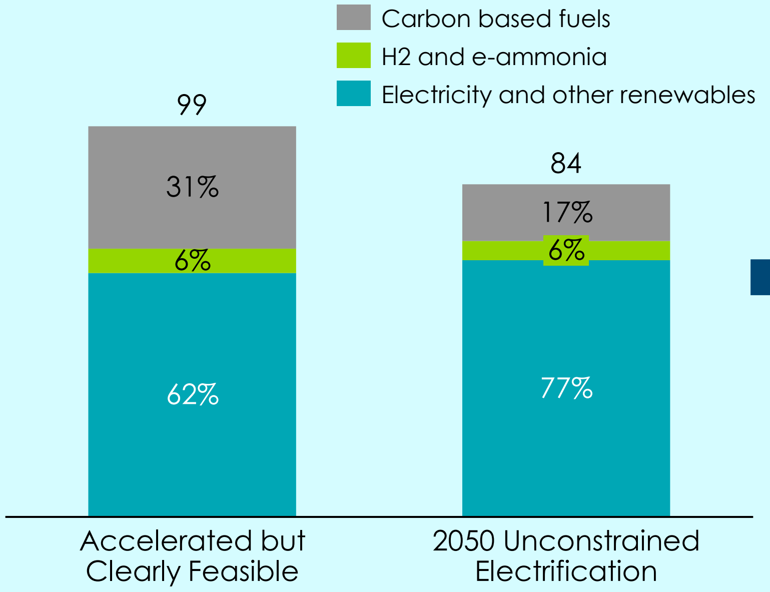
Outputs of the first two phases of work inform phase 3 analysis

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

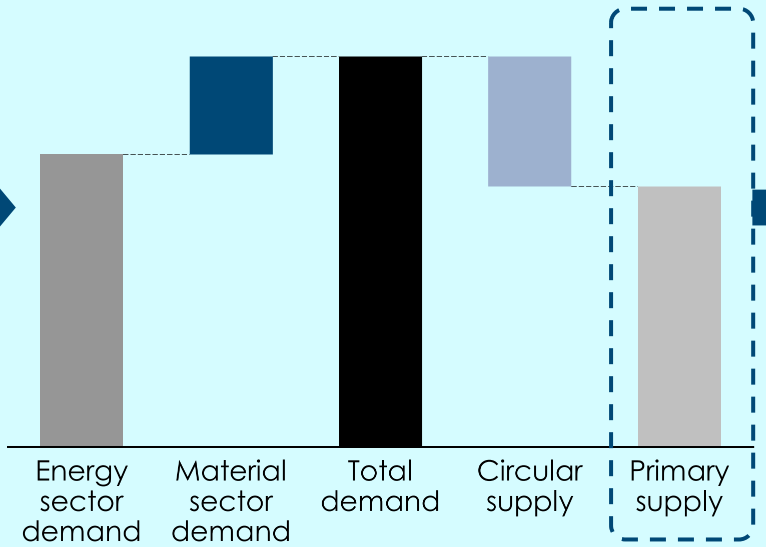
Phase 2
What is total carbon demand and how much of it can be circular

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

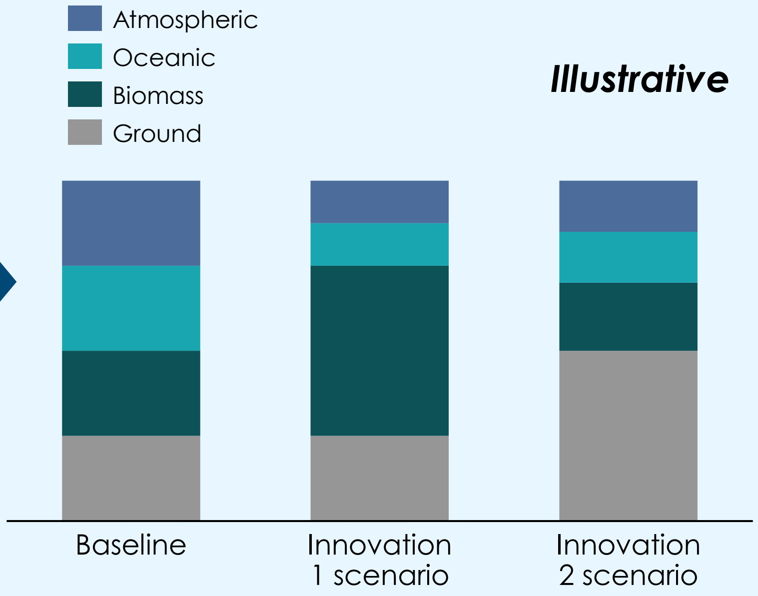
Final Energy Demand for ETC's ACF scenario in 2050
Thousand of TWh



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 CO_2/y
- Investment requirements for such as system are X

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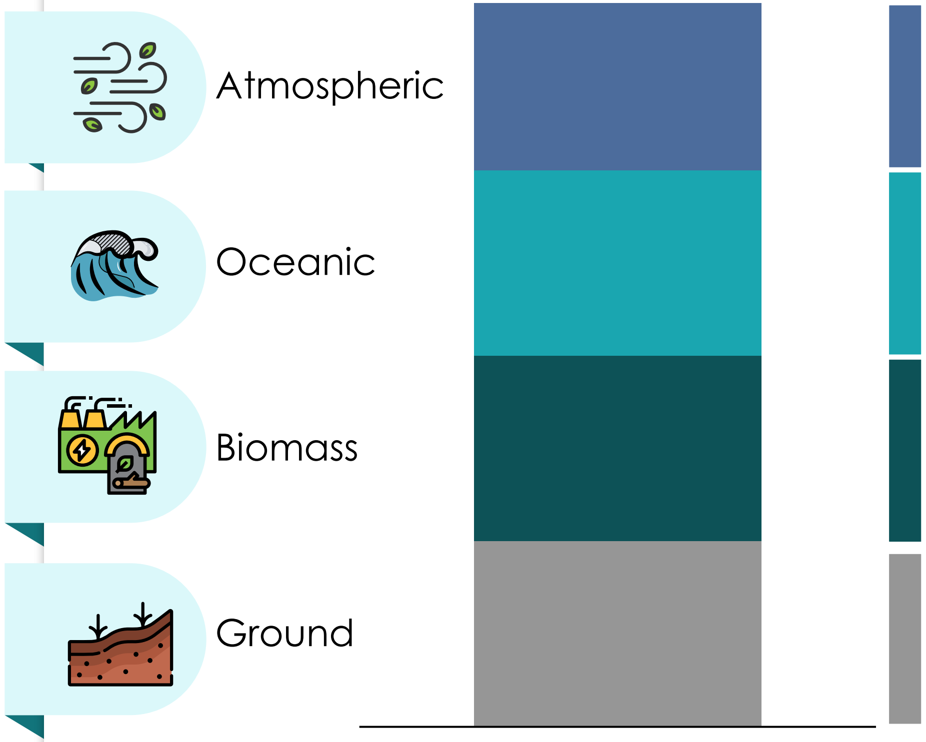
The analysis will focus on sustainable pathways for primary carbon sourcing and end-of-life carbon management

Sources of primary carbon supply

Illustrative



Direct capture + utilisation/storage

Biomass that meets sustainability criteria (e.g. not competing with other critical land-use)
+ point source capture
+ utilisation/storage OR **landfill**

Fossil + point source capture + utilisation/storage
OR
Fossil + landfill

Our analysis will focus on key questions and technologies related to sustainable supply and end-of-life carbon management

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 C**[1] But not yet economically accessible	**Direct Air Capture** Liquid and solid sorbents *(benchmark technology)*		***Cross-cutting carbon sources*** **CO_2 storage** • Depleted oil and gas fields and saline aquifers *(benchmark technologies)* • Sub-sea CO_2 injection • CO_2 to stone **Advanced landfill**
2. Oceanic	**~38,000 Gt C**[2] But not yet economically accessible	**Ocean-based CDR** Electrochemical separation		
3. Bioresources	**~550 Gt C**[3] But only an estimated **1.04 Gt** sustainable supply[4] 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 C**[5] Estimated recoverable		**Point Source capture** Liquid absorption *(benchmark technology)* Process modification Calcium Looping	

Notes/sources: 1) Assumes 425 ppm CO_2 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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- Bioresources
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Carbon capture technologies

Summary: CO_2 capture technologies

1. **Recent estimates suggest that the levelized cost of DAC could be up to 5× higher than previously expected by 2050.** High CAPEX remains the main barrier to large-scale deployment.

2. **o-CDR may be 60% lower cost than DAC by 2030, making it a valid alternative for direct CO_2 capture from the atmosphere.** However, this depends heavily on revenue from hydrogen byproduct sales.

3. **The power and cement sectors have the highest need for point source capture – as per ETC 2022 study – and also face the highest levelised CO_2 capture costs.**

4. **Process modification via the Allam-Fetvedt cycle is a promising CO_2 capture option for fossil power plants, offering a levelized cost of electricity comparable to that of conventional plants when 90$/t$CO_2$ carbon tax is applied.** However, implementation requires the construction of a new power plant.

5. **Calcium looping is the most economical emerging technology for cement plants offering strong integration potential. The levelized cost of capture is ~25% lower compared to current post-combustion methods.**

6. **Reliance on fossil carbon means 20–25% of emissions could remain unabated, even with 90% capture rates.** This is due to upstream and downstream emissions that capture technologies cannot address.

7. **Realising CO_2 capture systems requires four enablers:**

   - **Invest in technological innovation** in solvents and sorbents to improve capture rates and reduce energy consumption, bringing down overall costs.
   - **Enable Integration** of capture systems in existing industrial infrastructure—especially in steel and cement—can cut costs by up to 50% compared to standalone systems.
   - **Develop infrastructure** of CO_2 transport and storage to reduce handling costs and support widespread, reliable deployment.
   - **Implement supportive regulation** and finance, including carbon pricing, targeted subsidies, and robust MRV and liability frameworks, to unlock investment and ensure long-term viability.

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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	Carbon 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

Source: Systemiq Analysis

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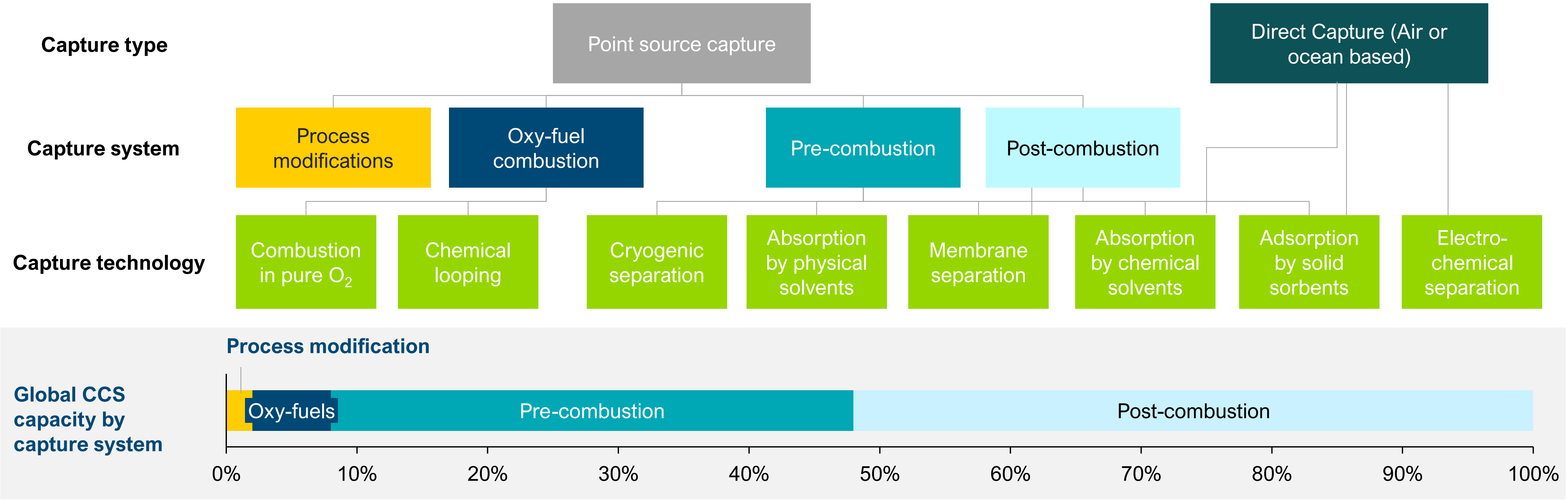
Despite a broad technology landscape, global carbon capture is dominated by pre- and post-combustion systems

Standard carbon capture technologies



Source: Systemiq for the ETC (2022), Cancawe (2018) Technology scouting – carbon capture

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

	Benefits	Challenges
Process modification	• Low operational cost and maintenance requirement • Very high CO_2 capture efficiency	• Potentially high CAPEX • **Limited to new process designs**
Oxy-fuel combustion	• Lowers mechanical failure risk • Generates near-pure CO_2	• Sourcing O_2 is expensive if waste streams unavailable • Potentially **high CAPEX for retrofit**
Absorption	• The most mature technology, widely in operation • Can reach high absorption efficiency (> 90% vol. CO_2)	• **Energy intensive** and potentially costly solvent regeneration • Solvents easily degraded by contaminants (e.g. SOx, NOx)
Adsorption	• Sorbents can regenerate at lower temperatures meaning lower energy costs and reduced waste	• Relatively high material costs (solid amines) • **Low selectivity of CO_2** over other gases (N_2, CH_4, H_2O)
Membranes	• Low maintenance requirement, easily installed at any stage • Low energy requirement	• **Low capture efficiency** at low partial pressure – requires flue gas recycling or additional membranes
Cryogenic Separation	• Mature technology, commercially used • Extremely high CO_2 recovery rates (99.99%)	• Risk of process blockage (due to ice or solid CO_2) • **High energy requirement** due to very low temperature large
Electrochemical	• Fully electrified operation facilitating renewable operation • Potential for high selectivity and very low energy requirements	• 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 CO_2 capture technologies which have the greatest potential to cut costs and accelerate deployment

Category		Technology	Process	TRL	Companies *Non-exhaustive examples*
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
Direct capture	Emerging technology	2 Ocean-based CDR	Electrochemical processes or contactors to extract CO_2 directly from seawater.	5-6	captura, Equatic, SeaO2
Point source capture		3 Liquid absorption	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, Aker Carbon Capture, carbon clean, Svante, Inventys
Point source capture		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
Point source capture	Emerging technologies	5 Calcium looping	Transformative techniques capturing CO_2 with lime by forming $CaCO_3$, then regenerated or burning fuel in pure oxygen	6-7	Air Products, ExxonMobil
Point source capture	Emerging technologies	6 Process modification (Allam-Fetvett 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

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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	TRL
Solid sorbent *Low Temperature heat*	• Novel sorbent materials with improved stability and reaction kinetics • Improve absorbent conductivity and heating efficiency	• Climeworks has 12 DAC pilot plants in operation, among which the largest DAC facility in Iceland (36 ktonsCO_2/y). • Plans for scaling up to **100 ktCO2/y until 2035.**	climeworks	**8-9**
			Global Thermostat	7-8
			GreenCap Solutions	7
			SUSTEON	4
			Kawasaki	4
Liquid solvent *High capture rate*	• Improve configuration for better flow pattern to improve performance and energy consumption. • Novel solvents (ionic liquids, phase change) • Limit corrosion in amine capture plants.	• Carbon engineering project in Texas aiming to capture up **to 1 MtCO_2/y in late 2025.**[1,2]	Carbon Engineering	**7-9**
			CSIRO	4
Electrochemical Electrified	• Development of ion-selective membranes that can drop the costs due to weaker bonding of the CO_2 on the capturing material. • Development of continuous process	• Start-ups developments using electro-swing adsorption or ion-selective membranes show potential of 3-4x reduction in energy consumption. • The technology has only been tested at **laboratory scale.**	Mission Zero Technologies	4
			VERDOX	3-4
			Bi-Polar Membrane Electro-Dialysis technology	2-3

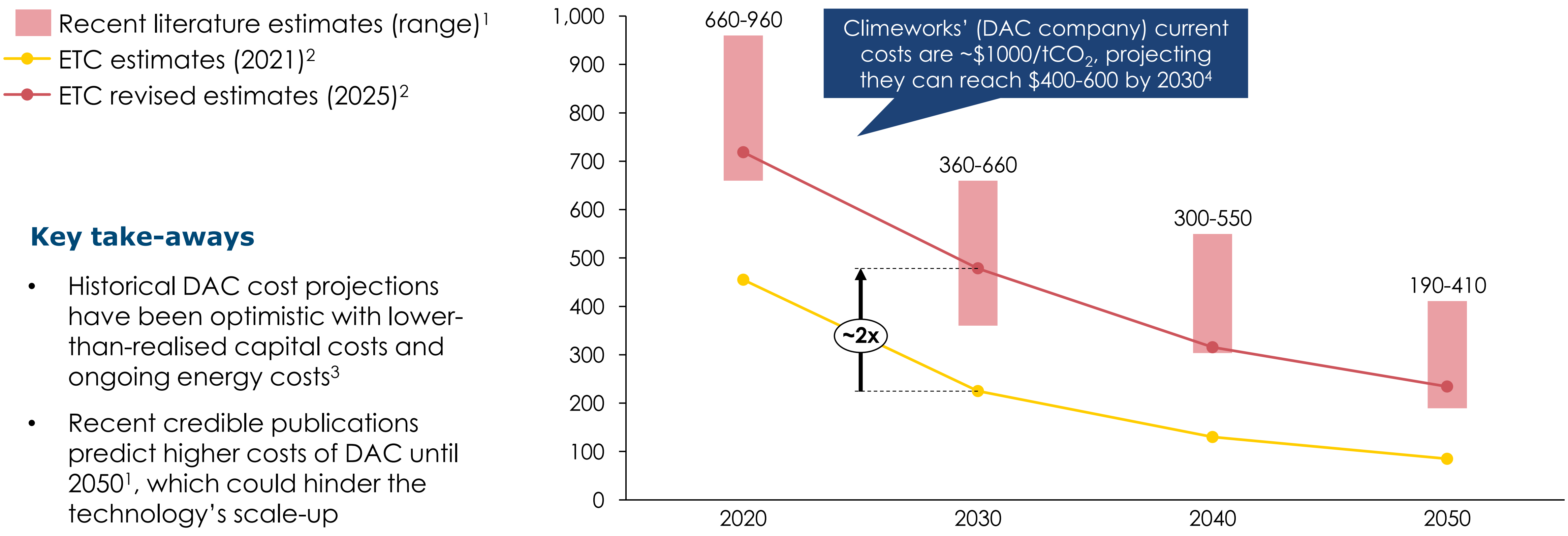
Notes: BPMED=Bi-Polar Membrane Electro-Dialysis technology
Sources:1) https://carbonengineering.com/news-updates/deployment-approach/ 2) https://decarbonfuse.com/posts/stratos-the-future-of-direct-air-capture-nears-completion 3) Filippo Bisotti et al. (2024) Direct Air capture (DAC) deployment: A review 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

2025 ETC Estimates Highly Preliminary

Levelised cost of CO_2 capture via DAC – projections 2020-2050

$/tCO2



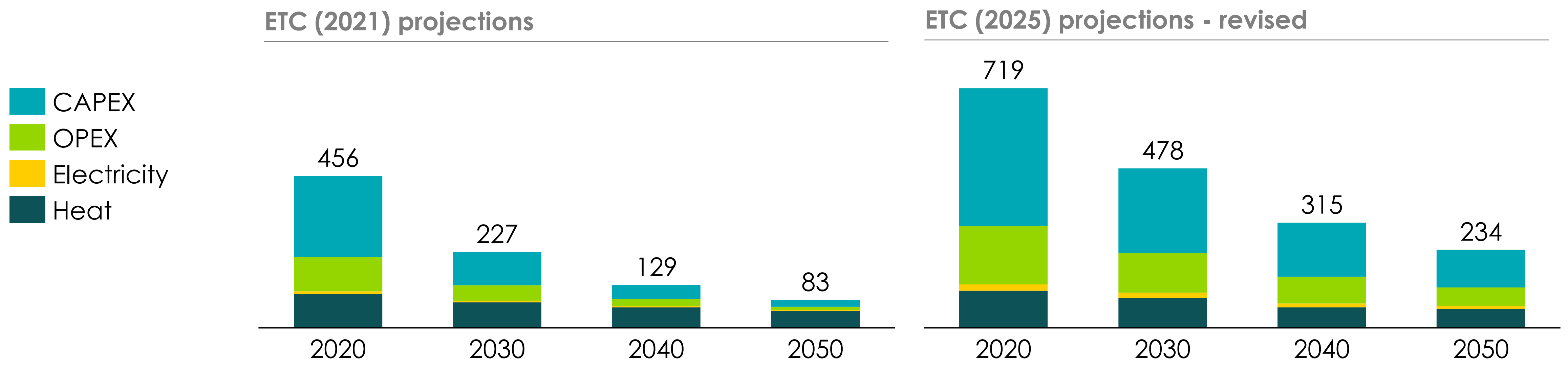
Key take-aways

- Historical DAC cost projections have been optimistic with lower-than-realised capital costs and ongoing energy costs[3]
- Recent credible publications predict higher costs of DAC until 2050[1], 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 DACC 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)

We have revised upwards our internal ETC estimates for the cost of DAC, factoring in real-world project CAPEX to replace literature estimates

Estimated levelised cost of direct air capture by cost driver, $/tCO_2$



Updated assumption		ETC (2021)	ETC (2025)	Comment / rationale
CAPEX $ / (tCO2/annum)	Current	1,470	2,500	Upwards revision of CAPEX based on real-world project[1]
	2050	140	800	Based on learning rate below
Learning rate % capex cost reduction each 2x increase of annual capacity deployed		12%	6%	Adjusted assumption downwards to align overall costs more closely with projected costs[3]
Electricity consumption kWh / tCO2	Current	250	370	Upwards revision of electricity consumption based on latest research and anticipated future technology trends[2,4]
	2050	180	230	

Notes/sources: 1) "Climeworks opens the world's largest carbon-capture facility in Iceland" (2021); 2) "Atmospheric alchemy: The energy and cost dynamics of direct air carbon capture" (Ozkan, 2024); 3) Previously applied learning rates vary widely and often refer to other low-carbon technologies such as solar and wind, due to limited historical data. Using single component learning rates has its limitations, e.g. assuming learning across all components, overlooking that some components are already widely used. 4) Electricity/heat price forecasts also updated to align with comparisons across other capture technologies.

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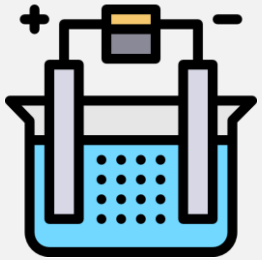
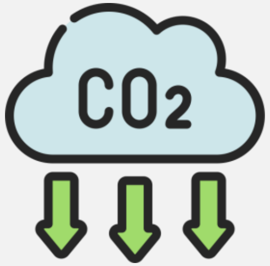
❷ Ocean-based CDR (o-CDR): removes dissolved carbon directly from seawater using a range of electrochemical processes

Overview of production process

1 Electrodialysis or electrolysis



2 CO_2 capture or precipitation



3 Neutralization and disposal of water

Electrochemical process

Electric current is used to create two streams: one **acidic** (rich in H^+) and one **alkaline** (rich in OH^-).

In case of electrolysis a H_2 by-product is produced.

CO_2 capture

CO_2 is removed from seawater, creating a deficit that enables the **ocean to absorb more atmospheric CO_2** - either during the treatment process or after the water is discharged back into the sea.

Return to Ocean

Seawater is **neutralized** before being returned to the ocean . This prevents potential disruption of the marine ecosystems.

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 CO2*	*~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: CO_2 binds with solvent/sorbent (like MEA) in a reactor. Desorption: The CO_2-rich solvent/sorbent is heated to release CO_2 and regenerate the solvent 2) OmnyaAlYafiee (2024) 3) Prince Aleta et al. (2023)

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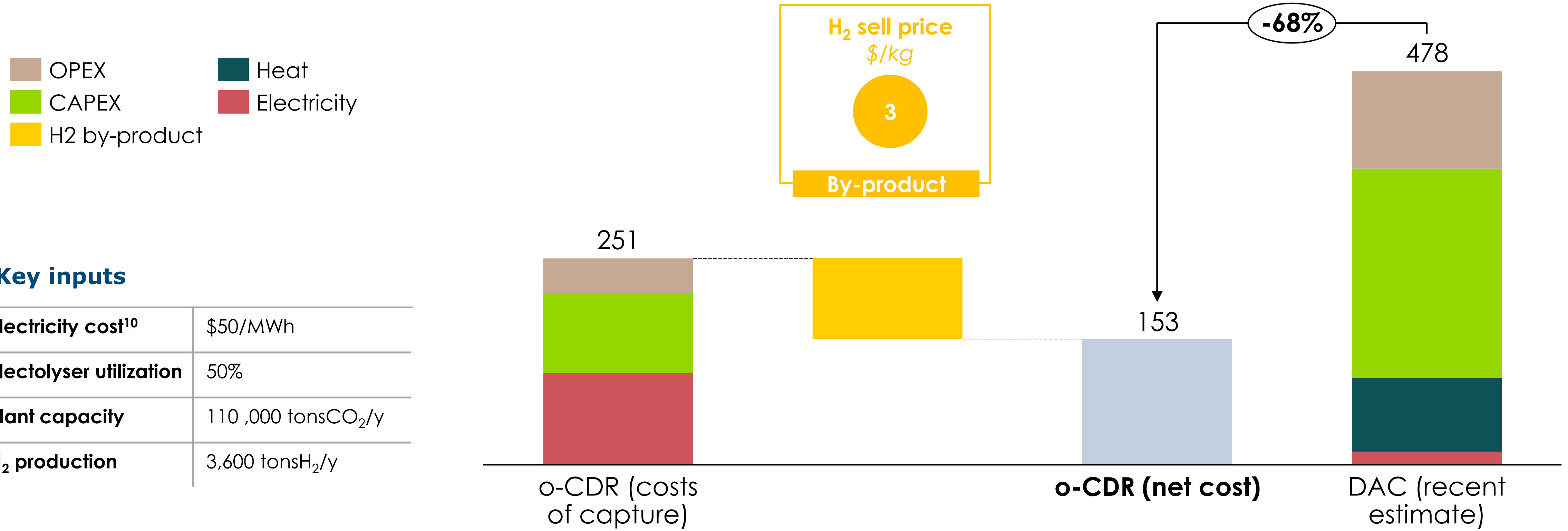
o-CDR net cost with hydrogen by-product could become more economical than DAC by ~70%

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

$/t$CO_2$



Key inputs

Electricity cost[10]	$50/MWh
Electolyser utilization	50%
Plant capacity	110 ,000 tonsCO_2/y
H_2 production	3,600 tonsH_2/y

Key takeaways on cost drivers and trends

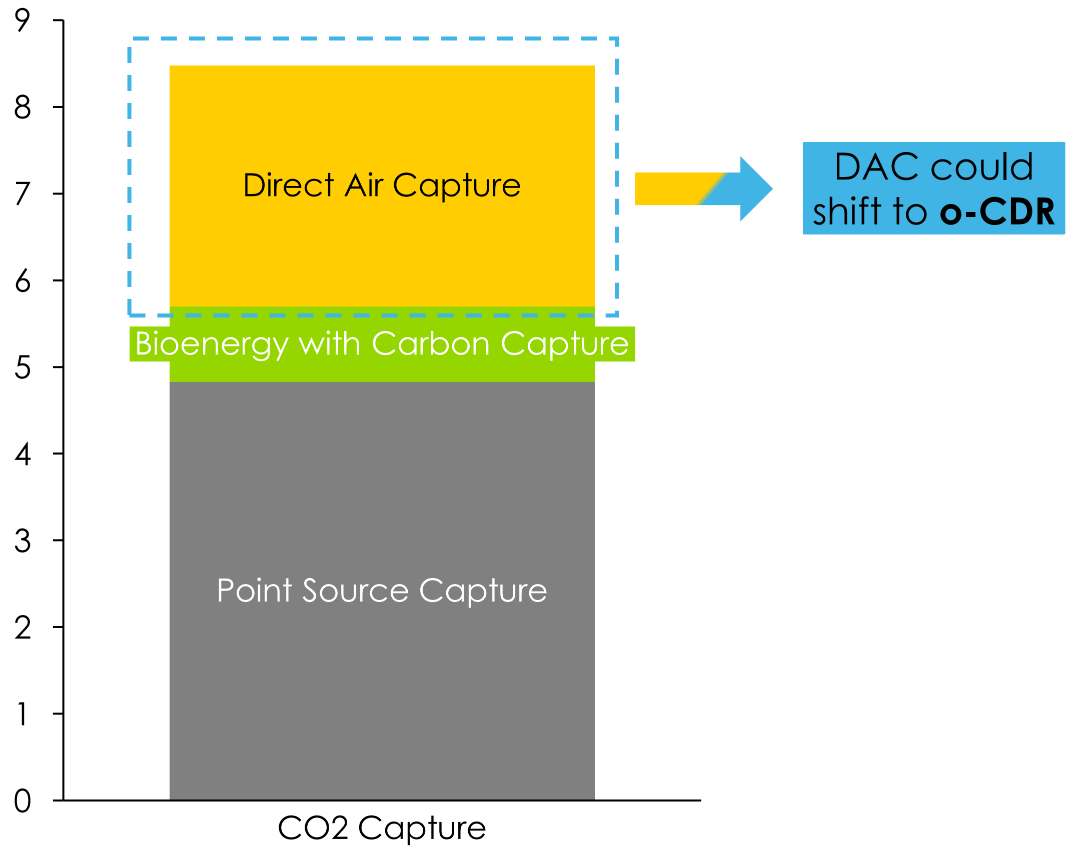
- Lower capex requirements and the valuable H_2 by-product could make o-CDR more economical than DAC. The H_2 is only produced in electrolytic o-CDR routes that involve electrolysis, and not electrodialysis process.
- Both DAC and o-CDR have high cost and scale-up risk, but DAC's stems from sorbent and 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

$GtCO_2$/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]

Notes: 1) Near coastlines to have access to water. Environmental evaluation is needed.
Sources: Systemiq analysis for the ETC (2023), ETC (2022), Carbon capture, utilisation and storage in the energy transition

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

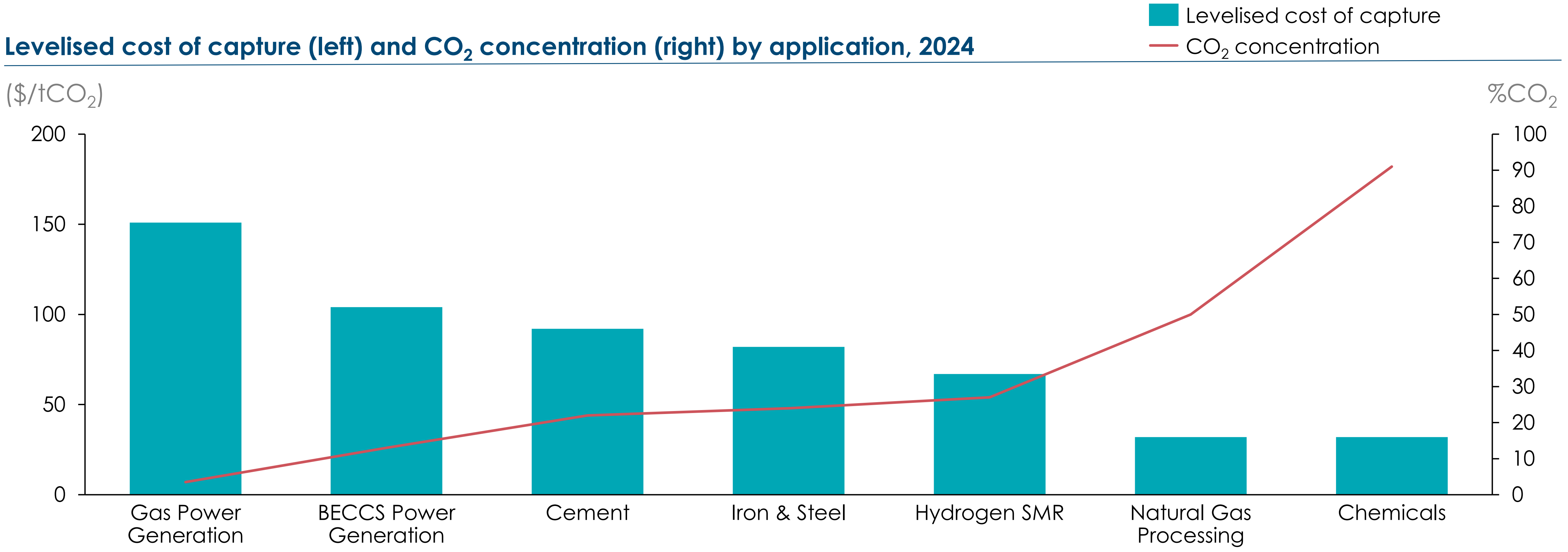
Goal	We need to believe…	Criteria for success	Evidence of progress
Rapid advancements in adoption, scaling up and cost reduction	**Technological advancements** will drive cost down and provide incentives	**Availability of low-carbon energy** Widespread availability of affordable, zero-carbon energy to power DAC/o-CDR facilities	**Already deployed DAC pilot projects by Climeworks are powered by geothermal energy[1]**
		Technological innovation Breakthroughs in sorbents and electrochemical systems to reduce energy and costs, and modular units accelerate commercialization.	**AI developments will boost screening and optimisation of new generation sorbents[2]**
		Deployment Target regions with abundant low-carbon energy but limited biomass, where DAC/o-CDR can unlock new carbon sourcing for local utilization.	**Twelve demonstrate integration with CO_2 utilisation, unlocking new markets opportunities[3]**
	Clear certification, environmental safeguards, and carbon accounting frameworks will reward negative emissions and build market demand for high-integrity carbon.	**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]	**Continuous efforts to establish durable carbon capture standards and accounting clarity. Most recent the CRCF regulation in 2024[4]**
		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.	**o-CDR pilot projects show no significant pH/ecosystem disruptions.** **Solid sorbent DAC innovations are safer and less water-intensive**

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 CO_2 and the cost of capture in different applications

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



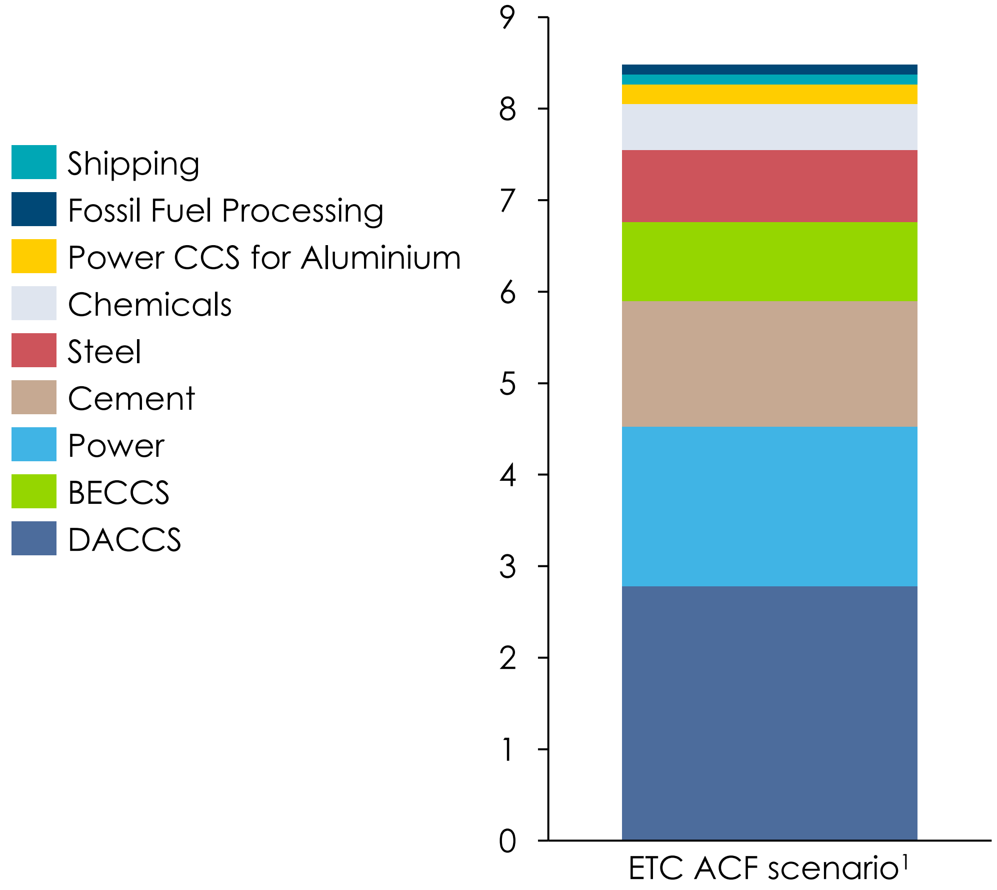
Key takeaways on cost drivers and trends

- Gas Power Generation is the costliest application to decarbonize, and it has the lowest CO_2 concentration in Point-source applications (3-4%)
- Capture costs are higher in applications with low concentrations of CO_2

Sources: ETC (2022) Carbon Capture, Utilisation and Storage in Energy Transition: Vital but Limited, Carbon tracker (2024) Curb your Enthusiasm, Bui et al. (2018)

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

Need for CO_2 emissions avoidance via point source capture by 2050 (MtCO_2 per annum)

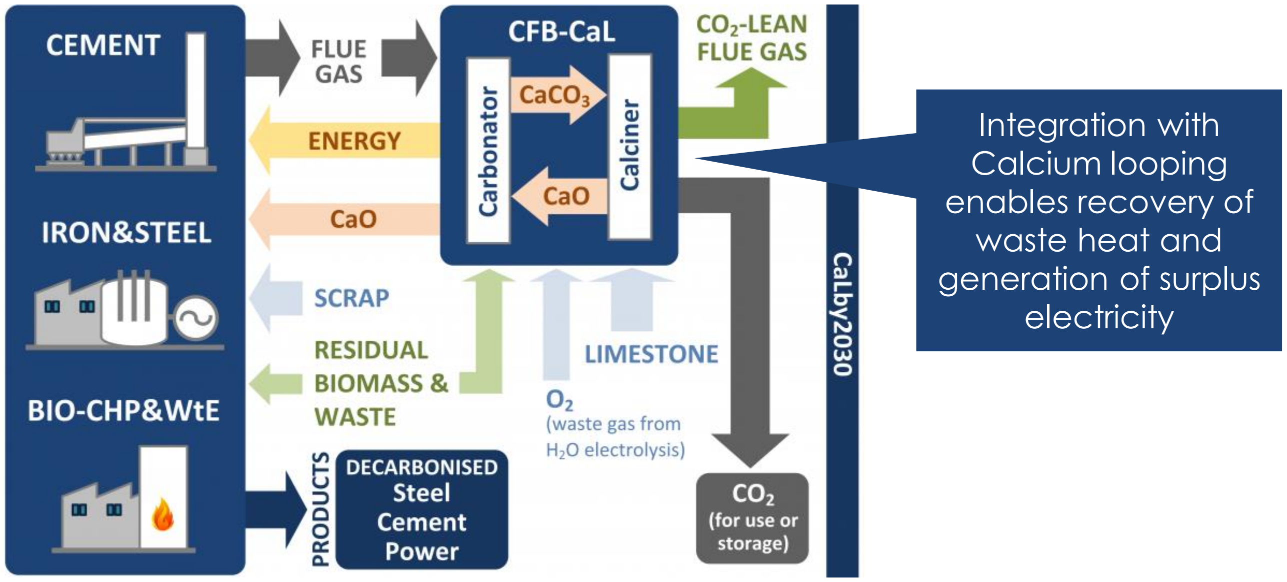


Emerging technologies that decarbonize sectors with high CO_2 capacity are evaluated:	Most applicable sectors:
Calcium looping CaLby2030 project, an EU-funded initiative involves 18 partners and aims for **commercial deployment of CaL** by 2030.	Cement Power
Process modification via Allam-Fetvedt Cycle 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

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

Overview of production process



1 CO_2 Capture (Carbonator)

CO_2-rich gas passes through a reactor with calcium oxide (CaO). The reaction forms calcium carbonate ($CaCO_3$)—capturing the carbon.

2 Sorbent Regeneration (Calciner)

The $CaCO_3$ is heated in a high-temperature reactor using pure O_2. It breaks back into pure CO_2 and CaO.

3 Loop and Reuse

The pure CO_2 is captured for storage or use. The regenerated CaO is looped back to capture more CO_2—repeating the cycle.

Comparison with widely used capture

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

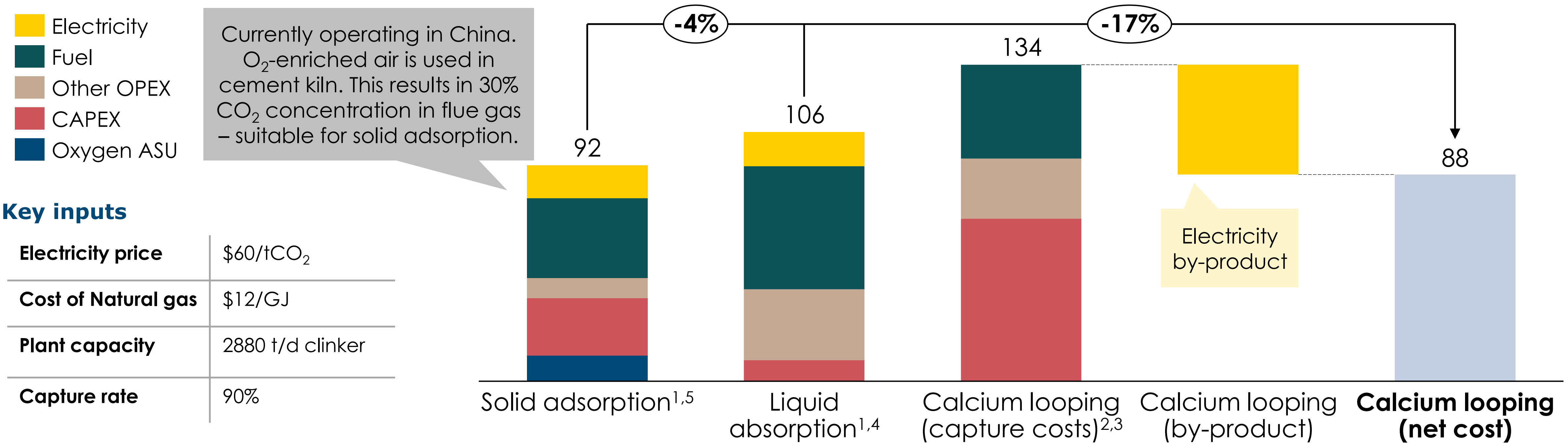
	CaL	PCC
Capture medium	*Solid sorbent (CaO)*	*Liquid solvent (MEA/amine)*
CO_2 capture rate[1]	*Typically ~90% Possible up to 99%*	*~90%*
Other emissions	*Spent CaO can replace raw materials in cement production*	*NOx emissions Methane leak Amine byproducts*
Retrofit Flexibility	*Needs hot-end integration 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 CO_2 abatement in cement process in 2025

$/t$CO_2$



Key inputs

Electricity price	$60/t$CO_2$
Cost of Natural gas	$12/GJ
Plant capacity	2880 t/d clinker
Capture rate	90%

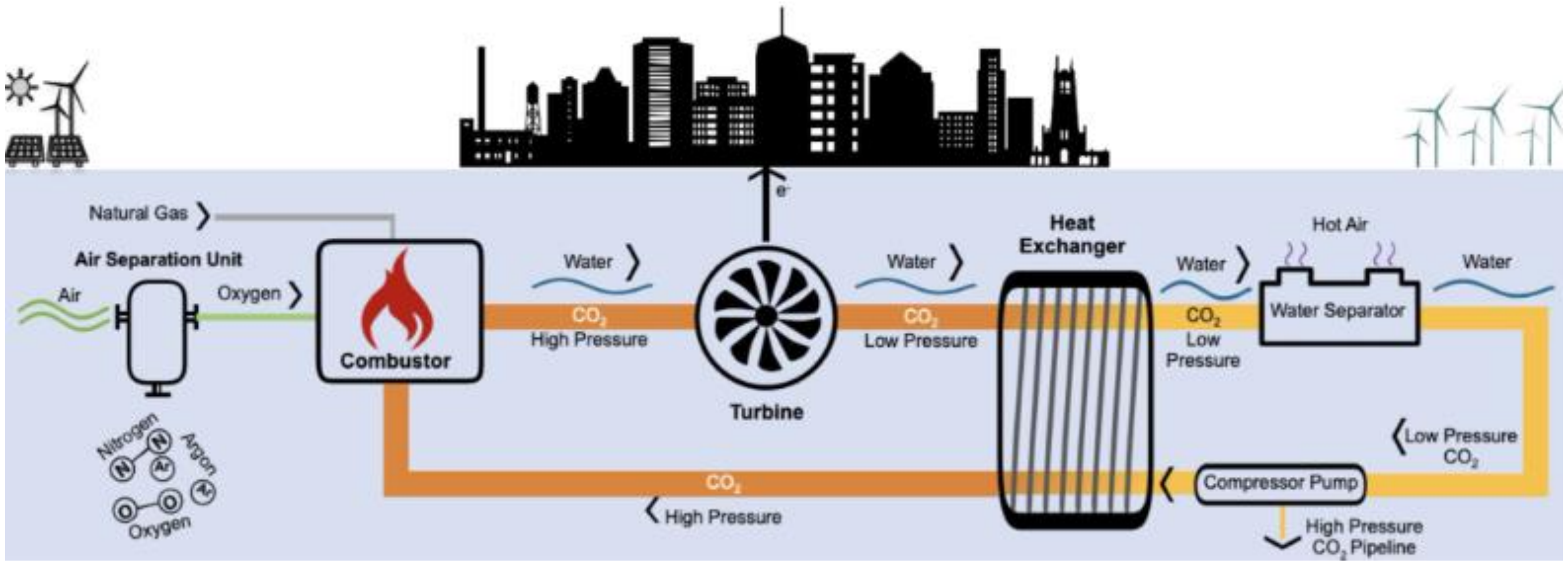
Key takeaways on cost drivers and trends

- 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 $/t$CO_2$, hence not a suitable option.
- Calcium looping is advantageous for application in cement production because it can tolerate impurities like dust, SOx, NOx 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

❻ Process modification: Captures CO_2 and utilizes it in the power production process via Allam-Fetvedt Cycle

Overview of production process



1 Combustion in pure O_2

Natural gas is combusted with pure oxygen in high-pressure, producing CO_2 and H_2. The high- temperature CO_2-H_2O 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 are removed, purifying the CO_2 stream.

3 CO_2 Recirculation and Export

A portion is compressed and utilised/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*
CO_2 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/H2*	*Natural gas; hydrogen blending in development*
CAPEX	*High (Air separation unit + CO2 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)

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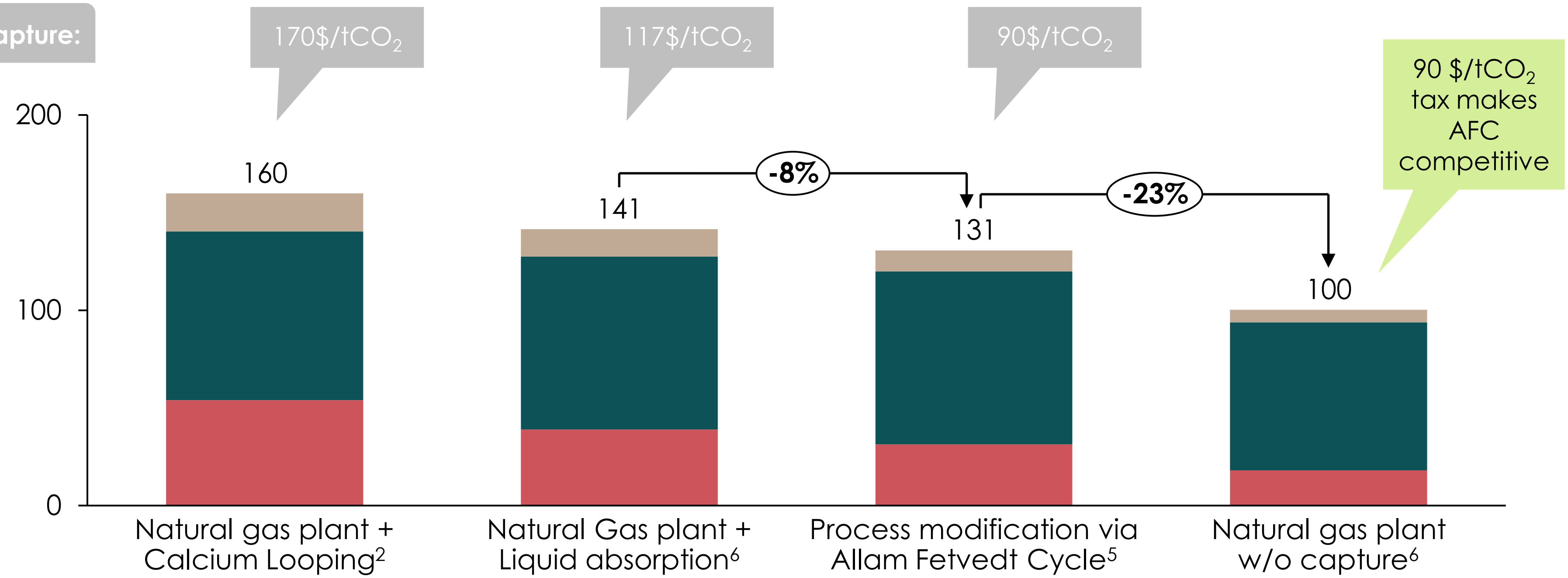
Process modification via Allam-Fetvedt Cycle (AFC) is the cheapest capture technology for power sector, being cost-competitive at 90 $/t$CO_2$ tax.

Levelised cost of electricity and planned projects for CO_2 capture in 2025

$/MWh

- O&M
- Fuel
- Capital cost



Key inputs

Cost of Natural gas[1]	$12/GJ
Plant capacities: Natural gas plant Allam plant	 650 MW 400 MW
Capture rate: Natural gas plant Allam plant	 90% 99%

Key takeaways on cost drivers and trends

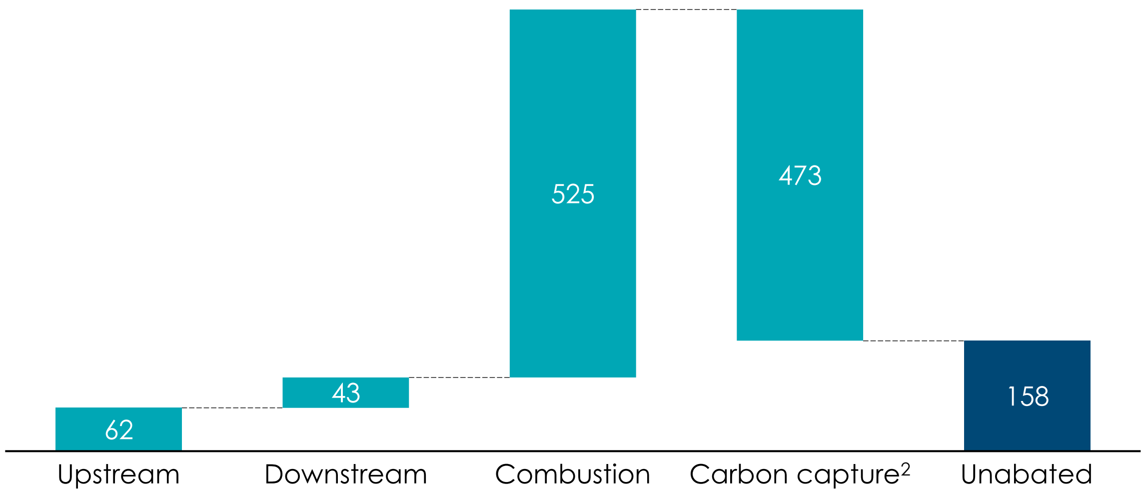
- Despite smaller plant size, Allam-Fetvedt Cycle results in:
  20% lower total capital requirement
  10% lower LCOE
- Cost of natural gas can greatly influence the results. However, the thermal efficiencies remain similar across processes, hence the comparison would not differ.
- Calcium looping costs 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 CO_2 capture technologies

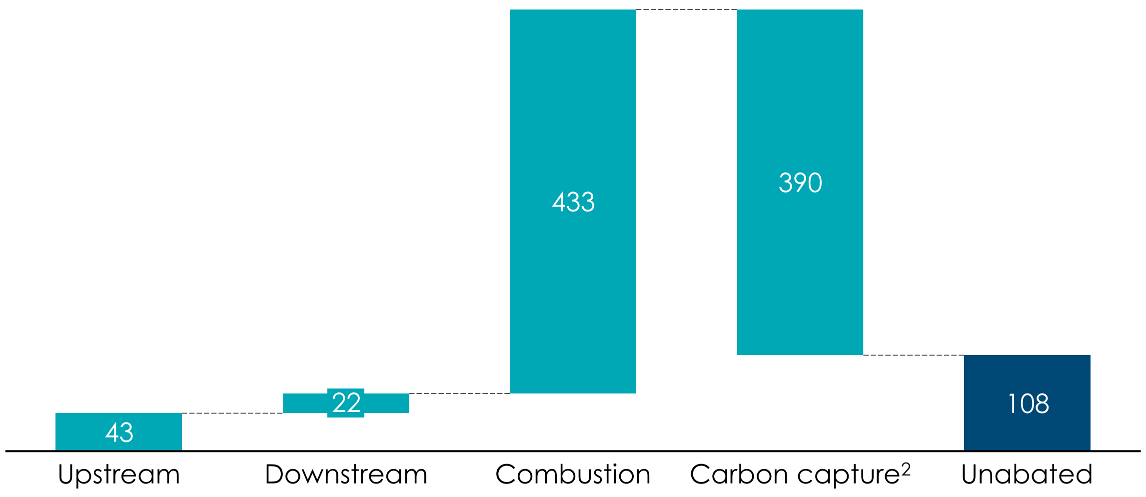
Emission intensity from oil use (2022)

kgCO_2-eq/barrel of oil equivalent[1]



Emission intensity from Natural gas use (2022)

kgCO_2-eq/barrel of oil equivalent[1]



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
Rapid scale-up of Point Source Capture across industrial and energy sectors, enabling near-term emissions reductions and supplying CO_2 for storage or utilization.	**Technological advancements** will drive cost down and provide incentives	**Technological innovation** Developments in solvents and sorbents can increase capture rates and reduce energy consumption	**New generation solvents and sorbents show great potential[2]**
		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 approaches[1]	**Pilot projects in Europe and Asia have successfully retrofitted cement and steel plants with carbon capture[3]**
		CO_2 handling infrastructure CO_2 transport and storage networks will scale alongside capture to reduce costs and enable large-scale deployment	**The Midwest Carbon Express and Northern Lights projects are scaling CO_2 transport and storage across multiple sites.[4]**
	Robust Policy, Funding, and Market Support will create a viable market and provide transparency of operation.	**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.	**U.S. 45Q tax credit, EU Innovation Fund, and UK CCS clusters are accelerating PSC deployment.**
		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 $MtCO_2$ with MRV[5]**

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

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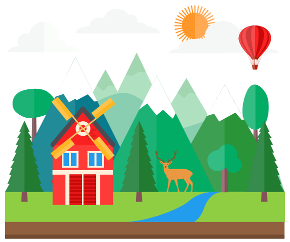
Bioresources

Biomass supply overview

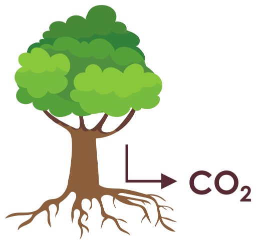
Biomass can only be considered sustainable if certain conditions are met

No competition with other critical uses of land



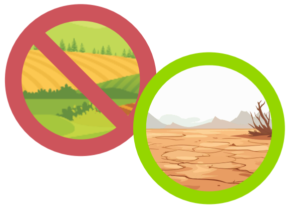
Biomass **sourcing must not displace essential functions of land**, including food production, housing and conservation

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

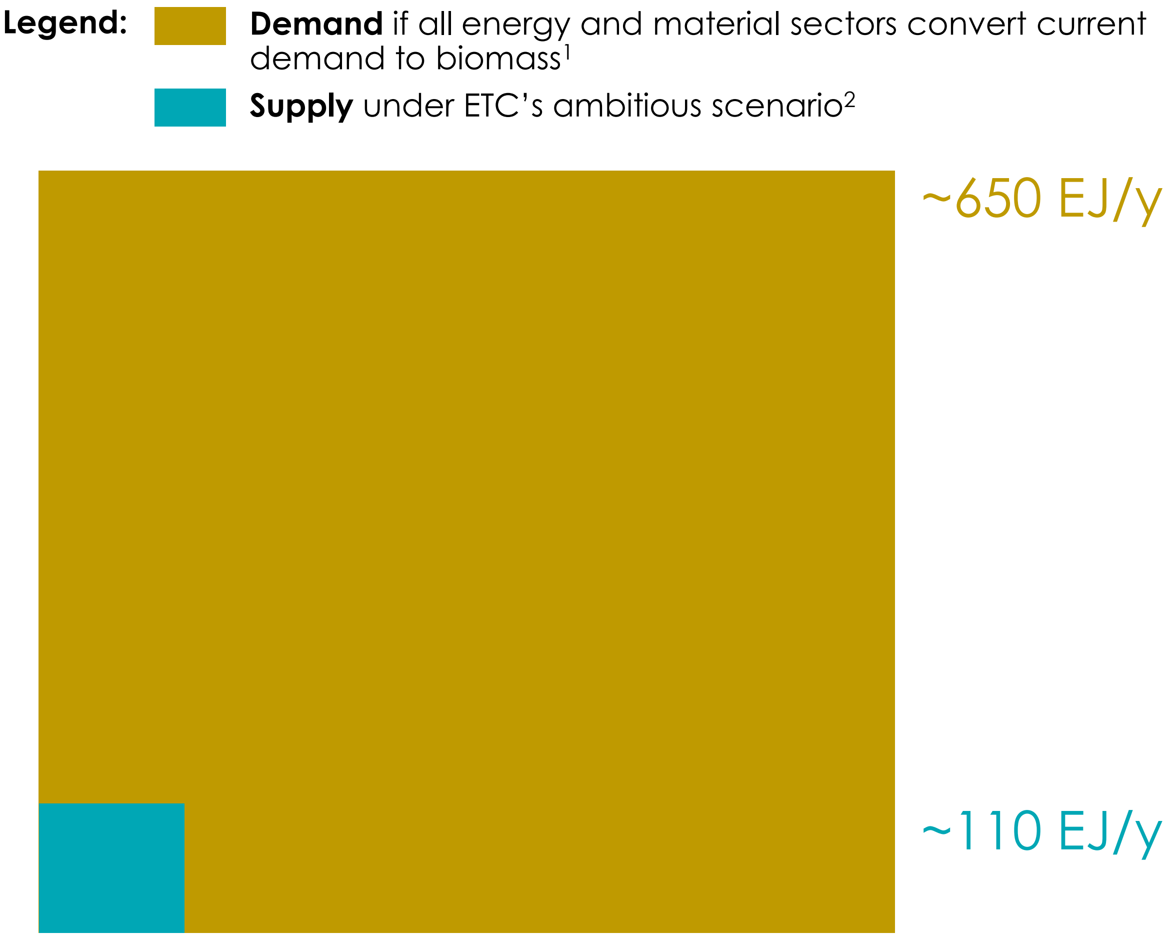
Projects must safeguard local environments and communities, delivering benefits without causing displacement or degradation

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

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



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)	▪ **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	• **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

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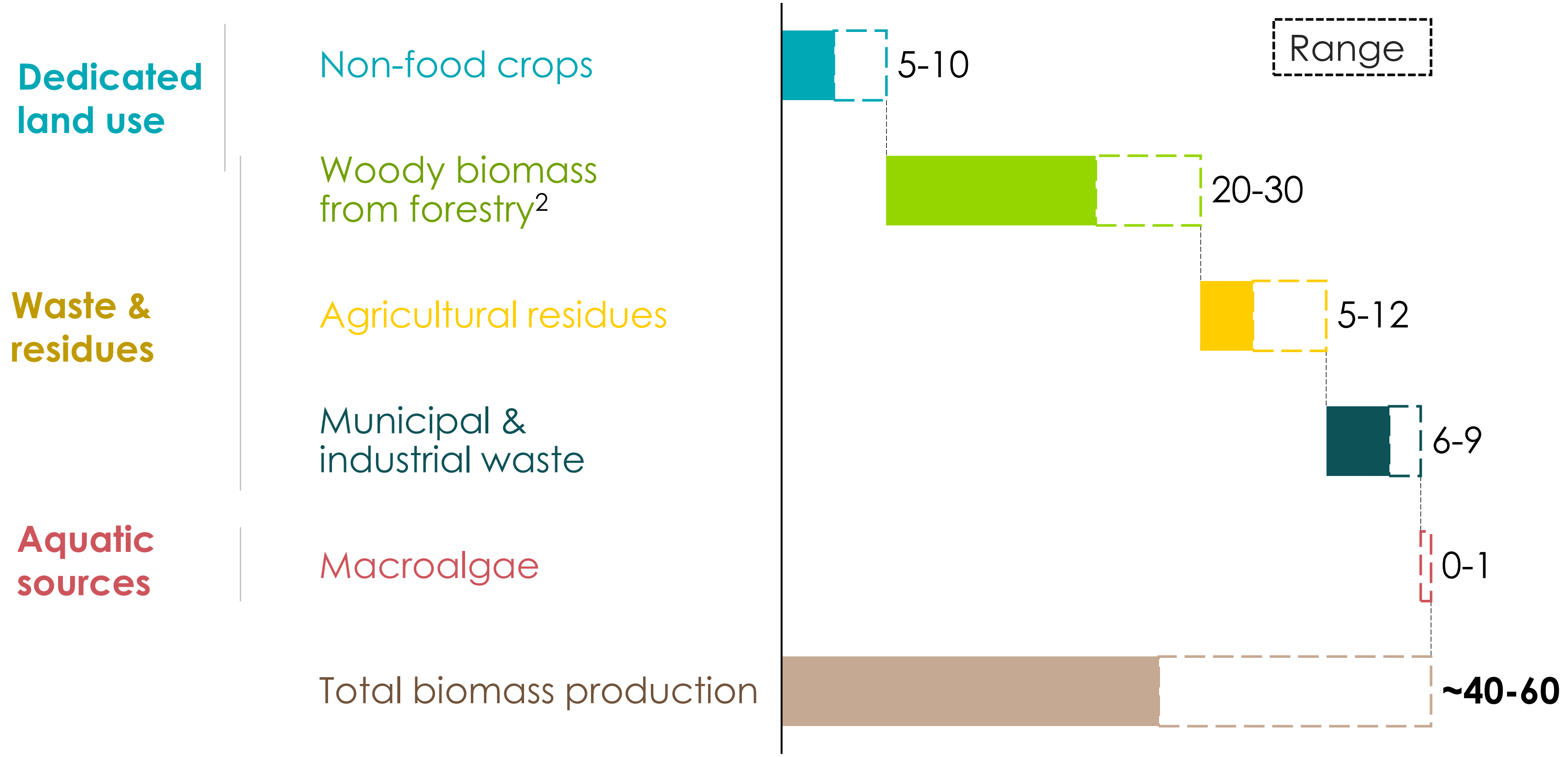
Bioresources – ETC has previously estimated prudent global supply of sustainable biomass at ~40-60 EJ/year, but disruptive innovation could change this

Global sustainable biomass[1] 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

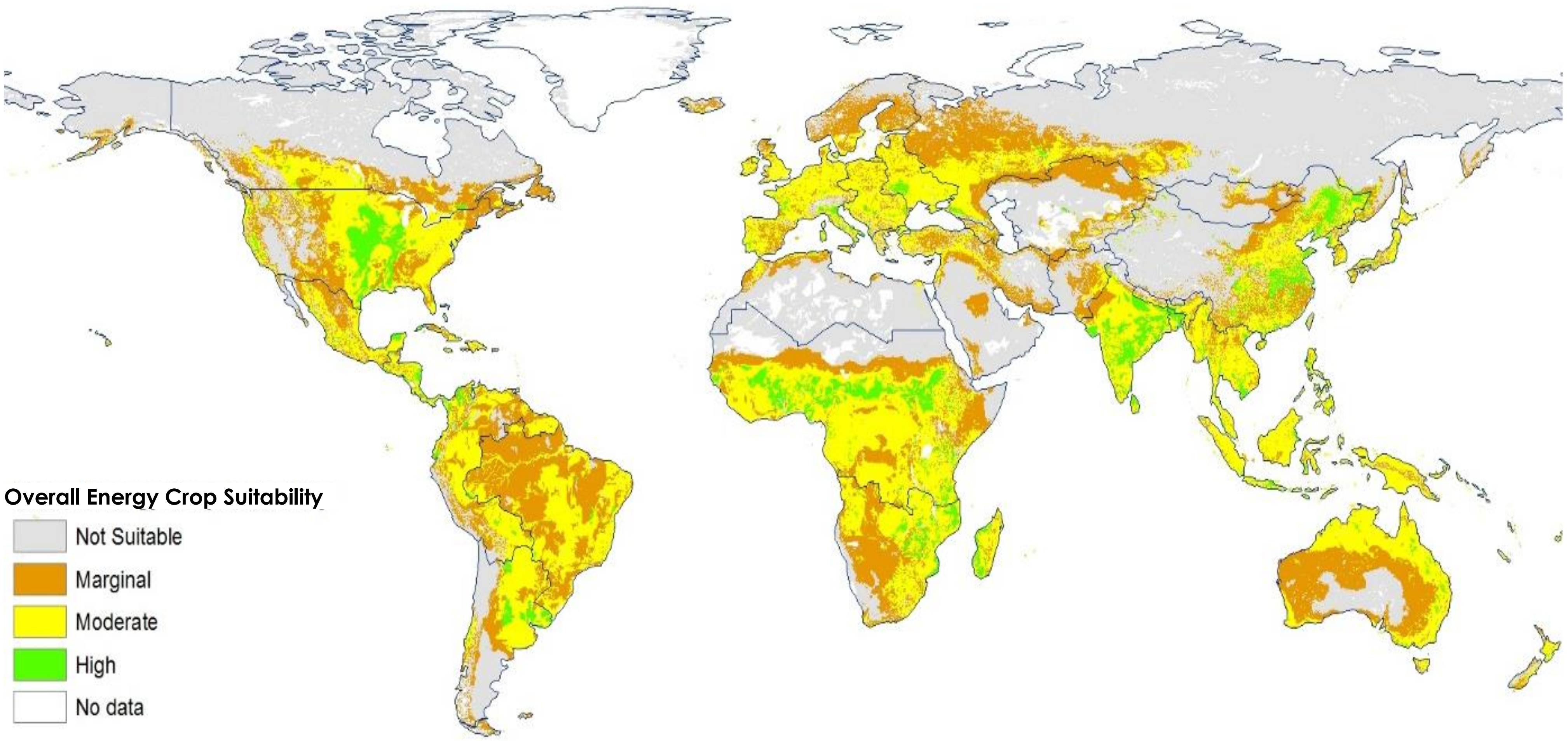
Increased collection to organic waste

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).

SYSTEMIQ

Energy crops suitability is highest in regions in India, China and the United States

Suitability of different energy crops globally today

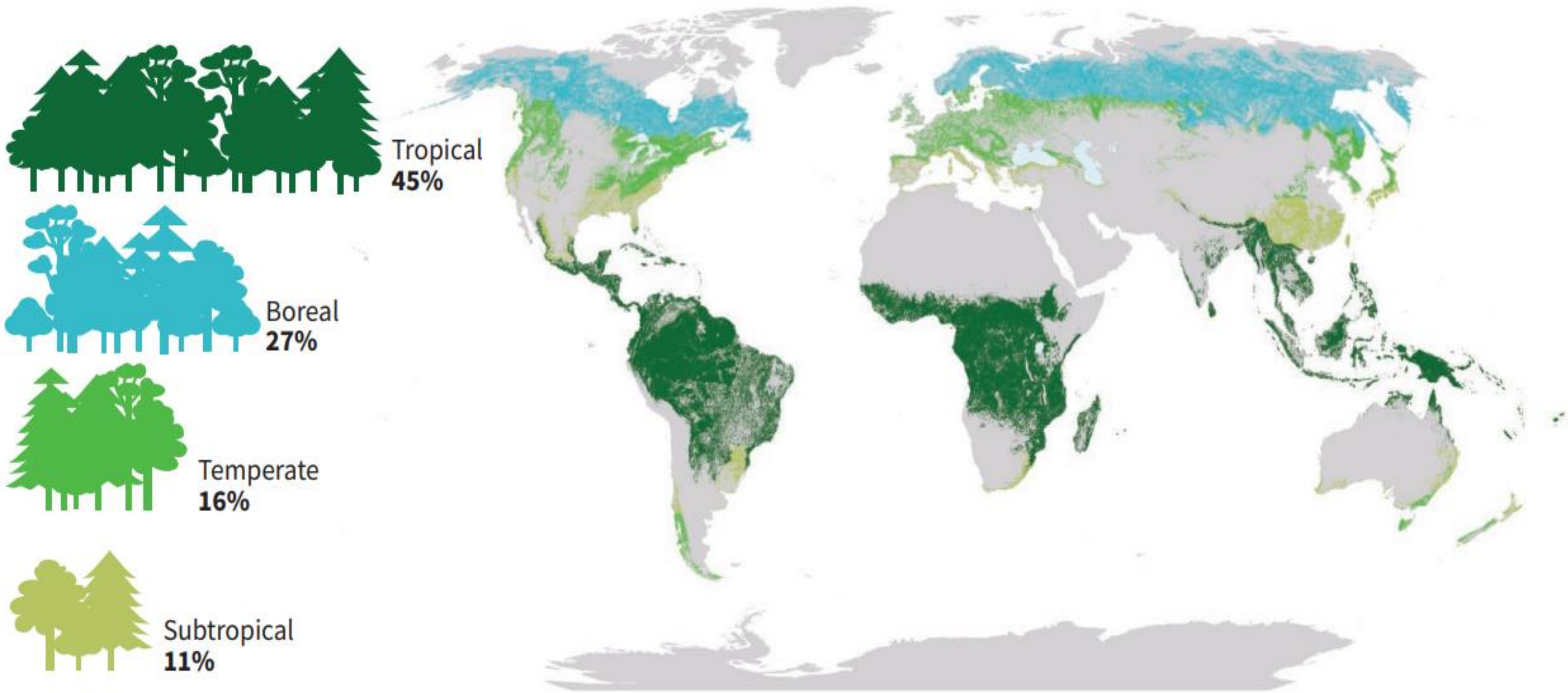


Notes: Suitability of energy crops by area from Cronin et al (2020). Energy crops included in the study include sugar and starch crops, oil crops, grasses and short rotation coppice/forestry crop
Source: Cronin. J., et al. (2020) Land suitability for energy crops under scenarios of climate change and land-use

SYSTEMIQ

Woody biomass resources are spread across boreal and tropical regions globally

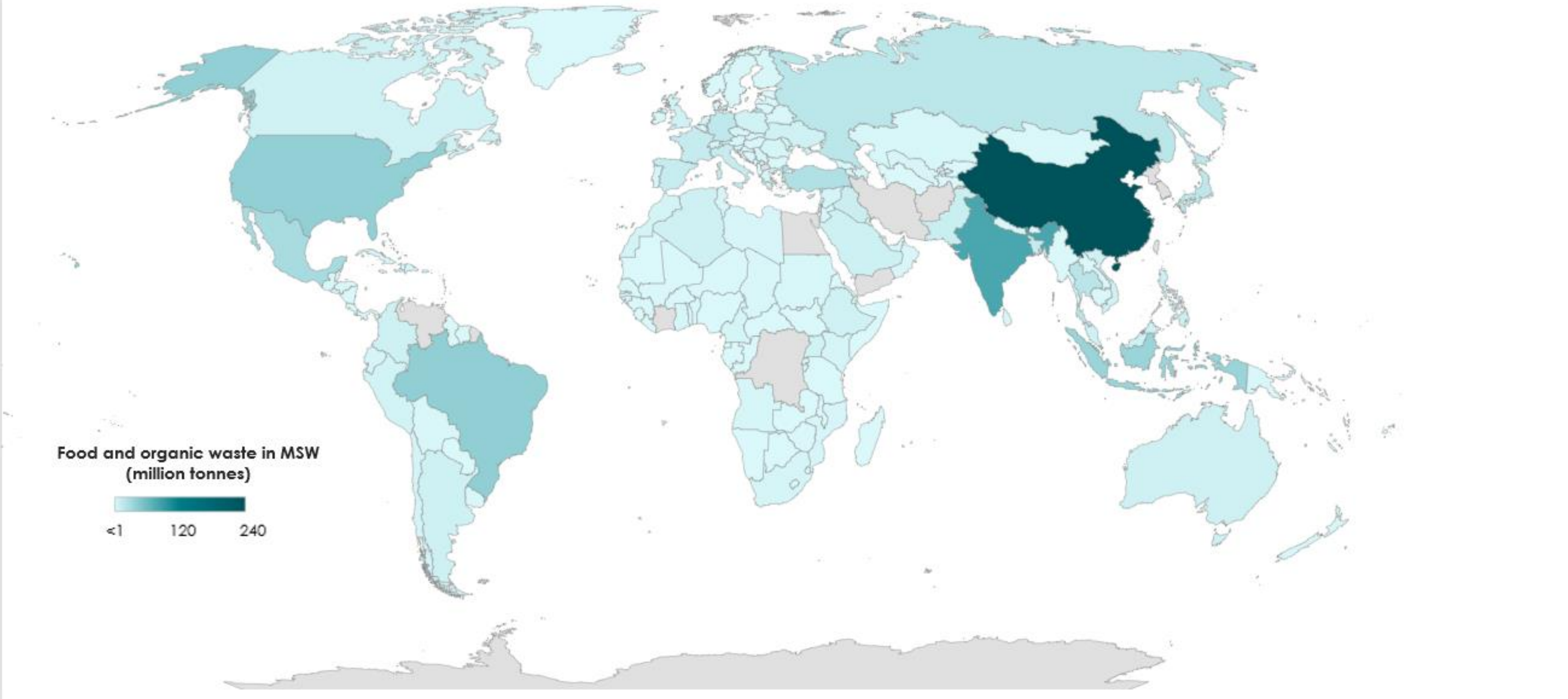
Location of different forestry resources globally today



Source: United National Economic Commission for Europe (UNECE), 2020 Boreal Forests

Municipal solid waste availability is aligned with countries with high populations and high shares of food/organic content in waste

Biogenic municipal solid waste globally today



Source: World Bank Group (2025) What a waste global database. Analysis takes total municipal waste tonnage, and share of expected food and organic waste to generate map

SYSTEMIQ

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

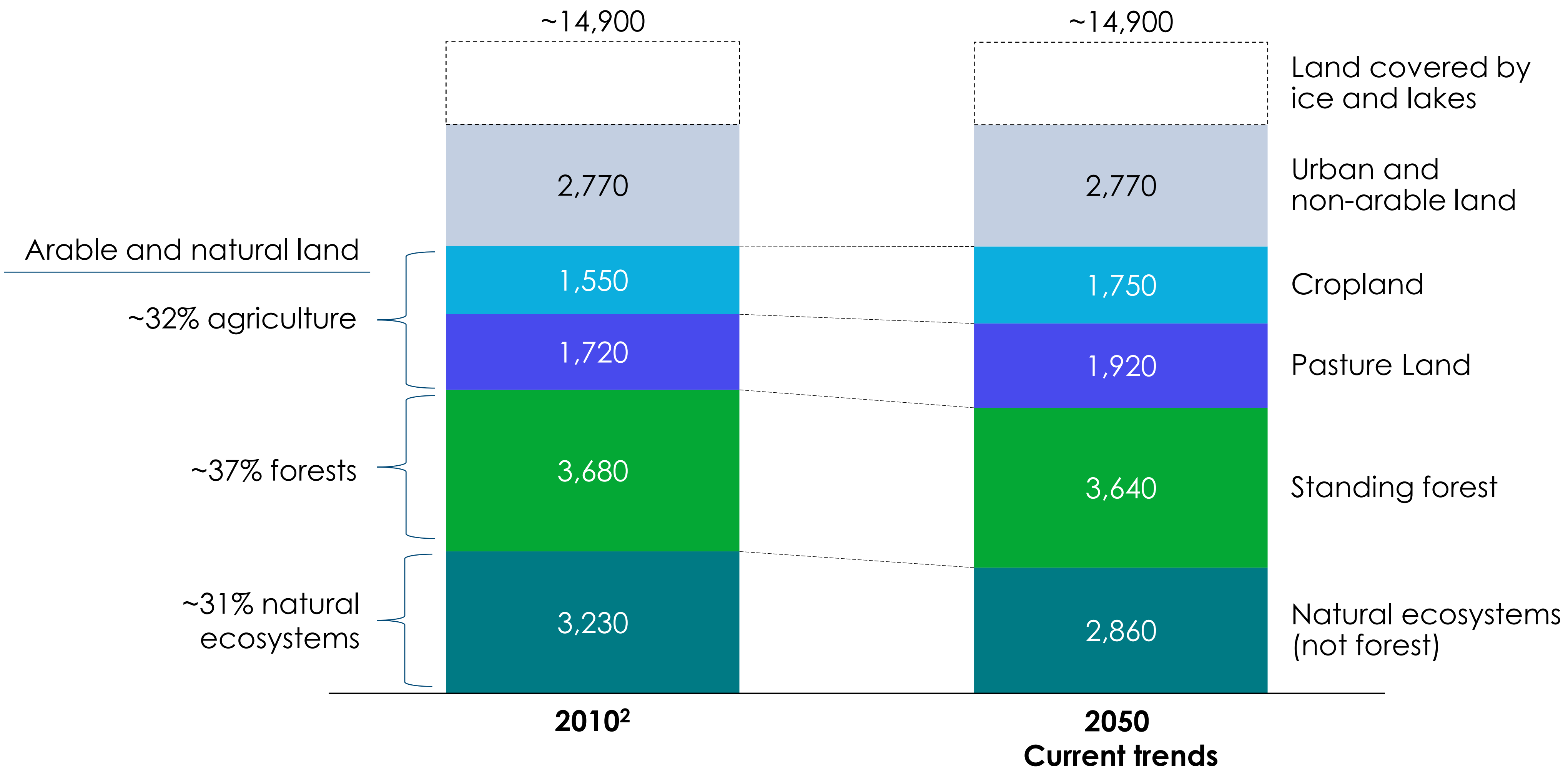
Different types of vegetation store carbon in different locations (roots vs stems). Therefore, depending on the native vegetation, **different plants will have advantages over other in terms of long-term carbon storage**

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**

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

Total global surface land use (million hectares)[1]

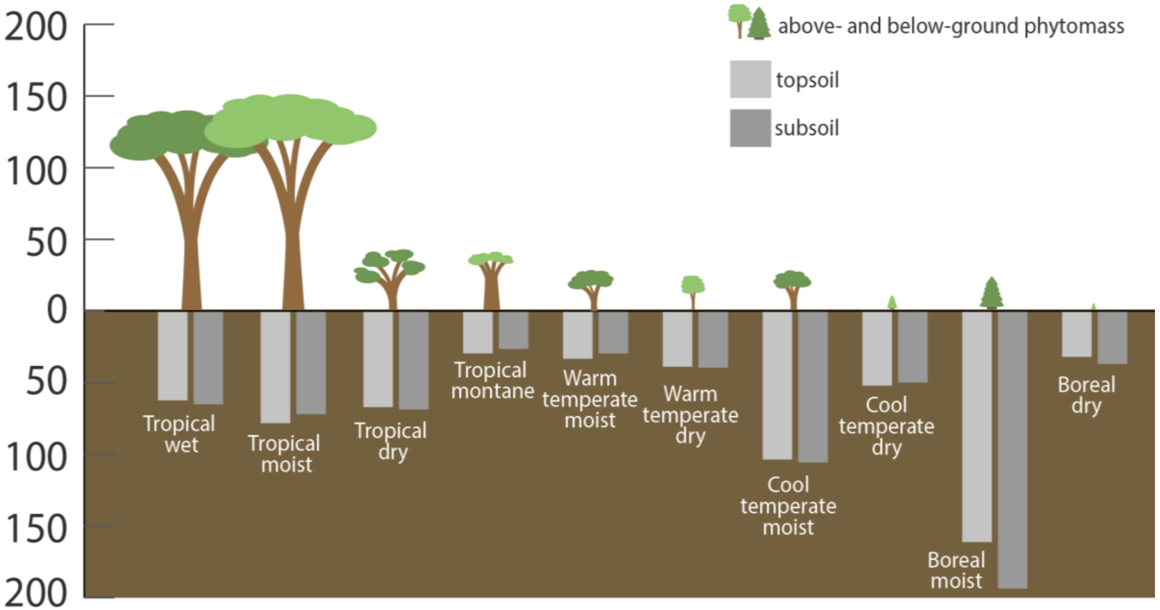


Source: ETC (2021) Bioresources within a Net-Zero Emissions Economy: Making a Sustainable Approach Possible

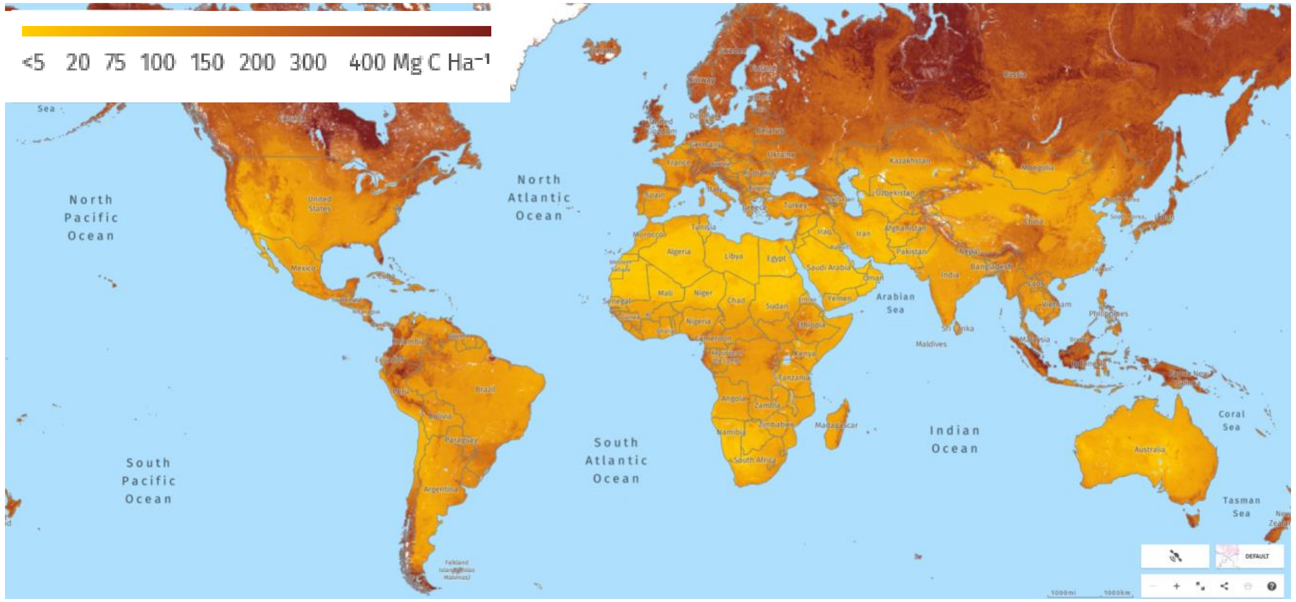
SYSTEMIQ

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

Organic carbon (gigatons carbon)



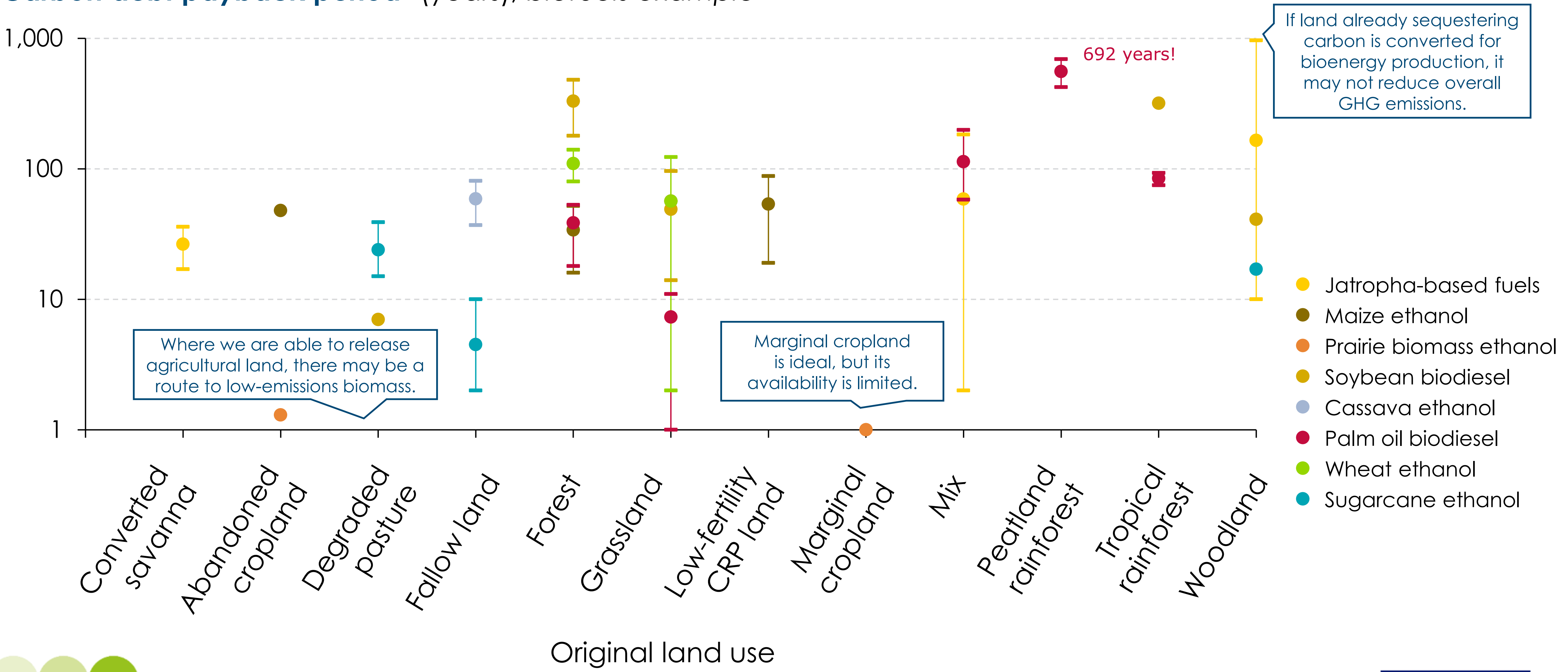
Soil carbon density (tonnes carbon / hectare)



Sources: Left: Adapted with permission from Figure 2 in Janowiak et al. (2017), Considering Forest and Grassland Carbon in Land Management from United States Department of Agriculture, Forest Service. Figure designed by Kailey Marcinkowski based on data from Scharlemann J.P.W. et al. (2014), Global soil carbon: understanding and managing the largest terrestrial carbon pool. Right: World Resources Institute, ISRIC, Sanderman et al. "Soil Carbon Density." Accessed through Global Forest Watch on 3rd July 2021. www.globalforestwatch.org.

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

Carbon debt payback period[1] (years), *biofuels example*



Note: GHG: greenhouse gas. (1) Carbon debt payback periods reported were compiled by Gasparatos et al. (2017) from a range of sources in the literature.
Source: Adapted from Table 1 of Gasparatos et al. (2017), Renewable energy and biodiversity: implications for transition to a green economy.

SYSTEMIQ

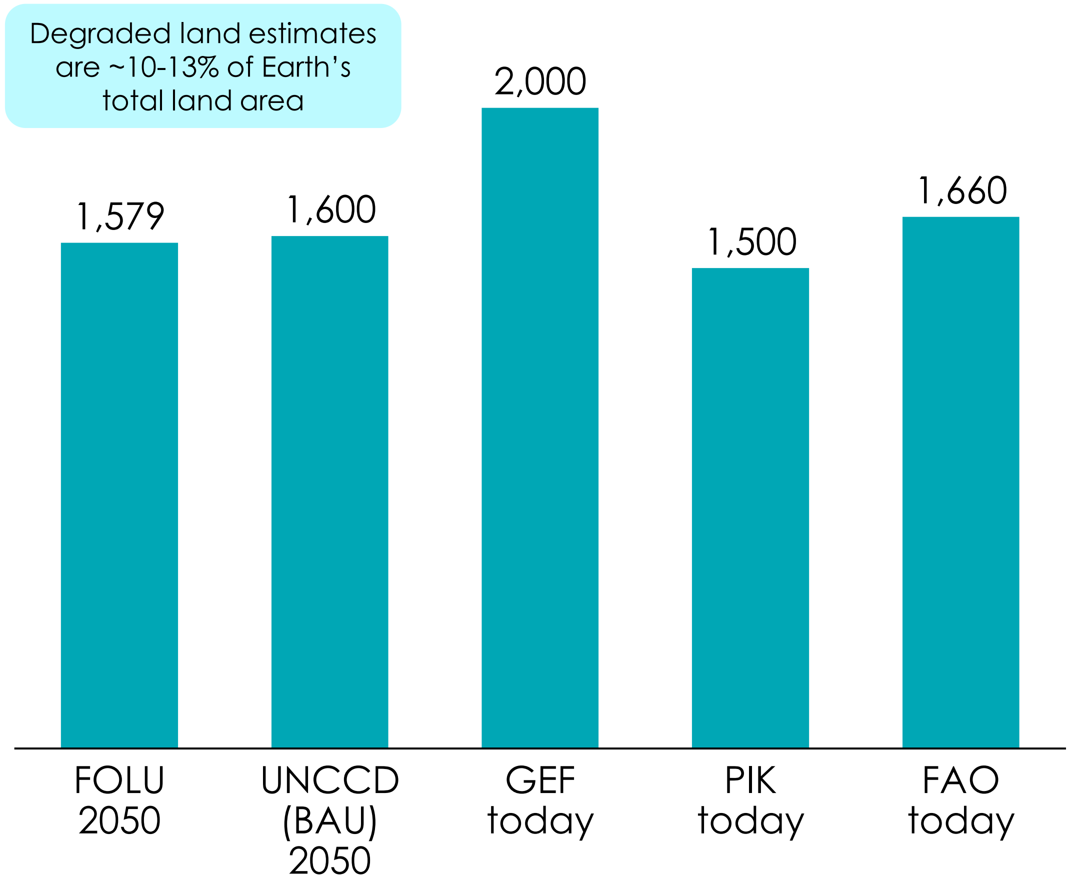
More productive land

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

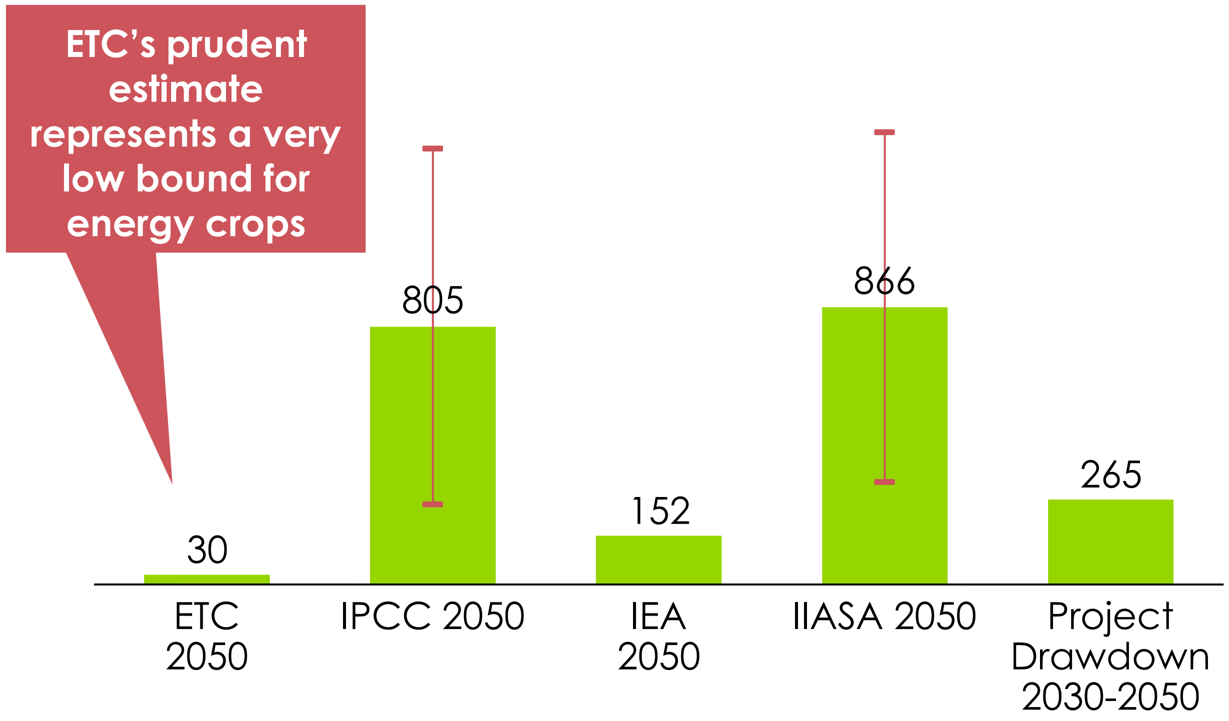
	Use of degraded or marginal land for energy crops, and not competing with food requirements	Energy crops cultivated on land which is freed up through system change, including dietary shifts, higher yields and reduction in food losses
+ / −	• Gives economic purpose to land • If managed appropriately could 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
i	• 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



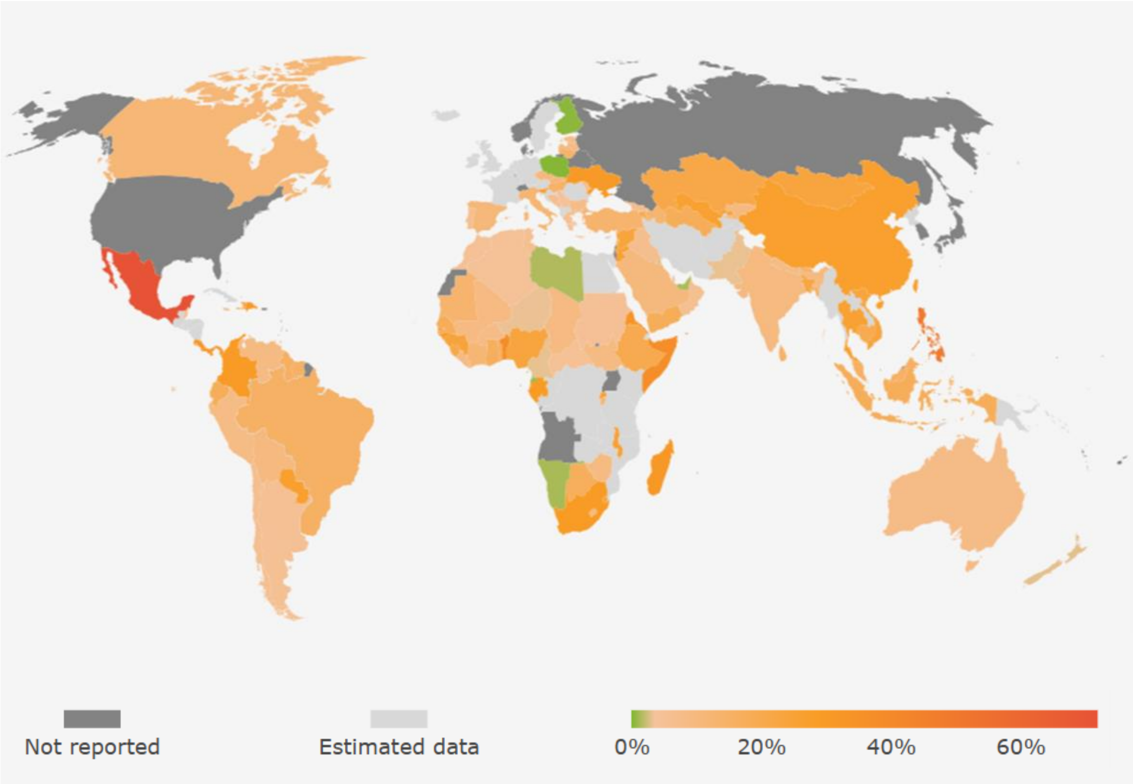
Range of estimates for energy crops on degraded land
Millions of ha



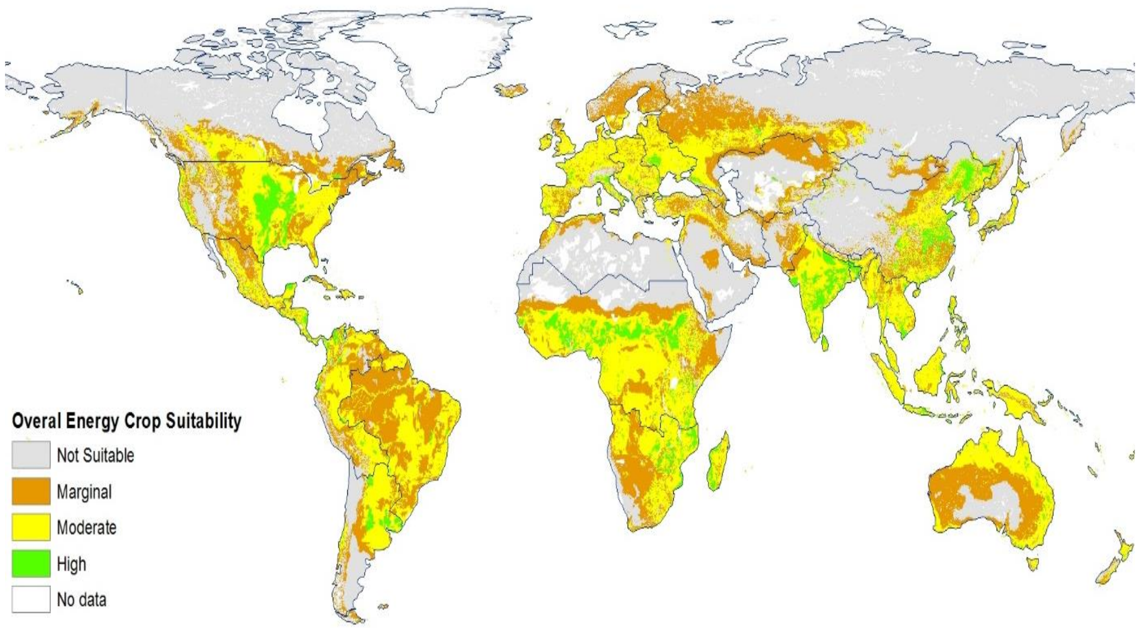
Sources: Food and Land-Use Coalition (FOLU) (2019) Growing Better, Global Environmental Facility (GEF) (2017) GEF-7 Replenishment Programming Directions, Potsdam Institute for Climate Impact Research (PIK) (2024) Transforming land management within planetary boundaries key to addressing global land use 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



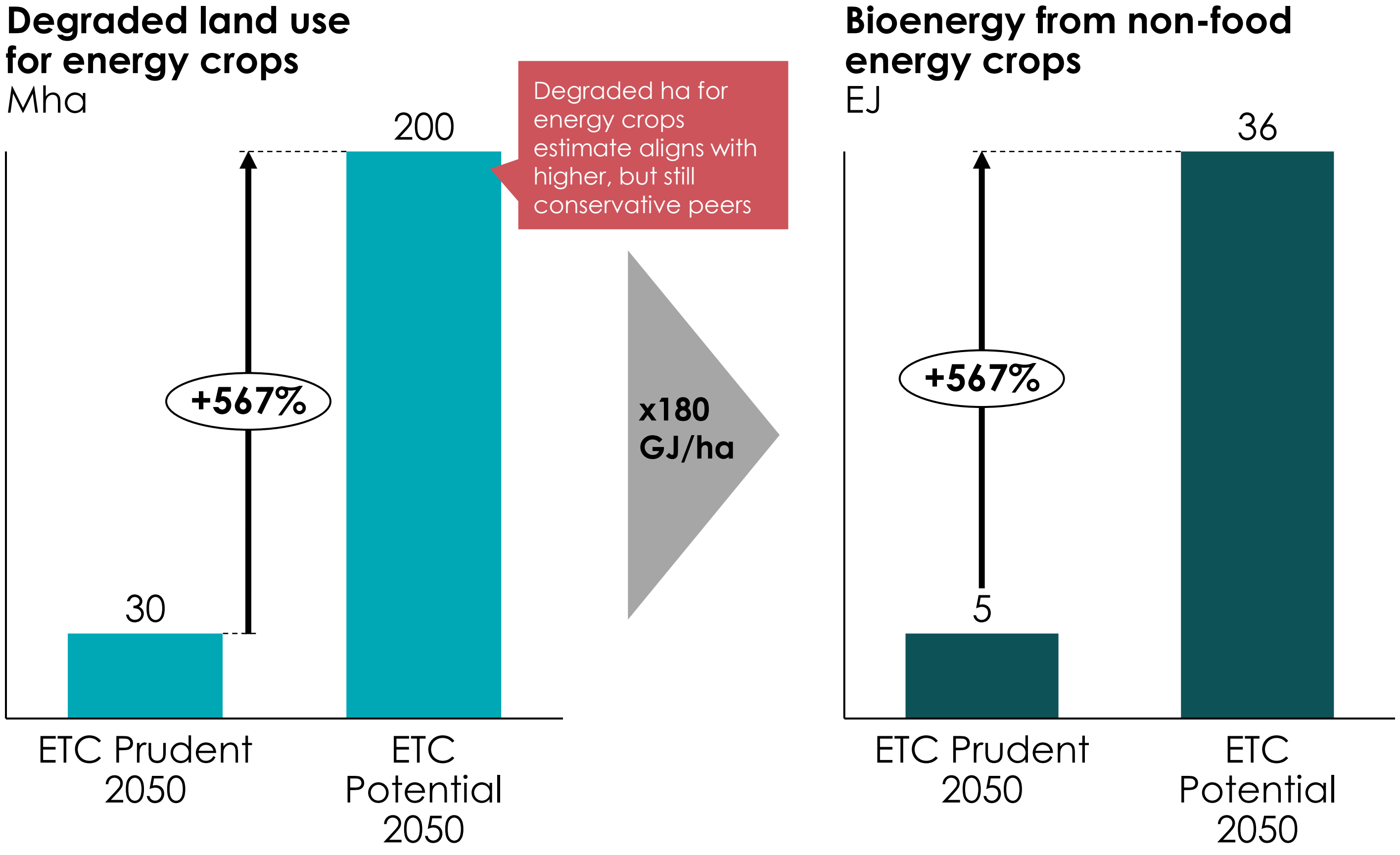
Suitability of energy crops by area
Millions of ha



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



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**

Sources: Systemiq analysis for the ETC (2025)

There is potential for high energy content biomass, however areas for new land are limited so they must offer high productivity

In focus next

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

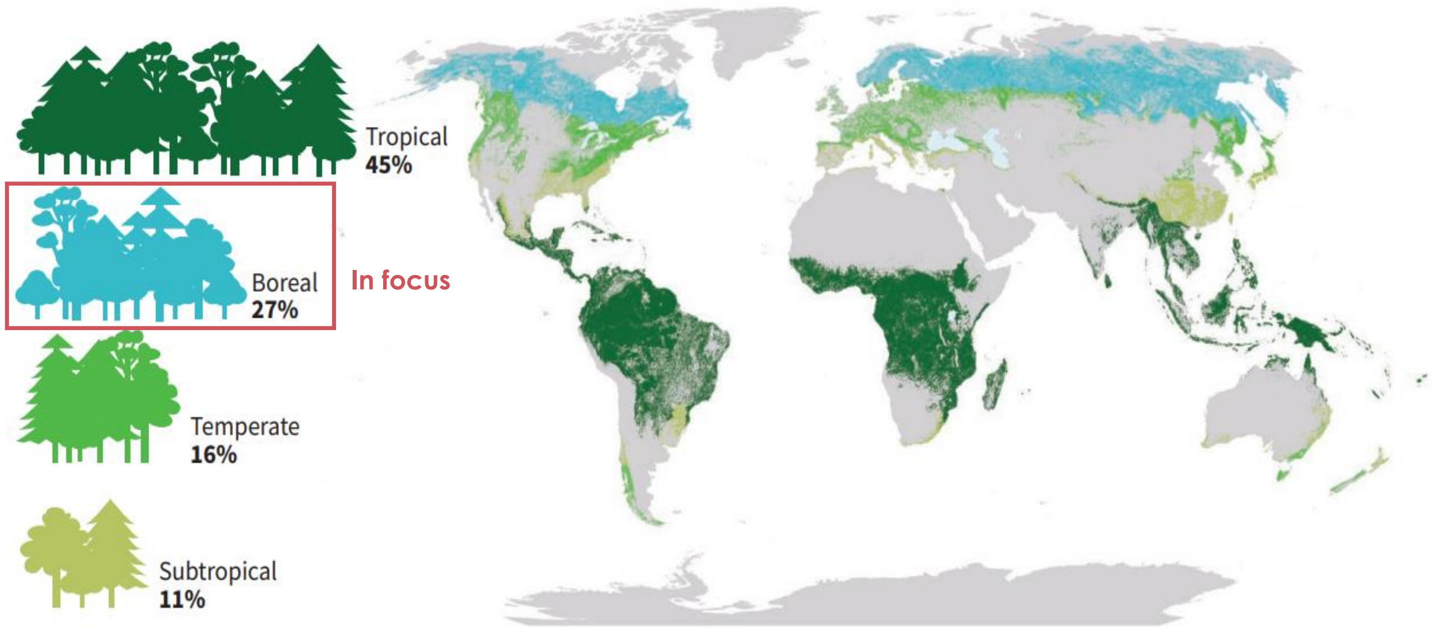
High fibre content cane, which have higher yield compared to traditional sugarcane

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

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

Boreal forests have increasing interest for use of biomass affected by natural disturbances

The boreal forests represent 27% of the world's forests, forming the largest terrestrial biome on earth



The boreal forests have high environmental and economic importance

- Contain **~32 per cent** of global terrestrial carbon stocks
- **Hot spot of biodiversity** providing multitude of ecosystem benefits
- Provide **17% of the total annual global timber** harvest
- Characterized by a **net gain in growing forest stock**, despite losses caused by forest disturbance (e.g. commercial logging)
- Increasing interest recently in using **logging residues and deadwood from wildfires or pest** outbreaks as biomass source

Source: United National Economic Commission for Europe (UNECE) (2024) Boreal forests, A global treasure

Case Study: Biomass from deadwood and pest-affected trees in Canada and Scandinavia

Unlocking Canada's boreal forest biomass

Background	Boreal forests offer significant biomass potential, but these sources are often not utilized for energy due to timber prioritization, logistics, environmental considerations and limited energy integration
Impact	Estimated **20–40 petajoules PJ/y from logging residues.** Additionally, up to **55% reduction in harvestable fiber** can be degraded in wildfires or pest outbreaks[1]. These events generate **over 50Mt/y salvageable biomass.**
Opportunity	Biomass extraction can help manage pest aftermath, **support forest regeneration**, and **provide low-grade bio-energy feedstock.**
Outcome	Extraction remains low **due to high logistical and cost barriers** (remote areas, poor access) and limited integration with energy systems

Canada vs. Scandinavia: Extraction comparison

	Canada (Quebec)	Scandinavia (Sweden)
Main biomass source	Deadwood from pests, salvage logging, post-disturbance residues	Logging residues, deadwood
Technical potential	Estimated potential of 20-40 PJ/y	Currenty 50 PJ/y Can scale up to 90 PJ/y[4]
Infrastructure	Emerging: Limited forest roads in remote boreal zones	Advanced: Forest terminals, district heating grids, and digital traceability
Extraction cost	Estimated at 1220$/ha[5]	Lower, due to efficient supply chains

Key takeaways on cost drivers and trends

- Canada's boreal forests offer significant technical potential for biomass, especially after disturbances, but **face higher extraction costs and less developed infrastructure than Scandinavia.**
- Sweden, with its efficient systems and sustainable management, leads in residue-based bioenergy, demonstrating the value of integrated forest management for climate and energy goals.

Note: 1) Not all fiber lost can be used for bioenergy
Sources: 2) United National Economic Commission for Europe (UNECE) (2024) Boreal forests, A global treasure 3) Daniel Gouge et al. (2021) Biomass procurement in boreal forests affected by spruce budworm: effects on regeneration, costs, and carbon balance 4) IEA Bioenergy (2014) 5) : Claudie-Maude Canuel et al. (2022)

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

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Where: Suitable in cold climates, in regions like Canada, Scandinavia and Russia

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- 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

CRISPR gene editing is being increasingly used within the energy and bioresource systems to enhance outputs and create alternative products

What is CRISPR gene editing?

A precision-based tool to alter DNA in living organisms, enabling targeted changes to specific genes. Compared to older methods of gene editing, CRISPR offers a faster and more efficient process which has been increasingly used across a range of applications.

How is CRISPR captured in our innovation deep-dives?

CRISPR is a subset of the gene editing technology we cover in the following innovation deep-dives:

1) Novel 2nd generation bioenergy crops (e.g. energy-cane)
2) Precision fermentation to produce alternative food

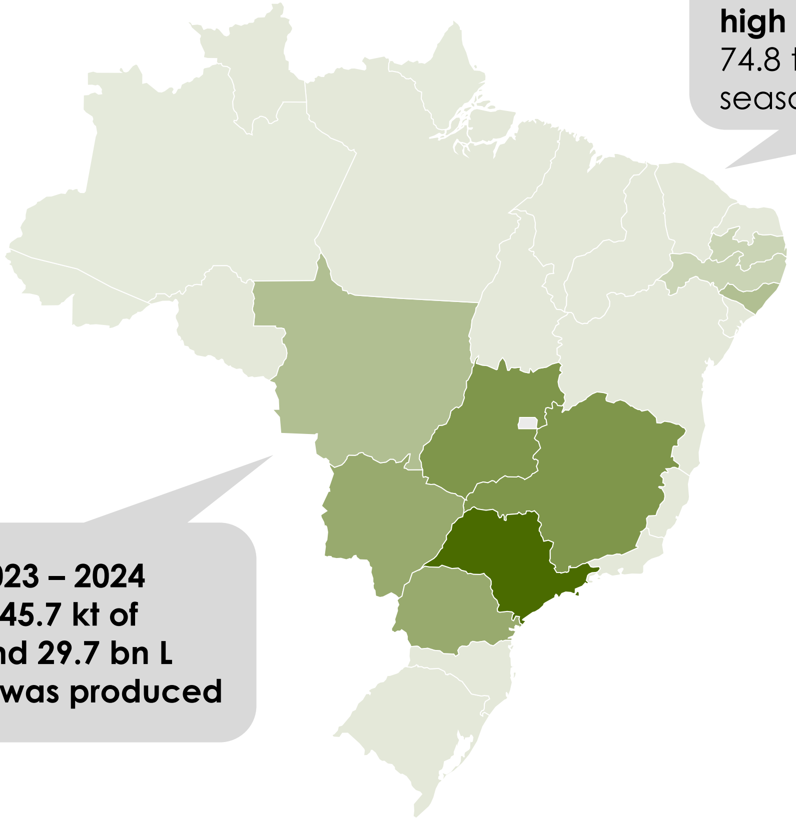
Applications of CRISPR for the energy/bioresources system	Real-world examples using CRISPR (non-exhaustive)
Improvements of bioenergy crops, such as enhanced yield, increased stress tolerances, disease resistance	• Engineered sugarcane varieties in Brazil to increase yields[1]
Precision fermentation of microbes (e.g. yeast, bacteria) to produce fats/proteins similar to animal products	• Dairy protein alternatives created with genetically modified microbes to create milk/cheese alternatives[2]
Optimisation of biofuel production by engineering feedstock traits or editing microorganism genes	• Research doubling bioethanol production from algae[3]

Sources/notes: 1) "Brazil develops non-transgenic CRISPR edited sugarcane" (Future Farming, 2022). 2) "Precision Fermentation & The Dairy Disruption" (RethinkX, accessed 2025). 3) "CRISPR: A Solution to the Global Energy Crisis?" (Synthego, 2019)

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

Productivity in the 2023 – 2024 season reached an all time high of 85.6 t/ha compared to 74.8 t/ha in the 2013 – 2014 season[1]



Sugarcane milling 2023 – 2024 (kt/year)

- 0 – 8,000
- 8,000 – 16,000
- 16,000– 33,000
- 33,000 – 75,000
- 75,000 – 150,000
- 150,000 – 300,000
- 300,000+

In the 2023 – 2024 season, 45.7 kt of sugar and 29.7 bn L ethanol was produced

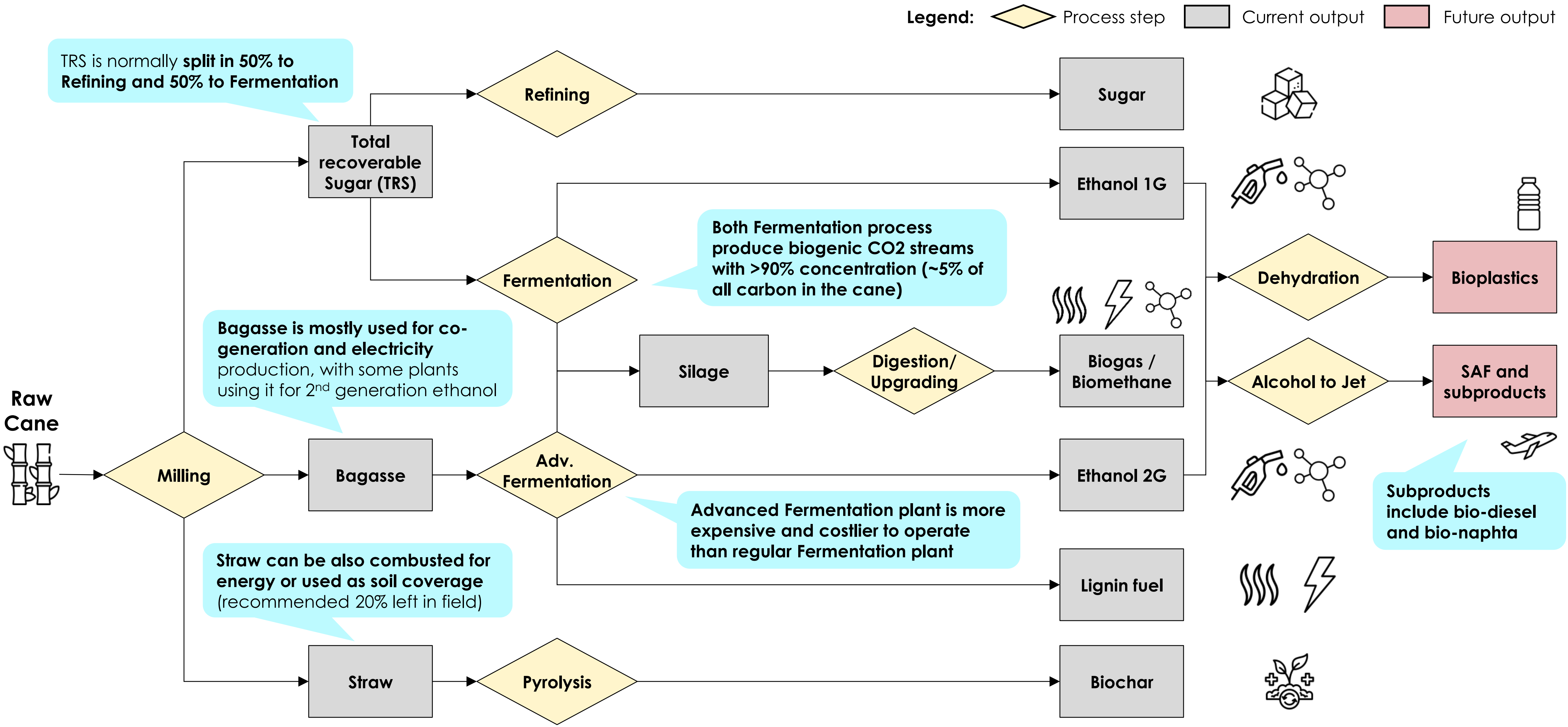
Brazil's Sugarcane: Historic Roots, Modern Debates on Sustainability and Food Security

- **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:**

raízen São Martinho bp bunge bioenergia

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



SYSTEMIQ

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)

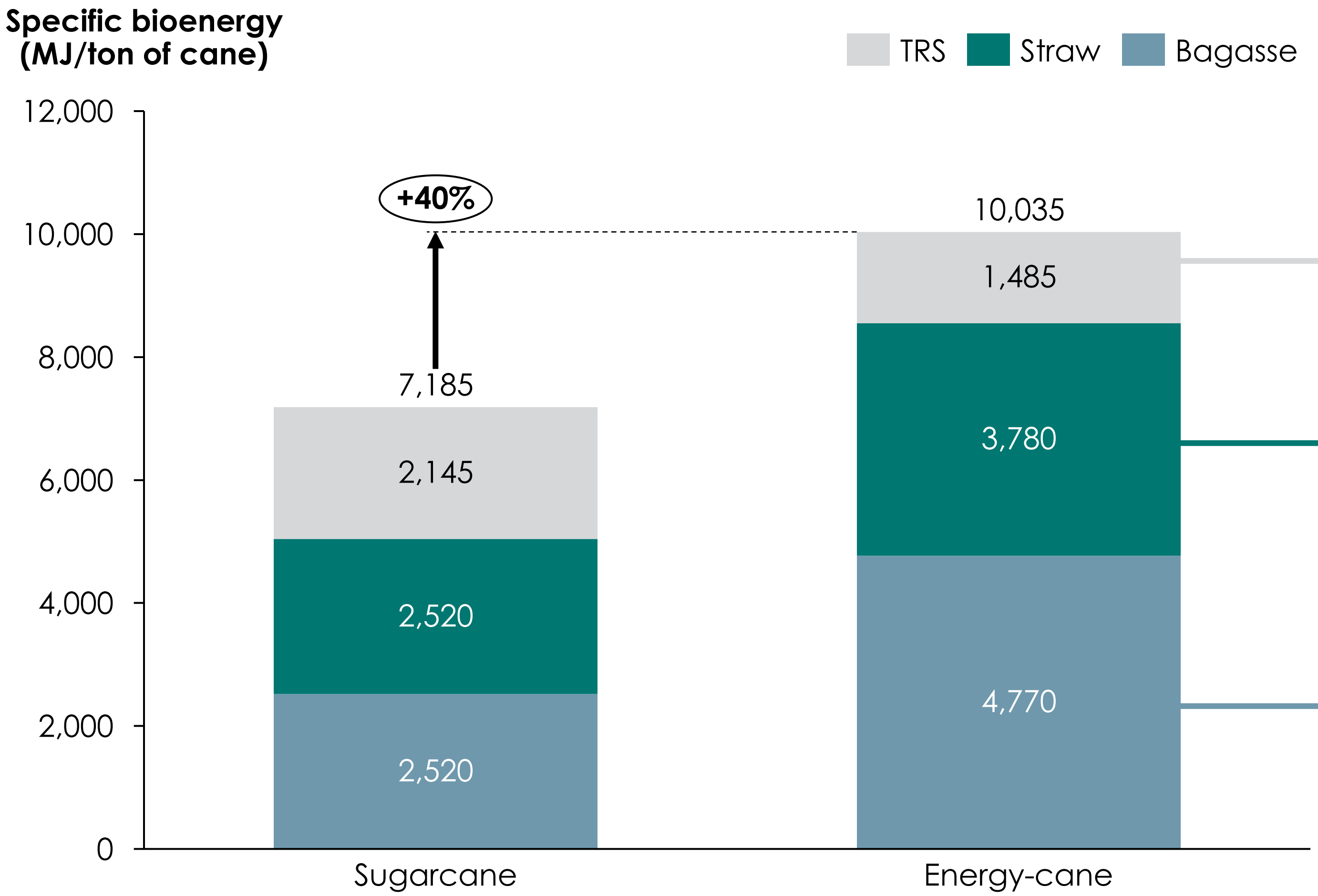
Note: 1) TRS = Total Recoverable Sugar. 2) In terms of dry mass of bagasse and straw 3) No data found online, but straw estimated to be the same as sugar cane or up to 2x more, as the total biomass per hectare may be up to 2x bigger in the Energy-cane as compared to regular sugar cane. 4) Costs based 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?

SYSTEMIQ

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 maximized[1]



Technical available biomass must consider market, plantation and refinery demand

- **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.

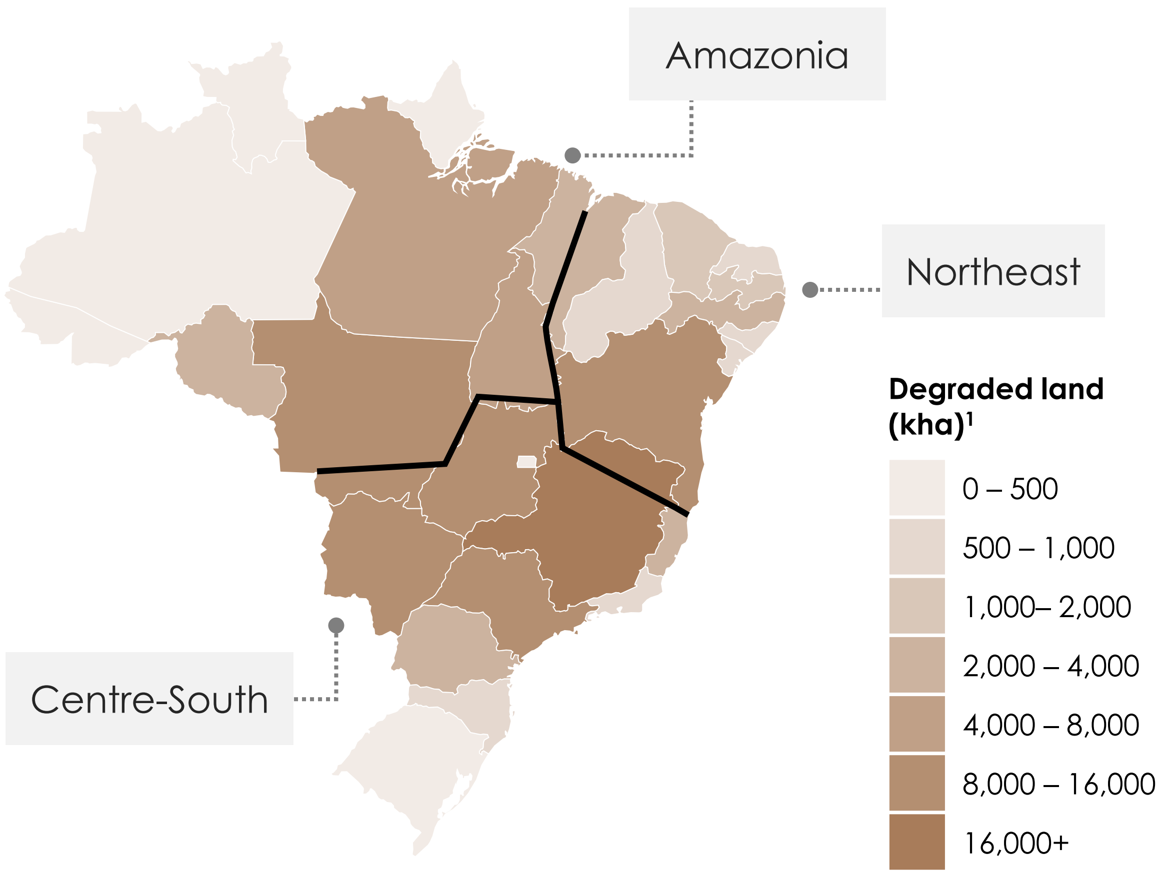
Refineries currently use **bagasse** for co-generation (heat and electricity), but other sources like heat electrification and renewable energy could maximize biomass availability

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/year[2]** – volume available if energy cane is planted on degraded land in established sugarcane regions (**66 million ha**)

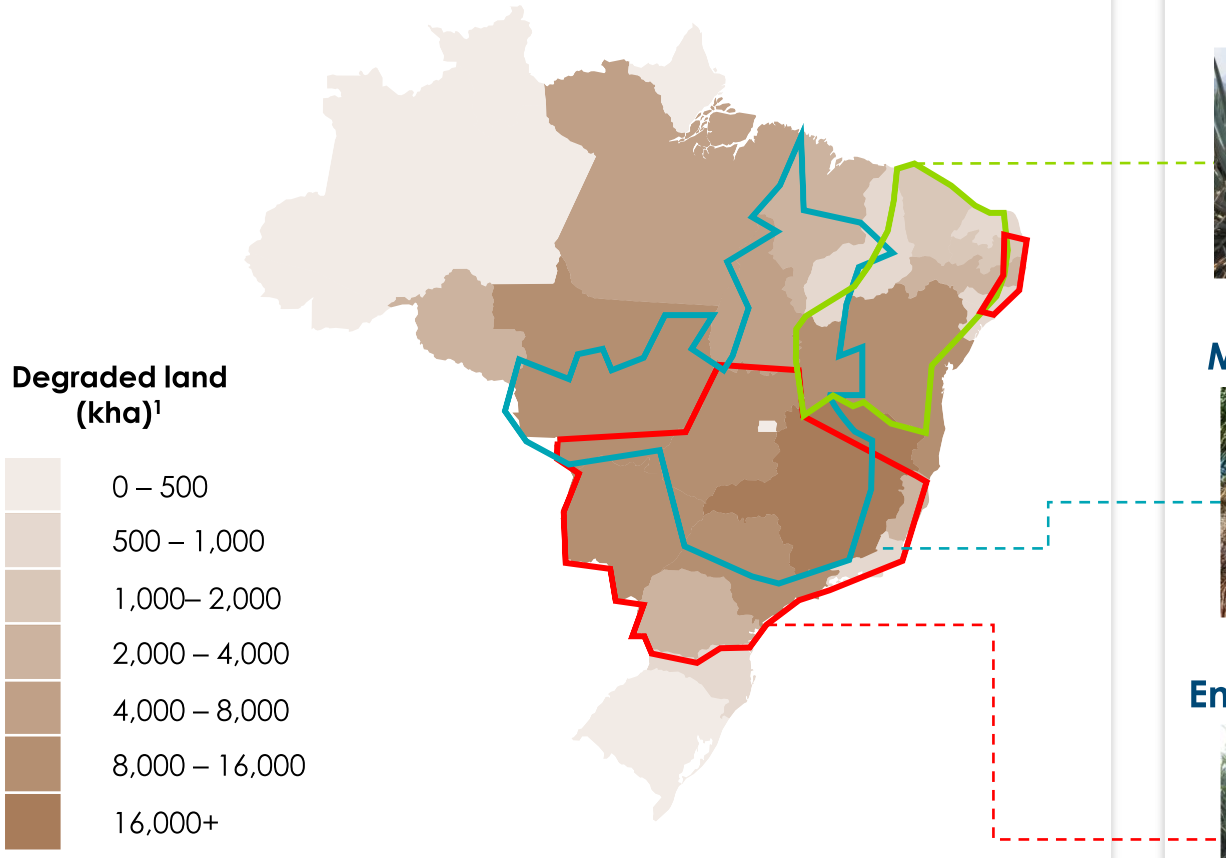
Considerations:

- 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: MAPBiomas 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

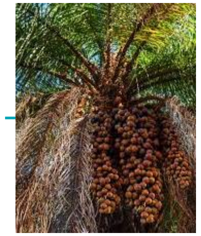


The selected crops are attracting interests from different players, keen to develop efficient bioenergy process

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

SYSTEMIQ

More available land
- Alternative foods

Summary: scaling alternative proteins to free up land for biomass supply

1. **Animal agriculture is currently responsible for the bulk of today's biomass demand.** Feed crops and pasture occupy ≈ 75 % of agricultural land, demonstrating a significant opportunity for land savings if animal products are substituted for less land intensive alternatives.
2. **Switching to alternative proteins is potentially the most viable way to cut agricultural land use.** While eating less meat and more plants can help, it depends on widespread changes in consumer behaviour, often requiring people to prepare and consume meals they find unfamiliar or undesirable. In contrast, emerging technologies like **biomass fermentation, precision fermentation and cultivated meat** now closely replicate the taste, texture and cooking performance of animal products, allowing people to keep their favourite foods while significantly reducing land use.
3. **Alternative proteins are projected to significantly reduce in cost, reaching parity with conventional meat by 2040.** Current 2-25× premiums are falling at ~20 % per capacity doubling, with techno-economic models showing production costs becoming competitive against today's meat prices in the 2030s[1].
4. **Our analysis demonstrates that rapid uptake of alternative proteins could free up 590 million hectares of land and displace 400 Mt of animal protein by 2050.** That is approximately an Australia-sized area no longer needed for feed or grazing.
5. **Freed land can deliver approximately 28 EJ yr^{-1} of bio-energy or ~1 Gt CO_2 yr^{-1} of carbon.** Achieving these dividends requires four enablers: affordable, attractive and accessible products, combined with land-use policies and incentives that lead to sustainable biomass production and biodiversity gains.

Sources: 1) Systemiq (2025). A Taste of Tomorrow – How protein diversification can strengthen Germany's economy. Commissioned by the Good Food Institute Europe, February 2025.

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	✗	Low: Animals **indirectly** rely on large amounts of land, water and energy to grow feed crops
	Alternative protein	✓	High: Microbes **directly** convert raw inputs into protein
Feed-to-protein efficiency	Animal protein	✗	Low: High feed-to-protein **conversion losses** occur due to animal metabolism, movement, and bodily functions
	Alternative protein	✓	High: Microbes achieve high yields due to **high biological efficiency** and **controlled production environments**
Production cycle duration	Animal protein	✗	Low: Livestock requires **months or years** to reach maturity
	Alternative protein	✓	High: 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**	• **Base ingredients in meat-like foods** • e.g., mycoprotein **(Quorn)**, fungal burgers		6-8	Quorn Solar Foods air protein	**~13%** more energy **~79%** less water **~92%** less GHGs **vs. beef**	**Very high (up to ~90%)** – but products do not fully replicate the look or taste of meat
2	**Precision fermentation (PF)**	Make **specific molecules** for use as **ingredients**	• **Functional ingredients** for food production • e.g., **egg white** for baking, casein, rennet		7	Perfect Day Geltor Every	**~15%** less energy **~85%** less water **~40%** less GHGs **vs. eggs**	**Very high (up to -60%)** – varies by ingredient
3	**Cultivated meat (CM)**	**Grow real meat** tissue from animal cells	• **Cuts of meat** including muscle, fat and tissue • e.g., **beef steaks,** chicken breasts		3-5	Mosa Meat Believer Upside Foods	**~50%** less energy **~88%** less water **~88%** less GHGs **vs. beef**	**Very high (up to -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".

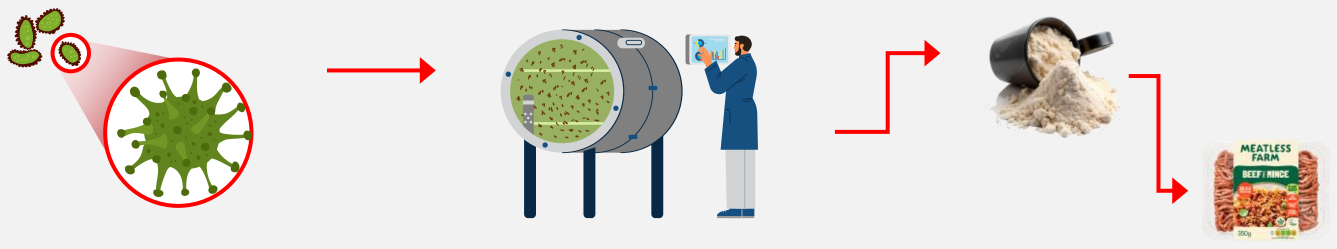
1 **Biomass fermentation:** method using naturally occurring microbes to bulk produce base ingredients for meat-like foods

Overview of production process

1 **Microbe species are selected**

2 **Microbes are grown in bioreactors**

3 **Biomass is harvested**



MICROBE SELECTION

Naturally occurring microbes are selected for high biomass yields and protein density, without targeting specific animal-equivalent proteins

CULTIVATION

Microbes are grown in bioreactors using:

- Sugars
- Nutrients
- Oxygen or CO_2
- Water
- Energy

PROTEIN HARVEST

- **Entire biomass is harvested** and processed
- **Protein-rich outputs used as base ingredients of meat-like products** (e.g., Quorn)

Worked example of benefits

Comparison of the resource and emission intensity of 1 kg of beef burger made using biomass fermented Quorn vs. beef[1]

	Biomass fermented Quorn	Beef	% delta vs. beef
Land	~4 m^2	~40 m^2	-90%
Water	~149 L	~713 L	-79%
Energy	~83 MJ	~70 MJ	+13%
Feed	~2 kg feed (sugars)	~25 kg feed	-92%
GHG emissions	~2.5 kg CO_2e[2]	~30 kg CO_2e	-92%
Beef burger	1kg	1kg	100%

Notes: [1] Though exact figures will vary based on the production set-up and geography, this table relies on average figures to give an illustrative sense of the difference in resource and emission intensity.
[2] Biomass fermentation estimates assume production with low-carbon energy. GHG emissions could be significantly higher under fossil-based energy systems.
Sources: Hendrix Genetics (2019), Reducing the environmental impact of animal production via breeding and alternative diets; University of Helsinki (2022), Biotechnology could provide an environmentally more sustainable alternative to egg white protein 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.

SYSTEMIQ

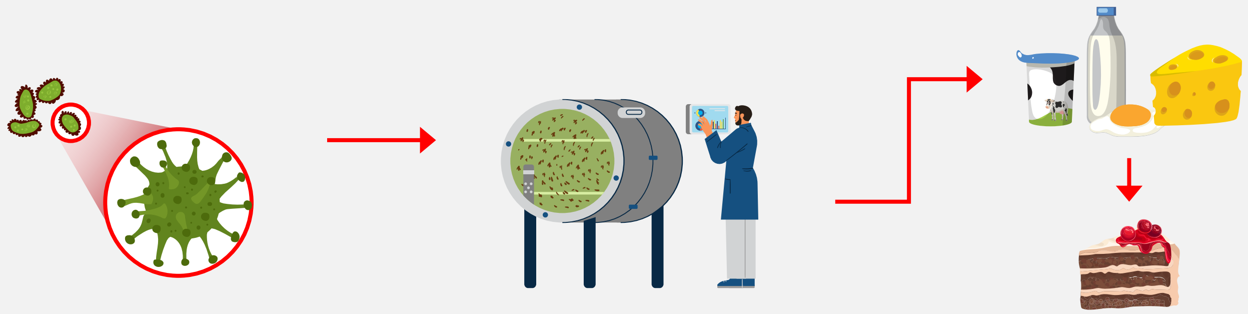
❷ **Precision fermentation:** method using genetically engineered microbes to selectively produce specific proteins and fats for food applications

Overview of production process

1 Microbes are engineered to produce a specific protein

2 Microbes are grown in bioreactors

3 Target proteins are extracted



MICROBE ENGINEERING

Genes are inserted in microbes to program them to convert specific inputs into target proteins, such as animal-identical dairy or egg proteins

CULTIVATION

Microbes are grown in bioreactors using:

- Sugars
- Nutrients
- Oxygen or CO_2
- Water
- Energy

PROTEIN EXTRACTION

- **Target proteins are extracted** from biomass and purified
- **Outputs added to recipes as functional ingredients,** e.g., casein, whey and collagen

Worked example of benefits

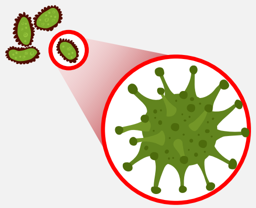
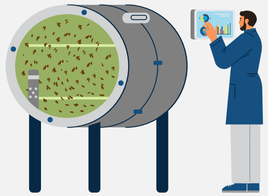
Comparison of the resource and emission intensity of 1 kg of egg white produced with precision fermentation vs. laying hens[1]

	Precision fermentation	Laying hens	*% delta vs. chicken*
Land	*~2.5 m²*	*~6.3 m²*	*-60%*
Water	*~85 L*	*~582 L*	*-85%*
Energy	*~25 MJ*	*~30 MJ*	*-15%*
Feedstock	*~3 kg sugars*	*~2.5 kg feed*	*+20%*
GHG emissions	*~2.8 kg CO_2e[2]*	*~4.7 kg CO_2e*	*-40%*
Egg white	*1kg*	*1kg*	*100%*

Notes: [1] Though exact figures will vary based on the production set-up and geography, this table relies on average figures to give an illustrative sense of the difference in resource and emission intensity. [2] Assumes production runs on low-carbon energy. Without low-carbon energy, GHG emissions would be 1.7-2.6 kgCO2e/kg of egg white.
Sources: Hendrix Genetics (2019), Reducing the environmental impact of animal production via breeding and alternative diets; University of Helsinki (2022), Biotechnology could provide an environmentally more sustainable alternative to egg white protein 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.

❸ **Cultivated meat:** method to produce whole cuts of meat from cells grown in bioreactors rather than in livestock

Overview of production process

① Cells are sourced from animals	② Cells are cultivated	③ Meat is harvested
		

CELL SOURCING

Muscle, fat, and connective tissue cells are sourced from animals and screened for their ability to multiply

CELL MULTIPLICATION

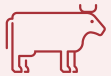
Cells are multiplied in bioreactors on bone-like structures (called 'scaffolds'), fed by nutrient-rich media containing sugars, vitamins, and growth factors

MEAT HARVESTING

Muscle, fat and connective tissue are harvested to make meat products identical to conventional meat

Worked example of benefits

Comparison of the resource and emission intensity of 1 kg of steak of cultivated vs. conventional beef[1]

			*% delta vs. beef*
Land	*~2.5 m²*	*~40 m²*	*-94%*
Water	*~86 L*	*~713 L*	*-88%*
Energy	*~30 MJ*	*~60 MJ*	*-50%*
Feedstock	*~2 kg sugars*	*~25 kg feed*	*-92%*
GHG emissions	*~4 kg CO_2e*[2]	*~30 kg CO_2e*	*-88%*
Beef steak	*1kg*	*1kg*	*100%*

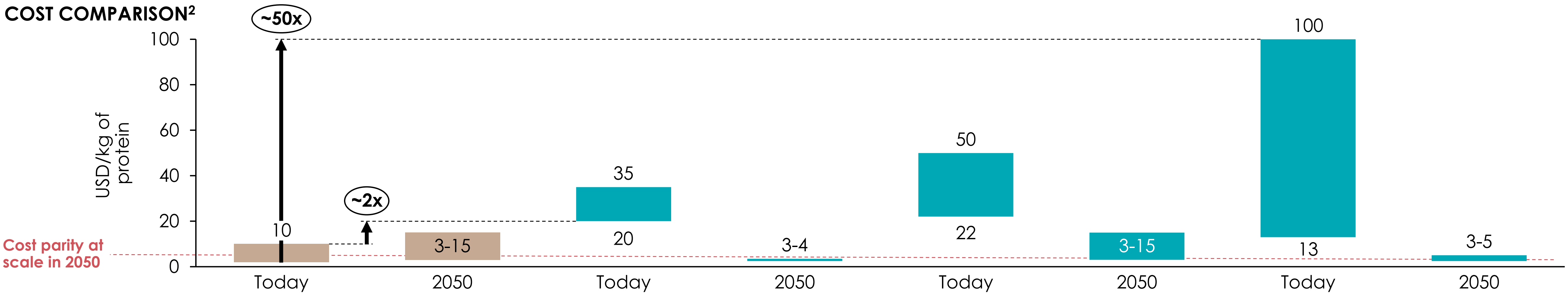
Notes: [1] Though exact figures will vary based on the production set-up and geography, this table relies on average figures to give an illustrative sense of the difference in resource and emission intensity. [2] GHG emissions are based on production using low-carbon energy; emissions would be significantly higher with fossil-based energy inputs.
Sources: 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), Cultivated Meat State of the Industry Report; Our World in Data (2022), Environmental impacts of food production; Gerten et al. (2020), Feeding ten billion people is possible within four planetary boundaries, Nature Sustainability.

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

Protein source:	Animals[1]	Biomass fermentation	Precision fermentation	Cultivated meat

COST COMPARISON[2]



COST DRIVERS

	Animals[1]	Biomass fermentation / Precision fermentation	Cultivated meat
Drivers of current high costs		• **Low cell/microbe density** in fermenters resulting in less product per batch • **Inefficient feedstock delivery** (batch feeding) resulting in long downtime and waste between feeds • **Energy-intensive extraction** of protein from broth	• **Limited cell density** of outputs • **High cell culture media costs** (~50% of total costs) • **Limited scale of bioreactors**
Levers to achieve cost parity by 2050		• **Increase culture density** with genetic engineering • **Streamline feedstock supply** (move from batch to continuous delivery) • **Scale up bioreactors** (larger units for efficiencies of scale)	• **Increasing cell density** • **Develop food-grade inputs** • **Increase yields** through tech and process improvements

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.

The ETC has modelled the potential for alternative proteins (APs) to reduce constraints on sustainable biomass supply following a 3-step methodology

Purpose of model is to estimate:

1. The **land area** that could be freed if **animal-based proteins** were partially **replaced by alternative proteins** (APs)
2. The **energy and carbon supply potential** of the land that is freed, assuming it is **in part replanted with energy crops**

3-step methodology

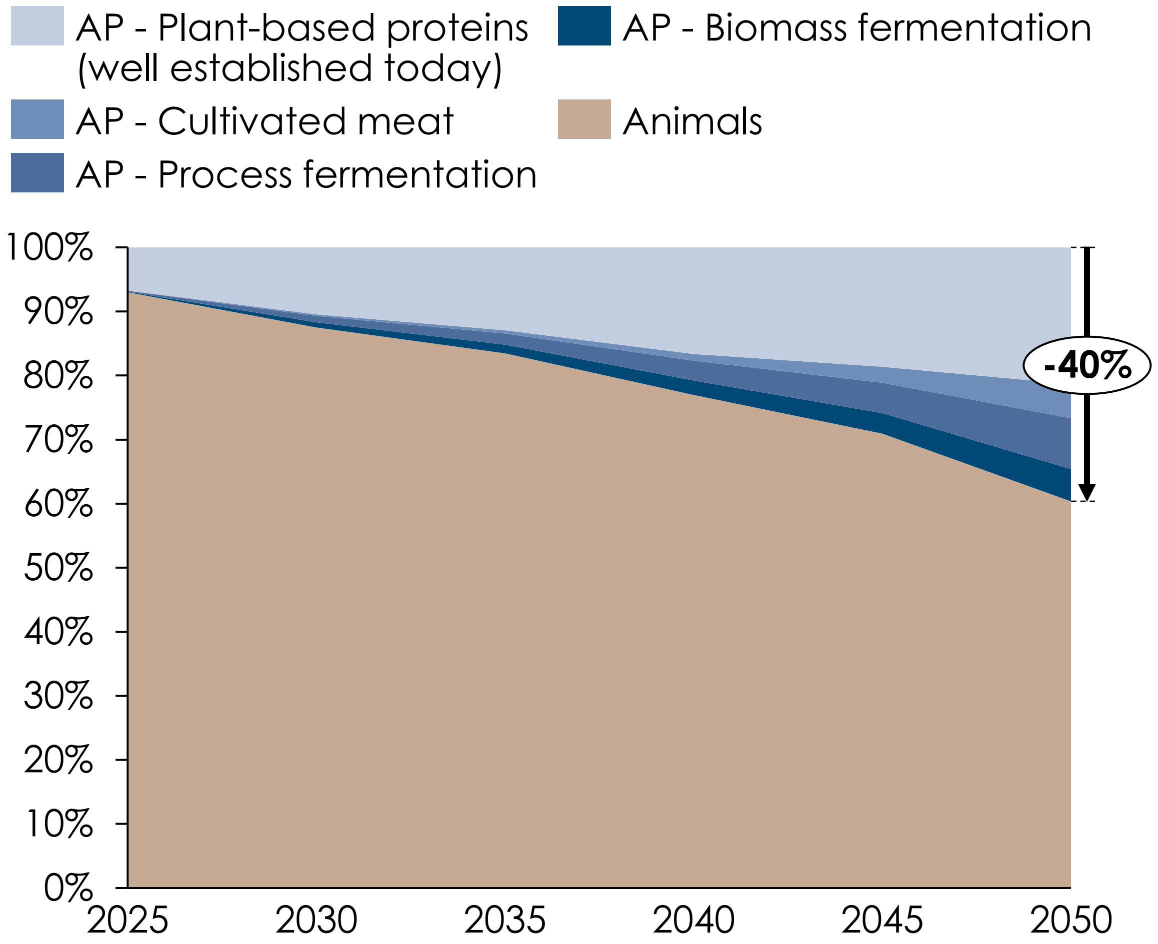
Step	1	2	3
	Estimate alternative protein uptake	**Calculate land freed from reduced animal protein demand**	**Quantify energy and carbon potential from freed land**
Short description	Projected adoption of APs (e.g. fermentation-based, cultivated) across meat, dairy, and eggs to 2050	Reduced animal protein production decreases feed demand, freeing up crop land and pasture	3 scenarios for reallocation of freed land to rewilding, managed forestry or energy crops
Key assumptions	▪ **Animal-based protein demand** through 2050 (differentiated by meat, dairy, egg) ▪ **AP substitution rates** through 2050 (differentiated by meat, dairy, egg) ▪ **Market share split** across AP technologies	▪ **Land-use intensity** by protein type and production method ▪ **Land required for animal protein** production without AP substitution ▪ **Land required for alternative protein**	▪ **Proportion of freed up land** dedicated to each type of use ▪ Biomass **yield rates** ▪ **Energy content** of biomass by type ▪ **Carbon content** of biomass by type

Key sources used: Systemiq (2025), *A Taste of Tomorrow: How Protein Diversification Can Strengthen Germany's Economy*; FAOSTAT; ETC (2021), *Bioresources Within a Net-Zero Emissions Economy: Making a Sustainable Approach Possible*; Expert interviews.

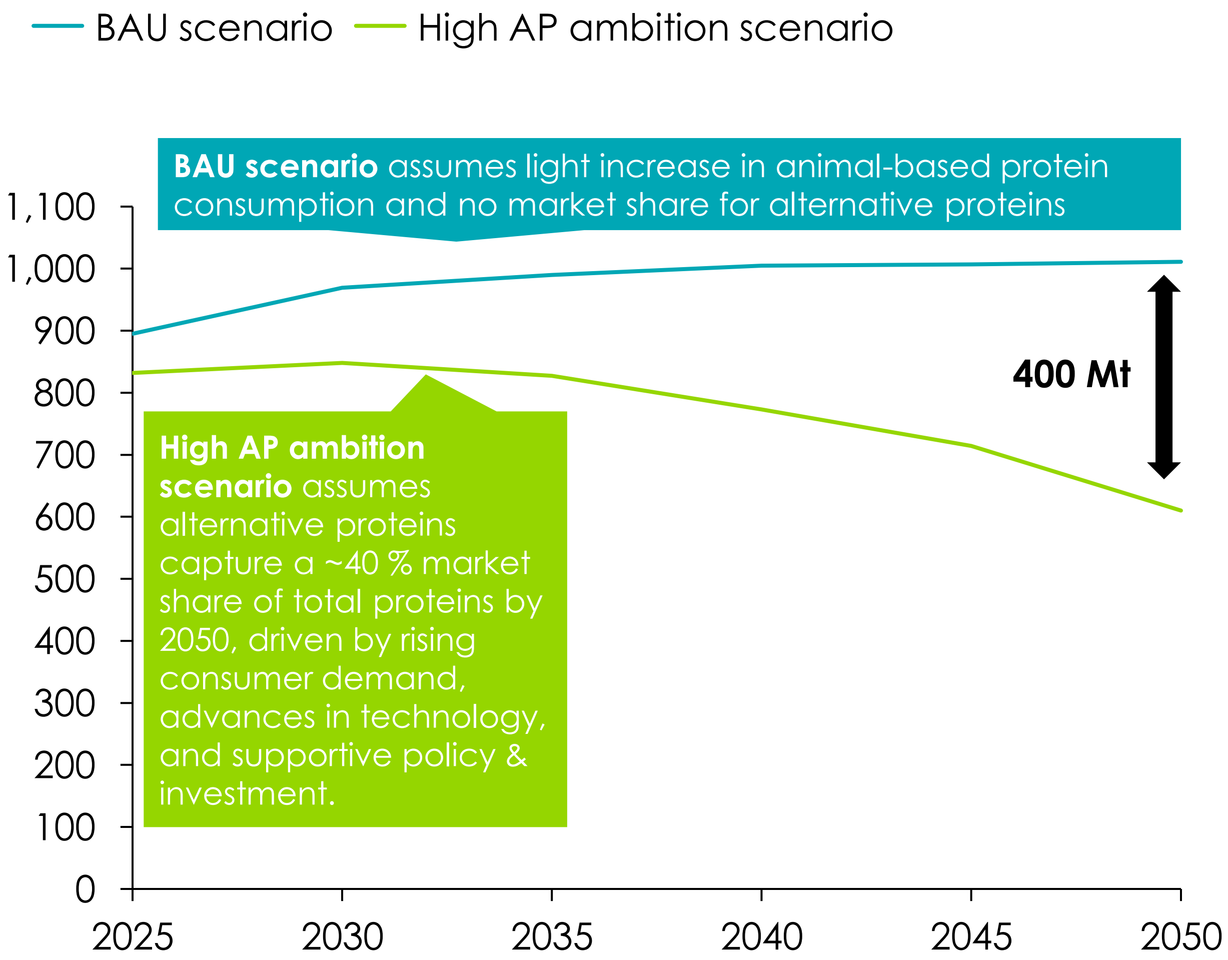
SYSTEMIQ

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 source[1]



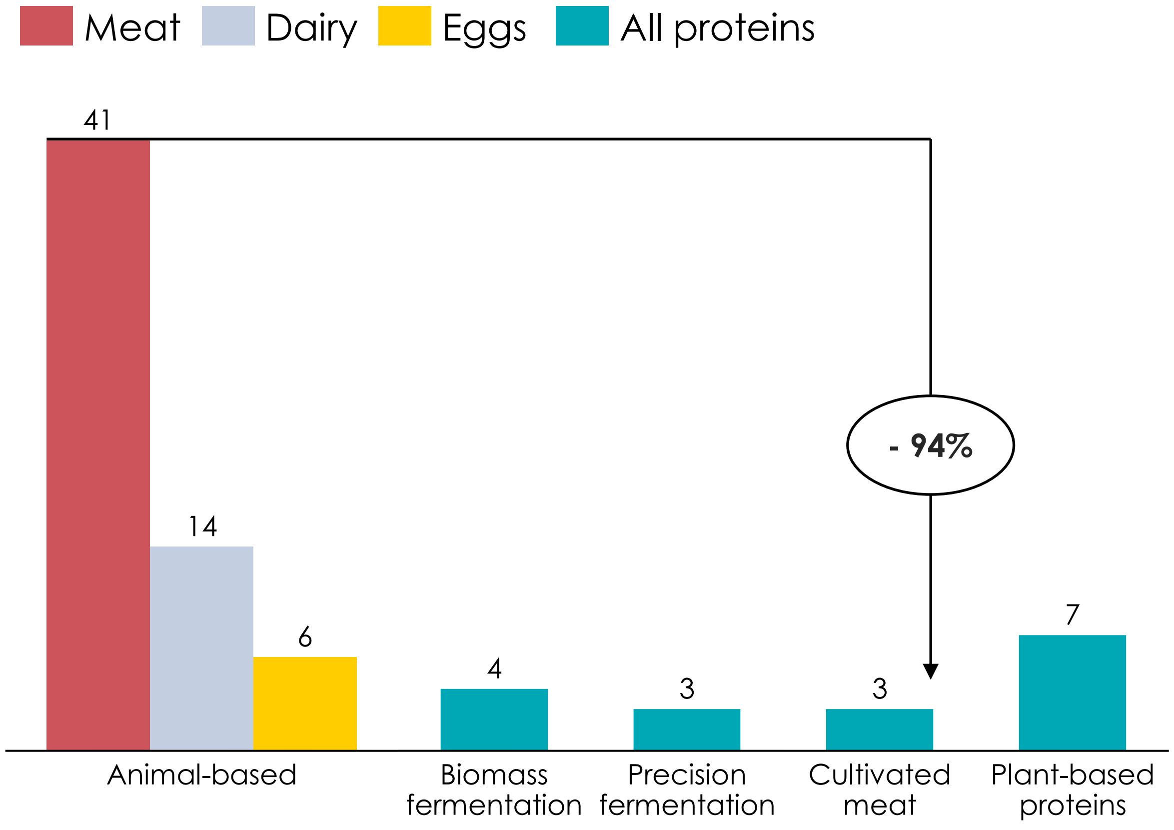
This uptake in alternative proteins could displace 400 Mt of animal-based proteins relative to a business-as-usual scenario
Net animal protein consumption[2], million tonnes



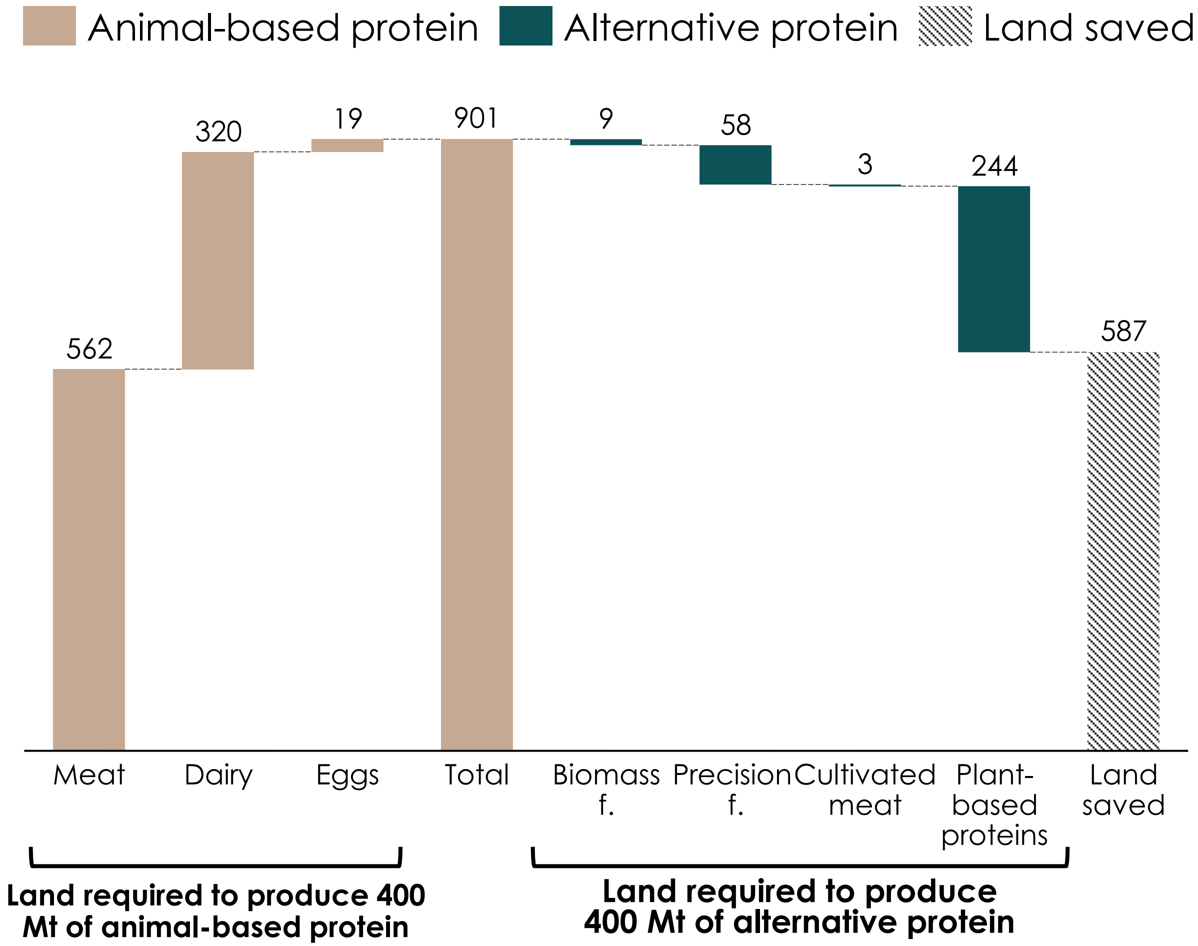
Notes: [1] In alternative proteins made via biomass fermentation, precision fermentation, or cultivation, cell-grown ingredients make up only ~5–20% of total protein weight; the rest comes from plants—driving plant-based proteins' dominant role in meeting 2050 global protein demand [2] Volume of animal 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, m^2/kg



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



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) + 80% to managed forests (470 Mha)	75% to nature (441 Mha) + 25% to energy crop plantations (147 Mha)
Outcome:			
EJ of useful energy	**N.a.:** land is returned to nature, 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	(+) **Biodiversity + carbon sequestration maximised;** restores soil condition & water cycle (−) **No energy output,** so other sustainable biomass routes must be scaled	(+) **Provides timber & 28 EJ of biomass energy** (−) **Moderate biodiversity impact** – better than energy-crop monocultures, worse than untouched nature (−) **Decades to reach maturity**	(+) **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.

SYSTEMIQ

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

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

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.

New sources and more available land - Macroalgae + microalgae

Summary: scaling alternative proteins to free up land for biomass supply

1. **Terrestrial crops dominate today's biomass footprint, occupying most of the world's arable land.** By partially substituting food, feed, and materials with ocean-based algae-derived products, we can reduce pressure on terrestrial cropland.

2. **Scaling macro- and micro-algae offers a viable alternative pathway.** Seaweed and microalgal systems can be deployed in oceans and on marginal land, avoiding competition with food crops. Algae derivatives—from hydrocolloids and proteins to biopolymers and biofuels—closely mimic conventional product performance while reducing land use.

3. **Techno-economic advances are driving down algae costs, but maybe not enough.** Despite projected cost declines because of technological advances and efficiencies of scale, current prices remain over 10× higher than conventional alternatives in some applications. Policy support may be needed to close the gap.

4. **Modelling suggests that by 2050, high algae adoption could free up 82 million hectares**, displacing ~395 Mt of food, and feed. If 80 % of that land were converted to managed forestry with additional ocean-farmed macro-algae being harvested for energy, the system would supply a total of ~10 EJ (4 EJ forestry biomass and 6 EJ of macroalgae biomass) per year and sequester ~0.3 Gt carbon per year.

5. **Realising these benefits requires four enablers:**

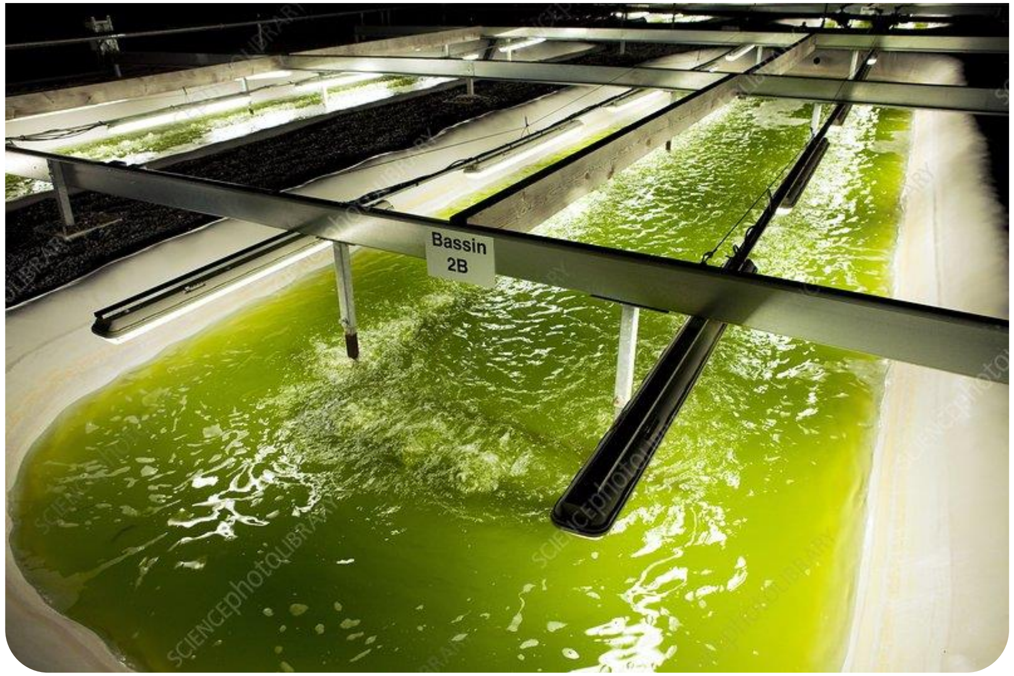
   - **Cost breakthroughs** in cultivation and processing to bring algae biomass to price parity with crops like soy and corn.
   - **Targeted subsidies** that reflect algae's environmental co-benefits—lower land, water, and fertiliser use, and better biodiversity outcomes.
   - **Infrastructure** investment in sea farms, photobioreactors, and processing for food, feed, and energy applications.
   - **End-market development** for algae-based foods and feeds to drive demand and de-risk scale-up.

Macroalgae is large plants grown in open water, while microalgae and microscope and grown in controlled systems

Macroalgae are large algae plants grown in coastal farms

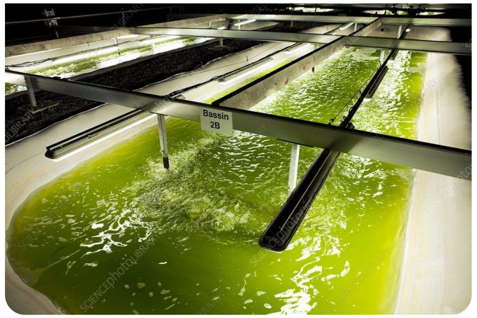
Fast-growing aquatic organisms that capture sunlight and nutrients to produce biomass. Commercially grown in coastal farms using ropes or nets suspended in the water, where they absorb nutrients and sunlight to grow rapidly.

Microalgae are microscopic plants typically cultivated in ponds



Microscopic organisms that use photosynthesis to convert sunlight, carbon dioxide, and nutrients into biomass. Cultivated in open ponds or closed systems.

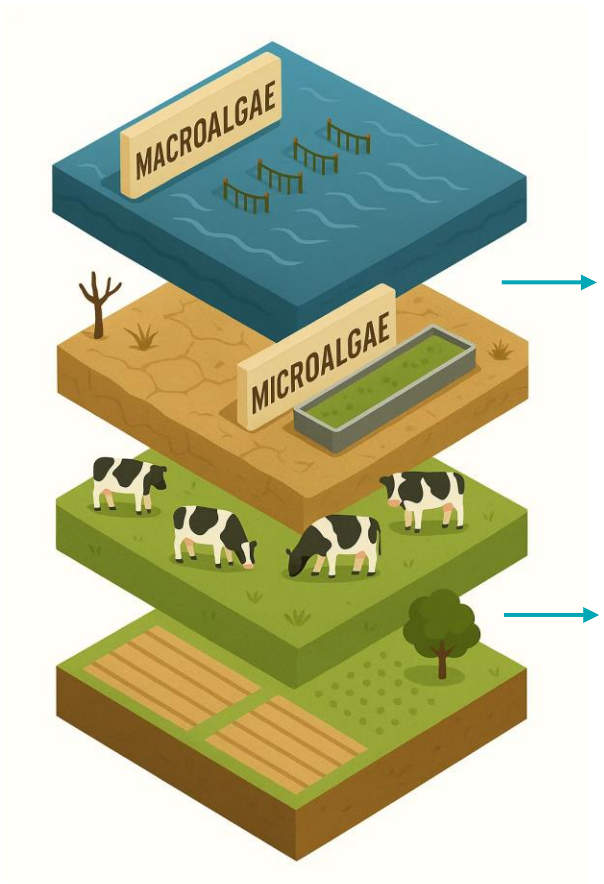
Both macro and micro algae offer pathways to increase overall biomass supply and efficiency

Innovations	Overview: Use case	Overview: TRL	Overview: Companies	Benefits: Efficiency potential	Benefits: Land saving potential
1 **Macro-algae** 	• **Ruminant feed additive:** mixing small amounts of red seaweed into the diet of cows improves feed conversion and reduces methane emissions. • **Forage-maize substitution:** kelp can be fed to cows in place of a share of their corn feed. • **Direct conversion to biofuels**	7-8	Atlantic Sea Farms Oceanium	• **Zero arable land,** freshwater or fertilisers. • **+14% feed conversion gain** in cattle[1]	• **Supplementing 0.05% of ruminant feed with red seaweed** could save 50 Mha of land by 2050.[1]
2 **Micro-algae** 	• **Soybean meal substitution:** used as protein supplement in animal feed • **Palm and soybean oil (vegetable oil) substitution:** used in cooking • **Fish-meal substitution:** used as feed for aquaculture	8-9	Algama Allmicroalgae natural products	• **7–25× more protein** per ha than soy[3]	• **100 algae facilities (111 ha each) in Thailand** could replace 10 % of world fishmeal on just 11,100 ha.[2]

Sources: [1] Spillias, et al (2023). Reducing global land-use pressures with seaweed farming. Nature Sustainability, 6(4), 380–390.; [2] Beal, C. M., Gerber, L. N., Thongrod, S., Phromkunthong, W., Kiron, V., Granados, J., Archibald, I., Greene, C. H., & Huntley, M. E. (2018). Marine microalgae commercial production improves sustainability of global fisheries and aquaculture. Scientific Reports, 8, 3354. [3] Mosibo, O. K., Ferrentino, G., & Udenigwe, C. C. (2024). Microalgae proteins as sustainable ingredients in novel foods: Recent developments and challenges. Foods, 13(5), 733.

By expanding productive area and improving feed efficiency, algae can displace crop demand and free land for rewilding and biomass production

Two distinct levers show how macro-algae and micro-algae relieve pressure on cropland and pasture



Drivers of land efficiency	Efficiency mechanism
New space cultivation introduces new productive surface area, reducing demands on cropland	• **Blue field expansion (macro-algae):** Growing macroalgae at sea adds new productive area **without taking up land**. It can replace soy, starches, and fish-based ingredients, easing pressure on farmland and oceans while freeing land for biomass or restoration. • **Brown field expansion (micro-algae):** Protein- and oil-rich micro-algae can displace soy-meal in livestock rations and high-deforestation palm-oil in food and oleochemical supply chains, freeing cropland and plantations elsewhere.
Livestock efficiency boosters improve nutrient uptake in cattle, reducing demand for animal feed	**Adding 0.2–0.5 % red seaweed to cattle feed lifts feed-conversion efficiency by approximately 14%,** meaning less feed and cropland per kg beef or milk[1]. Methane reduction from cattle is also possible (potential for up to ~80% reduction), although longer-term studies needed for a range of diets/animals.

Minimal to zero land footprints mean that expanding algal food, feed and additive supply can liberate cropland and pasture, freeing space for biomass production and ecosystem restoration.

Source: [1] Spillias C. & Krause-Jensen D., Global Benefits of Large-Scale Seaweed Farming (IIASA 2021) – assumes 20 t DW ha-¹ seaweed yield (turn14view0); NREL, Economic, GHG and Resource Assessment for Fuel and Protein Production from Microalgae: 2022 Algae Harmonization Update (2024) – 150 Mt biomass from 3.9 M ac ≈ 1.6 M ha marginal land (turn5view0); Global Methane Hub, State of the Science – Asparagopsis (2024) – 0.5 % inclusion cuts methane 52-80 % and improves feed-conversion efficiency (~6 %) (turn9search1).

Beyond land efficiencies macro algae can also be converted directly into biofuels, making a significant contribution to global biomass supplies

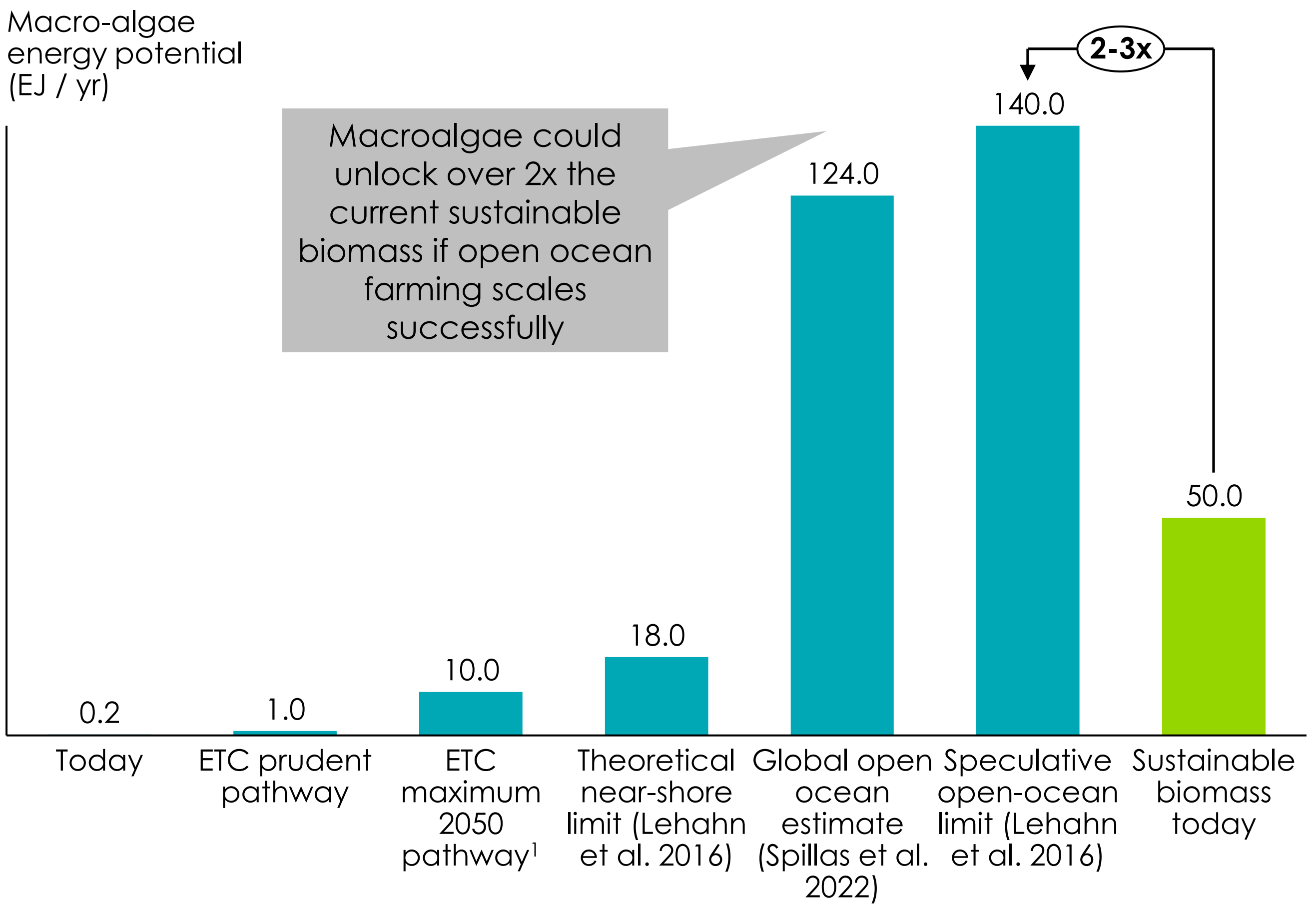
Macro algae presents a significant opportunity to increase global biomass energy supply

- **Opportunities**
  Ocean-based biomass. Fast-growing kelp and other macro-algae require no land, irrigation or fertiliser and can store carbon while supporting marine habitats.

- **Barriers**
  Technology & cost barriers. Offshore farm CAPEX, de-watering, and labour currently keep macro-algae fuels over double the cost of terrestrial crop-derived biomass.

  Scaling open ocean seaweed farming limited by high CAPEX of floating infrastructure, though integration with other blue economy sectors (like wind or aquaculture) may improve viability.

- **Exclusions**
  Microalgae is not a viable energy pathway Microalgae remain costly and resource intensive, making them best suited to food, feed, and nutraceutical applications. The ETC excludes them from all bioenergy pathways.



If scaled efficiently, macroalgae could meaningfully expand global biomass supply by adding a fully ocean-based source. Reaching this potential requires advances in cultivation systems and integrated biorefineries to close the current cost gap.

Notes: [1] The 10 EJ 'ETC energy-max' case assumes 100 % of future macro-algae output is sent to fuel or low-value material applications, with no extra allowance for food, feed or speciality chemicals. Source: Spillias et al. (2022) Reducing global land-use pressures with seaweed farming. Nature Sustainability; Lehahn et al. (2016), Global potential of offshore and shallow waters macroalgal biorefineries to provide for food, chemicals and energy: feasibility and sustainability. Nature Sustainability, 6, 168–179; Energy Transitions Commission (2024). Bioresources Within a Net-Zero Emissions Economy: Making a Sustainable Approach Possible.

❶ Macro algae: supplementing ruminant feed with red seaweed could improve feed-conversion efficiency by 14%, reducing land use demands

Comparison of kelp and soy production processes

1. Farming	2. Processing	3. Animal feed
Red seaweed is grown in coastal tanks or rope lines. It doesn't need arable land, freshwater or synthetic fertilisters	**Harvested kelp is chopped and kept stable** in airtight bags for storage & transport	**Introduced as a tiny fraction into ruminant diets** resulting in a 7% feed conversion efficiency
Maize is grown on arable land, requiring freshwater, fertilisers & pesticides	**Kernels are dried** and stored in silos and preserved	**Grain provides around 50–70 % of feedlot rations** as the main energy source for grain fed cattle

Worked example of benefits

Resource and emission impacts of producing maize for 1kg of beef, with vs. without seaweed supplementation[1]

	With seaweed	Pure maize	% delta vs. pure maize
Land	3 m²	3.6 m²	-14%
Fresh water	2000 L	2322 L	-14%
Energy	9 MJ	10.5 MJ	-14%
Fertilisers	0.1 kg	0.12 kg	-14%
GHG emissions[2]	7.5 kg CO2e	12.5 kg CO2e	-40%
Beef	1kg	1kg	100%

Notes: [1] Though exact figures will vary based on the production set-up and geography, this table relies on average figures to give an illustrative sense of the difference in resource and emission intensity. [2] Indicative GHG emission savings for whole ruminant lifecycle, and not just GHG emissions from maize production. Sources: Spillias, et al (2023). Reducing global land-use pressures with seaweed farming. Nature Sustainability, 6(4), 380–390; Poore & Nemecek 2018 global LCA databases for crop land/energy/GHG factors; Mekonnen & Hoekstra 2011 crop water footprints; USDA-NREL Corn Grain LCA Update 2020 for maize energy and fertiliser use; Thomas et al. 2021 LCA of Saccharina latissima cultivation; Liu et al. 2023 commercial kelp farm LCA (Shandong).

❷ Ocean farmed seaweed can produce ethanol with reducing water & GHG impacts, offering a lower-impact alternative to sugarcane

Comparison of kelp ethanol and energy cane ethanol production processes

1. Cultivation	2. Processing	3. Fermentation & Distillation
Macroalgae is grown in coastal tanks or rope lines. It doesn't need arable land, freshwater or synthetic fertilisters	**Harvested kelp is chopped and kept stable** in airtight bags for storage & transport	**The kelp is fermented and distilled** into fuel-grade ethanol
Cultivated on arable land in tropical/sub-tropical regions; requires fertilisers, fresh water and pesticides.	**Cane is harvested;** stalks are crushed to extract juice. Fibrous residue is burned to provide process steam and electricity.	**Sucrose-rich juice is fermented and distilled** to produce fuel-grade ethanol

Worked example of benefits

Resource & emission impacts of producing 1 litre of fuel-grade ethanol: seaweed vs. sugar cane[1]

	Seaweed	Sugar cane	*% delta vs. cane*
Land	*0 m²*	*1.5 m²*	*-100%*
Fresh water	*50 L*	*2100 L*	*-98%*
Energy[2]	*13 MJ*	*7 MJ*	*+86%*
Fertilisers	*0 kg*	*0.009 kg*	*-100%*
GHG emissions	*0.23 kg CO2e*	*0.75 kg CO2e*	*-69%*
Ethanol	*1 L*	*1 L*	*100%*

Notes: [1] Though exact figures will vary based on the production set-up and geography, this table relies on average figures to give an illustrative sense of the difference in resource and emission intensity. [2] In practice, cane ethanol production is self sufficient from an energy perspective,as the ethanol itself is used to power the process. Sources: Philippsen A. Energy Input, Carbon Intensity, and Cost for Ethanol Produced from Brown Seaweed. MSc thesis, Univ. Victoria, 2013 – 10.1 g CO_2e MJ^{-1}; EROI 1.7; freshwater ≈50 L; Gerbens-Leenes P.W. & Hoekstra A.Y. The Water Footprint of Sweeteners and Bio-ethanol (UNESCO-IHE, 2009) – 2 450 L H_2O L^{-1} ethanol for Brazilian sugarcane (global avg ≈ 2 855 L); Poore J. & Nemecek T. Science 360, 987-992 (2018) – cropland intensity dataset; 1.5 m^2 L^{-1} derived for sugarcane ethanol; Nguyen-Tan D. et al., Energy Conversion & Management (2023) – fossil energy 6.9–7.2 MJ L^{-1}; 0.63–0.67 kg CO_2e L^{-1};

SYSTEMIQ

❸ Micro algae: replacing soy-protein isolate with Spirulina meal may reduce land use, but requires co-location with waste heat and CO_2 to be efficient

Comparison of microalgae and soy protein production processes

30% of the world's microalgae production is sold for animal feed. Strains like spirulina are a low-fat protein source, with amino acid profiles **comparable to eggs and better than soy**. Unlike crops, they **don't compete for arable land** and can yield much more protein per hectare.[1]

1. Cultivation	2. Processing	3. Protein isolate
Single celled algae are grown in ponds on degraded land using CO_2 + sunlight (or waste heat) as inputs.	**Cells are de-watered** using a centrifuge and then spray dried.	**Dry powder is blended into** breads, snacks, pasta and beverages as a high-protein, vitamin–rich ingredient.
Soybeans are grown on arable land, and require freshwater, fertilisers & pesticides.	**Oil is removed from the soybeans,** and the remaining meal is washed and processed to create a high-protein powder.	**Dry powder is blended** into the same types of foods, adding flavour-neutral protein.

Worked example of benefits

Comparison of the resource and emission intensity of 1 kg of edible protein from spirulina vs soy[2]

	Spirulina	Soy	% delta vs. soy
Land	3 m²	15 m²	-87%
Fresh water[3]	1500 L	9000 L	-84%
Energy[4]	20 MJ	20 MJ	100%
Fertilisers	0.44 kg	0.3 kg	+47%
GHG emissions[5]	12 kg CO2e	10 kg CO2e	+17%
Edible protein	1kg	1kg	100%

Notes: [1] Davis, R. et al. (2024). Economic, GHG, and resource assessment for fuel and protein from microalgae: 2022 harmonization update (NREL/TP-5100-87099). National Renewable Energy Laboratory. [2] Though exact figures will vary based on the production set-up and geography, this table relies on average figures to give an illustrative sense of the difference in resource and emission intensity. [3] U.S. Department of Energy. (2023). Transforming the future of marine aquaculture: A circular economy approach (DOE/EE-2753). Office of Energy Efficiency & Renewable Energy. [4,5] Figures assume cultivation in a warm climate (or use of waste heat) so that only modest pumping and drying energy is needed; actual values rise or fall significantly with reactor design and local power mix. Sources: Frehner A. & Stucki M. (2025) "Sustainable algal proteins produced on potato and other controlled agri-food streams – Environmental impact assessment of micro-algae production as feedstuff (A'propos project, WP4)", Zurich Univ. Applied Sciences.

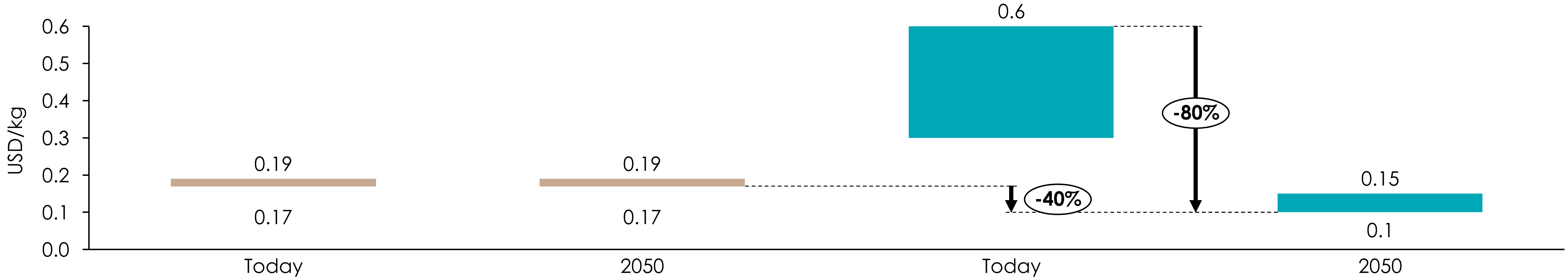
SYSTEMIQ

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

Cost per kg of dry biomass

Food source:	Maize	Macroalgae

COST COMPARISON[1]



COST DRIVERS

Levers to achieve cost parity by 2050

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

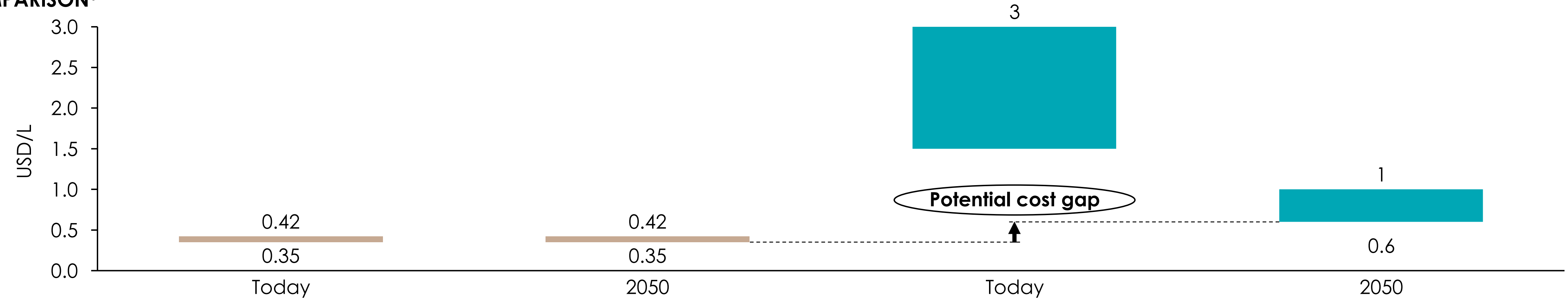
Notes: [1] Ranges reflect cost variations by biomass type, geography, and production method, representing global averages.
Sources: Kite-Powell H. L. et al., Estimating Production Cost for Large-Scale Seaweed Farms (JWAS, 2025); US DOE ARPA-E MARINER project; Stekoll M. S. et al., US DOE BETO 2023 Billion-Ton Report; World Bank Commodity Markets Outlook (May 2023); USDA ERS Feed Grains Market Outlook (Apr 2025); DOE BETO Bioenergy Technologies Portfolio (2022). Krause-Jensen, D., Lavery, P., Duarte, C.M., et al. (2023). Global potential of offshore and shallow waters macroalgal biorefineries to provide for food, chemicals and energy: feasibility and sustainability. Nature Sustainability, 6, 168–179; U.S. Department of Energy, Bioenergy Technologies Office (2023). 2023 Multi-Year Program Plan; National Renewable Energy Laboratory (2022). Techno-Economic Analysis for Seaweed-Based Biorefineries; Kim, J., Jung, J., & Lee, C. (2017). "A review on the production technologies of marine macroalgae biofuels." Renewable and Sustainable Energy Reviews, 73, 205–215; Energy Transitions Commission (2024). Bioresources Within a Net-Zero Emissions Economy: Making a Sustainable Approach Possible.

Energy cane leads on cost today, and it remains unclear if tech advances can help macro algae reach cost parity without policy interventions

Cost per L of ethanol produced with energy cane vs macroalgae

Fuel source:	Energy cane	Macroalgae

COST COMPARISON[1]



COST DRIVERS

Drivers of current high costs

Levers to achieve cost parity by 2050

- **Logistics is the top cost driver.** Harvesting, dewatering, and moving heavy 90% water macro-algae adds ~25 % to ethanol cost. Mechanical harvesters and high-pressure presses can shrink this cost by more than 60 %.
- **Steam & power dominate conversion costs.** Breaking seaweed down with steam and then distilling the alcohol makes up roughly 40 % of the price. New heat-saving stills and membrane filters can cut that bill in half.
- **Scale reduces CAPEX.** Scaling from pilot size to very large (300 million-litre-per-year) refineries spreads the fixed costs and drops the price another 25–40 %.
- **Co-products boost revenue.** Selling alginate, proteins, and biogas can offset OPEX, pushing macro-algae ethanol toward US $0.7–1.0 L^{-1}.

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

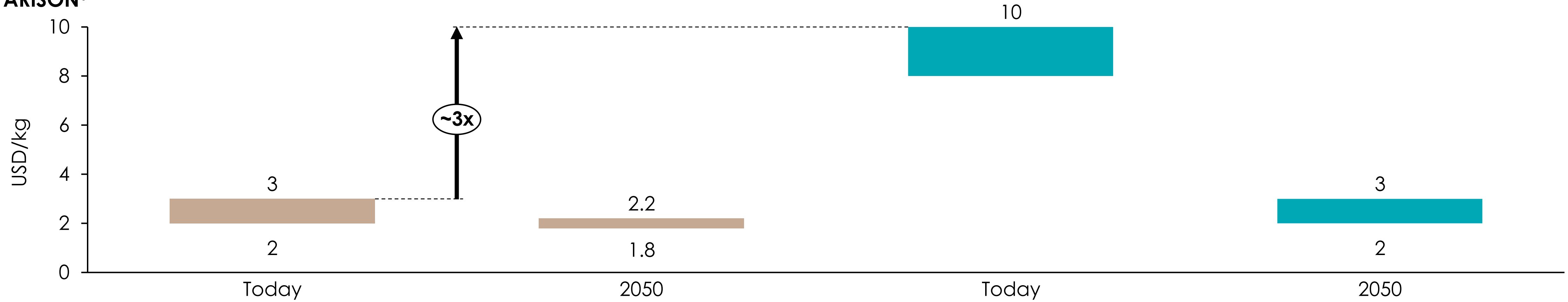
Sources: Krause-Jensen, D., Lavery, P., Duarte, C.M., et al. (2023). Global potential of offshore and shallow waters macroalgal biorefineries to provide for food, chemicals and energy: feasibility and sustainability. Nature Sustainability, 6, 168–179; National Renewable Energy Laboratory (2022). Techno-Economic Analysis for Seaweed-Based Biorefineries; Milledge, J.J. et al. (2024). "Macro-algae biofuels: Technology, economics and LCA." Algal Research; International Renewable Energy Agency (IRENA). Innovation Outlook: Advanced Liquid Biofuels, 2023; U.S. Department of Energy, Bioenergy Technologies Office (2023). 2023 Multi-Year Program Plan.

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

Cost per kg of protein isolate

Food source:	Soy	Microalgae

COST COMPARISON[1]



COST DRIVERS

Drivers of current high costs	
Levers to achieve cost parity by 2050	• **Scale matters most.** Multi-hectare shallow ponds or thin-film photobioreactors spread capital and labour over far more output, trimming those costs by 70–80%. • **Increase biomass density.** Raising cell density from means far less water to remove, cutting thickening and drying energy by about 70 %. • **Engineer better strains.** Strains that contain over 70 % protein and grow faster stretch the same feed, CO_2, and labour over more product, reducing the cost per kilo of protein. • **Co-products boost revenue.** Pigments and omega-3 oils can contribute to some of the operating bill, reducing the potential cost of bulk protein.

Notes: [1] Ranges reflect cost variations by biomass type, geography, and production method, representing global averages.
Sources: Green Circle Capital. GC Protein Pricing Review Year-End 2023 (soy isolate costs); National Renewable Energy Laboratory. Economic, Greenhouse Gas, and Resource Assessment for Fuel and Protein Production from Microalgae: 2022 Harmonization Update (microalgae cost baseline & 2050 targets); Davis R. et al. (2016). Process Design and Economics for the Production of Algal Biomass (NREL/TP-5100-64772) (cultivation cost model); Assunção J. & Malcata F.X. (2020). "Enclosed non-conventional photobioreactors for microalga production: A review." Algal Research 52: 102107 (intensification levers); Huesemann M. et al. (2023). "DISCOVR strain pipeline screening – Part I: Maximum specific growth rate across 38 candidate microalgae." Algal Research 71: 102996 (strain-improvement potential).

The ETC has modelled the potential for scaling macro and micro algae to increase sustainable biomass supply following a 3 step methodology

Purpose of model is to estimate:

1. The **land area** that could be freed if macro and micro algae partially replaced terrestrial crops
2. The sustainable **energy and carbon supply potential** of the freed land and the **increase in biomass supply from macro algae**

3-step methodology

Step	1	2	3
	Estimate macro and micro algae scaling potential	**Calculate land saving potential from macro and micro algae**	**Quantify energy potential from freed land + increase in biomass**
Short description	Projected adoption of algae products as a share of food and animal feed.	Increased supply of algae products reduces demand for terrestrial products, freeing up crop land	3 scenarios for reallocating freed land to rewilding, biomass, and macroalgae energy production
Key assumptions	▪ **Demand for products algae could displace** through 2050 (split by food, and feed) ▪ **Algae adoption rates** through 2050 (differentiated by food and feed) ▪ **Market share split** across macro and micro algae	▪ **Land-use intensity** by product and algae type ▪ **Land required for terrestrial based products** without algae substitution ▪ **Land required for algae**	▪ **Proportion of freed up land** dedicated to each type of use ▪ Biomass **yield rates** ▪ **Energy content** of biomass by type ▪ **Carbon content** of biomass by type

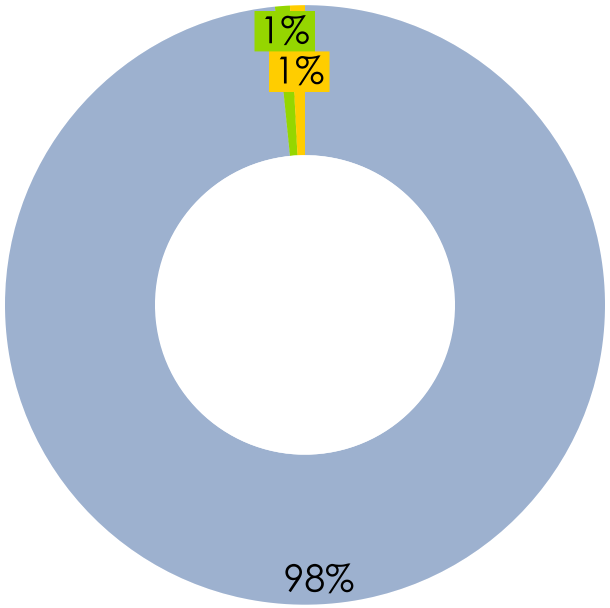
Key sources used: World Bank (2023), Global seaweed new and emerging markets report 2023; FAOSTAT; ETC (2021), *Bioresources Within a Net-Zero Emissions Economy: Making a Sustainable Approach Possible;* Expert interviews.

① Algae products uptake: algae derivatives are expected to make up relatively small shares of food and animal feed by 2050

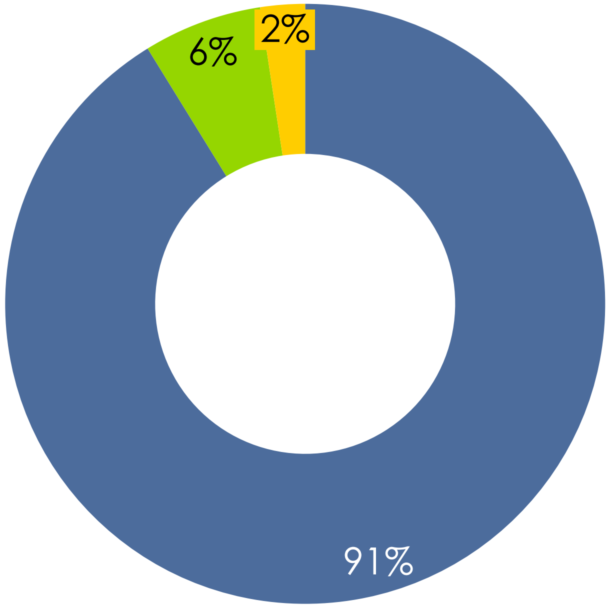
In a high ambition scenario, algae derivatives could capture small shares of the global demand for food and animal feed in 2050

Breakdown of global demand by source[1]

Food | Macroalgae | Microalgae | Feed



Global demand food mass
14,000 Mt



Global animal feed mass
1,880 Mt

Sources:FAO, Seaweed Trade and Market Potential; Greene, C.H. & Scott-Buechler, C.M. (2022). Algal solutions: Transforming marine aquaculture from the bottom up for a sustainable future. PLOS Biology, 20(10), e3001824; Makkar, H.P.S. et al. (2016). Seaweeds for livestock diets: A review. Animal Feed Science & Technology, 212, 1–17; Park, S. et al. (2024). Production of safe cyanobacterial biomass for animal feed using wastewater and drinking-water-treatment residuals. Heliyon, 10, e01167;

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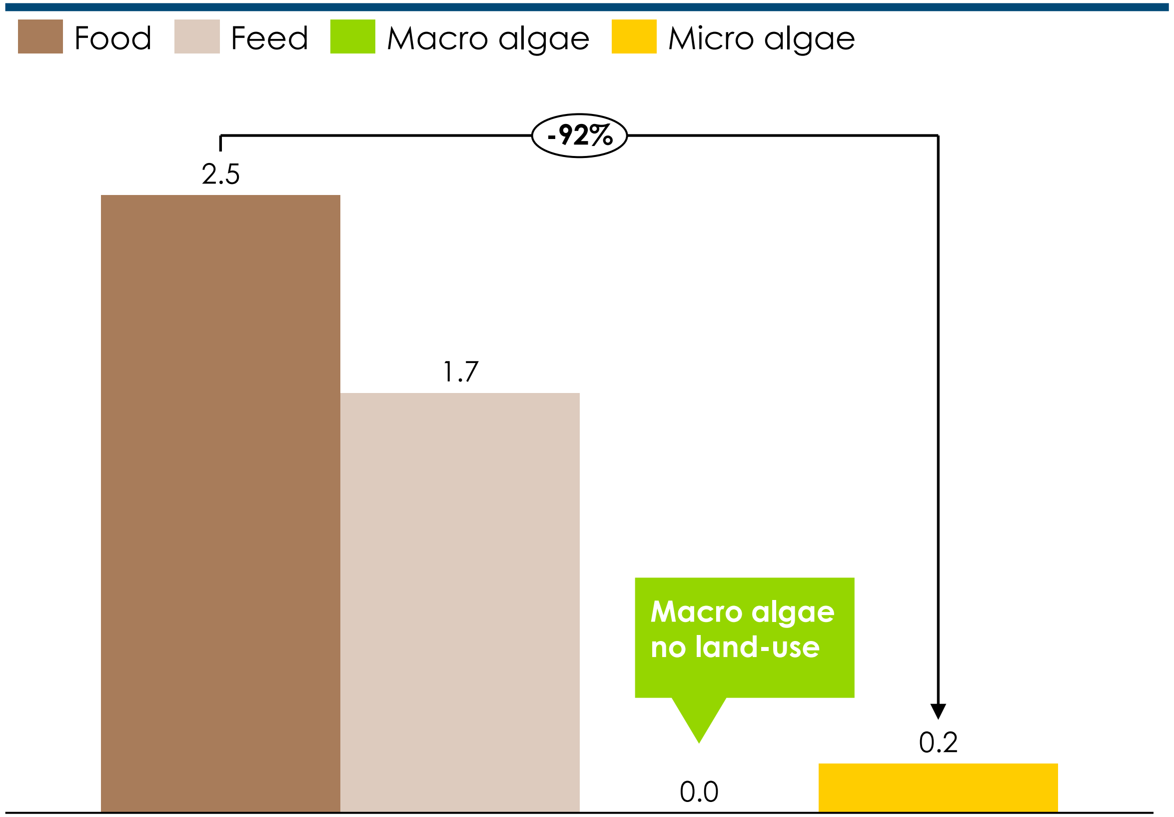
② Freed up land: 81 million hectares of land could be freed up by 2050 if algae displaces 395 Mt of food and animal feed

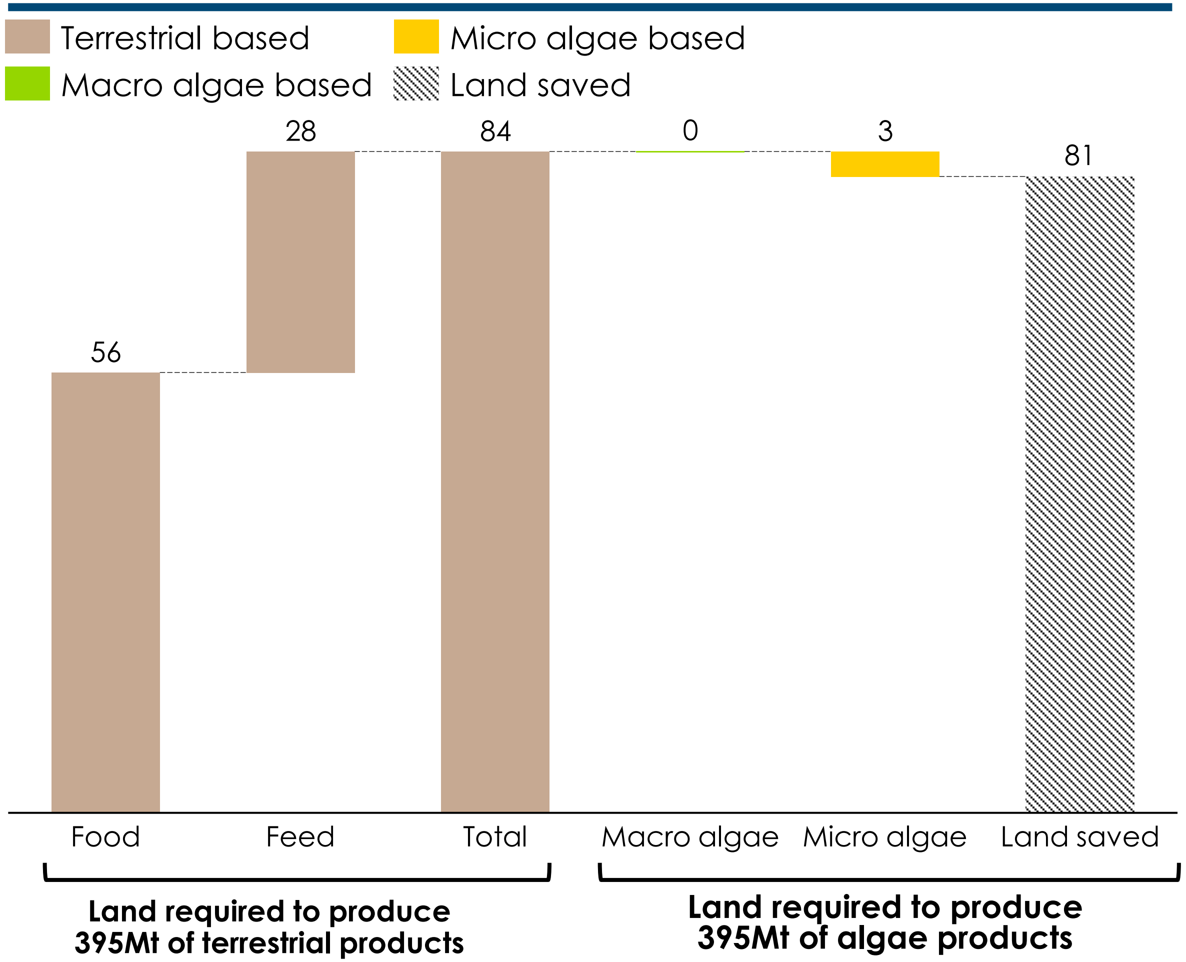
Algae could significantly reduce land usage compared to conventional food, and animal feed in best case scenario

Land-use intensity by product source, m^2/kg



81 Mha of land – 16% of cropland for animal feed[1] – would be freed if 395 Mt of food and animal feed were sourced from algae

Land required for terrestrial vs. algae based inputs, million hectares (Mha)



Sources: 1) Corresponds to ~2% of total agricultural land and (FAOSTAT) ~16% of cropland for animal feed (World Resources Report) 2) U.S. Department of Energy, Emerging Resources: Microalgae, Macroalgae, and Point-Source Carbon Dioxide Waste Streams; 3) Our World in Data (2023), Cereal Yields; USDA data via Our World in Data, Corn Yields.

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③ Energy and carbon potential: 81 million hectares of land could yield 10 EJ of energy and ~0.3 Gt of carbon per year by 2050, depending on land use

Algae can replace crops for food and feed—freeing land for rewilding or biomass. While macroalgae yield energy more efficiently when converted directly, crop substitution also reduces water and fertiliser use.

Scenario: *We assess how different land uses impact the energy and carbon sequestration, assuming macroalgae is always scaled.*	Land is rewilded + macroalgae	More managed Forestry + macro algae	More energy Crops + macro algae
	100% to nature (81 Mha)	20% to nature (16 Mha)	75% to nature (61 Mha)
	+6EJ of macro algae biomass used for energy	+ 80% to managed forests (65 Mha); +6EJ of macro algae energy biomass	+ 25% to energy crops (20 Mha); +6EJ of macro algae energy biomass
Outcome:			
EJ of useful energy	**6 EJ** of macro algae biomass	**4 EJ** of woody biomass including primary products and residues + **6EJ** of macro algae biomass for energy	**4 EJ** of energy crops from for example energy cane or switchgrass + **6EJ** of macro algae biomass for energy
Gt of carbon sequestration	**0.16 Gt** carbon stored in macroalgae biomass	**0.3 Gt** carbon stored in woody biomass	**0.3 Gt** available carbon in energy crops
Trade-offs	⊕ **Biodiversity + carbon sequestration maximised;** restores soil condition & water cycle ⊖ **No energy output,** so other sustainable biomass routes must be scaled ⊖ **Biomass from marine algae** without terrestrial biodiversity impacts	⊕ **Macro algae supplements biomass supply** with 0 land use impact ⊕ **Provides timber** as well as biomass ⊖ **Moderate biodiversity impact** – forested area better than energy-crop monocultures ⊖ **Decades to reach maturity**	⊕ **Significant biodiversity impact** on planted area, but large area returned to nature ⊕ **Fast growing crops** that produce yield every year ⊕ **Macro algae supplements biomass supply** with 0 land use impact

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

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Scaling macro and micro algae to free up land for sustainable biomass supply requires several conditions to be met

Goal	We need to believe…	Criteria for success	Measuring success	Evidence of progress
Rapid scaling of macro- and micro-algae substitutes frees up arable land, a portion of which is redirected to sustainable biomass pathways for energy and materials.	**Algae derivatives are adopted** and scaled at pace	**Affordability** Cost-parity with conventional inputs (soymeal etc.)	**Algae reach cost parity for its use cases**	**Production cost reductions over up to 80% reported over the past decade**
		Attractiveness Taste & performance match incumbent products	**Algae reaches 1% food demand and 8% animal feed market share**	**UK-based Notpla raised £20M in Sept 2024 to scale seaweed-lined boxes and films.**
		Accessibility Infrastructure & financing mobilised for ponds and sea farms	**Displace 395 Mt of terrestrial crops**	**Seaweed farming is central to the EU's bioeconomy strategy, with over 200 startups active globally in 2022.**
	Freed land is returned to nature and converted to biomass	**Freed land** Land is freed up as result of the shift to algae-based products.	**81 Mha of land liberated**	**Spillas et al., 2022 estimate that substituting human diets with algae at rate of 10% globally would spare up to 110 million hectares of land.**
		Land & sea allocation Freed-up land is rewilded and used for biomass, as well as scaling macro-algae biomass.	**80% to managed forests (66 Mha) + 6EJ of macro-algae biomass**	**IEA projects total bioenergy supply from short rotation woody crops to rise from 25EJ to 40EJ in 2050.**

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. NREL (2025) Techno-Economic and Life Cycle Analysis for Microalgae Conversion Pathways to Fuels and Products

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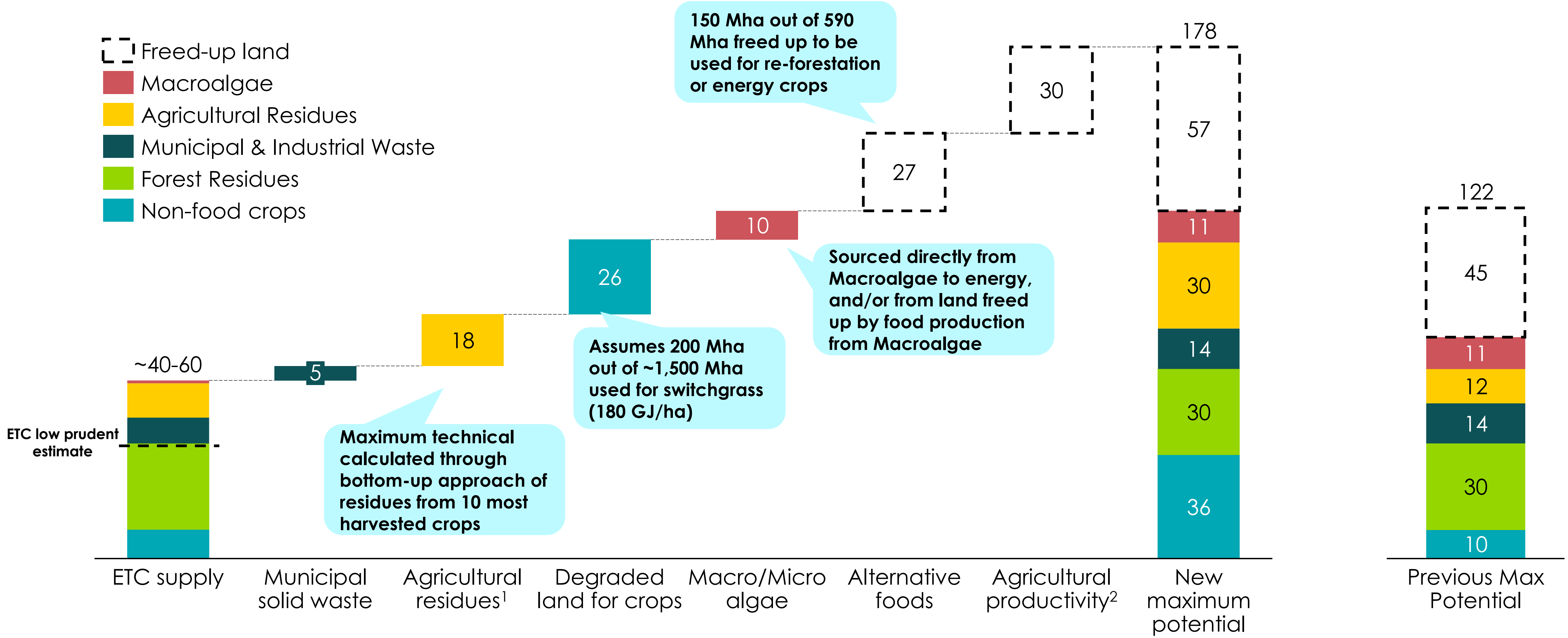
Biomass supply summary – a new possible maximum scenario estimates that sustainable biomass availability around ~180EJ

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

Summary: Biomass conversion technologies

1. **Biofuels are produced from biogenic carbon from living biomass or from organic wastes.** While 1st generation can displace land area used for food and 3rd and 4th generation have low TRL, 2nd generation emerges as an option that valorizes biomass considered as waste

2. **There are different routes to convert biomass into high-end carbon-based molecules,** which depend on the primary biomass source and the desired product. Intermediary products are often produced.

3. **Novel catalysts lift yields by ~2–20 %,** with the biggest gains in early-stage paths like cellulosic ethanol and alcohol-to-jet.

4. **Advanced reactors,** membrane, micro-channel, fluidised-bed, **may increase yield by 8–20 %** through superior heat/mass transfer and residence control.

5. **These yield gains shave 4 – 8% off conversion costs, yet fossil fuels remain cheaper;** feedstock prices dominate, so credits or carbon pricing will still be needed

6. **Yield improvements can return 30% savings on primary biomass required for bio-SAF production.**

7. **Making bio-based carbon molecules viable depends on:**

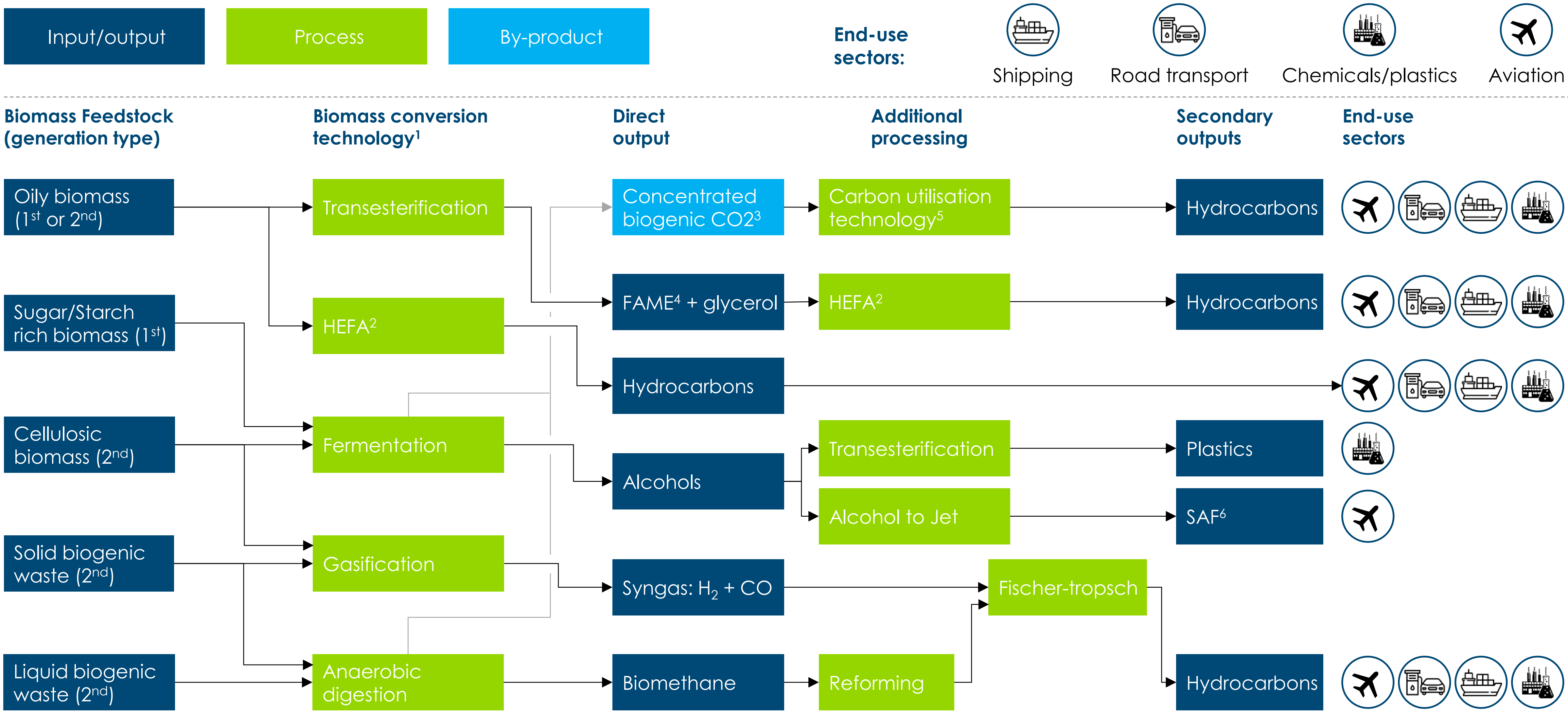
    - **Global definition of sustainable biomass,** to avoid legislation misalignments
    - **Maximization of local resources,** to secure reliable supply of biomass (processed or un-processed)
    - **Market creation for new bio-molecules,** to allow for trading of molecules and incentivized supply and demand
    - **Demand incentives,** to generate demand and facilitate offtake agreements
    - **Accelerated deployment,** to ensure that costs will decrease over time

Biofuels are fuels derived from biogenic carbon found in living biomass or organic waste

	1st Generation	2nd Generation	3rd Generation	4th Generation
Feedstock	Food crops (e.g., sugarcane, corn, palm oil)	Non-food biomass (e.g., cellulosic waste, UCO[1], biogenic MSW[2])	Macroalgae	Genetically engineered microbes
Working principles (non-extensive)	Fermentation Transesterification Hydro-processing	Gasification Anaerobic digestion Fermentation	Lipid extraction + HEFA[3] Fermentation HTL[4] / Pyrolysis	Synthetic biology Photobiological conversion
Current TRL	9 Commercial process from different feedstocks	6 – 9 Some commercial, but most in scale-up stage	3 – 5 Pilot stage projects facing economic hurdles	2 – 4 Lab-scale or conceptual scale
Environmental considerations	Competes with land usage for food production	Valorisation of wastes and residues	No land needed, but risk of spread in open water	No land needed, but issues if organisms are released/escape

Notes: 1) UCO = Used Cooking Oil; 2) MSW = Municipal Solid Waste; 3) HEFA = Hydro Processed Esters and Fatty Acids; 4) HTL = Hydrothermal liquefaction

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 by synthetized. 4) FAME = Fatty Acid Methyl Ester. 5) See phase two slide 84 diagram for detailed view of routes. 6) SAF = Sustainable Aviation Fuel

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

Type of innovation	Description	Deployment examples[1]	Companies	TRL
Catalysts	• Novel catalyst **aim to improve conversion and yield of desired products**, decreasing primary biomass needed and **decreasing the activity of competing reactions**	• Innovaturbo yeast for starch feedstocks is **used in 60 % of U.S. corn-ethanol plants** • Cellic Ctec enzymes **dominates cellulosic biomass fermentation** (Raizen, GranBio, Beta Renewables)	novozymes	7 – 9
		• Indonesia's new biorefinery—**HydroFlex plant #50**—will use Topsoe catalysts to make **6 000 gpd of renewable diesel and SAF**.	TOPSOE	9
		• FOAK plant inaugurated in Georgia in 2024, with a capacity of **10 MM gpy of SAF from ethanol at a cost of U$ 200 MM**	LANZAJET	7 – 8

Reactors	• New reactor designs aim to improve reaction kinetics or reduce equipment CAPEX
	• Example of new reactors configuration:
	  • **Micro-channel reactors**
	  • **Membrane reactors**
	  • **Fluidized bed reactors**
	  • **Modular reactors**
		• Fluidized bed reactor technology installed in Alberta, which **gasifies MSW to produce ~1,000 barrels per day of methanol**	Enerkem	6 – 8

		• Microchannel FT + Upgrading reactor with two projects in early stage (Shell in the UK and Bayou Fuels in the US) and one small demo plant owned by ENI in the US	VELOCYS	6 – 7
		• Memthane AnMBR technology treats diverse industrial effluents. Examples of **adoption by a meat processing plant in the US** and **by a dairy farm in Europe**	VEOLIA	7

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

Catalysts: A catalyst speeds up a chemical reaction by lowering its activation energy, allowing reactants to turn into products more quickly

Overview of catalysts activity in a reaction (example hydrogenation reaction)

$$C_2H_4 + H_2 \rightarrow C_2H_6$$

1. Reactants are fed to chamber
2. One of the reactants is adsorbed by the catalyst
3. Both reactants are adsorbed by the catalysts
4. Product is formed

Types of Catalysts (Non-exhaustive)

BIOLOGICAL CATALYSTS

Enzymes or protein molecules that speed-up **life sustaining reactions** or that **break up complex organic structures** into useful organic chemicals

INORGANIC CATALYSTS

Metal compounds, sometimes rare metals, which are **suitable for more aggressive reactants and harsher conditions**

MOFs[1]

Novel catalysts chemistries with **higher selectivity**, which are **crystalline structure with metal anodes** and **organic linkers**

Estimated yield gains for some routes

Catalyst R&D helps low-TRL processes most, but other areas also need development.

Non-exhaustive

Lower TRL processes

Route	Catalyst type	*Baseline t/t[2]*	*Yield gain%*
Oily Biomass → FAME	Biological	*~0.9*	*3 – 10%*
Oily Biomass → HVO / SAF	Inorganic	*0.75 – 0.81[4]*	*9 – 13%*
Sugar / Starch → Ethanol	Biological	*0.42 – 0.46[3]*	*2 – 10%*
Cellulosic Biomass → Ethanol (lower TRL)	Biological	*~0.37 – 0.43*	*3 – 20%*
Ethanol → SAF (lower TRL)	Inorganic	*~0.5*	*18 – 20%*
Ethanol → Ethylene	Inorganic	*~0.57*	*5%*

Notes: 1) MOFs = Metal Organic Frameworks; 2) Baseline refers to common achievable industrial conversions in terms of tone of product per tone of feedstock. Ranges given for cases for feedstock sensitivity and processing; 3) Low end for starch, higher end for sugar

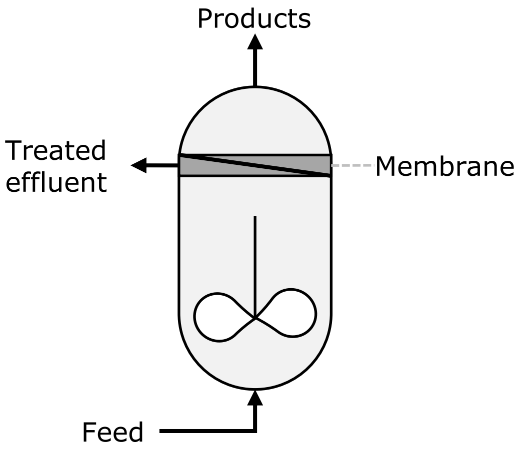
Sources: UNICAMP (2017) sunliquid® - Delivering a Proven Technology Solution for Commercial Cellulosic Ethanol Production; DOE (2017) One-Step High-Yield Production of Fungible Gasoline, Diesel, and Jet Fuel Blend Stocks from Ethanol without Added Hydrogen; Tengler, E. (2021) With Investment From Shell, LanzaJet Looks To Produce 10 Million Gallons Of Ethanol-Based Jet Fuel By 2023; Novozymes (2022) New yeast innovations deliver unparalleled performance for bioenergy industry; Sica, P., et al., (2025) Pre-adaptation of yeast (Saccharomyces cerevisiae) strains to very high gravity can improve fermentation parameters and reduce osmotic stress; SRS (2024) Transesterification; Mayo, S. (2024) Hybrid catalyst loading reduces fill cost and carbon footprint; Ngcobo, M., et al., (2024) A minireview on solid acid catalysts for dehydration of bioethanol to renewable ethylene: An update on catalysts development progress

Reactors: Innovative reactor design aim to improve conversion by improving, for example, heat transfer and molecule contact

Overview of innovative reactors

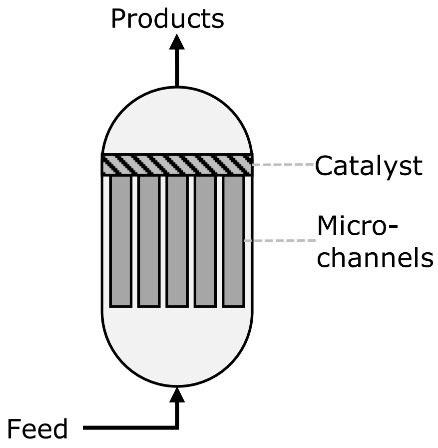
Non-exhaustive

MEMBRANE REACTOR[1]



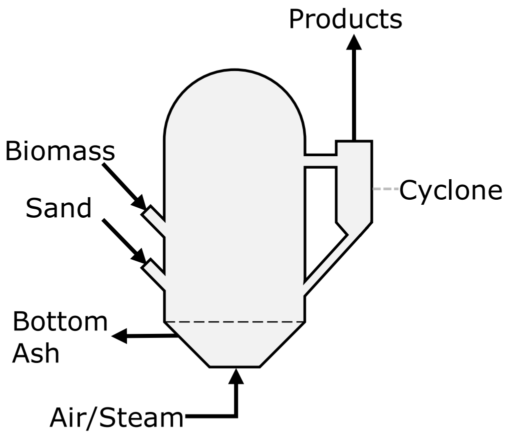
Membrane reactors **keep biomass-solids locked inside digester, increasing conversion**. Membrane lets out **clear effluent with almost no active sludge**, which **pushes biomethane yield** close to the theoretical maximum

MICROCHANNEL REACTOR



Micro-channel reactors use **millimetre scale passages** that give **ultra-fast heat transfer** and **short diffusion** distances, keeping **temperature uniform** and **reactants perfectly mixed, boosting conversion and selectivity per unit volume**

FLUIDISED BED REACTOR[2]



In fluidized bed reactors, crushed **biomass fluidizes in a hot sand/steam bed**, keeping **temperature even and gas-solid contact high.**
The bed also acts as **heat carrier and tar-cracking catalyst, boosting syngas yield**

Estimated yield gains for reactors

Smart reactor designs can unlock major yield gains

Non-exhaustive

#		*Baseline t/t*[3]	*Yield gain%*
1	**Membrane reactors for liquid waste anaerobic digestion**[4]	*~0.43* [5]	*~8 - 20%*
2	**Microchannel reactors for syngas conversion into Fischer-Tropsch liquids**	*~0.36*	*~10 – 14%*
3	**Fluidised bed reactor for solid biomass (cellulose or solid biogenic waste) gasification for methanol synthesis**	*0.48* [6]	*~20%*

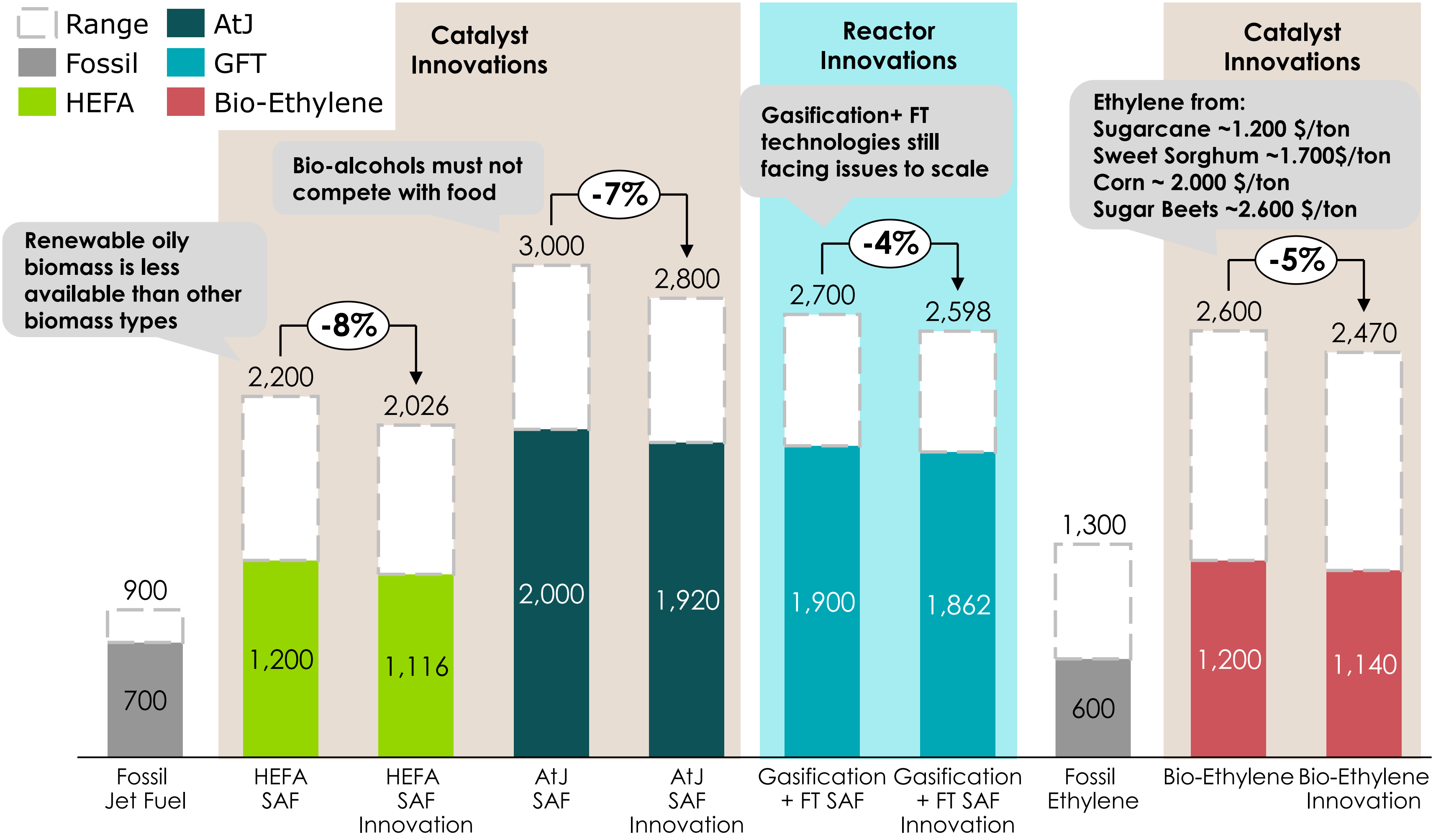
Notes: 1) Membrane reactors example specific for liquid biogenic waste anaerobic digestion, but similar working principle for other applications; 2) Fluidized bed reactors example specific for biomass and solid biogenic waste gasification, but similar working principle for other applications; 3) Baseline refers to common achievable industrial conversions in terms of tone of product per tone of feedstock. Ranges given for cases for feedstock sensitivity and processing; 4) Benchmarking will depend on type of effluent; 5) Assumes a ratio of COD (Chemical Oxygen Demand) to VSS (Volatile Suspended Solids) of 1.4 kg/kg; 6) Depends on MSW composition

Sources: ETIP Bioenergy (2021) Biomass to Liquids (BtL) via Fischer – Tropsch a brief review; Pu, Y., et al., (2022) Pollutant Removal and Energy Recovery from Swine Wastewater Using Anaerobic Membrane Bioreactor: A Comparative Study with Up-Flow Anaerobic Sludge Blanket; Lutze, R., et al., (2020) Comparison of CSTR and AnMBR for anaerobic digestion of WAS and lipid-rich flotation sludge from the dairy industry; ENERKEM (2025) Ecoplanta Receives Approval; Hakandai, C., et al., (2022) Conversion of municipal solid waste o hydrogen and its storage to methanol;

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 end[1]

$/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) Byoethylene 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

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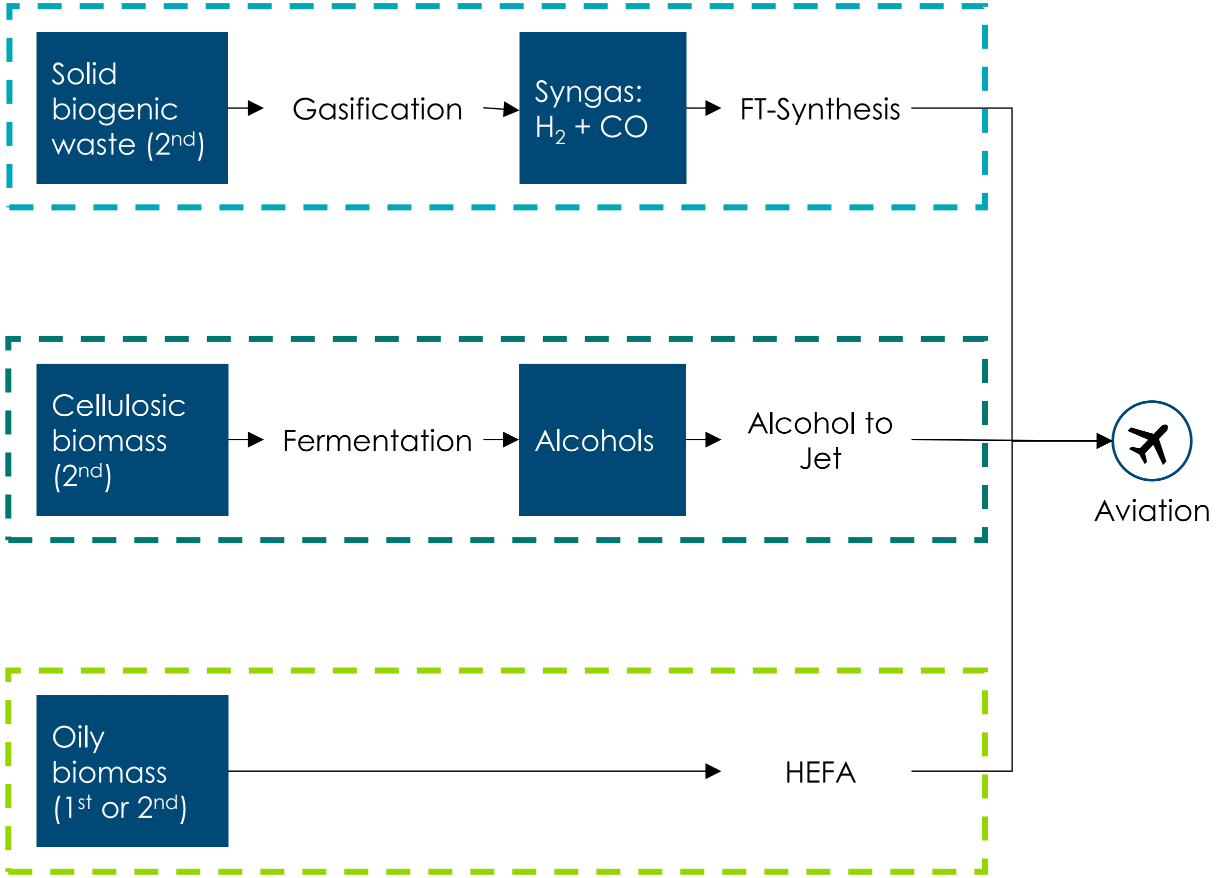
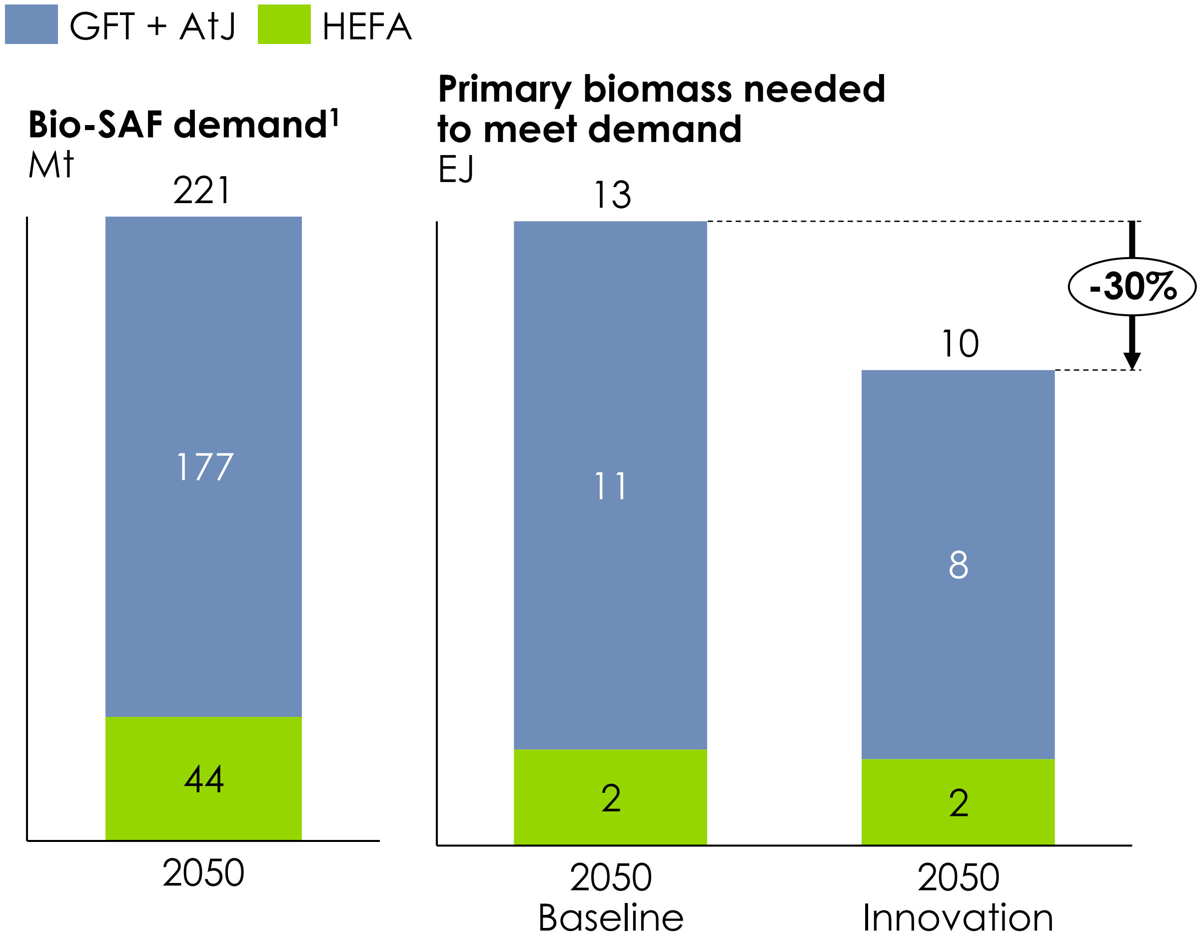
Catalyst and reactor innovations across key bio-SAF routes could cut primary biomass demand by ~30% for key end-use sectors like aviation

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

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Securing feedstock and demand incentives accelerates deployment and cuts costs

Goal	We need to believe…	Criteria for success	Evidence of progress/status
Goal **Advanced bio-based carbon molecules become a viable alternative for fossil-based carbon molecules**	**Feedstock are made more accessible** through precise regulation, maximisation of local resource use and commodity pricing	**Sustainable biomass regulations** Global definition of sustainable biomass, which is inclusive without compromising other areas (e.g., land use)	Currently, **divergent definitions of sustainable biomass drive regulatory misalignment.**
		Maximisation of local resources Development of local collection or local processing, to concentrate feedstocks	**Several studies map regional biomass potential**, and **small-scale projects are already operating**[1]
		Market creation Creation of commodities markets which make bio-based molecules tradable (e.g., biomethane, biogenic CO_2)	**Europe leads,** with countries having biomethane, CO_2 and even Syngas markets
	Increased demand pushes for faster deployment, which over time reduce the technology costs	**Demand incentives** Blending mandates and emission targets, which create a solid demand for bio-based chemicals and materials, facilitating offtake agreements	**Many countries enforce blending mandates and sectoral emission caps, yet ambition must rise to spur large-scale projects**
		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	**IEA Bioenergy states that 111 bio-SAF facilities[2] have been announced (~33 Bn L/year)**, but most are in very early planning stage

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)

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Agenda

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

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End-of-life management

Summary: end-of-life carbon management

1. **Established geological CO_2 storage options (depleted oil & gas reservoirs and saline aquifers) are low cost and sufficient in storage capacity.** However, limitations may block their scale-up (e.g. injection rate limits, CO_2 leakage risk and monitoring, environmental and regulatory challenges, geological suitability varies).

2. **CO_2 mineralisation pathways offer a promising alternative** (e.g. in situ underground injection of CO_2 to form solid carbonates in reactive rocks) with high injection rates, no risk of CO_2 leakage, and no need for monitoring.

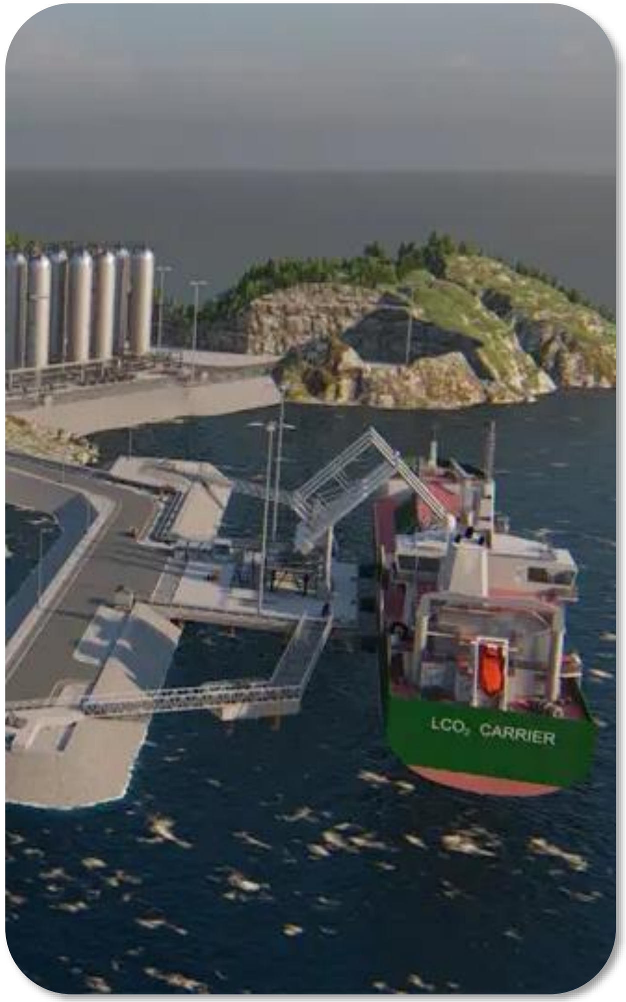
3. **Cost of mineralisation today is 50% higher than depleted oil & gas reservoirs and saline aquifers but has significantly higher CO_2 storage capacity.** This results in wider geographic availability which could potentially reduce transportation costs.

4. **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.**

5. **Advanced landfilling technologies will be needed to reduce the GHG emissions of mismanaged landfill sites**, e.g. pre-landfill material recovery and biological treatment, landfill gas capture and management systems.

6. **Advanced landfills could cost marginally more (+ $30/tonne waste) than managed landfills today** and be highly cost-competitive against incineration with CCS.

7. **Realising adoption of end-of-life carbon management requires 5 enablers:**
   - **Technological innovation:** developments in promising CO_2 mineralisation pathways
   - **Long-term liability and monitoring**: reliable systems for monitoring, reporting, and verifying (MRV) CO_2 storage integrity and managing long-term liability
   - **Commercial CO_2 market intermediaries:** CO_2 T&S networks can reach greater economies of scale with market intermediaries that provide CO2 T&S as a service to multiple parties
   - **Landfill policy mandates and requirements:** strict policies addressing the management of GHG emissions from landfills (e.g. requirements to install landfill gas capture systems)
   - **Incentives for landfill technology deployment:** e.g. commercial contracts to procure electricity/heat from landfill gas capture projects, tax credits for energy generation



Our deep dives will focus on emerging CO_2 and solid C storage technologies which have the greatest potential to cut costs and prevent leakage

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

Emerging technologies

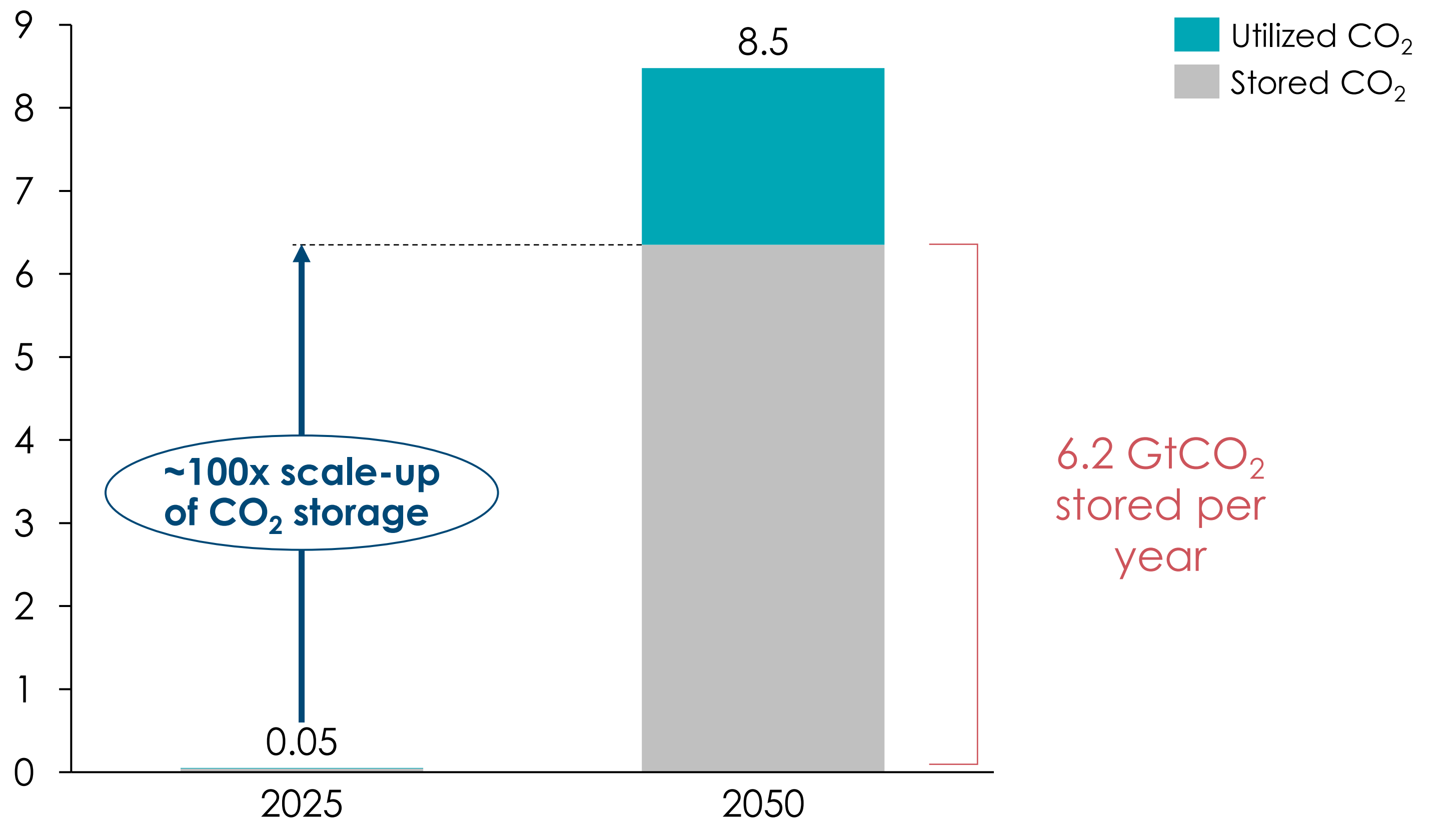
Notes/Sources: 1) Peter Kelemen et al. (2019) An overview of the status and challenges of CO2 Storage in Minerals and Geological Formations 2) Kyuhyun Kim et al. (2023) A review of carbon mineralization mechanism during geological CO2 storage 3) Ahmed Bashir et al. (2024)

End-of-life management: CO_2 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 $GtCO_2$ per annum of captured CO_2 in 2050, the majority (6.2 $GtCO_2$) will need to be stored
2. Current CO_2 sequestration in sedimentary formations is around 50 $MtCO_2$ (0.05 $GtCO_2$) per year — 100-fold scale-up is required by 2050 to meet climate targets[2]

Carbon capture and carbon utilization and storage volumes[1]
$GtCO_2$ p.a.



Notes/Sources: 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. ETC (2022), Carbon capture, utilisation and storage in the energy transition 2) IEA (2024) Annual CO2 capture capacity vs CO2 storage capacity, current and planned, 2022-2030

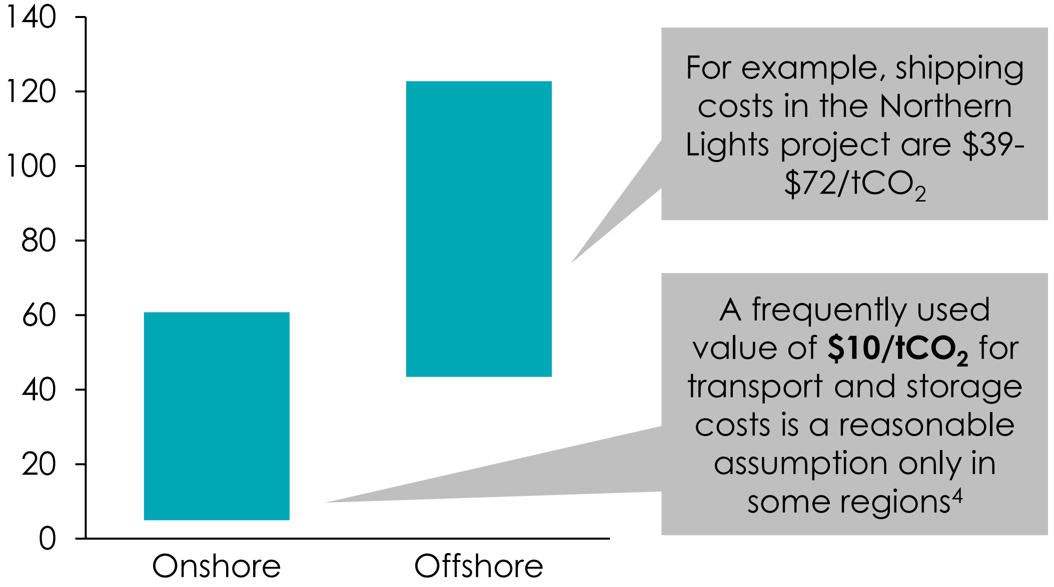
Established geological options are low cost and sufficient in storage capacity

Range of estimated onshore and offshore sedimentary CO_2 storage capacity

$GtCO_2$

Cost of CO_2 transport and storage in depleted oil & gas reservoirs and saline aquifers, 2025

$/$tCO_2$ transported and stored

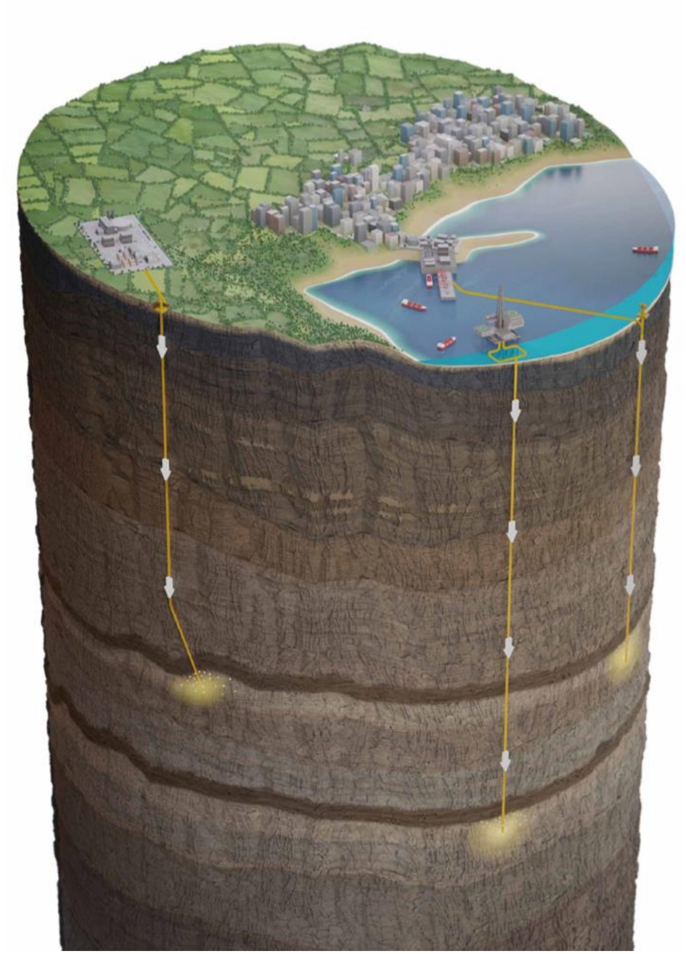


5 key variables affecting the costs:

- 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



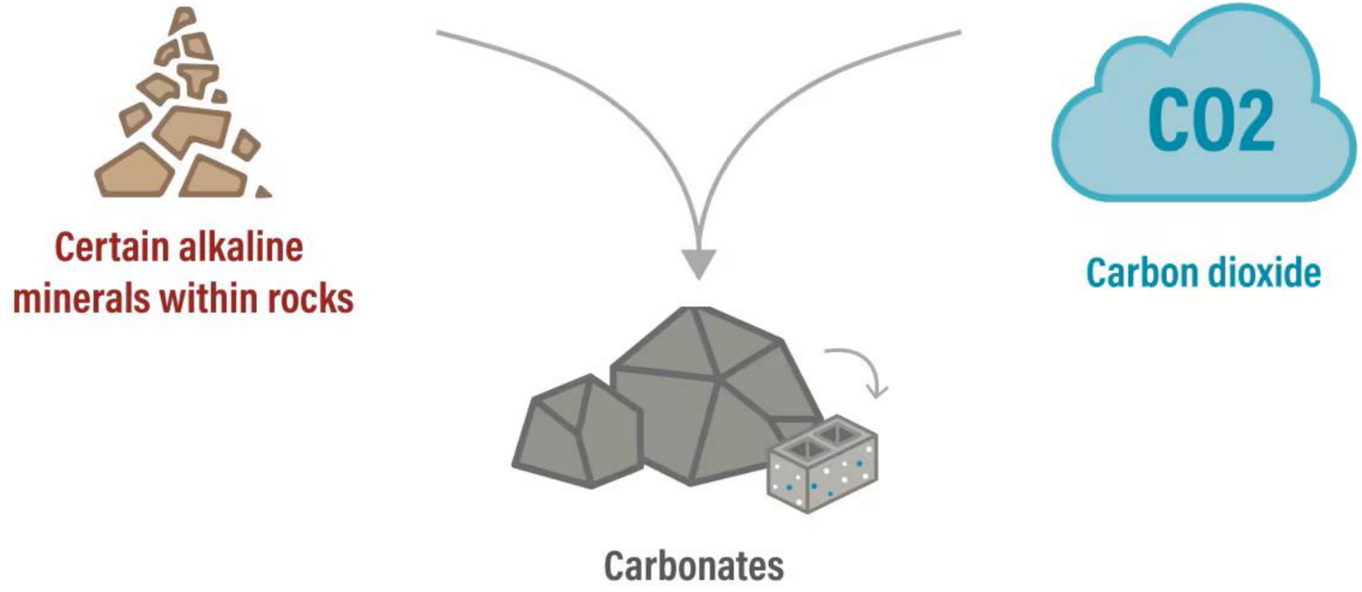
Potential limitations	Description
Injection rates limits	Annual injection is capped by reservoir pressure, risk of fracturing caprock, and potential for induced seismicity, slowing deployment. Some sources indicate this can limit global CO_2 injections up to 2 $GtCO_2$/y.[1]
Leakage risk and monitoring	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 CO_2 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)

❹ CO_2 mineralisation (in situ): Underground injection of CO_2 to form solid carbonates in reactive rocks

Overview of production process



1 CO_2 Injection into Reactive Rock

CO_2 is injected underground into basaltic or ultramafic rock formations. It dissolves in formation water, increasing its acidity (forming H_2CO_3)

2 Dissolution of Silicate Minerals

The acidic water reacts with Mg-, Ca-, and Fe-rich silicate minerals in the rock, releasing metal cations (e.g., Mg^{2+}, Ca^{2+}, Fe^{2+}) into solution.

3 Formation of Stable Carbonate Minerals

The metal ions bind with carbonate ions (CO_3^{2-}) to form solid minerals like calcite or magnesite, permanently locking CO_2 in rock.

Comparison with widely used storage

Comparison of CO_2 mineralisation with CO_2 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)

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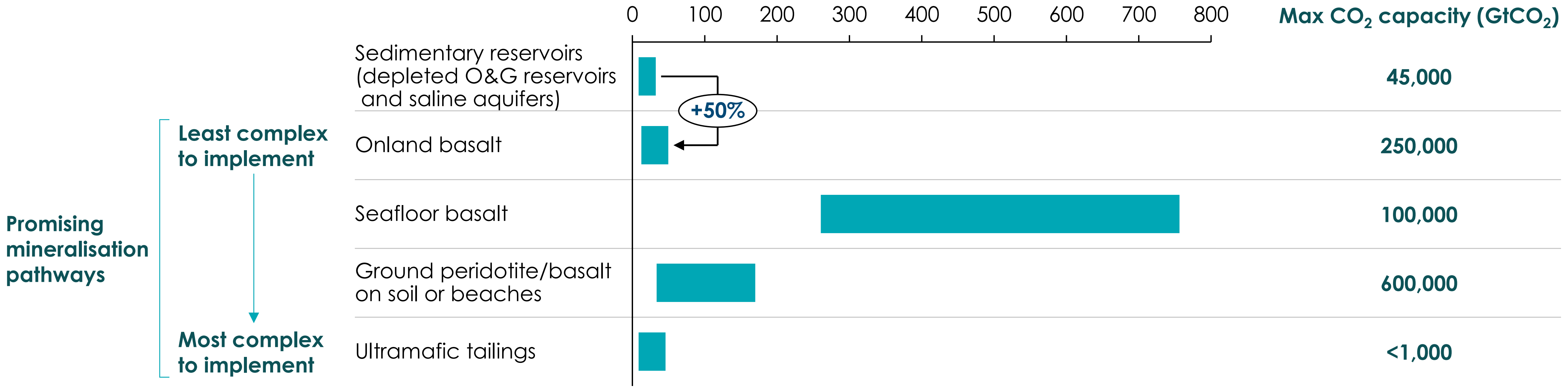
Cost of mineralisation today is 50% higher than depleted oil & gas reservoirs and saline aquifers, but has significantly higher capacity CO_2 storage

Cost of CO_2 storage for sedimentary reservoirs and most promising mineralisation pathways, 2025

$/t$CO_2$ stored



Key takeaways on cost drivers and trends

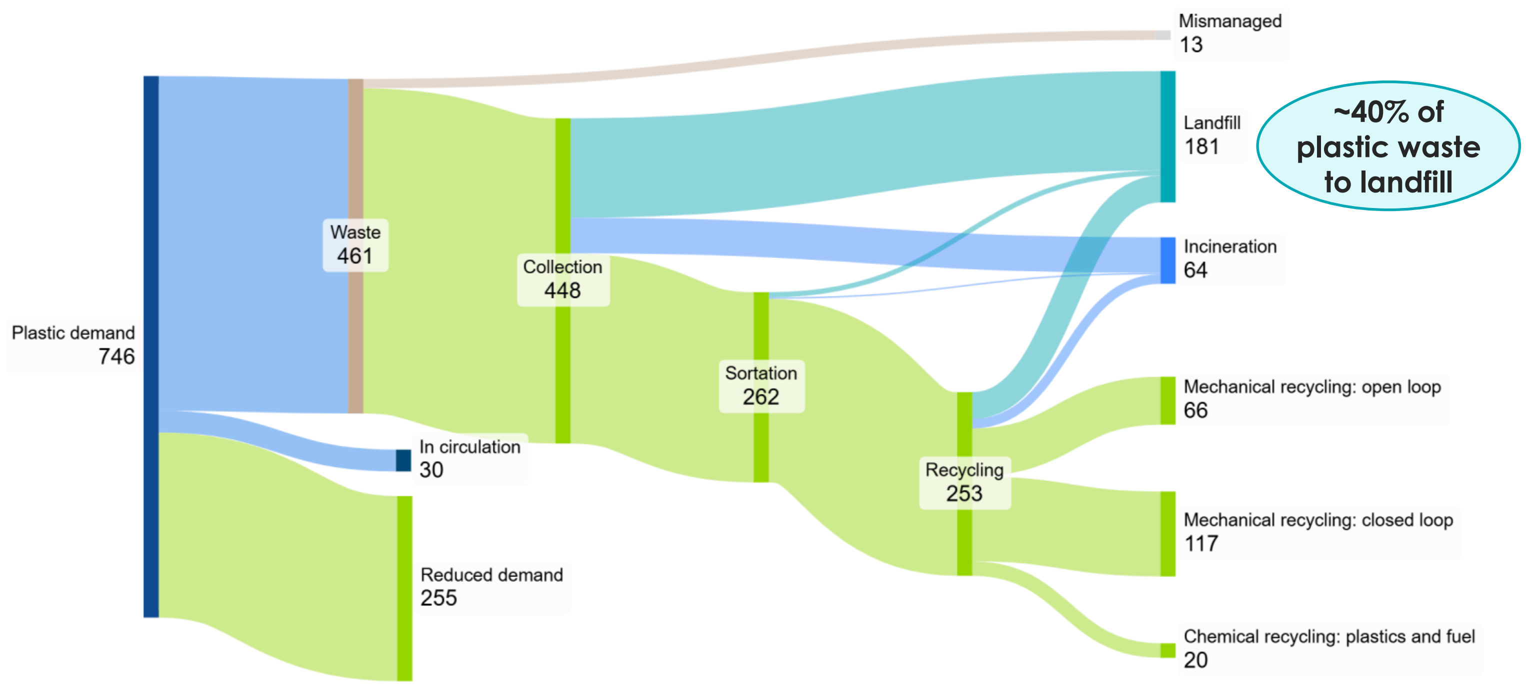
- Sequestration in **on-land basalt and ultramafic tailings could become competitive** with storage in sedimentary reservoirs, but costs rise significantly for storage in seafloor basalts.
- Different pathways **can complement one another** other as their geological occurrences do not typically overlap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

Notes/Sources: 1) Peter Kelemen et al. (2019) An overview of the status and challenges of CO2 Storage in Minerals and Geological Formations 2) Erin Smith et al. (2021) The cost of CO2 transport and storage in global integrated assessment modelling 3) Hugh Barlow (Global CCS Institute 2025)

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, 2040[1], *million metric tonnes*



- Current practices of solid carbon waste management via landfill and incineration are significant drivers of climate change, together emittting CO_2-equivalent gases of approximately 1.2 $GtCO_2$/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

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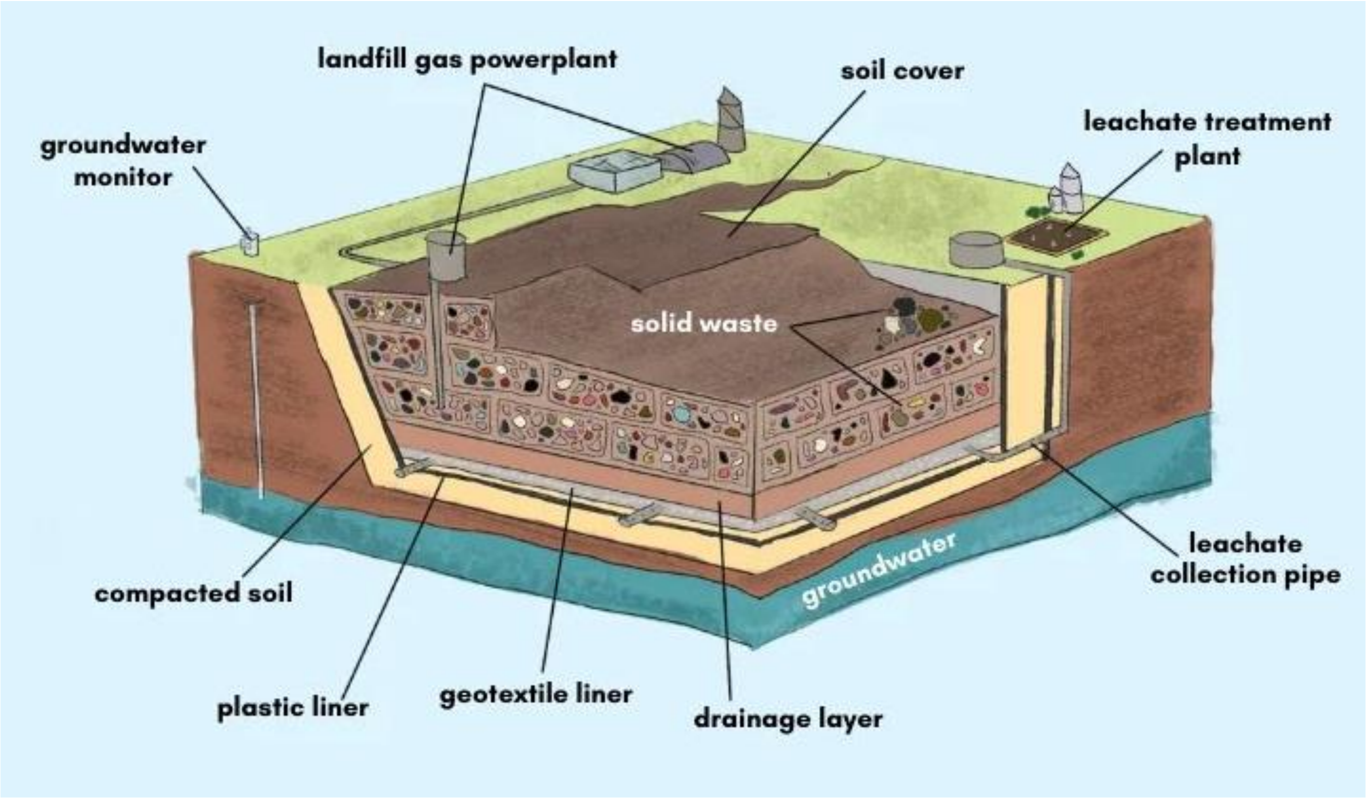
Landfill today: sanitary (or "managed/engineered") landfills are the different names for controlled landfill sites with environmental controls implemented



Sanitary landfill (shown left):

- Functions as a sealed vault, not open to the elements
- Engineered coverings with plastic/geotextile liners
- Equipped with leachate collection and treatment plants
- May have landfill gas capture and utilisation plants

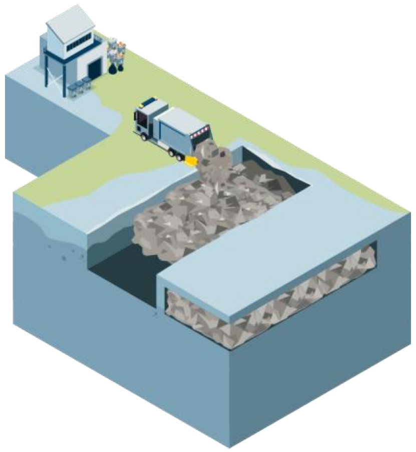
In comparison to…

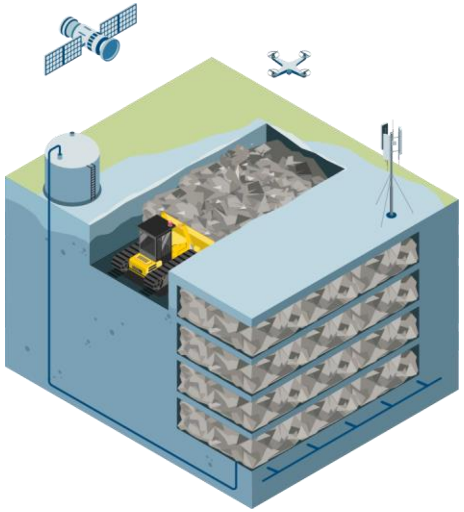
Unsanitary landfill: open waste dumpsites without protective linings; runoff leachate risks contaminating soil and water bodies

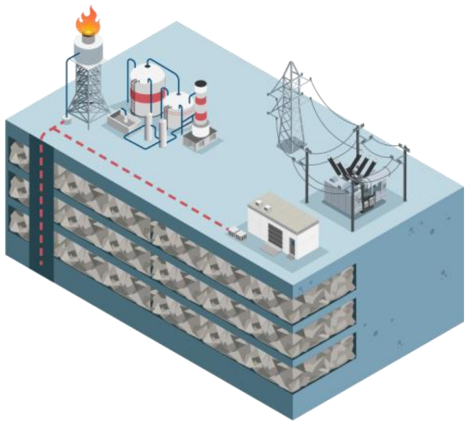
Image source: https://www.macaranga.org/floods-rising-seas-make-dumps-more-dangerous/

❻ **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 detection[2]

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 systems[2]

Landfill gas (methane, CO_2) 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

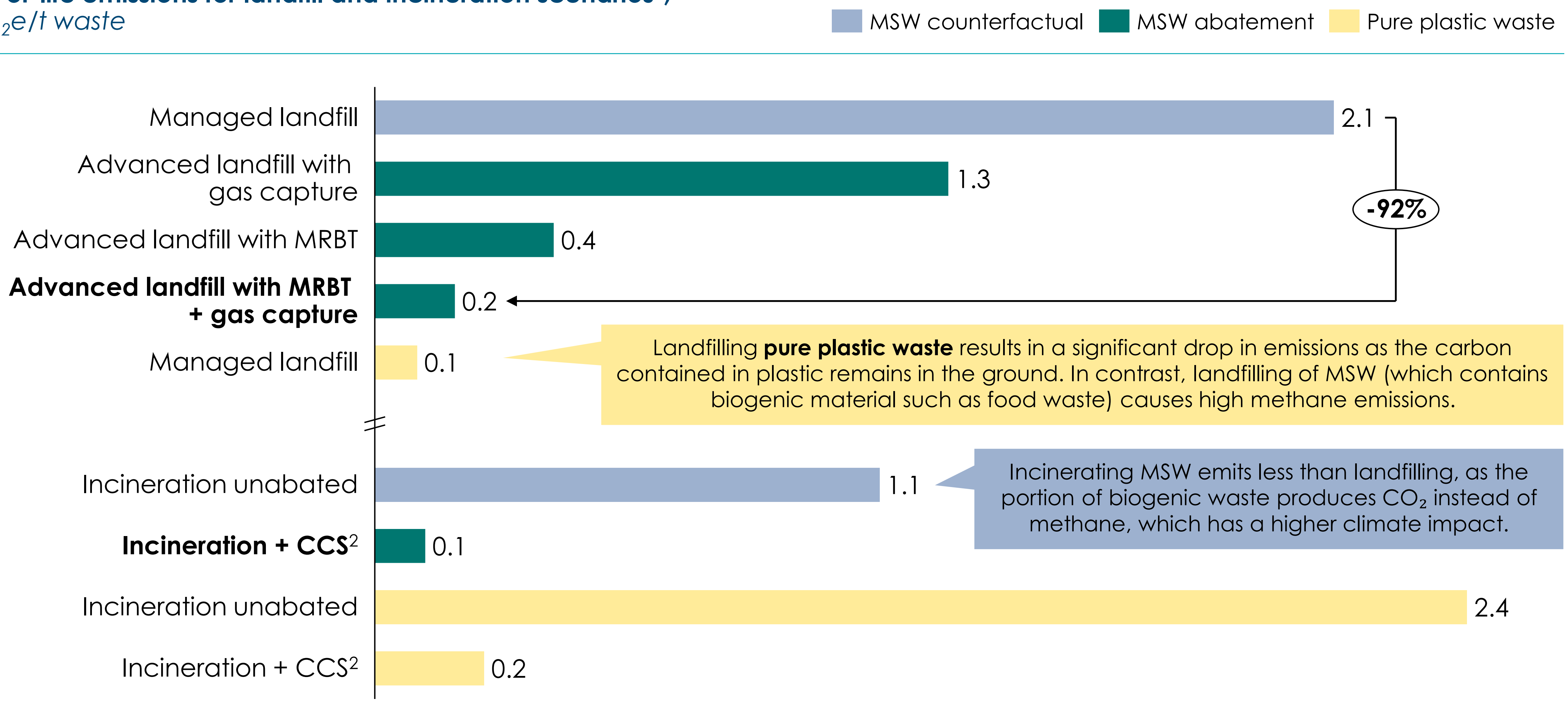
	Advanced landfilling	Incineration
GHG emissions (per t MSW)	*~0.2 tCO2e[3]*	*~0.7-1.2 tCO2e[4]*
Land requirement (ha/Mt MSW)	*10+*	*0.1*
Non-GHG environment impacts	*Potential leachate groundwater contamination*	*Toxic air pollutants if not properly controlled*
Regulatory alignment	*Increasing landfill 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 tCO_2e/t waste) to incineration with CCS

End-of-life emissions for landfill and incineration scenarios[1],
tCO_2e/t 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.

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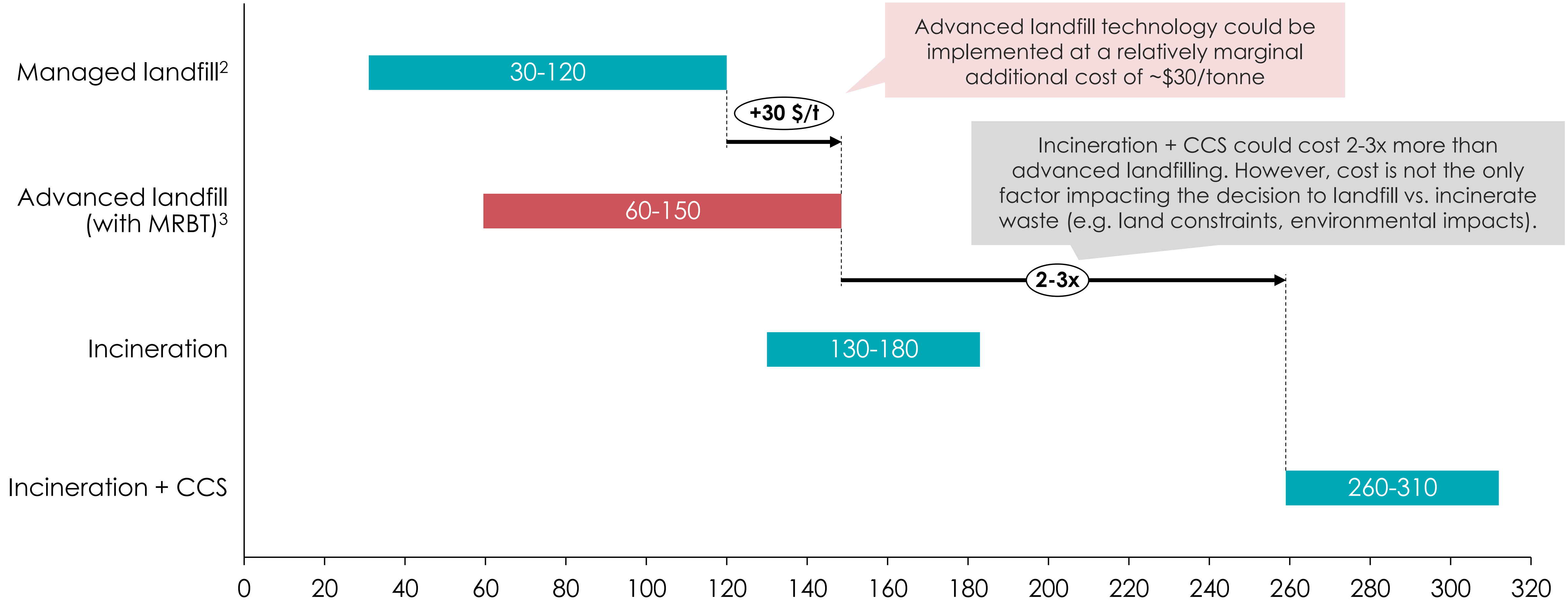
Advanced landfills could cost marginally more than managed landfills today and be highly cost-competitive against incineration with CCS

Cost of end-of-life measures for waste[1], *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.

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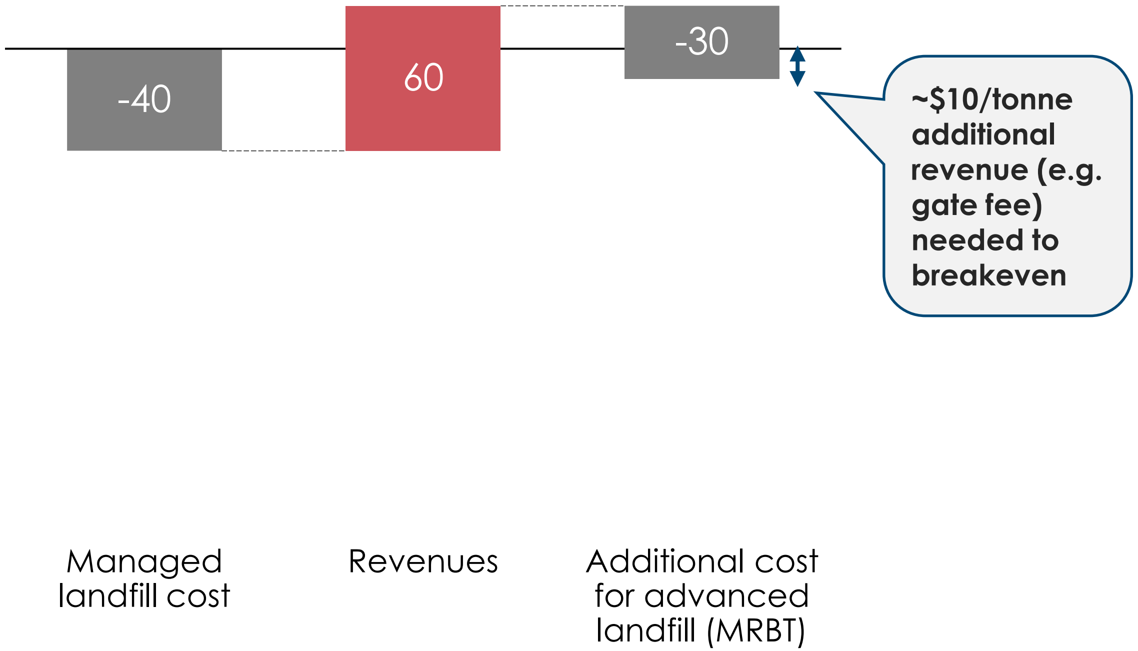
Adoption of advanced landfill technologies could have a marginal impact on project economics compared to scaling CCS on incinerators

Costs and revenues of end-of-life measures for waste[1], *USD/t waste*

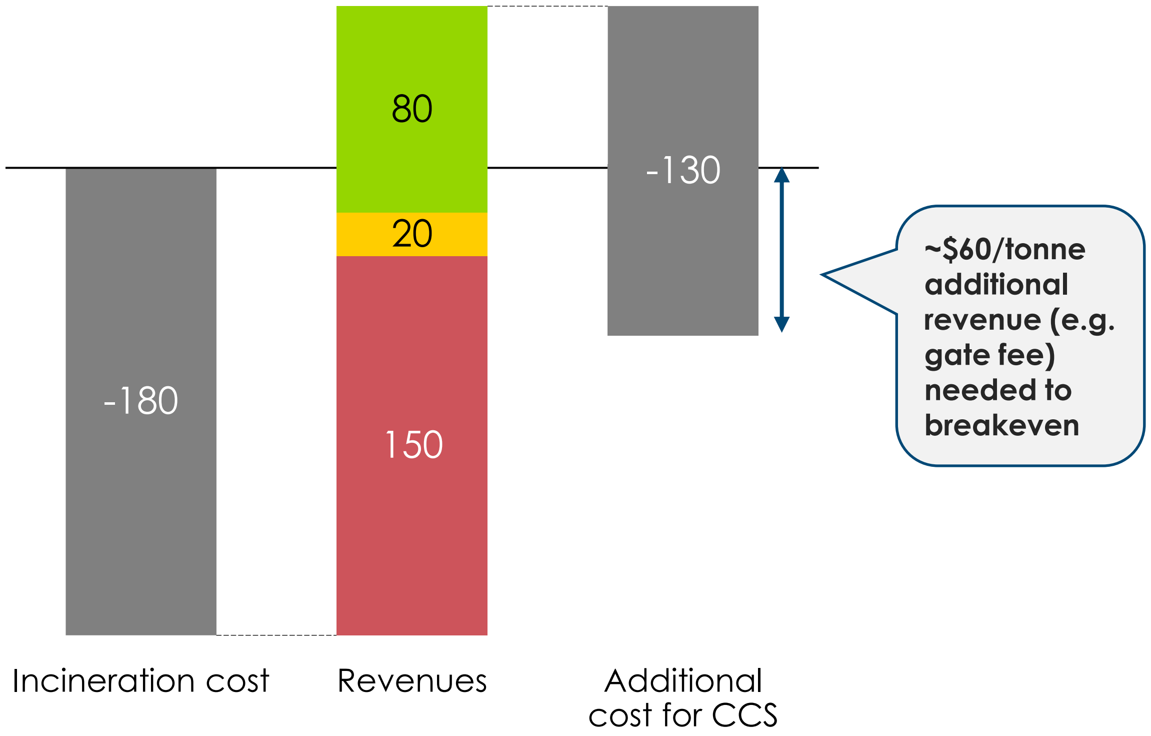
Costs | Electricity | Heat | Gate fees

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



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).

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Landfilling of plastic waste generated between now and 2040 is forecasted to constitute a marginal fraction (0.0005%) of Earth's total land area

Earth's total land area:

~15,000 million hectares (Mha)

	Theoretical maximums		Forecasted
Scenario description	Assuming all MSW generated sent to landfill	Assuming all plastic waste sent to landfill	Fraction of plastic waste sent to landfill[2]
Global cumulative waste landfilled (2025-2040)	45.1 Gt	7.4 Gt	**3.6 Gt**
Land requirement[1]	0.85 Mha	0.14 Mha	**0.07 Mha**
% of Earth land area	0.01%	0.001%	**0.0005%**

Notes/sources: 1) Assumes landfill depth of 30m and height of 10m. 2) Systemiq (2024) Plastic Treaty, Global rules scenario.

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 CO_2 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 $MtCO_2$ with MRV[1]**
		Commercial CO_2 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 CO_2 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 gas[3]**

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**

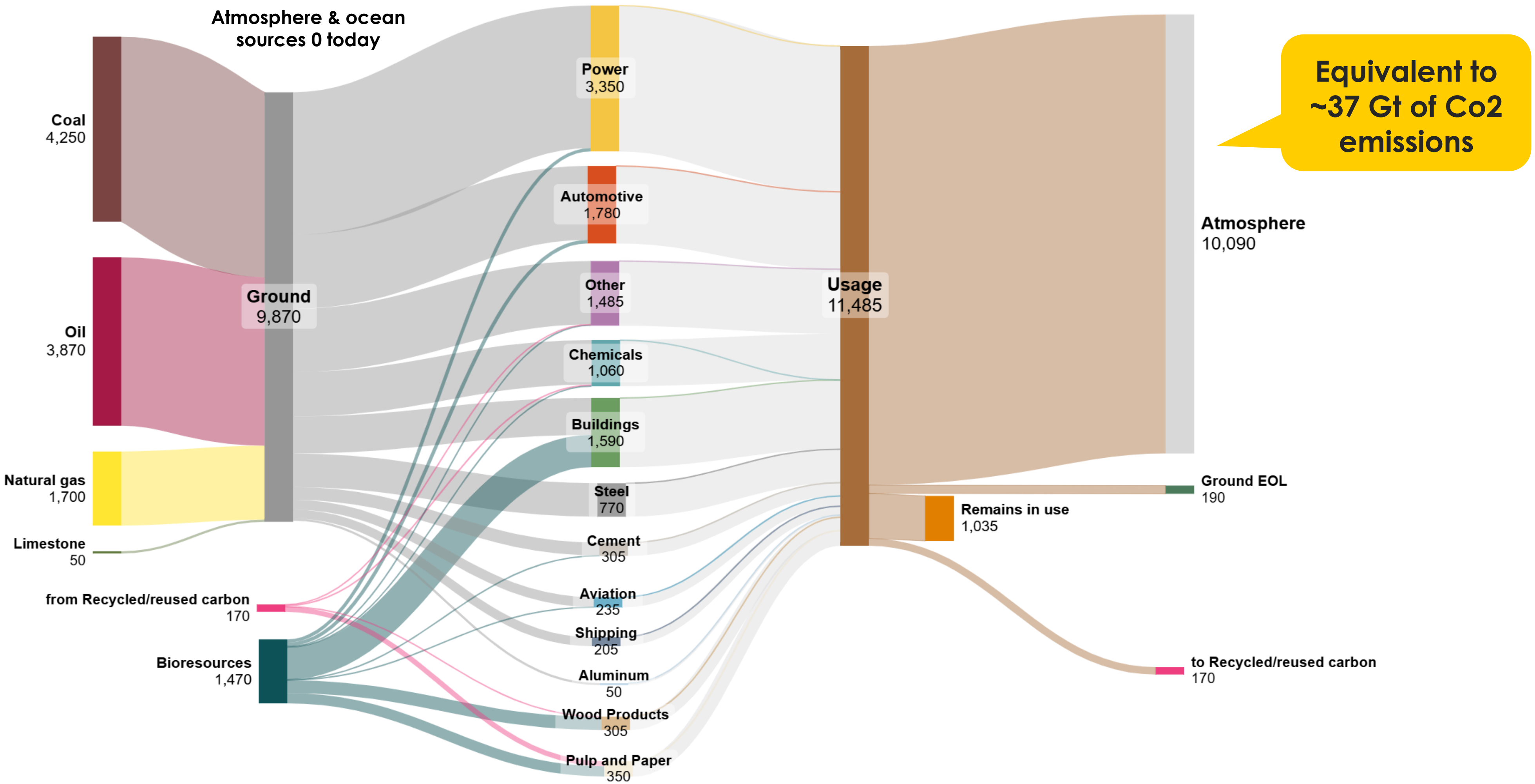
SYSTEMIQ

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)

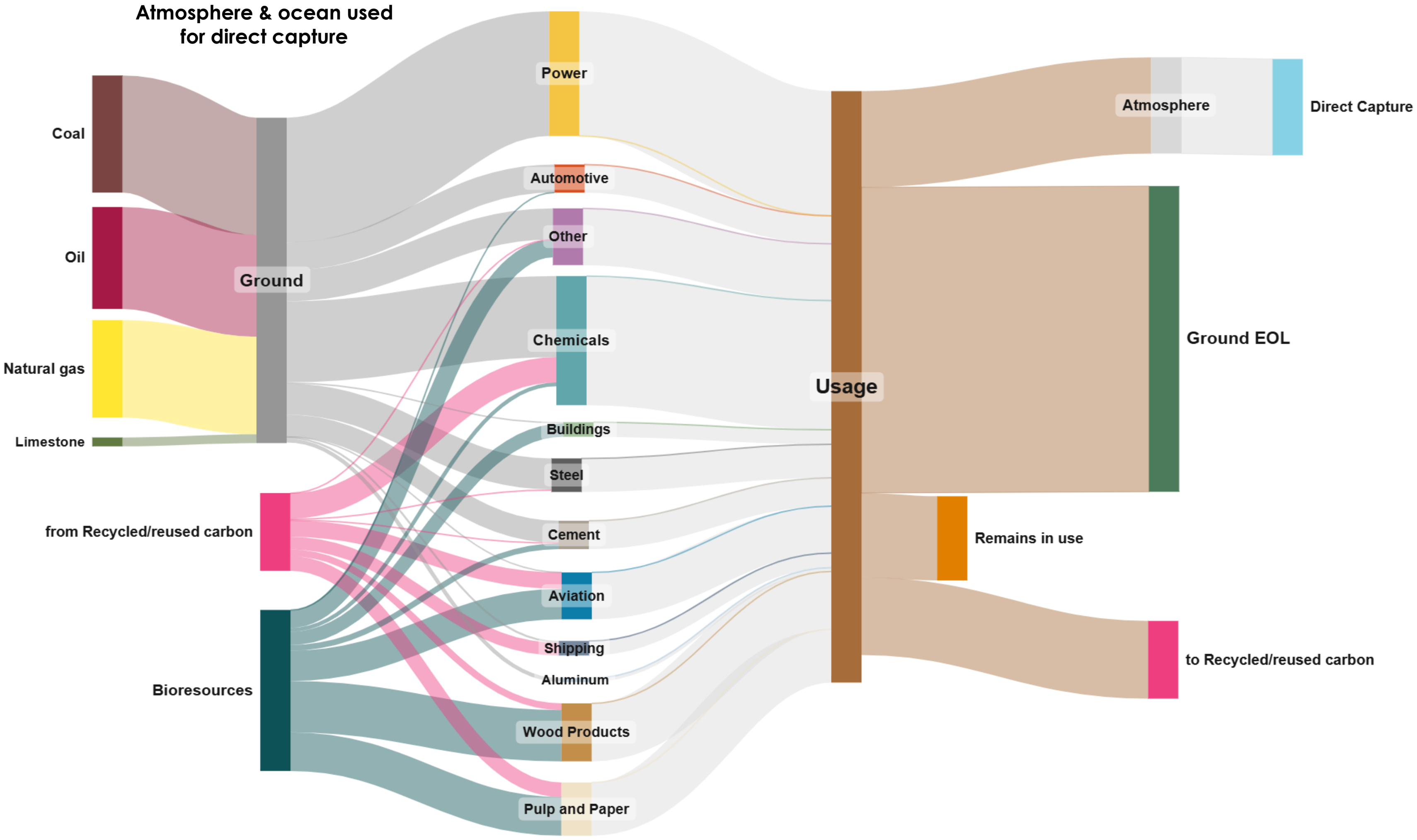
SYSTEMIQ

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