Energy Transitions Commission

QCF Carbon Molecules Phase 2 – the extent we can reuse and recycle carbon molecules

26 02 2025

Agenda

- Introduction to work program
- The case for carbon efficiency
- Reduce and recycle material
- Recycling carbon
- High circularity scenario
- Barriers and the policy landscape

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- **Introduction to work program**
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Carbon molecules project: Sizing the demand for carbon [carbon atoms and carbon-based molecules] within a low emissions economy and assessing the sustainable and feasible options for their supply.

Aim:

Shape the narrative and conversation around low-carbon emission molecules in the lead-up to COP30

Organised in four sprints / questions

1. How large a role can and should direct electrification play in a zero emission economy?
2. The role of hydrogen and non-carbon H2 derivatives

Our topic today

3. The potential to recycle and reuse carbon molecules
4. Sources of primary carbon: costs and sustainability

Phase 2: the potential to recycle and reuse carbon molecules

Integration in broader carbon molecule project

By sizing minimum and maximum volume of carbon molecules that can be reused and recycled (for energy and non-energy), we understand the implications for the primary supply of new carbon still required to support a prosperous global economy

	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**	**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)	• 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	• Workshop • Report reviews • Report launch at COP		

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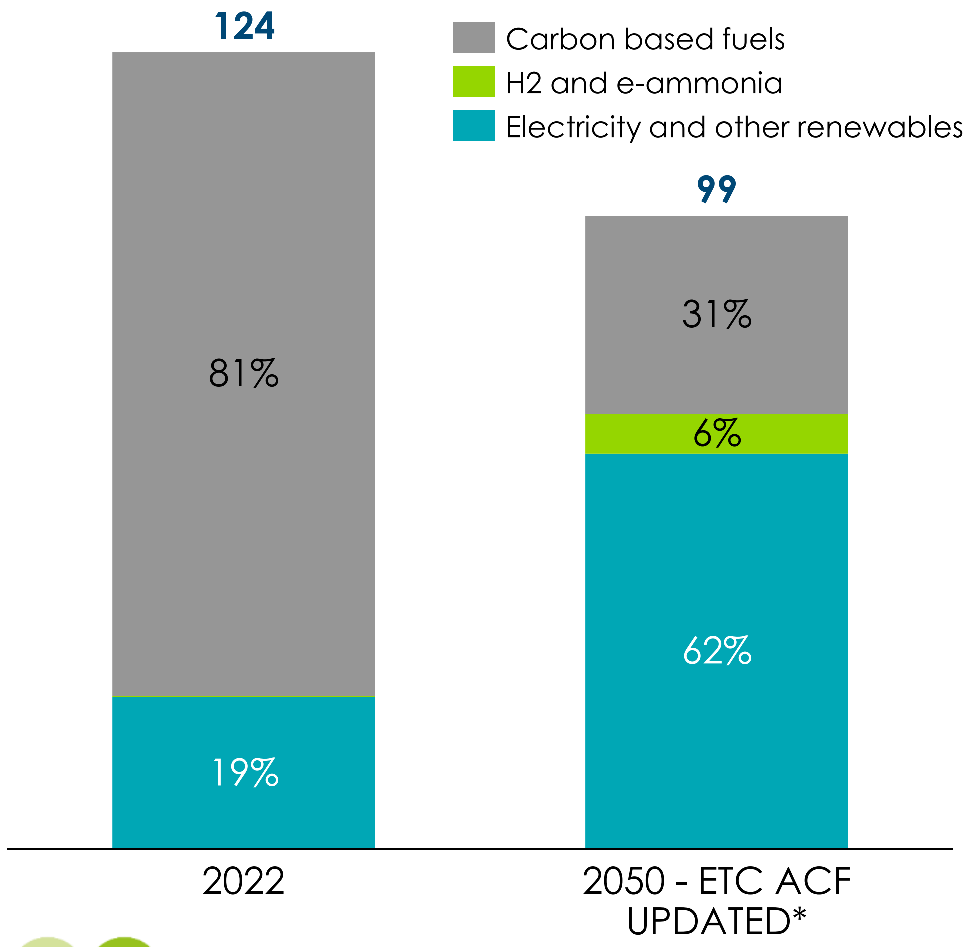
From Phase 1: The energy system demands ~11Gt of carbon usage today, expected to decrease to 3.3Gt by 2050 in a decarbonization scenario

Final Energy Demand for 2022 and ETC's ACF scenario in 2050

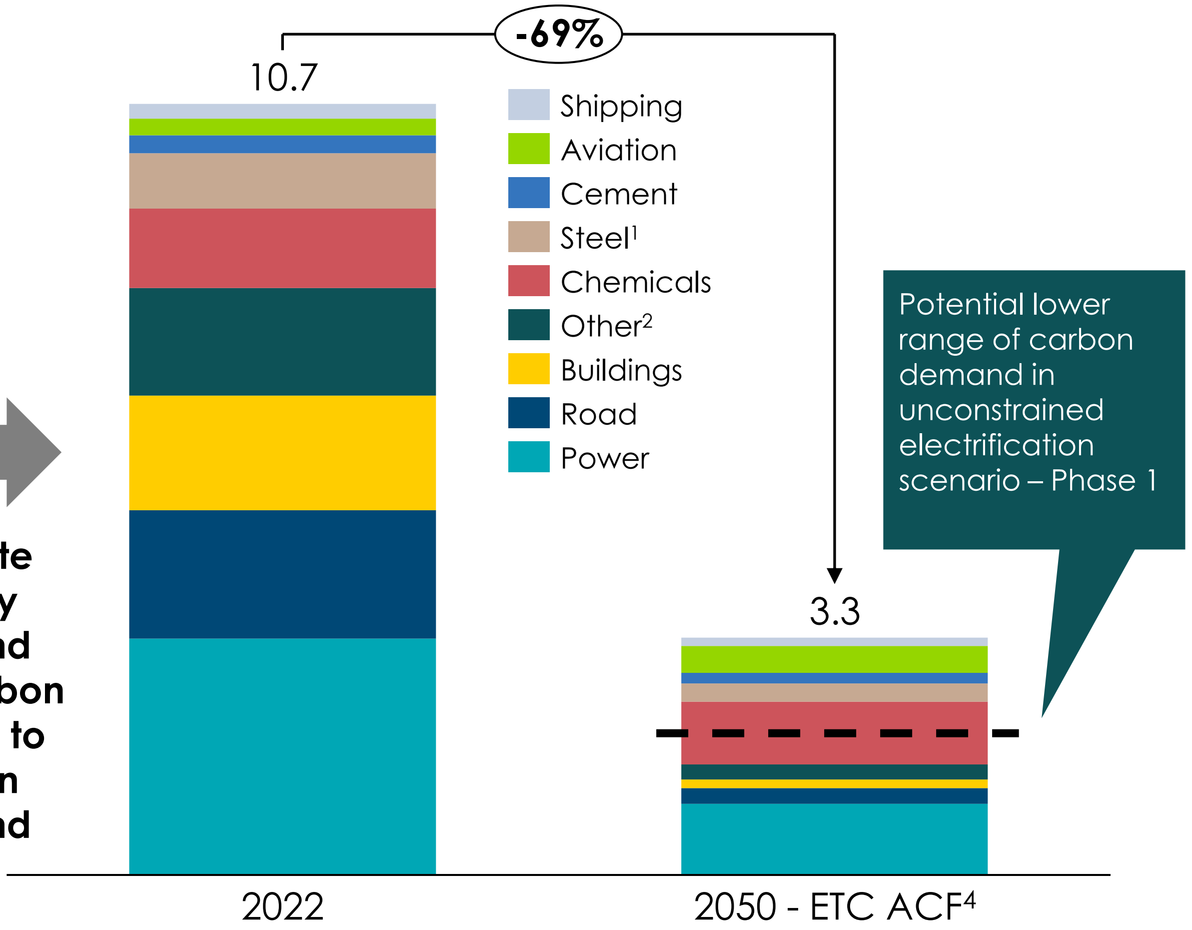
Thousand of TWh



Translate energy demand from carbon sources to carbon demand

Carbon Demand Across the Energy Sector

Giga tons of carbon (C)



Sources: Energy: Systemiq analysis (2025), based on Fossil Fuels in Transition (ETC, 2023); Chemicals: Planet Positive Chemicals Report (Systemiq, 2022, BAU Net-Zero scenario); Biomass: ETC Bioresources report (2021); Steel: MPP STS (2022); Cotton, Bitumen and Soda Ash: Systemiq analysis (2025) Energy sector = ACF scenario. 1. Include energy based carbon feedstocks, a proportion of which which end in the final products (e.g. chemicals for plastics and steel), and others end in process emissions. 2. Includes remaining demand remaining sectors, primarily other industry and other transport. *Minor updates made from ETC Fossil Fuels phase down report. Carbon-based fuels include those fuels that also require carbon sources, e.g. e-methanol and synthetic aviation fuels.

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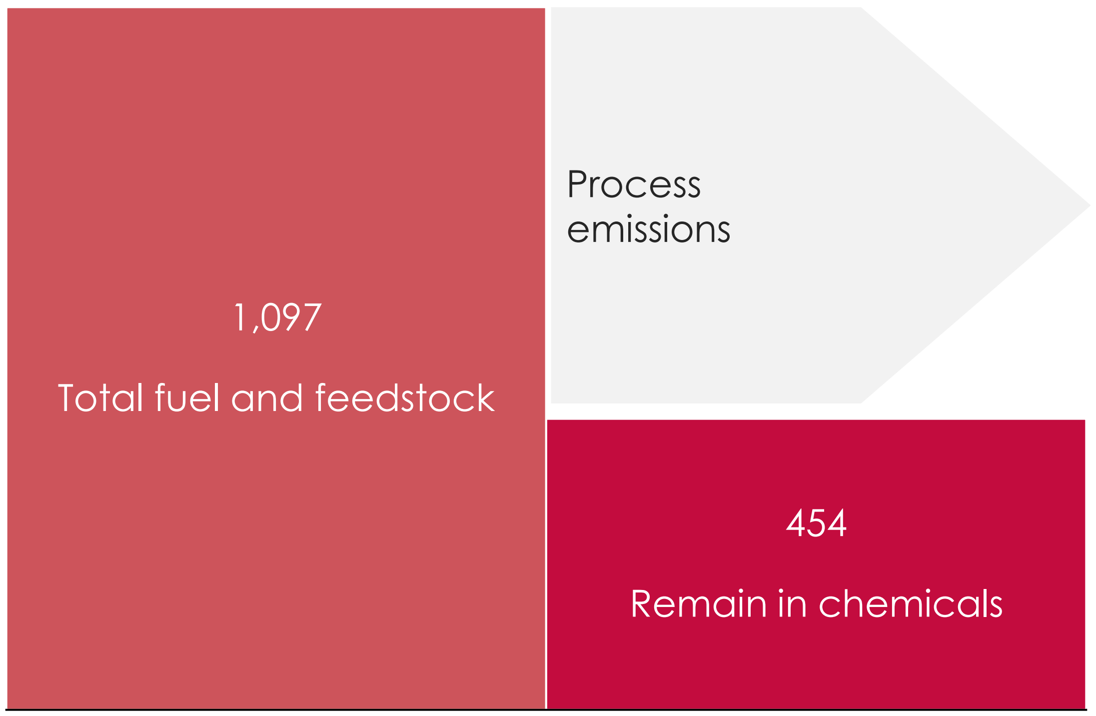
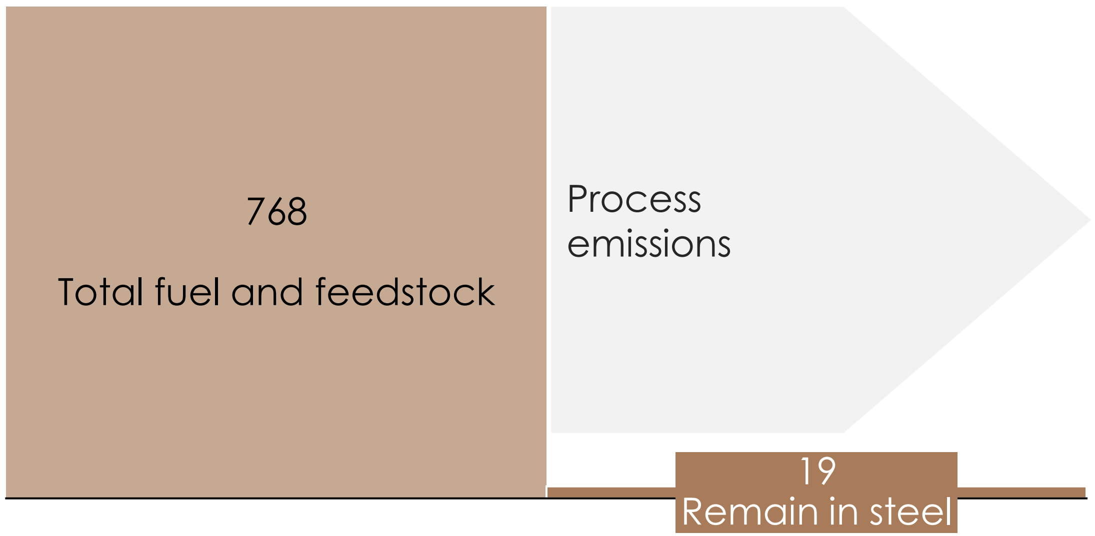
In energy carbon demand, energy feedstocks that end in the materials produced are included

Total carbon demand for chemical sector, 2022
Million tons of carbon (C)



Total carbon demand for steel sector, 2022
Million tons of carbon (C)

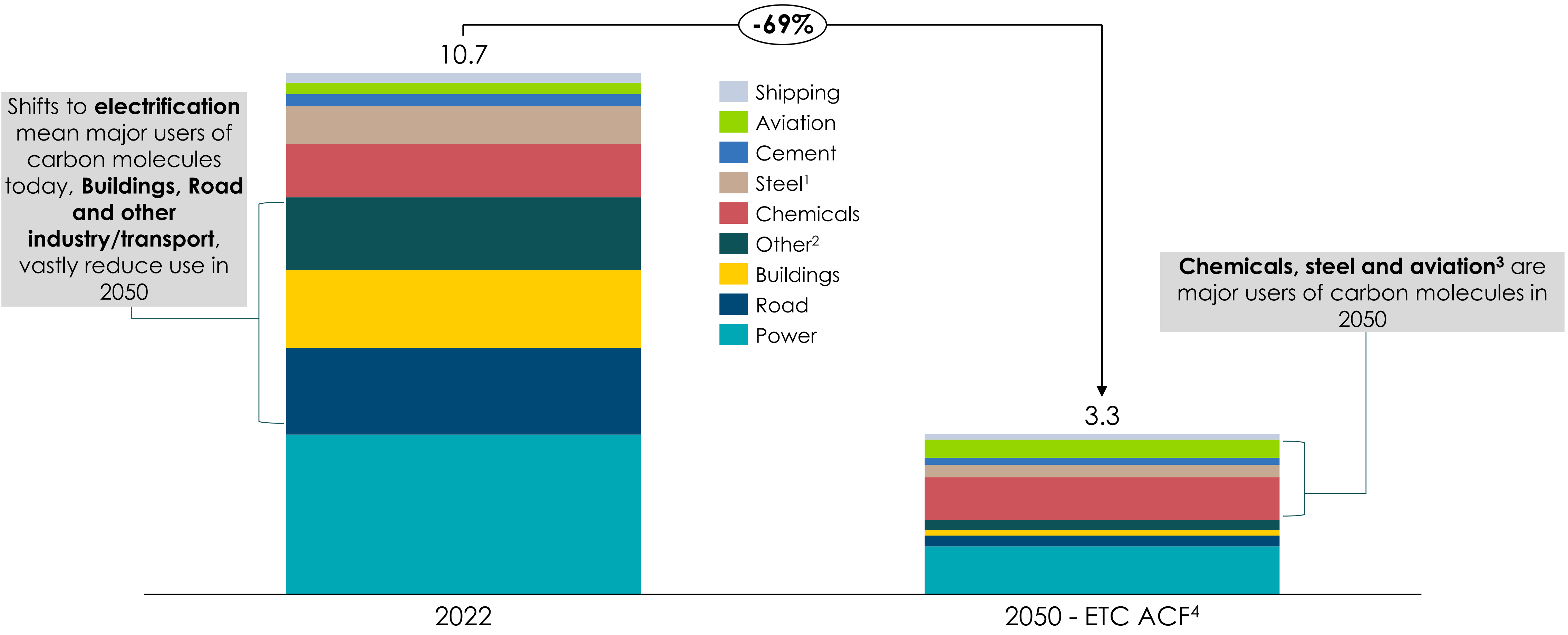


Sources: Energy: Systemiq analysis (2025), based on Fossil Fuels in Transition (ETC, 2023); Chemicals: Planet Positive Chemicals Report (Systemiq, 2022, BAU Net-Zero scenario); Steel: MPP STS (2022);

Carbon molecule demand in the energy system reduces from 2022 as major sectors decarbonize, but some will still be reliant on molecules in 2050

Carbon Demand Across the Energy Sector

Giga tons of carbon (C)



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1. Include energy based carbon feedstocks, a proportion of which which end in the final products (e.g. chemicals for plastics and steel), and others end in process emissions. 2. Includes remaining demand remaining sectors, primarily other industry and other transport. 3. Sectors like aviation rely on carbon sources like bio-based SAFS and power-to-liquids to decarbonize. Some volumes of production in chemicals and steel reliant on fossil + CCS routes to decarbonize, e.g. naptha steam crackers + CCS. 4. ACF = Accelerated but clearly Feasible scenario from ETC's *Fossil Fuels in Transition* report (2023)

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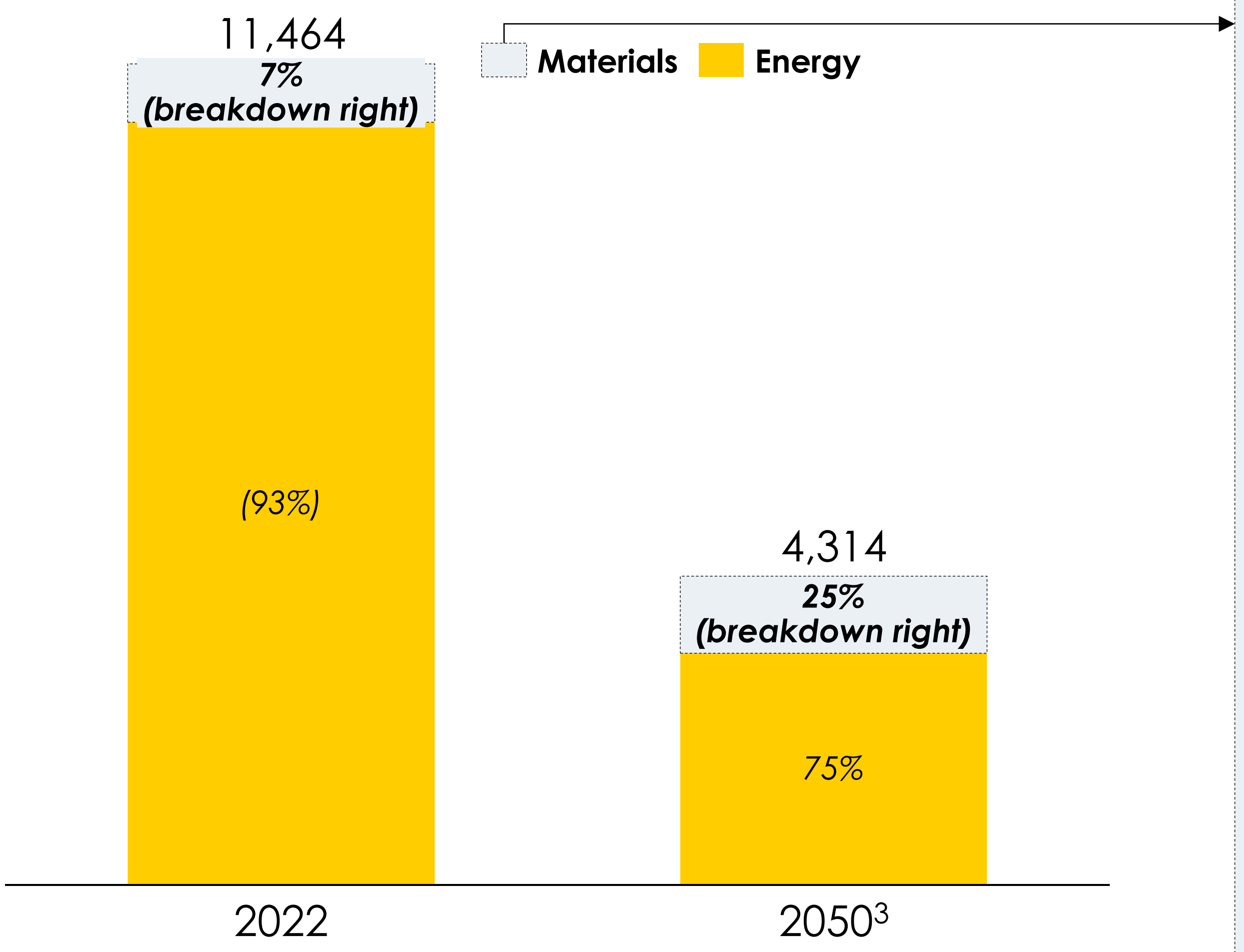
Material sector demand is added to the demand outlook, which could be up to ~1.2 Gt of C by mid-century

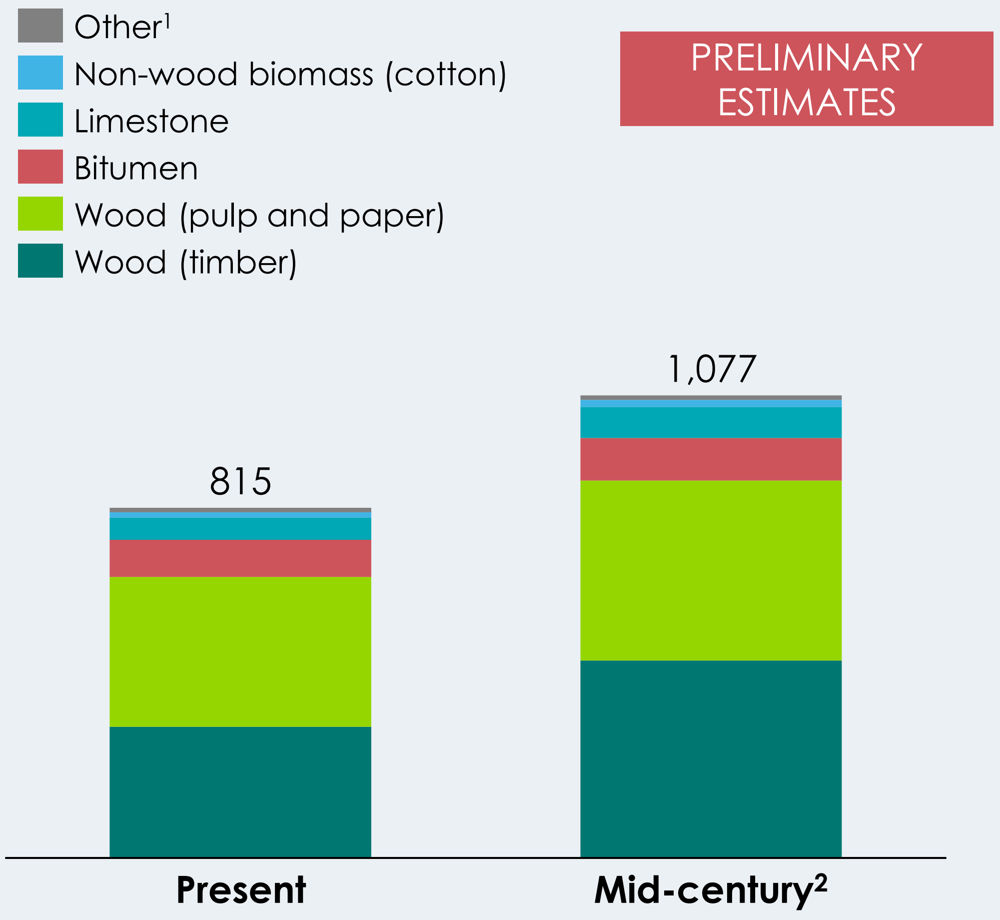
Carbon Demand Across the Energy and Material Sectors

Million tons of carbon (C)



Carbon Demand Breakdown Across Major Materials

Million tons of carbon (C)



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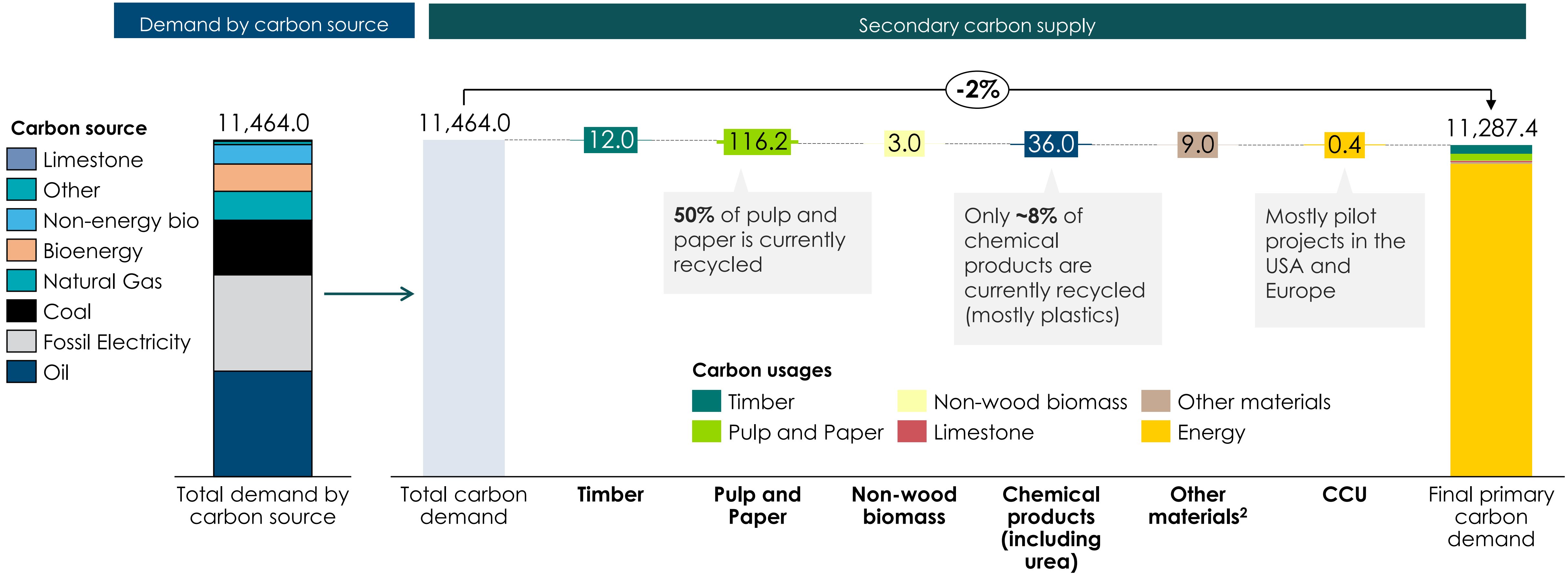
Notes. 1) Includes carbon ash, biochar, carbon fibre, charcoal, 2) Assumes BAU growth, with limited circularity. 3) Energy sector = ACF scenario.

Today, carbon molecules are predominantly from fossil-based sources and in a mostly linear system

Carbon Demand by source and Circular Methods Across Major Materials, Present

Million tons of carbon (C)



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Notes: 1) Ethylene, Propylene, Methanol (non-energy uses), Benzene, Toluene, Xylene, C4 chemicals. 2) Includes limestone, bitumen, soda ash, carbon ash, biochar, carbon fibre, charcoal.

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Key sectors will still require carbon in 2050, and will have to source it from (constrained) sustainable sources, or from secondary supply

Carbon sources

Primary supply	Fossil
	Rock
	Bioresources *(Constrained)*
	Air
Secondary supply	**Emissions from industrial processes**
	Recycled materials

Air is the only theoretically unconstrained, sustainable carbon source…

… but demand can be met by **improved carbon efficiency** via secondary supply

Carbon demand in net zero future

Fuel	**Aviation**
	Shipping
	Road transport
	Heating
	Power
Material	Wood, pulp and paper
	Aggregate
Feedstock	**High value chemicals**[1]
	Urea
	Cement

Aviation, aggregates, and high-value chemicals face the toughest decarbonization challenges and will likely still rely on carbon by 2050.

Source: Carbon Capture, Utilisation & Storage in the Energy Transition: Vital but limited (ETC, 2022).

1) High value chemicals such as methanol, ethylene, olefins and BTX – often as a feedstock for plastics

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Secondary supply can be met by recycling within the material sector …

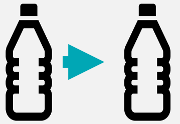
Not exhaustive

Mechanical recycling

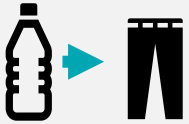
Physically processing waste materials (mainly plastics, metals, and paper) without changing their chemical structure.

This typically involves **sorting, cleaning, shredding, and re-melting** materials to produce new products, or to use the materials for new applications.

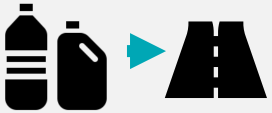
Examples:



PET bottles can be recycled into new PET bottles



PET bottles can be recycled into polyester in textiles

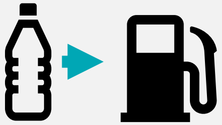


Plastics can be crushed and used as aggregate in asphalt

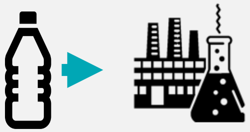
Chemical recycling

Processes that **break down polymers into individual monomers** or other hydrocarbon products that can then serve as building blocks or feedstock to produce polymers again.

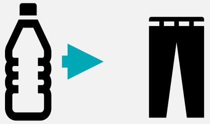
Examples:



Gasification can turn waste into fuel



Pyrolysis can convert waste back into base chemicals



Depolymerisation can convert PET to rTPA, which can be used to make poly-ester based products

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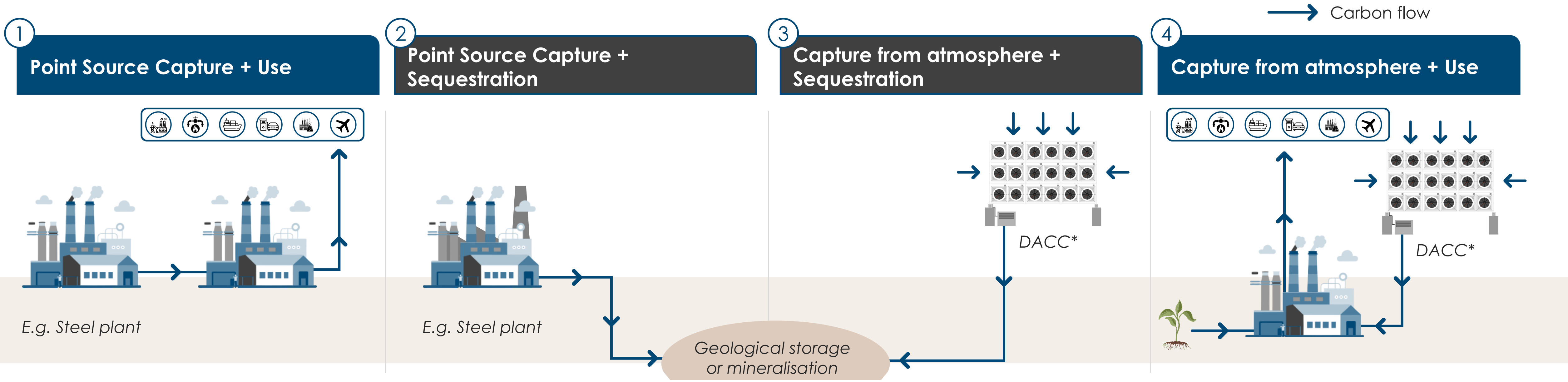
… or by recycling carbon across sectors via CCU



Constraints

Scaling of carbon capture technologies are limited: forecasted to be **6.9 – 10.a $GtCO_2$** captured per annum by **2050**

1

- More expensive than storage
- CO_2 is still emitted at end of life

- High storage availability, though it is very localized
- Slow to scale:
  - Only 0.25 GtCO2 of storage is estimated to be 'injection-ready' today
  - Current injection capacity of 0.5–5 MtCO2/year per site
- Risk of leakage and long-term monitoring requires strong regulation

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- Low CO_2 concentrations lead to higher costs and higher energy requirements than point source
- CO_2 is still emitted at end of life

Focus of this sprint

*Direct Air Carbon Capture

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

Material and carbon circularity solution set

Technology-deep-dives

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

1 What are the **key levers** that could enable **higher circularity?**

What are the **techno-economics, limitations and barriers** to key **technologies?** 2

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1. Reduce demand for carbon molecules can come through actions in eliminating, re-using and substituting materials

Deep-dive next

	Eliminate	Re-use	Substitute
Description	**Remove or reduce** any material that does not serve an essential function	Business models promoting **re-use of materials**, reducing single-use and extending product lifetime	**Substitution** to less carbon intensive materials
Examples	Nestlé Pure Life: Eliminating neck tear-offs from Pure Life water	cupclub: Coffee shop network using reusable and interchangeable cups with deposit system	Coca-Cola: Replacing plastic rings on beverage multipacks with carboard clips
	SKANSKA: Modular designs to reduce surplus material use	Vinted: Recommerce of textiles and household goods	ALPLA: Bio-based and recyclable paper bottles
	VOLVO: Lightweighting vehicles to reduce material and fuel use	Uber: Sharing the utility of vehicles to multiple users	Ford: Soy instead of petroleum-based foam in car seats

Reuse deep-dive for packaging

At scale, packaging reuse can deliver both resource efficiency and negative cost GHG reductions

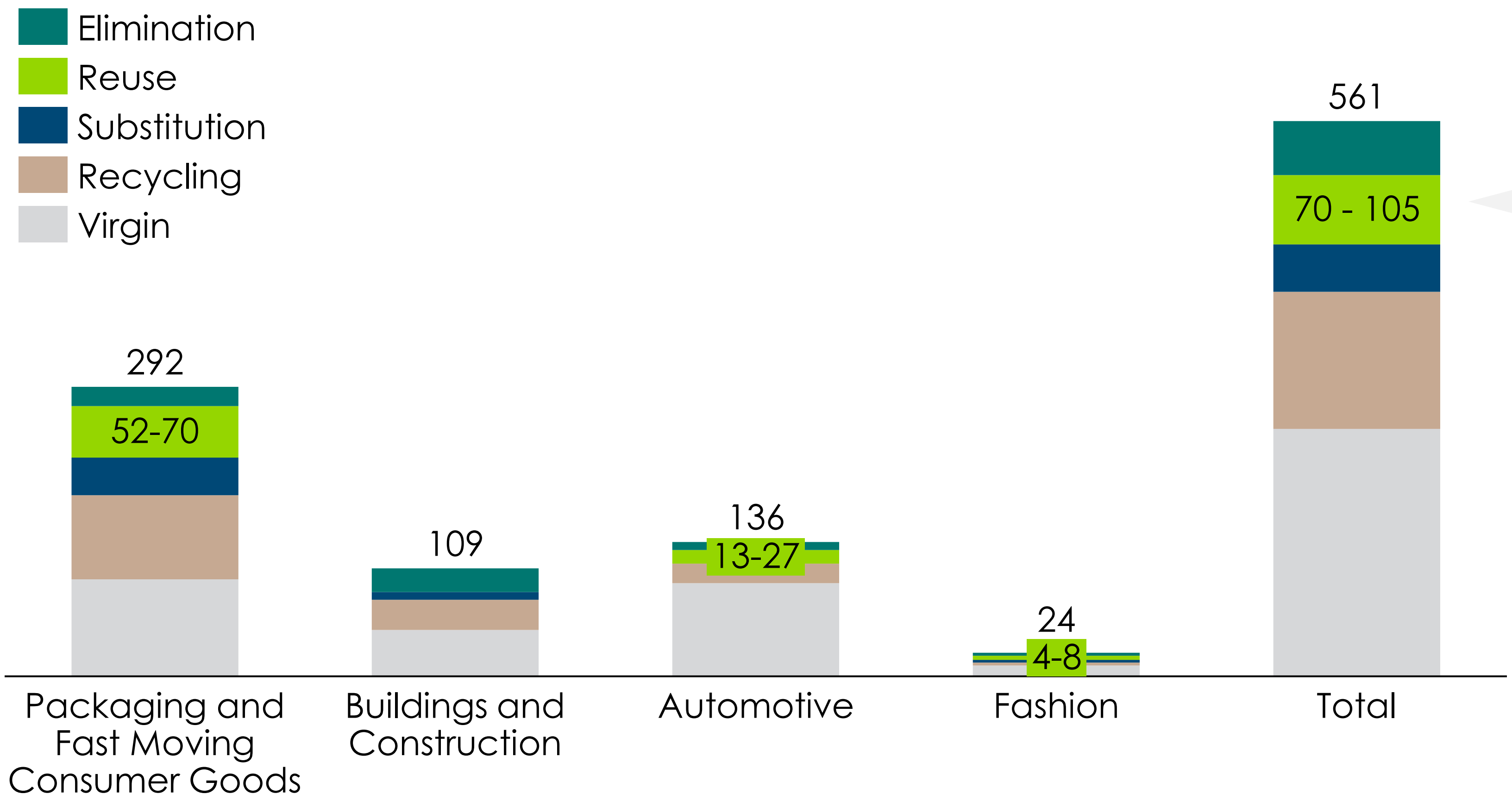
- Reuse models could **significantly cut mid-century chemicals demand in key plastic-using sectors**—packaging, textiles, and automotive—by 12-20%.
- Due to large share of carbon demand from packaging and comparatively low need for consumer behaviour change, refill and return systems are assumed to be the largest lever.
- System cost of refill and return systems vary between sectors but **transport and reprocessing costs lead to an average of 2x cost of single use**, but **costs can fall below single-use when reuse systems are scaled.**
- Additionally to large cost reductions, **GHG emissions and resource can deliver negative abatement costs** when achieved at scale.
- Despite this, ramp-up of reuse models is slowed by **high up-front costs and long payback periods.**
- Promising economics but high up-front costs make reuse models ideal candidates for policy support and subsidization

Reuse models could reduce mid-century chemicals demand in 3 of the top plastic using sectors

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

Preliminary

Mt petrochemical intermediates



Together, upstream circularity measures could account for more demand reduction than recycling.

Reuse is the largest potential lever and could account for **12 - 20%** of total reduction in demand.

Note: These figures will be revised based on the outcomes of the chemical recycling deep dive

Source: Planet Positive Chemicals (Systemiq, 2022)., Achieving Zero-Carbon Buildings: Electric, Efficient, and Flexible (ETC, 2025).
1) Reuse is defined as "where a product's utility is still valued but its delivery through a new business model requires less material for the same output."

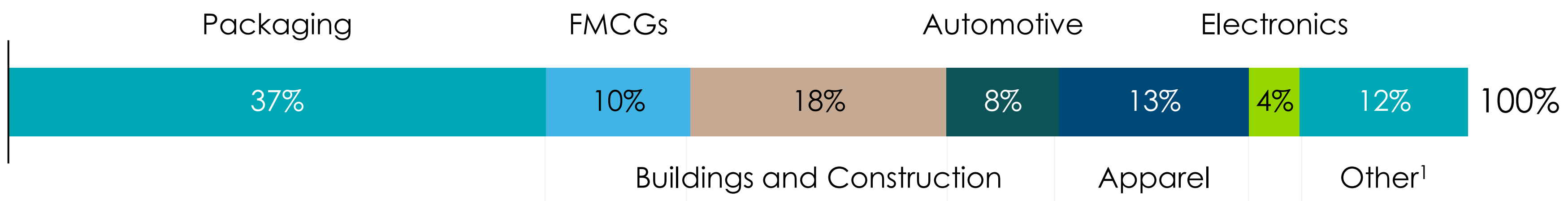
We are focusing on reuse where it displaces single-use through innovative business models

Deep-dive next

Reuse model	Description	Sectors	Company *Non-exhaustive examples*
Packaging reuse and refill	Services and businesses which provide the utility previously furnished by single-use items. Includes B2C and B2B packaging through: - Refill systems (from home or from businesses) - Return systems (from home or on-the-go)	Packaging	sodastream, RECUP, ECOVER, Loop, DANONE WATERS, Algramo, Carrefour, Wild
Recommerce of consumer goods	Reuse by a third party via C2C retail, or businesses which collect, refurbish, and resell finished products.	Household goods; textiles; electronics	depop, Vinted, BackMarket, ebay, The RealReal, amazon resale, IKEA
X-as-a-service	Sharing economy replacing single ownership items. Includes most examples of sharing economy, such as (not exhaustive): - Automotive-as-a-service (e.g. carshares, city bikes and scooters services) - White-goods-as-a-service (e.g. launderettes) - Clothes-as-a-service (e.g. rental websites) - Buildings-as-a-service (e.g. coworking spaces)	Automotive; textiles; household goods; construction	Lime, Grab, Uber, omio, citi bike, HURR, wework

Packaging reuse may be the largest lever for demand reduction, covering the largest sector and requiring less behaviour change than other options

Basic chemical demand by sector, %, 2050



Lever	Description	Sectors covered	Max potential range[2]
Packaging reuse and refill	• Applies to the largest demand sector	✓ Packaging	37%
Recommerce of consumer goods	• Applies to limited number of sectors	✓ Apparel, ✓ Electronics	17%
X-as-a-service	• Applies to wide range of sectors • **Requires high levels of behaviour change** • Unlikely to largely displace single ownership models	✓ Buildings and Construction, ✓ Automotive, ✓ Apparel, ✓ Electronics	43%

X-as-a-service is widely applicable but likely to remain niche in most sectors

Max potential range[2]

Sources: Planet Positive Chemicals (Systemiq, 2022)., X-as-a-service (Systemiq, 2024). Resale Report 2023 (ThredUp, 2023).
1) Includes the medical sector, fisheries, aquaculture and agriculture. 2) Maximum coverage, assuming scaled to 100% of sector

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Customer-facing new delivery models can be split into four categories

Packaging is managed by consumer *(most common)* | **Packaging is managed by business** *(emerging)*

Transported to homes

Reuse at home

1. User acquires container
2. Container is emptied
3. Refill is acquired

Most applicable sectors
- Liquid products (cleaning products, beverages)
- Hygiene products

Examples

by Humankind

sodastream

Return from home

1. User acquires container
2. Container is emptied
3. Container is collected, cleaned, and refilled

Most applicable sectors
- Food and beverage (takeaway and groceries)
- Hygiene products

Examples

Loop

Transported to hubs

Reuse on the go

1. User acquires container
2. Container is emptied
3. Container is brought to dispenser and refilled

Most applicable sectors
- Dried goods (e.g. pantry items)
- Beverages
- Liquid products

Examples

Algramo

Return on the go

1. User acquires product
2. Container is emptied
3. Container is dropped off, cleaned, and refilled

Most applicable sectors
- Food and beverage

Examples

RECUP

Ellen MacArthur Foundation, Reuse – rethinking packaging (2019).

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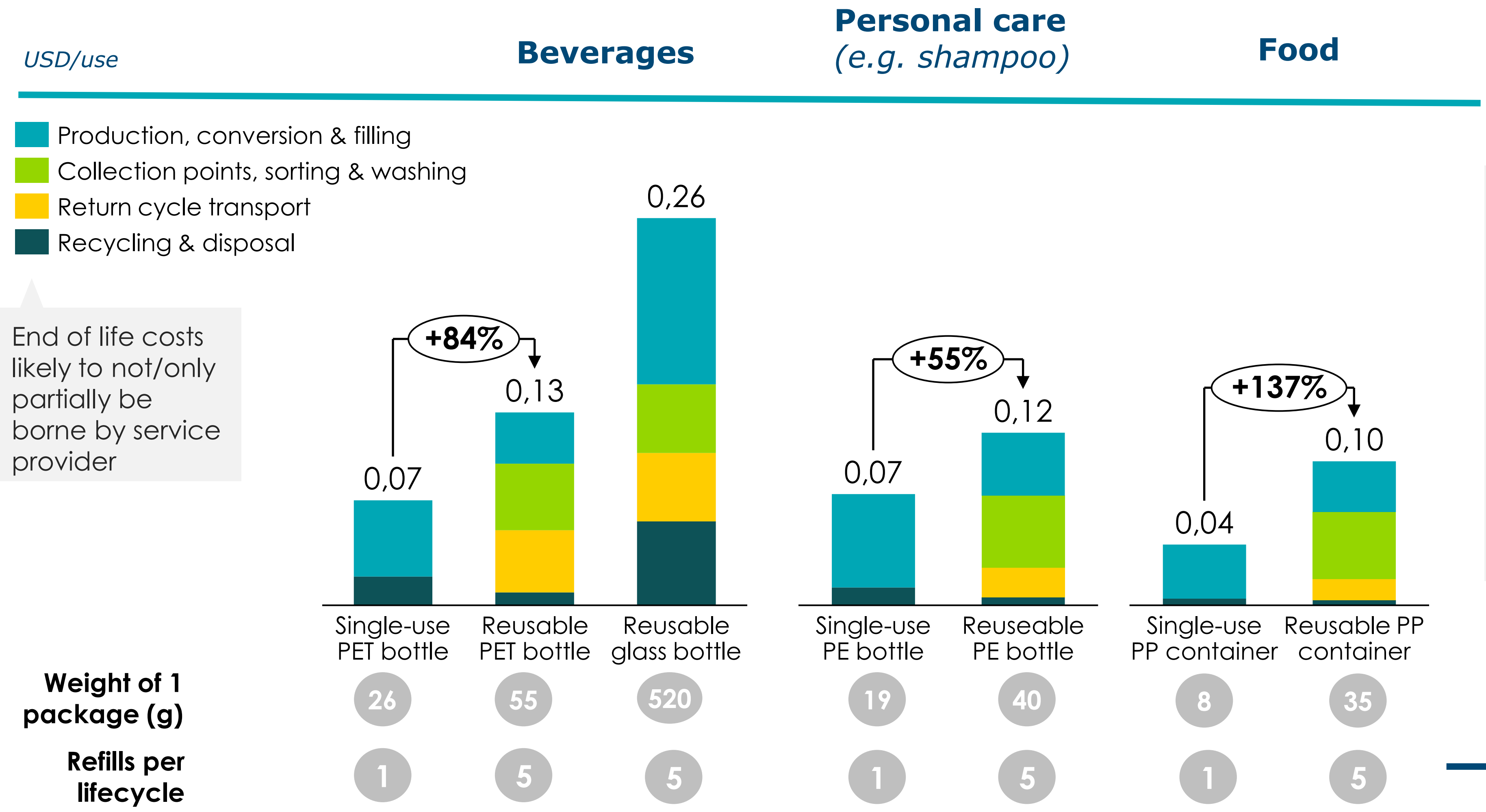
Cost of new delivery models vary between materials and uses, but transport and reprocessing costs lead to a 55-137% increased system cost of single use



Key takeaways

- The main driver of cost increase is **the shift to heavier materials**
- Differential is largest for applications shifting from flexible packaging to rigid packaging (*e.g. food and glass*)

Source: Ellen MacArthur Foundation ,Unlocking a reuse revolution: scaling returnable packaging (2023).
Reuse model assumes return rates of 80%, and lifecycle of 5 uses for reusable items. Costs for entire system, based on EU data.
1) Includes EPR fees and other externalities,. PE = Polyethylene. PET= Polyethylene Terephthalate, PP = Polypropylene

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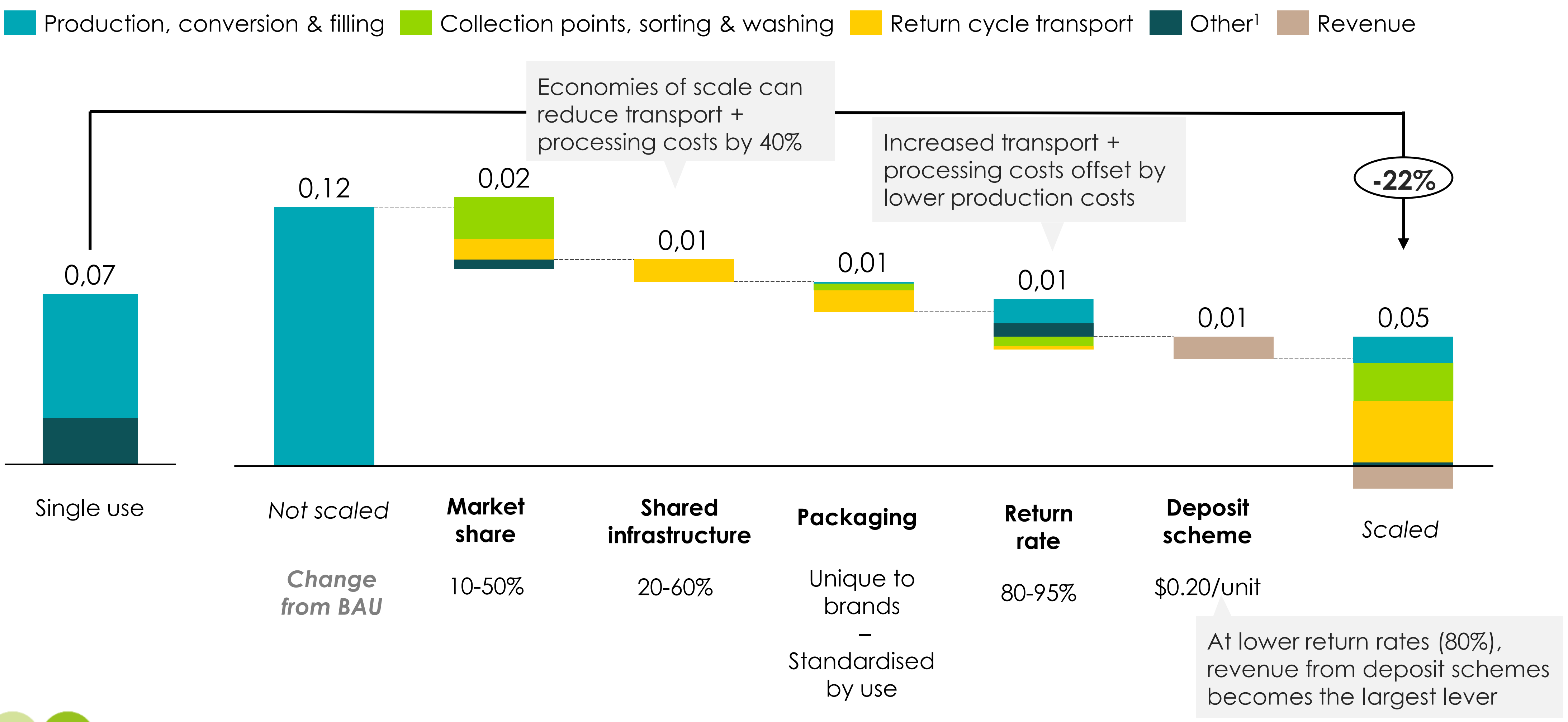
High collection and processing costs drop with scale and consumer incentives, resulting in ~22% cost savings vs single use when at scale

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



Source: Ellen MacArthur Foundation, Unlocking a reuse revolution: scaling returnable packaging (2023).
Note: % changes in levers based on stretch scenario in above report. 1) Includes EPR fees and other externalities.

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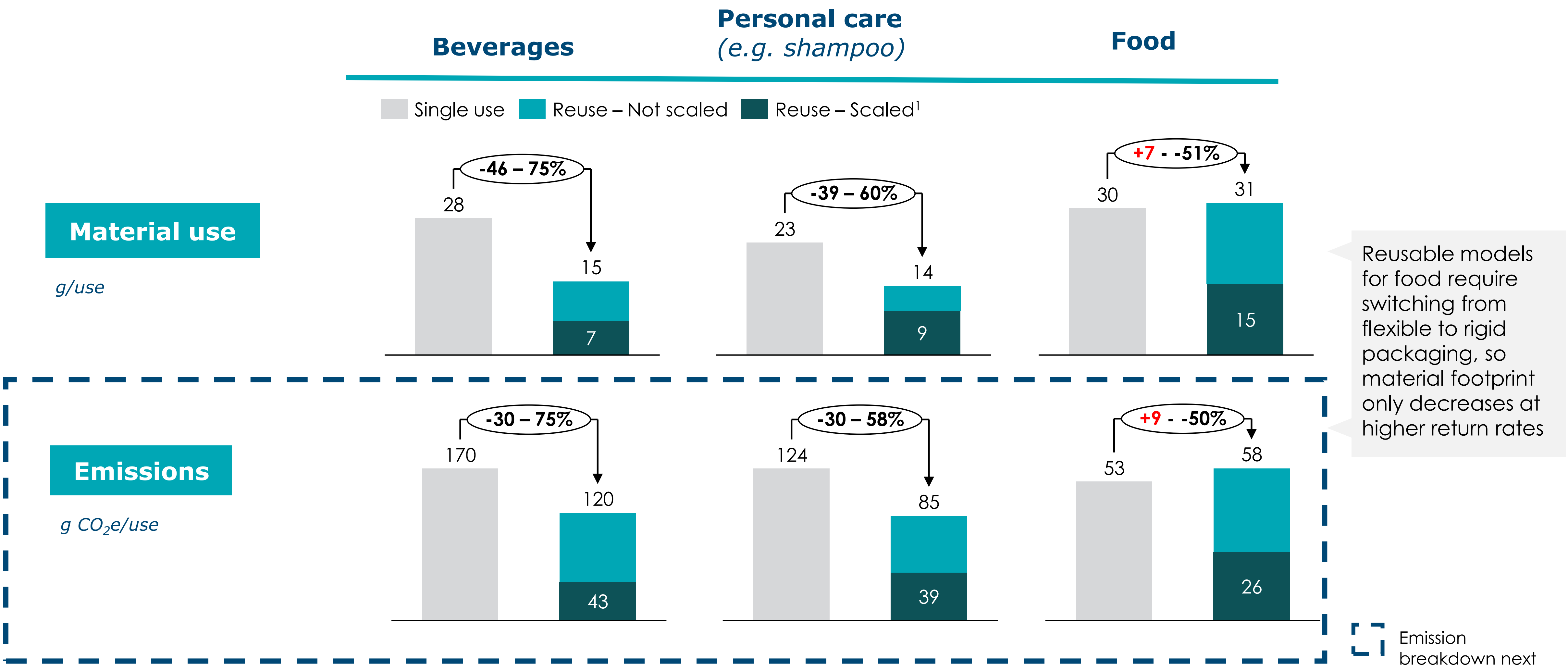
At scale, reuse models could limit GHG emissions and resource use across all uses



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

1) Lowest cost = result of all levers on previous slide being applied. 2) When including all blue water (surface or groundwater), 10x more water is required to produce a single use 2L PET bottle, than wash a returnable 2L PET bottle. Freshwater is used in manufacture and cleaning, and is closer to being equivalent.

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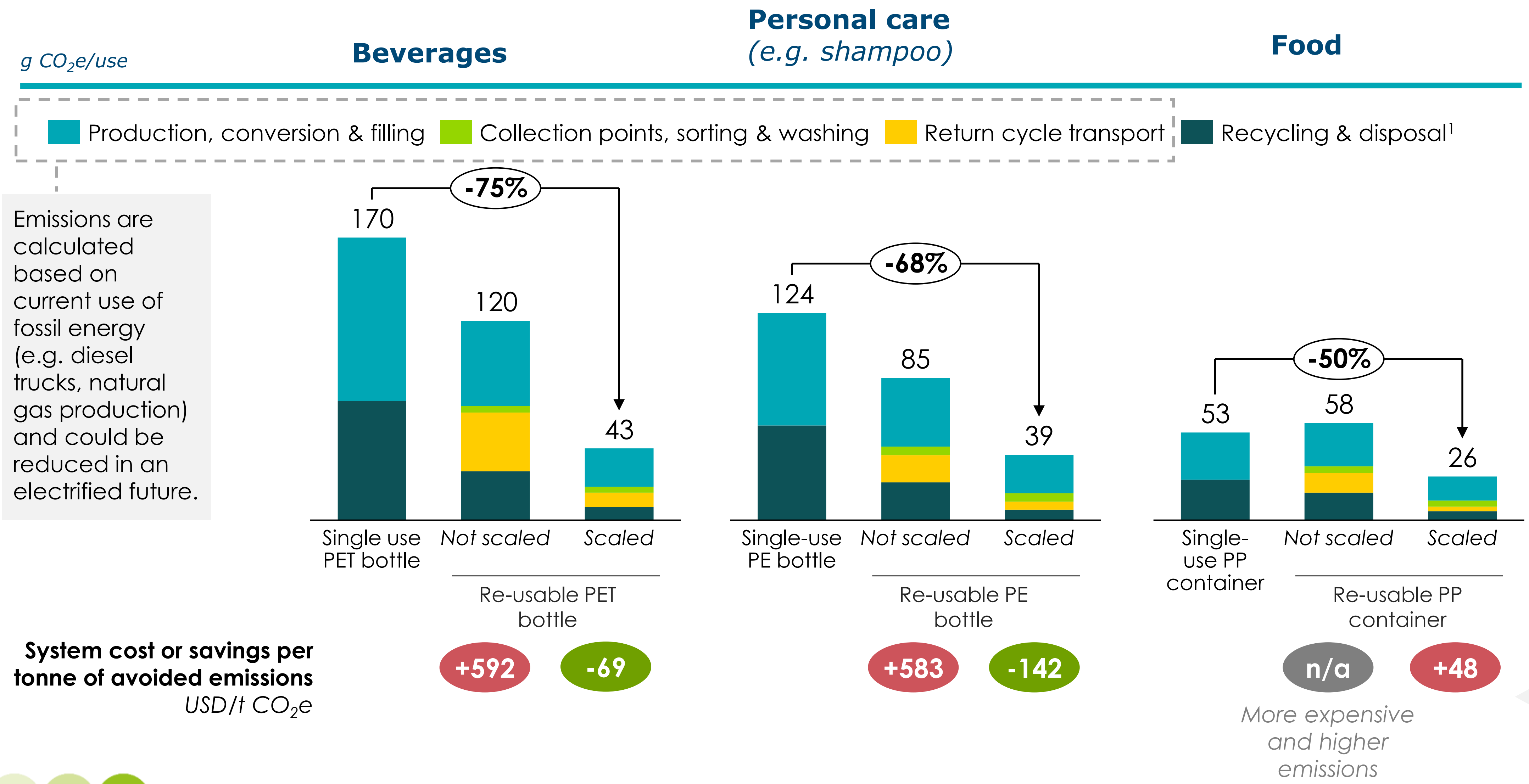
Despite their initial cost premium per tonne, at scale, packaging reuse models could deliver larger negative abatement costs than other solutions



Other examples:

Ethanol production + CCS $60

Mechanical recycling, plastic: $45

Solar PV: $20

Car sharing: -$90

Source: Ellen MacArthur Foundation, Unlocking a reuse revolution: scaling returnable packaging (2023). Material economics, the circular economy a powerful force for climate mitigation (2018) Emissions defined as: Production: Process emissions. Filling, collection, sorting, washing: energy consumption of machinery and building. Transport: Emissions from diesel trucks. Recycling and disposal: assumes 2/3 incineration, 1/3 landfill

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Implementing large-scale behavioral change requires well-designed policy and system-wide change

	Drivers	Barriers
Customers	• New delivery models tap into **new customer bases with demands for more efficient and sustainable solutions.** • New delivery models enable **subscription-based services** or pay-per-use systems which can increase customer loyalty, and provide brands with better customer analytics.	• **Operationalization and implementation can be a challenge** • **Customers can be resistant** to adapt to new models, especially when they require more effort. • Pooled packaging or bulk dispensing may **reduce branding opportunities.**
Regulation	• Certain single-use plastic uses have been banned via the EU's **Single-Use Plastics Directive.** • Voluntary pledges such as the **Ellen MacArthur Foundation Commitments for Circularity** commit businesses and governments to reuse targets.	• **Policy drivers are not punitive enough** to drive system change. • **Virtually no subsidies exist** to support the investment needed to shift to large-scale reuse subsidies.
Costs	• Policies such as the **EU Extended Producer Responsibility Directives** hold producers responsible for end-of-life processes, increasing the cost of single-use solutions. The **EU ETS** and **UK Plastic Tax** increase the cost of plastic production. • At scale, reuse models can offer **low-cost reduction of resource use and GHG emissions**.	• New models require **significant upfront investment,** and revenue models are recurrent, leading to long payback periods. • Setting up circular systems (e.g., reusable packaging infrastructure) **may only be cost effective at scale.**

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Material and carbon circularity solution set

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	Utilise waste CO_2	• **Hydrogenation to methane or methanol** • **Electrochemical reduction** • **Reverse Water Gas shift** • **Biocatalysis** • Plasma-catalytic treatment

Enablers

Actions: Design for recycling, sortation, collection

Technologies:
- Track and trace, material passports
- **Advanced AI and robotics sorting**

1 What are the **key levers** that could enable **higher circularity?**

2 What are the **techno-economics, limitations and barriers** to key **technologies?**

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Enablers: Key enablers across the waste system, allow for higher recycling rates

Deep-dive next

	Design for recycling	Collection	Sorting
Description	**Designing products** with end-of-life recycling in mind Can reduce recycling losses by 13%	**Collection of waste** – curbside collection, drop-off centres, community collection points	**Sorting** collected material into categories based on their type and recyclability
Examples	Coca-Cola: Bottle cap straps making lid less likely to lost Colgate: Switch toothpaste from multi-material to single material tubes  Clear instead of coloured bottles, improving value of plastic at end of life	**Established systems** Formal curbside collection Informal sector collection (waste pickers) Drop-off centres **Potential innovations** Digital market places for waste pickers, aggregators and off-takers	**Established systems** Materials Recovery Facility sorts and processes waste streams for recycling **Potential innovations** • Sensor based solutions • Artificial intelligence and robotic sorting • Real-time analysis of sorted waste to optimize process

Source: Systemiq analysis (2024)

Advanced sortation

Advanced sortation could contribute to removing the sortation bottleneck and improve global recycling rates

- The plastic waste management system is currently highly inefficient – **only 8-9% of total plastic waste is recycled**. The majority of losses occur between collection and sortation, **due to limited capacity of sortation infrastructure**.
- Overcoming the sortation bottleneck requires **improving the economics of sortation**, either via policy, or through technological advances.
- **Currently, of the 20% of waste that enters the sortation system, 50% goes to recycling.**
- AI-enabled systems can be implemented across the collection and sortation system, including data analytical software, smart bins, materials recovery facilities with sensors and robot for efficient sortation.
- By improving the quality and purity of the sorted materials, better separation, material sortation, and optimization can **improve the current sortation to recycling yield by 25%.**
- Although digitized sortation systems have high energy and capex costs, these are mitigated by increased efficiency + final revenue**, as more and purer high-value waste is recovered**.
- **Digitisation could improve the performance of the sortation sector** and contribute to expanding the sortation infrastructure, delivering more waste to recycling.

Only 8-9% of plastic currently makes it through the collection and sortation process

Fate of global plastic waste, 2019

Million metric tonnes

The biggest loss happens after collection, as sortation infrastructure is limited and costly

8-9% of all plastic waste is recycled (mostly rigid monomaterial packaging e.g. PET)
Even in best in class countries, this increases to around 14% (EU)

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

The sortation bottleneck will mostly be solved via supportive policy frameworks, but technological advancements could improve economics

	What?	How?
Direct policy interventions	Set **policy targets** for collection, and sortation Further **subsidise** MRFs	*The EU Packaging and Packaging Waste Directive sets binding recycling targets*
Indirect policy interventions	**Valorise waste materials** Increasing **cost virgin production, incineration and landfill** Establish **deposit return schemes for high value waste**	***Extended Producer Responsibility** shifts the financial and operational responsibility of plastic waste management to producers, creating a business case for scaled sortation* *The EU is considering applying the ETS to the incineration of waste from 2028*
Making MRFs more efficient	**Improving sortation yields and purities**, and reducing costs	*Digitisation of sortation* *Improved analystics*

Focus of the deep dive

Systemiq analysis based on Plastic Treaty Futures (Systemiq, 2024) and Advanced Sortation for Circularity (Eunomia, 2024).

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

Material synthesis → Product Design and manufacture → Retail and distribution → Use phase → Collection → Sorting → Recycling → End-of-life (linear)

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

Examples
Not exhaustive

SOEX · GLACIER · greyparrot · AMP ROBOTICS · TOMRA

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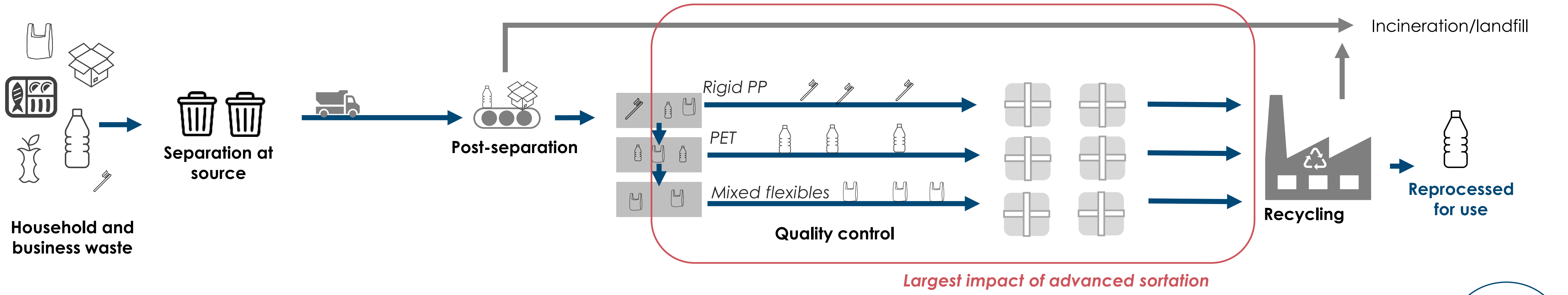
Where sortation infrastructure exists, advanced sortation could improve plastic recycling yields by up to 25%

Illustrative



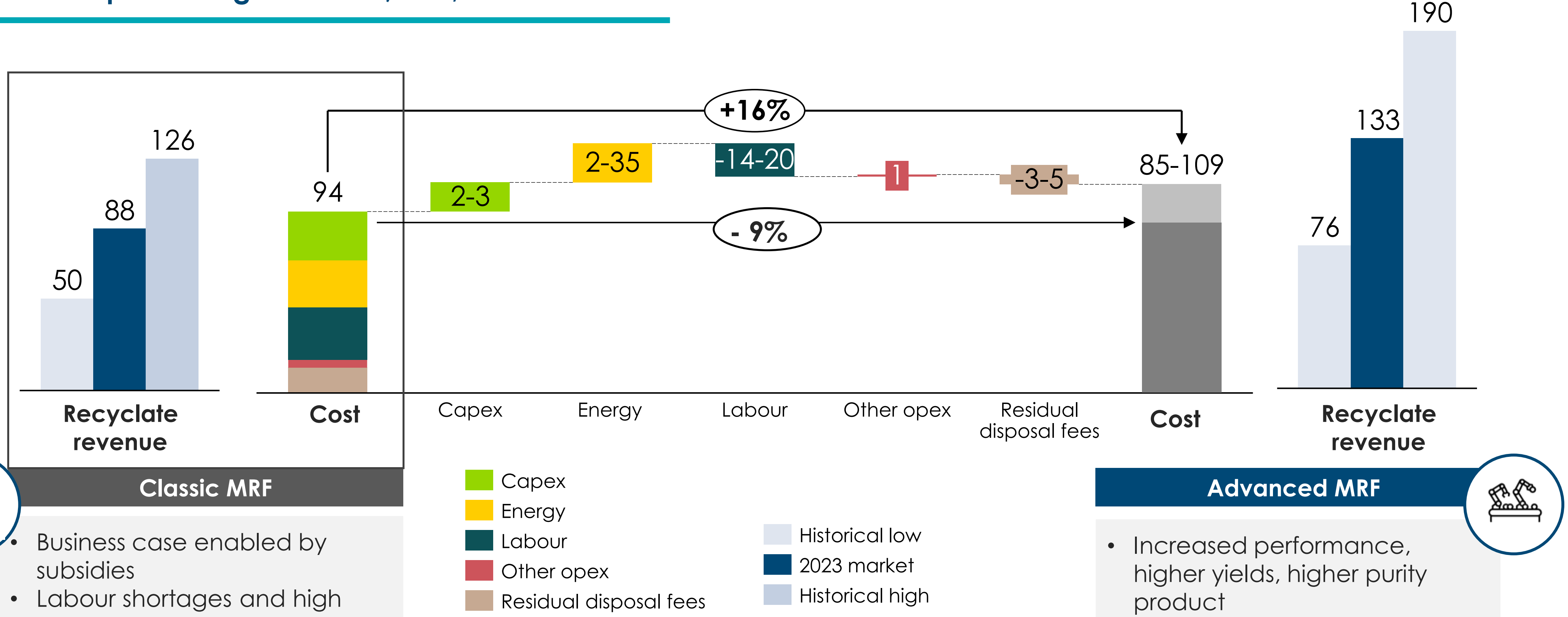
	Material separation		Sortation		Recycling yield		Compound yield improvement +25%
Non- automated system	• Some manual separation	80%	• Physical (density-based) sortation • Manual quality control • **Limited capacity to sort flexible plastics**	85%	• Wide range of purities • **Higher rates of contamination,** resulting in need for sortation at the recycling plant	60%	Equivalent to only a 12% final recycling yield in current system
Advanced system	• Design for recycling • Smart bins • Optimised collection • Robotic post-separation	85%	• Advanced sensors • Instantaneous contamination control • **Can sort based on chemical makeup**	95%	• **Up to 99% purity** • Ability to grade bales • **Better sortation of contact sensitive materials** (~11% of the overall stream)	80%	

Sources: Advanced Sortation for Circularity (Eunomia, 2024). Plastic pathways (PWC, 2022). Turning Trash Into Treasure: How AI Is Revolutionizing Waste Sorting (Forbes, 2024). How AI Robots help reduce the cost of waste sorting in MRFs (Recleye, 2024). Olawade. D.B. et al., Smart waste management: a paradigm shift enabled by artificial intelligence, Waste Management Bulletin, 2 (2), 2024.
Notes: Based on fictional MRF in the Netherlands, sorting household and business waste

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

Illustrative

Cost of waste processing in an MRF, USD/t waste



Classic MRF

- Business case enabled by subsidies
- Labour shortages and high labour costs

Advanced MRF

- Increased performance, higher yields, higher purity product
- Commercially viable

Notes: Based on 70,000t MRF in Michigan, 2023. CAPEX: Included cost of building + machinery, amortised over 20 years. AI MRF assumes addition of 2 sensor + robot machinery, costing $12000000 each. Energy: Assumes increase of 20-70%. Electricity cost: Low: ~$40/MWh, High: ~$80/MWh. Residual disposal fees: Assumed $80/t gate fee. Revenue: Assumes 25% higher yield and 20% higher value in AI MRF.Source: MoA Material Recovery Facility Feasibility Study, (Michigan State, 2023). How AI Robots help reduce the cost of waste sorting in MRFs (Recleye, 2024). ReShaping Plastics (Systemiq, 2022)., Bradshaw SL, Aguirre-Villegas HA, Boxman SE, Benson CH. Material Recovery Facilities (MRFs) in the United States: Operations, revenue, and the impact of scale. Waste Manag. 2025

Advanced sortation and improved analytics could bolster supportive policy measures

Material synthesis → Product Design and manufacture → Retail and distribution → Use phase → Collection → Sorting → Recycling → End-of-life (linear)

Lower costs

Transport and collection costs (often 1.5-2x cost/t of sortation) **will fall**

Scaling MRF capacity will unlock more collection and sortation

Higher purities can facilitate mechanical and chemical recycling

Advanced sortation enables improvements **where collection and sortation rates are already high**

Better data

Improved analytics can be fed back into the design process for plastic objects to further maximise sortation rates.

Smart bins can provide **better information about waste disposal**

Digitisation and better analytics can deliver **better data to support the policies needed** to solve the sortation bottleneck

Source: Plastic Treaty Futures (Systemiq, 2024), Advanced Sorting for Circularity (Eunomia, 2024).

Mechanical recycling

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

Material and carbon circularity solution set

Technology-deep-dives

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

1 What are the **key levers** that could enable **higher circularity?**

2 What are the **techno-economics, limitations and barriers** to key **technologies?**

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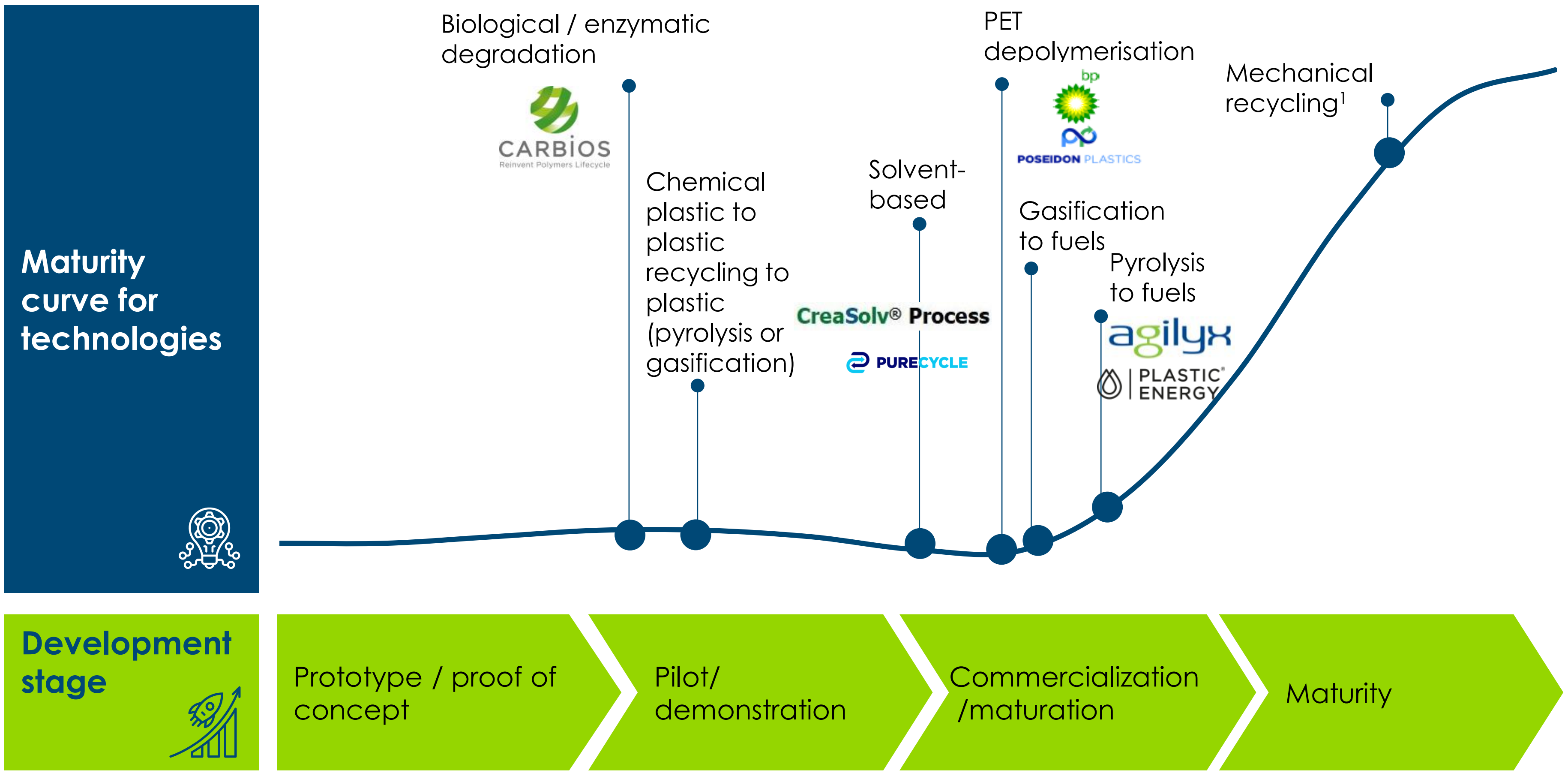
Different recycling technologies are along the maturity curves, with mechanical recycling the most advanced commercially

Plastic and chemical recovery technologies and their maturity (examples)



- End-to-end system for **Plastic to Plastic** recycling is immature despite all the hype – but commercialization of low volumes has started
- Most focus so far has gone to **Plastic or waste to Fuels** which is easier to find small, decentralised markets and requires less scale and less capital investments

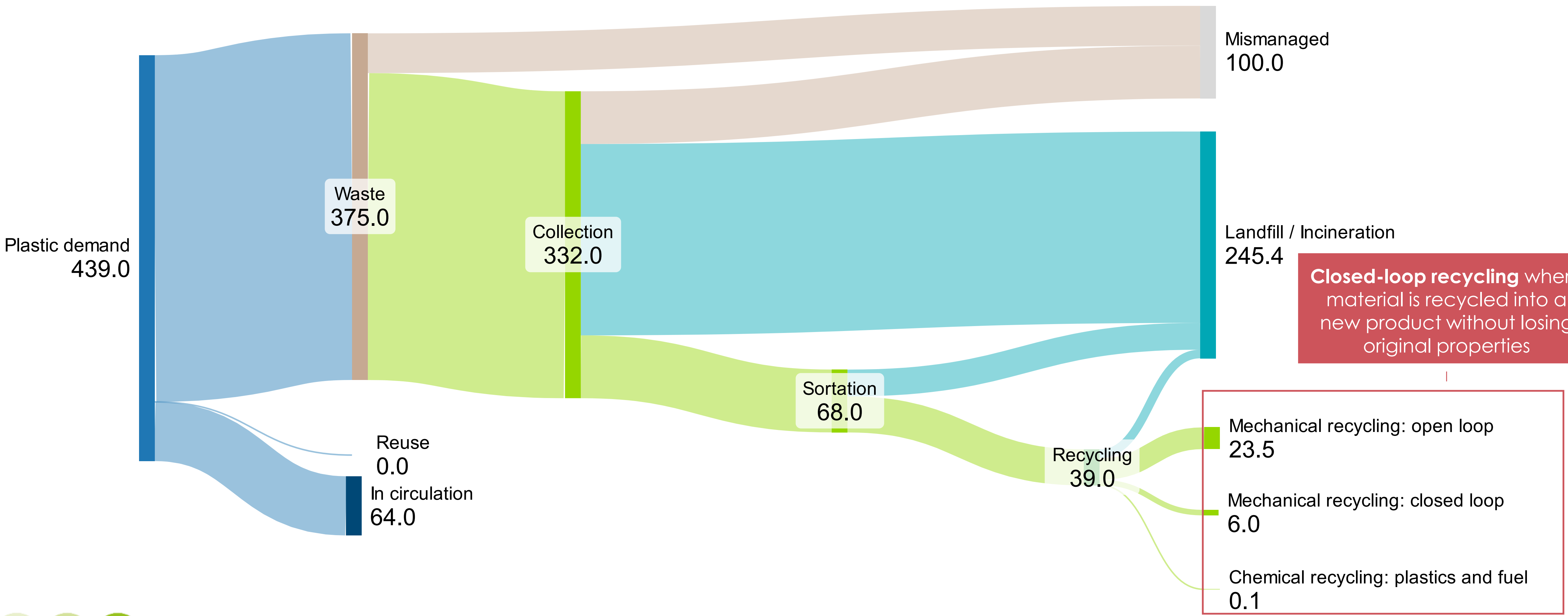
Source: Systemiq analysis (2024)
Note: 1. For a limited range of plastic feedstock types

Mechanical or physical recycling is the current dominant technology type for recycling waste…

	Mechanical (current dominant technology)	Solvent based
Description	**Physically processing** waste materials by cleaning shredding and reforming without changing chemical structure	**Solvents dissolve** and **separate polymers** in plastic waste, allowing for extraction and purification materials without altering their chemical structure
Examples	*Not exhaustive* VEOLIA, WM WASTE MANAGEMENT, suez	PURECYCLE, CreaSolv® Process
Advantages	• **Vast majority for plastic recycling to date** with large installed capacity worldwide • **Low energy input** and GHG balance	• **Tolerance** for multilayers plastic or multi-plastic materials • **High-quality output** • **Low-energy input** and GHG balance
Challenges	• Low tolerance for input contamination (e.g. issues with colour, odor, properties). • Limitations for high performance/high quality application (e.g. food grade)	• Requires solvent management and recovery • Feedstock specific technology, requiring same sorting as Mechanical recycling

However, only a small amount of material is mechanically recycled today, and even less is closed-loop

Fate of global plastic waste, 2019, *Million metric tonnes*

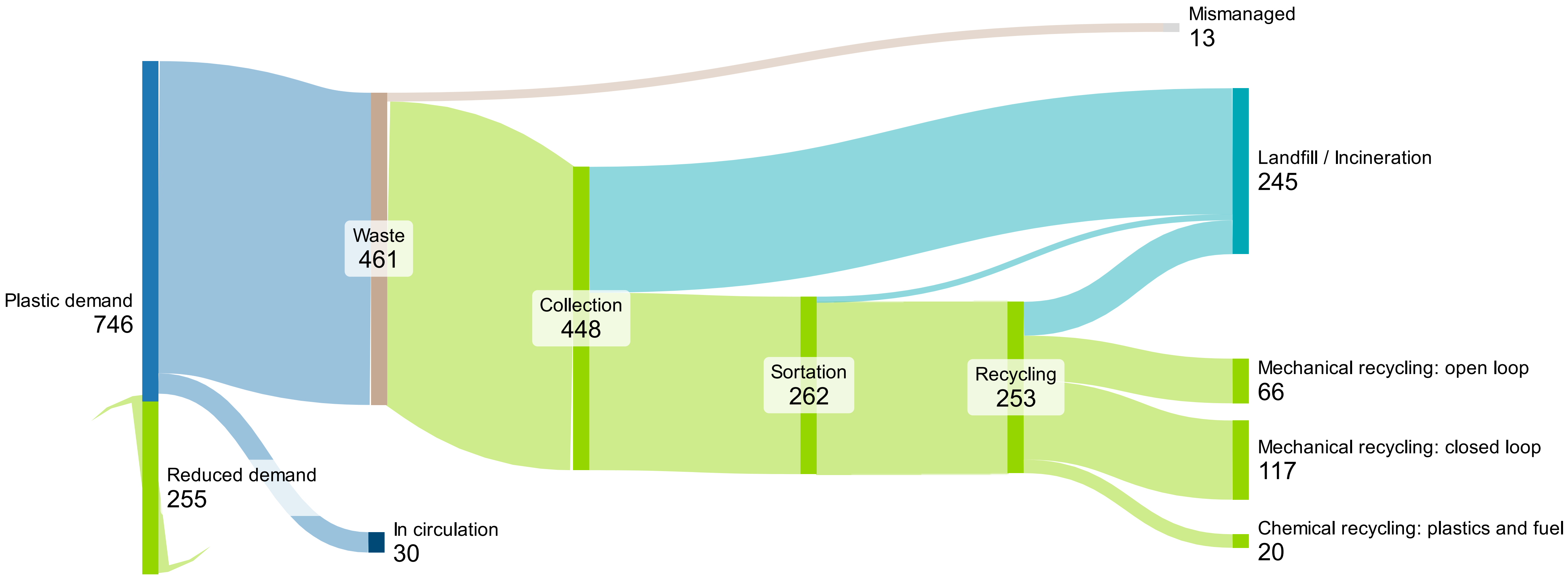


Closed-loop recycling where material is recycled into a new product without losing original properties

Source: Systemiq (2024) Plastic Treaty, BAU

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

Fate of global plastic waste, 2040, *Million metric tonnes*



Source: Systemiq (2024) Plastic Treaty, Global rules scenario

A number of policy actions would need to be in place to support this higher rate of recycling

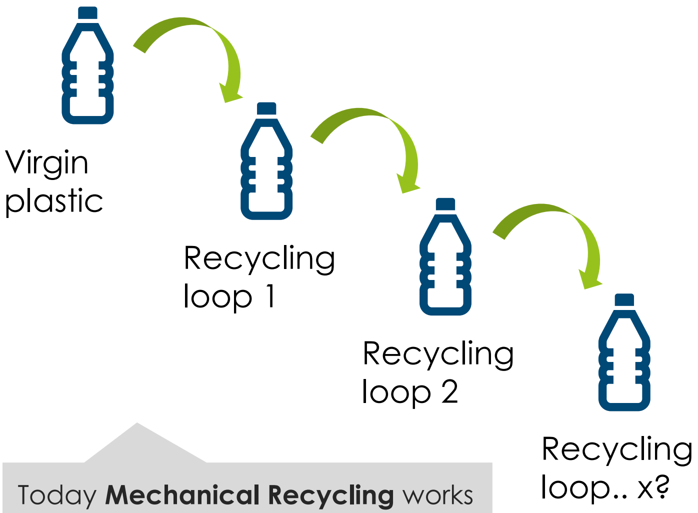
Lever Group	Policy lever description
Reduce virgin plastic production and consumption	Policy targets to reduce virgin plastic volumes
	Virgin plastic fees to fund solutions across the plastic lifecycle
Eliminate avoidable and problematic plastic and chemicals	Phaseout criteria for problematic plastics, polymer applications and chemicals of concern
	Bans on avoidable single-use plastics
Expand circularity	Design rules for safe reuse, repair, durability and cost-effective recycling
	Targets for collection and recycling rates
	Modulated EPR scheme applied across sectors

Source: Systemiq Plastic Treaty (2024). List provided is a subset interventions in the Global Full Lifecycle Scenario that related to increase recycling.

Mechanical recycling faces technical limitations that prevent it being the only solution to circularity

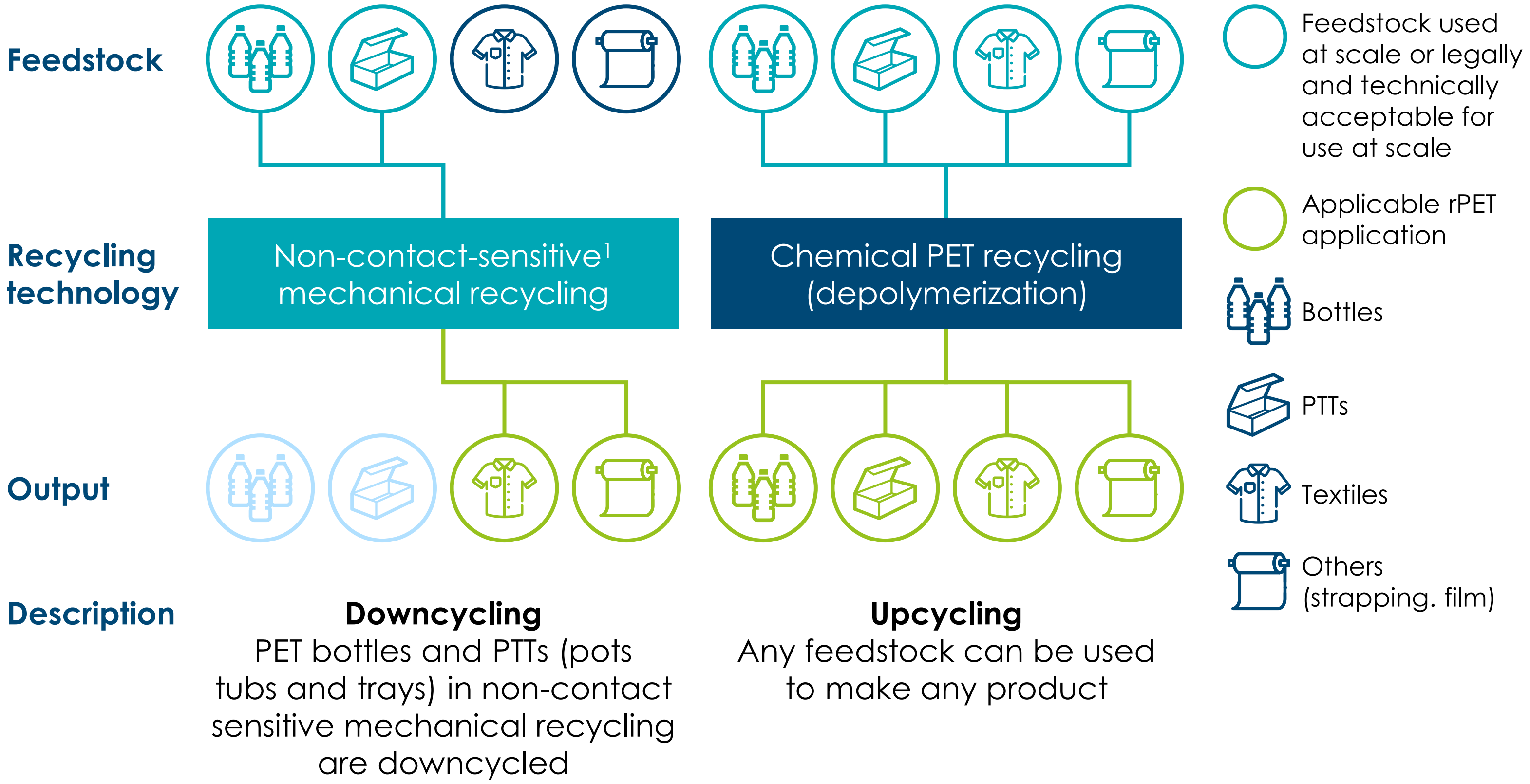
Challenge 1: Mechanical recycling degrades polymer properties

Heat, mechanical stress and oxidation and during recycling and reprocessing **degrade polymer properties**[1]



Today **Mechanical Recycling** works well because **>90% of input is virgin** plastic. But over time, plastic properties degrade. It is unknown at which point degradation becomes an issue.

Challenge 2: Mechanical recycling has limitations in delivering virgin-equivalent quality products when feedstocks are contaminated –chemical recycling could be complementary to this challenge



Notes: rPET = recycled PET plastic, PTTs = pots tubs, trays. Source: Systemiq (2023) *Circularity of PET/polyester packaging and textiles in Europe* Huiying Jin et al (2012) *The effect of extensive mechanical recycling on the properties of low density polyethylene*. *1.* Sources suggest plastic can only be recycled 2-3 times before quality becomes too poor for use, but is highly dependent on plastic type and recycling treatment. In a highly controlled environment, scientists were able to recycle a HDPE bottle a max of 10 times. 2. Non-contact sensitive means materials that are not intended to come into direct contact with products that require high safety and hygiene standards, such as food, beverages, cosmetics, and medical products.

Agenda

- Introduction to work program
- The case for carbon efficiency
- Reduce and recycle material
- **Recycling carbon**
- High circularity scenario
- Barriers and the policy landscape

Chemical recycling and thermo conversion

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

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1 What are the **key levers** that could enable **higher circularity?**

What are the **techno-economics, limitations and barriers** to key **technologies?** 2

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Despite CO_2 reduction potential and abundant feedstock availability, chemical recycling faces challenges to scaling

- Chemical recycling technologies remain **more expensive** than unabated fossil-based alternatives and mechanical recycling, with sorted plastic largely prioritized for mechanical methods.
- In pyrolysis and depolymerisation, waste feedstock cost and pretreatment costs are the main drivers.
- In gasification, the cost required for the large feed volumes is the main cost driver, whereas feedstock could even reach negative values if unsorted and of low quality.
- PET depolymerization and mechanical recycling offer the **highest potential CO_2 reduction—up to 2.5 tons CO_2 per ton of product.**
- There are **1,130 million tons of carbon** in mixed plastic waste that that could be theoretically suitable for chemical recycling (e.g., pyrolysis and gasification) but techno-economics remain an issue
- Chemical recycling could be complementary to role of mechanical recycling, **avoiding material downgrading and process otherwise unrecyclable feedstocks**, however would need overcome challenges with feedstock tolerance and economics

Our deep-dives will focus on chemical recycling and thermos conversion technologies which have reached or are nearing commercialization

	Technology	Process	TRL	End-Use Sector	Companies *Non-exhaustive examples*
1	**Pyrolysis**	Plastic waste[1] is heated without oxygen causing the polymer chains to break into smaller hydrocarbons[2]. This process produces pyrolysis oil, gases and solid residues[3]. The oil is further refined to create diesel, gasoline or naphtha[4].	6-8[5]	Chemicals, Transportation, Power	agilyx, Plastic Energy, Brightmark, BASF We create chemistry, OMV, Mura
2	**Depolymerisation**	Plastic waste is broken down into its basic building blocks using catalysts, solvents or enzymes[7]. This produces monomers, oligomers, and some solid by-products[8]. The monomers can be repolymerized into high-quality plastics, recovering high-value chemical feedstocks.	5-8[9]	Chemicals, plastics manufacturing	Syre, revalyu, bp, Carbios, Eastman
3	**Gasification**	Feedstock undergoes thermal decomposition at high temperatures to break into smaller hydrocarbons. Limited oxygen or steam is then added, converting the hydrocarbons into syngas. *Note: gasification is a technology used not only to recycle chemicals, but also to gasify coal and biomass.*	7-8[6]	Power, heat, chemicals	SunGas Renewables, Sumitomo SHI FW, Enerkem, OMNI Conversion Technologies

Sources/Notes: 1) Waste plastic has to first be sorted from non-plastic waste (e.g., metals, glass, organic residues); certain types of plastics also have to be excluded (PET, PVC); 2) This process can be batch, semi-continuous or continuous. 3) Typical ratios of pyrolyser output: 70-80% pyrolysis oil; 10-20% non-condensable gases (incl. methane, ethane, hydrogen), which can be used to power the pyrolyser process; and 10-20% solid residue (e.g., char, inorganic fillers, etc.). 4) Hydrotreatment and catalytic upgrading may also be incorporated to improve fuel quality. 5) Many pilot/demonstration-scale projects exist at TRL 7-8, including by Plastic Enregy and Agilyx; full commercialization at TRL 9 or above have challenges (e.g., feedstock purity at scale). 6) Some projects at TRL 8-9, such as Enerkem in Canada, have now shut down as struggled to reach FID. To date, there is no operational waste gasifier at TRL 8-9 7) Hai Wang et al. (2013) 8) Rahimi et al. (2017)9) Schwarz et al. (2021) 10) Kirstein et al. (2023)

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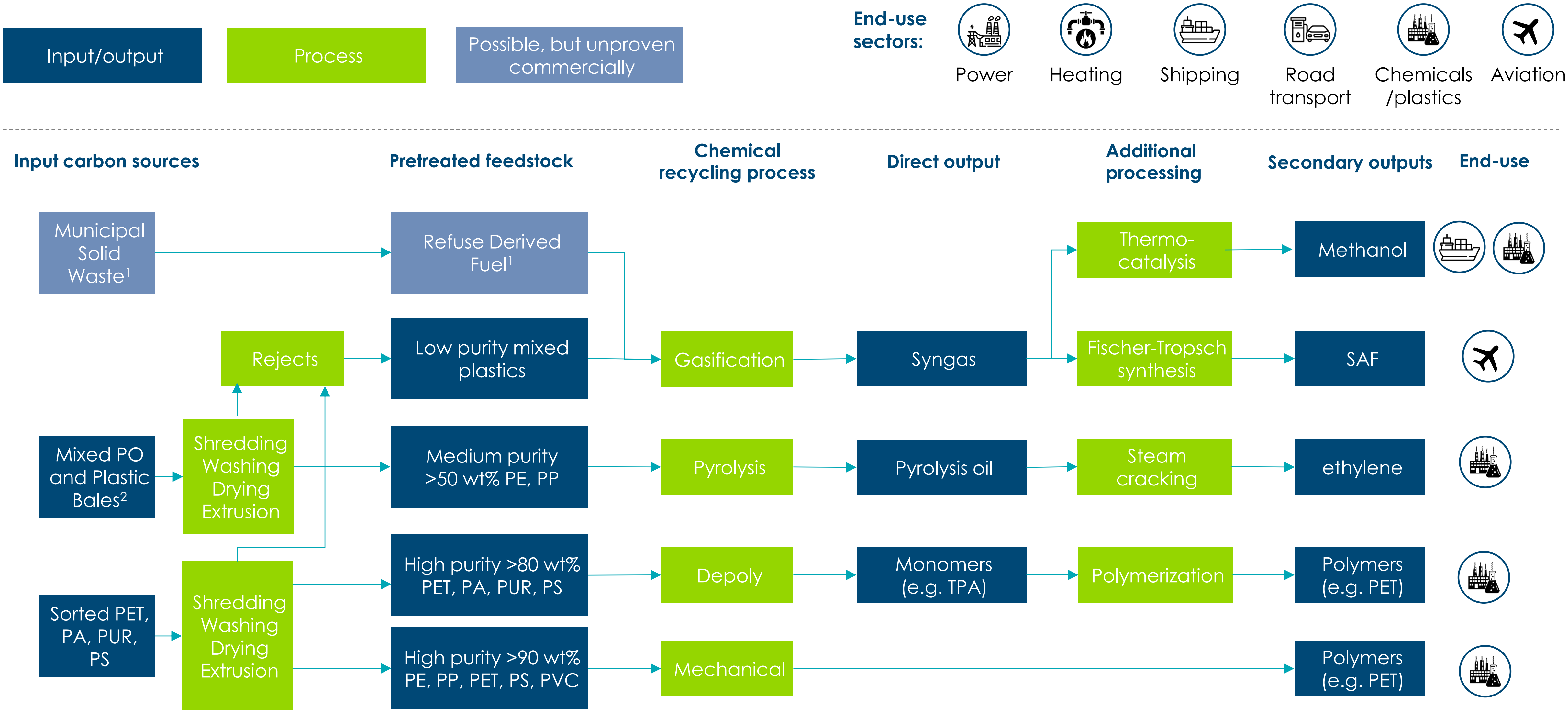
Chemical recycling and thermo-conversion pathways differ by their outputs and end-use sectors



Notes: PET = Polyethylene terephthalate , PA = Polyamide, PUR = Polyurethane, PE = polyethylene, PO = Polyolefins, PS = Polystyrene, PVC = Polyvinylchloride
1) Municipal solid waste (MSW) and Refused derived fuel (RDF) -which is sorted waste from MSW- might be used as gasification feedstock in the future, but they are not developed yet 2) Includes PE, PP, PET, traces PS, multilayer flexibles (i.e. originated from different plastic-based aluminum and paper layers) and clogged materials (i.e., plastic items inside or tied up with others).

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1 Pyrolysis of waste plastics produces a naphtha-like liquid that can be fed into traditional steam crackers to produce olefins

Overview

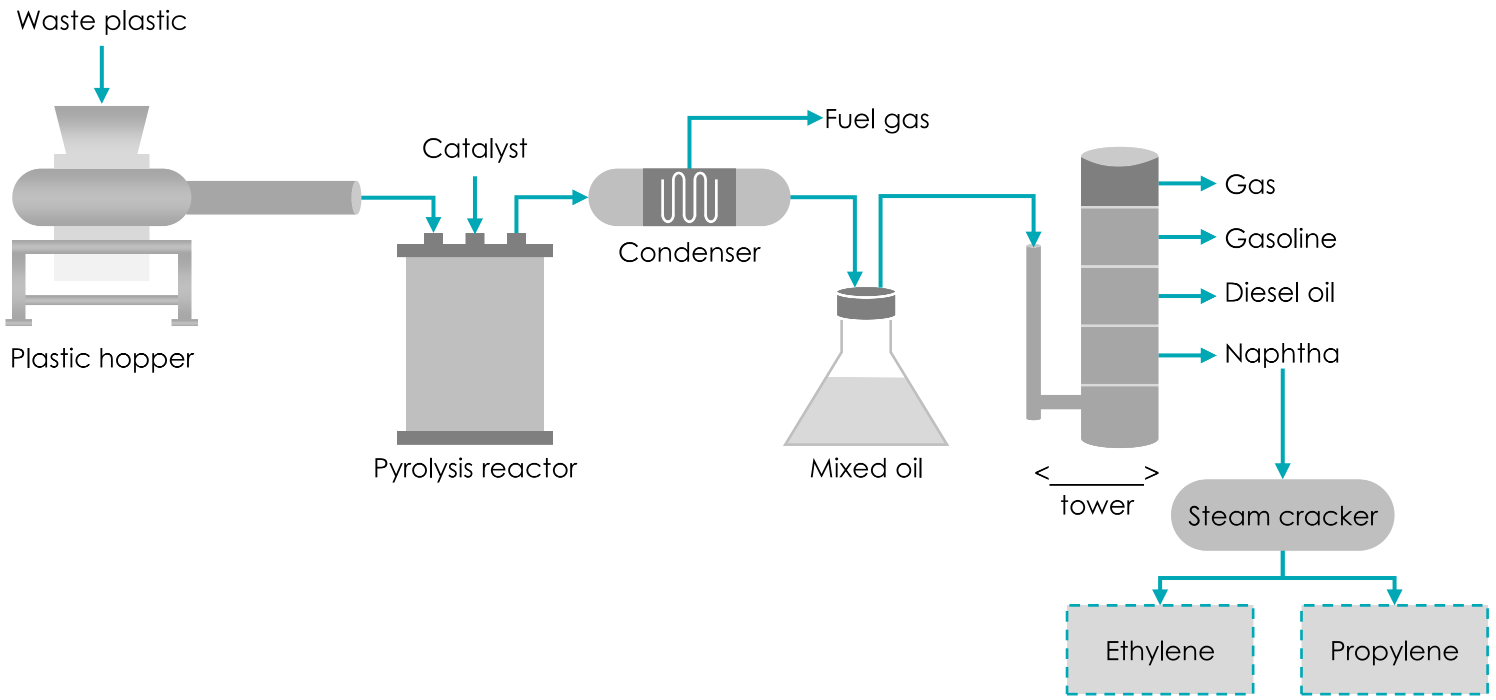
- **Current TRL**: 6-8, commercial projects and first-of-a-kind projects being launched in late 2020s[1]

Advantages

- **Tolerance for mixed and contaminated plastics:** tolerates non-plastic materials at small amounts (e.g. organics, metals) making it suitable for real-world waste streams
- **Easier fit with existing petro infrastructure and 'recycling' concept today:** Products can be drop-in in existing steam crackers that produce the building blocks of main polyolefins

Challenges

- **Limited feedstock centralization:** due to limited tolerance to other types of feedstocks, difficult to centralize large volumes
- **Pyrolysis oil often needs upgrading:** The quality of the product is affected by inconsistent waste composition (PO-rich).
- **Multiple products (gas, liquid, and char)**: Difficult to control and optimize yields.



Pyrolysis reaction:
Thermal degradation of waste material in the absence of oxygen, in a cylindrical chamber.

Pyrolysis product:
The pyrolytic gases are condensed to yield a hydrocarbon distillate, comprising aliphatics and aromatic hydrocarbons.

Steam cracker:
The resulting petroleum equivalent mixture is further processed to valuable products

Sources/Notes: 1) Plastic Energy plant in Malaysia, New Hope Energy in Texas, Brightmark in Georgia.. 2) Process flow diagram illustrates catalytic pyrolysis. Note individual real-world projects will have variations on the process shown in the diagram, which is simplified

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2 PET Depolymerisation breaks down plastic back to monomers, allowing for repolymerization back to high quality product

Overview

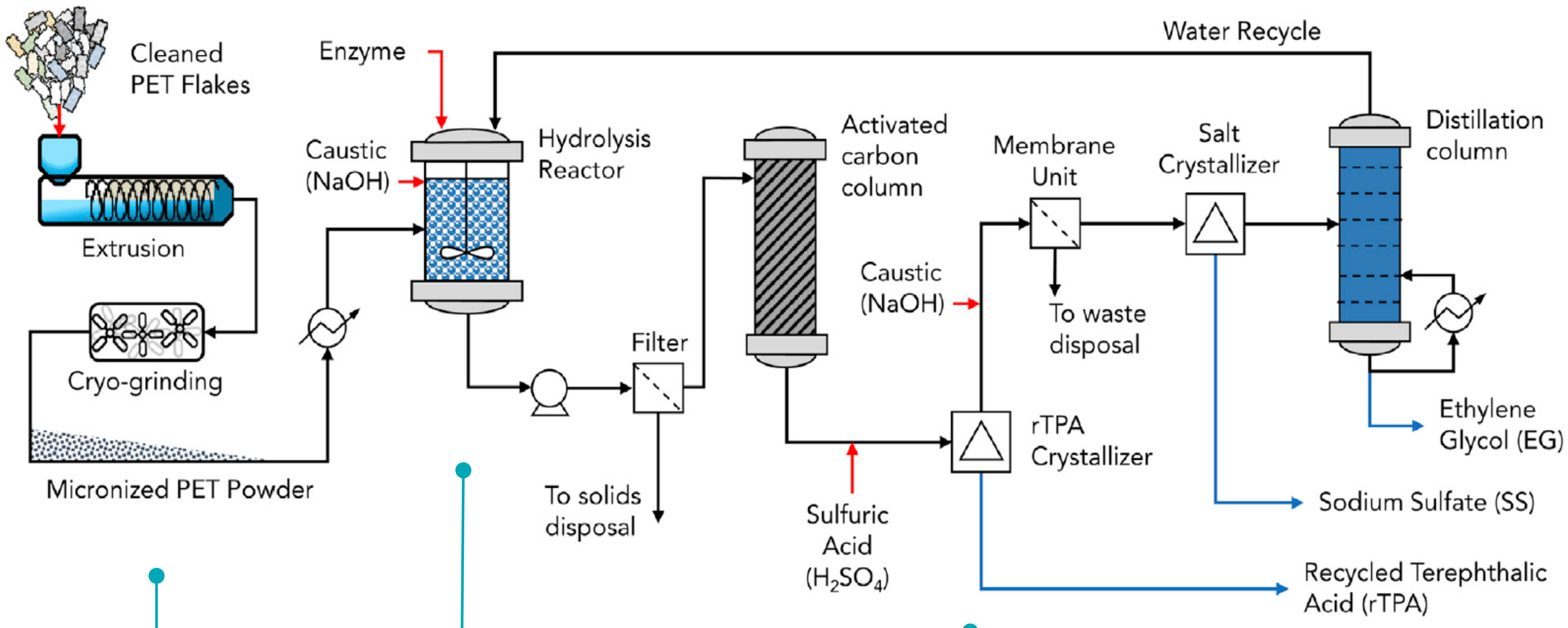
- **Current TRL**: 5-8. Eastman PET facility in Tennessee achieves on-spec initial production with revenue in 2024 [1]. Plans similar facilities in Texas and France [2].

Advantages

- **High product purity:** Achieves virgin-quality PET.
- **Integration with existing production lines:** Monomers are directly compatible with conventional polymer production, contributing to a closed-loop system
- **Low energy demand:** Operation at moderate temperatures (150–250°C) compared to pyrolysis (400–800°C) or gasification (often >800°C), reducing energy consumption carbon emissions [3].

Challenges

- **Feedstock limitations:** Does not process mixed plastics.
- **Process economics:** Costly pre-treatment steps for PET flakes.
- **Chemical & Solvent Handling:** If relied on chemicals, it requires strict handling and recovery



Feedstock pretreatment: Preparation for lower crystallinity PET powder

PET depolymerization: Chemicals/Enzymes that promote >90% depolymerization

Purification: Enable >90% rTPA recovery while minimizing chemical use for pH control

By-product recovery: >65% EG recovery

Notes/Sources: The process diagram illustrates PET depolymerization via enzymatic route, which is more environmentally friendly than chemical-based depolymerization. Similar route is used by Carbios. Individual real-world projects will have variations on the process shown in the diagram, which is simplified1) Eastman molecular recycling facility 2) Eastman selected to receive investment 3) Bohre et al. (2023)

3 Gasification offers a route to fully recycle mixed waste to produce syngas for downstream conversion into chemicals and fuels

Overview

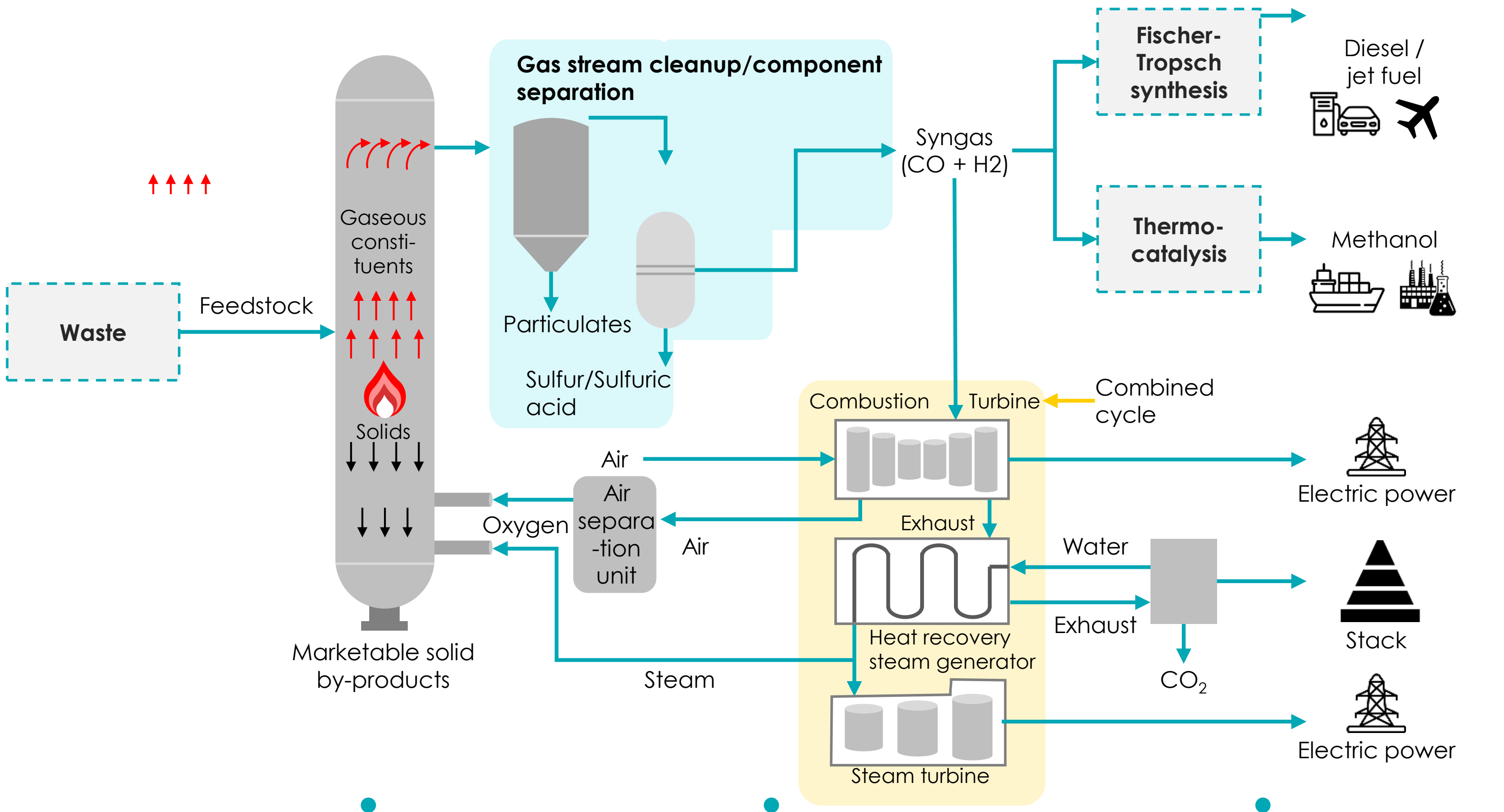
- **Current TRL**: 7-8[1], commercial projects and first-of-a-kind projects being launched in 2020s.[2]

Advantages

- **Tolerance for mixed waste stream as feedstock:** tolerates non-plastic materials, such as organic residues, textiles and biomass, making it suitable for real-world waste streams.[3]
- **Produces e syngas:** output is starting block for several downstream chemicals and fuel products.
- **Potentially high conversion of carbon**: fully breaks down plastic into H_2 and CO (up to 90% carbon efficiency[4], avoiding heavy hydrocarbons or waxes).

Challenges

- **Intolerance to presence of some heteroatoms[2] in feedstock**: e.g., polyvinyl chloride (PVC) require special handling as it can cause corrosion issues.
- **Large scale required for economics:** scaling gasifiers of waste has historically been a struggle.



Gasifier:
High temperature/pressure vessel where O_2 and steam are directly contacted with the feed causing a series of chemical reactions

Syngas:
The syngas can be further converted to H_2 and CO_2 by WGS reaction.

Polygeneration plants:
H_2 enriched syngas can be used to make gasoline and diesel fuel or other synthetic fuels

Sources/Notes: 1) Metals need to be removed from waste stream before entering the gasifier, but plastics do not need to be separated from organics. 2) GoBiGas project in Sweden 3) Atoms that are neither C nor H. 4) Autothermal gasification units which have a steam/oxygen feed is used. 4) Bashir et al., 2025. Note: closer to 50% efficiency for mixed waste. Note individual real-world projects will have variations on the process shown in the diagram, which is simplified

Technologies have different trade-offs, but feedstock challenges are common across the three technologies

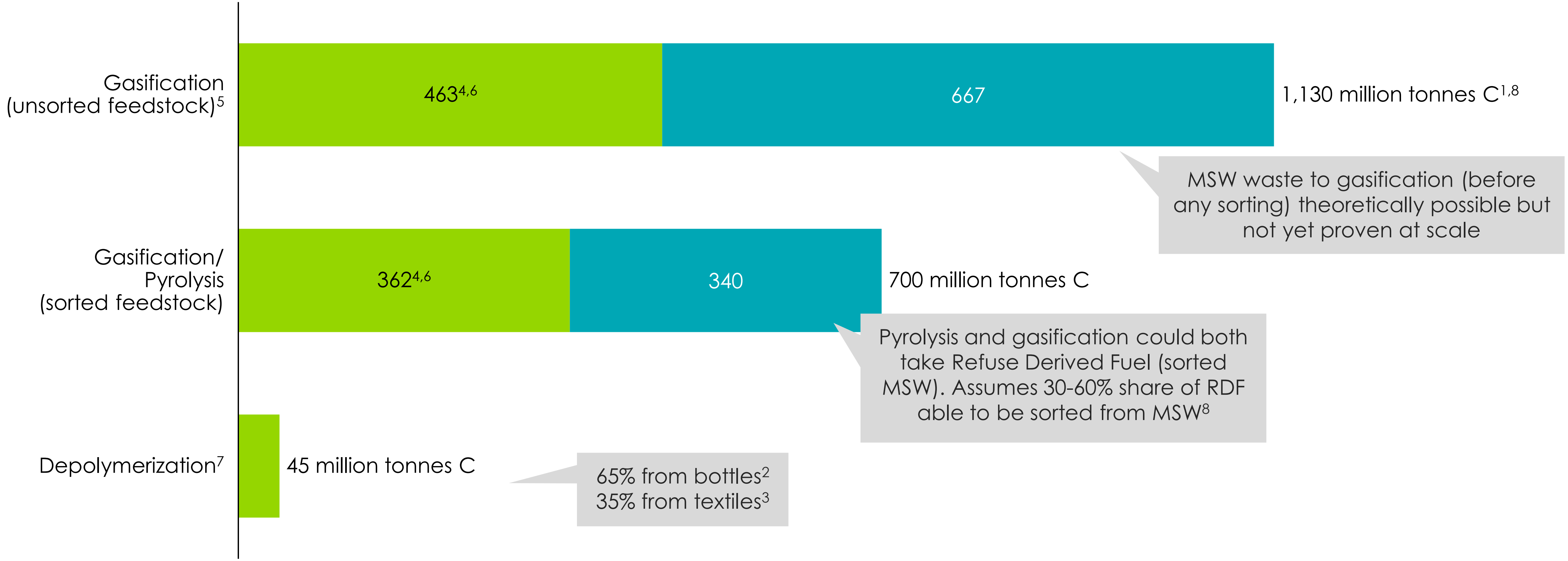
	Pyrolysis	Depolymerisation	Gasification
Advantages	• Tolerates mix of contaminated plastics and some **non-plastic materials** (e.g. 1-7 wt% metals/glass/dirt[2]) • **Easy integration** with existing steam crackers	• Achieves **high product quality** – virgin PET equivalent output • Can **integrate with existing** production lines • Enables **close-loop recycling**, by even upgrading the material.	• **Tolerance for mixed waste** feedstock[3] • Produces **syngas**, which can be utilized in several downstream routes.
Challenges	• **Feedstock:** Low <0.3wt% tolerance to PVC • Relies on **existing petrochemical** infrasturcture	• **Feedstock:** Does not process mixed-waste feedstock • **Pre-processing** of feedstock costly	• **Feedstock:** Requires high feedstock volumes to be economically viable • Requires scale for business case

Sources/Notes: 1) Bohre et al. (2023) 3) Metals need to be removed from waste stream before entering the gasifier, but plastics do not need to be separated from organics 2) Feedstock Quality Guidelines for Pyrolysis of Plastic Waste (2022)

Chemical recycling technologies have a wide range of theoretical waste feedstock volumes by 2050

Global theoretical feedstock volumes for chemical recycling technologies
Million tonnes of Carbon(2050)

Mixed municipal waste
Plastic waste



MSW = Municipal Solid Waste; RDF = Refuse-Derived Fuel

Sources/Notes: 1) Total MSW projected volume in 2050 from: Municipal solid waste generation worldwide in 2020, and projections from 2030 to 2050 (Statista, 2024). 2) McNeely et al. (2024) 3) Greenblue study (2017). 4) Assumes 646 million tons of plastic waste in 2050 from: Systemiq Plastic Treaty BAU scenario. Suitable plastic waste for gasification assumed to be a maximum of 80% from ReShaping Plastic (Systemiq, 2022) 5) High technology uncertainty as to whether future gasification technologies/facilities would be able to handle unsorted MSW. Total volumes of MSW shown here for perspective on potential future volumes. 6) Approximately 30% of collected plastic is discarded to mixed plastic waste (Systemiq, 2022) 7) PET, PE and PP account for the highest polyer production volumes - each ~100Mt/y. Depolymerisation of any other polymer has minimal capacity. (Saputra Lase, 2023) 8. Breakdown is uncertain of sorted MSW, 20% of carbon is estimated in MSW. More specifically 12% plastics, 13% yard trims, 29% paper and paperboard, 14% food scraps, 9% metals, 8% rubber/leather/textiles, 14% glass/wood/other (Ikramul Hoque, 2020). Biomass waste for fuels will not be double-counted.

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The two major challenges of feedstock compatibility and quality limit the final potential of any one technology

✗ *Incompatible* ✗ *Technology emerging*

Feedstock		PET	HDPE	LDPE + LLDPE	PP	PVC	PS	Other plastic	MSW[3]
Clean/sorted waste	Mechanical recycling						✗	✗	✗
	Depolymerisation		✗	✗	✗	✗	✗	*PA only*	✗
	Pyrolysis[2]	✗				✗		✗	
	Gasification					✗			
	Incineration								
Contaminated waste	Mechanical recycling	✗	✗	✗	✗	✗	✗	✗	✗
	Depolymerisation	✗ (emerging)	✗	✗	✗	✗	✗	✗	✗
	Pyrolysis[2]	✗				✗		✗	✗
	Gasification	✗ (emerging)				✗		✗	✗
	Incineration								✗

Key takeaways

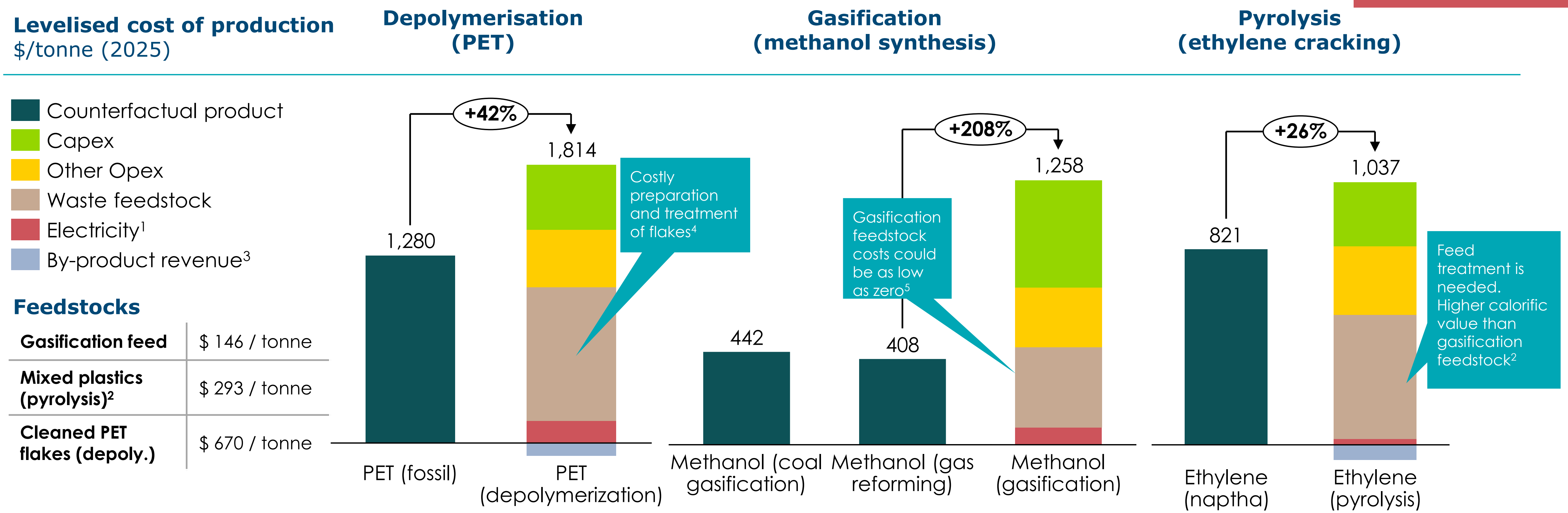
- Mechanical recycling, chemical reprocessing[1], pyrolysis, and gasification are **complementary technologies and must be built in tandem**
- **Sorting and preprocessing of feedstock is a key enabler**

Note: (1) Includes solvent-based and depolymerization. (2) "Pyrolysis operators require well sorted, clean, and largely homogenous feedstock – in the vicinity of 85% polyethylene (PE) and polypropylene (PPI)", Alliance to End Plastic Waste (August 2022), Feedstock Quality Guidelines for Pyrolysis of Plastic Waste. (3) Municipal Solid Waste. Assuming Refuse Derived Fuel (RDF) as clean/sorted waste.

High feedstock costs and technology capex drive the cost-competitiveness of chemical recycling pathways

Preliminary

Levelised cost of production
$/tonne (2025)



Feedstocks

Gasification feed	$ 146 / tonne
Mixed plastics (pyrolysis)[2]	$ 293 / tonne
Cleaned PET flakes (depoly.)	$ 670 / tonne

Key takeaways on cost drivers and trends

- Cost-competitiveness driven by price of feedstock (assumed here to be high-calorific/sorted MSW, i.e. Refuse-Derived Fuel)
- High capex/opex of gasification technology limiting cost-competitiveness with fossil-based chemicals production
- Feedstock handling and mechanical pretreatment are the cost drivers. Pricing based on historical lows leads to cost-competitiveness with fossil routes.

Notes: 1) Assumes baseload PPA power (~$60/MWh). Midpoint of lower bound (~$40/MWh) for low-cost H2 production region (Spain) and upper bound (~$80/MWh) for high-cost region (Germany). 2) RDF = Refuse Derived Fuel (i.e. high-calorific sorted MSW). Assumed cost from the amount of electricity and steam which would have been generated if not coming from refused-derived fuel. 3) Char By-product for pyrolysis, assumed to be sold at equivalent value for RDF. 4) Depoly estimation is based on published data: Singh et al. (2021) 5) Gasification feed could become negative, if low quality MSW is used. However, such feed will require further pre-treatment which adds cost.

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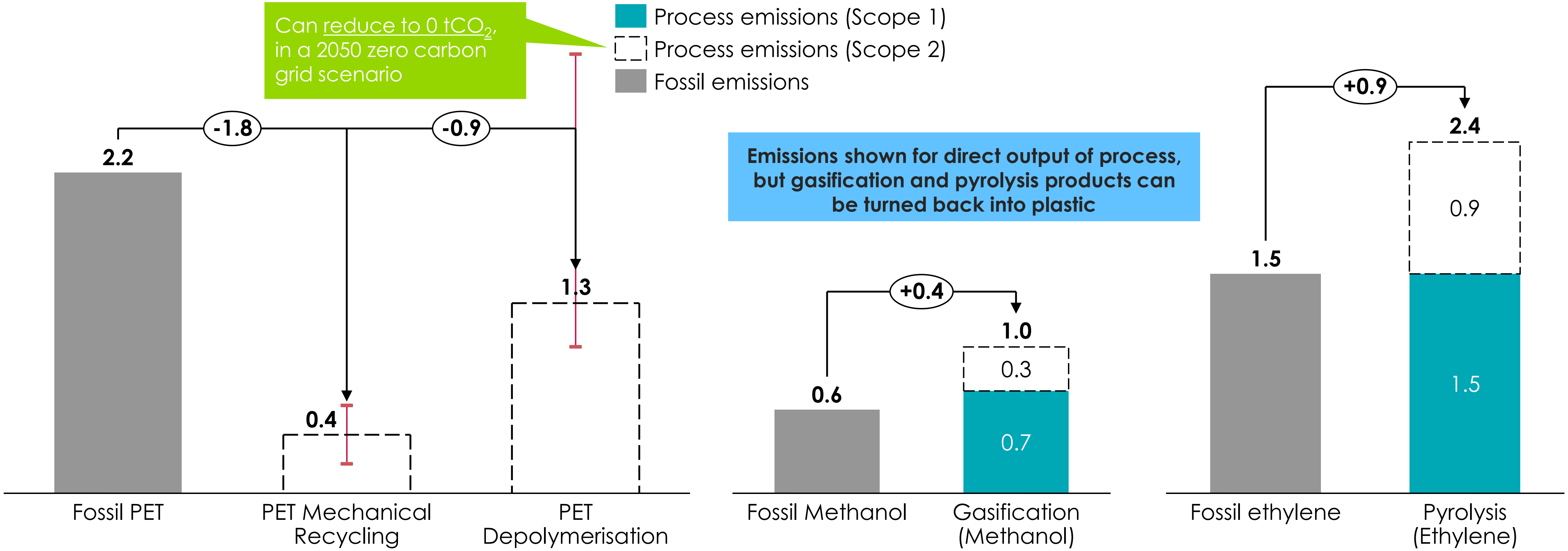
Mechanical recycling and depolymerisation reduce overall CO_2 emissions more effectively, because fossil polymer production is avoided

Preliminary

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



Notes: PET depolymerization shows a wide range of CO_2 emissions depending on the technological path that is followed.
Sources: 1) CE Delft (2019) 2) Uekert et al. (2022) 3) Uekert et al. (2023 Sources: 1) CE Delft (2019) 2) Uekert et al. (2022) 3) Uekert et al. (2023). Carbon footprint of fossil methanol based on Methanol institute (2023) *Carbon Footprint of Methanol. Fossil Ethylene based on* Chemical and Engineering news (2021) *The search for greener ethylene and* University of Illinois (2022) *A breakthrough discovery in carbon capture conversion for ethylene production*. Fossil emissions for PET based on Eco-profiles produced for Plastic Europe; LCI Assessment for Cradle-to-Gate (Raw Materials/Energy, Precursos production, Polymer production). Gasification based on NREL (2022) Techno-Economic Analysis of Waste Plastic gasification to Methanol Process. Pyrolysis emissions LCA varies, values here reflect Energy and Environmental Science (2023) Techno-economic analysis and life cycle assessment for catalytic fast pyrolysis of mixed plastic waste

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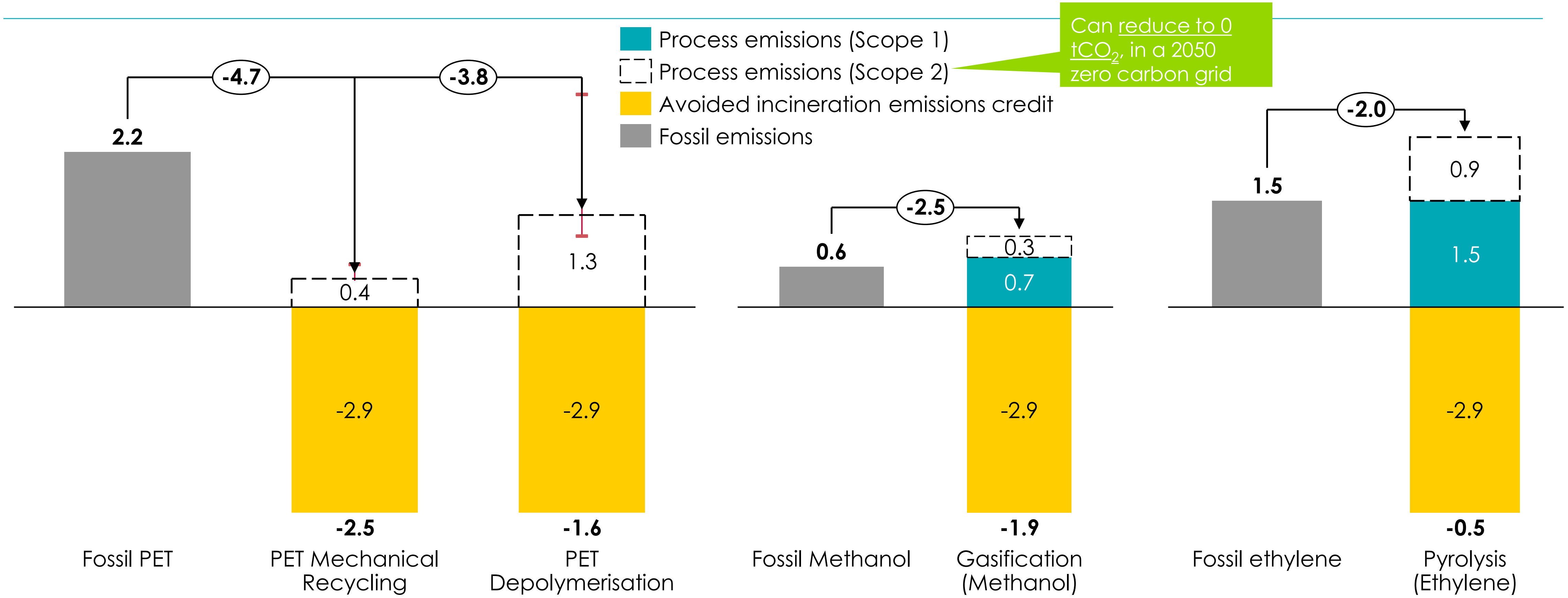
In full chain analysis pyrolysis and gasification provide emissions savings, because CO_2 emissions incineration are avoided

Preliminary

CO_2 emissions for recycling processes, compared with fossil production
tCO_2 / tonne of product output



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

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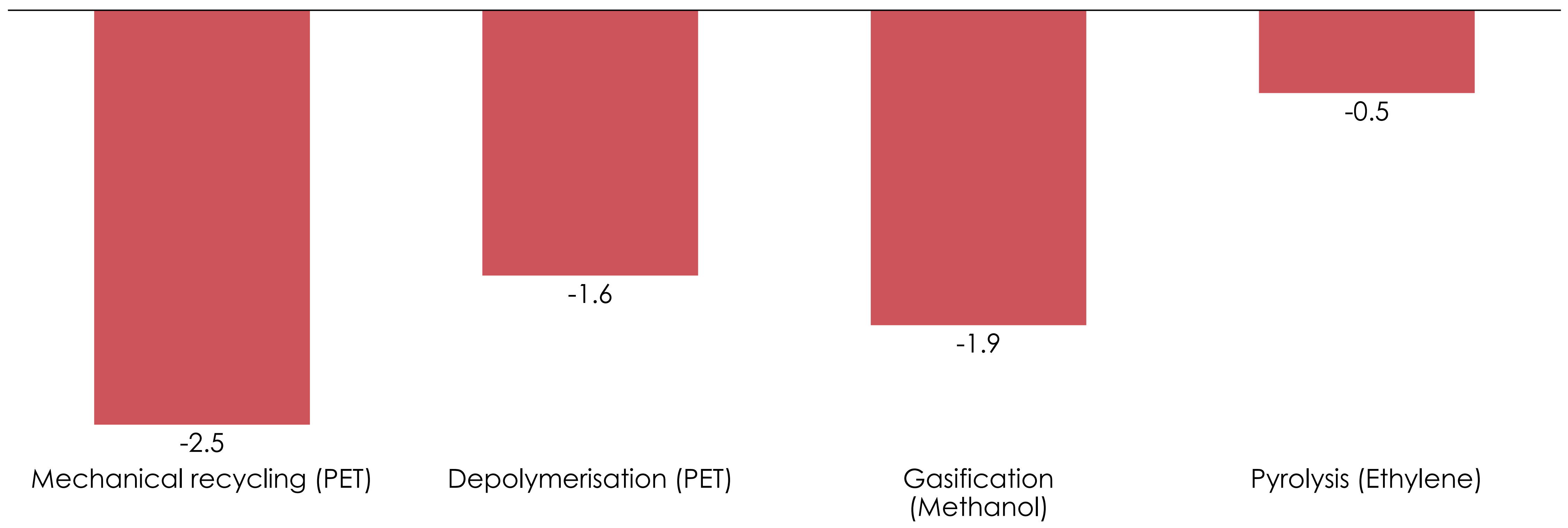
Mechanical recycling can offer the largest emission savings versus fossil its fossil route

Preliminary

Net emission savings versus fossil alternative product
tCO_2 / tonne of product output



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

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Arguments against chemical recycling and thermo conversion technologies question whether they should be prioritised as circular solutions

Arguments for and against chemical and thermo conversion technologies

Proponents of chemical and thermo conversion technologies argue benefits of[1]:

- Ability to take difficult-to-recycle plastic and other waste as feedstock, which would otherwise result in incineration or landfill
- Delivers 'virgin-quality' output that mechanical recycling cannot deliver

Arguments opposing these technologies[1,2]:

- Only 'partially recycling' where plastic to fuel instead of plastic to plastic route taken
- Question health impacts of emissions from processes on local communities if strict controls not followed
- Low on the waste hierarchy and should not receive government/policy support to overcome challenges instead of solutions like reuse
- Could compete with and cannibalize mechanical recycling, which has a better carbon footprint

European Commission Waste Directive's, 'Waste Hierarchy', prioritizing prevention first down to disposal

Sources: 1. Systemiq (2024) Plastic Treaty Futures, Zero Waste Europe (2024) Fifty years: chemical recycling's fading promise. Not exhaustive for all arguments for and against chemical recycling and thermos conversion.

Better, cheaper sortation and supportive standardised policy is needed to support the scaling of chemical recycling

Cost reduction	Scale advanced sortation and pre-treatment
	Reduce feedstock and electricity costs
Financial penalties for linear systems	EPR scheme applied across sectors
	Carbon pricing on plastic production and incineration
	Landfill disincentivised via gate fees or taxation of leakage
Standardisation	Design for chemical recycling, maximising of recyclable materials
	Establish industry-wide standards for feedstock and outputs to facilitate scale-up

Key takeaways

Cheaper electricity and high-quality feedstocks could reduce cost of chemical recycling

Carbon pricing and EPR schemes could **increase the cost of incineration and waste disposal**, reducing the cost delta and creating a market for high-quality recycling feedstock

Achieving consensus on the safety and quality of outputs could **bolster policy support**

Source: Systemiq Plastic Treaty (2024). List provided is a subset interventions in the Global Full Lifecycle Scenario that related to increase recycling.

Demand reduction is the lever with the largest potential, but demand reduction and chemical will require overcoming system inertia

Preliminary

Primary carbon demand reduction potential in the chemicals sector, 2050

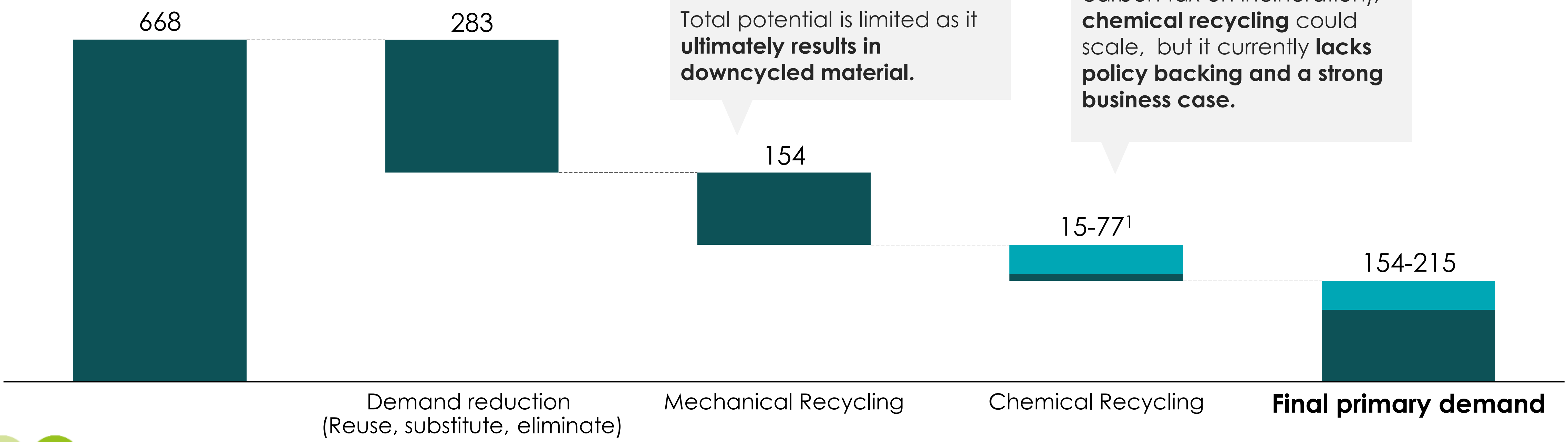
Million tons of carbon (C)

Demand reduction (especially reuse) has a high potential due to cost savings but **requires system-wide change.**

Mechanical recycling will scale as a result of **better collection and sortation and expected policy support,** resulting in more high purity feedstock.

Total potential is limited as it **ultimately results in downcycled material.**

With cheap energy and high counterfactual costs (e.g. a carbon tax on incineration), **chemical recycling** could scale, but it currently **lacks policy backing and a strong business case.**



Sources: Energy: Systemiq analysis (2025), based on Fossil Fuels in Transition (ETC, 2023); Chemicals: Planet Positive Chemicals Report (Systemiq, 2022, BAU Net-Zero scenario), and Systemiq (2024) Plastic Treaty Futures.; 1) Based on Systemiq reports – final number being refined.

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

Material and carbon circularity solution set

Technology-deep-dives

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

1 What are the **key levers** that could enable **higher circularity?**

What are the **techno-economics, limitations and barriers** to key **technologies?** 2

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CCU

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CCU will be a key source of sustainable CO2, but will require subsidies and convincing carbon pricing to scale

- The **source of CO2** is important as this **will determine the carbon intensity of downstream fuels/products**. Renewable/biogenic sourced CO2 is expected to be limited in the long-term. Air sourced CO2 will require DAC technologies, where costs are still high. Point source carbon capture may be able to fill the gap in demand.
- **Technology breakthroughs have the potential to change the evolving CCU landscape**. A range of CCU technologies are likely to improve over the next 5-10 years, e.g. developing new processes and catalysts that reduce capital/operating costs
- The **cost gap between fossil and CCU derived fuels/chemical** varies between CCU technologies and **can be significant.** Cost reductions in key inputs such as hydrogen and electricity will be needed.
- **Carbon pricing changes the economics along the value chain.** Emissions taxes push industries toward carbon capture, and selling CO_2 to offtakers (e.g., fuel producers) can be cheaper than storage. Meanwhile, fuel buyers (e.g., shippers) must balance high fuel prices with emissions taxes.
- If technologies do scale and acquire sufficient renewable/biogenic CO2 sources, then **key sectors** such as **chemicals for plastic, shipping and aviation** could be **supplied by circular carbon**.
- **Total demand for CCU** derived products is expected to be **small relative to CO2 capture** available (~27%).

The CCUS value chain can be split into four distinct stages

The CCUS value chain

Carbon Source → **Capture** → **Transport** → **End of Life** (**Storage** / **Utilization**)

Carbon Source	*Concentration range*	*Capture technology*	*Transport options*
Fossil **Non-fossil processes (e.g. cement)** **Bioresources** **Air**	• Blue hydrogen • Cement • Steel • Coal power • Bioenergy power • Bioenergy H_2 • Refineries • Gas power	• Liquid solvents & solid sorbents • Oxy-combustion • Membranes • Process modifications	• Pipeline • Ship • Truck • Rail

End of Life

> 1 Gt
- Depleted oil & gas fields
- Saline aquifers
- Mineralization

< 1 Gt

Long-term use (non-exhaustive):
- Concrete curing
- Aggregates
- Long life-time plastics, e.g. construction

Short-term use (non-exhaustive):
- Synfuels
- Low life-time plastics
- Food industry
- Fertiliser (urea)

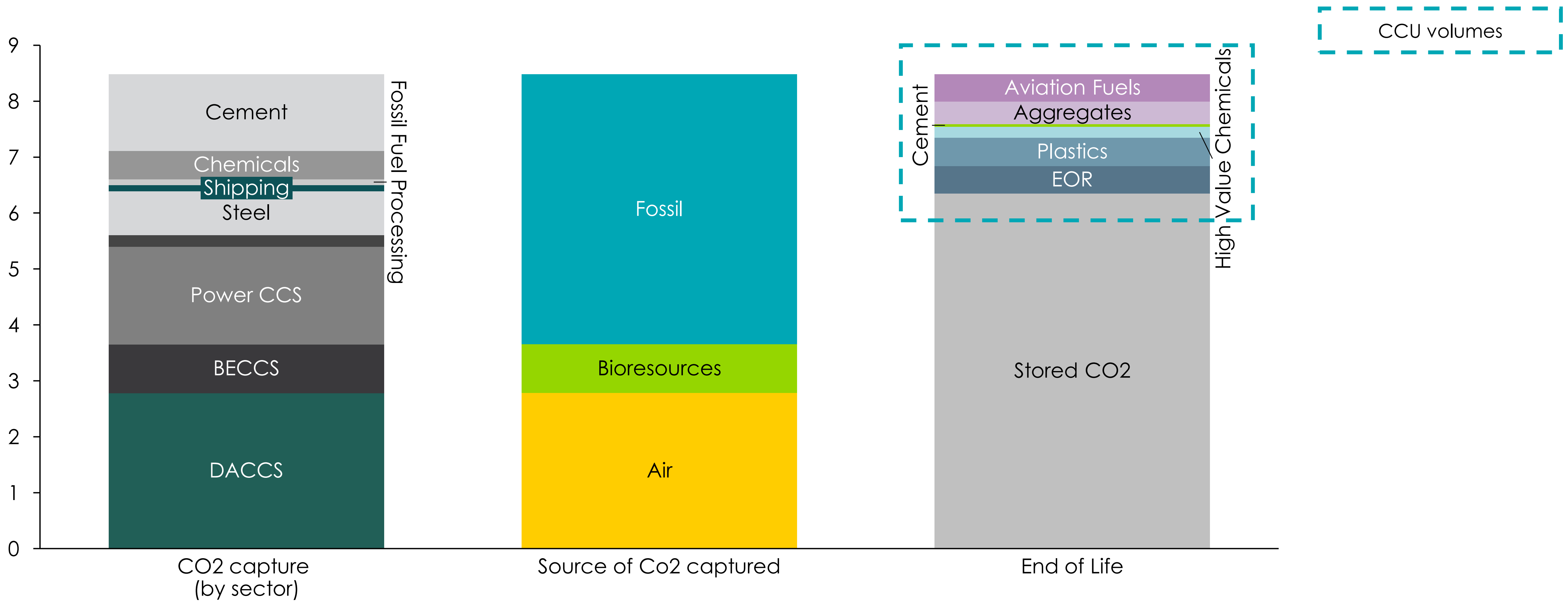
Source: Systemiq analysis for the ETC (2022)

We previously assumed that a majority of captured CO_2 would be sequestered in a net zero 2050, with a small range of utilisation end-use cases

ETC Analysis (2022)

CCUS volumes in 2050 under ACF Scenario

$GtCO_2$ p.a.



Note: 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. EOR = enhanced oil recovery. CCU = carbon capture and utilization. CCS = carbon capture and storage. DACCS = direct air carbon capture and storage. DACCU = direct air carbon capture and utilization. BECCS = bioenergy with carbon capture and storage. Note that the majority of point source CCS emissions will come from fossil processes and combustion, and industrial processes. 1) Point source CCU on bioresources can also offer net zero emissions

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

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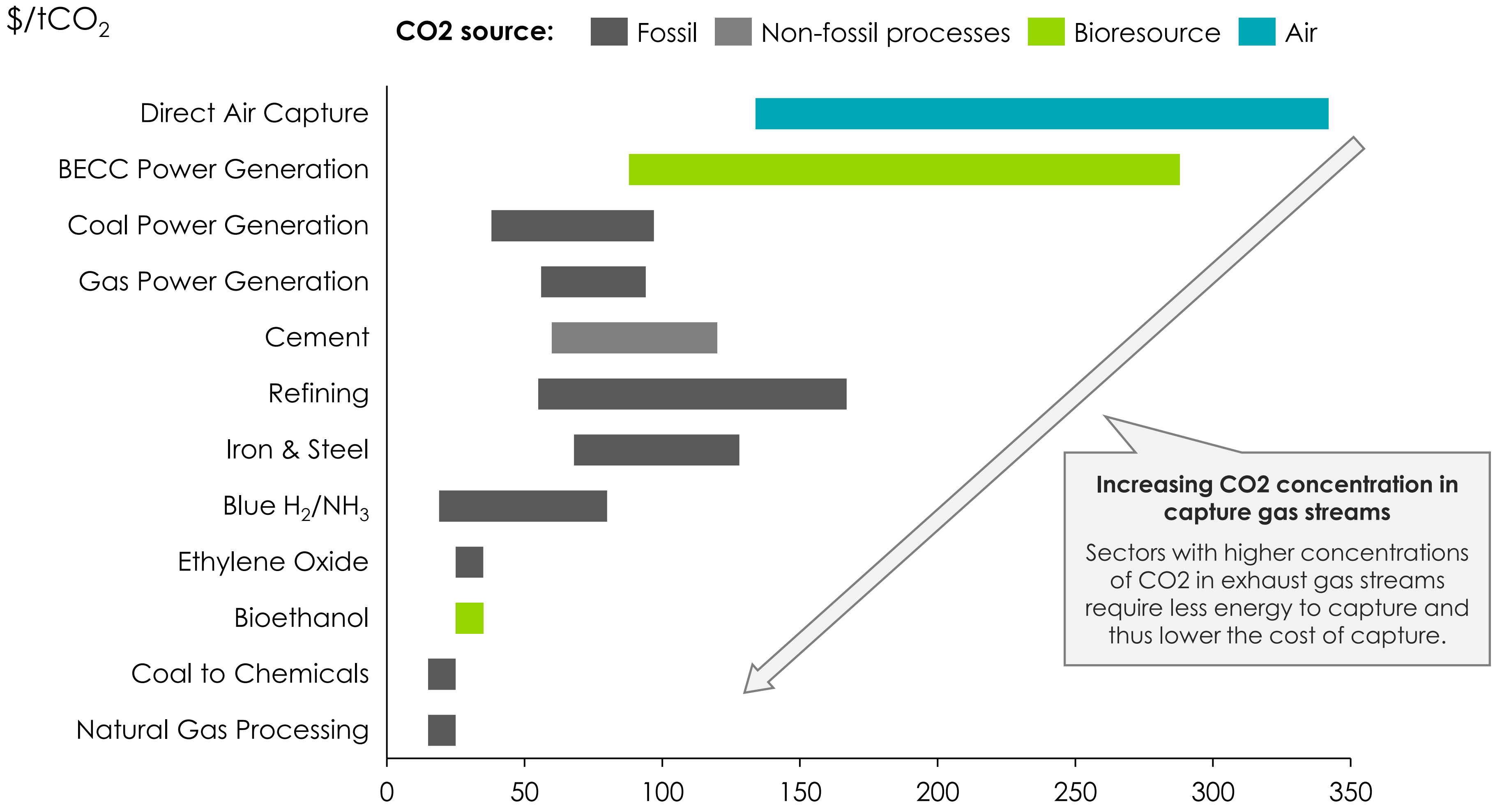
Costs of carbon capture vary widely by sector depending on CO2 concentration in capture gas streams

ETC Analysis (2022)
To revisit in Phase 3

Range of levelised cost of capture estimates by sector today



Air: high cost of capture today, although future cost reductions expected; unlimited availability

Bioresources: wide range of relative costs; limited availability of CO2 source in long-term

Non-fossil processes: average cost of capture; key industries deploying CCS technology (e.g. cement)

Fossil CO2 sources: low-to-average cost of capture; uncertainty of long-term viability

Notes: Coal to chemicals refers to methanol and ammonia.

Source: IEA (2017) CCUS in Clean Energy Transitions (2021), GCCSI (2017), Global costs of carbon capture and storage, IEAGHG (2014), CO_2 capture at coal-based power and hydrogen plants, Keith et al. (2018), A Process for Capturing CO_2 from the Atmosphere, NETL (2014), Cost of capturing CO_2 from Industrial sources, Rubin et al (2015), The cost of CO_2 capture and storage; Bloomberg NEF CCUS Costs and Opportunities for Long Term CO_2 Disposal (2021); Fuss et al (2018) 2018. Negative emissions—Part 2: Costs, potentials and side effects

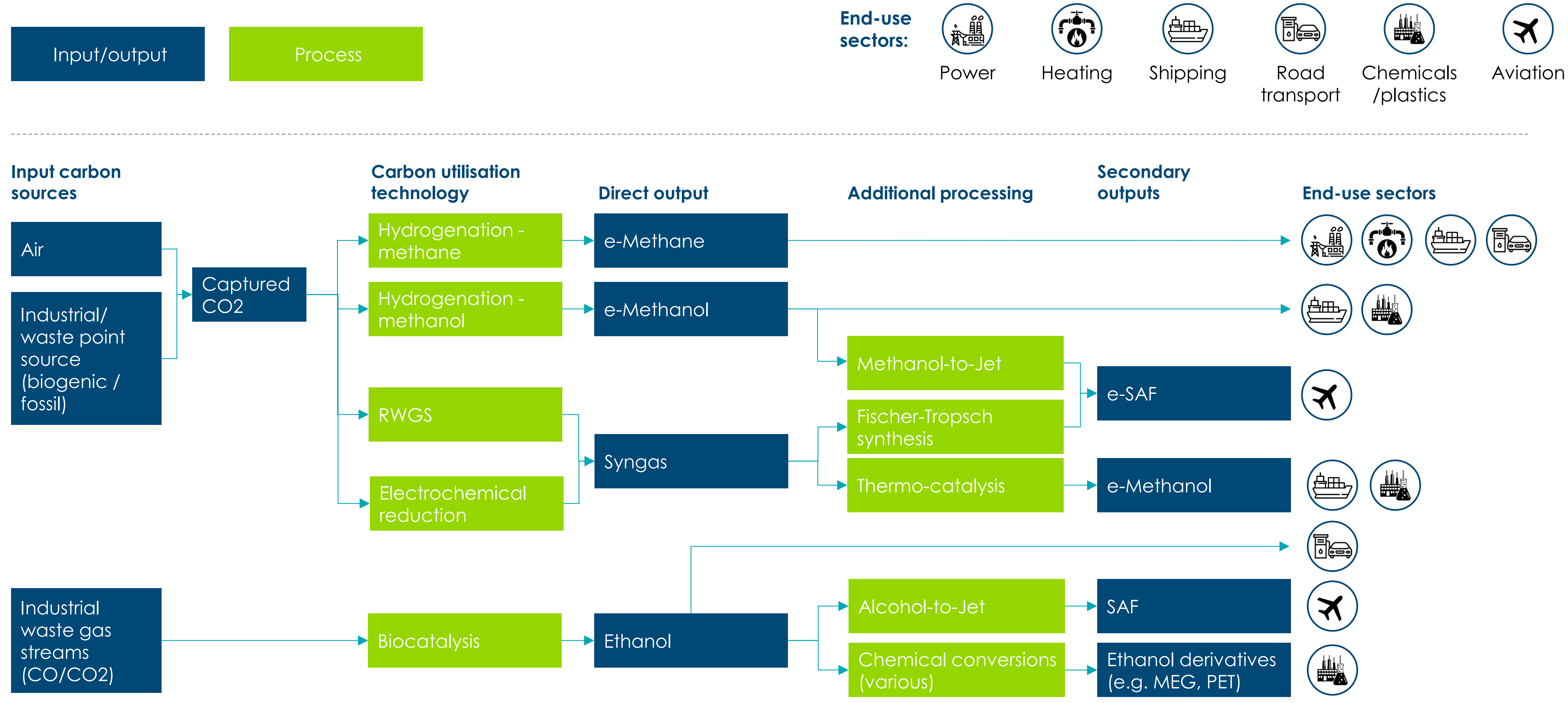
Our deep-dives will focus on CO2 utilization technologies which have reached or are nearing commercialisation

Focus of deep-dives (high TRL*)
*Technology Readiness Level

	Technology	Process	TRL	End-Use Sector[4]	Companies (Non-exhaustive examples)
1	**Hydrogenation to methane[1]**	CO_2 and H_2 catalytically react at high temperature and pressure to produce methane and water	7-8	Heating, Power Generation, Road Transport	IHI, MAN Energy Solutions, thyssenkrupp
2	**Hydrogenation to methanol**	CO_2 and H_2 catalytically react at high temperature and pressure to produce methanol and water	7-8	Shipping, Chemicals, Aviation	Johnson Matthey, Carbon Recycling International, TOPSOE
3	**Reverse Water Gas Shift (RWGS)**	CO_2 and H_2 catalytically react to produce syngas, which can be further processed to produce other fuels/chemicals	7-8	Chemicals, Aviation, Shipping, Road Transport	OXCCU[5], MAN Energy Solutions, Johnson Matthey, Shell
4	**Electrochemical reduction**	Electrolyser reduces CO_2 to CO, which is either used in syngas or reacted with H_2 to produce other derivative fuels/chemicals	5-9[2]	Chemicals, Aviation, Shipping, Road Transport	twelve, sunfire, TOPSOE
5	**Biocatalysis**	Selective biocatalytic enzymes convert waste gases into ethanol, which can then be used to produce other fuels/chemicals	8-9[3]	Road Transport, Chemicals, Aviation	LanzaTech, synata bio
	Plasma-catalytic treatment	High-energy plasma is utilised to break down captured CO_2 into CO, used with H2 as syngas to produce fuels/chemicals	3-5	Chemicals, Aviation, Shipping, Road Transport	ArcelorMittal (*Pilot project at steel plant*) + D-CRBN (*Technology provider*)

Sources/Notes: 1) Also known as methanation or the Sabatier Process. 2) TRL 5-9 for the production of carbon monoxide (also for production of formate). TRL 5-6 for low-temperature aqueous electrolyte systems and TRL 8-9 for high-temperature solid oxide electrolysers. Note that other products are possible with electrochemical reduction (e.g. methanol, ethanol, ethylene), although these technologies are ~ TRL 3. (CIT Renergy, 2024). 3) TRL 8-9 refers to technologies converting CO2 to ethanol (e.g. LanzaTech operating commercial facilities since 2018). Lower TRL (~3-5) would apply for different conversion routes such as biocatalytic conversion to methanol. 4) Including potential for further processing of technology's direct output (e.g. conversion of methanol to jet fuel). 5) OxCCU is also developing a single-step CO2 to fuel Fischer-Tropsch pathway (lower TRL).

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



Source: ETC and Systemiq analysis (2025)

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1/2 E-methane/-methanol production via catalytic hydrogenation offers high conversion efficiency and operational scalability for a range of use cases

Overview – catalytic hydrogenation

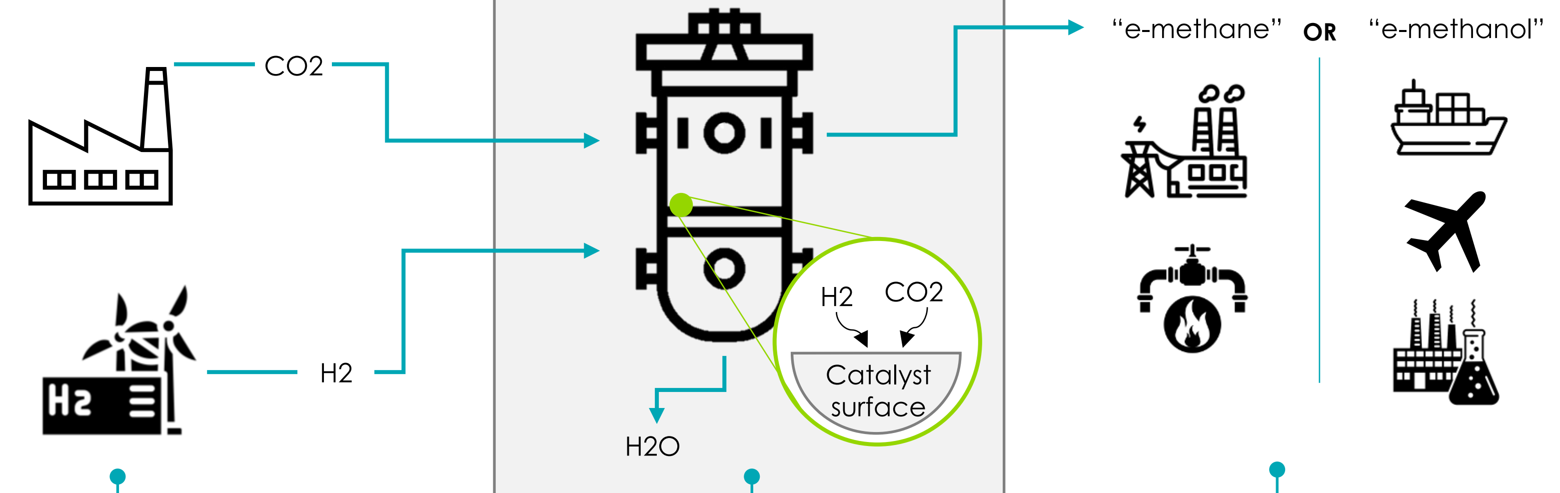
- **Current TRL**: 7-8[1], commercial projects and first-of-a-kind projects being launched in late 2020s[2,3]
- **Challenges:** securing long-term offtake from downstream sectors and sufficient volumes of sustainable CO_2 sources

Advantages

- **High conversion rates:** optimized catalysts are able to ensure maximum feedstock utilization[4]
- **Operational scalability:** conversion and reactor technologies able to designed for a wide range of operating capacities
- **Material availability:** catalysts are typically made with common/inexpensive materials (e.g. nickel, copper) and not precious metals

Simplified Process Diagram

Focus of tech deep-dive



Input Feedstocks:
Hydrogen is produced and CO_2 is captured, both of which are fed as pure input streams into the catalytic hydrogenation reactor.

Catalyst Reactor:
Specific temperature / pressures and selective catalysts are used to produce desired products (e.g. typically copper-based catalyst for methanol).

Output & Applications:
Methane (from methanation) can be utilised in natural gas applications (e.g. power, heating) whereas methanol can be directly used in shipping/chemicals or further processed to produce jet fuel.

Sources/Notes: 1) CCUS Technology Innovation (IEA). 2) Ren-Gas selects MAN Energy Solutions' methanation technology for its Tampere e-methane plant (Jan 2025). 50MW_{el} with commercial operation in 2027. 3) Johnson Matthey technology selected for one of the largest planned e-methanol plants in Europe (Jan 2025). 140kt/year, expected to come online in 2027. 4) For example, Johnson Matthey claims ~99% carbon / hydrogen efficiency with eMERALD™ CO_2 to methanol technology (Johnson Matthey)

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3 Reverse Water Gas Shift (RWGS) technology offers operational scalability and the versality of converting syngas to other fuels and chemicals

Overview - RWGS

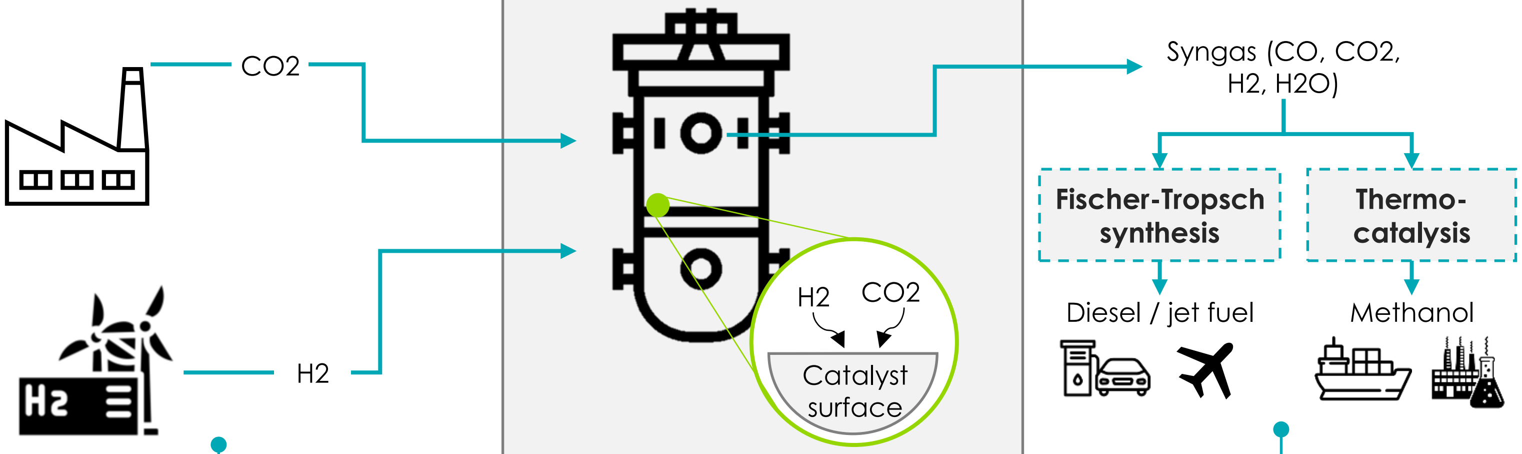
- **Current TRL:** 7-8, demonstration and pilot projects underway; multiple technology developers active[1]
- **Challenges:** high energy input to main high temperatures (typically 600-900°C); development of efficient/stable catalysts

Advantages

- **Established technology:** well-studied materials and process conditions to produce desired syngas specifications
- **Output versatility:** syngas produced via RWGS is a crucial building block for the synthesis of fuels and chemicals, such as methanol and Fischer-Tropsch fuels
- **Operational scalability:** conversion and reactor technologies able to designed for a wide range of operating capacities

Simplified Process Diagram

Focus of tech deep-dive



Input Feedstocks: Hydrogen is produced and CO2 is captured, both of which are fed as pure input streams into the catalytic RWGS reactor.

RWGS Catalytic Reactor: Specific temperature / pressures and selective catalysts (e.g. copper, platinum, rhodium) are used to produce syngas.

Output & Applications: Syngas can then be converted with further processing steps to other products (e.g. jet fuel, diesel, methanol)

Sources: Transforming CO2 to valuable feedstocks - Emerging catalytic and 2 technological advances for the reverse water gas shift reaction (Triviño et al, 2023)
Notes: 1) For example, Shell and MAN Energy Solutions pilot plant in 2023; OxCCU's OXESYN™ technology; Johnson Matthey's HyCOgen™ technology.

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4 Commercial electrochemical reduction of CO2 offers high product selectivity & purity of CO, with low-temperature electrolysis under development

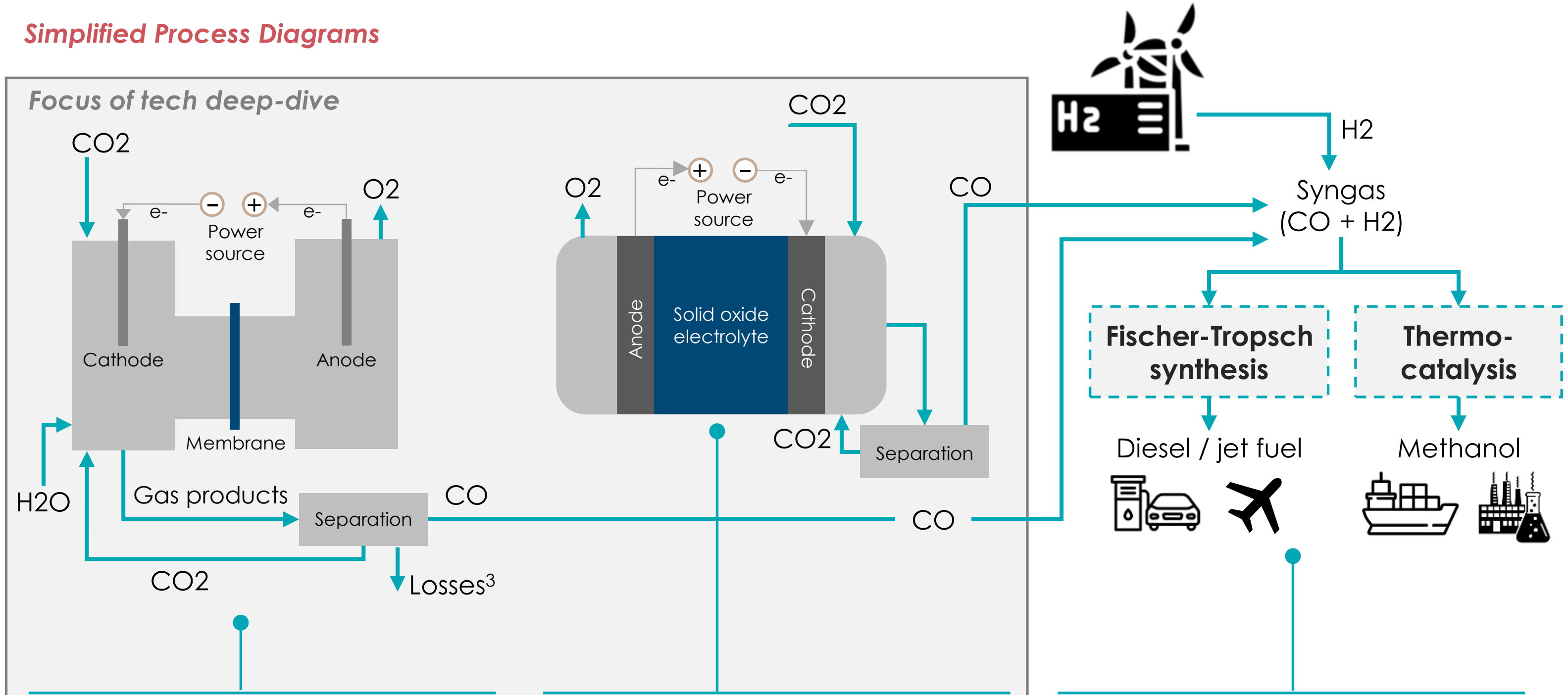
Overview - electrochemical reduction

- **Current TRL (low-temperature electrolysis):** 5-6, to produce CO with low-temperature aqueous electrolyte systems
- **Current TRL (high-temperature electrolysis):** 8-9, to produce CO with Solid Oxide Electrolyzer Cells (SOECs)[2]
- **Challenges:** high energy demand, electrolyte degradation, reactor sealing (specific to SOECs), carbonate formation[1]

Advantages

- **High CO purity:** outputs are up to 99.995% CO purity[2]
- **Low energy consumption (low-temp. electrolysis):** ability to operate under mild conditions (~ambient pressures and temperatures)
- **Operational flexibility:** modularity of the technology enables flexibility of operating individual stacks under varying load

Simplified Process Diagrams



Electrochemical reduction (low-temperature): Aqueous-based electrolyser converts CO2 to CO. Different cell configurations are possible (e.g. H-type cells, flow cells, and membrane electrode assemblies).

Electrochemical reduction (high-temperature): Solid oxide electrolyser cell (SOEC) converts CO2 to CO. Temperatures reach up to 600-800°C to drive process efficiency, powered by an external electricity source.

Output & Applications: CO can be mixed with hydrogen to produce syngas, which can then be converted with further processing steps to other products (e.g. jet fuel, diesel, methanol)

Sources: CO2 conversion to CO via plasma & electrolysis: a techno-economic & energy cost analysis (Osorio-Tejada et al., 2024); Electrochemical reduction of CO2 (CIT Renergy, 2024). Notes: 1) Carbonates may precipitate in salt form and block the catalyst surface at the cathode. Carbonate ions may also transfer to the anode, reacting back to CO2 and leading to lower carbon efficiencies. 2) For example, Topsoe eCOs™ technology. 4) Trace amounts of CO2/CO/H2.

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5 Commercial biocatalysis technology offers a versatile and efficient route for production of ethanol and its fuel/chemical derivatives

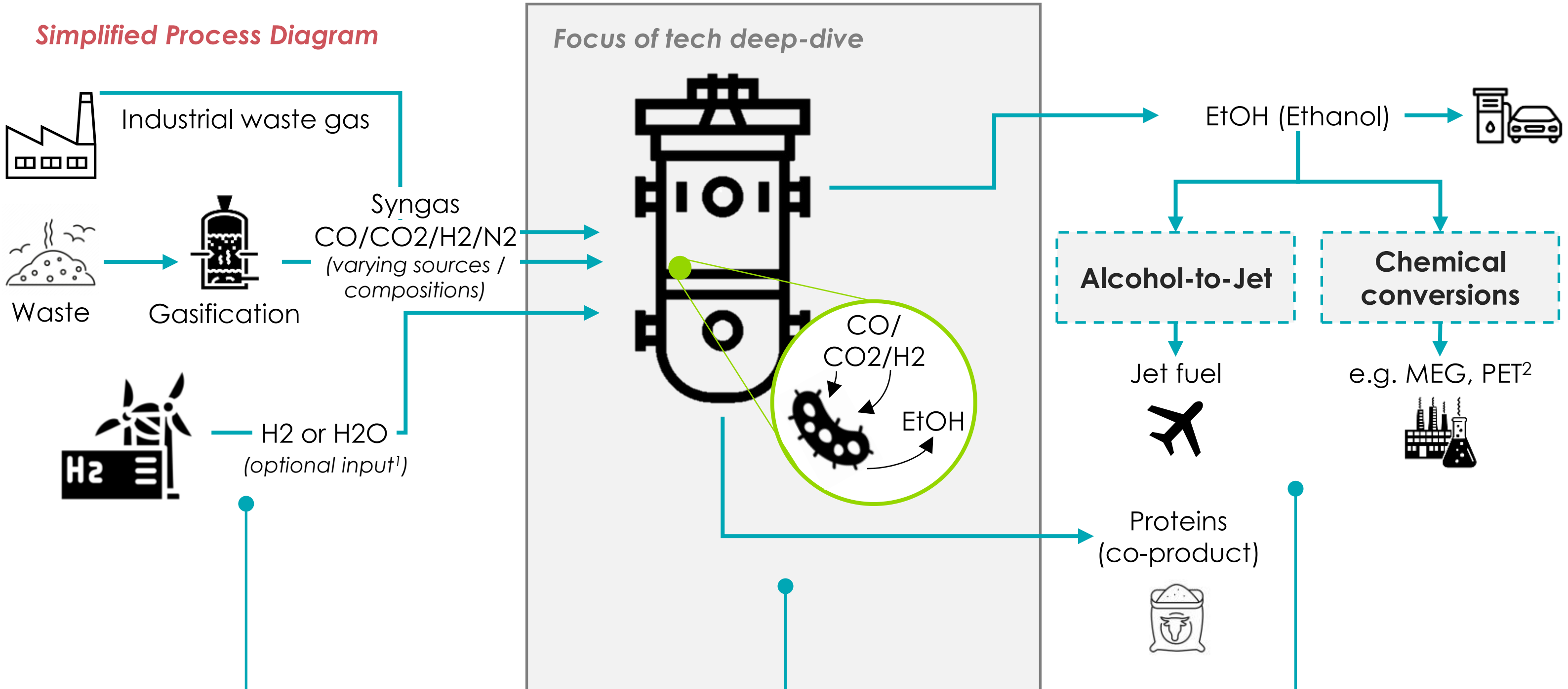
Overview - Biocatalysis

- **Current TRL:** 8-9, commercial facilities converting CO_2 to ethanol have been operating since 2018[3]
- **Challenges:** effective removal of contaminants and refinement of microbial strains for varying input gas streams

Advantages

- **Input gas versatility:** some biocatalysis processes (e.g. LanzaTech[1]) can handle a wide range of gas compositions
- **Minimal feedstock treatment:** some waste / industrial off gas streams (e.g. steel) may not require CO_2 capture deployment
- **Operational scalability:** conversion and reactor technologies able to designed for a wide range of operating capacities

Simplified Process Diagram



Input Feedstocks:
Syngas is captured from industrial emissions/waste gasification, with varying compositions of CO_2, CO and H_2 depending on the source. Additional H_2 or H_2O input may be required.[1]

Biocatalysis / Fermentation Reactor:
Selective and proprietary catalytic microbes are used to convert input syngas into ethanol and other co-products (e.g. protein).

Outputs & Applications:
Ethanol can be used directly in road transport or converted to sustainable jet fuel or chemical derivatives. Protein co-products can be used for animal feed.

Sources: Waste to Energy Workshop - Sean Simpson LanzaTech (BETO, 2017); Waste Flue Gas CO to Innovative Biofuel Production (2012)

Notes: 1) LanzaTech's gas fermentation process can use gas streams with flexible CO and H2 input gas ratios. If there is zero/low H2 in the gas feed, the proprietary fermentation microbe can make H2 from CO and H2O as required via the biological water gas shift reaction. 2) MEG = monoethylene glycol, PET = polyethylene terephthalate. 3) LanzaTech has 6 operating commercial facilities since 2018. Lower TRL (~3-5) would apply for different conversion routes such as biocatalytic conversion to methanol.

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CCU techno-economics and projects vary by their distinct advantages and operational challenges

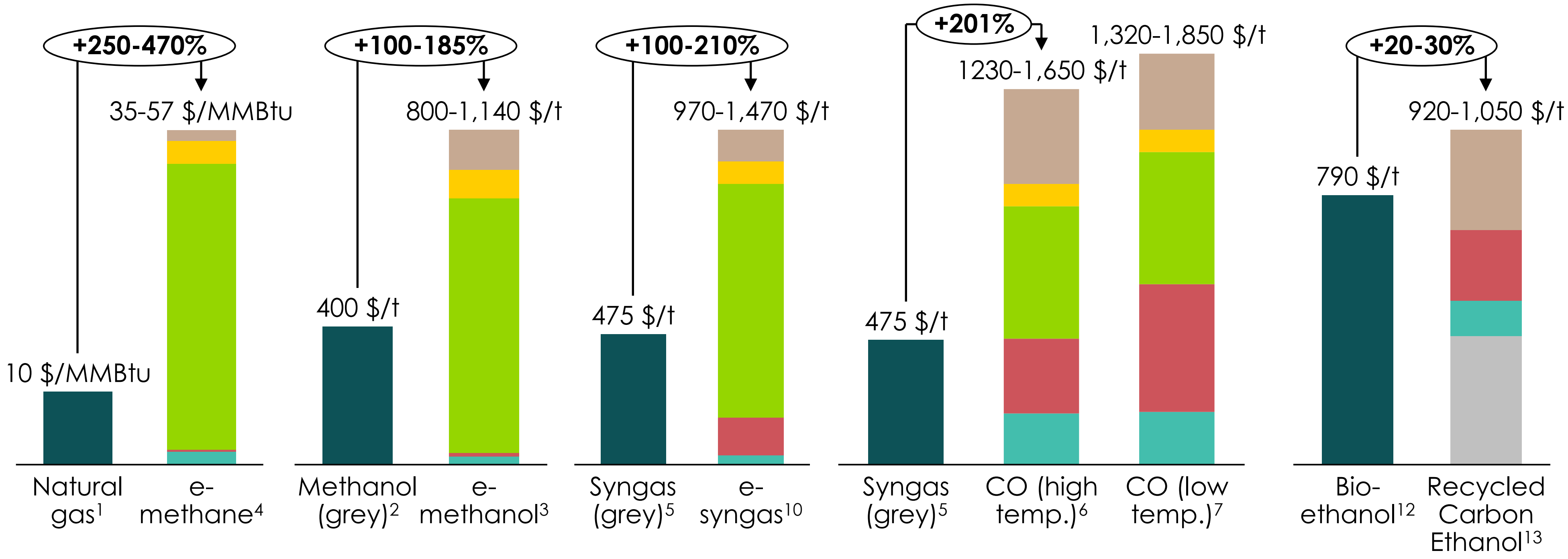
	Hydrogenation (Methane)	Hydrogenation (Methanol)	Electrochemical Reduction (CO, Syngas)	RWGS (Syngas)	Biocatalysis (Ethanol)
Advantages	• Optimized catalysts are able to ensure **high conversion rates** • Technologies **can be scaled** to a wide range of operating capacities • Catalysts are made with common/inexpensive materials[1]		• **High CO purity:** outputs are up to 99.995% CO purity • Technology is modular • Dependent on H2 for syngas	• **Well-established technology** • Many applications for syngas	• Depending on feedstock, **minimal treatment can be needed**[2] • Technologies can be scaled to a wide range of operating capacities
Challenges	• High costs - **dependent on H2 input** • Current projects are **struggling to reach long-term offtake**		• **High energy use** • **Electrolyte degradation**, leaks, and **byproduct accumulation**	• **High energy use** for heating (600-900°C) • Development of efficient/stable catalysts	• Effective removal of **contaminants**[2] • **Refinement of microbial strains** for varying input gas streams

Notes: 1) e.g. nickel, copper 2)Dependent on feedstock. Some industrial waste gases can be processed with minimal treatment, but removal of contaminants remains an issue.
Sources: Techno-economic and life cycle analysis of synthetic natural gas production from low-carbon H2 and point-source or atmospheric CO2 in the United States (Lee et al., 2024); EU PtX modelling (MPP, 2024); Planet Positive Chemicals (Systemiq, 2022); Performance and Cost Analysis of Liquid Fuel Production from H2 and CO2 Based on the Fischer-Tropsch Process (Zang et al, 2021); E-Fuels: A techno-economic assessment of European domestic production and imports towards 2050 (Soler et al, 2024); Life cycle assessment of ethanol production from silicomanganese alloy off-gas (Carbotech, 2024); Life cycle assessment of ethanol production from BOF gas (Carbotech, 2023); NEPIC Conference (LanzaTech, 2016)

Hydrogenation competitiveness driven by high costs of hydrogen production; electrochemical reduction driven by high capex and electricity requirements

Levelised cost of prod. $/unit output (2030) | **Hydrogenation to Methane** | **Hydrogenation to Methanol** | **RWGS** | **Electrochemical Reduction** | **Biocatalysis**

- Counterfactual fuel
- Capex
- CO2 feed
- H2 feed
- Electricity
- Other Opex
- Syngas feed[11]



Key inputs

CO2 cost[8]	$60/tCO2
Green H2 cost[9]	Low: ~$3/kg High: ~$5/kg
Electricity cost[9]	Low: ~$40/MWh High: ~$80/MWh

Key takeaways on cost drivers and trends

- Cost of hydrogenation/RWGS driven by cost of renewable hydrogen; CO2 cost not a significant factor
- Catalytic reactor technology not expected to realise major capex cost reductions in future given high TRL established technologies
- Costs driven by high capex electrolysers / cost of electricity
- Low temperature systems (TRL 5-6) are less efficient than high temperature systems (TRL 8-9)
- Costs driven by high capex / syngas feed
- Marginal cost premium against existing bioethanol applications

Sources/Notes: 1) Ten-year historical mean of EU Natural Gas TTF. 2) 20-year historical mean (Methanex). 3) EU PtX modelling (MPP, 2024). 4) "E-methane: a new gas for a net-zero future? (IEA, 2024)"; Lee et al, 2024. 5) Assumed cost for grey syngas (steam reforming) utilised for Fischer-Tropsch synthesis of fuels (2:1 H2:CO ratio). 6) Detz et al., 2023 . 7) CIT Renergy, 2024; Osorio-Tejada et al., 2024. 8) Cost of CO2 capture from an industrial point source. 9) Assumes baseload PPA power. Lower: ES, upper: DE. 10) Project SkyPower e-SAF modelling (Systemiq, 2024). 11) Cost of syngas feed (industrial waste gas) based on equivalent displaced energy with natural gas. 12) Conventional ethanol from corn (IRENA). 13) Capex from LanzaTech (EIC presentation, 2022; IEA Bioenergy, 2020)

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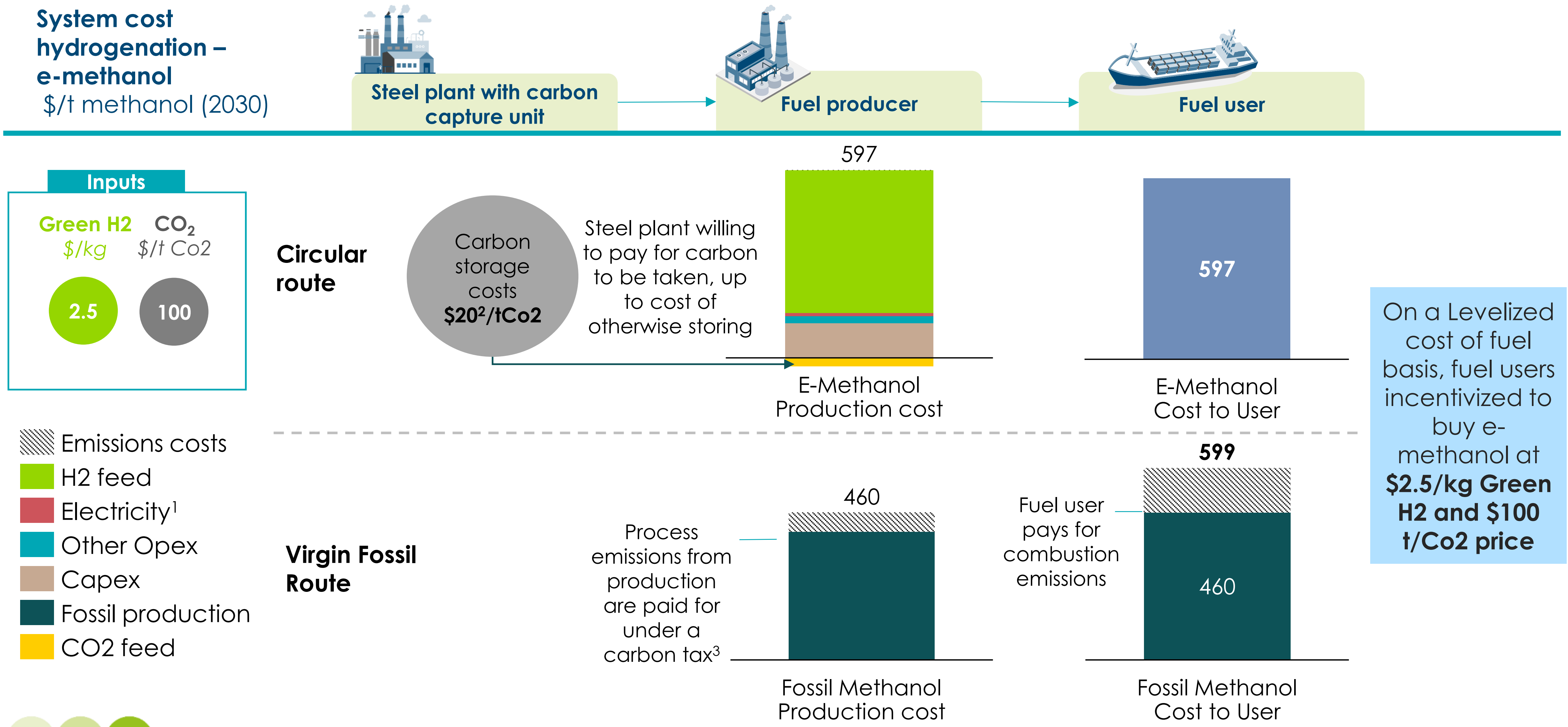
Scenario: A combination of a carbon price and lower H2 prices will allow utilization technologies to become competitive with fossil

Illustrative

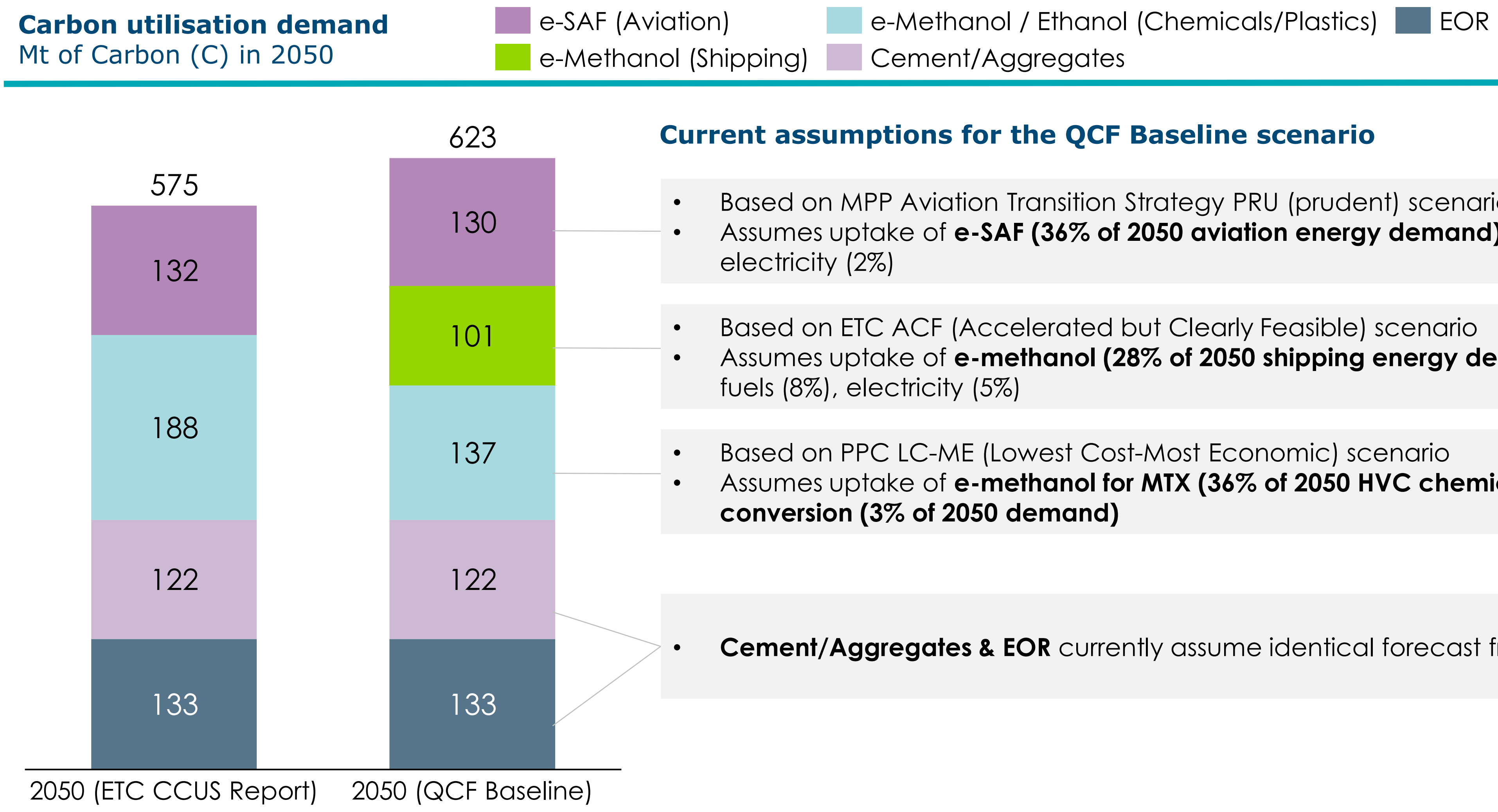


Source: Systemiq Analysis based on Planet Positive Chemicals (Systemiq, 2022), Carbon Footprint of Methanol (Methanol Institute, 2022). 1) Electricity cost of $60/MWh 2) Cost of storage based on CCUS, ETC, 2022). 3) Process emission based on Methanol Institute 2022, small amount of emission are assumed for the e-methanol route based on power use from a decarbonized grid in Europe. Other cost assumptions on previous slide

SYSTEMIQ

The previously assumed maximal potential for CCU could be raised by uptake of e-methanol fuel applications

Carbon utilisation demand
Mt of Carbon (C) in 2050



Current assumptions for the QCF Baseline scenario

- Based on MPP Aviation Transition Strategy PRU (prudent) scenario
- Assumes uptake of **e-SAF (36% of 2050 aviation energy demand),** bio-SAF (49%), hydrogen (13%), electricity (2%)

- Based on ETC ACF (Accelerated but Clearly Feasible) scenario
- Assumes uptake of **e-methanol (28% of 2050 shipping energy demand),** ammonia (59%), fossil fuels (8%), electricity (5%)

- Based on PPC LC-ME (Lowest Cost-Most Economic) scenario
- Assumes uptake of **e-methanol for MTX (36% of 2050 HVC chemicals demand)** and **ethanol conversion (3% of 2050 demand)**

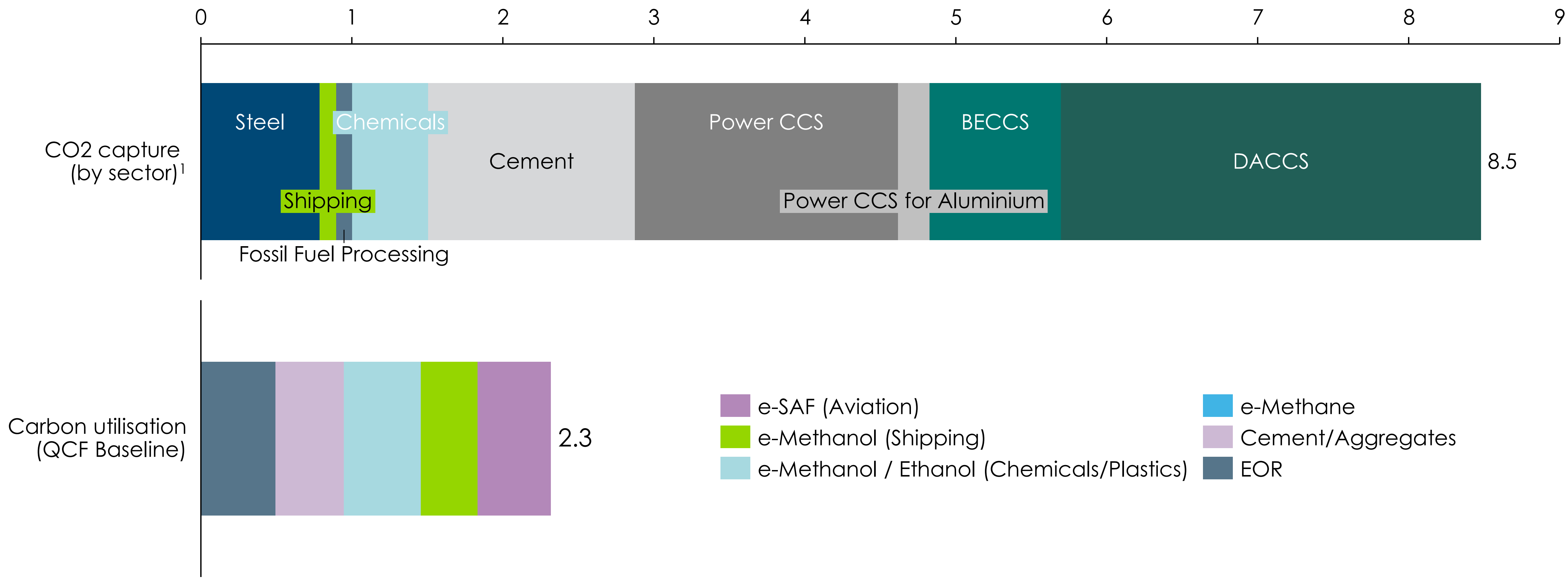
- **Cement/Aggregates & EOR** currently assume identical forecast from ETC CCUS Report

HVC = High Value Chemicals; EOR = Enhanced Oil Recovery; MPP = Mission Possible Partnership; PPC = Planet Positive Chemicals

By 2050, volumes of carbon required for utilisation may only take up a small portion (~27%) of all carbon capture in the economy

Carbon capture and carbon utilisation volumes in 2050

$GtCO_2$ p.a.



EOR = enhanced oil recovery. CCU = carbon capture and utilization. CCS = carbon capture and storage. DACCS = direct air carbon capture and storage. DACCU = direct air carbon capture and utilization. BECCS = bioenergy with carbon capture and storage.

Note: 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.

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

SYSTEMIQ

Techno-economics of CCU technologies and product offtake potential in different markets will be the driving factors for scale-up

		Hydrogenation to Methane	Hydrogenation to Methanol	RWGS	Electrochemical Reduction	Biocatalysis
What you need to believe for technology to scale	A business case within range of fossil	• Falling price of hydrogen reduces LCOX of product(s) • Raising carbon price reduces the green premium			• Learning rates for electrolysers for reduced capex • Sourcing of low-cost /renewable electricity	• Abundant and low-cost sourcing of industrial carbon waste gas feedstocks
	Offtaker markets ready	• Compliance market for e-methane and e-LNG in heating and transport emerges	• SAF + shipping blending mandates drive offtake of e-SAF and e-methanol • High carbon pricing and regulation pushes plastic production to low-carbon feedstocks			• SAF mandates • Sustained demand for low-carbon ethanol in road transport/plastics
Key takeaways		• **Reducing the green premium via reducing the cost of green H_2 or raising the carbon price is the largest factor impacting cost-competitiveness of production routes** • **Scale-up is highly dependent on demand / willingness-to-pay in end-use markets (aviation, shipping, chemicals)**				• **Suitable carbon feedstock sourcing may limit scale-up over long-term**

Agenda

- Introduction to work program
- The case for carbon efficiency
- Reduce and recycle material
- Recycling carbon
- **High circularity scenario**
- Barriers and the policy landscape

High circularity scenario

We have estimated the maximum impact of circularity levers by sector

		Assumptions – change by 2050	Source
Reduce demand	Reduce, reuse	**Chemicals**: ~30% demand reduction from eliminate + reuse	Plastic Treaty Analysis, Global Rules Scenario, aligned with PPC
	Substitution	**Chemicals**: ~10% demand reduction in plastic goods **Wood, pulp and paper:** ~15% increase due to substitution of plastic packaging and from concrete/steel to timber	**Chemicals**: Planet Positive Chemicals **Pulp and Paper**: Systemiq analysis based on Planet Positive Chemicals **Wood**: Systemiq analysis of FAO data (wood)
	Sortation	**Chemicals**: ~ 57% sortation by 2040 (from 8% today)	Plastic Treaty Analysis, Global Rules Scenario
Recycle material	Mechanical Recycling	**Chemicals**: ~ 40% of plastic recycled by 2050 **Pulp and paper**: ~ 85% packaging recycled by 2050, ~ 40% other **Wood**: ~ 25% recycling of recovered wood to particle board **Glass**: 70%	**Chemicals**: Plastic Treaty Analysis, ReShaping Plastics **Pulp and Paper**: Systemiq analysis based on EU targets[1] **Wood**: Systemiq analysis based on corporate targets[2] **Glass**: Systemiq analysis based on EU targets[3]
Recycle carbon	Chemical Recycling	**Chemicals**: ~ 4% - 20% of plastic waste recycled by 2050	Plastic Treaty Analysis, Global Rules Scenario ReShaping Plastics
	CCU	~ 58% used for **energy** ~ 20% used for **chemicals** Rest used for cement/aggregates	Systemiq analysis based on ETC CCUS reports, MPP data, and Planet Positive Chemicals

Sources: Plastic Treaty Future (Systemiq, 2024), Planet Positive Chemicals (Systemiq, 2022), Carbon Capture, Utilisation and Storage in the Energy Transition (ETC, 2022). 1) EU Packaging and Packaging Waste Directive targets 85% of paper packaging recycling by 2030 2) IKEA targets 30% of recycled wood by 2030 3) the PPWD mandates 75% of glass packaging to be recycled, and the Waste Framework Directive mandates 70% recycling of construction materials

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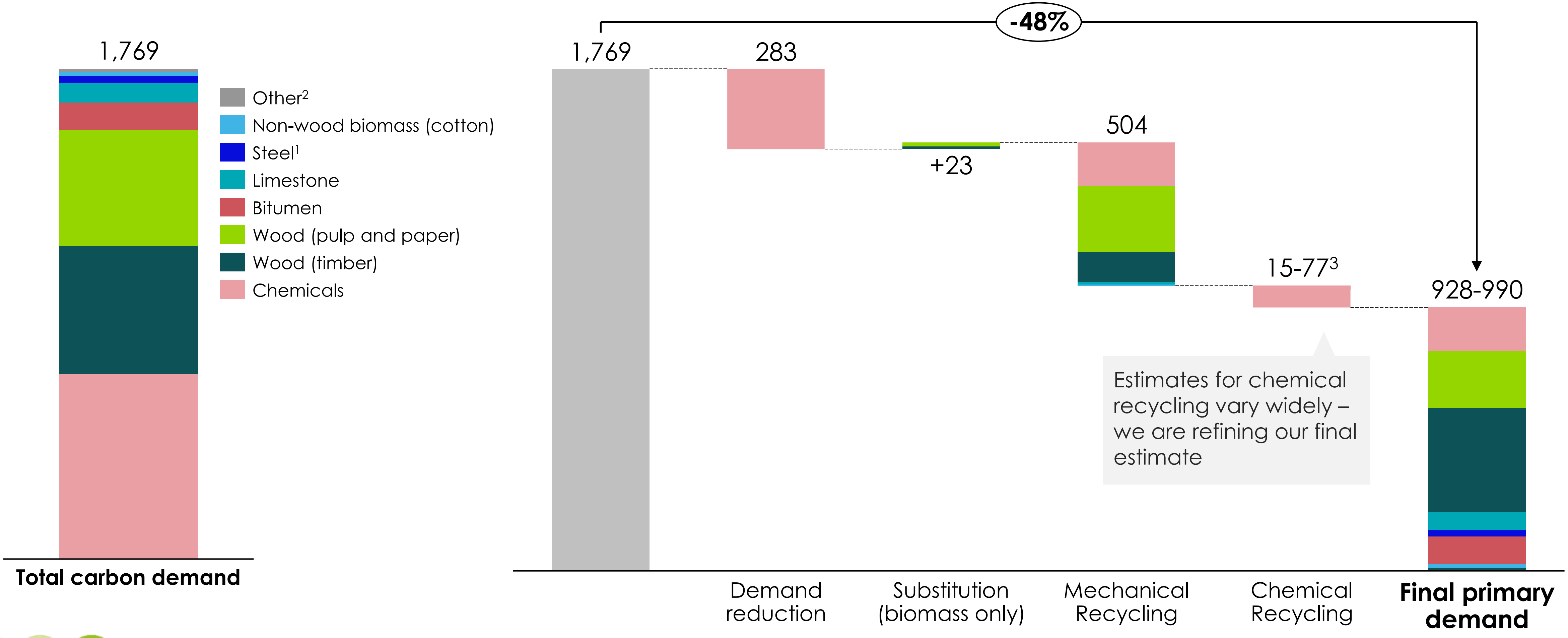
For materials sectors, the largest potential to recycle and reuse materials comes from mechanical recycling

Preliminary

Carbon recycling potential in the Materials Sector, 2050

Million tons of carbon (C)



Sources: Energy: Systemiq analysis (2025), based on Fossil Fuels in Transition (ETC, 2023); Chemicals: Planet Positive Chemicals Report (Systemiq, 2022, BAU Net-Zero scenario), and Systemiq (2024) Plastic Treaty Futures.; 1) Chemicals and steel includes the feedstock from the energy system that has remained in the material, i.e. plastic. 2) Other includes carbon ash, biochar, carbon fibre, charcoal 3) Based on range in Systemiq reports.

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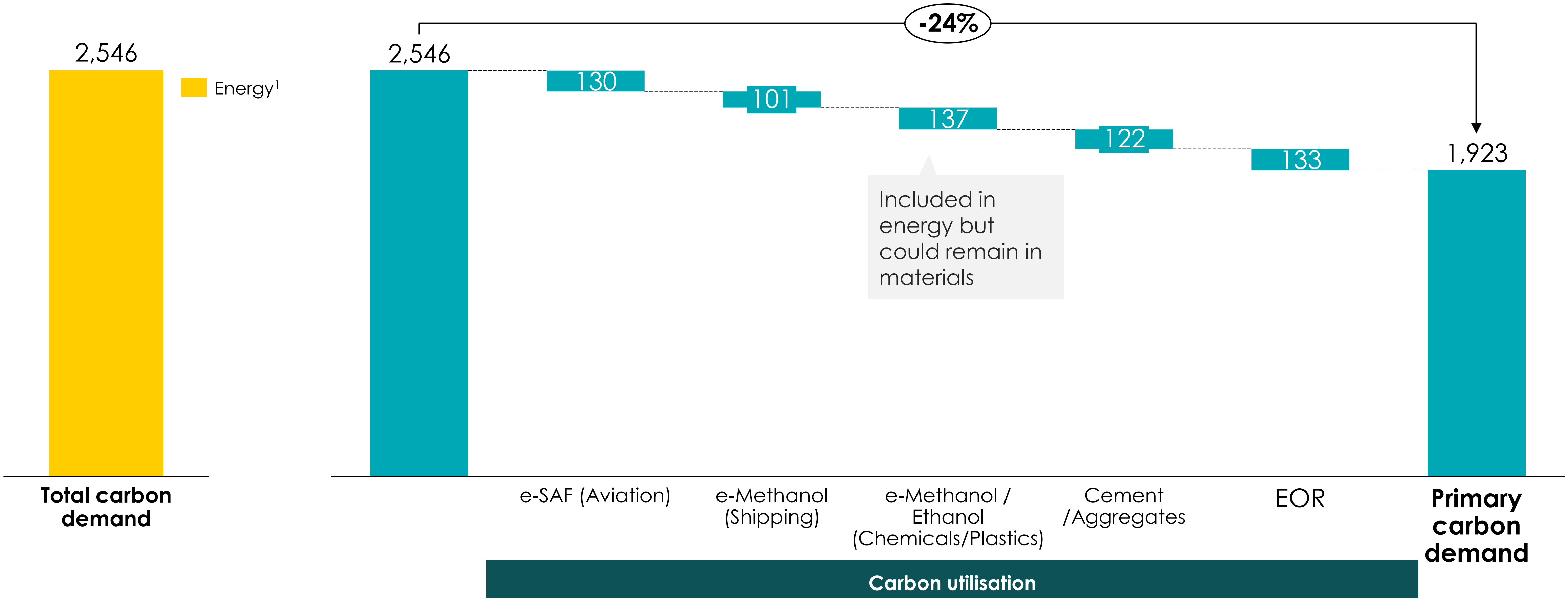
CCU is the main lever for the remainder of carbon usage in the energy sector

Preliminary

Carbon utilization potential from enery sector Carbon, 2050

Million tons of carbon (C)



Sources: Energy: Systemiq analysis (2025), based on Fossil Fuels in Transition (ETC, 2023); Chemicals: Planet Positive Chemicals Report (Systemiq, 2022, BAU Net-Zero scenario), and Systemiq (2024) Plastic Treaty Futures.; 1) Excludes energy feedstocks used that remain in steel and chemicals, which are included in materials potential recycling

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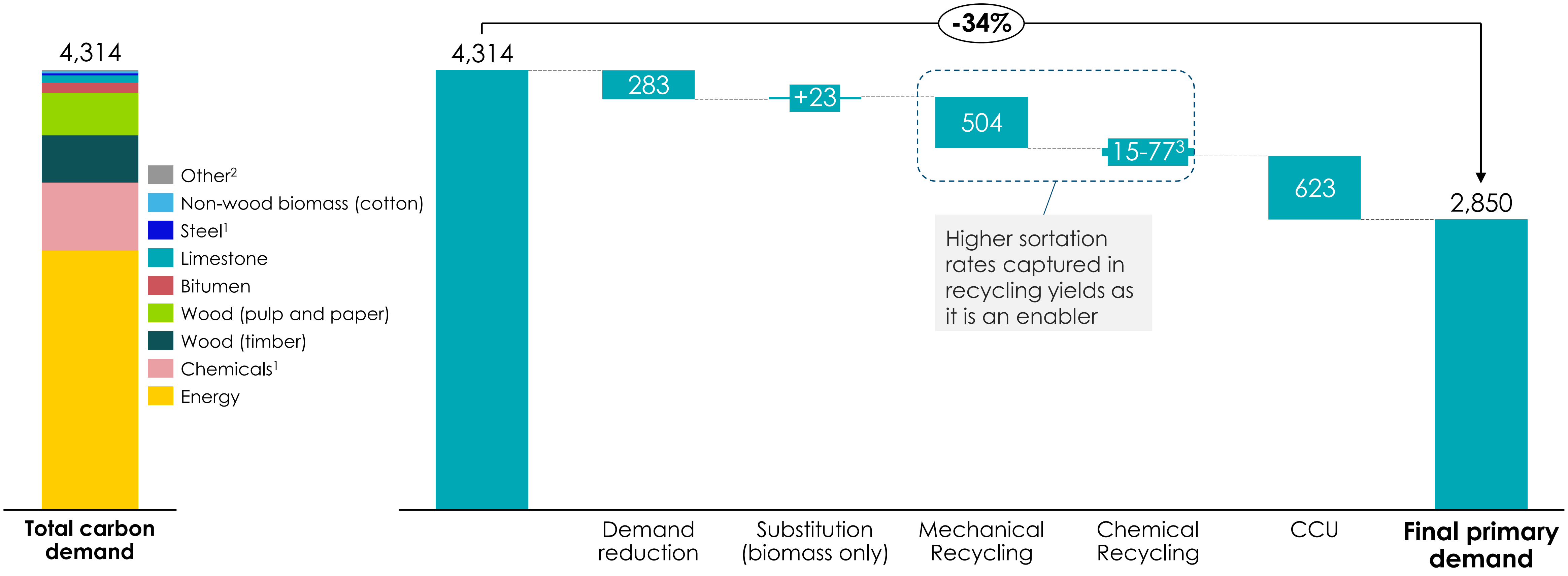
Stretch scenario: taken together, these levers could reduce primary demand for carbon in 2050 by a third

Preliminary

Carbon Demand Across the Energy and Material Sectors, 2050

Million tons of carbon (C)



Sources: Energy: Systemiq analysis (2025), based on Fossil Fuels in Transition (ETC, 2023); Chemicals: Planet Positive Chemicals Report (Systemiq, 2022, BAU Net-Zero scenario), and Systemiq (2024) Plastic Treaty Futures.; Biomass: ETC Bioresources report (2021); Steel: MPP STS (2022); Cotton, Bitumen and Soda Ash: Systemiq analysis (2025) Notes. 1) Chemicals and steel includes the feedstock from the energy system that has remained in the material, i.e. plastic. 2) Other includes carbon ash, biochar, carbon fibre, charcoal) Based on range in Systemiq reports.

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SYSTEMIQ

While there are technological limitations, the main barriers to scaling circularity are systemic and economic

Economic

- Cheap and abundant fossil
- No consequences to end of life emissions
- Prioritization of consumer marketing/preferences above environmental impacts
- End-sector use markets scaling, e.g. SAFS
- Export of waste to regions with lower environmental standards

Technology barriers

- Immaturity and complexity of new technologies
- Fundamental performance limitations – e.g. feedstock

Organization/legislative

- Lack of infrastructure (e.g. global south waste collection infra)
- Inadequate legislation and enforcement
- Opacity in the system making it hard to make decision
- Regulation is setting increasingly stringent requirements for feedstocks and output (e.g. food grade plastic standards)

Source: Systemiq analysis.

New and upcoming policies could help overcome certain barriers, but they are very localised and included limited enforcement mechanisms

Italic: still under discussion

Making linearity more expensive	Under the **Extended Producer Responsibility framework, countries can** hold producers accountable for the entire lifecycle of their product. Italy, the United Kingdom, and Spain established **a plastic tax under EPR.** *Carbon pricing, such as the **EU ETS**, increases the cost of fossil production and may be extended to incineration.* The EU has **banned export of waste to non-OECD countries** from 2026. An increasing number of net waste importers, such as are following China's lead in **banning the import most difficult-to-recycle materials.**	Very localised impact
Making circularity cheaper	Countries like Germany and Norway have implemented successful **deposit systems for bottles and cans**, significantly reducing sortation costs and increasing recycling rates.	
Setting standards	The EU **Ecodesign for Sustainable Products Regulation** and **Packaging and Packaging Waste Directive** set requirements for the design of materials by use category (e.g. furniture), to improve reusability and recyclability. The US and the EU are establishing standards for **sustainable feedstocks for CO_2**, defining sustainable biomass, and establishing a "waste hierarchy" which prioritizes prevention, reuse, recycling, and recovery over disposal.	Setting targets but limited enforcement
Tackling difficult waste	The **EU End-of-Life Vehicles Directive** and **Waste Electrical and Electronic Equipment Directive** regulate the collection and treatment of waste that falls outside of traditional sortation.	
Increasing cooperation and capacity	*UNEA is negotiating a **Global Plastics Treaty**, an international legally binding agreement currently aiming to address plastic pollution worldwide by reducing plastic waste, enhancing recycling, and transitioning towards a circular economy for plastics by 2040.* The Basel Convention was amended in 2019 to include plastic waste, requiring **reporting and informed consent for international plastic waste shipments.**	Level of ambition still under discussion

Source: Systemiq analysis.

The Global Plastic Treaty could reduce primary demand for carbon in plastics by >50%, but only if negotiations do not water down ambition

A Paris-agreement style binding international agreement under negotiation by **the UNEP.**

Expected to be finalized by **2025** with participation from **175+ countries.**

Aims

1. **Reduce Plastic Production** – Implement global limits and regulations to curb virgin plastic production.
2. **Promote Circular Economy** – Encourage reuse, refill systems, and high-quality recycling.
3. **Ban Harmful Plastics** – Phase out problematic plastic products and chemicals.
4. **Improve Waste Management** – Strengthen global waste collection and recycling infrastructure.
5. **Hold Polluters Accountable** – Introduce Extended Producer Responsibility (EPR) and funding mechanisms for waste management.

Key ongoing negotiations

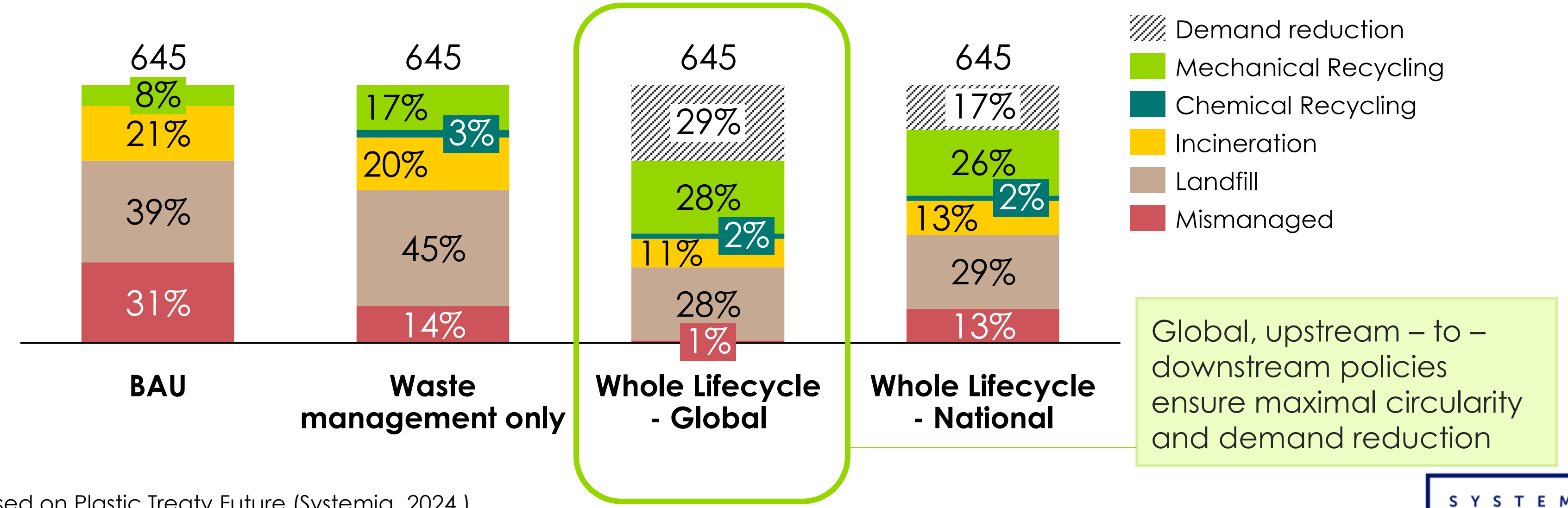
Whether to regulate just plastic **waste** or also production.

Whether to allow flexibility for national policies **or enforce standardized global measures.**

How to fund waste management and ensure fair burden-sharing, especially for developing nations.

Global plastic waste fates according to different outcomes of plastic treaty negotiations, 2040

Million tons/ year



Source: Systemiq analysis based on Plastic Treaty Future (Systemiq, 2024.)

SYSTEMIQ

The RED second delegated act specifies which CO2 feedstocks are eligible for e-fuel (RFNBO) production in Europe

RED III[1] and the second Delegated Act[2] lays out specific rules for which sources of CO_2 are eligible and until what point in time to consider emissions "avoided" and meet e-fuel criteria

CO2 origin	Eligible for RFNBO classification
Air (direct air capture)	Eligible in all cases
Biogenic CO2 e.g. bioethanol, bioenergy power, biomethane	Eligible in all cases
Point source - Industrial processes e.g. limestone calcination process emissions in cement	Only eligible until **2040**[3]
Point source - Other fossil-based combustion e.g. emissions from coal/gas used in industrial heating	Only eligible until **2040**
Point source - Fossil-based power generation	Only eligible until **2035**

- **Origin of CO_2 used in e-fuels** determines whether emissions can be considered "avoided" or not and therefore if the fuel can be considered a RFNBO
- **Industrial point sources e.g. from cement or steel production eligible until 2040**; given the long lifetime of these assets (20 years +), reliance on industrial CO_2 now could lead to stranded assets
- **Most projects in the pipeline in Europe plan to source CO_2 from biogenic sources** (as DAC remains too expensive), following this legislation.

Sources: 1) Renewable Energy Directive (RED III); 2) RED Delegated Act 2; 3) Exact timeline still to be confirmed. While the Delegated Act does not specify the exact timeline for industrial process CO2 emissions, it is likely that it would be regulated to follow a similar timeline as fossil-based combustion in industry as the avoided emissions from carbon capture would be unable to be double-counted for both the industrial site (e.g. cement) and the RFNBO (e.g. e-methanol/kerosene)

Next steps

Calculate and compare a **linear scenario**

Explore the **trade-offs** between different barriers and linear/non-linear solutions

Develop **innovation briefs** on key technologies

Phase 3 begins Q2