



Energy
Transitions
Commission

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

26 02 2025

Agenda

	Time (UKT)	Speaker
Welcome	11:00-11:05	Adair
Section 1: Introduction and case for carbon efficiency	11:05-11:35	Andrea
Section 2: Reduce and Recycle material		Antoinette
Deep-dive: Reuse models		
Deep-dive: Advanced sortation		
Discussion	11:35-11:50	
Mechanical recycling	11:50-12:10	Andrea
Section 3: Recycling carbon		Ioannis
Deep-dive: Chemical recycling and thermo conversion		
Discussion	12:10-12:25	
Deep-dive: Carbon utilisation	12:25-12:45	Ioannis
Section 4: High Circularity Scenario		Andrea
Section 5: Barriers and policies		
Discussion	12:45-13:00	



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 phases / 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

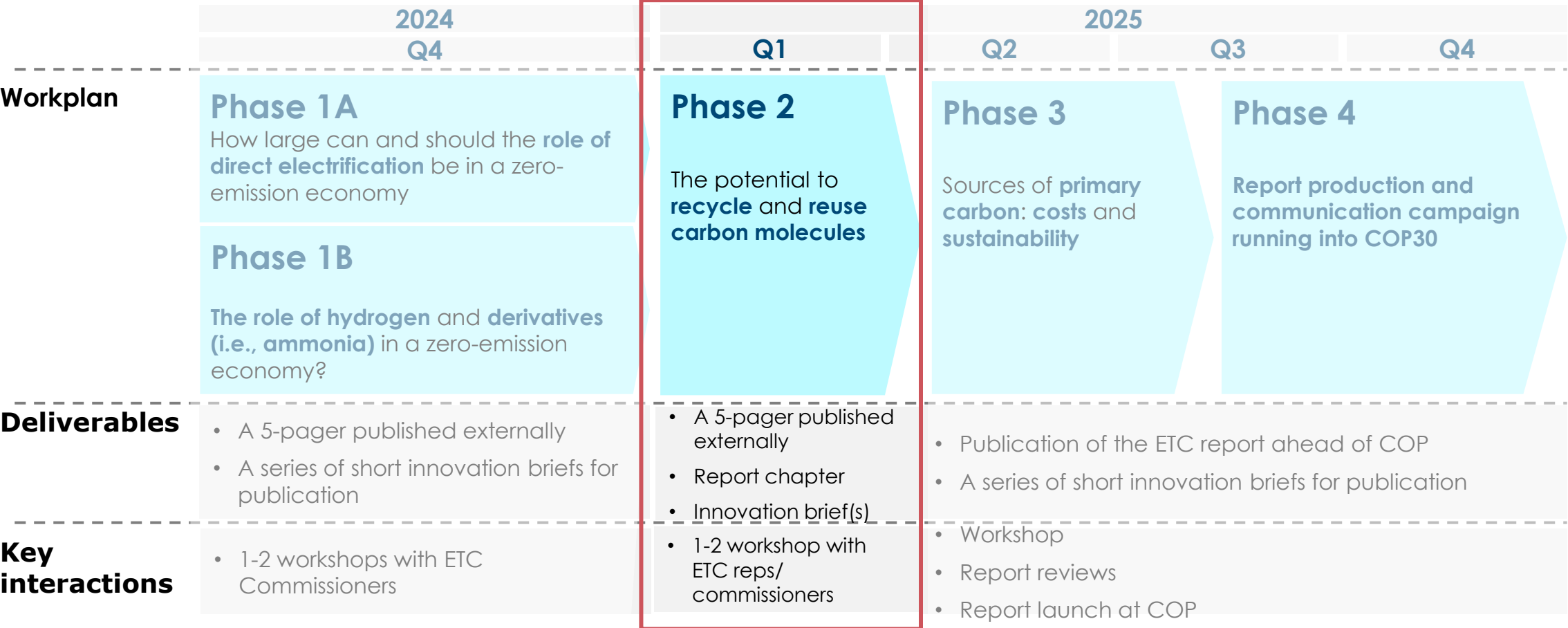
Our topic today

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



Agenda

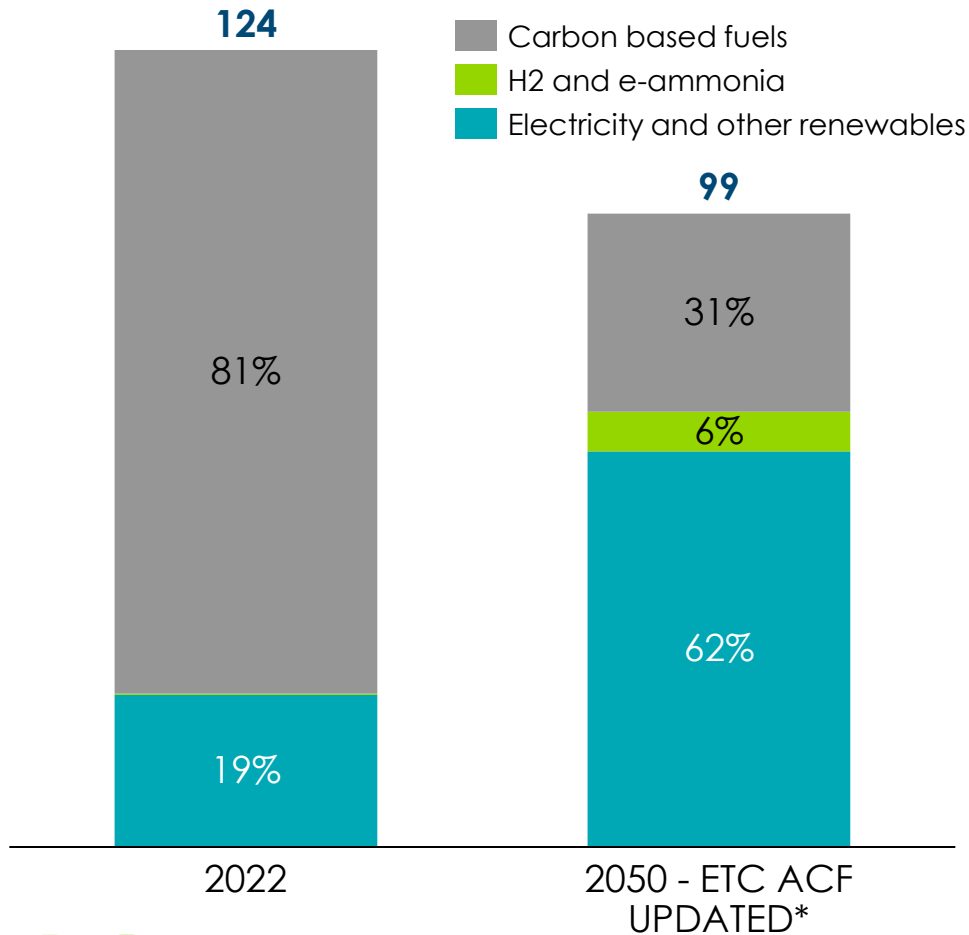
- Introduction to work program
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From Phase 1: The energy system demands ~11Gt of carbon usage today, expected to decrease to 3.3Gt by 2050 in a decarbonization scenario

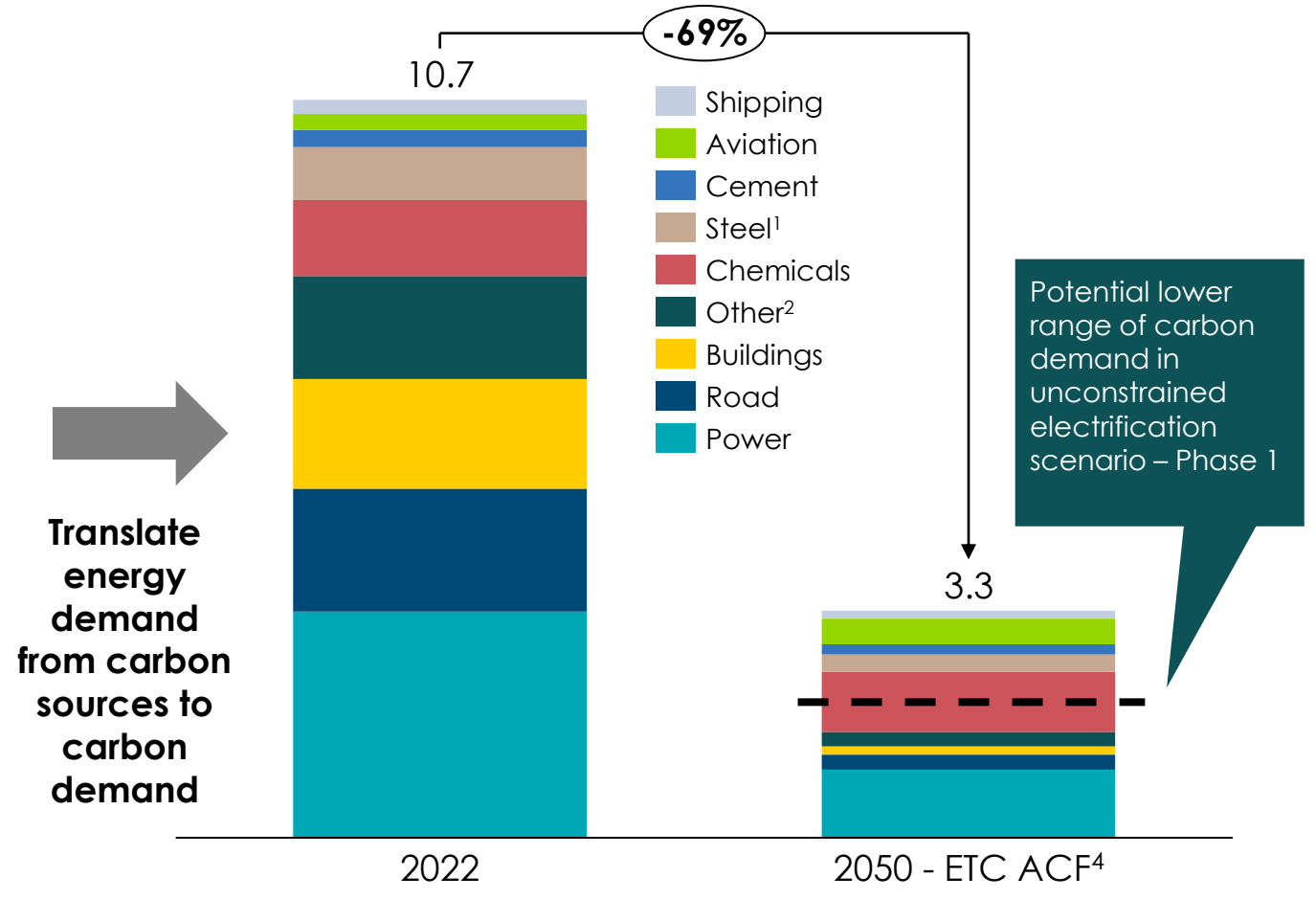
Final Energy Demand for 2022 and ETC's ACF scenario in 2050

Thousand of TWh



Carbon Demand Across the Energy Sector

Giga tons of carbon (C)

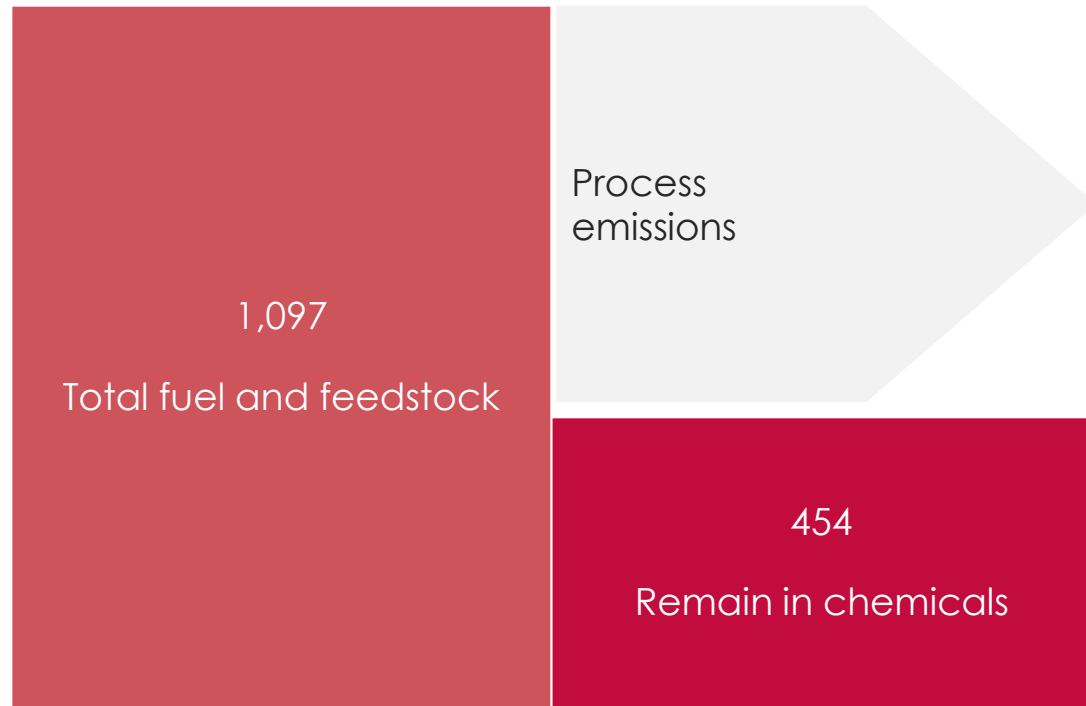


Sources: Energy: Systemiq analysis (2025), based on Fossil Fuels in Transition (ETC, 2023); Chemicals: Planet Positive Chemicals Report (Systemiq, 2022, BAU Net-Zero scenario); Biomass: ETC Bioresources report (2021); Steel: MPP STS (2022); Cotton, Bitumen and Soda Ash: Systemiq analysis (2025) Energy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

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

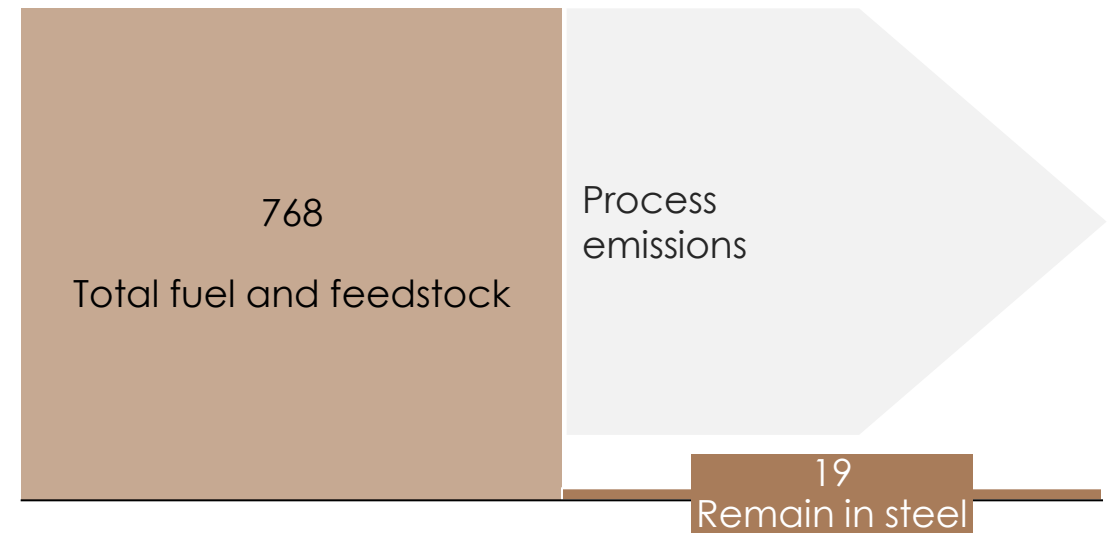
Total carbon demand for chemical sector, 2022

Million tons of carbon (C)



Total carbon demand for steel sector, 2022

Million tons of carbon (C)

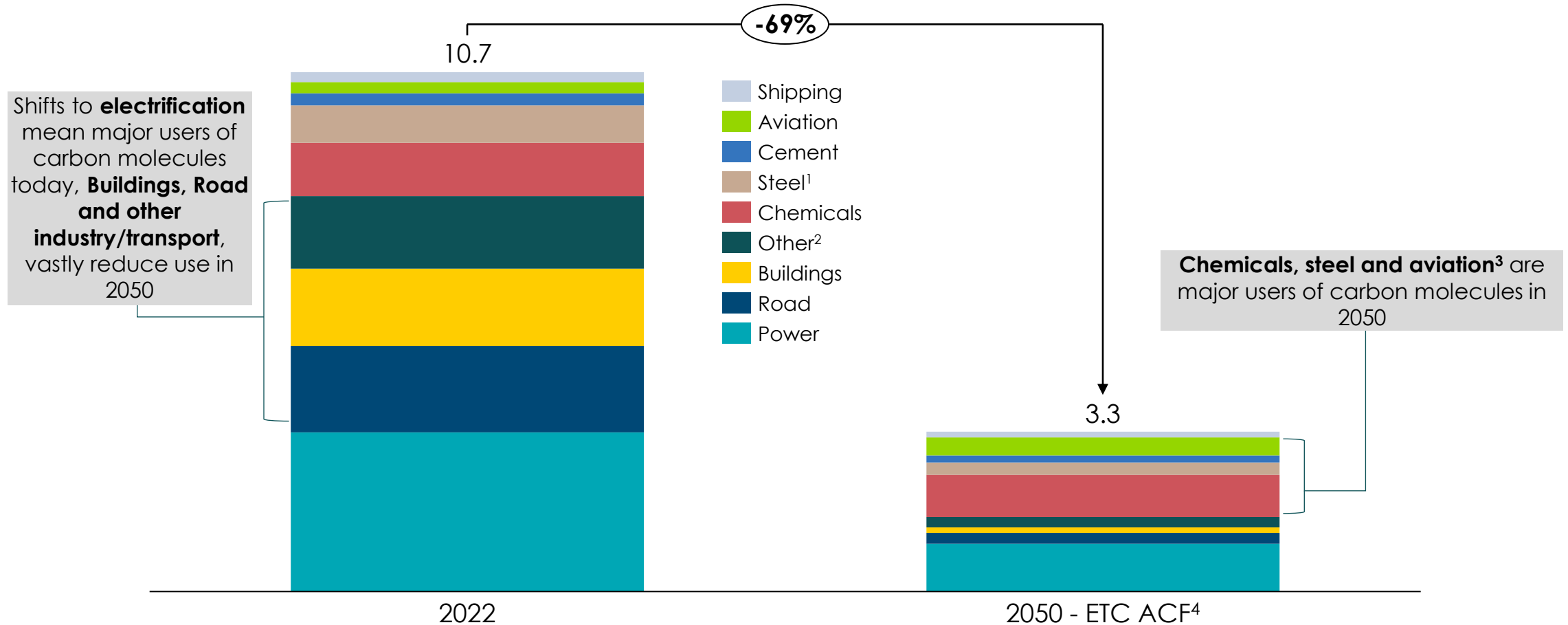


Sources: Energy: Systemiq analysis (2025), based on Fossil Fuels in Transition (ETC, 2023); Chemicals: Planet Positive Chemicals Report (Systemiq, 2022, BAU Net-Zero scenario); Steel: MPP STS (2022);

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)



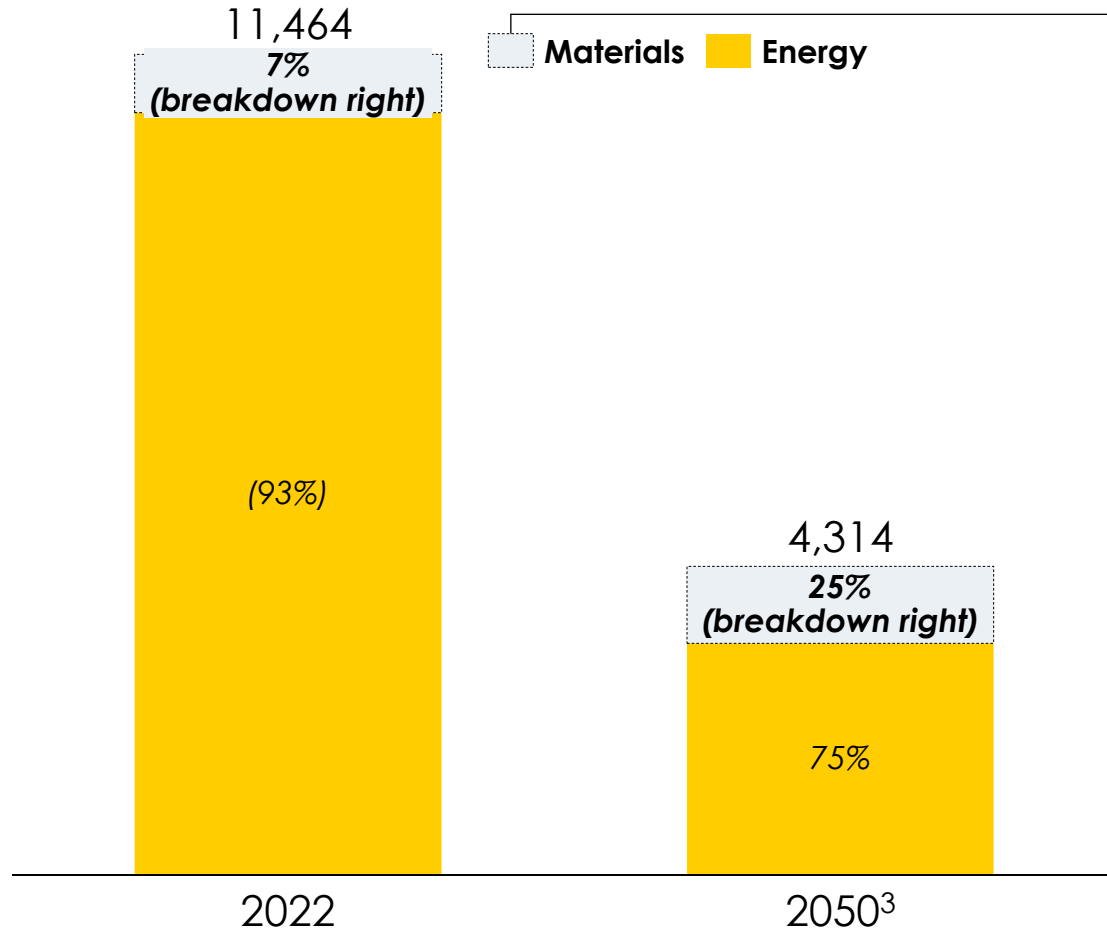
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1. Include energy based carbon feedstocks, a proportion of which which end in the final products (e.g. chemicals for plastics and steel), and others end in process emissions. 2. Includes remaining demand remaining sectors, primarily other industry 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)

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)

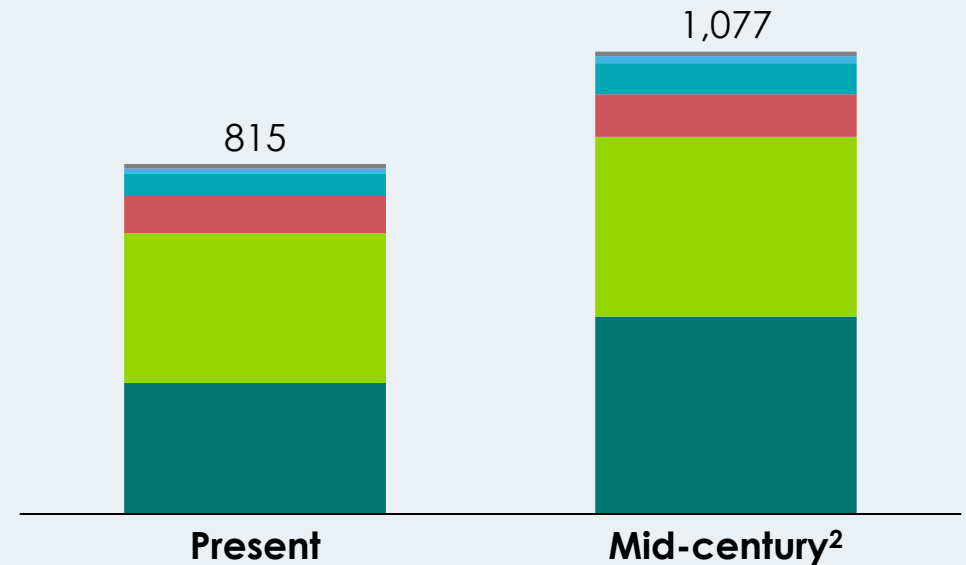


Carbon Demand Breakdown Across Major Materials

Million tons of carbon (C)

- Other¹
- Non-wood biomass (cotton)
- Limestone
- Bitumen
- Wood (pulp and paper)
- Wood (timber)

PRELIMINARY ESTIMATES



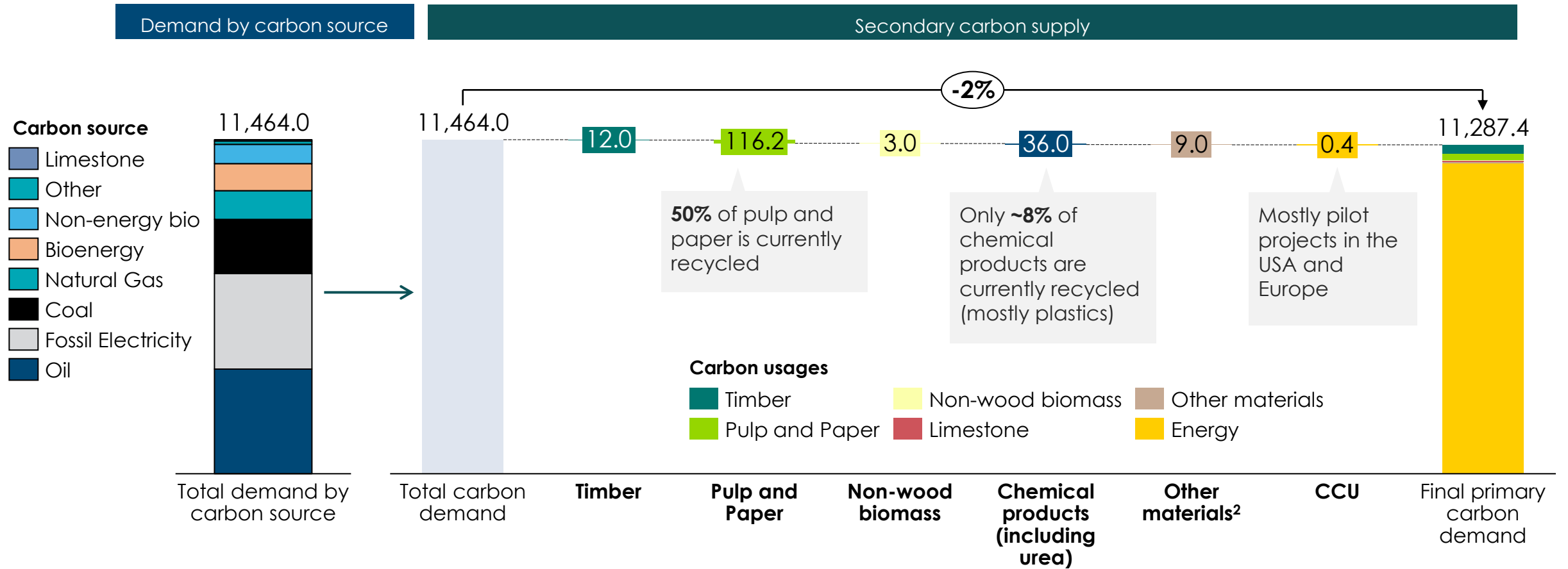
Sources: Energy: Systemiq analysis (2025), based on Fossil Fuels in Transition (ETC, 2023); Chemicals: Planet Positive Chemicals Report (Systemiq, 2022, BAU Net-Zero scenario); Biomass: ETC Bioresources report (2021); Steel: MPP STS (2022); Cotton, Bitumen and Soda Ash: Systemiq analysis (2025)
 Notes: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



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)
 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.

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	<ul style="list-style-type: none"> AI lightweighting and optimization tech New re-use technology & delivery models 	<p>Actions: Design for recycling, sortation, collection</p> <p>Technologies:</p> <ul style="list-style-type: none"> Track and trace, material passports Advanced AI and robotics sorting
2. Recycle material	Physical or mechanical recycling of material	<ul style="list-style-type: none"> Mechanical recycling Solvent-based recycling 	
3. Recycle carbon	Chemical recycling of material and thermo conversion Utilise waste CO ₂	<ul style="list-style-type: none"> Depolymerisation Pyrolysis Gasification 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	<p>Remove or reduce any material that does not serve an essential function</p>	<p>Business models promoting re-use of materials, reducing single-use and extending product lifetime</p>	<p>Substitution to less carbon intensive materials</p>
Examples	<p> Eliminating neck tear-offs from Pure Life water</p> <hr/> <p>SKANSKA Modular designs to reduce surplus material use</p> <hr/> <p> Lightweighting vehicles to reduce material and fuel use</p>	<p> cupclub Coffee shop network using reusable and interchangeable cups with deposit system</p> <hr/> <p>Vinted Recommerce of textiles and household goods</p> <hr/> <p>Uber Sharing the utility of vehicles to multiple users</p>	<p> Replacing plastic rings on beverage multipacks with cardboard clips</p> <hr/> <p>ALPLA Bio-based and recyclable paper bottles</p> <hr/> <p> Soy instead of petroleum-based foam in car seats</p>



Reuse for packaging

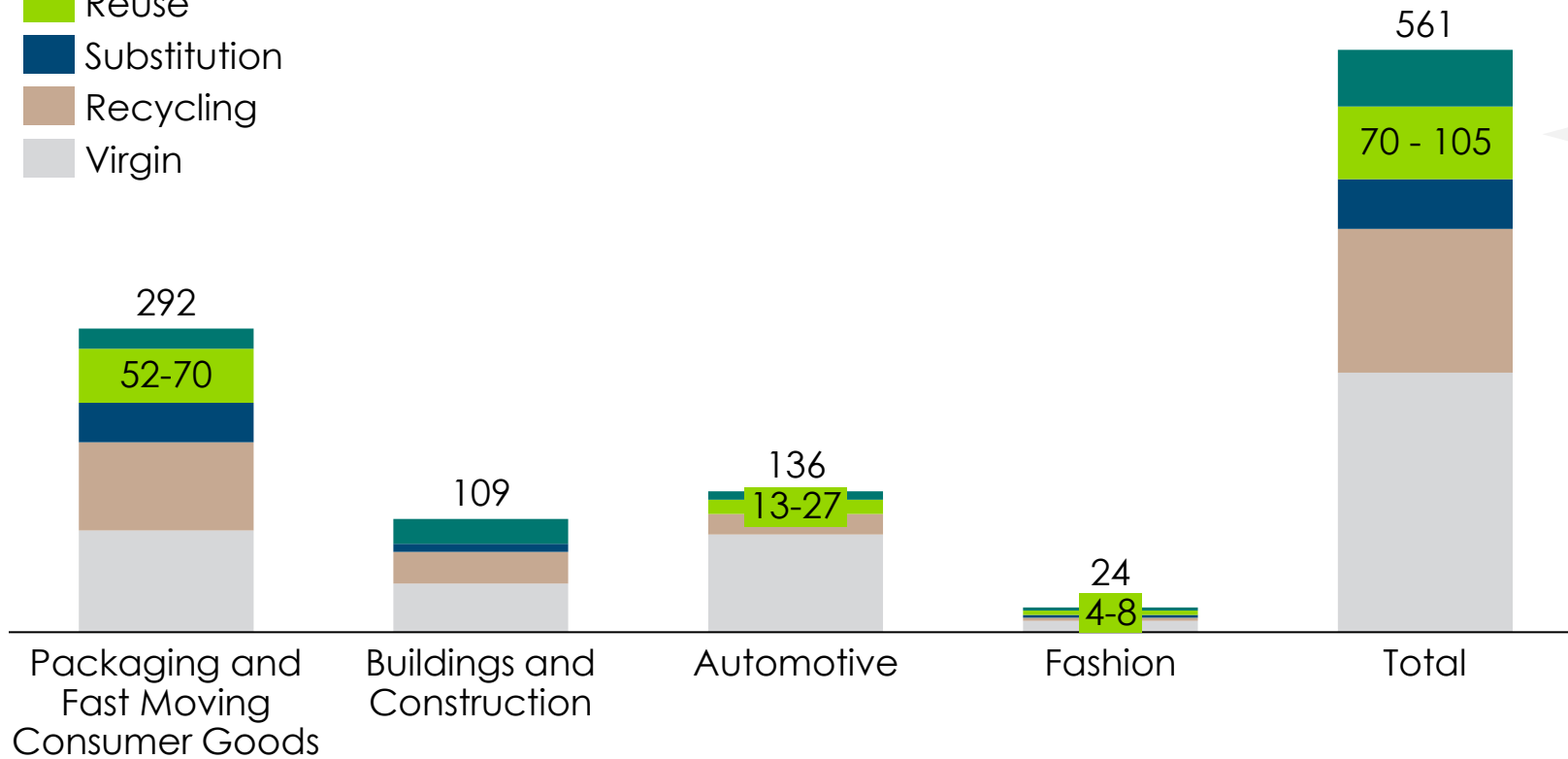


Reuse models could reduce mid-century chemicals demand in 3 of the top plastic using sectors

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."

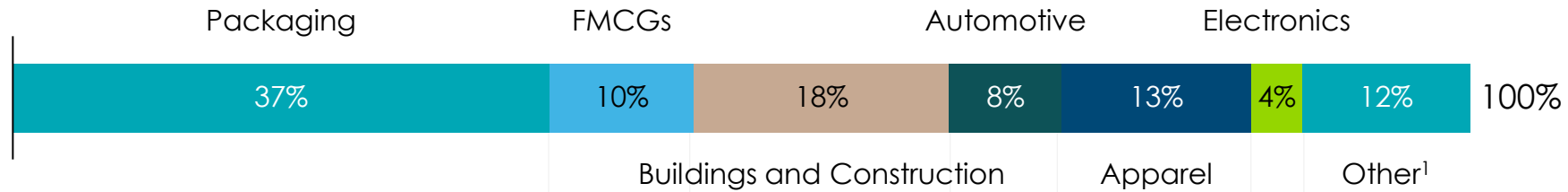
We are focusing on reuse where it displaces single-use through innovative business models

 Deep-dive next

Reuse model	Description	Sectors	Company <i>Non-exhaustive examples</i>
Packaging reuse and refill	<p>Services and businesses which provide the utility previously furnished by single-use items.</p> <p>Includes B2C and B2B packaging through:</p> <ul style="list-style-type: none"> - Refill systems (from home or from businesses) - Return systems (from home or on-the-go) 	Packaging	
Recommerce of consumer goods	<p>Reuse by a third party via C2C retail, or businesses which collect, refurbish, and resell finished products.</p>	Household goods; textiles; electronics	
X-as-a-service	<p>Sharing economy replacing single ownership items.</p> <p>Includes most examples of sharing economy, such as (not exhaustive):</p> <ul style="list-style-type: none"> - Automotive-as-a-service (e.g. carshares, city bikes and scooters services) - White-goods-as-a-service (e.g. laundrettes) - Clothes-as-a-service (e.g. rental websites) - Buildings-as-a-service (e.g. coworking spaces) 	Automotive; textiles; household goods; construction	

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

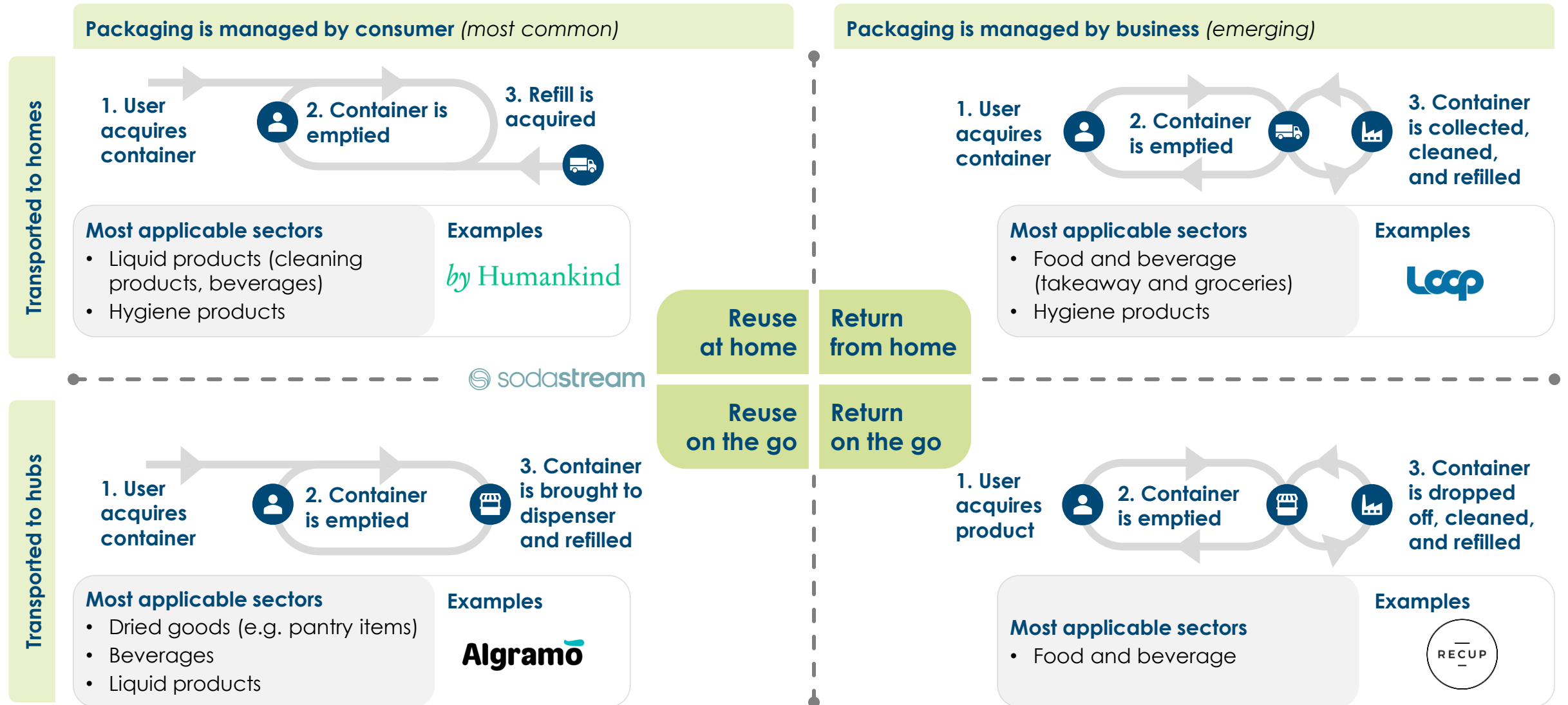


Option	Applicability	Max Potential Range ²
Packaging reuse and refill <ul style="list-style-type: none"> Applies to the largest demand sector 		37%
Recommerce of consumer goods <ul style="list-style-type: none"> Applies to limited number of sectors 		17%
X-as-a-service <ul style="list-style-type: none"> Applies to wide range of sectors Requires high levels of behaviour change Unlikely to largely displace single ownership models 	<p>X-as-a-service is widely applicable but likely to remain niche in most sectors</p>	43%



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

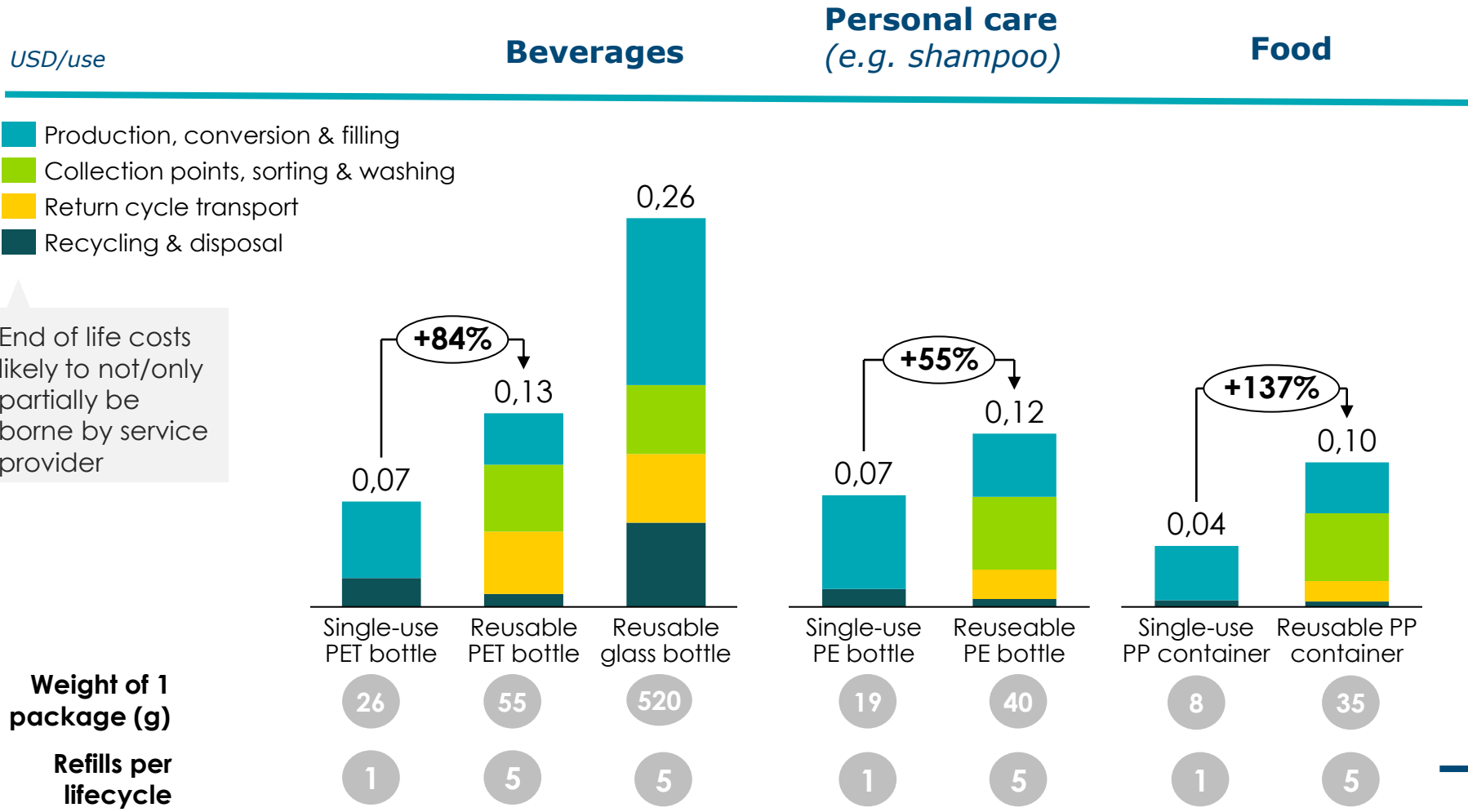
Customer-facing new delivery models can be split into four categories



sodastream



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



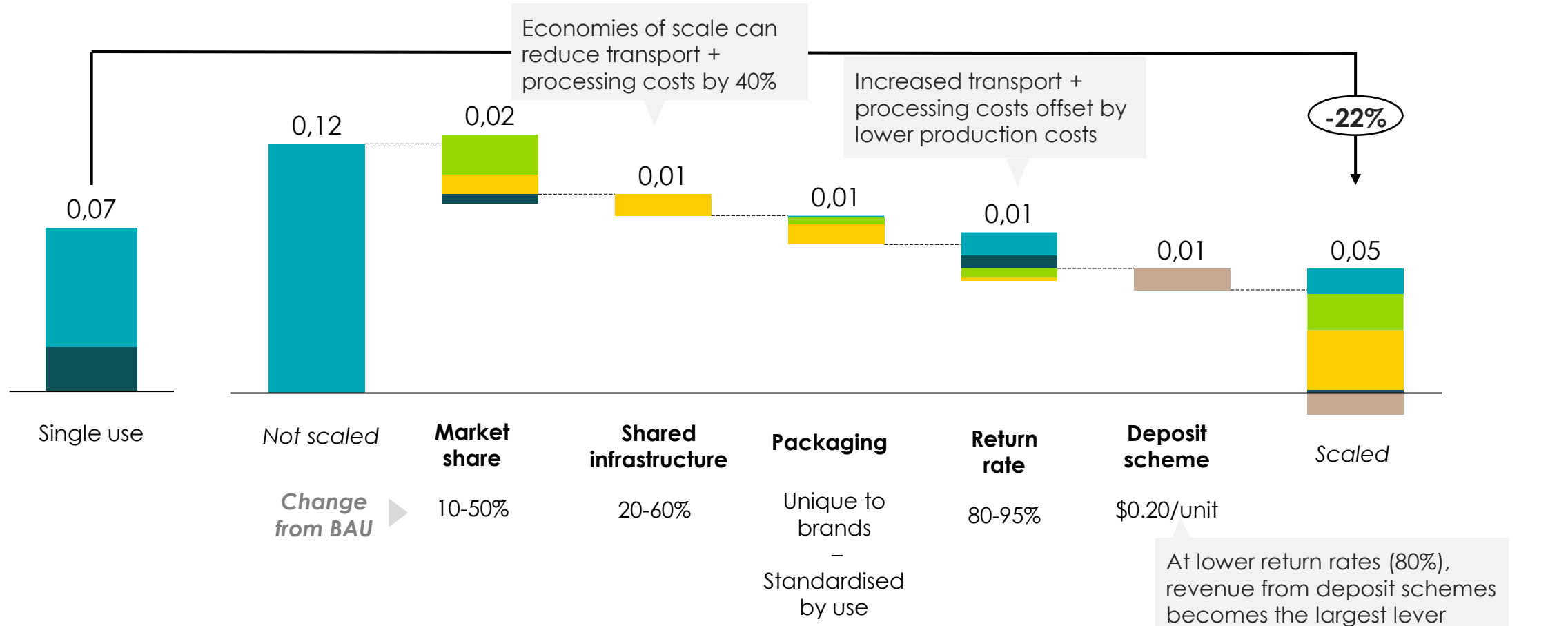
Source: Ellen MacArthur Foundation, 'Unlocking a reuse revolution: scaling returnable packaging' (2023). Reuse model assumes return rates of 80%, and lifecycle of 5 uses for reusable items. Costs for entire system, based on EU data. PE = Polyethylene. PET = Polyethylene Terephthalate, PP = Polypropylene

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

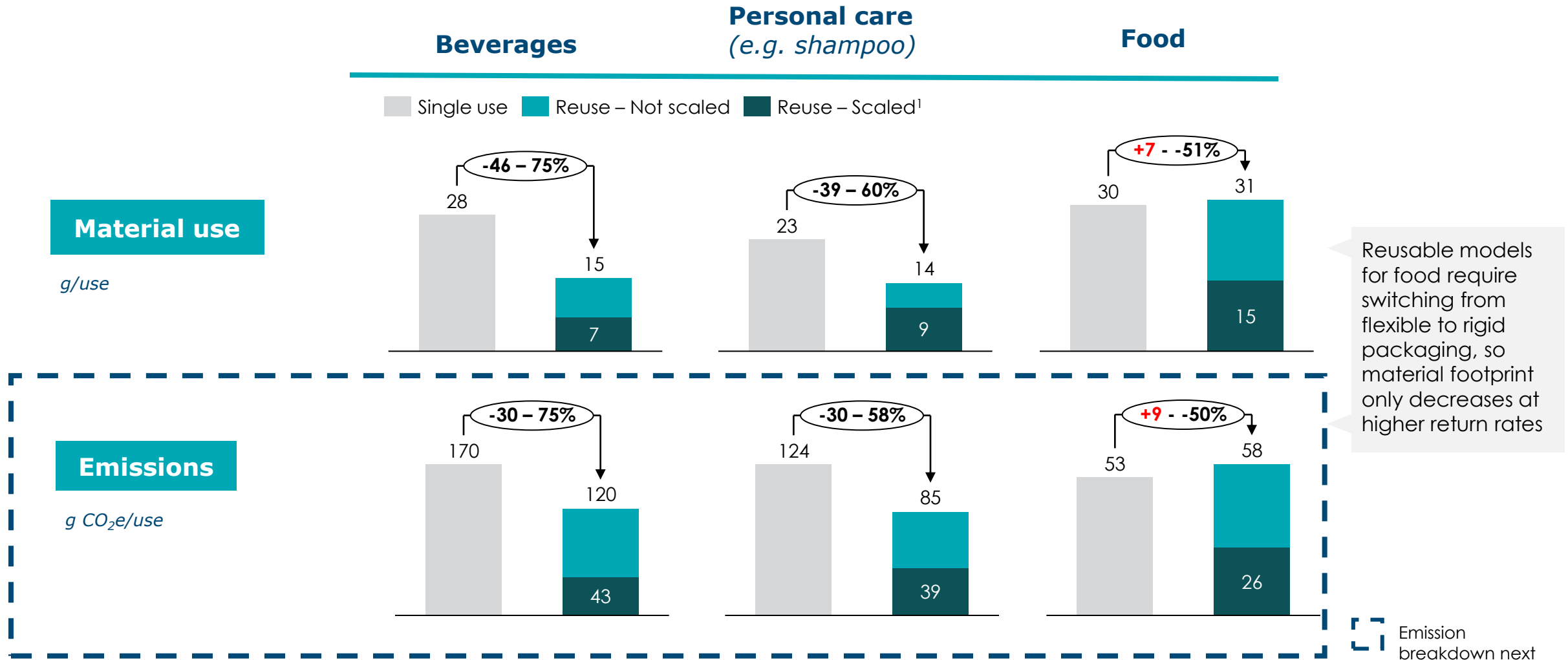
USD/use

■ Production, conversion & filling
 ■ Collection points, sorting & washing
 ■ Return cycle transport
 ■ Recycling and disposal
 ■ Revenue



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

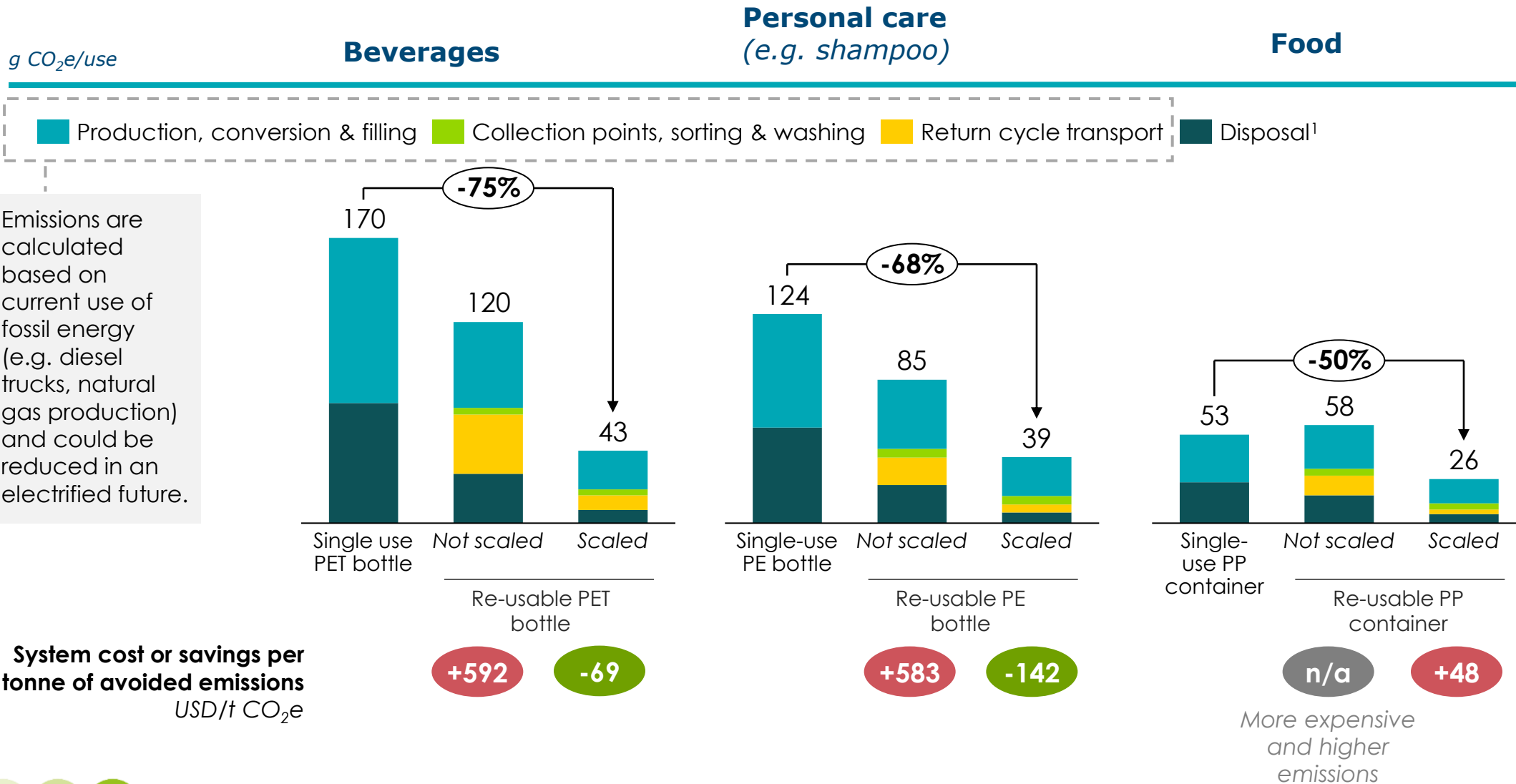
At scale, reuse models could limit GHG emissions and resource use across all uses



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.

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



Emissions are calculated based on current use of fossil energy (e.g. diesel trucks, natural gas production) and could be reduced in an electrified future.

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

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



Customers



Regulation



Costs

Drivers

- 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.
- 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.
- 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.**

Barriers

- **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.**
- **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.
- 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.**

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

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












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

2



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

 Deep-dive next

	Design for recycling 	Collection 	Sorting 
Description	<p>Designing products with end-of-life recycling in mind</p> <p>Can reduce recycling losses by 13%</p>	<p>Collection of waste – curbside collection, drop-off centres, community collection points</p>	<p>Sorting collected material into categories based on their type and recyclability</p>
Examples	<p> Bottle cap straps making lid less likely to lost</p> <hr/> <p> Switch toothpaste from multi-material to single material tubes</p> <hr/> <p> Clear instead of coloured bottles, improving value of plastic at end of life</p>	<p>Established systems</p> <ul style="list-style-type: none">  Formal curbside collection  Informal sector collection (waste pickers)  Drop-off centres <p>Potential innovations</p> <ul style="list-style-type: none">  Digital market places for waste pickers, aggregators and off-takers 	<p>Established systems</p> <ul style="list-style-type: none">  Materials Recovery Facility sorts and processes waste streams for recycling <p>Potential innovations</p> <ul style="list-style-type: none"> • Sensor based solutions • Artificial intelligence and robotic sorting • Real-time analysis of sorted waste to optimize process



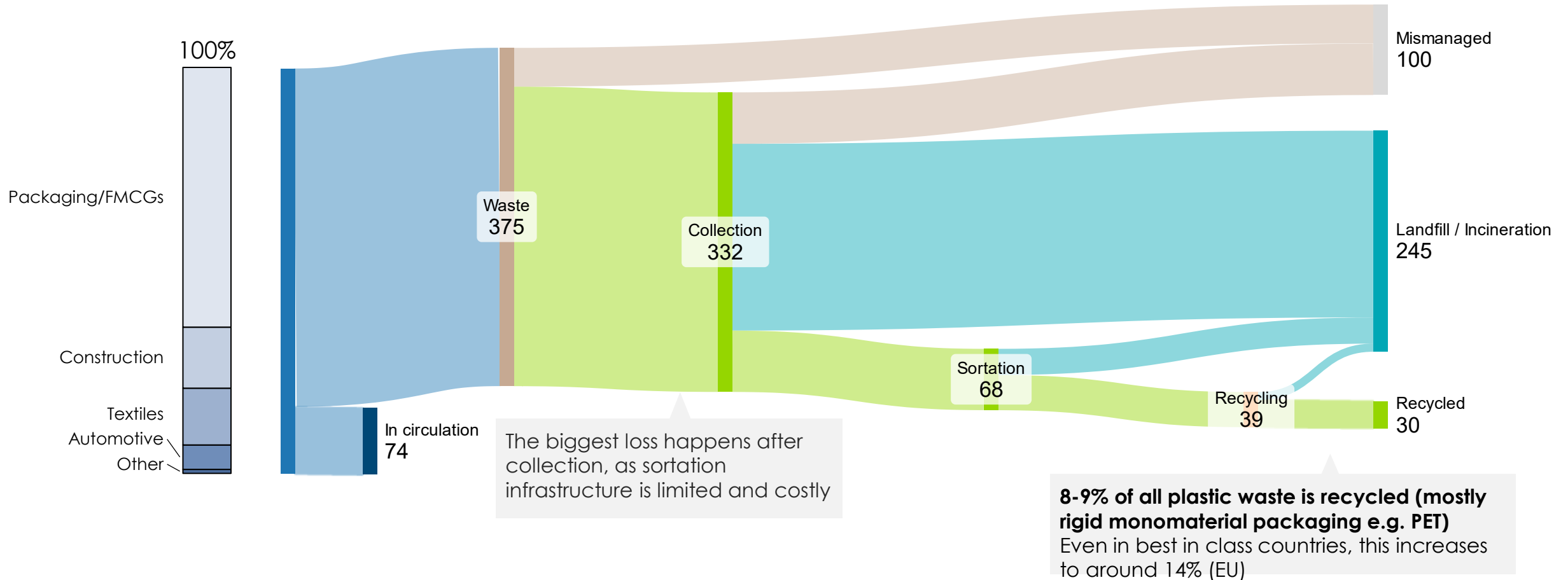
Source: Systemiq analysis (2024)

Advanced sortation



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







Fate of global plastic waste, 2019
Million metric tonnes



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).

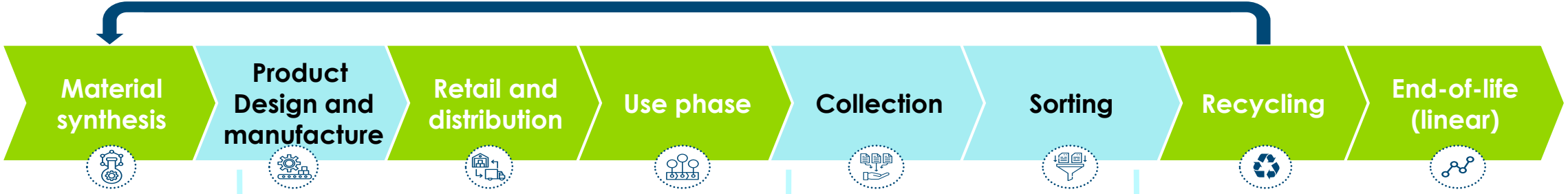


The sortation bottleneck will mostly be solved via supportive policy frameworks, but technological advancements could improve economics

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

Focus of the deep dive

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



Designing for recycling **Sortation at source** **Separation and sortation**

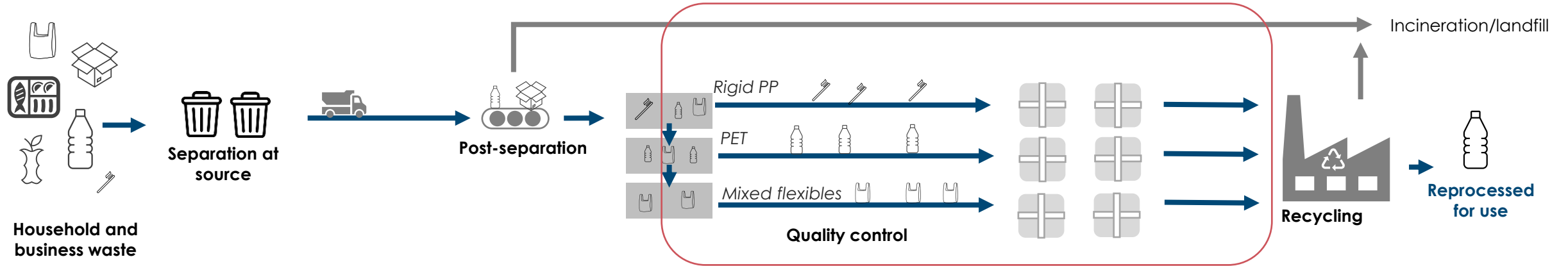
Current system	<ul style="list-style-type: none"> • Single-material items 	<ul style="list-style-type: none"> • Manual waste segregation 	<ul style="list-style-type: none"> • Mechanical sortation • Manual sortation
Digitisation and AI-enabled technologies	<ul style="list-style-type: none"> • Digital sorting watermarks • Photonic markers • Blockchain technology 	<ul style="list-style-type: none"> • Smart bins 	<ul style="list-style-type: none"> • High-tech sensors • Robotic sorting • Optimising process per load of feedstock

Examples
Not exhaustive



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

Illustrative



Largest impact of advanced sortation

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%

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%

Equivalent to only a 12% final recycling yield in current system

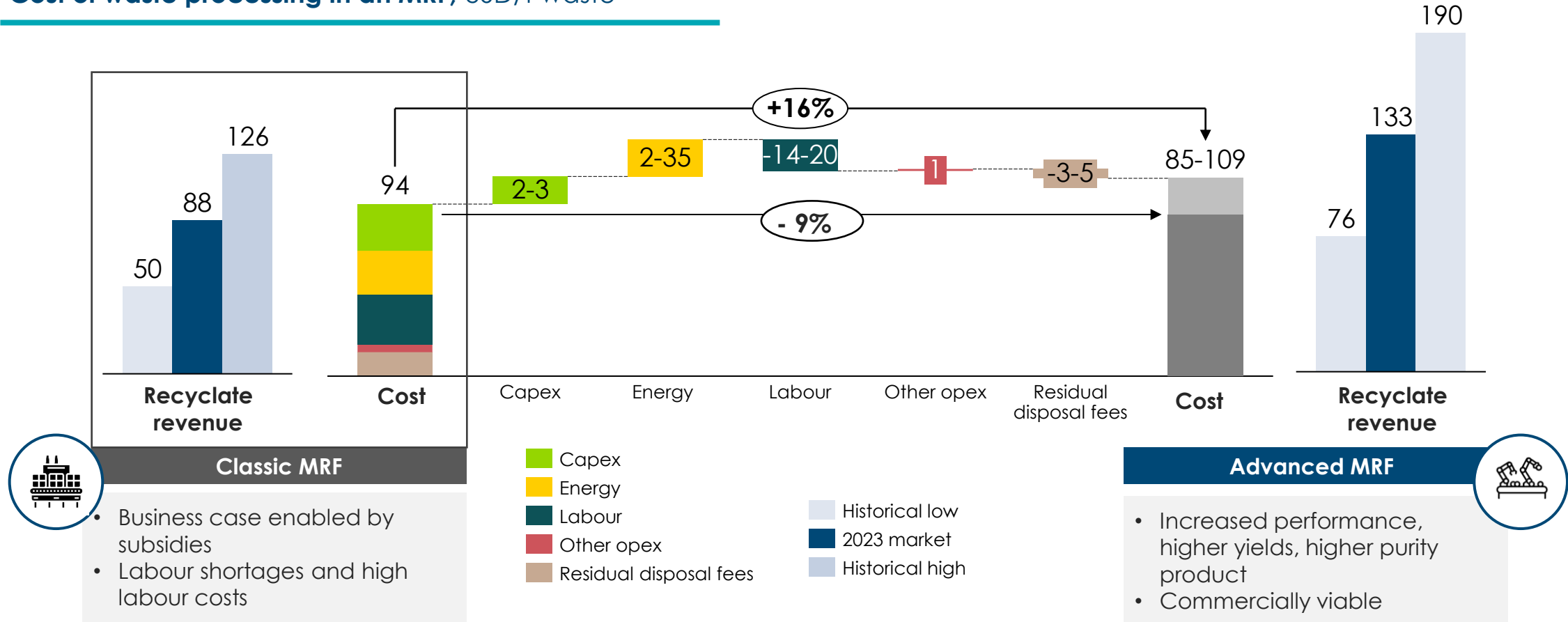
Sources: Advanced Sortation for Circularity (Eunomia, 2024). Plastic pathways (PWC, 2022). Turning Trash Into Treasure: How AI Is Revolutionizing Waste Sorting (Forbes, 2024). How AI Robots help reduce the cost of waste sorting in MRFs (Recleye, 2024). Olawade, D.B. et al., Smart waste management: a 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

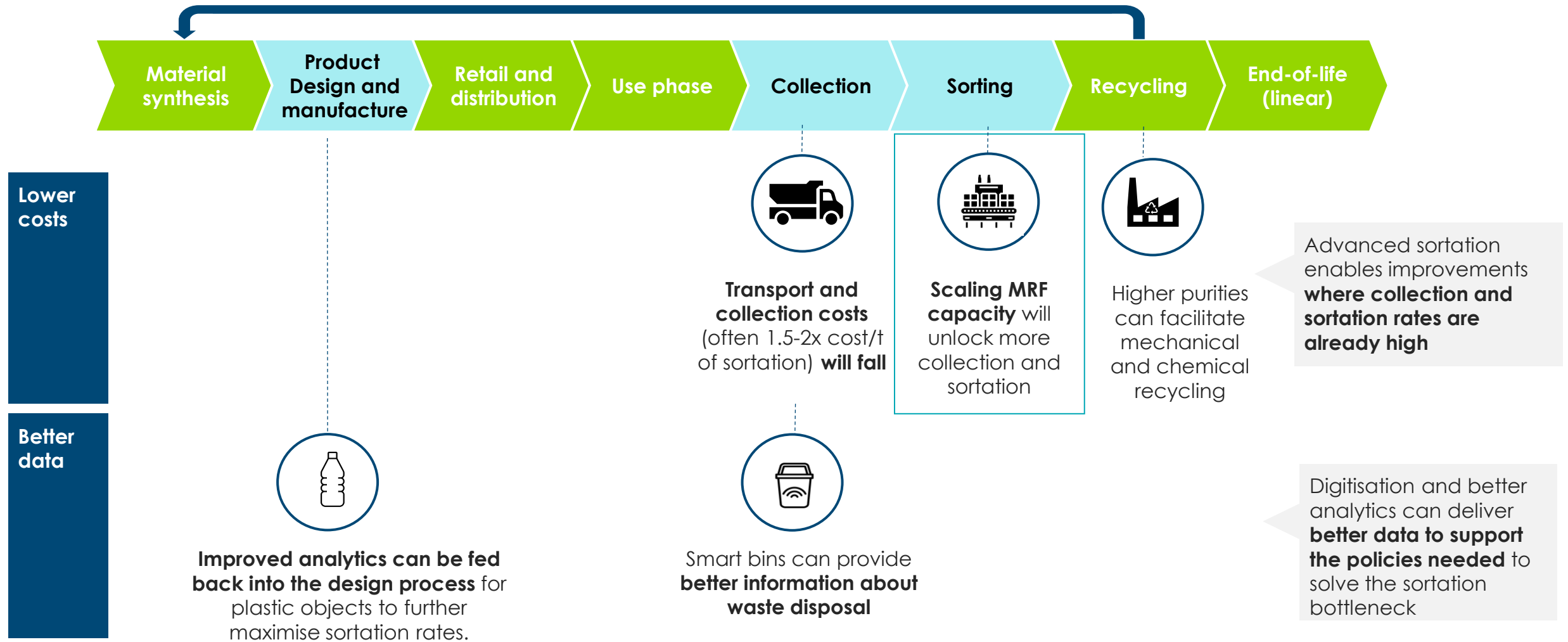
Cost of waste processing in an MRF, USD/t waste



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



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	<ul style="list-style-type: none"> AI lightweighting and optimization tech New re-use technology & delivery models 	
2. Recycle material	Physical or mechanical recycling of material	<ul style="list-style-type: none"> Mechanical recycling Solvent-based recycling 	<p>Actions: Design for recycling, sortation, collection</p> <p>Technologies:</p> <ul style="list-style-type: none"> Track and trace, material passports Advanced AI and robotics sorting
3. Recycle carbon	Chemical recycling of material and thermo conversion Utilise waste CO ₂	<ul style="list-style-type: none"> Depolymerisation Pyrolysis Gasification <ul style="list-style-type: none"> 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**?

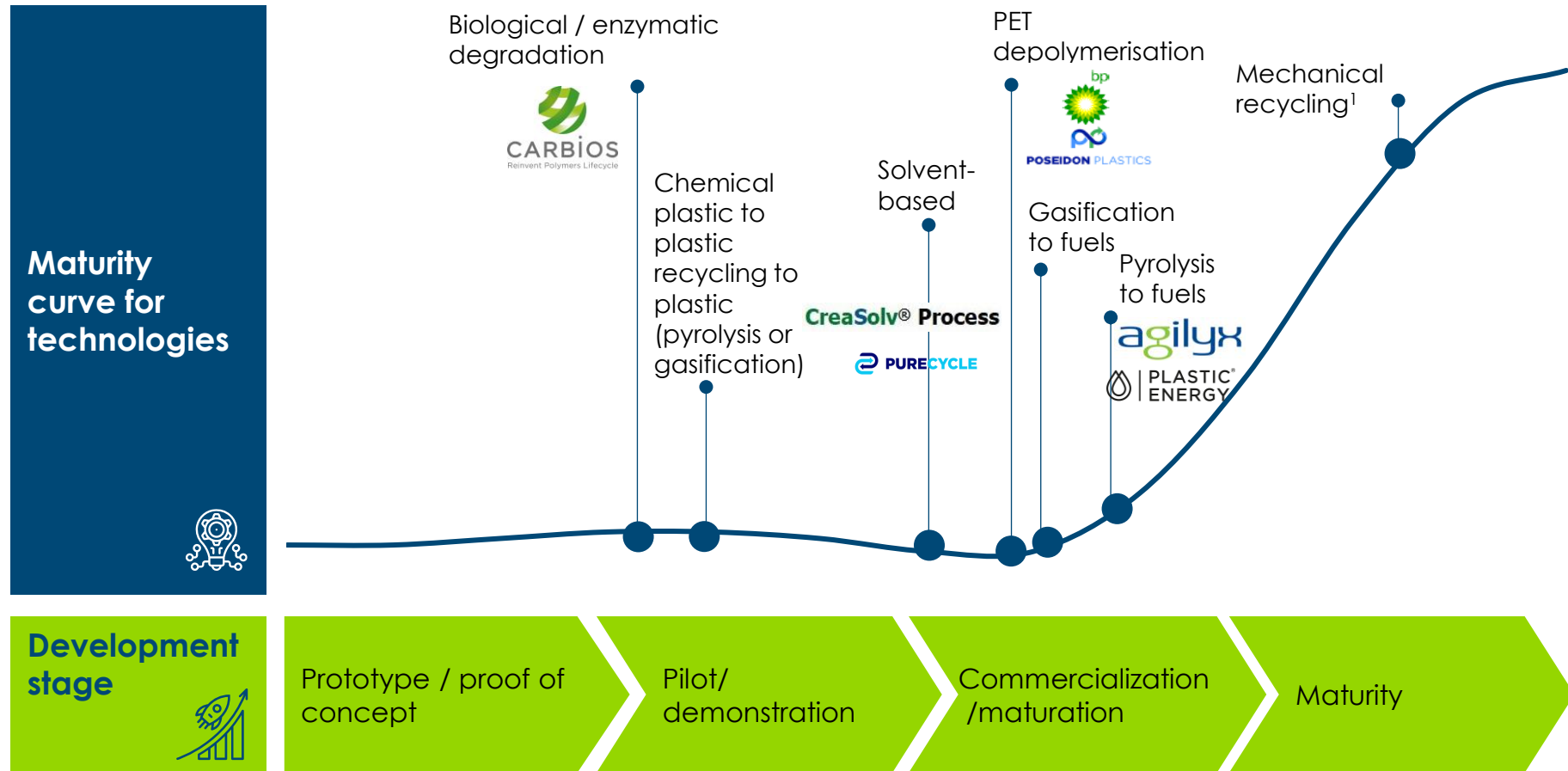
What are the **techno-economics, limitations and barriers** to key **technologies**?

2



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

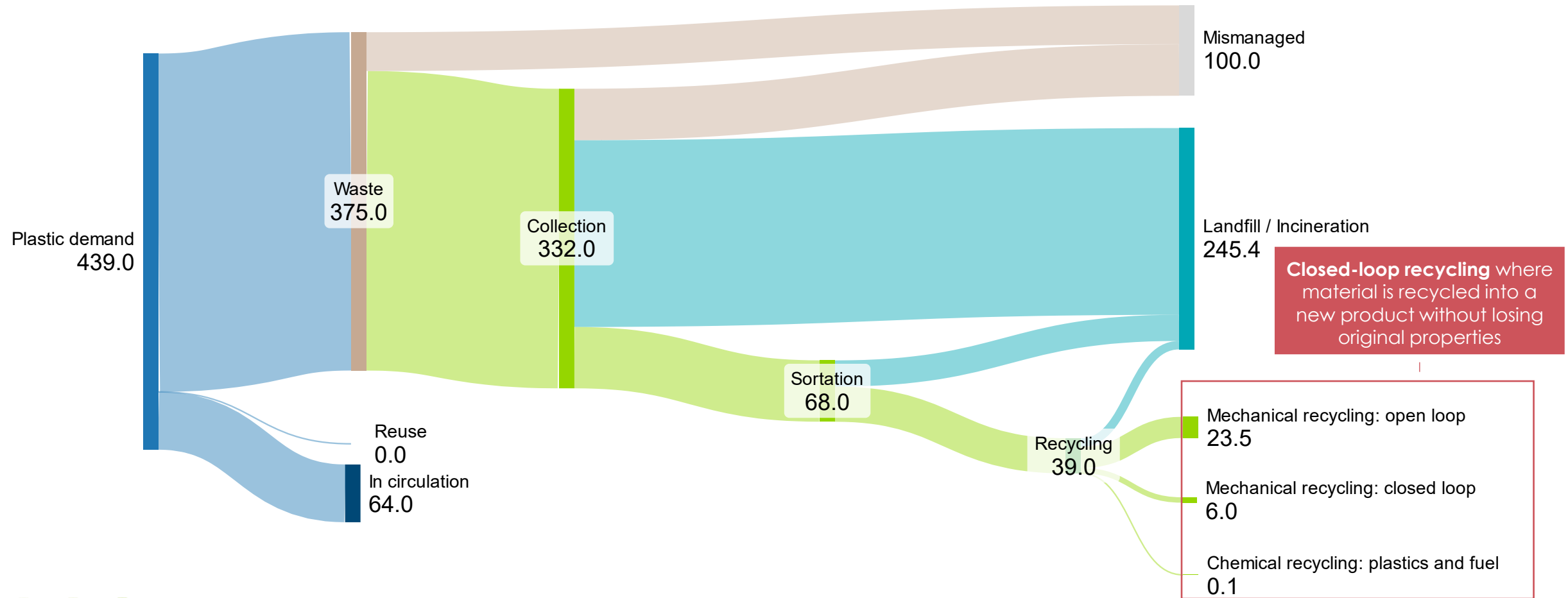
Mechanical or physical recycling is the current dominant technology type for recycling waste...

	Mechanical (current dominant technology)	Solvent based
Description	<p>Physically processing waste materials by cleaning shredding and reforming without changing chemical structure</p>	<p>Solvents dissolve and separate polymers in plastic waste, allowing for extraction and purification materials without altering their chemical structure</p>
Examples	<p>Not exhaustive</p> 	
Advantages	<ul style="list-style-type: none"> • Vast majority for plastic recycling to date with large installed capacity <u>worldwide</u> • Low energy input and GHG balance 	<ul style="list-style-type: none"> • Tolerance for multilayers plastic or multi-plastic materials • High-quality output • Low-energy input and GHG balance
Challenges	<ul style="list-style-type: none"> • Low tolerance for input contamination (e.g. issues with colour, odor, properties). • Limitations for high performance/high quality application (e.g. food grade) 	<ul style="list-style-type: none"> • 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

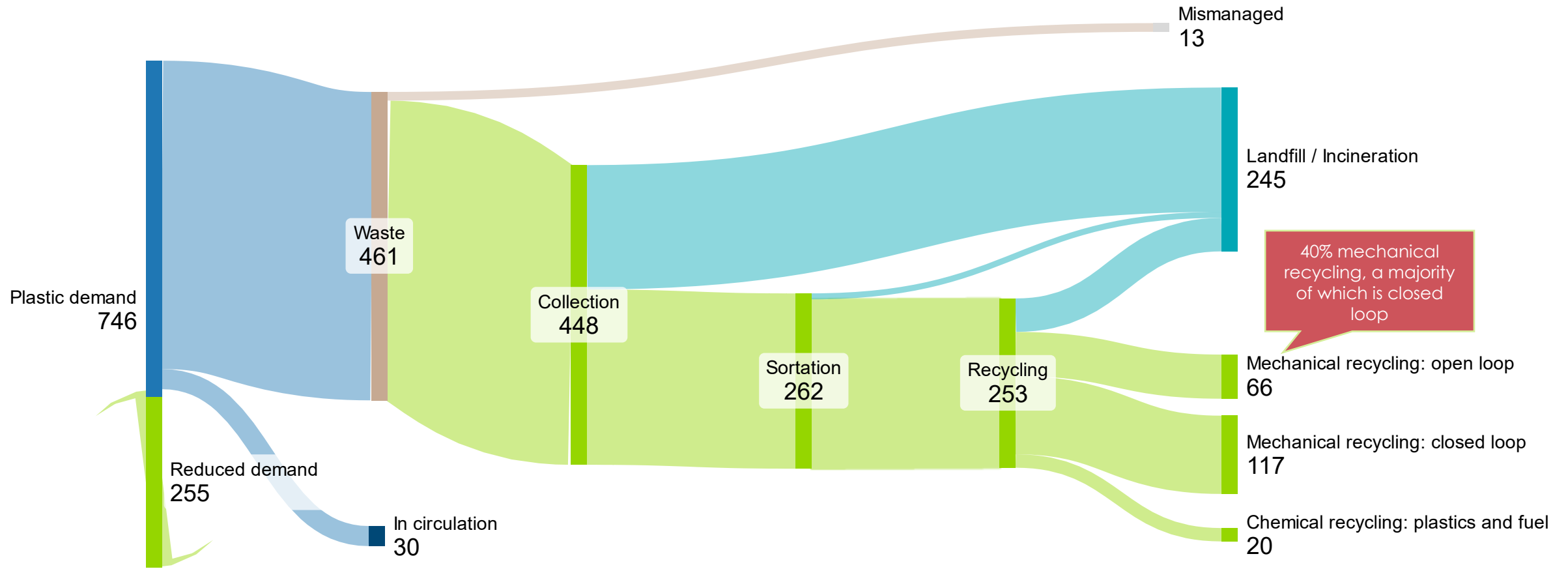


Source: Systemiq (2024) Plastic Treaty, BAU










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

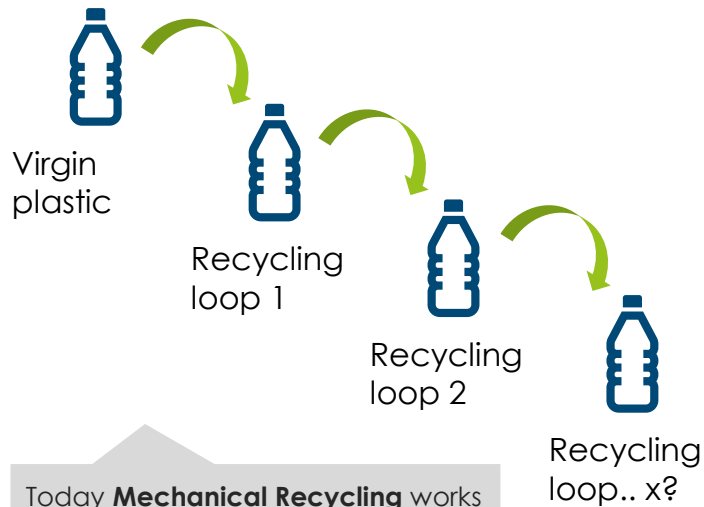
Lever Group	Policy lever description
Reduce virgin plastic production and consumption	 Policy targets to reduce virgin plastic volumes
	 Virgin plastic fees to fund solutions across the plastic lifecycle
Eliminate avoidable and problematic plastic and chemicals	 Phaseout criteria for problematic plastics, 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

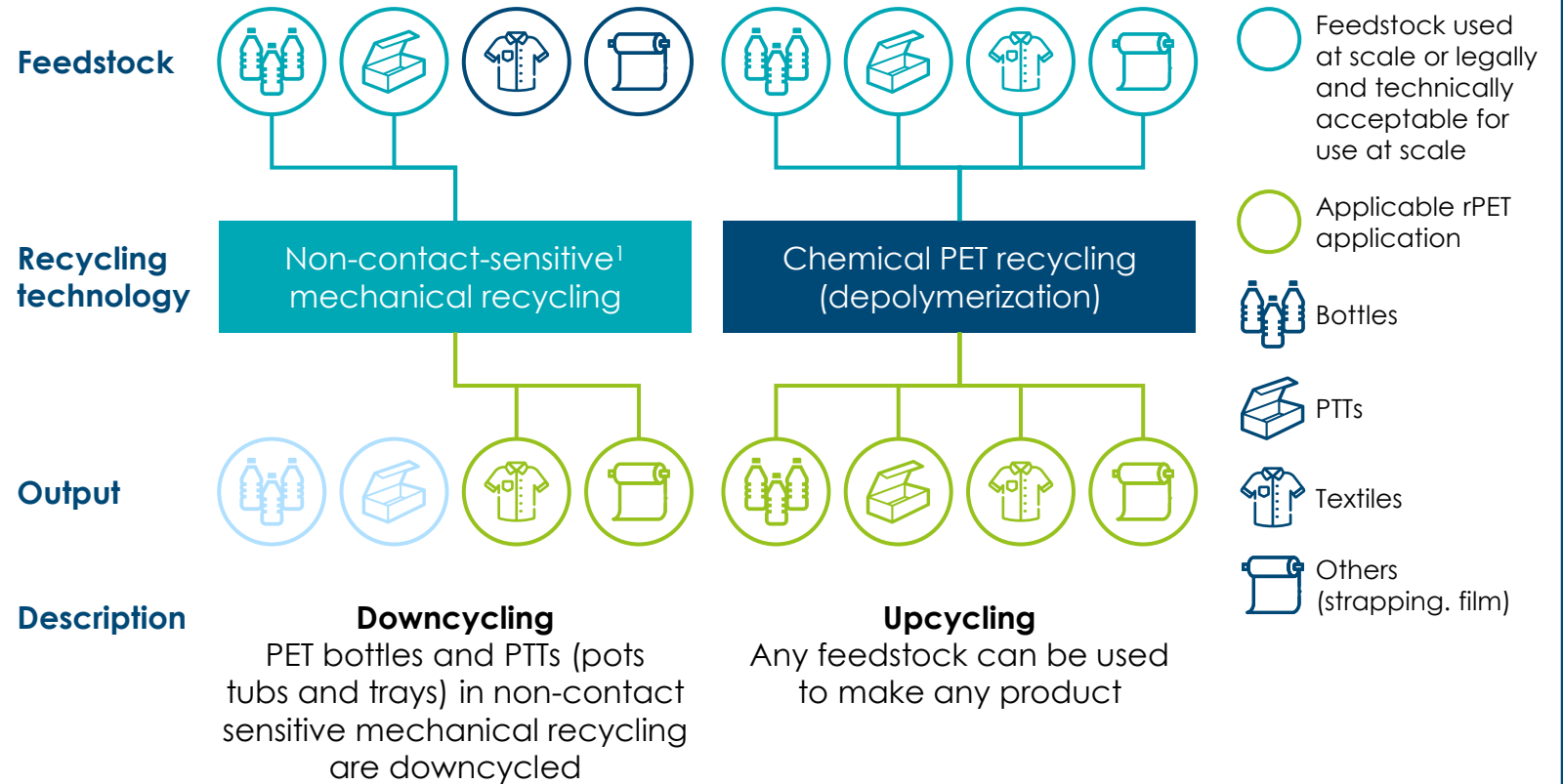
Challenge 1: Mechanical recycling degrades polymer properties

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

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

2



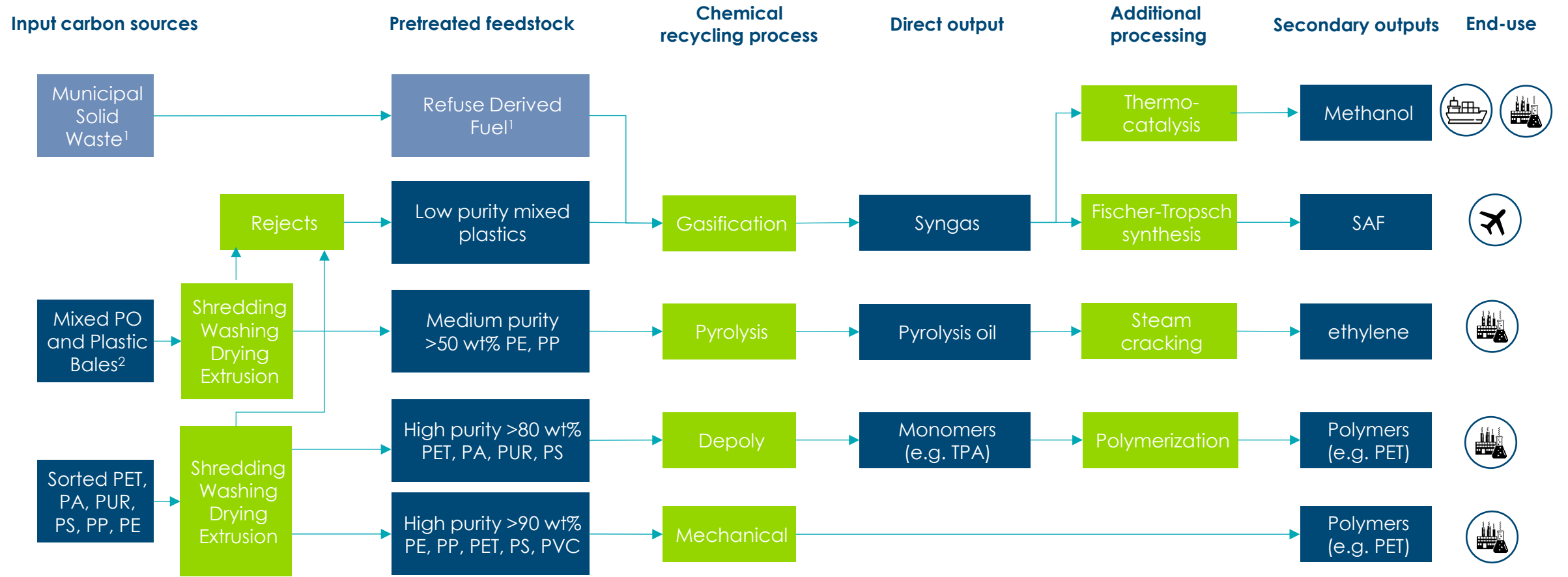
Our deep-dives will focus on chemical recycling and thermos conversion technologies which have reached or are nearing commercialization

Technology	Process	TRL	End-Use Sector	Companies <i>Non-exhaustive examples</i>
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	
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	
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. <i>Note: gasification is a technology used not only to recycle chemicals, but also to gasify coal and biomass.</i>	7-8 ⁶	Power, heat, chemicals	

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. \(2023\)](#)



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).

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

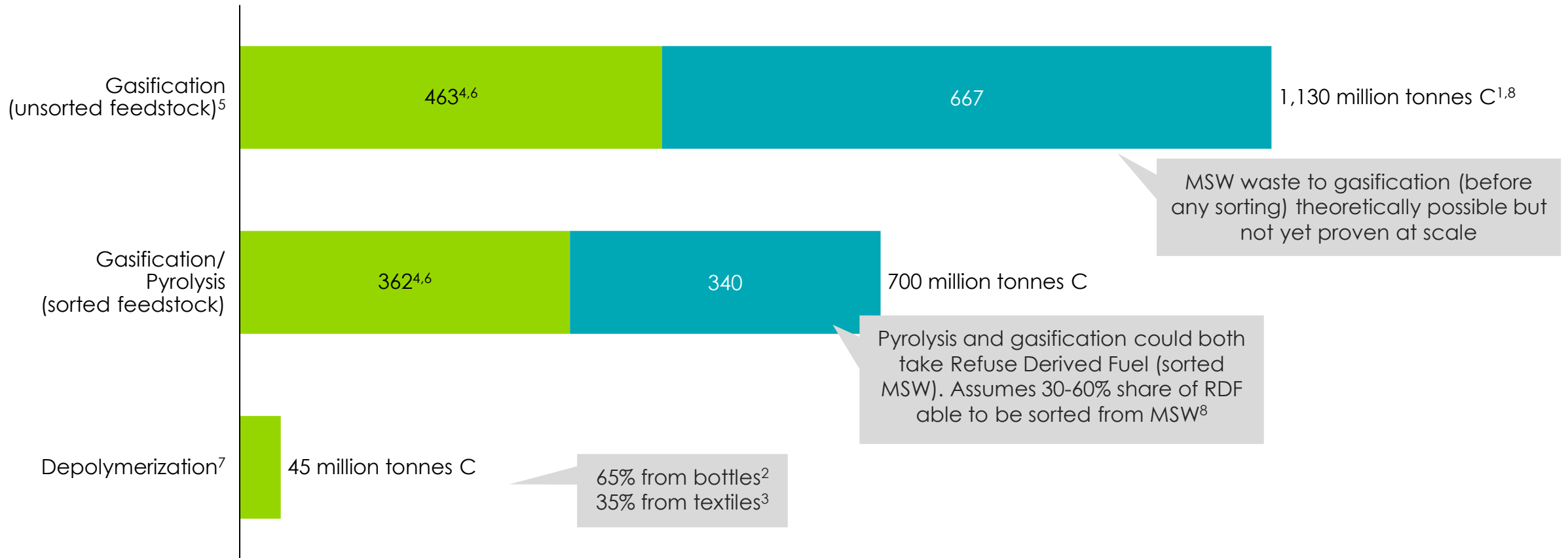
	Pyrolysis	Gasification	Depolymerisation
Advantages	<ul style="list-style-type: none"> Tolerates mix of contaminated plastics and some non-plastic materials (e.g. 1-7 wt% metals/glass/dirt²) Easy integration with existing steam crackers 	<ul style="list-style-type: none"> Tolerance for mixed waste feedstock³ Produces syngas, which can be utilized in several downstream routes. 	<ul style="list-style-type: none"> Achieves high product quality – virgin PET equivalent output Can integrate with existing production lines Enables close-loop recycling, by even upgrading the material.
Challenges	<ul style="list-style-type: none"> Feedstock: Low <0.3wt% tolerance to PVC Numerous product lines, relies on existing petrochemical infrastructure 	<ul style="list-style-type: none"> Feedstock: Requires high feedstock volumes to be economically viable Requires scale for business case 	<ul style="list-style-type: none"> Feedstock: Does not process mixed-waste feedstock Pre-processing of feedstock costly



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 polymer 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.



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

✗ Incompatible ✗ Technology emerging

	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	✗	✗	✗	✗	✗	✗	✗
	Pyrolysis ²	✗				✗	✗	✗
	Gasification	✗				✗	✗	✗
	Incineration							✗

Key takeaways

- Mechanical recycling, chemical reprocessing¹, 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

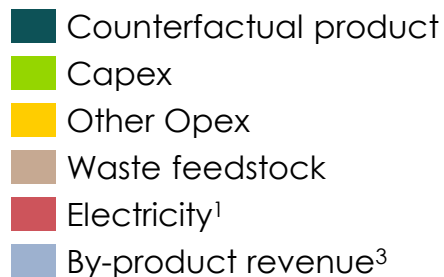
Preliminary

Levelised cost of production
\$/tonne (2025)

Depolymerisation
(PET)

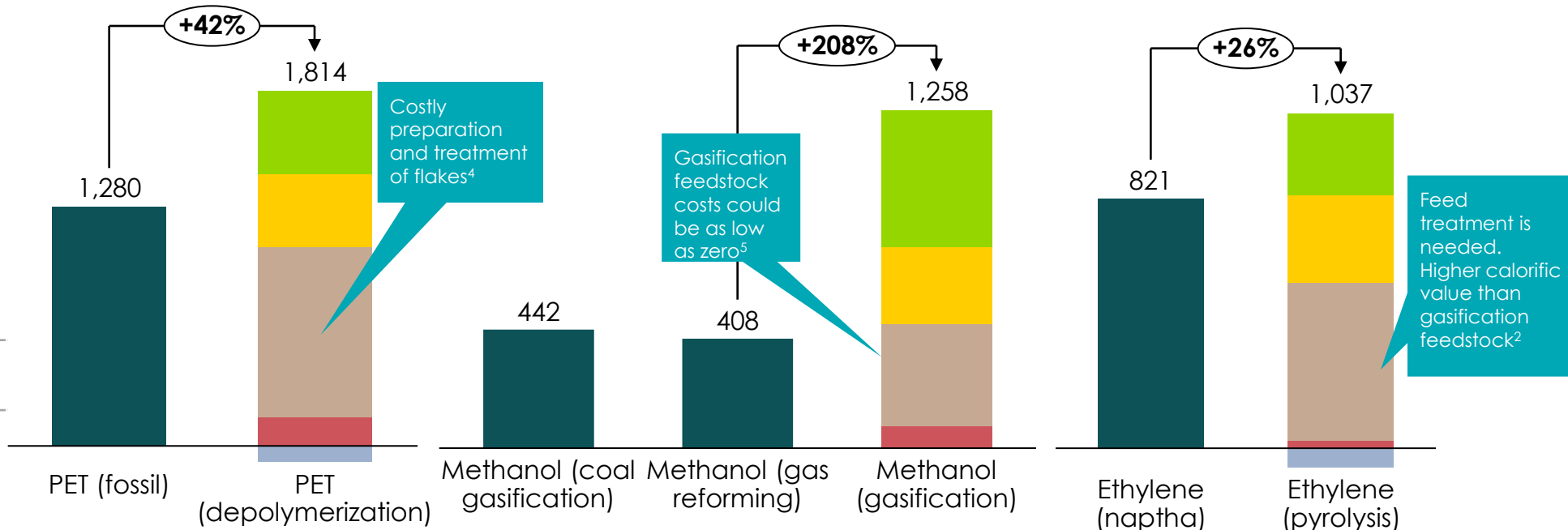
Gasification
(methanol synthesis)

Pyrolysis
(ethylene cracking)



Feedstocks

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



Key takeaways on cost drivers and trends

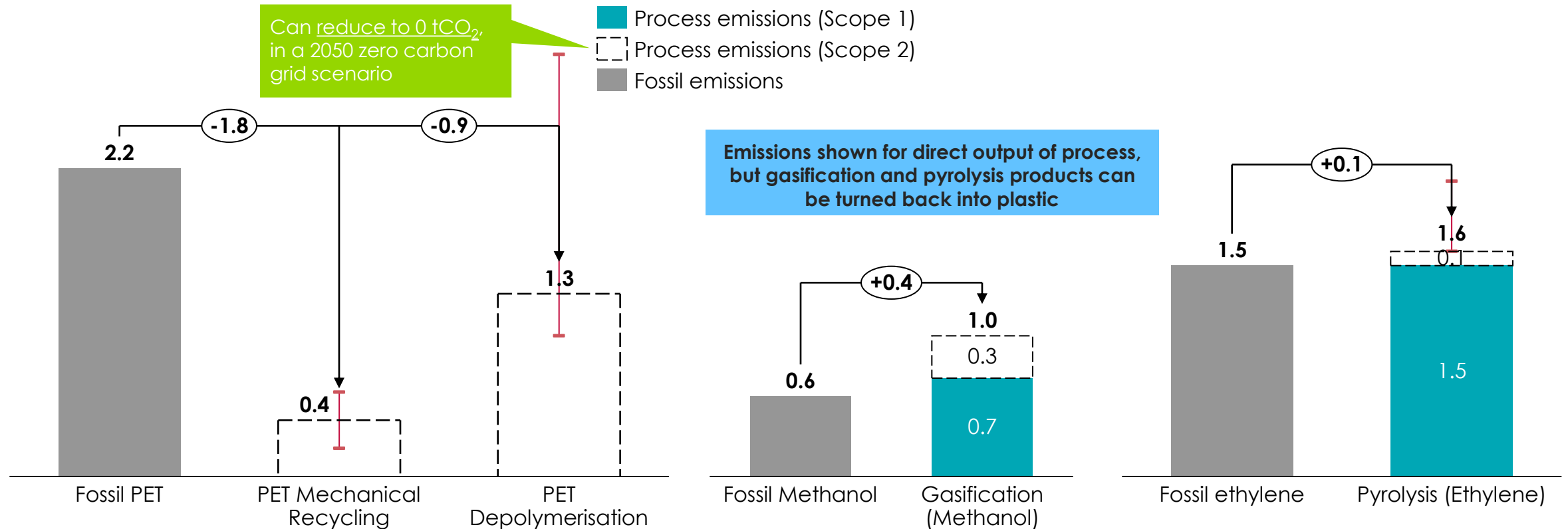
- Cost-competitiveness driven by price of feedstock (assumed here to be high-calorific/sorted MSW, i.e. Refuse-Derived Fuel)
- High capex/opex of gasification technology limiting cost-competitiveness with fossil-based chemicals production
- Feedstock handling and mechanical pretreatment are the cost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

Mechanical recycling and depolymerisation reduce overall CO₂ emissions more effectively, because fossil polymer production is avoided

Preliminary

Emissions within each recycling process vs avoided emissions of fossil route
tCO₂ / tonne of product output

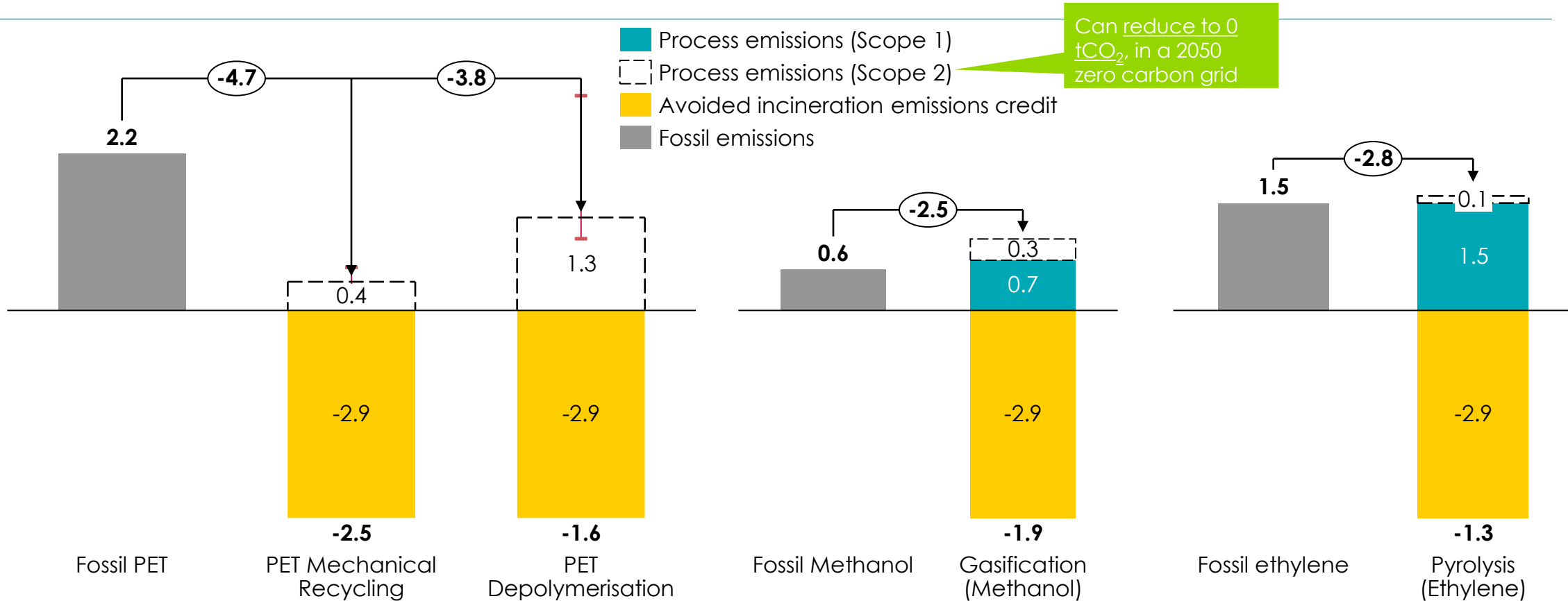


Notes: PET depolymerization shows a wide range of CO₂ emissions depending on the technological path that is followed.
Sources: 1) CE Delft (2019) 2) [Uekert et al. \(2022\)](#) 3) [Uekert et al. \(2023\)](#) Sources: 1) CE Delft (2019) 2) [Uekert et al. \(2022\)](#) 3) [Uekert et al. \(2023\)](#). Carbon 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, Precursors 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](#)

In full chain analysis pyrolysis and gasification provide emissions savings, because CO₂ emissions incineration are avoided

Preliminary

CO₂ emissions for recycling processes, compared with fossil production
tCO₂ / tonne of product output



Can reduce to 0 tCO₂ in a 2050 zero carbon grid

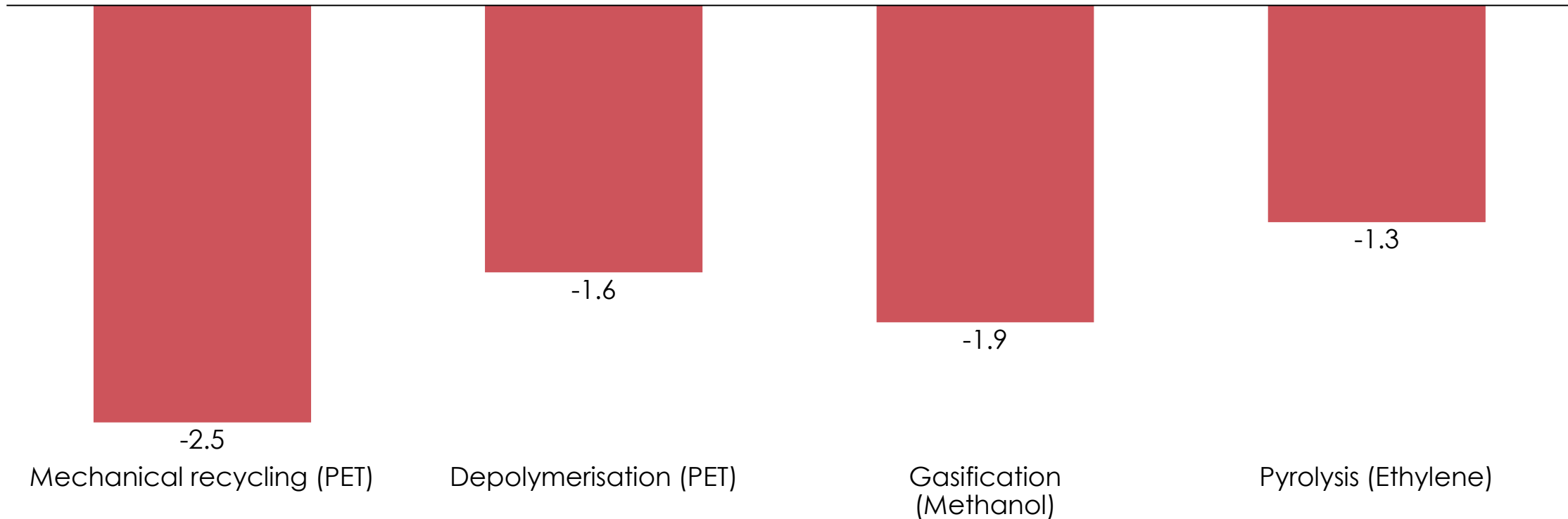
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Mechanical recycling can offer the largest emission savings versus fossil its fossil route

Preliminary

Emission from technologies including incineration savings
tCO₂ / 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, Precursors 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](#)



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 of¹:

- 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

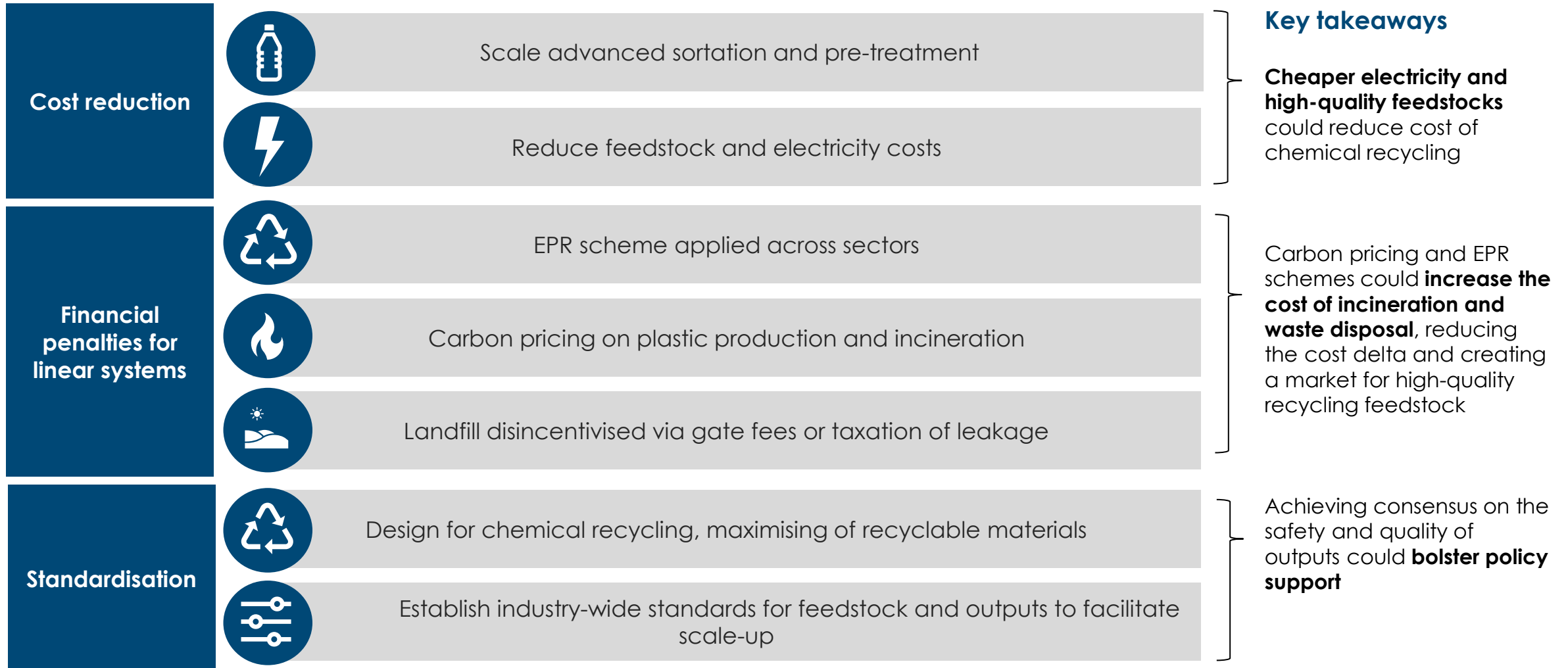
Arguments opposing these technologies^{1,2}:

- 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



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



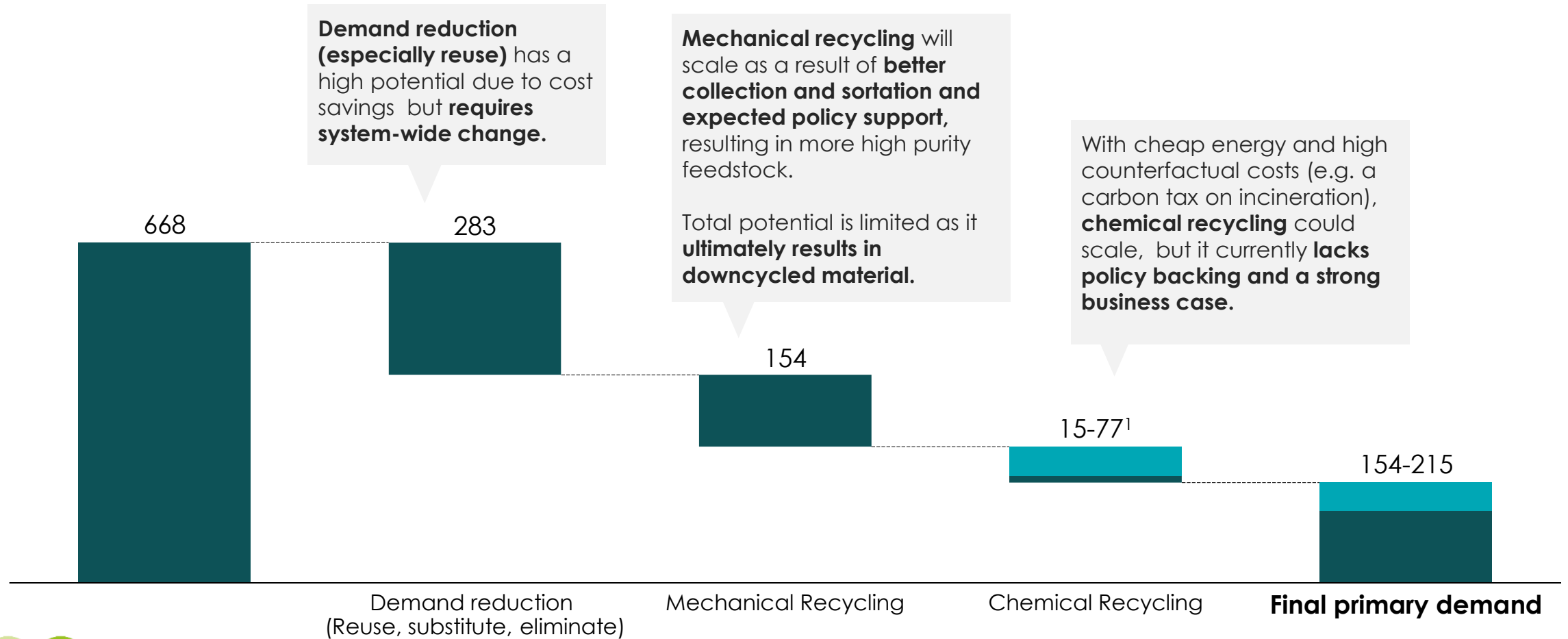
Source: Systemiq Plastic Treaty (2024). List provided is a subset interventions in the Global Full Lifecycle Scenario that related to increase recycling.

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)



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.

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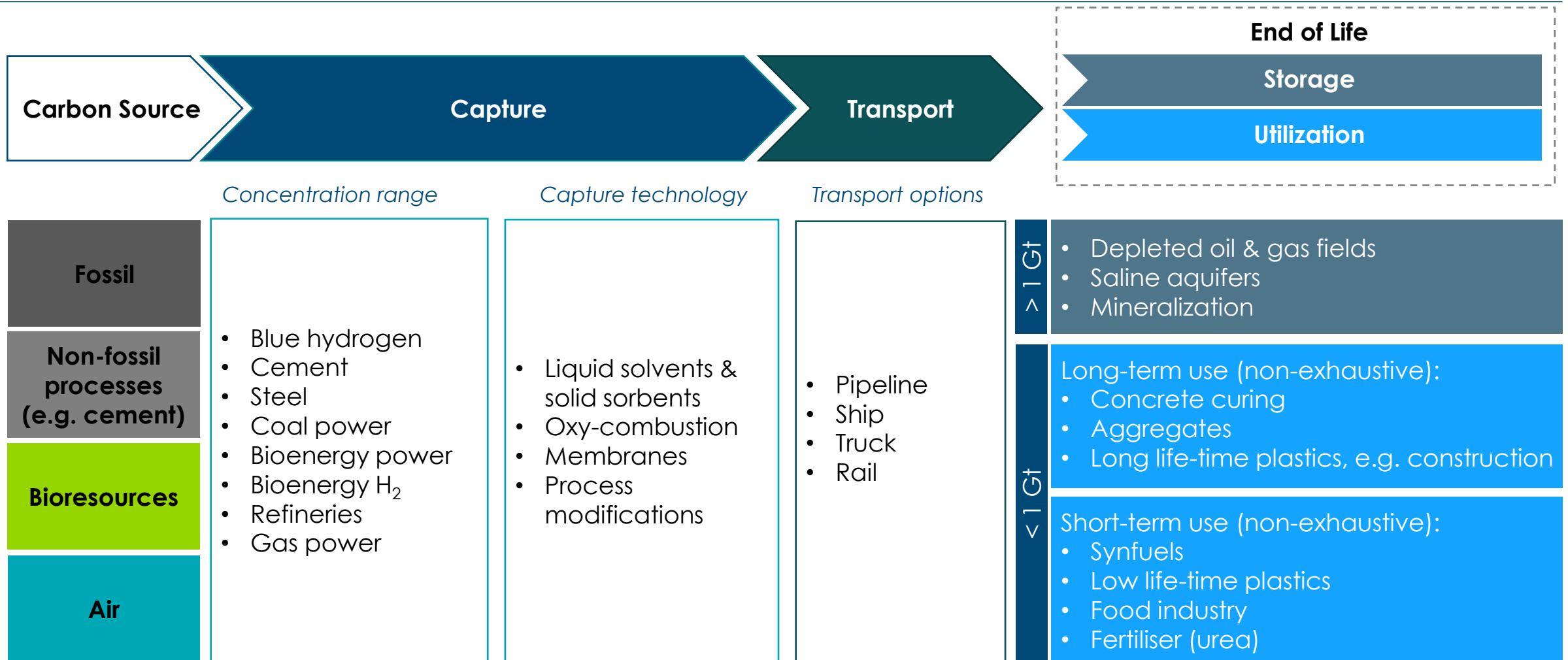


CCU



The CCUS value chain can be split into four distinct stages

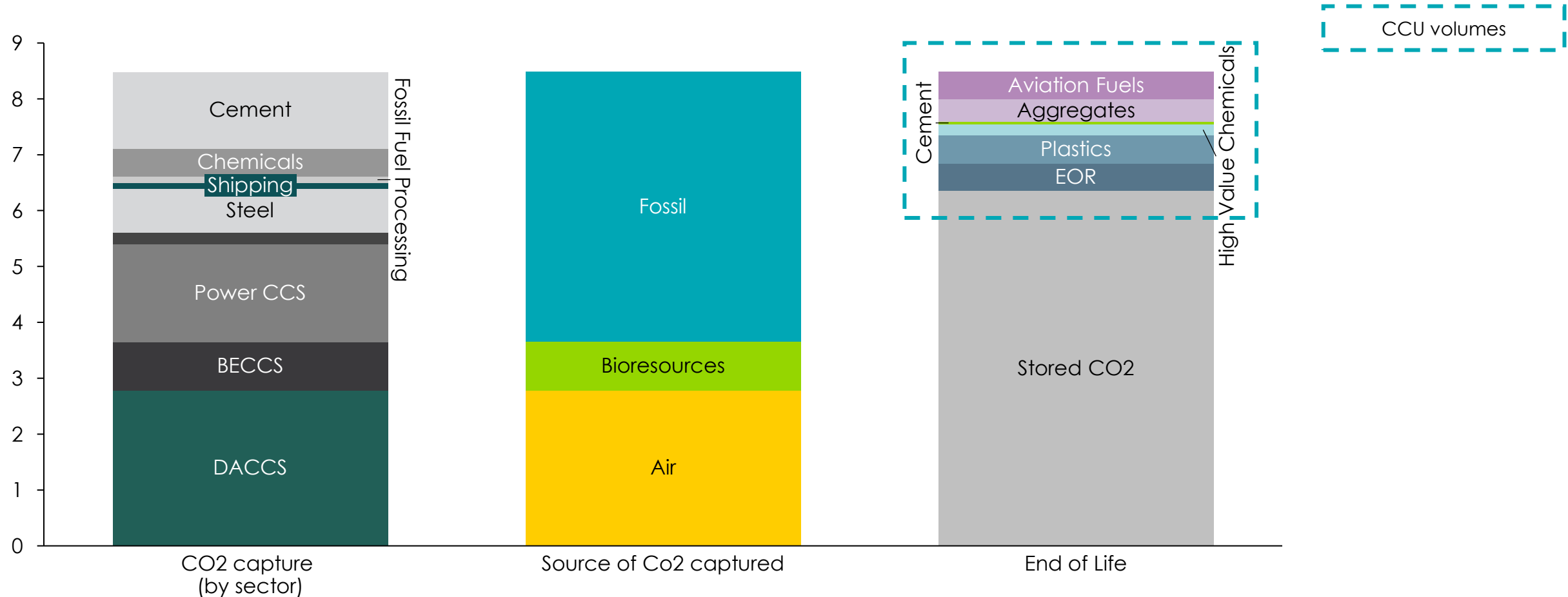
The CCUS value chain



We previously assumed that a majority of captured CO₂ would be sequestered in a net zero 2050, with a small range of utilisation end-use cases

CCUS volumes in 2050 under ACF Scenario
GtCO₂ p.a.

ETC Analysis (2022)



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



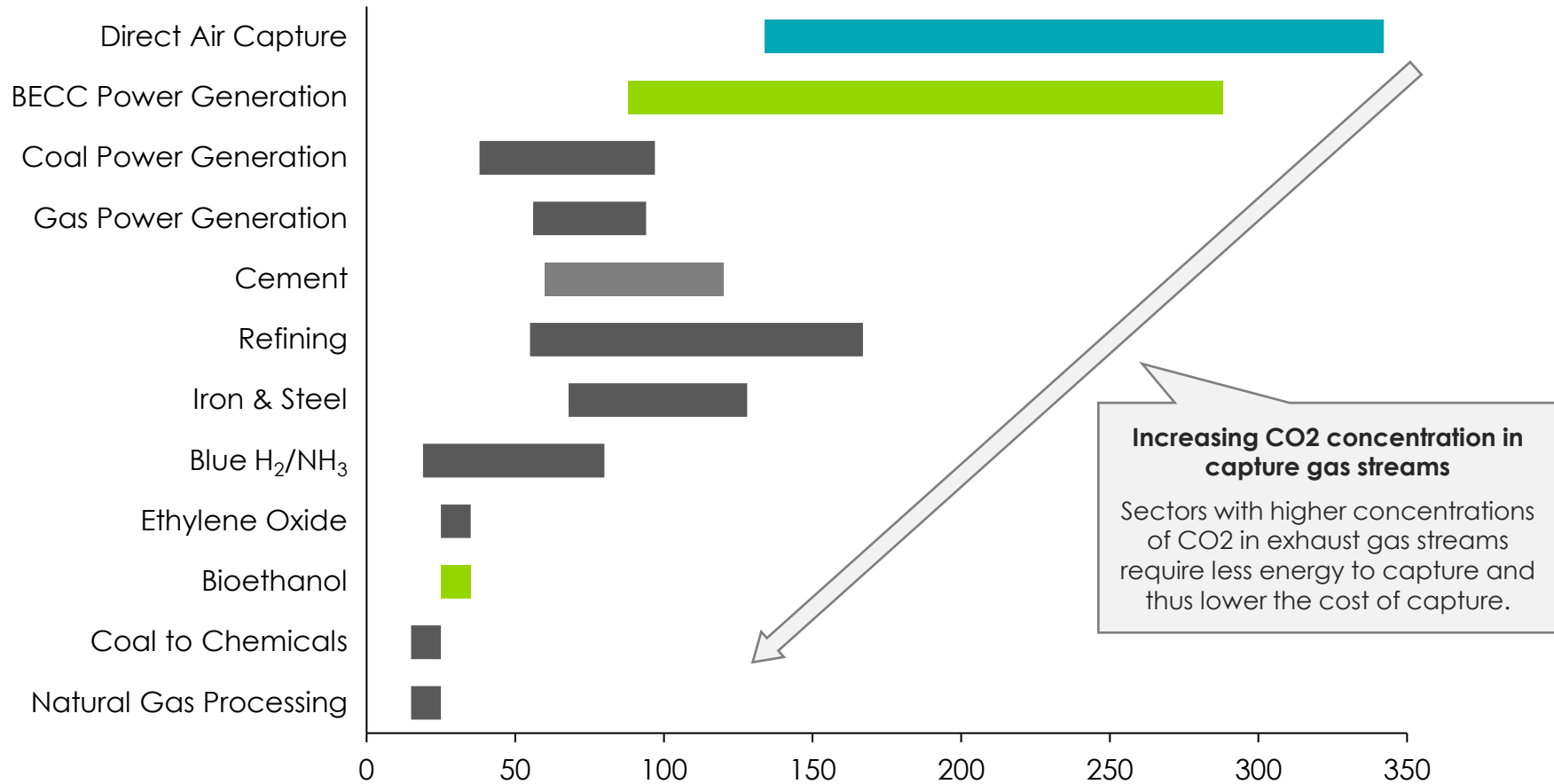
Costs of carbon capture vary widely by sector depending on CO₂ concentration in capture gas streams

ETC Analysis
(2022)
To revisit in
Phase 3

Range of levelised cost of capture estimates by sector today

\$/tCO₂

CO₂ source: ■ Fossil ■ Non-fossil processes ■ Bioresource ■ Air



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

Increasing CO₂ concentration in capture gas streams
Sectors with higher concentrations of CO₂ in exhaust gas streams require less energy to capture and thus lower the cost of capture.

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), CO₂ capture at coal-based power and hydrogen plants, Keith et al. (2018), A Process for Capturing CO₂ from the Atmosphere, NETL (2014), Cost of capturing CO₂ from Industrial sources, Rubin et al (2015), The cost of CO₂ capture and storage; Bloomberg NEF CCUS Costs and Opportunities for Long Term CO₂ Disposal (2021); Fuss et al (2018) 2018. Negative emissions—Part 2: Costs, potentials and side effects



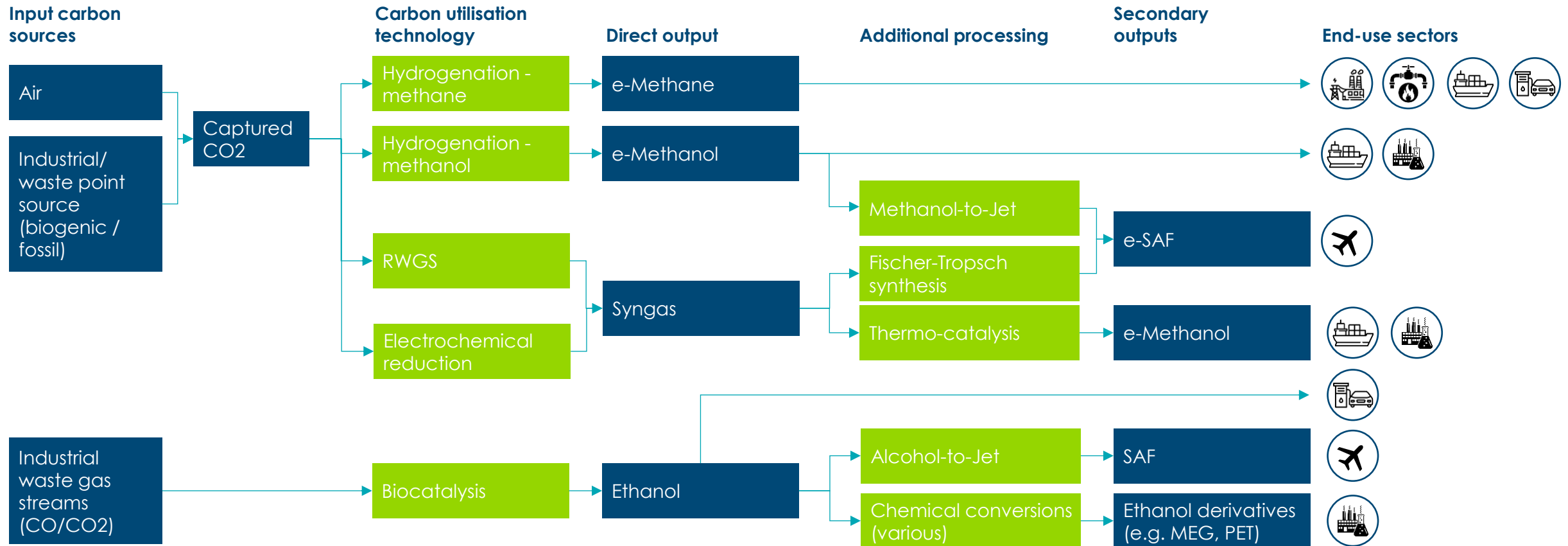
Our deep-dives will focus on CO2 utilization technologies which have reached or are nearing commercialisation

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

Technology	Process	TRL	End-Use Sector ⁴	Companies <i>Non-exhaustive examples</i>
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	JM 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, JM 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	5-8 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 H ₂ 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 electrolyzers. Note that other products are possible with electrochemical reduction (e.g. methanol, ethanol, ethylene), although these technologies are ~ TRL 3. (CIT Renegy, 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)

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	<ul style="list-style-type: none"> 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 materials¹ 		<ul style="list-style-type: none"> High CO purity: outputs are up to 99.995% CO purity Technology is modular Dependent on H₂ for syngas 	<ul style="list-style-type: none"> Well-established technology Many applications for syngas 	<ul style="list-style-type: none"> Depending on feedstock, minimal treatment can be needed² Technologies can be scaled to a wide range of operating capacities
Challenges	<ul style="list-style-type: none"> High costs - dependent on H₂ input Current projects are struggling to reach long-term offtake 		<ul style="list-style-type: none"> High energy use Electrolyte degradation, leaks, and byproduct accumulation 	<ul style="list-style-type: none"> High energy use for heating (600-900°C) Development of efficient/stable catalysts 	<ul style="list-style-type: none"> Effective removal of contaminants² 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)

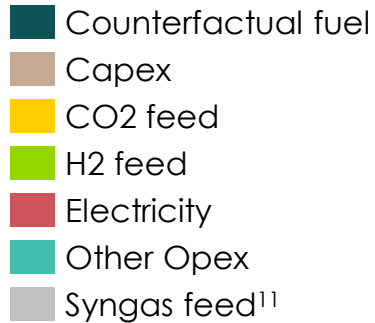
Hydrogenation to Methane

Hydrogenation to Methanol

RWGS

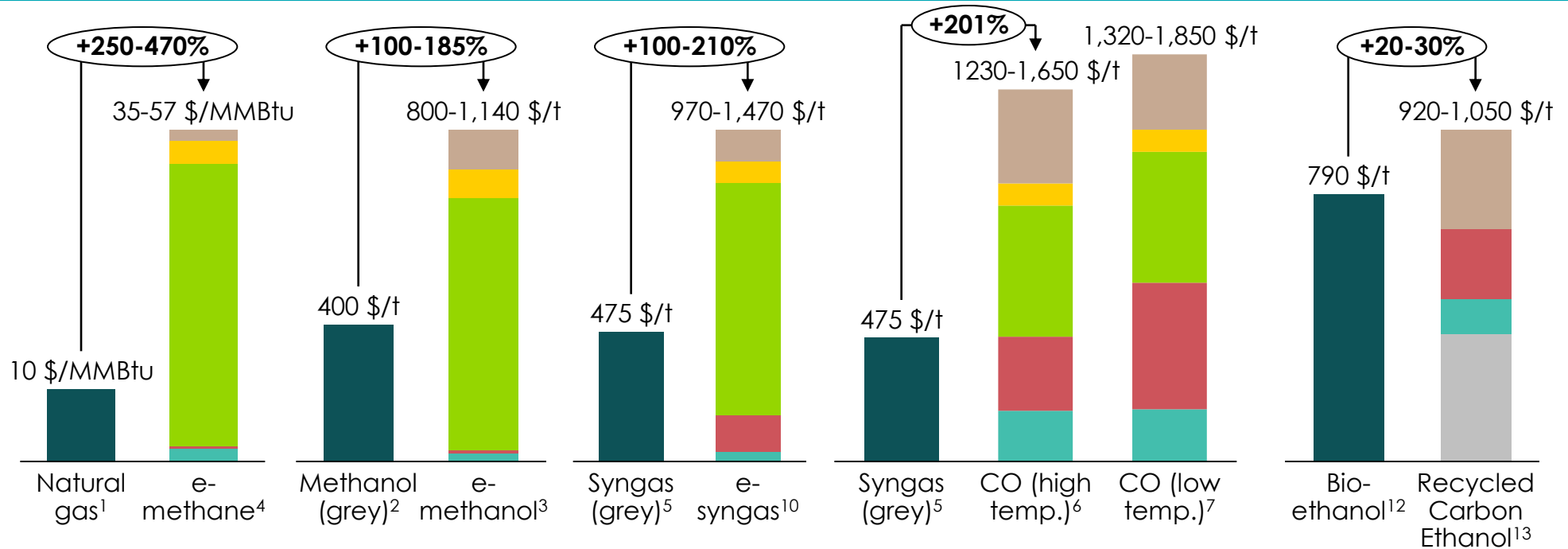
Electrochemical Reduction

Biocatalysis



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

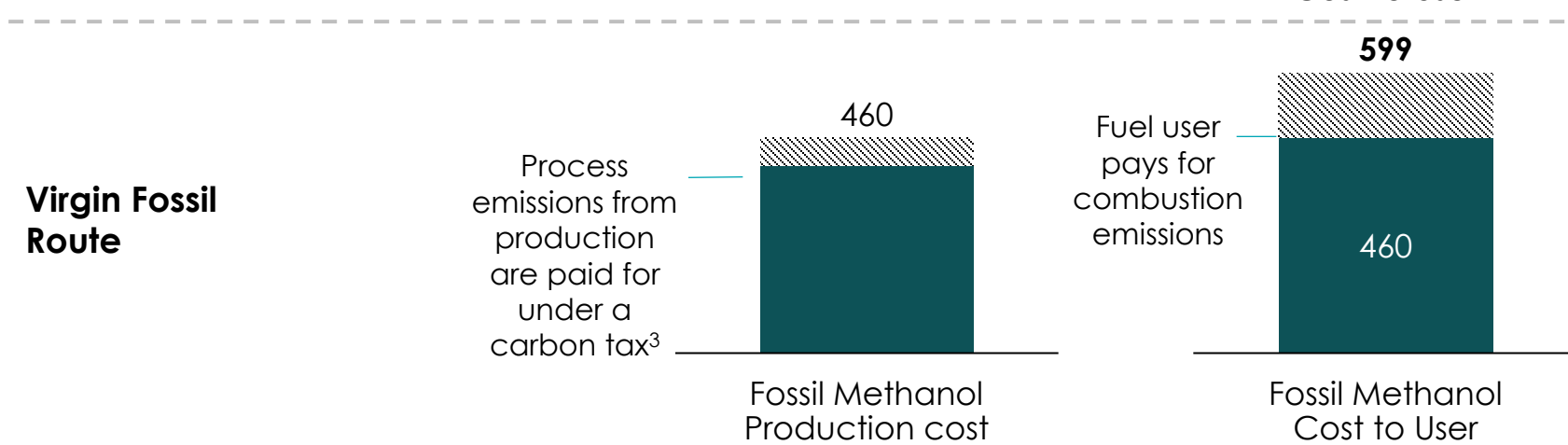
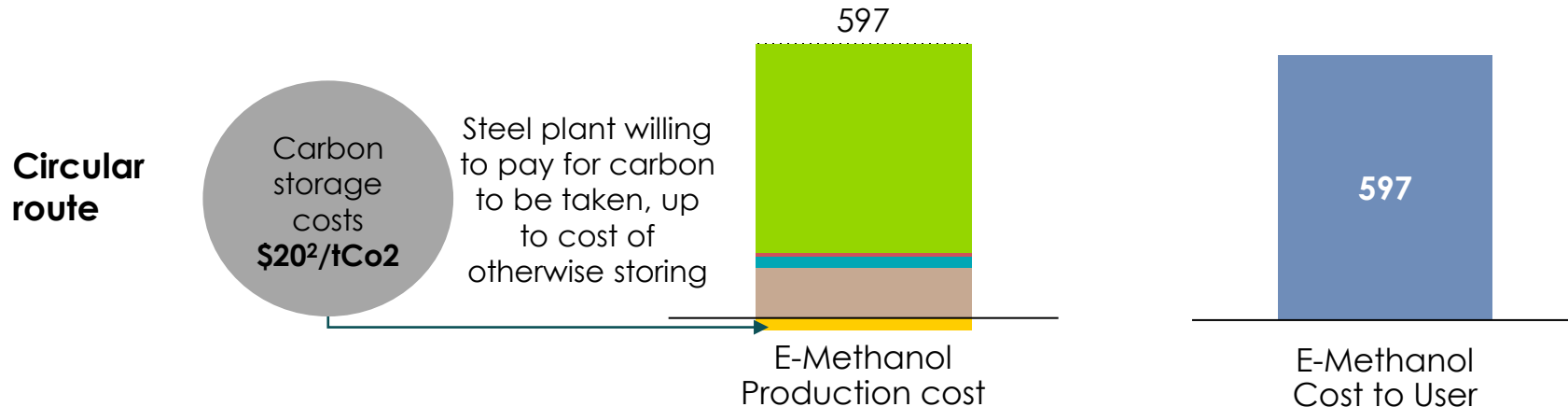
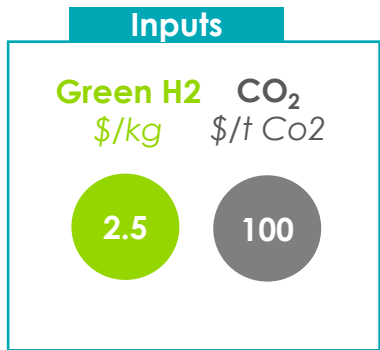
- Cost of hydrogenation/RWGS driven by cost of renewable hydrogen; CO2 cost not a significant factor
- Catalytic reactor technology not expected to realise major capex cost reductions in future given high TRL established technologies
- Costs driven by high capex electrolyzers / cost of electricity
- 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 TIE. 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)

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

Illustrative

System cost hydrogenation – e-methanol
\$/t methanol (2030)



On a Levelized cost of fuel basis, fuel users incentivized to buy e-methanol at \$2.5/kg Green H2 and \$100 t/Co₂ price

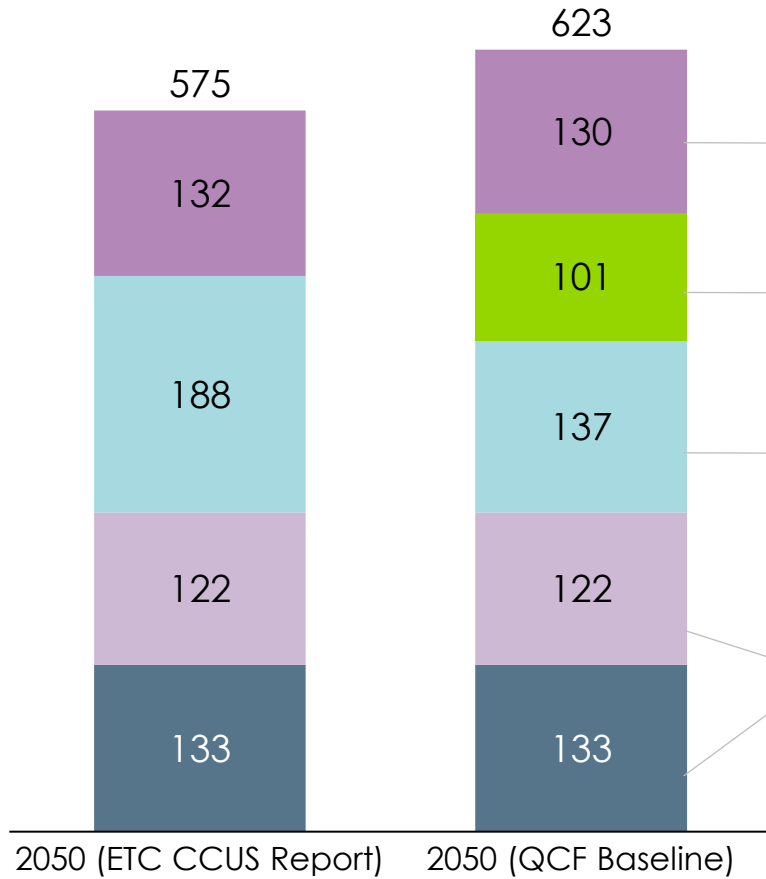
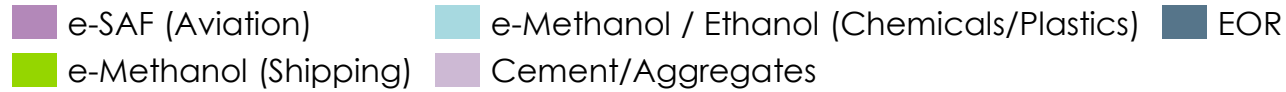
- Emissions costs
- H2 feed
- Electricity¹
- Other Opex
- Capex
- Fossil production
- CO₂ feed



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

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

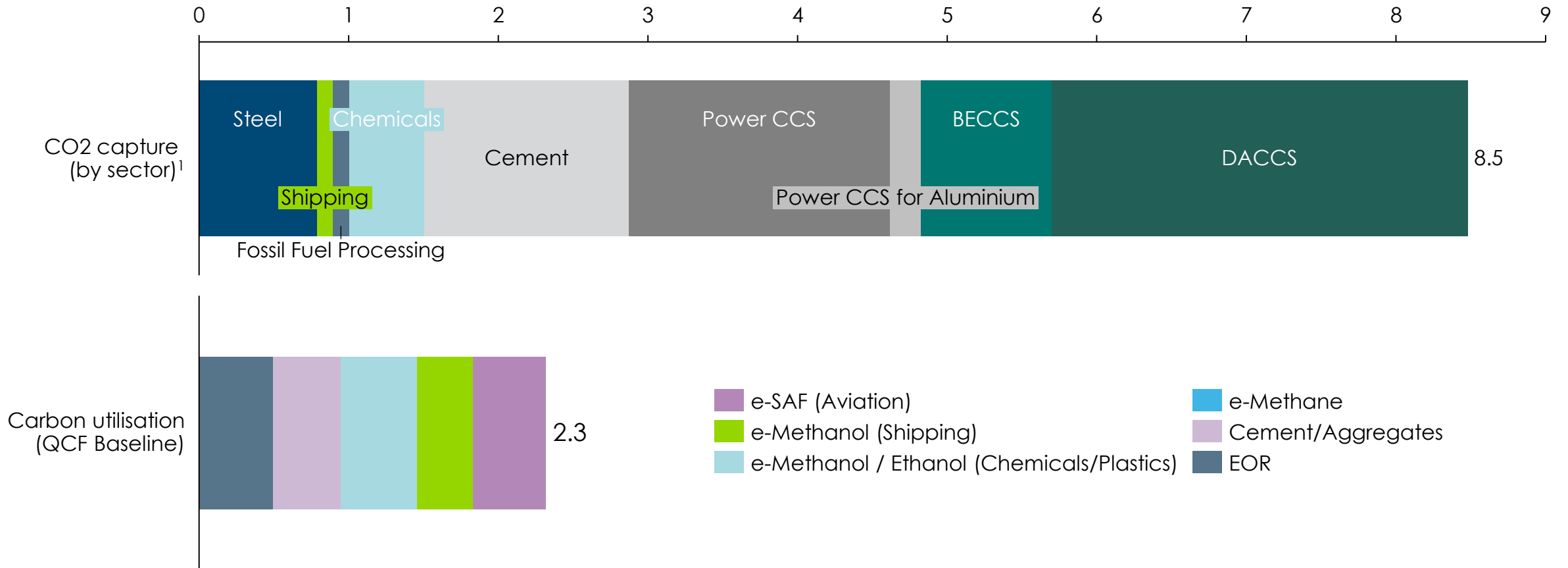


HVC = High Value Chemicals; EOR = Enhanced Oil Recovery; MPP = Mission Possible Partnership; PPC = Planet Positive Chemicals

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

GtCO₂ 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*



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	<ul style="list-style-type: none"> Falling price of hydrogen reduces LCOX of product(s) Raising carbon price reduces the green premium 			<ul style="list-style-type: none"> Learning rates for electrolyzers for reduced capex Sourcing of low-cost /renewable electricity 	<ul style="list-style-type: none"> Abundant and low-cost sourcing of industrial carbon waste gas feedstocks
	Offtaker markets ready	<ul style="list-style-type: none"> Compliance market for e-methane and e-LNG in heating and transport emerges 	<ul style="list-style-type: none"> SAF + shipping blending mandates drive offtake of e-SAF and e-methanol High carbon pricing and regulation pushes plastic production to low-carbon feedstocks 			<ul style="list-style-type: none"> SAF mandates Sustained demand for low-carbon ethanol in road transport/plastics
Key takeaways		<ul style="list-style-type: none"> Reducing the green premium via reducing the cost of green H₂ 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) 				<ul style="list-style-type: none"> 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

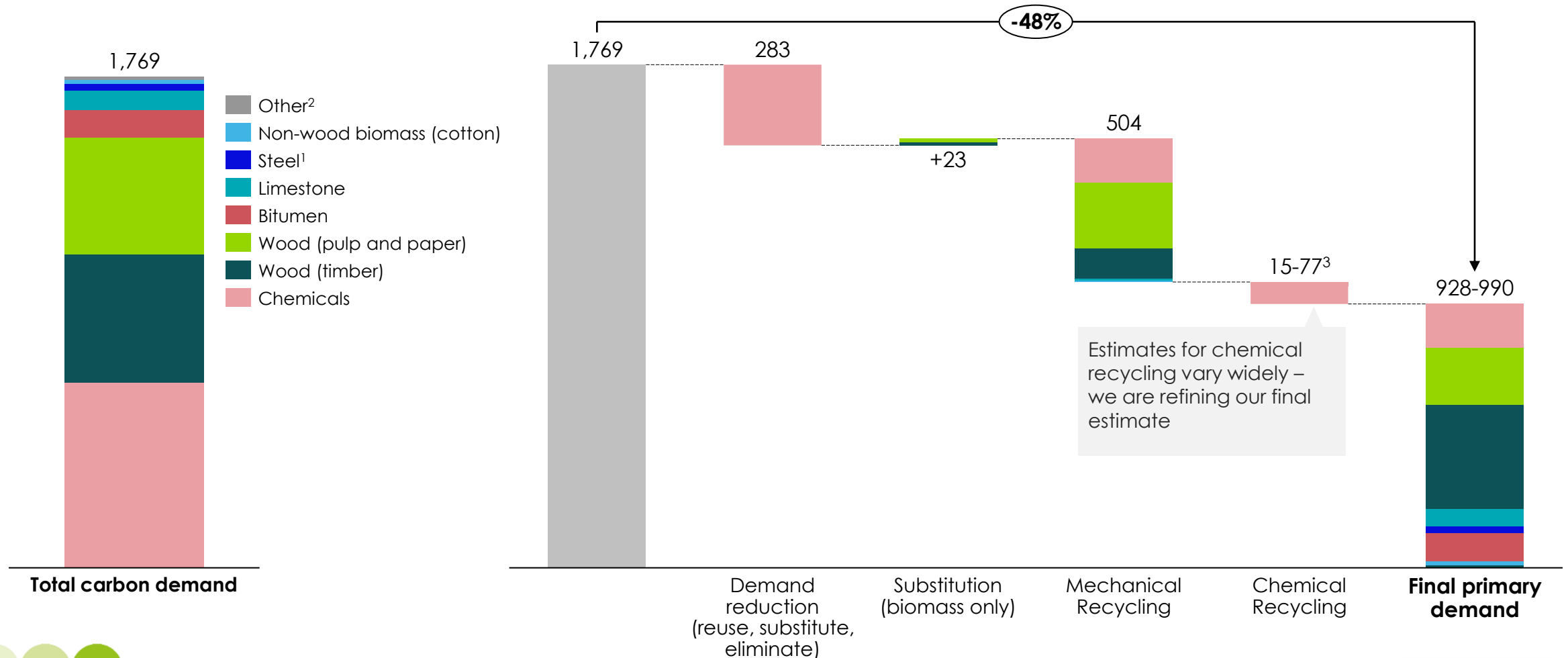


For materials sectors, the largest potential to recycle and reuse materials comes from mechanical recycling

Preliminary

Carbon recycling potential in the Materials Sector, 2050

Million tons of carbon (C)



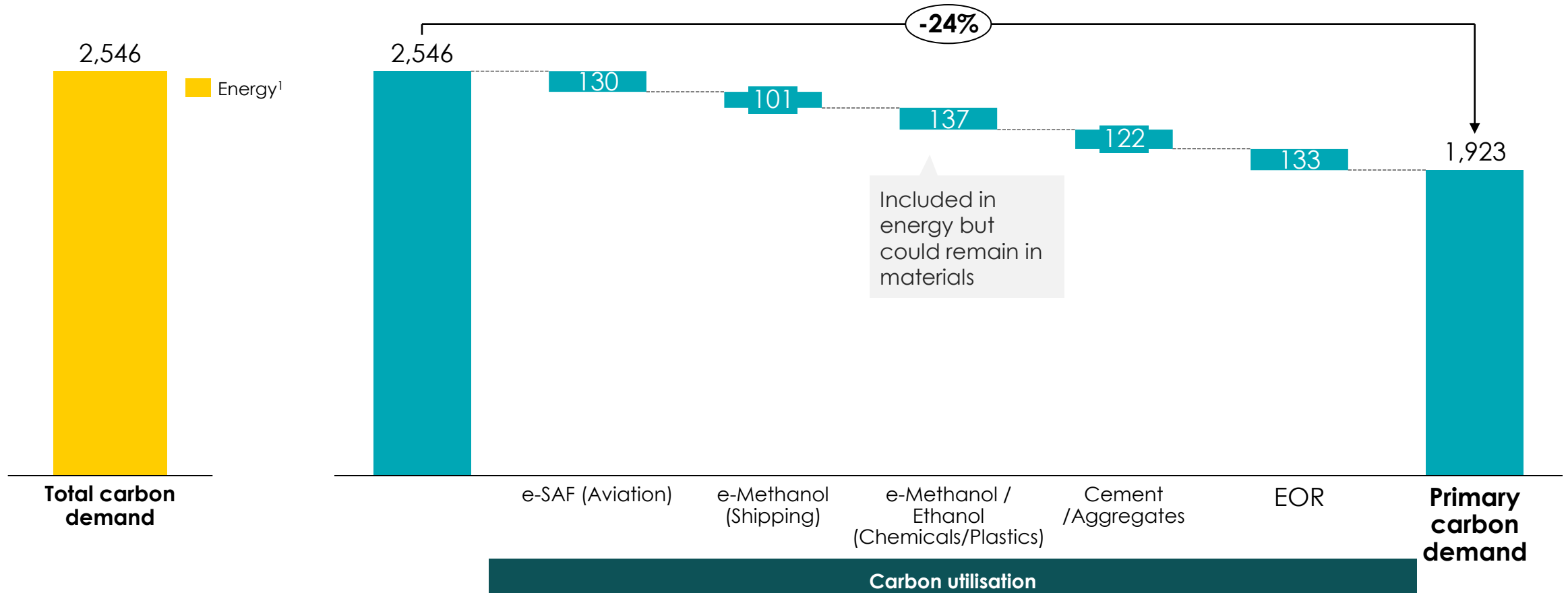
Sources: Energy: Systemiq analysis (2025), based on Fossil Fuels in Transition (ETC, 2023); Chemicals: Planet Positive Chemicals Report (Systemiq, 2022, BAU Net-Zero scenario), and Systemiq (2024) Plastic Treaty Futures.; 1) Chemicals and steel includes the feedstock from the energy system that has remained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

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

Preliminary

Carbon utilization potential from energy sector Carbon, 2050

Million tons of carbon (C)



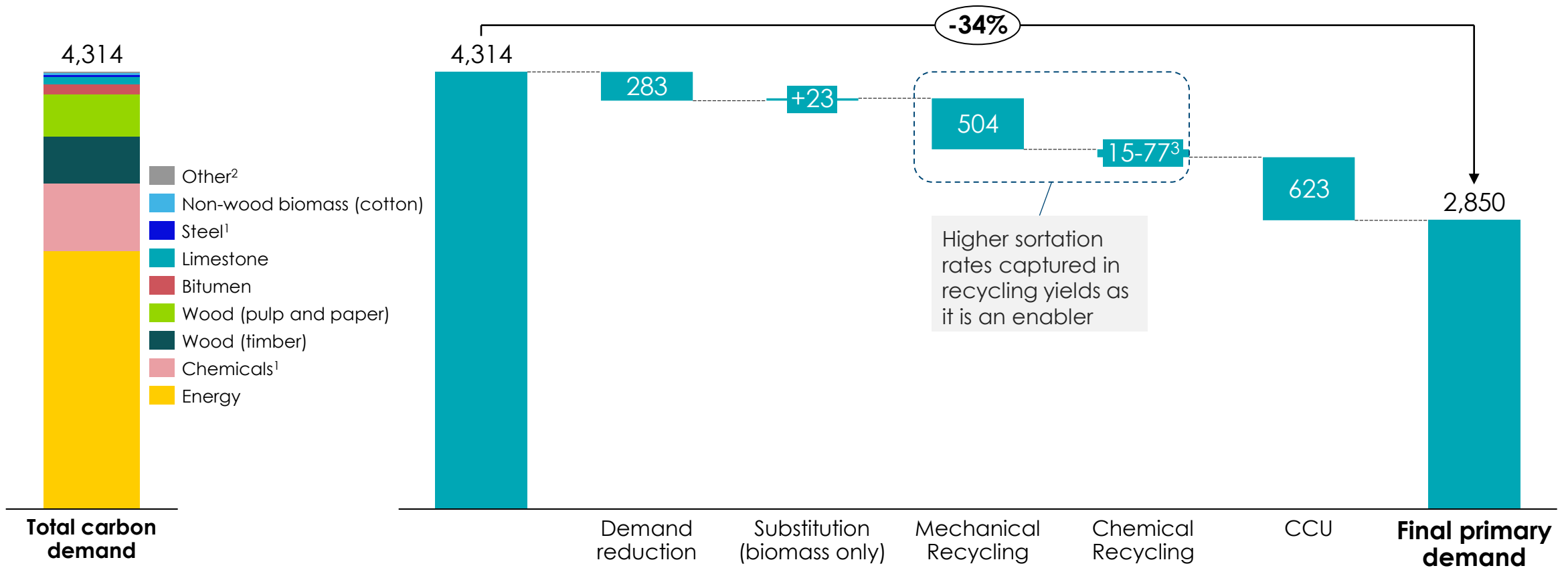
Sources: Energy: Systemiq analysis (2025), based on Fossil Fuels in Transition (ETC, 2023); Chemicals: Planet Positive Chemicals Report (Systemiq, 2022, BAU Net-Zero scenario), and Systemiq (2024) Plastic Treaty Futures.; 1) Excludes energy feedstocks used that remain in steel and chemicals, which are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

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



Economic

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



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

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 CO₂**, 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**

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

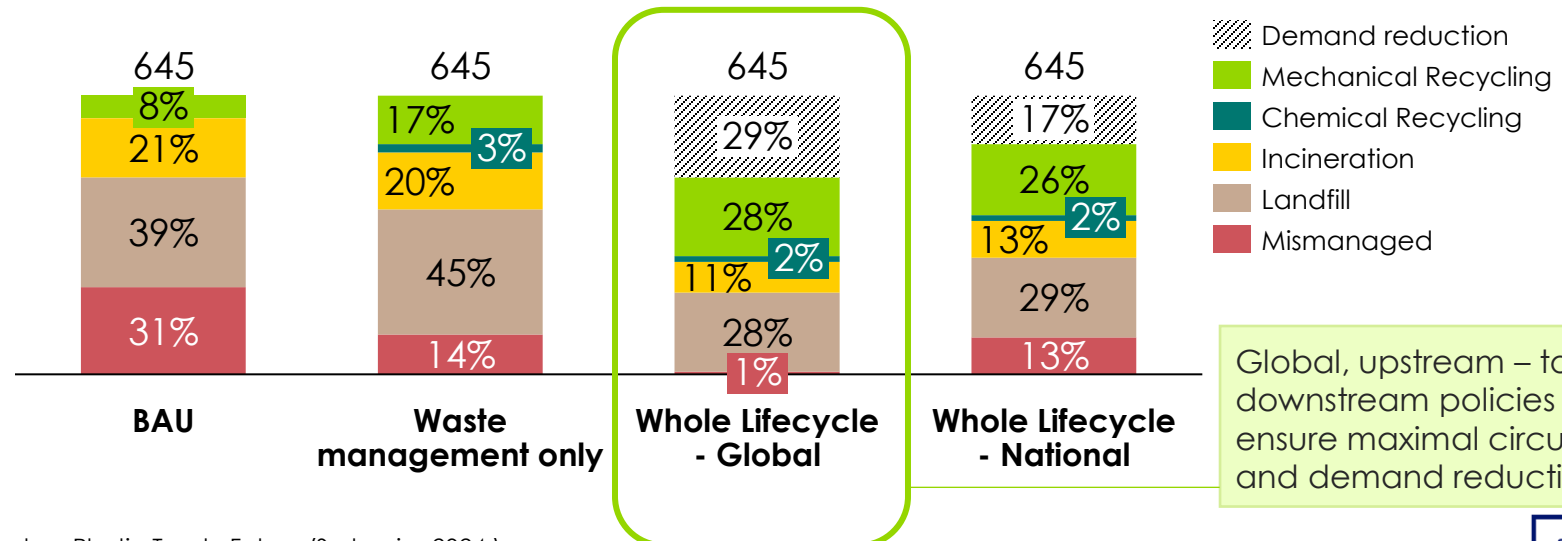
Whether to regulate just plastic **waste** or also production.

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



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

RED III¹ and the second Delegated Act² lays out specific rules for which sources of CO₂ 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 CO ₂ 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 CO₂ 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 CO₂ now could lead to stranded assets
- **Most projects in the pipeline in Europe plan to source CO₂ 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

