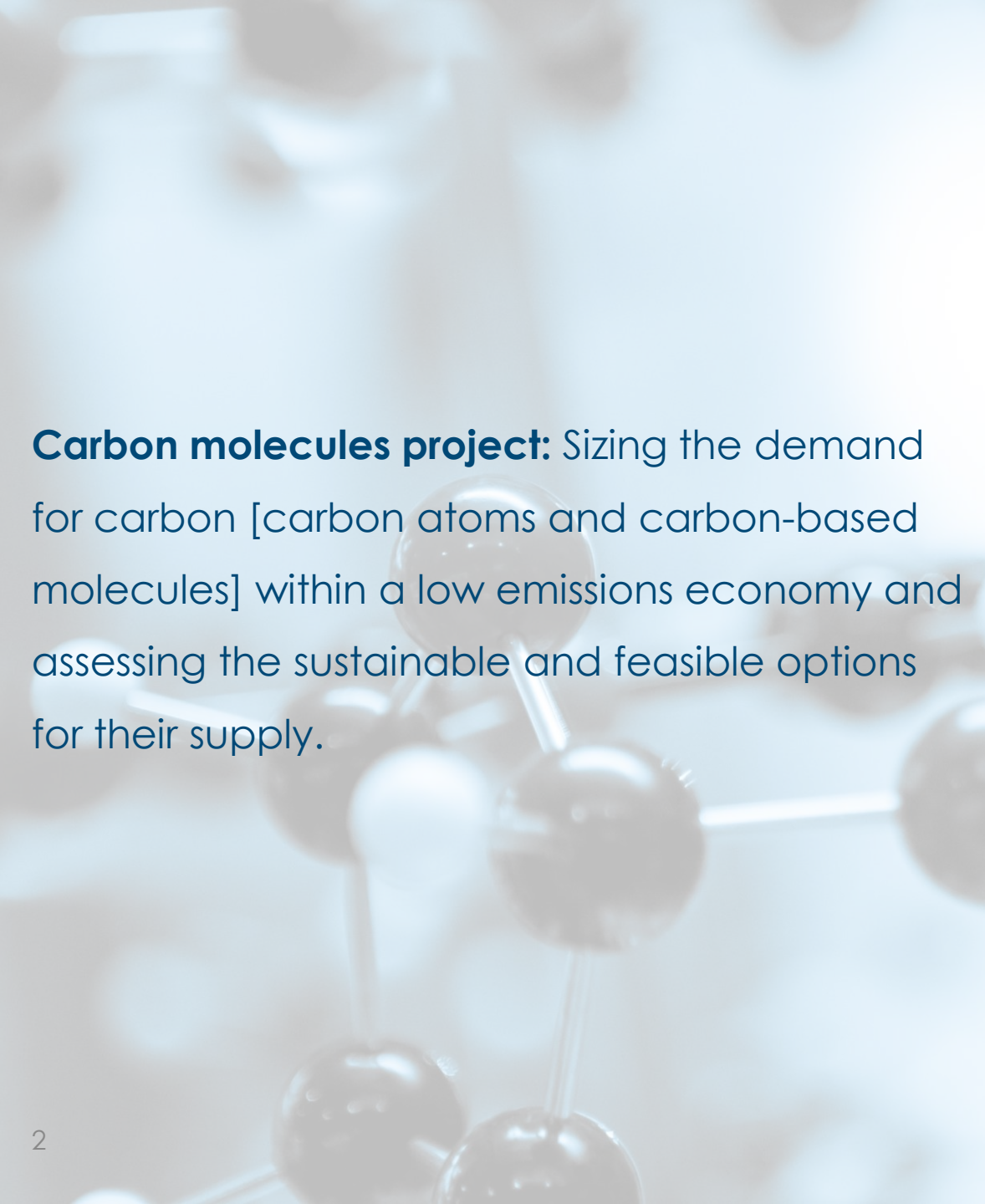




Energy
Transitions
Commission

Low-carbon Molecules: emerging conclusions

*ETC Commissioners Meeting
20th March 2025*



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

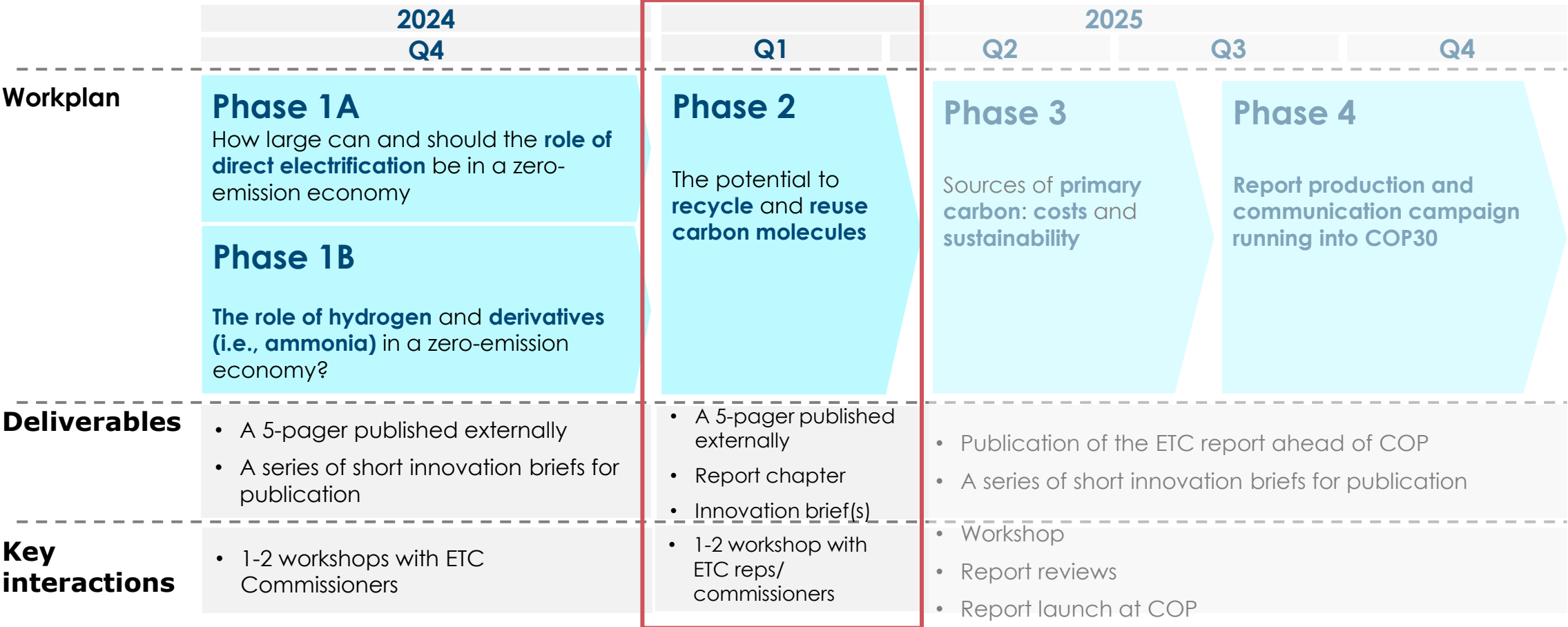
Our topics today

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
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



Currently Ongoing



Agenda

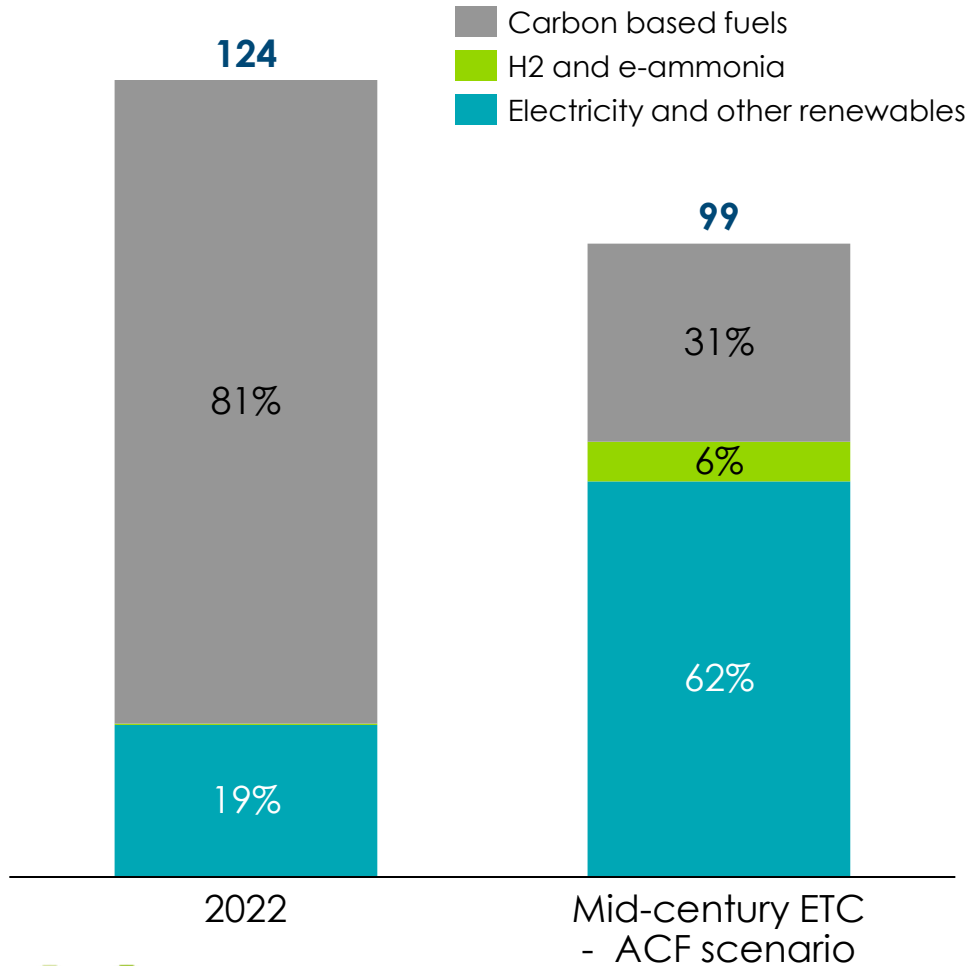
- **The demand for carbon molecules**
- The role of electrification and hydrogen
- The potential to recycle and reuse carbon



The need for carbon molecules in our energy system will decline with decarbonization, but up to 3.3 Gt will still be required by mid-century

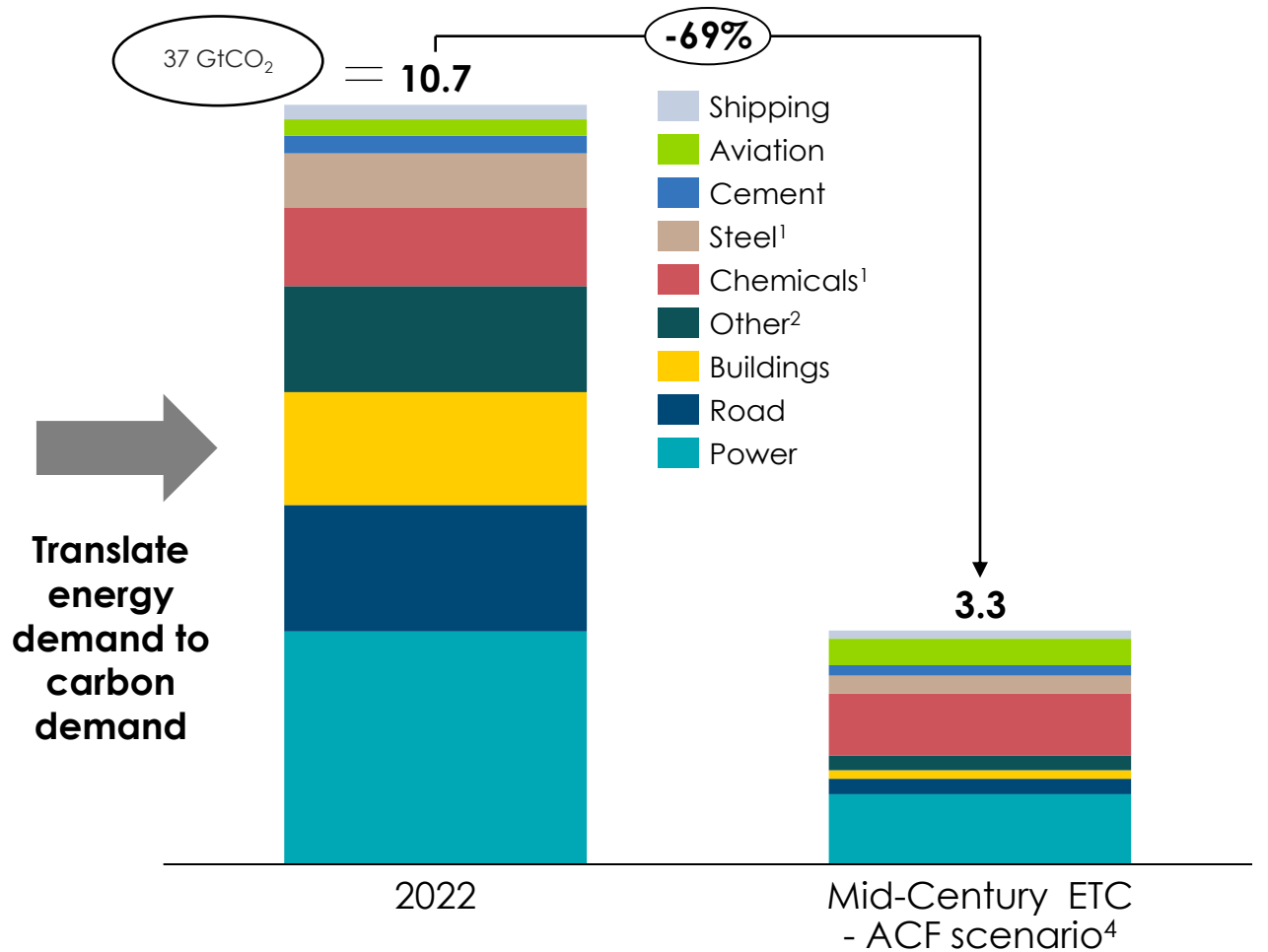
Final Energy Demand for 2022 and ETC's Accelerated but Clearly Feasible (ACF) scenario in 2050

Thousand of TWh



Carbon Demand Across the Energy Sector

Gigatons of carbon (C)

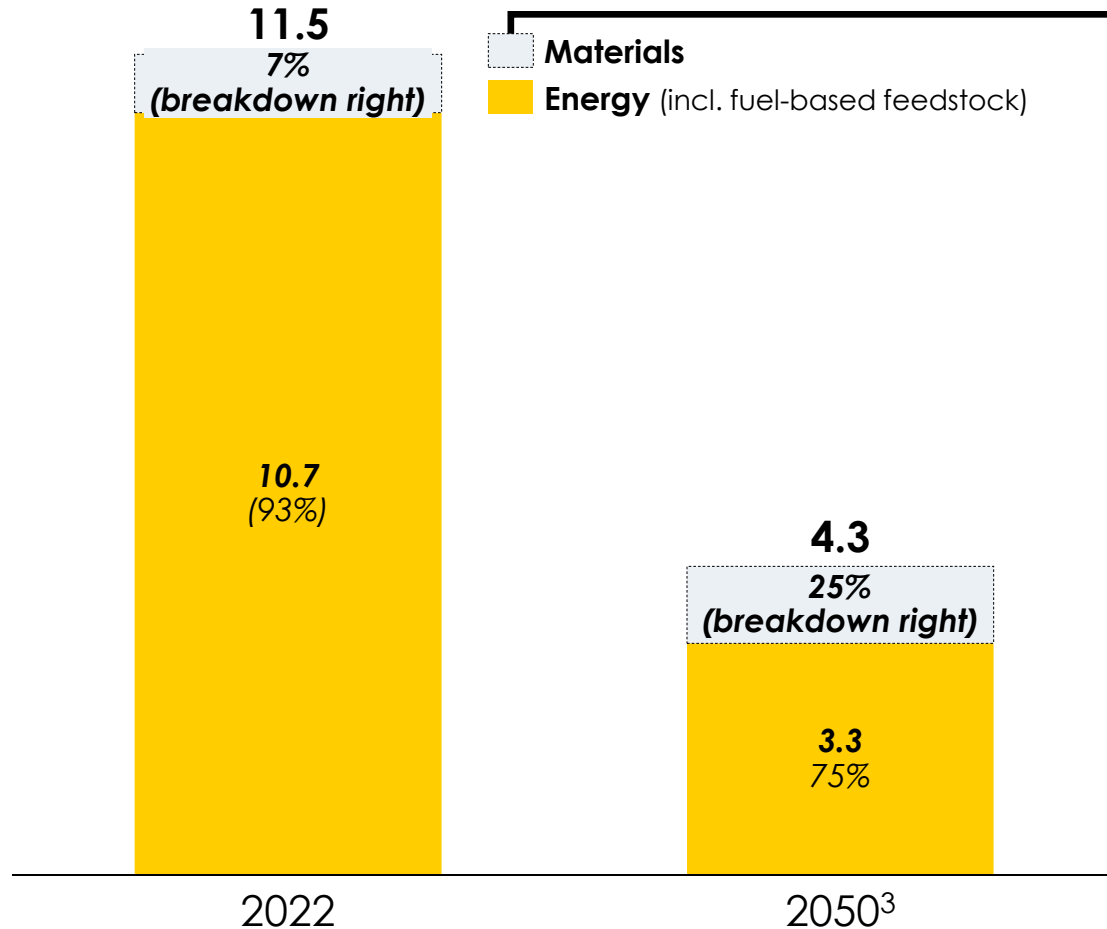


Notes: *ACF = Accelerated but Clearly Feasible scenario, based on ETC Fossil Fuels in Transition (2023) with minor updates. Sources: Chemicals: Planet Positive Chemicals Report (Systemiq, 2022, BAU Net-Zero scenario); Biomass: ETC Bioresources report (2021); Steel: MPP STS (2022); Cotton, Bitumen and Soda Ash: Systemiq analysis (2025) . 1. Include energy based carbon feedstocks, a proportion of 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. Carbon-based fuels include those fuels that also require carbon sources, e.g. e-methanol and synthetic aviation fuels.

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

Carbon demand across the energy and material sectors

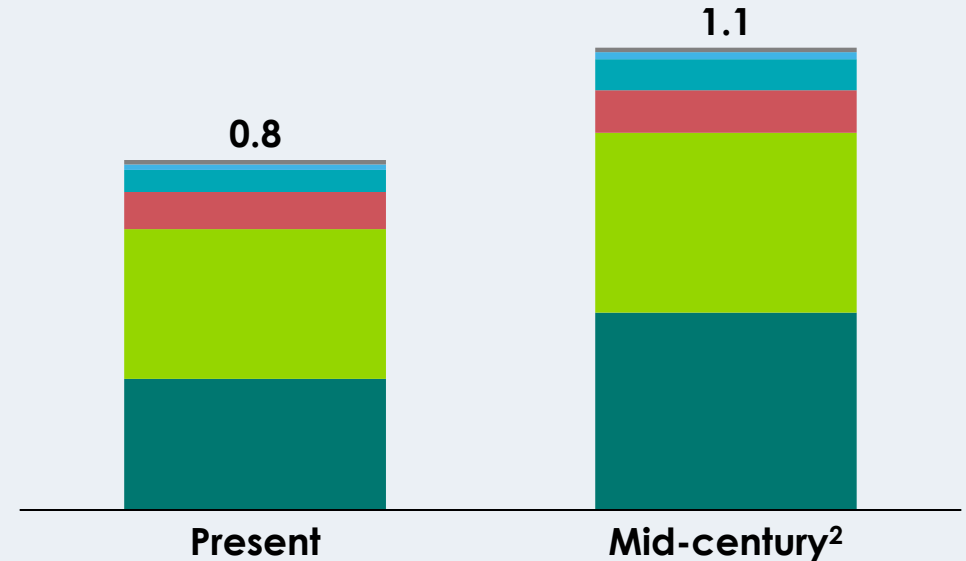
Gigatons of carbon (C)



Carbon demand breakdown across major materials

Gigatons of carbon (C)

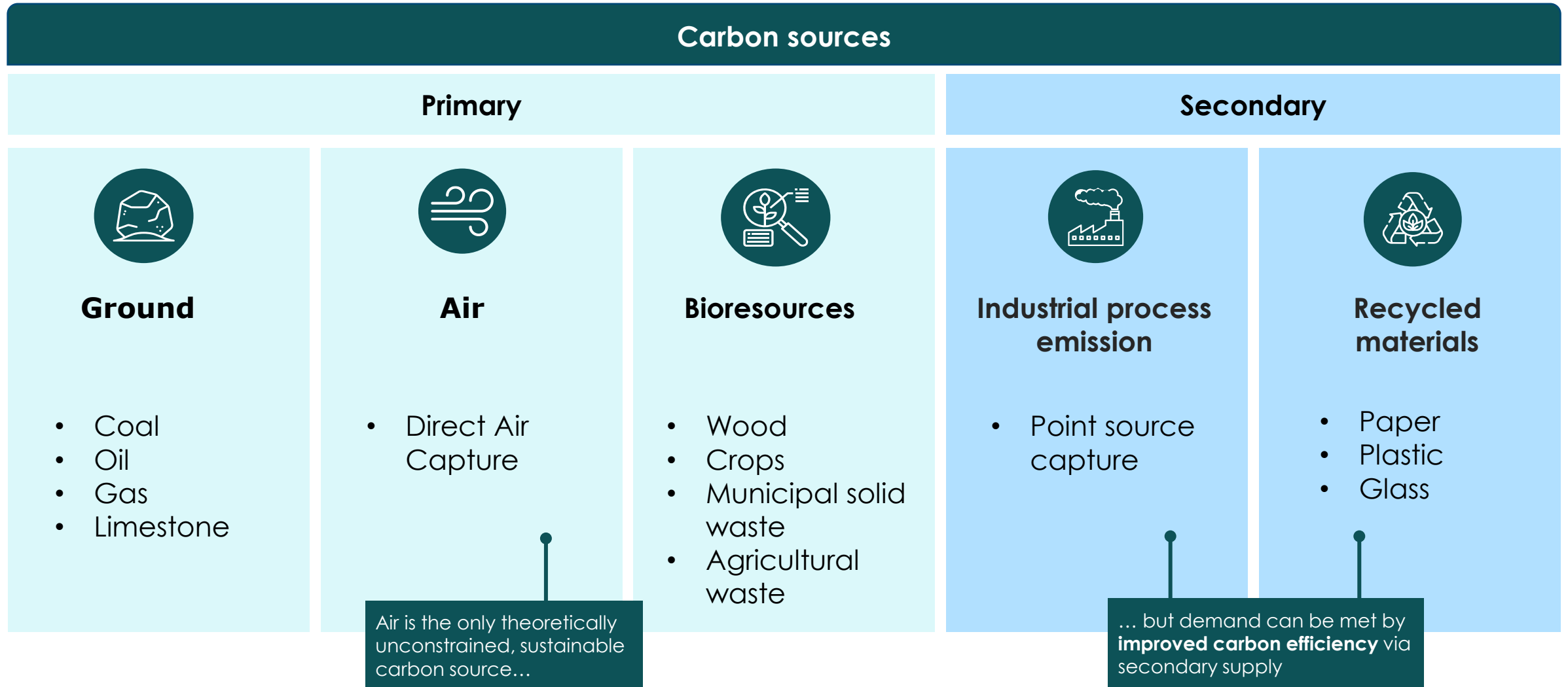
- Other¹
- Non-wood biomass (cotton)
- Limestone
- Bitumen
- Wood (pulp and paper)
- Wood (timber)



Source: Energy: Systemiq analysis (2025), based on Fossil Fuels in Transition (ETC, 2023); Chemicals: Planet Positive Chemicals Report (Systemiq, 2022, BAU Net-Zero scenario); Biomass: ETC Bioresources report (2021); Steel: MPP STS (2022); Cotton, Bitumen and Soda Ash: Systemiq analysis (2025)
 Note: 1) Includes carbon ash, biochar, carbon fibre, charcoal, 2) Assumes BAU growth, with limited circularity. 3) Energy sector = ACF scenario.



The case for carbon efficiency: Carbon comes from multiple sources, but sustainable carbon is scarce....



Agenda

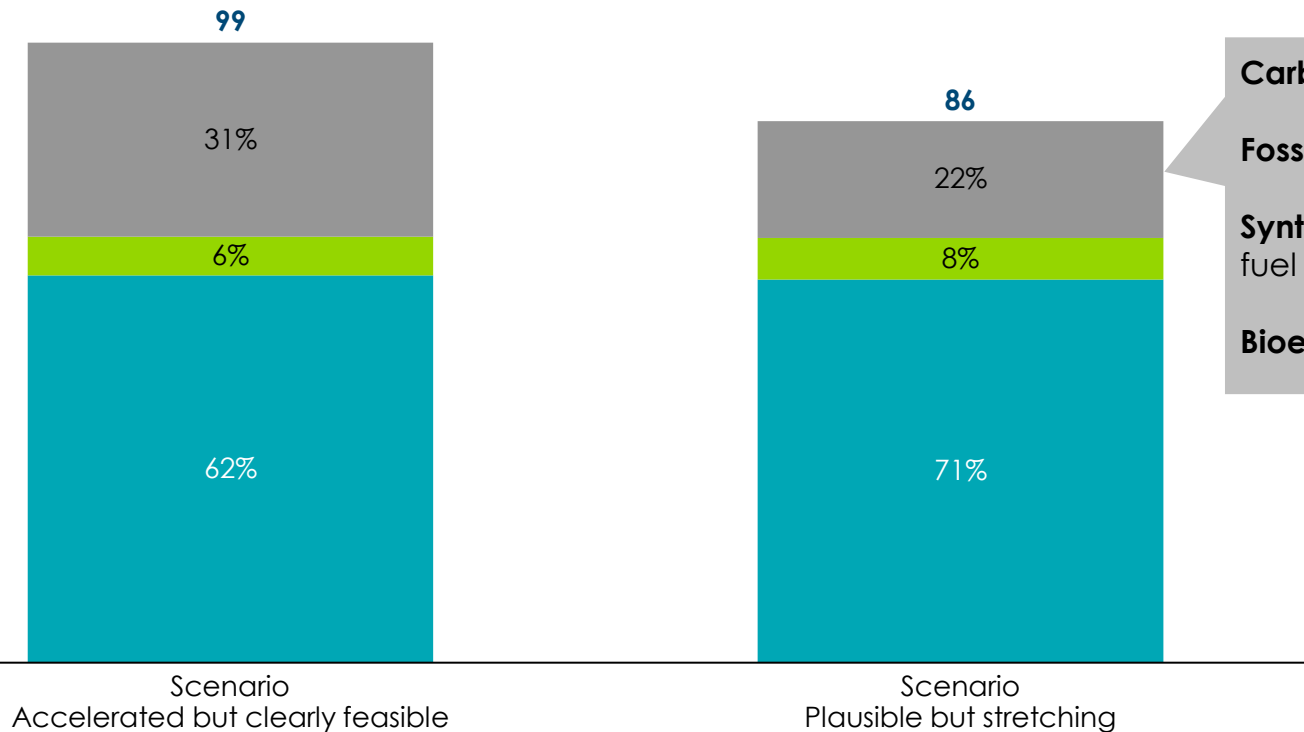
- The demand for carbon molecules
- **The role of electrification and hydrogen**
- The potential to recycle and reuse carbon



Our projections suggest electrification will take a large share of final demand in the energy system, but 20-30% demand for carbon-based fuels remains

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

■ Carbon based fuels ■ H2 and e-ammonia ■ Electricity and other renewables



Carbon molecules include:






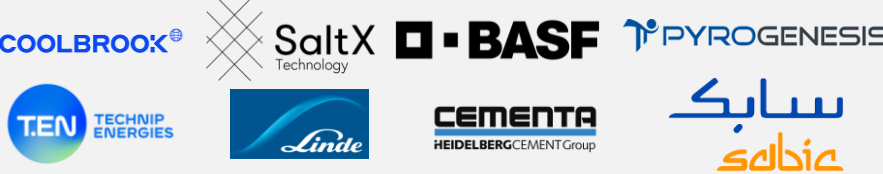






Fossil fuels: Coal, oil, gas direct use (10%)

Synthetic fuels: e-methanol, power-to-liquid fuel aviation fuel (4%)

Bioenergy: (8%)



Three disruptions could reduce reliance on carbon molecules in the energy system

Technology disruption 	Sectors impacted 	TRL 	Companies 
1 Industrial heat electrification (>600°C), including e-crackers for chemicals	(Heavy-) industry (cement), chemicals 	6-9	
2 Molten Oxide Electrolysis and Electrowinning	Steel/iron production 	4-5	
3 Li-ion solid state batteries	Trucking  Shipping  Aviation 	7	

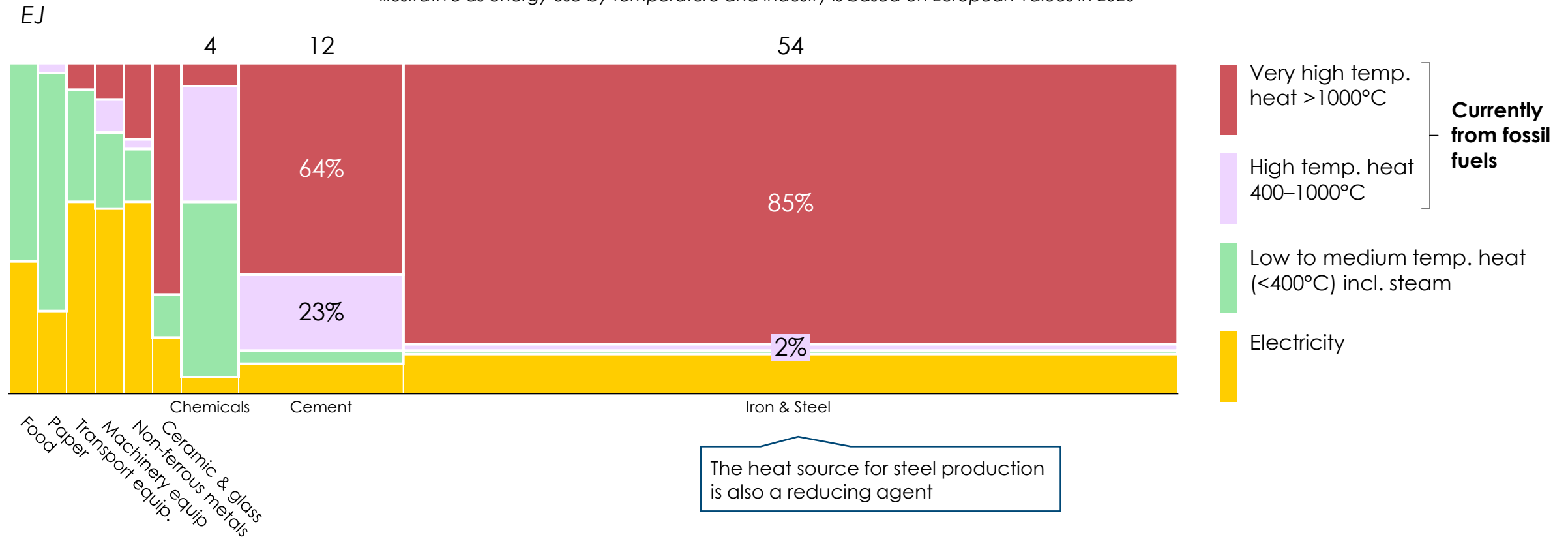
Source: Systemiq Analysis for ETC (2024) based on [Silvia Madeddu](#) (2020), [Fraunhofer ISI](#) (2024); [ARENA](#) (2024), [Agora Industry](#) (2024), [The Chemical Engineer](#) (2024), [Carbon Commentary](#) (2023), [Fast company](#) (2024), [IEA](#) (2024), [ETP Clean Energy Technology Guide](#), [Recycling Today](#) (2024), [TNO](#) (2020), [Fraunhofer ISI](#) (2023)



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

Energy use by temperature and industry sector¹ in 2050 (EJ)

Illustrative as energy use by temperature and industry is based on European values in 2020

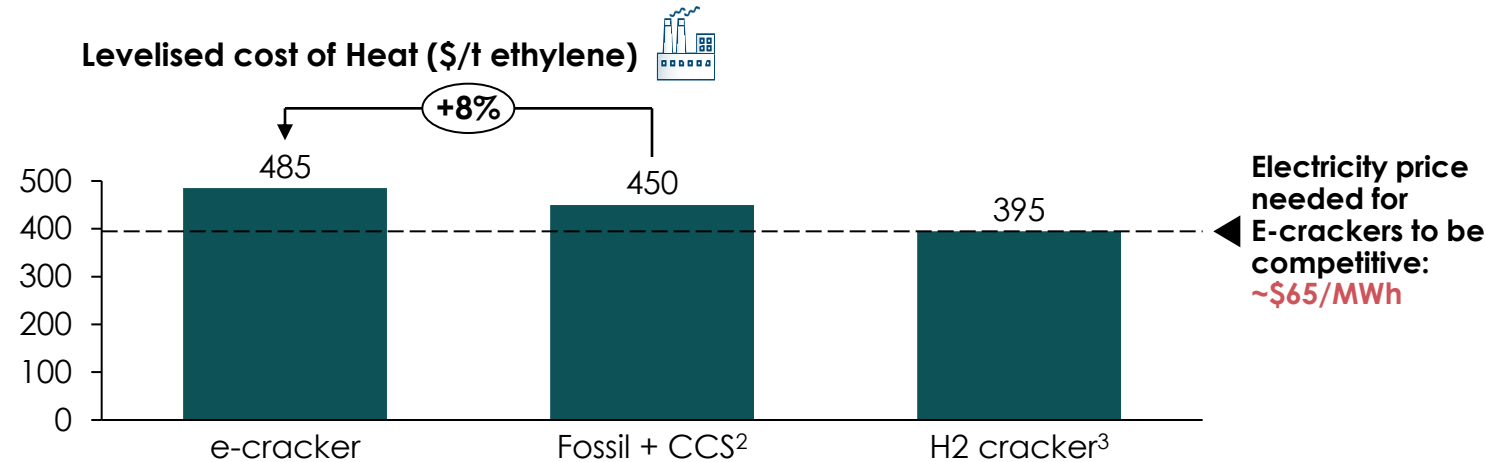
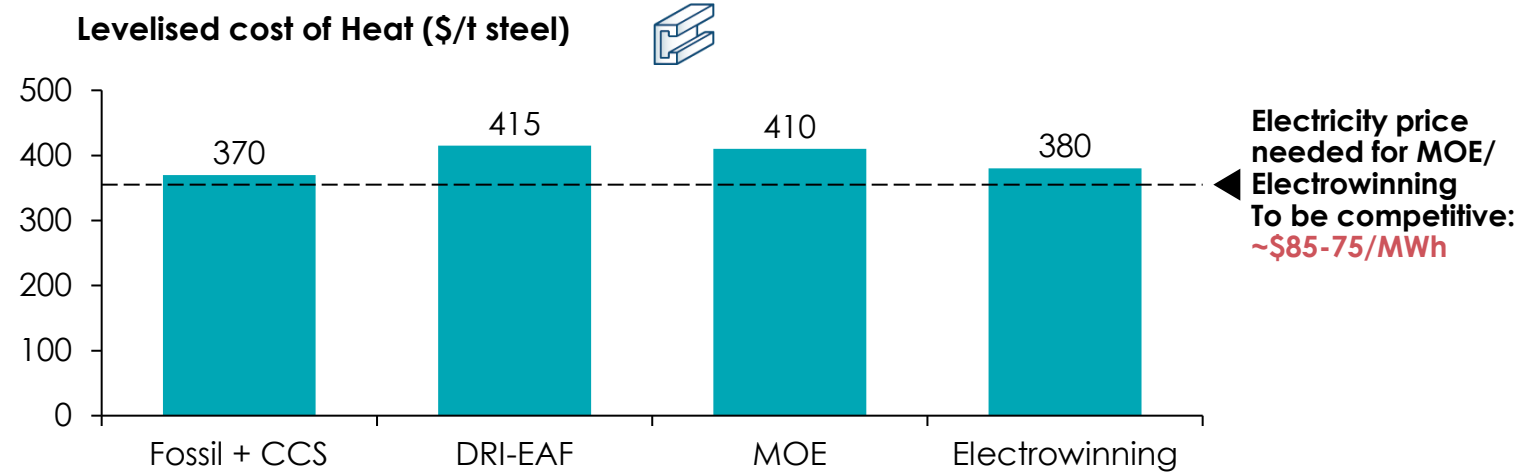


Notes: 1. Data representing energy split by temperature in EU across the sectors applied to a global level based on a study from Madeddu (20220) with adaptations for the chemical sector to include plastics from Coolbrook (2024).
 Sources: Final energy demand in 2050 based on Systemiq analysis (2024) from ETC (2023), Fossil Fuels in Transition Report; Silvia Madeddu (2020), The CO₂ reduction potential for the European industry via direct electrification of heat supply. Coolbrook (2024), Electric cracking: RotoDynamic Reactor cuts 100% of CO₂ in steam cracking



Electricity prices drive competitiveness of high temperature heat, and electrification of steel/iron making

Levelized cost of heat in steel and chemicals (\$/t steel) 2050



Potential barriers

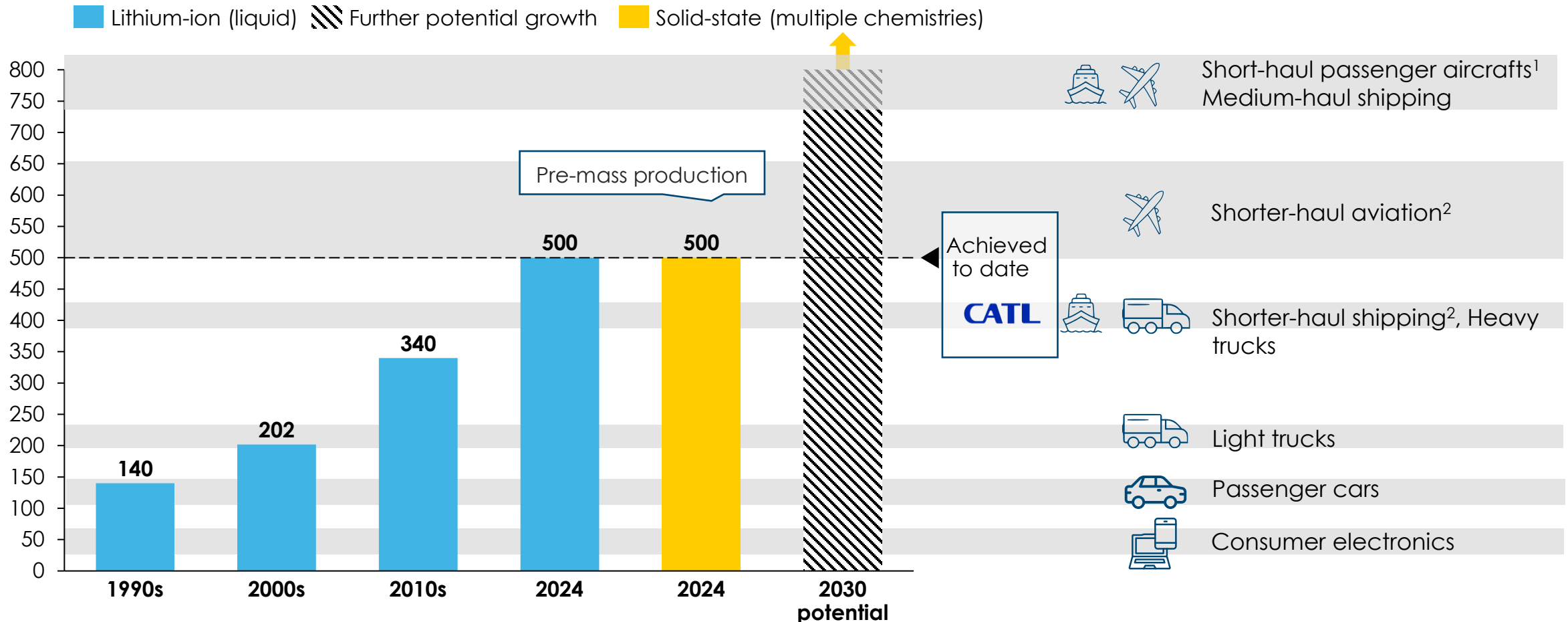


- Requires firm 24/7 clean power source¹
- Cost uncertainty
- Material durability under high temperatures

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

Top-tier battery cell energy density by decade and today
Gravimetric densities, Wh/kg

Minimum viable battery density for sector use case Examples

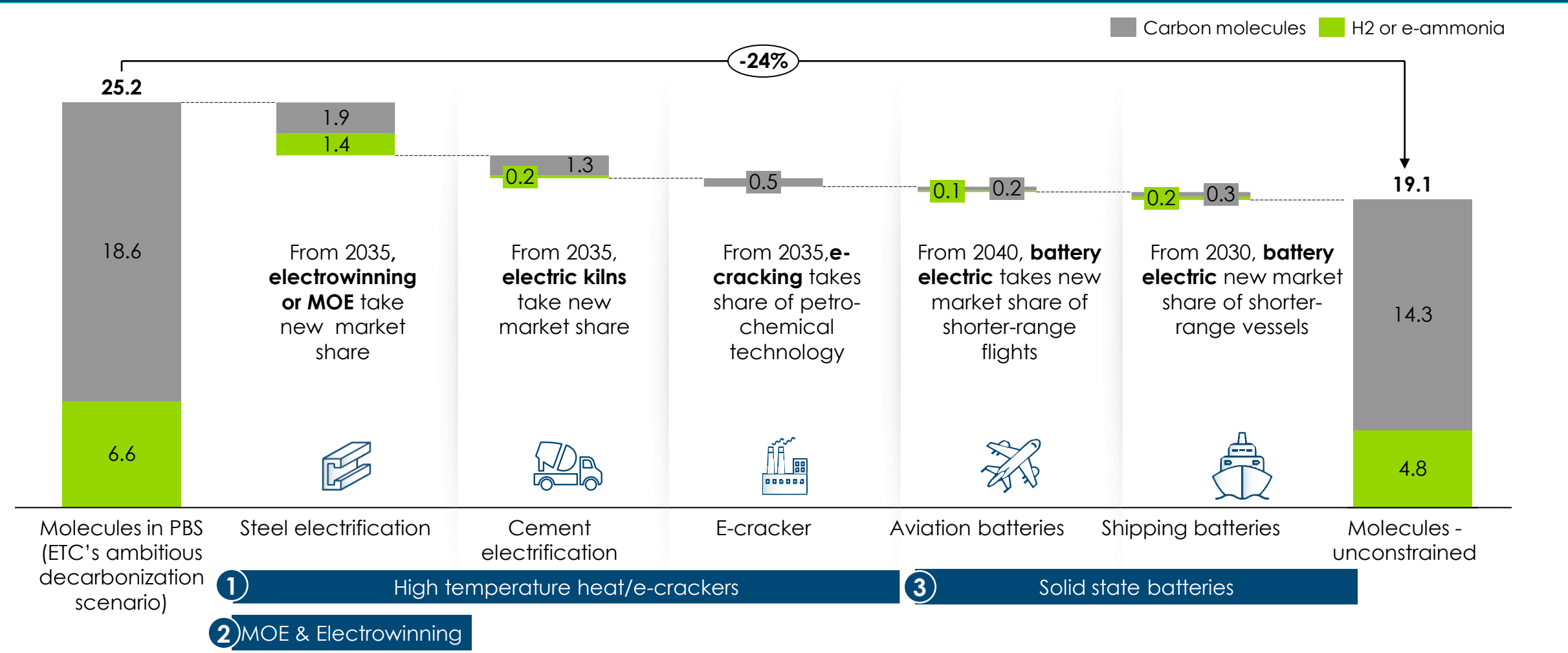


Notes: Currently dominant lithium-ion batteries use liquid electrolytes, current solid-state batteries predominantly use lithium, other ions (e.g., sodium) can be used; Minimum density at which first full battery-electric models are feasible, 1) Typical twin-engine narrowbody aircraft with a range of 600 miles would require 800 Wh/kg, larger models 1000 Wh/kg, 2) Uptake in niche, shorter haul segments. At an energy density of 1,000 Wh/kg, most regional (~1,000 nautical miles) aviation can turn full electric.
Sources: ETC analysis based on RMI (2023) X-Change.

With key 1) high-temperature industrial heat, 2) iron/steel electrification and 3) solid-state batteries, demand for molecules can be reduced by ~24%

Molecules in the energy system – Possible But Stretching (PBS) to Unconstrained share 2050

Final Energy Consumption, Thousand TWh



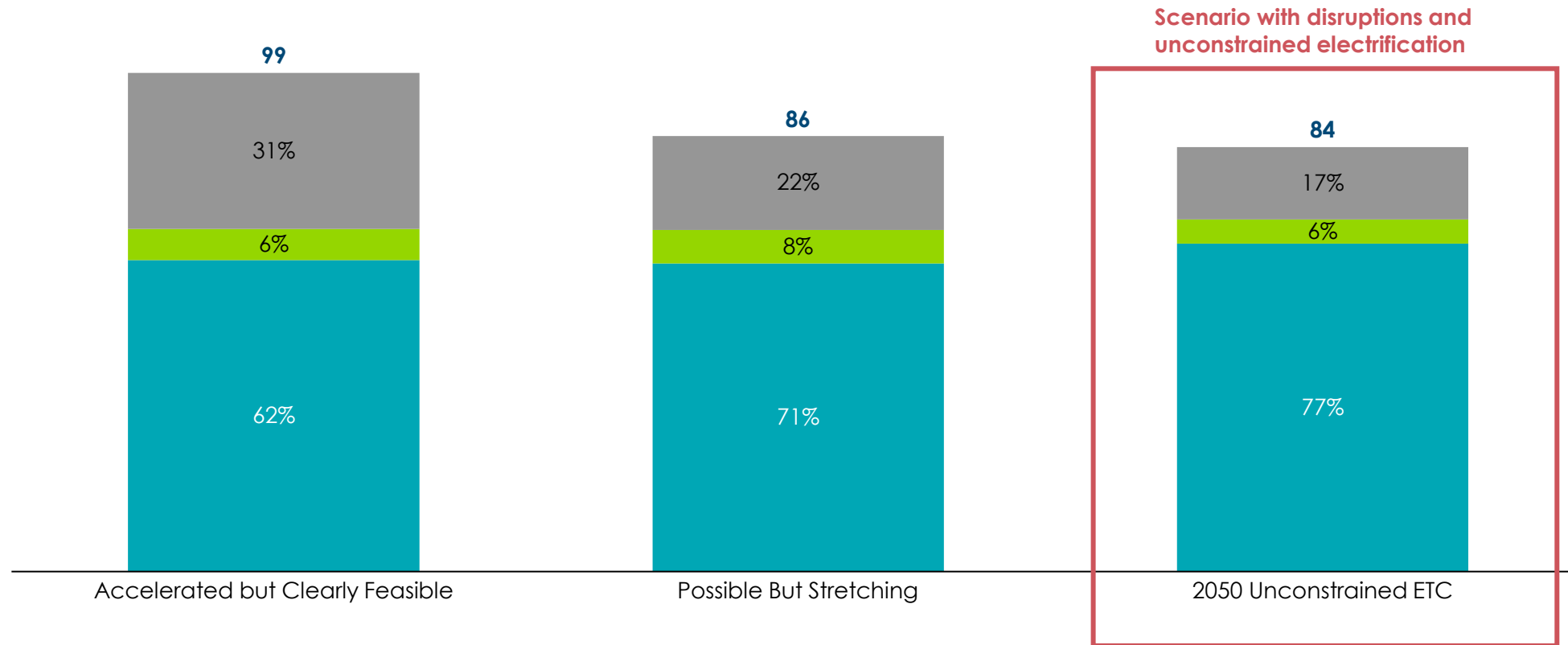
Source: Systemiq analysis for ETC (2024) based on Fossil Fuels in Transition (2023), Planet Positive Chemicals Report (Systemiq, 2022, BAU Net-Zero scenario); Steel: MPP STS (2022) Aviation: MPP STS (2022) Notes: PBS = Possible But Stretching ETC decarbonization scenario. *estimated at 15% of all nautical miles travelled, ^estimated at 20% of energy demanded

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

Global final energy demand by energy source and scenario

Thousand TWh (%), 2050

Carbon based fuels H2 and e-ammonia Electricity and other renewables



Note: STEPS = Stated Policies; ACF = Accelerated but Clearly Feasible; PBS = Possible but Stretching; *Remainder of electricity demand based on ACF scenario demand. CCS power assumes 30% energy penalty to power capture unit
Sources: 2022 scenario: Taken from ETC; ACF and PBS scenario: Taken from ETC FFIT Report 2023; IEA NZE, Taken from World Energy Outlook 2023

Agenda

- The demand for carbon molecules
- The role of electrification and hydrogen
- **The potential to recycle and reuse carbon**



To understand how much of carbon demand can be circular, four key re-use and recycling technologies and enablers are explored

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	<ul style="list-style-type: none"> Mechanical recycling Solvent-based recycling 	Actions: Design for recycling, sortation, collection
3. Recycle carbon	Chemical recycling of material and thermo conversion	Depolymerisation <ul style="list-style-type: none"> Pyrolysis Gasification 	Technologies: <ul style="list-style-type: none"> Track and trace, material passports
	Utilise waste CO ₂	Hydrogenation to methane or methanol <ul style="list-style-type: none"> Electrochemical reduction Reverse Water Gas shift Biocatalysis Plasma-catalytic treatment 	Advanced AI and robotics sorting

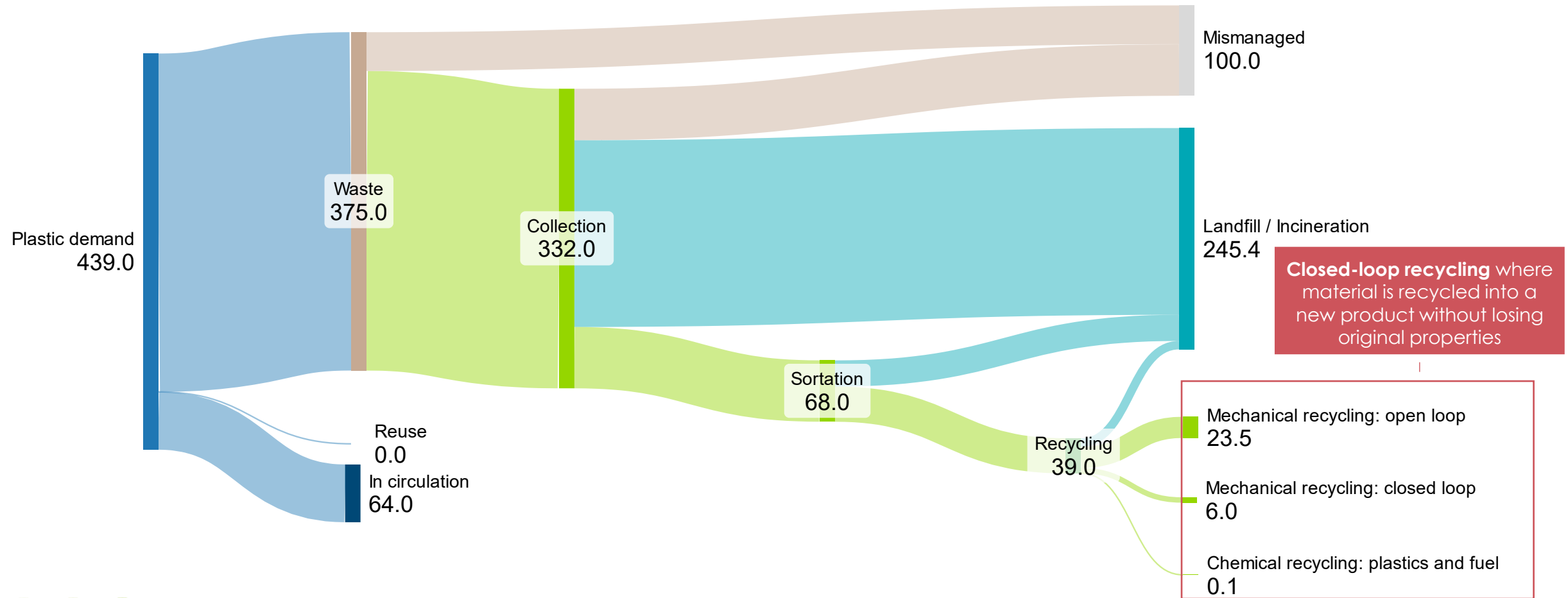
1 What are the **key levers** that could enable **higher circularity**?

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



In the plastic system, only a small amount of material is recycled today, and even less is closed-loop

Fate of global plastic waste, 2019, Million metric tonnes

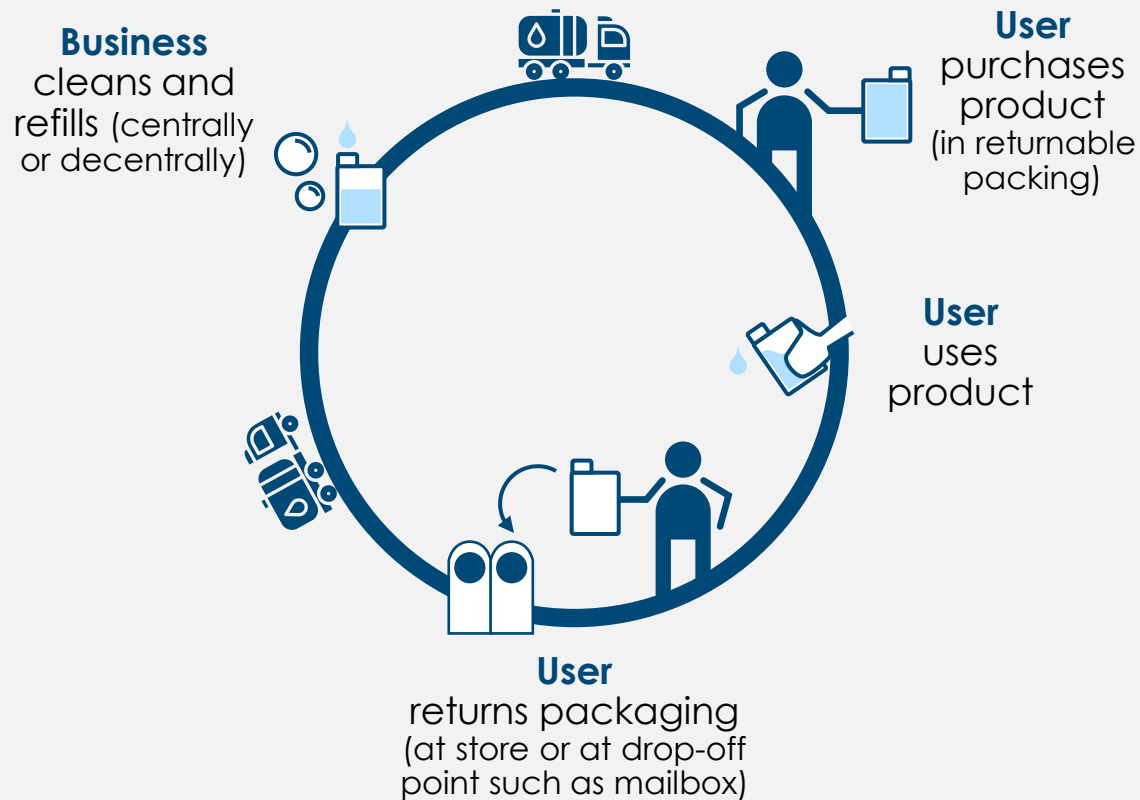


Source: Systemiq (2024) Plastic Treaty, BAU



At scale, re-use models could deliver benefits relative to single-use virgin plastic production

Simplified example of a Re-use model



At scale re-use models for beverage and personal care products could deliver benefits relative to single use virgin plastic...

~22%

Less system costs
(USD/per use)



60-75%

Less plastic use
(grams plastic/per use)



58-75%

Less emissions
(g Co2e/ per use)



Source: Systemiq analysis for ETC (2025), Ellen Macarthur Foundation (2024)

Re-use requires scale to become economic and consumer behavior change, so would need policy support

Barriers to re-use scaling

1. Ingrained consumer behaviour



2. Cheap and convenient, single-use plastic



3. Requires scale but has high upfront-costs



4. Requires system change (e.g. brands and retailers marketing, operations)



What needs to change for re-use to scale

1. Consumer preferences and habits shift



2. Single-use bans/penalties (e.g. EU Single use plastic Directive)



3. Government support to first movers



4. Sector specific packaging regulation, including re-use/refill targets

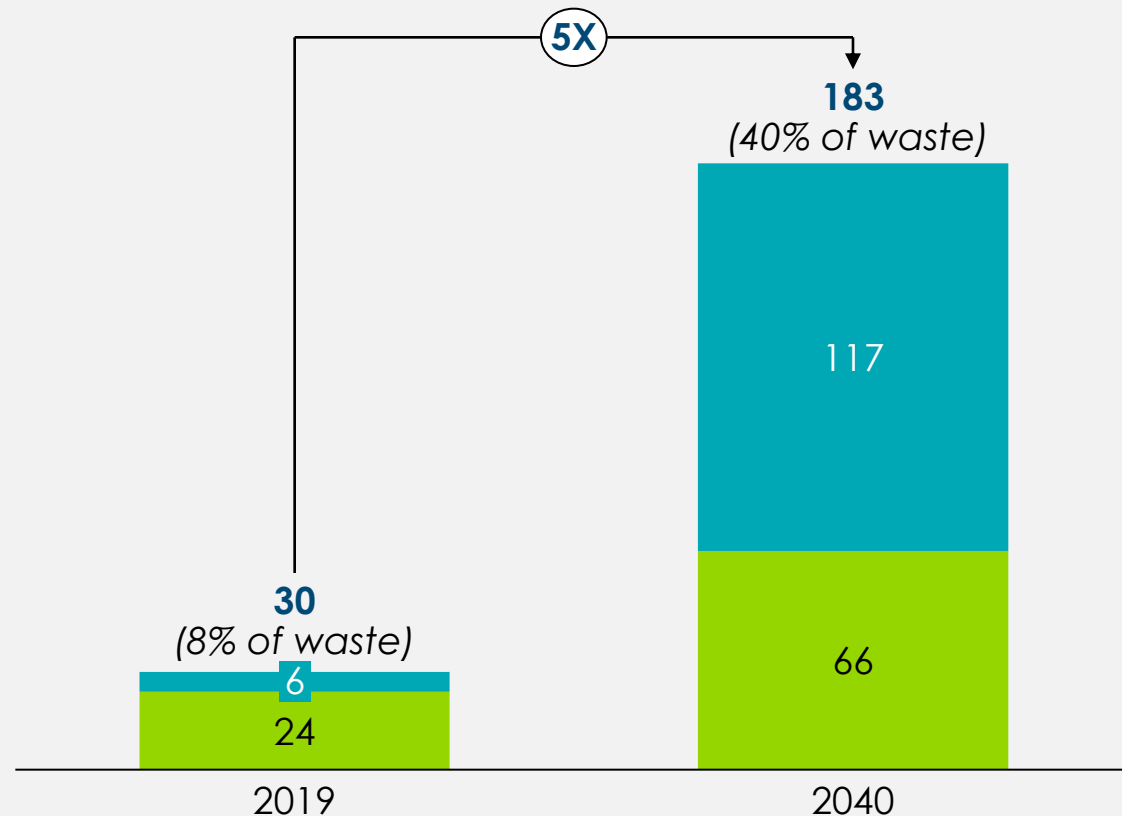


Mechanical recycling share is expected to increase, but will need significant policy support to overcome challenges




Mechanical recycling volumes global, 2019 and 2040

Million metric tonnes and share of plastic waste (%)




■ Closed loop mechanical ■ Open loop mechanical



Barriers to scaling Mechanical recycling

1. Degradation of material resulting in inferior product 
2. Feedstock limitations (tolerance for contamination) 
3. Weak business case due to cheap, abundant virgin feedstock 

What we need to believe to scale Mechanical recycling

1. Policies targets to
 - Reduce virgin plastic volumes
 - Increase collection and recycling
 - Ban single-use and problematic plastic
2. Design rules for safe re-use, repair and recycling 
3. Modulated Extended Producer Responsibility schemes and/or virgin plastic fees 

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

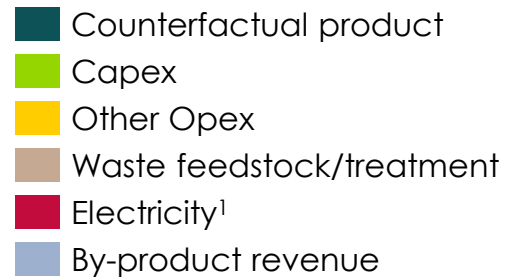
Reduction of waste feedstock costs can make chemical recycling cost-competitive

Levelised cost of production
\$/tonne (2025)

Depolymerisation
(PET)

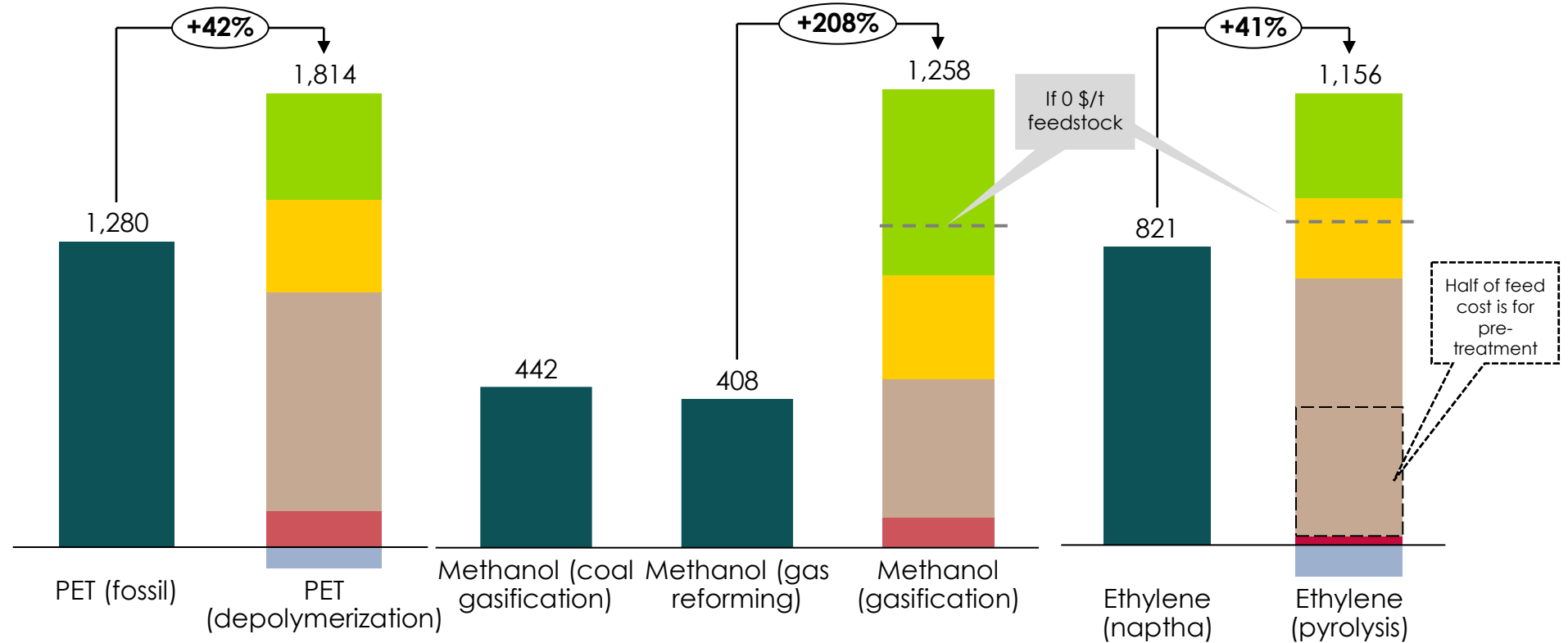
Gasification
(methanol synthesis)

Pyrolysis
(ethylene cracking)



Feedstocks

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



Cost of feedstock and pre-treatment needed for competitiveness

\$ 278 / ton waste feedstock including treatment

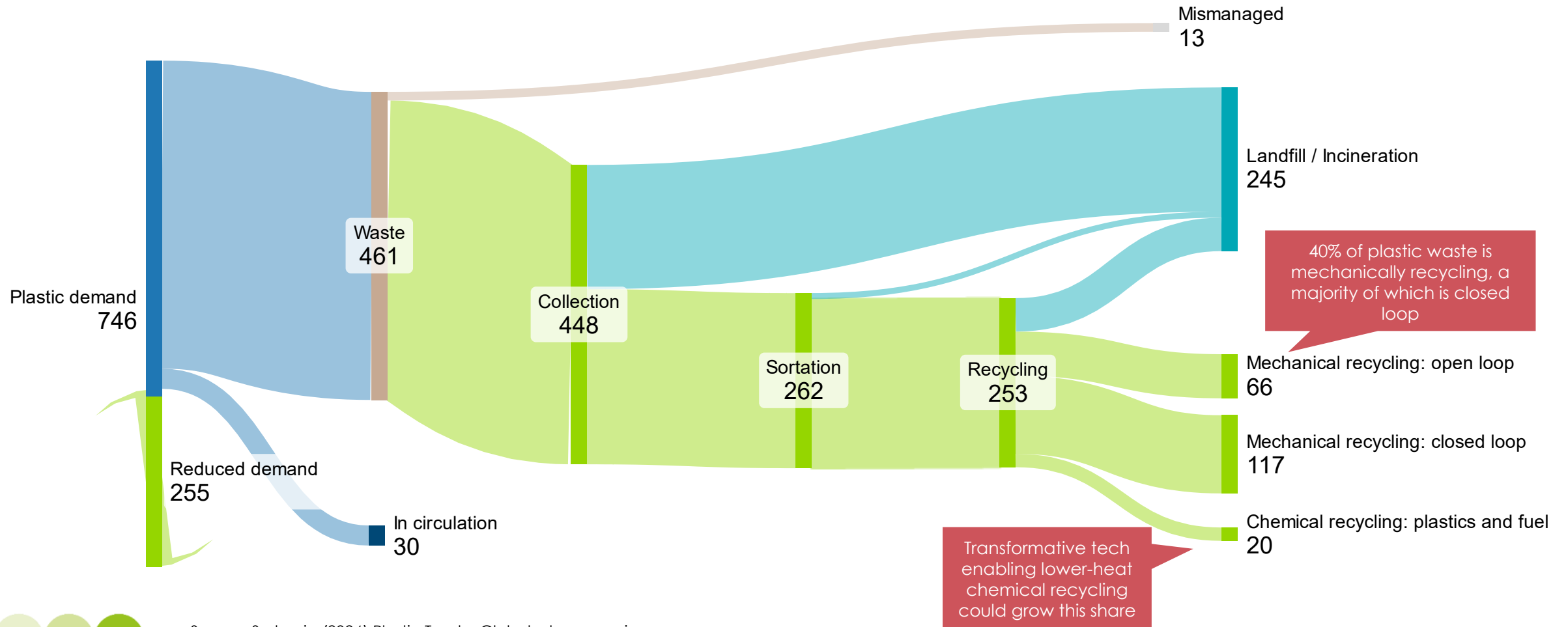
\$ -181 / ton waste feedstock including treatment

\$ 155 / ton waste feedstock including treatment

Sources: Depoly estimation is based on published data: Singh et al. (2021). Gasification and pyrolysis based on BEIS, NREL and Systemiq PCC model.
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).

In an ambitious scenario, the share of waste being recycled is expected to grow through to 2040, but 53% still goes to landfill or incineration

Fate of global plastic waste, 2040, Million metric tonnes

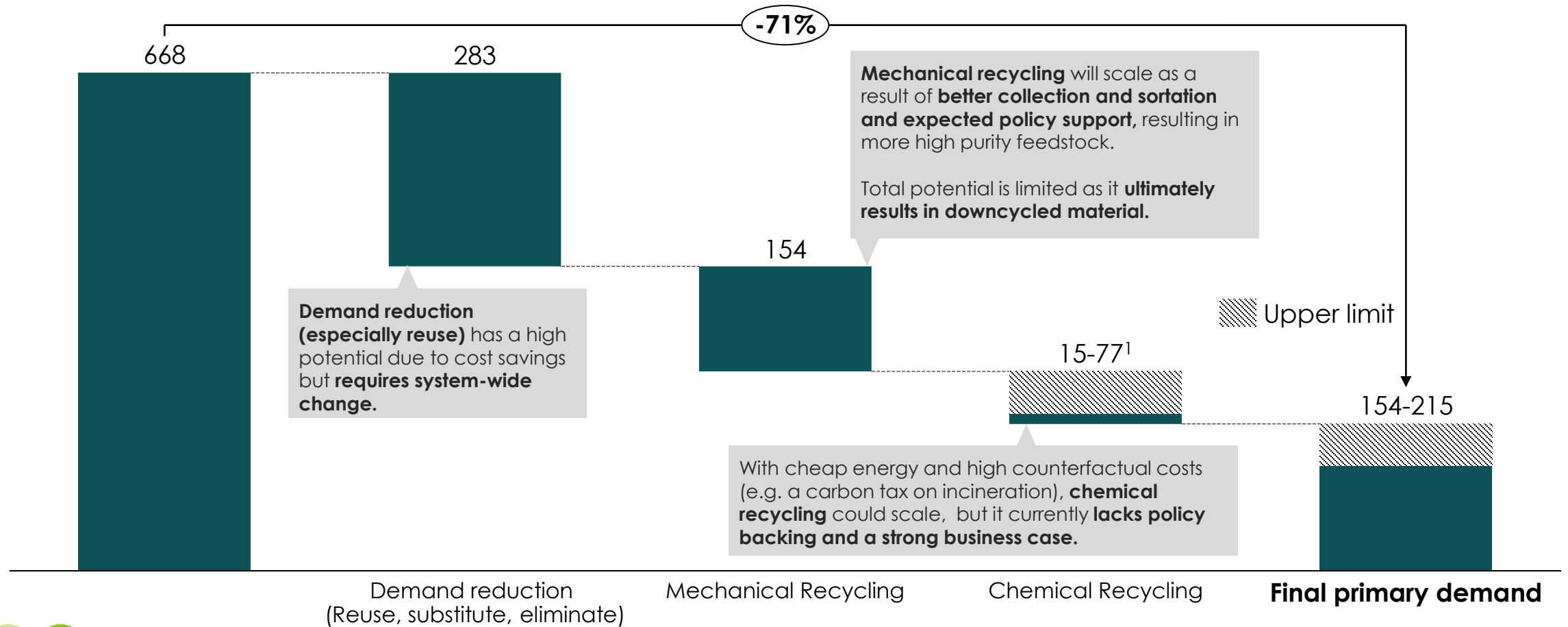


Source: Systemiq (2024) Plastic Treaty, Global rules scenario

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

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.

CCU technologies: High hydrogen production costs challenge economics, making biocatalysis the only cost-competitive option

Levelised cost of prod.
\$/unit output (2030)

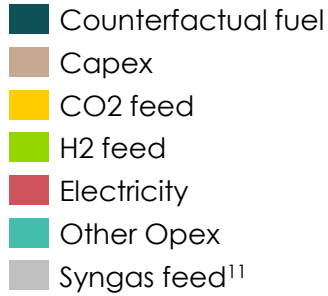
Hydrogenation to Methane

Hydrogenation to Methanol

RWGS

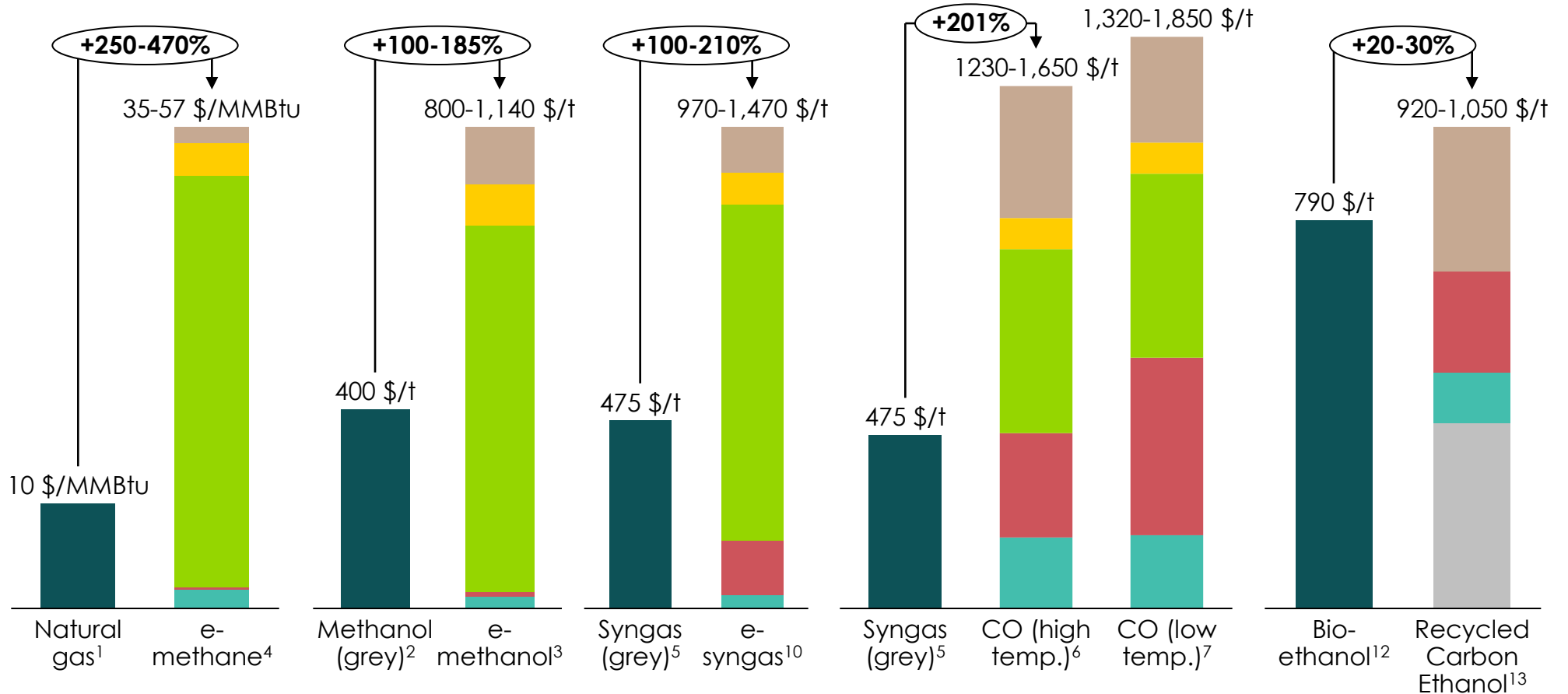
Electrochemical Reduction

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

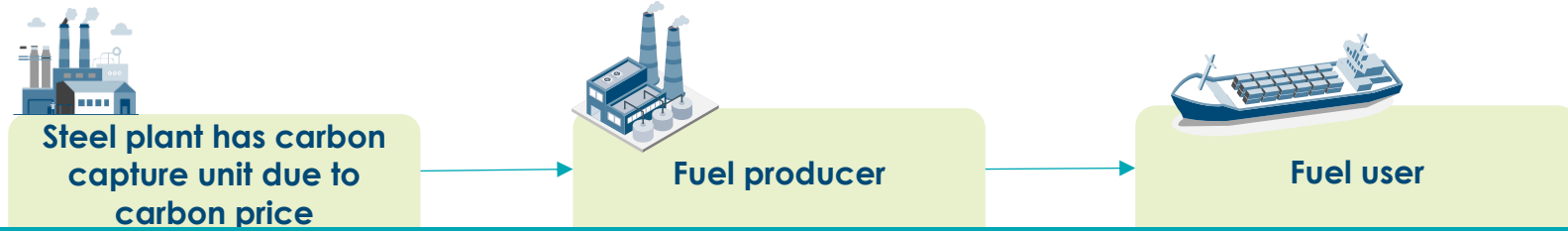


Sources/Notes: 1) Ten-year historical mean of EU Natural Gas TTF. 2) 20-year historical mean (Methanex). 3) EU PtX modelling (MPP, 2024). 4) "E-methane: a new gas for a net-zero future? (IEA, 2024)"; Lee et al. 2024. 5) Assumed cost for grey syngas (steam reforming) utilised for Fischer-Tropsch synthesis 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)

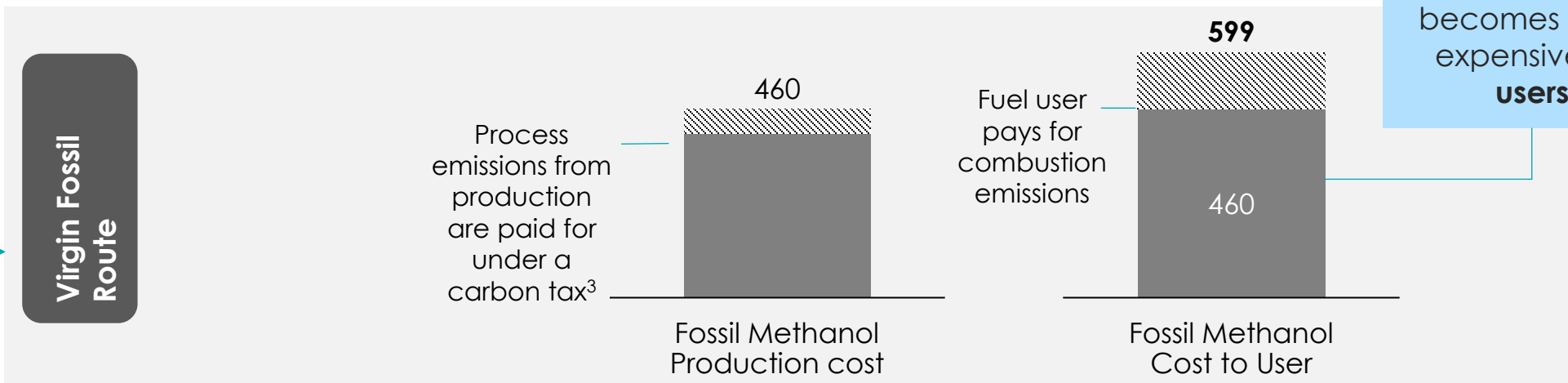
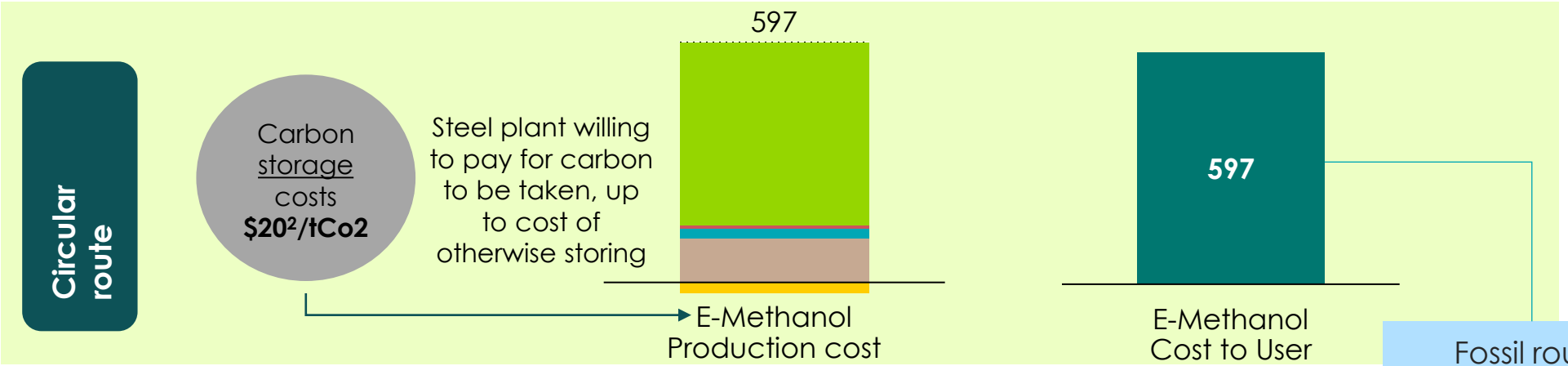
Scenario: A carbon price of \$100/t CO₂ with H₂ price of \$2.5/kg H₂ could make CCU pathways competitive with fossil

Illustrative

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



- Emissions costs⁴
- H₂ feed
- Electricity¹
- Other Opex
- Capex
- Fossil production
- CO₂ feed



Fossil route becomes more expensive for users

Green H₂ CO₂ price

\$/kg \$/t Co₂

2.5 100

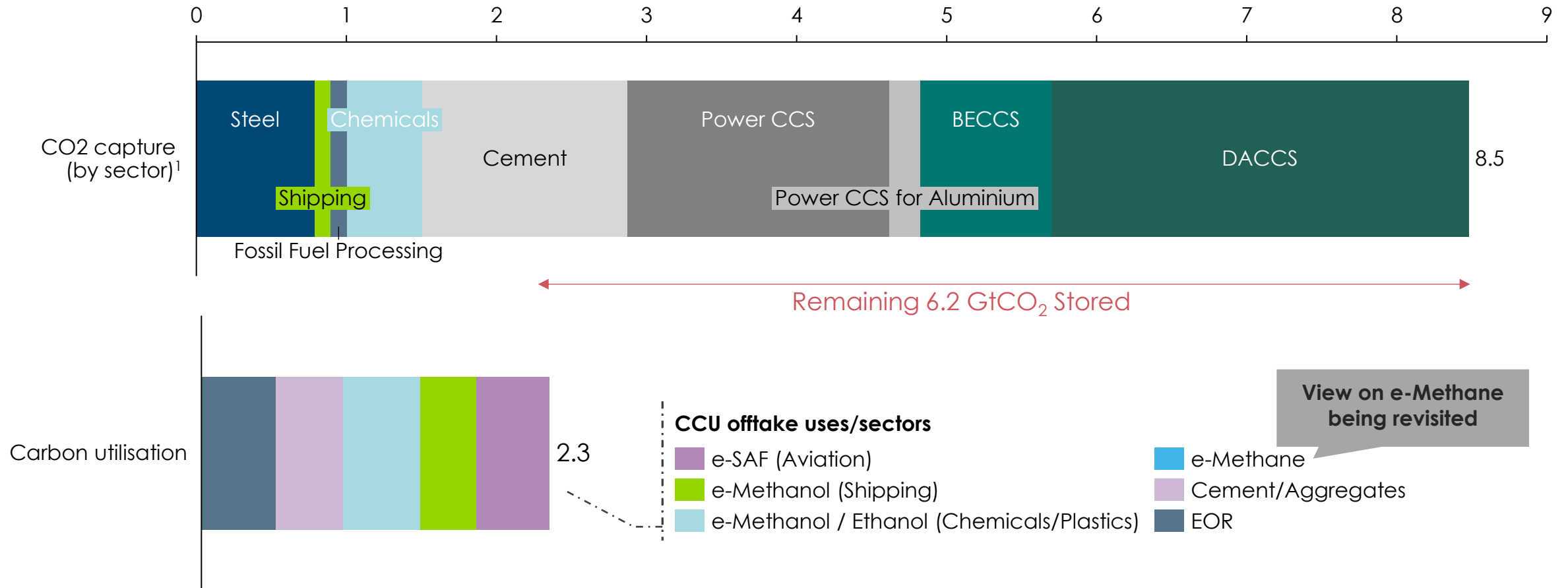
Inputs

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 4) e.g. under the EU Emissions Trading Scheme

27% of all carbon captured might be utilized a second time, leaving a majority stored

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

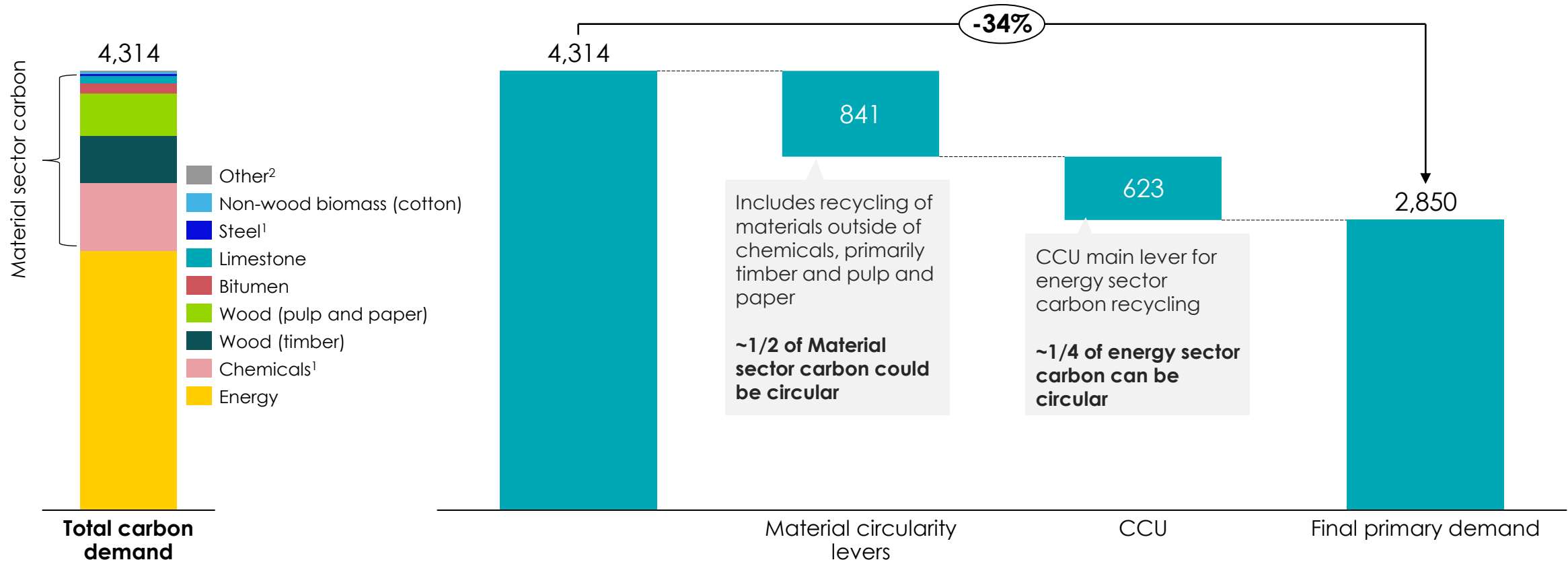


Stretch scenario: taken together, these levers could reduce primary demand for carbon in 2050 by a third

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.

Next steps



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



Develop **innovation briefs** on key technologies



Phase 3 begins Q2

