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

	2024	2025			
	Q4	Q1	Q2	Q3	Q4
Workplan	**Phase 1A** How large can and should the **role of direct electrification** be in a zero-emission economy **Phase 1B** **The role of hydrogen** and **derivatives (i.e., ammonia)** in a zero-emission economy?	**Phase 2** The potential to **recycle** and **reuse carbon molecules**	**Phase 3** Sources of **primary carbon: costs** and **sustainability**	**Phase 4** **Report production and communication campaign running into COP30**	
Deliverables	• A 5-pager published externally • A series of short innovation briefs for publication	• A 5-pager published externally • Report chapter • Innovation brief(s)	• Publication of the ETC report ahead of COP • A series of short innovation briefs for publication		
Key interactions	• 1-2 workshops with ETC Commissioners	• 1-2 workshop with ETC reps/ commissioners	• Workshop • Report reviews • Report launch at COP		

Currently Ongoing

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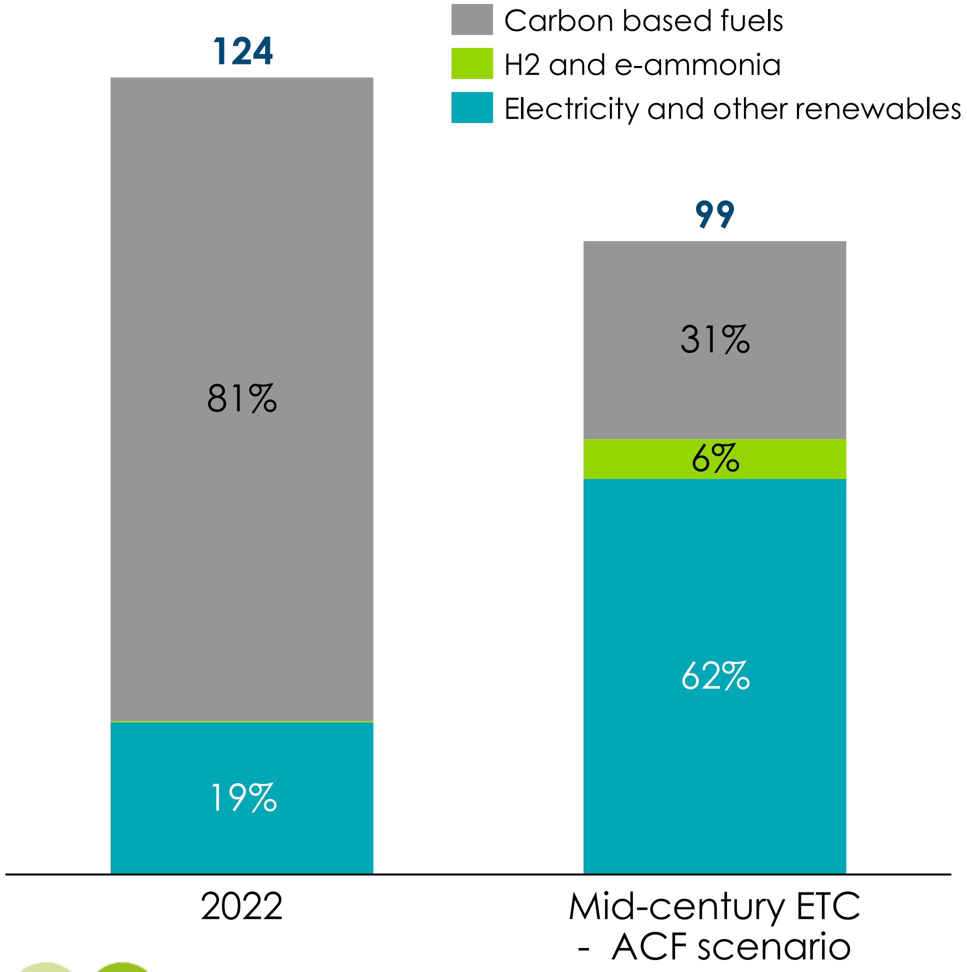
Agenda

- **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

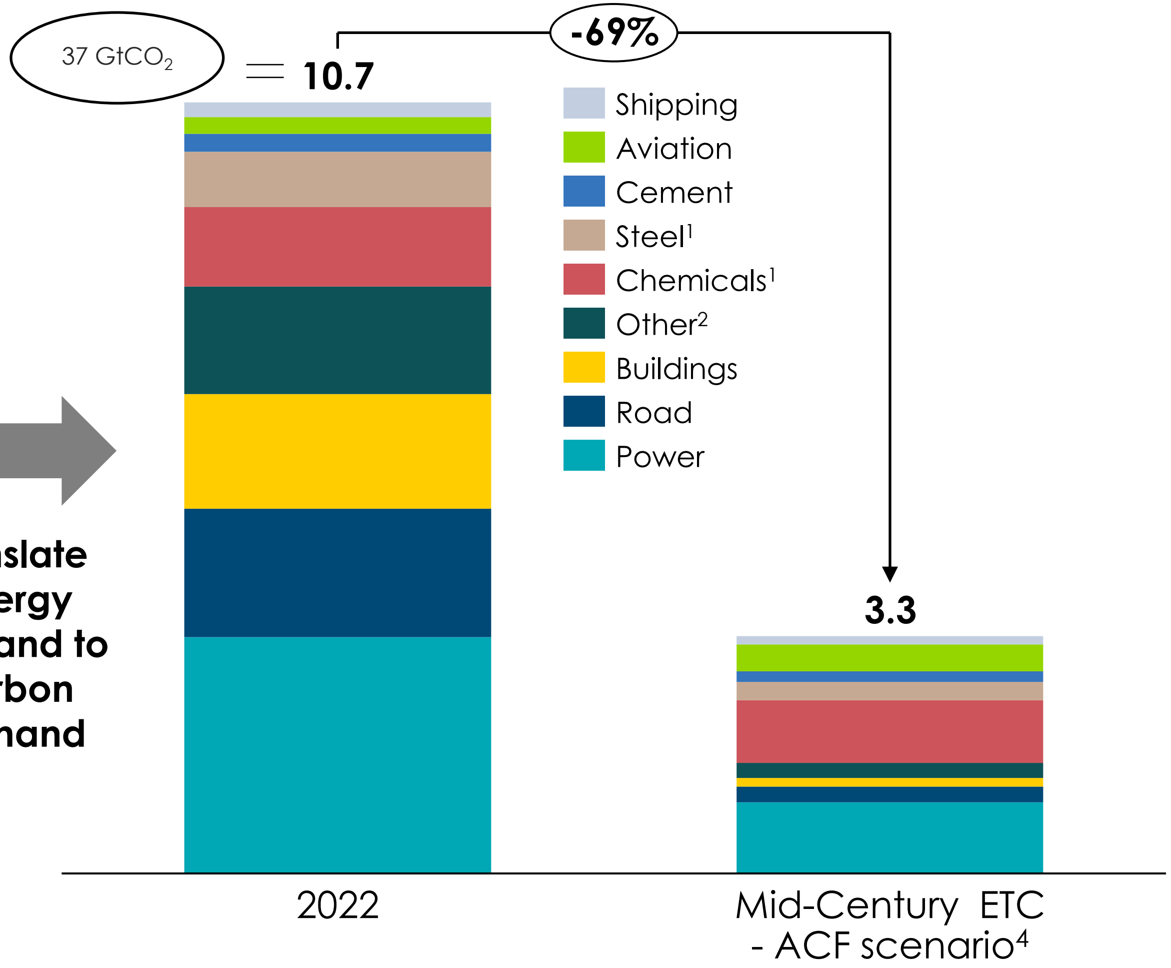
Thousand of TWh



Translate energy demand to carbon demand

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 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.

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Molecules will likely be essential in aviation, chemicals, fertilisers, shipping; for other sectors electrification will likely dominate

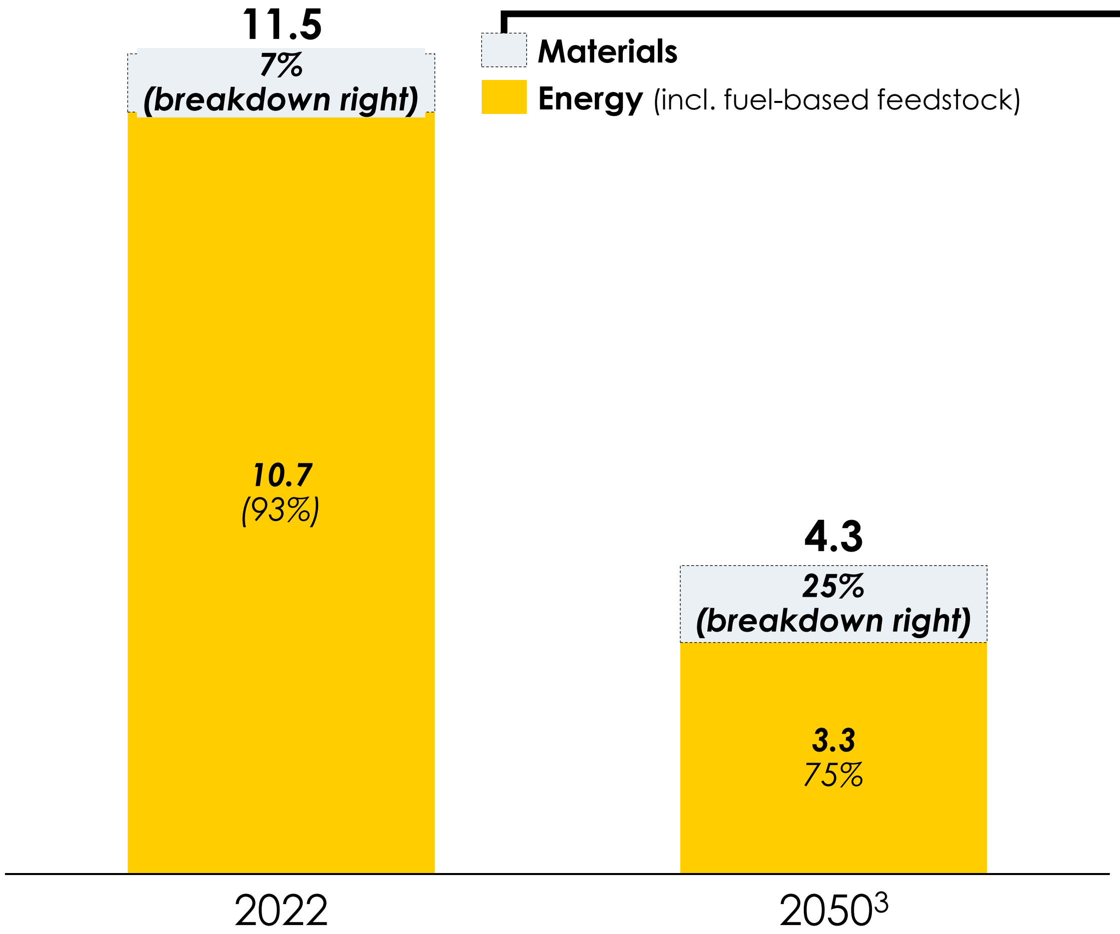
Likelihood of role	Potential Application	Current Fossil Fuel Demand[1] – Coal	Current Fossil Fuel Demand[1] – Gas	Current Fossil Fuel Demand[1] – Oil	Sector power demand in 2050 – Final and Intermediate	Share of electricity in FED in 2050
Most likely role for molecules	Aviation			5.5 mb/d	5,000 TWh	
	Shipping			5 mb/d	4,000 TWh	
Some role, depending on costs vs. electrification	Plastics and Petrochemicals; Fertilisers/Ammonia	230 Mtce	500 bcm	17 mb/d	3-6,000 TWh	
	Iron / Steel-making	900 Mtce	100 bcm		9,000 TWh	
	Other industry	750 Mtce	600 bcm	4 mb/d	12,000 TWh	
Minimal role – electrification wins	Power, Road Transport, Buildings	4,000 Mtce	3,000 bcm	67 mb/d	35-40,000 TWh	

[1] Demand is for direct use of fossil fuels.
Source: Systemiq analysis for the ETC; ETC (2023), *Fossil Fuels in Transition*.

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

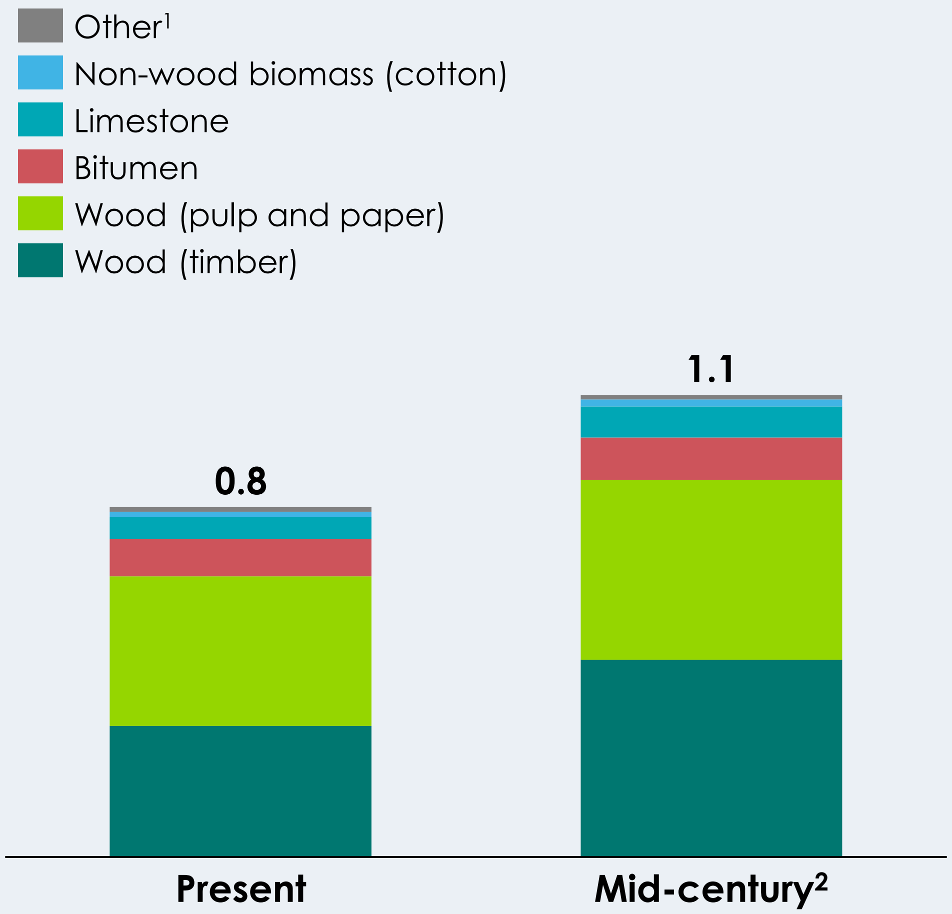
Carbon demand across the energy and material sectors

Gigatons of carbon (C)



Carbon demand breakdown across major materials

Gigatons of carbon (C)



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.

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

Carbon sources

Primary

Ground

- Coal
- Oil
- Gas
- Limestone

Air

- Direct Air Capture

Air is the only theoretically unconstrained, sustainable carbon source…

Bioresources

- Wood
- Crops
- Municipal solid waste
- Agricultural waste

Secondary

Industrial process emission

- Point source capture

Recycled materials

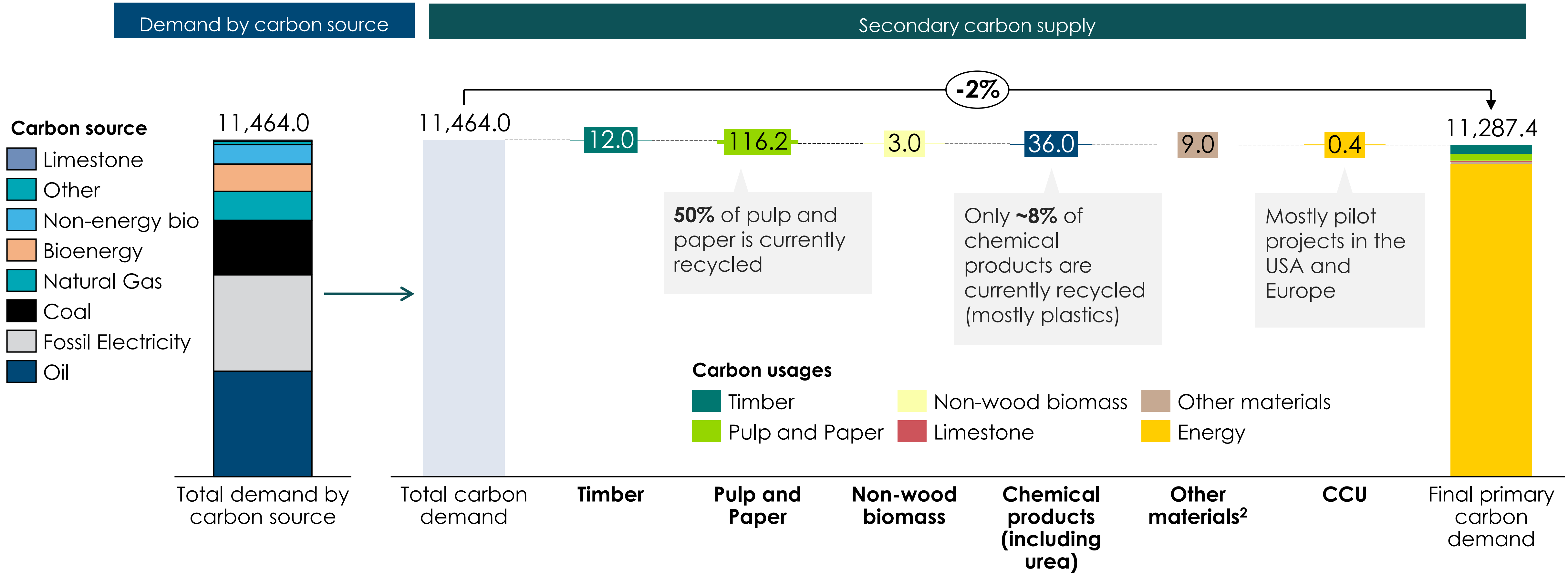
- Paper
- Plastic
- Glass

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

…and today, carbon molecules are predominantly from fossil-based sources and 98% of demand is only used once

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

Million tons of carbon (C)



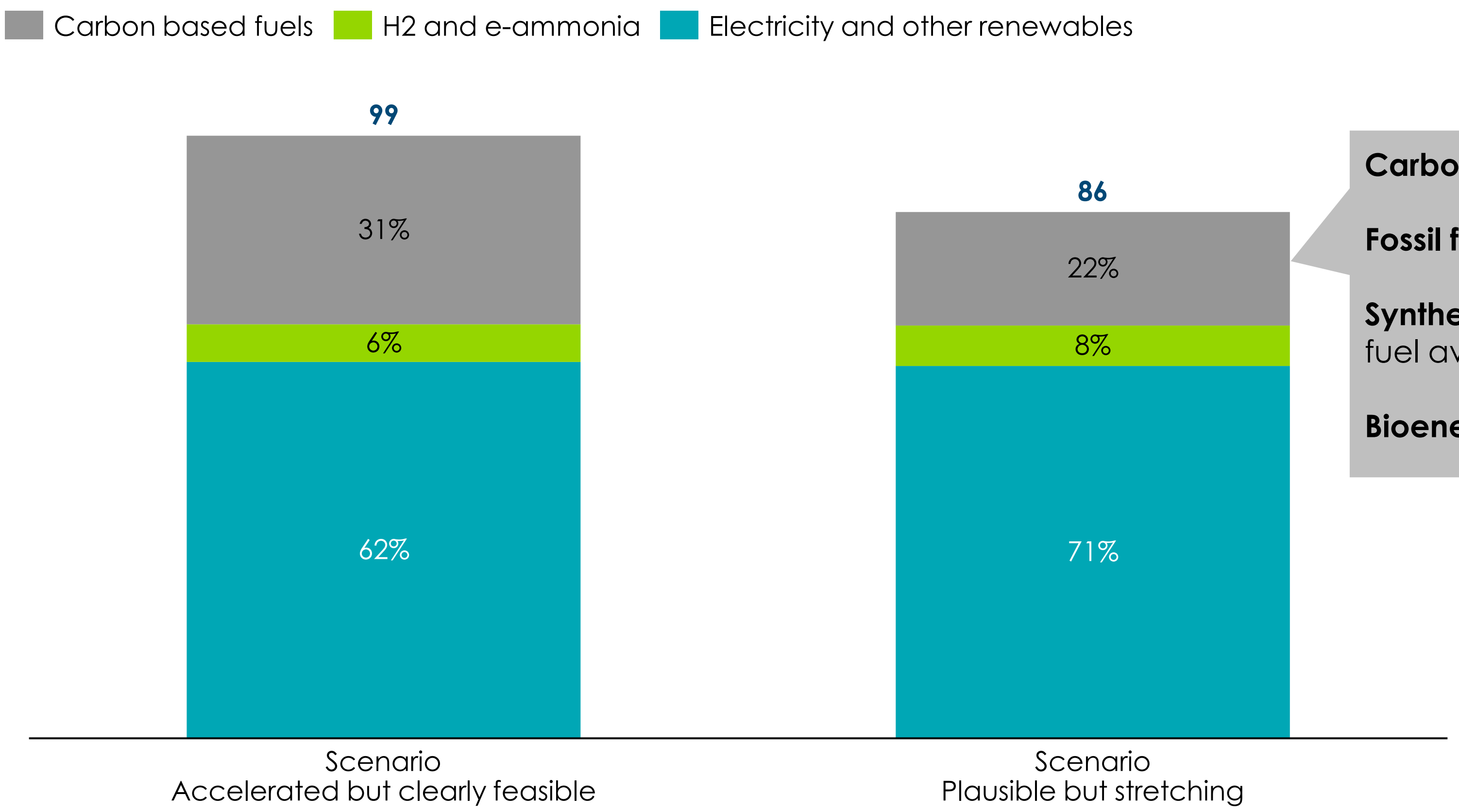
Sources: Energy: Systemiq analysis (2025), based on Fossil Fuels in Transition (ETC, 2023); Chemicals: Planet Positive Chemicals Report (Systemiq, 2022, BAU Net-Zero scenario); Biomass: ETC Bioresources report (2021); Steel: MPP STS (2022); Cotton, Bitumen and Soda Ash: Systemiq analysis (2025)
Notes: 1) Ethylene, Propylene, Methanol (non-energy uses), Benzene, Toluene, Xylene, C4 chemicals. 2) Includes limestone, bitumen, soda ash, carbon ash, biochar, carbon fibre, charcoal.

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 molecules include:

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

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

Bioenergy: (8%)

Note: STEPS = Stated Policies; ACF = Accelerated but Clearly Feasible; PBS = Possible but Stretching; Sources: 2022 scenario: Taken from ETC; ACF and PBS scenario: Taken from ETC FFIT Report 2023;

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

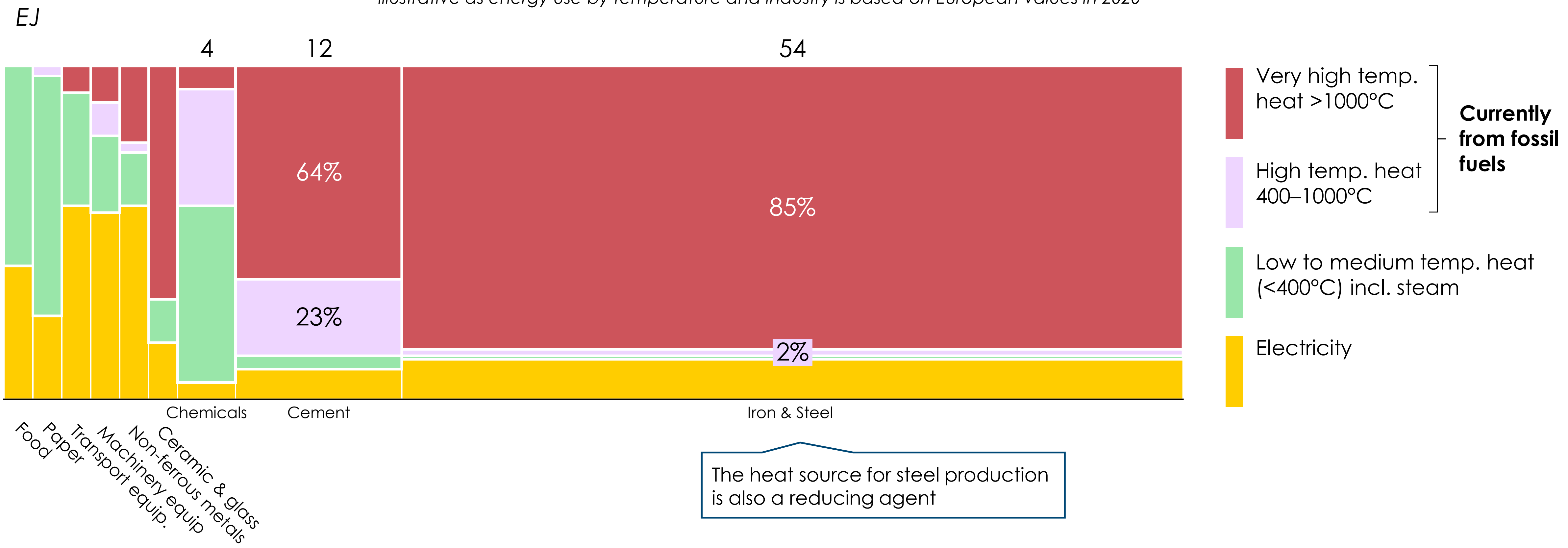
Technology disruption	Sectors impacted	TRL	Companies
1 Industrial heat electrification (>600°C), including e-crackers for chemicals	(Heavy-) industry (cement), chemicals	6-9	Coolbrook, SaltX Technology, BASF, PyroGenesis, T.EN Technip Energies, Linde, Cementa HeidelbergCement Group, سابك sabic
2 Molten Oxide Electrolysis and Electrowinning	Steel/iron production	4-5	Boston Metal, John Cockerill, Fortescue Future Industries, ArcelorMittal, Element Zero, electra
3 Li-ion solid state batteries	Trucking; Shipping; Aviation	7	CATL, Toyota, CALB, Solid Power, BYD, LG Chem, QuantumScape

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 (2023Fast 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 sector[1] in 2050 (EJ)

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

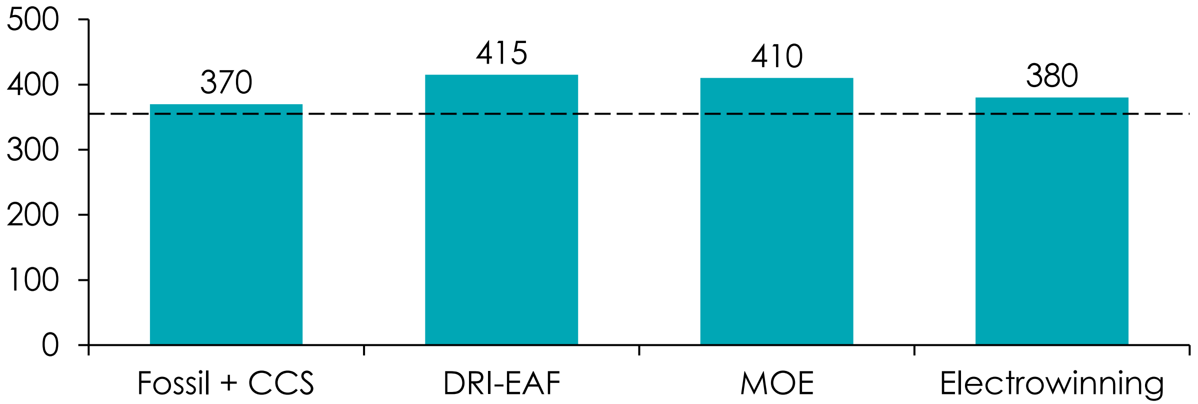


Notes: 1. Data representing energy split by temperature in EU across the sectors applied to a global level based on a study from Madeddu (20220) with adaptions for the chemical sector to include plastics from Coolbrook (2024).
Sources: Final energy demand in 2050 based on Systemiq analysis (2024) from ETC (2023), Fossil Fuels in Transition Report; Silvia Madeddu (2020), The CO_2 reduction potential for the European industry via direct electrification of heat supply. Coolbrook (2024), Electric cracking: RotoDynamic Reactor cuts 100% of CO_2 in steam cracking

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

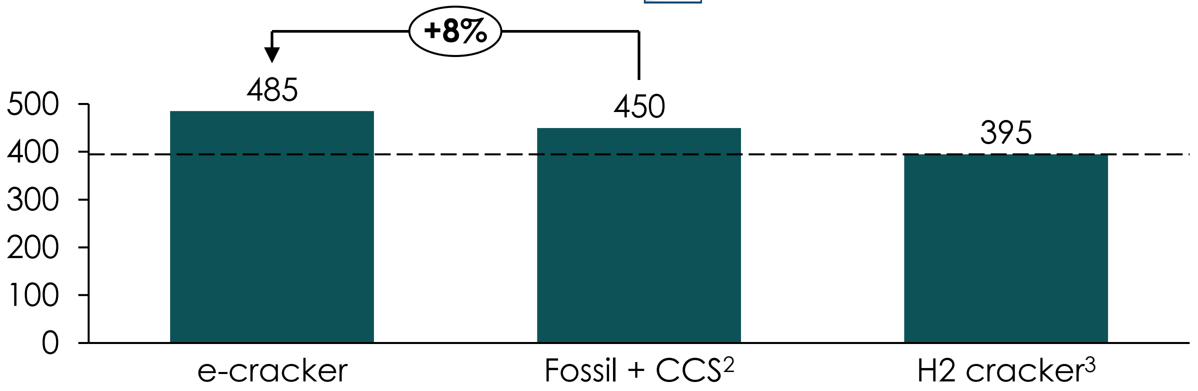
Levelized cost of heat in steel and chemicals ($/t steel) 2050

Levelised cost of Heat ($/t steel)



Electricity price needed for MOE/ Electrowinning To be competitive: ~$85-75/MWh

Levelised cost of Heat ($/t ethylene)



Electricity price needed for E-crackers to be competitive: ~$65/MWh

Potential barriers

- **Requires firm 24/7 clean power source[1]**
- **Cost uncertainty**
- **Material durability under high temperatures**

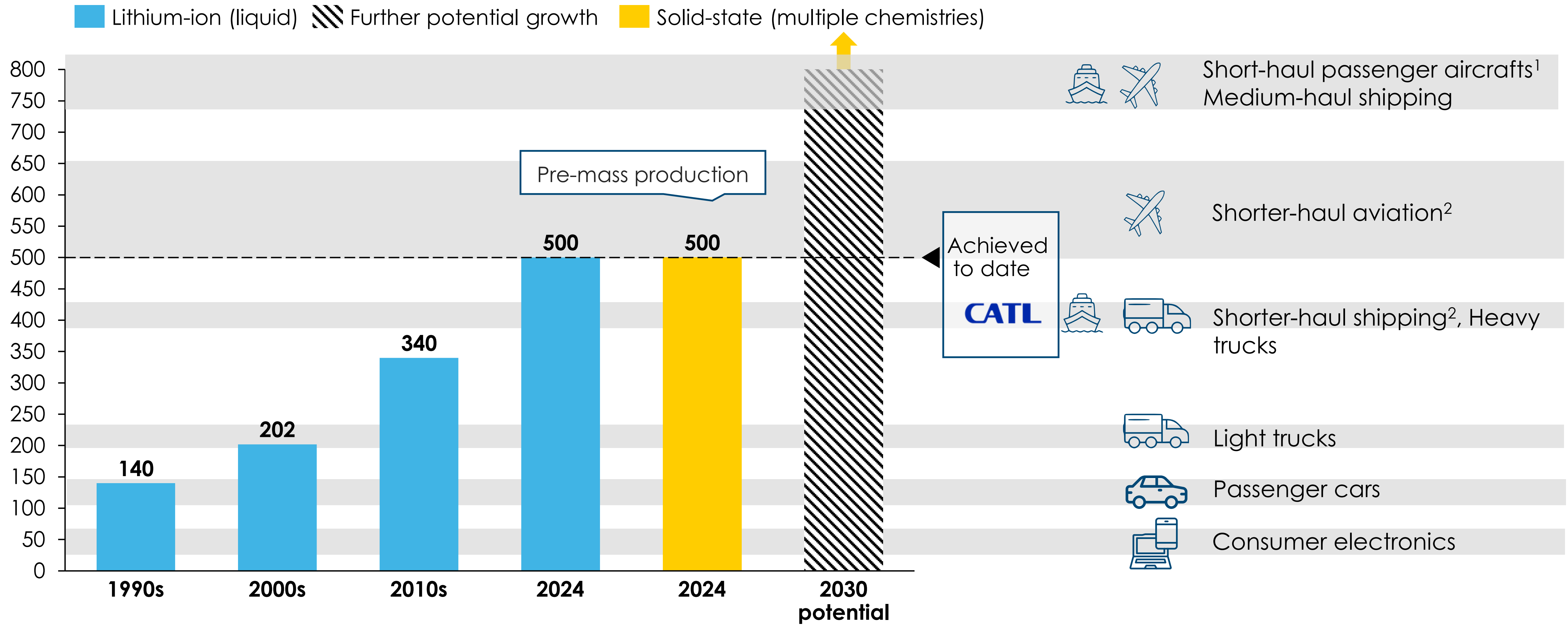
Source: Systemiq analysis based on Mission Possible Partnership (2022), Making net-zero steel possible and planet positive chemicals (2023). 1. High temperature heat, and MOE require 24/7 high temperature heat, while electrowinning works with intermittent power supply

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

3

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

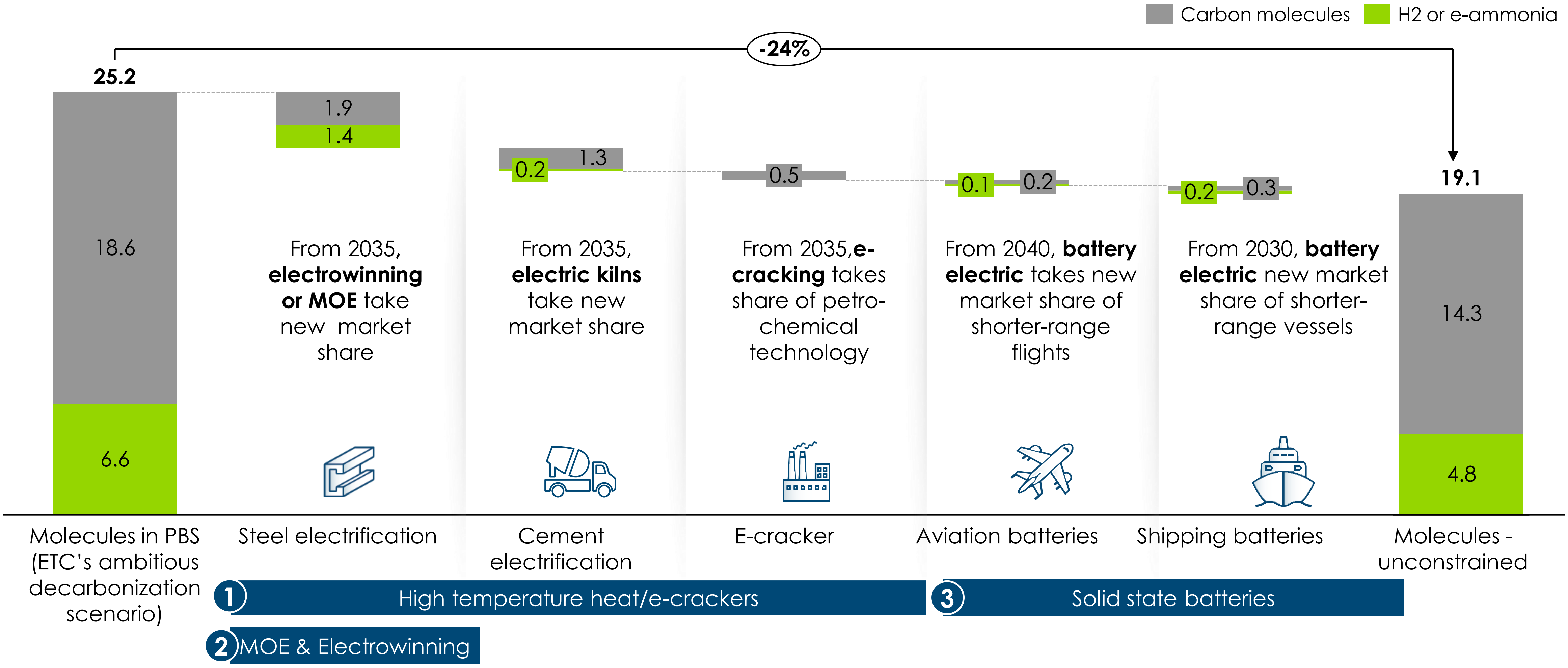
Minimum viable battery density for sector use case *Examples*



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%

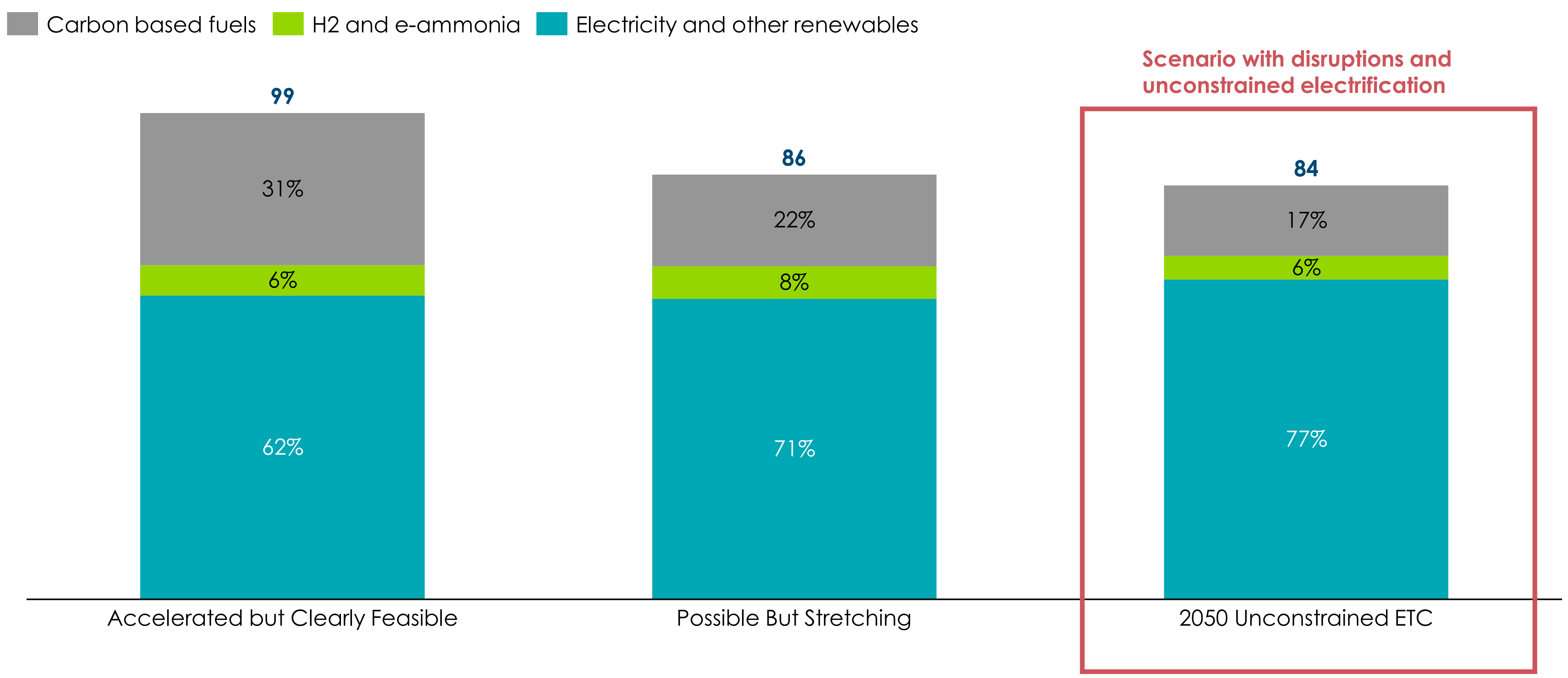
Molecules in the energy system – Possible But Stretching (PBS) to Unconstrained share 2050
Final Energy Consumption, Thousand TWh



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 ~15% of final energy demand

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



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

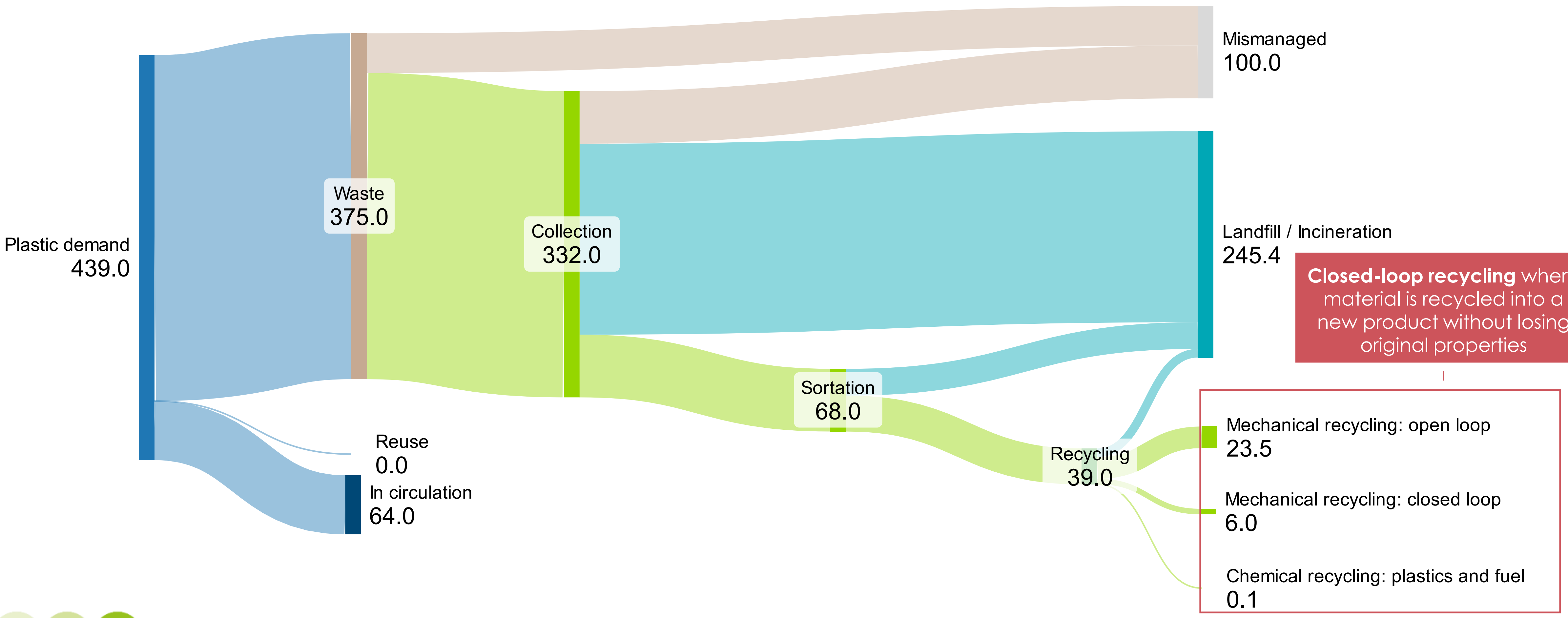
Lever	Actions	Relevant technologies	Enablers
1. Reduce demand	Eliminate, Reuse, Substitute	• AI lightweighting and optimization tech 1 New re-use technology & delivery models	
2. Recycle material	Physical or mechanical recycling of material	• Mechanical recycling • Solvent-based recycling	**Actions:** Design for recycling, sortation, collection **Technologies:** • Track and trace, material passports 2 Advanced AI and robotics sorting
3. Recycle carbon	Chemical recycling of material and thermo conversion	3 Depolymerisation • Pyrolysis • Gasification	
	Utilise waste CO_2	4 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

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*

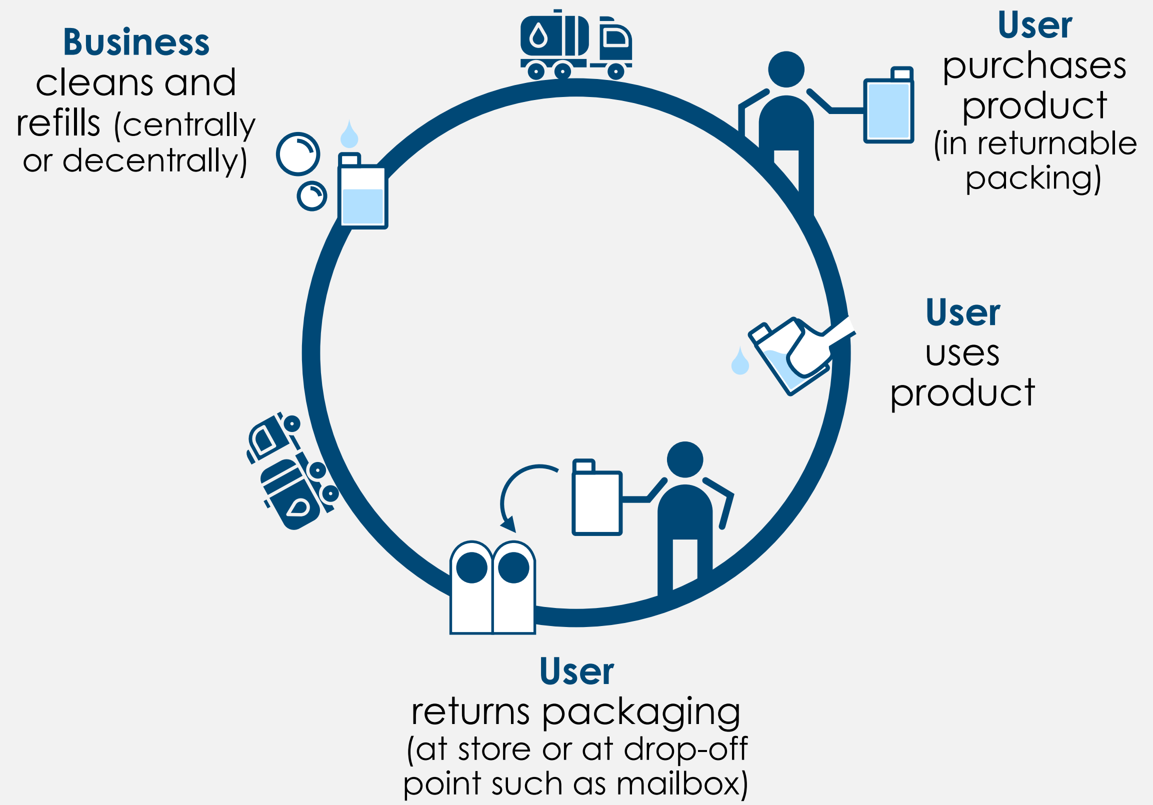


Closed-loop recycling where material is recycled into a new product without losing original properties

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)

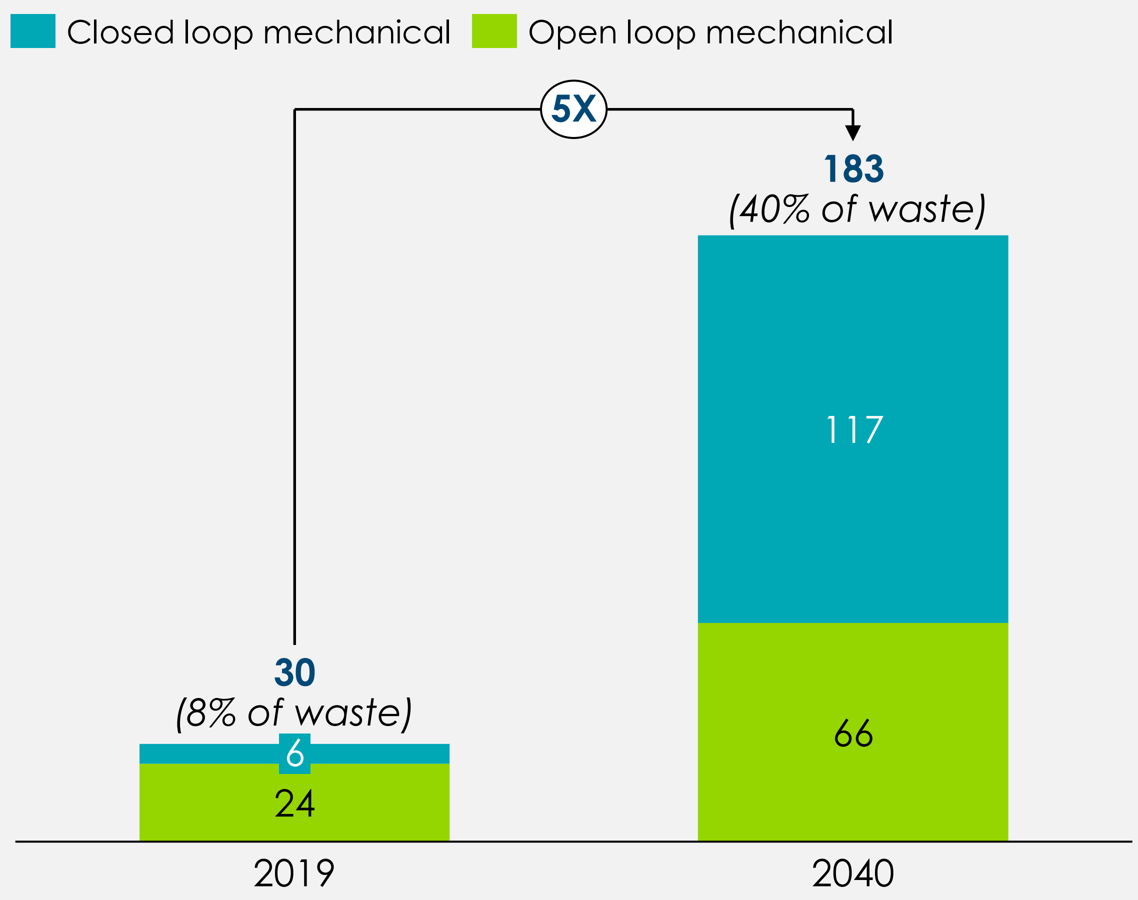
Re-use requires scale to become economic and consumer behavior change, so would need policy support

Barriers to re-use scaling	What needs to change for re-use to scale
1. Ingrained consumer behaviour	1. Consumer preferences and habits shift
2. Cheap and convenient, single-use plastic	2. Single-use bans/penalties (e.g. EU Single use plastic Directive)
3. Requires scale but has high upfront-costs	3. Government support to first movers
4. Requires system change (e.g. brands and retailers marketing, operations)	4. Sector specific packaging regulation, including re-use/refill targets

Source: Systemiq analysis for ETC (2025)

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 (%)



Barriers to scaling Mechanical recycling

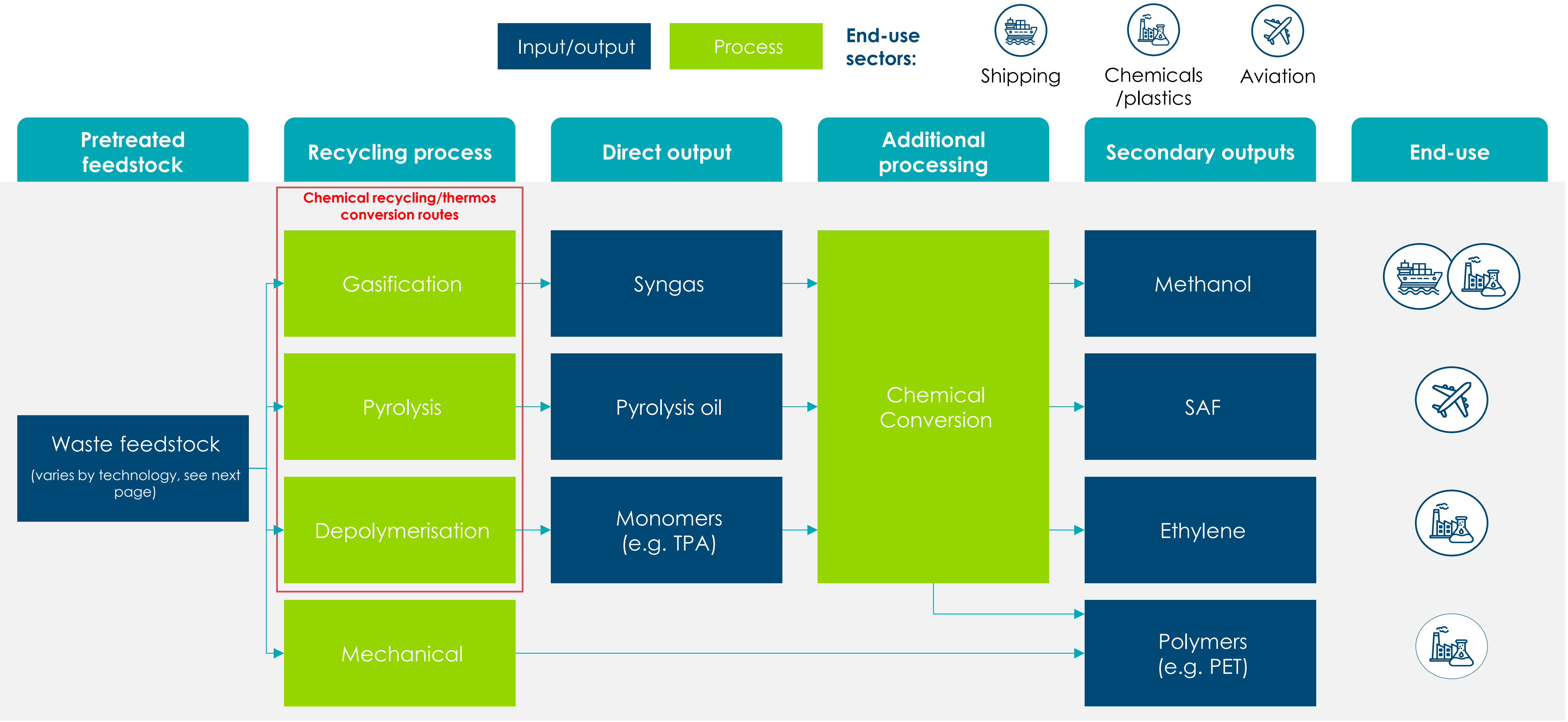
1. Degradation of material resulting in inferior product
2. Feedstock limitations (tolerance for contamination)
3. Weak business case due to cheap, abundant virgin feedstock

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

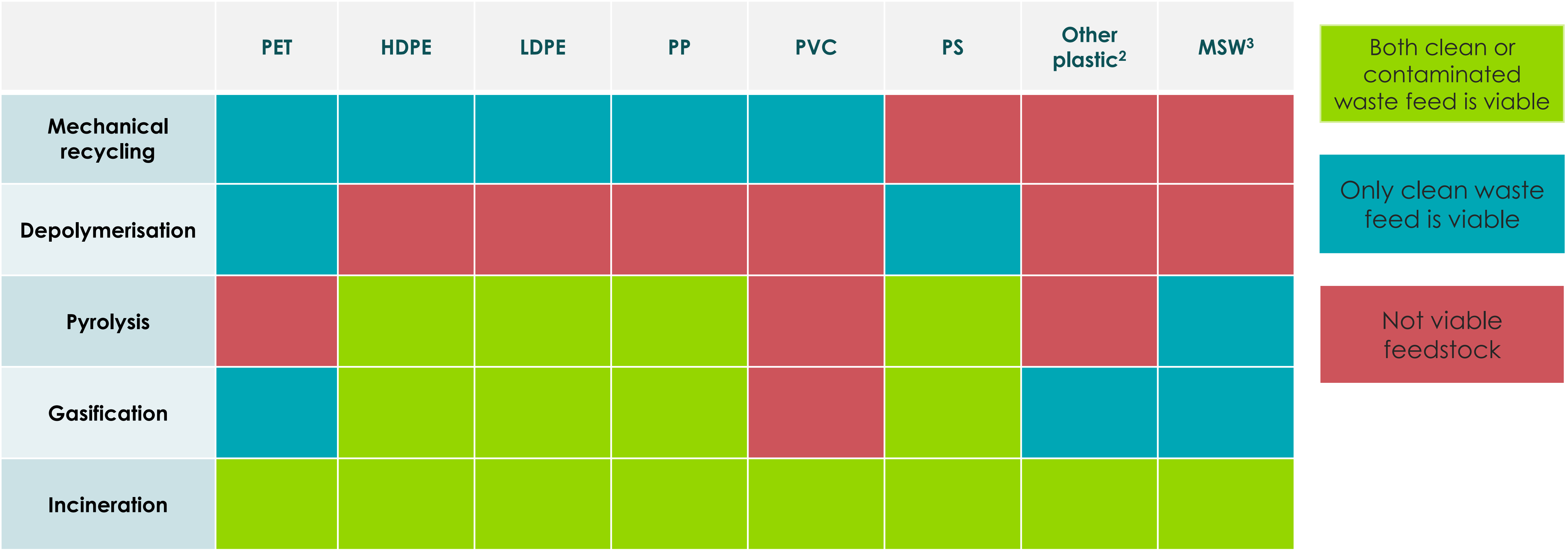
Source: Systemiq Plastic Treaty (2024). List provided is a subset interventions in the Global Full Lifecycle Scenario that related to increase recycling.

Chemical recycling and thermo-conversion pathways enable circular carbon supply to multiple end-use sectors



…but face two major challenges of feedstock compatibility and quality that could limit the final potential of any one technology

Mechanical and Chemical Recycling technologies are **complementary and must be built in tandem due to feedstock tolerances**

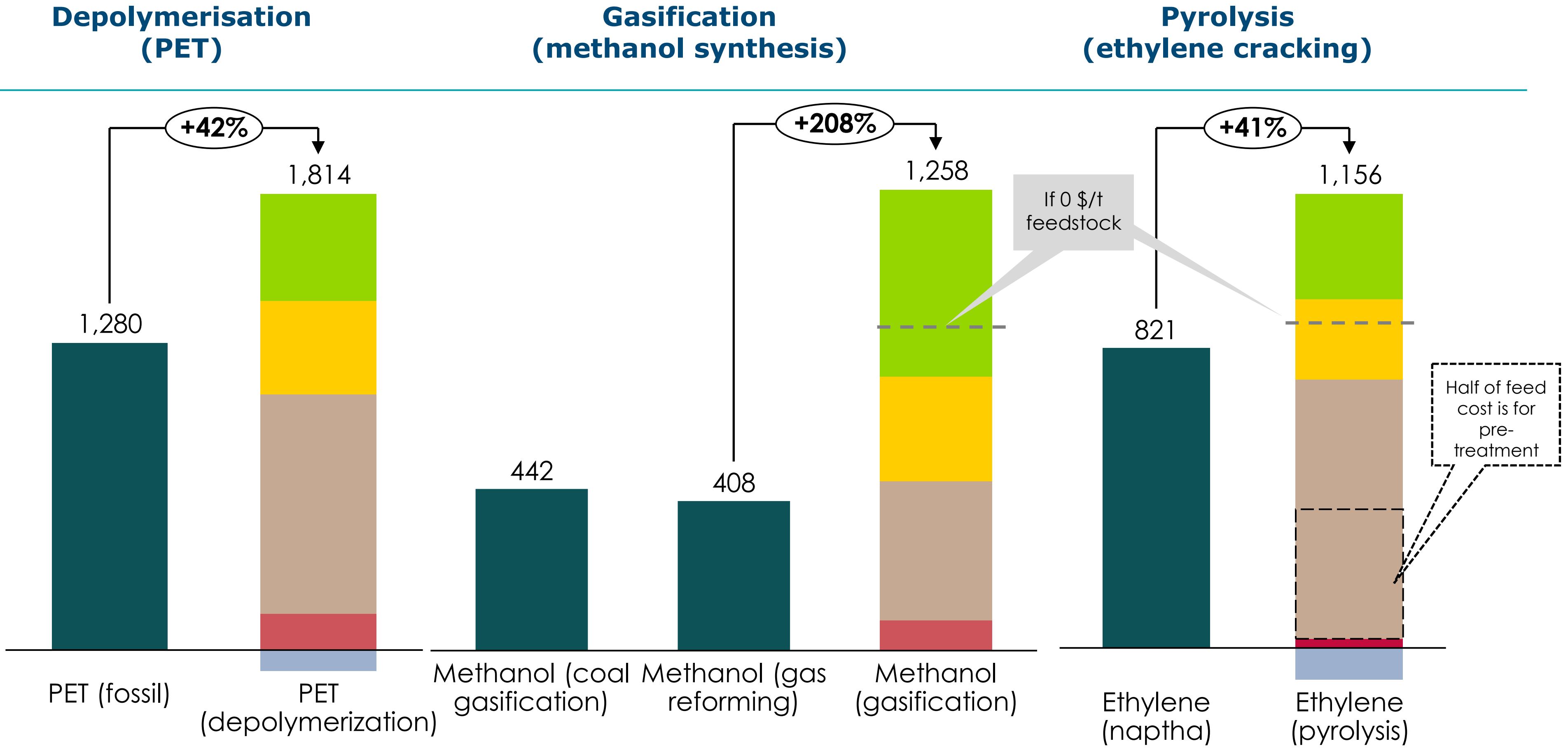


Source: Systemiq Analysis for ETC (2025)
Note: : (1) "Pyrolysis operators require well sorted, clean, and largely homogenous feedstock – in the vicinity of 85% polyethylene (PE) and polypropylene (PPI)", Alliance to End Plastic Waste (August 2022), Feedstock Quality Guidelines for Pyrolysis of Plastic Waste. (2) rest 30% of total plastic production (e.g. PU, ABS, PA, PC, POM) (3) Municipal Solid Waste, includes plastic(10% mixed plastics, 30% paper/wood, 40% organics,10% inorganics and others). Assuming Refuse Derived Fuel (RDF) as clean/sorted waste.

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

Levelised cost of production
$/tonne (2025)

- Counterfactual product
- Capex
- Other Opex
- Waste feedstock/treatment
- Electricity[1]
- By-product revenue



Feedstocks

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

Cost of feedstock and pre-treament 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).

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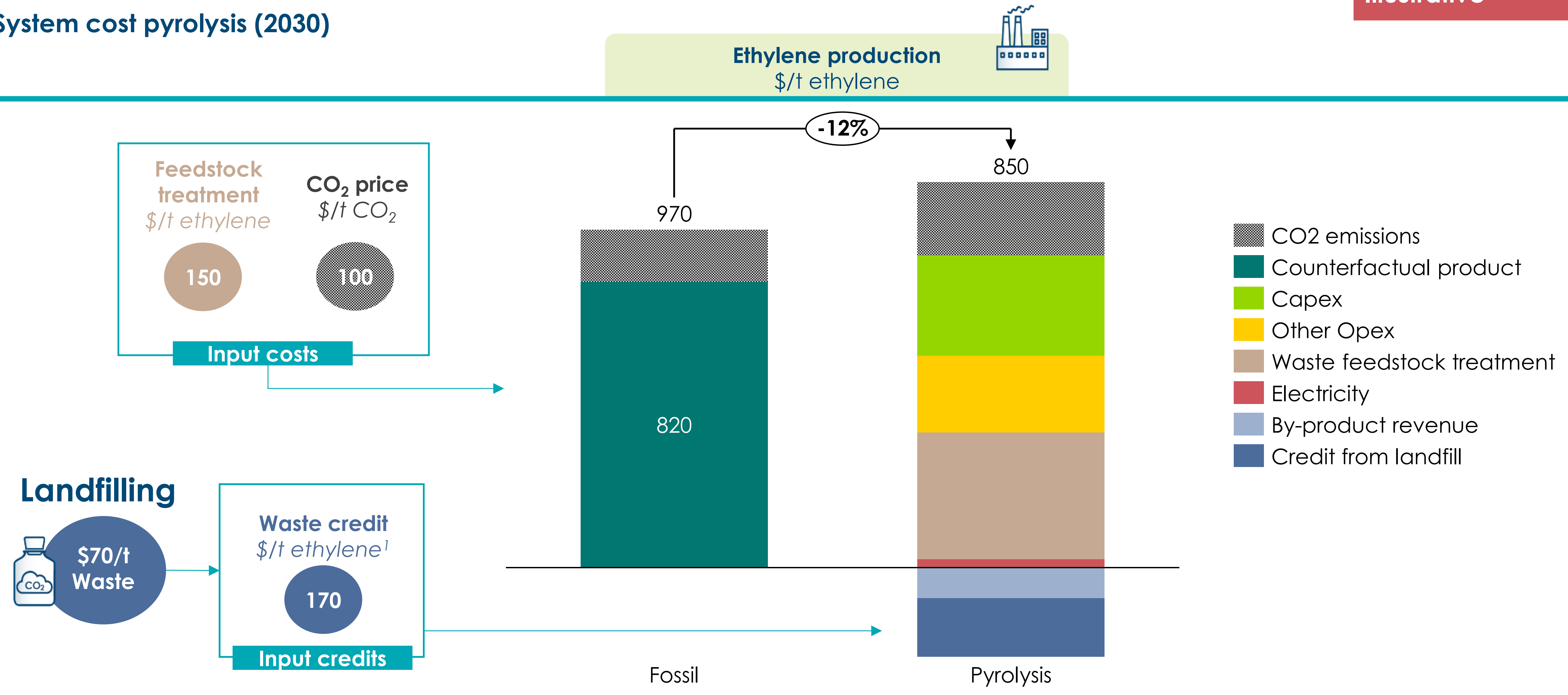
Scenario: If recyclers are paid the cost of landfilling to treat waste plastic, pyrolysis product is cheaper than the fossil alternative

Illustrative

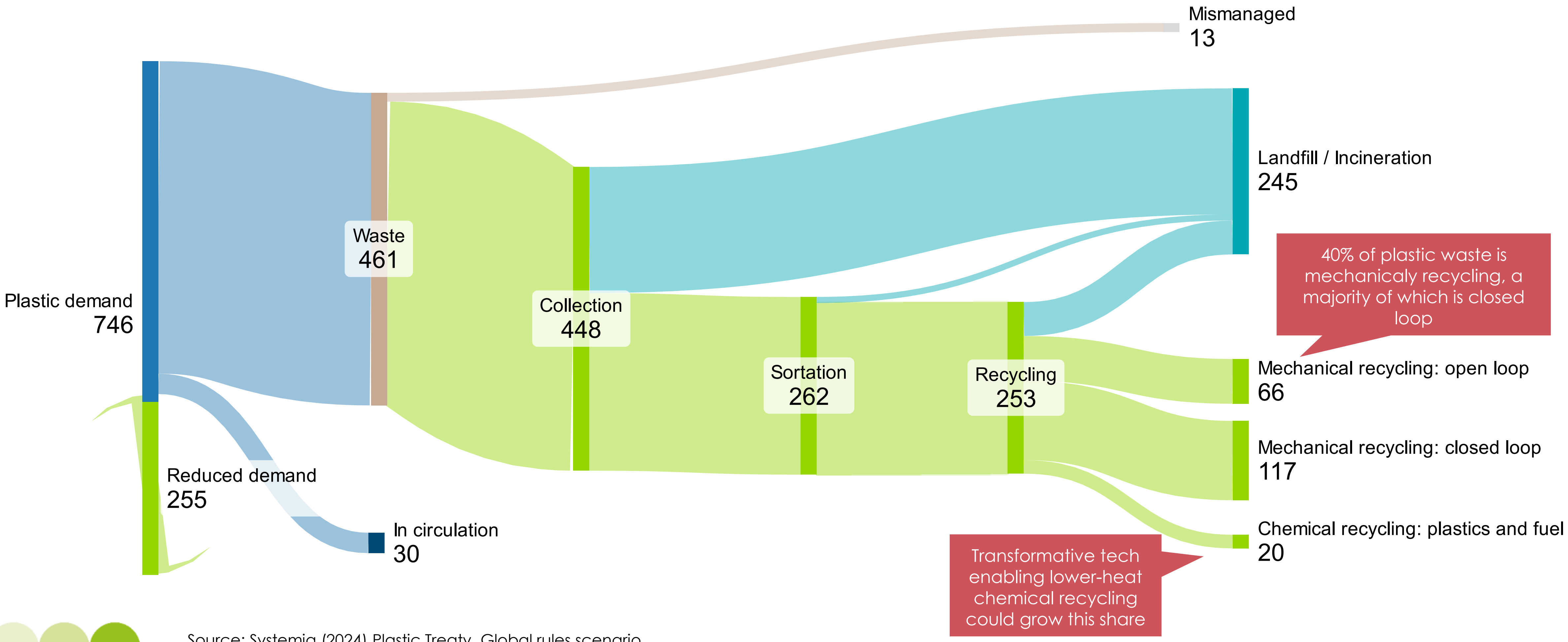
System cost pyrolysis (2030)



Sources: Systemiq PPC model, Tomic et al. (2024). Notes: 1) One tonne of ethylene requires 2.4 tonnes of plastic waste. Note: Long-term contracts, often 10-year or more, create legal and financial barriers to phasing out incineration

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*



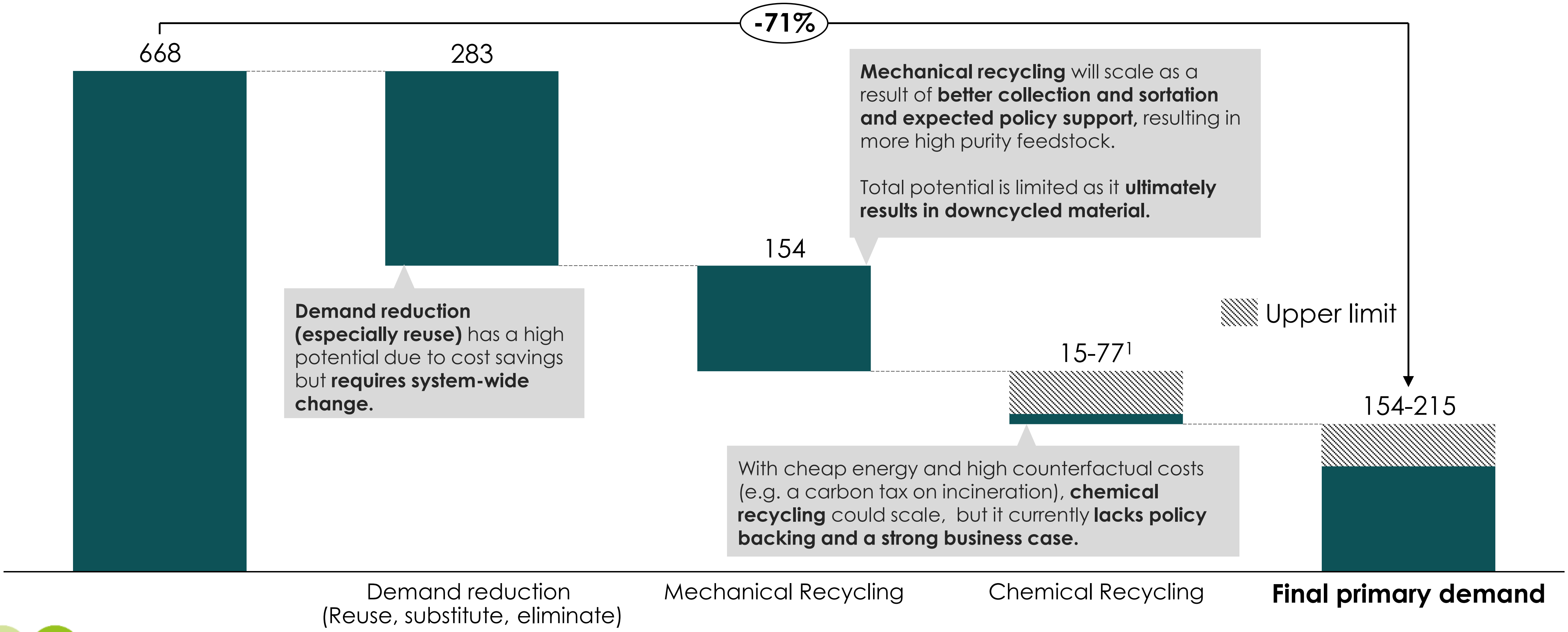
Source: Systemiq (2024) Plastic Treaty, Global rules scenario

Stetch 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)

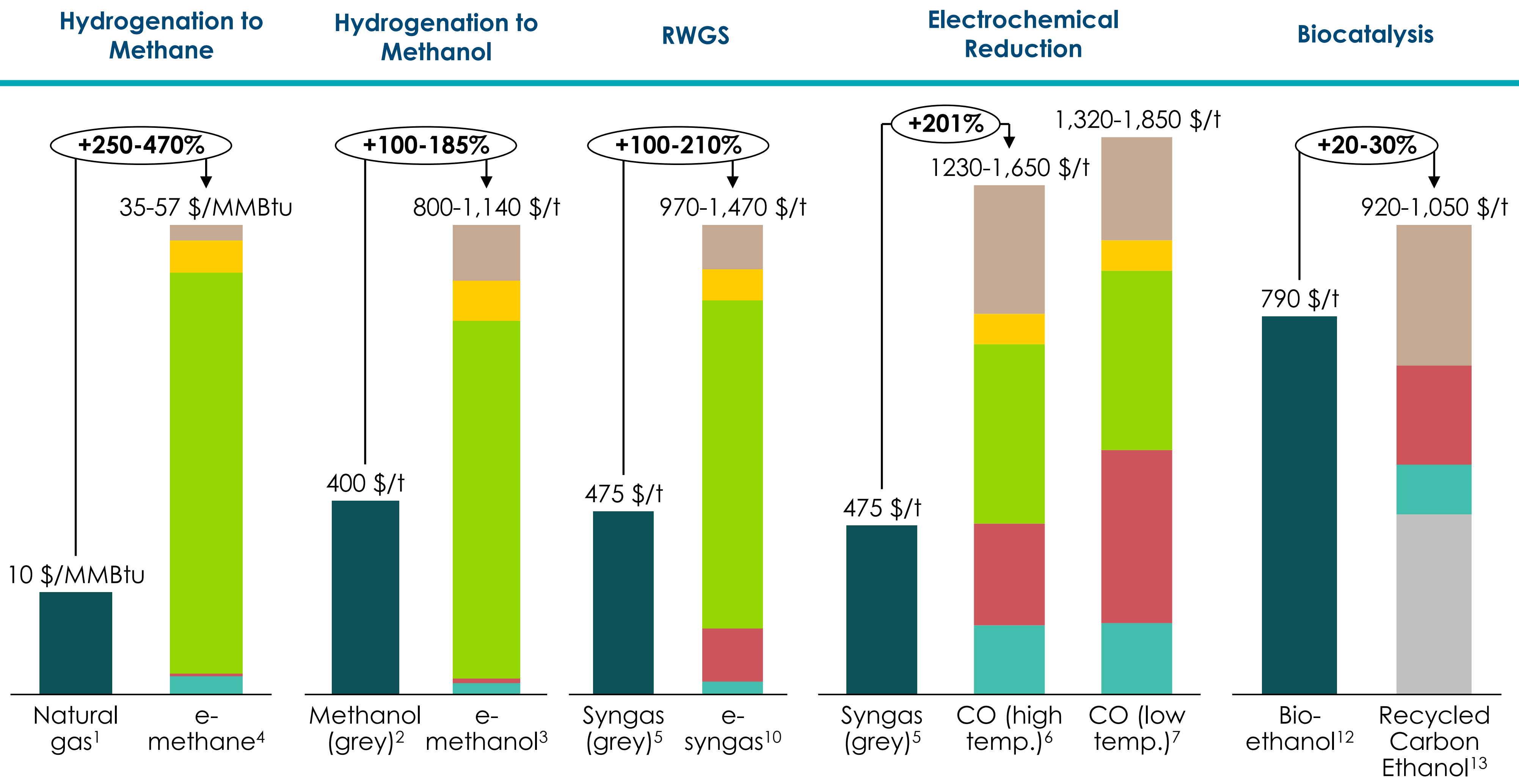


Sources: Energy: Systemiq analysis (2025), based on Fossil Fuels in Transition (ETC, 2023); Chemicals: Planet Positive Chemicals Report (Systemiq, 2022, BAU Net-Zero scenario), and Systemiq (2024) Plastic Treaty Futures.; 1) Based on Systemiq reports – final number being refined.

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

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

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



Key inputs

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

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

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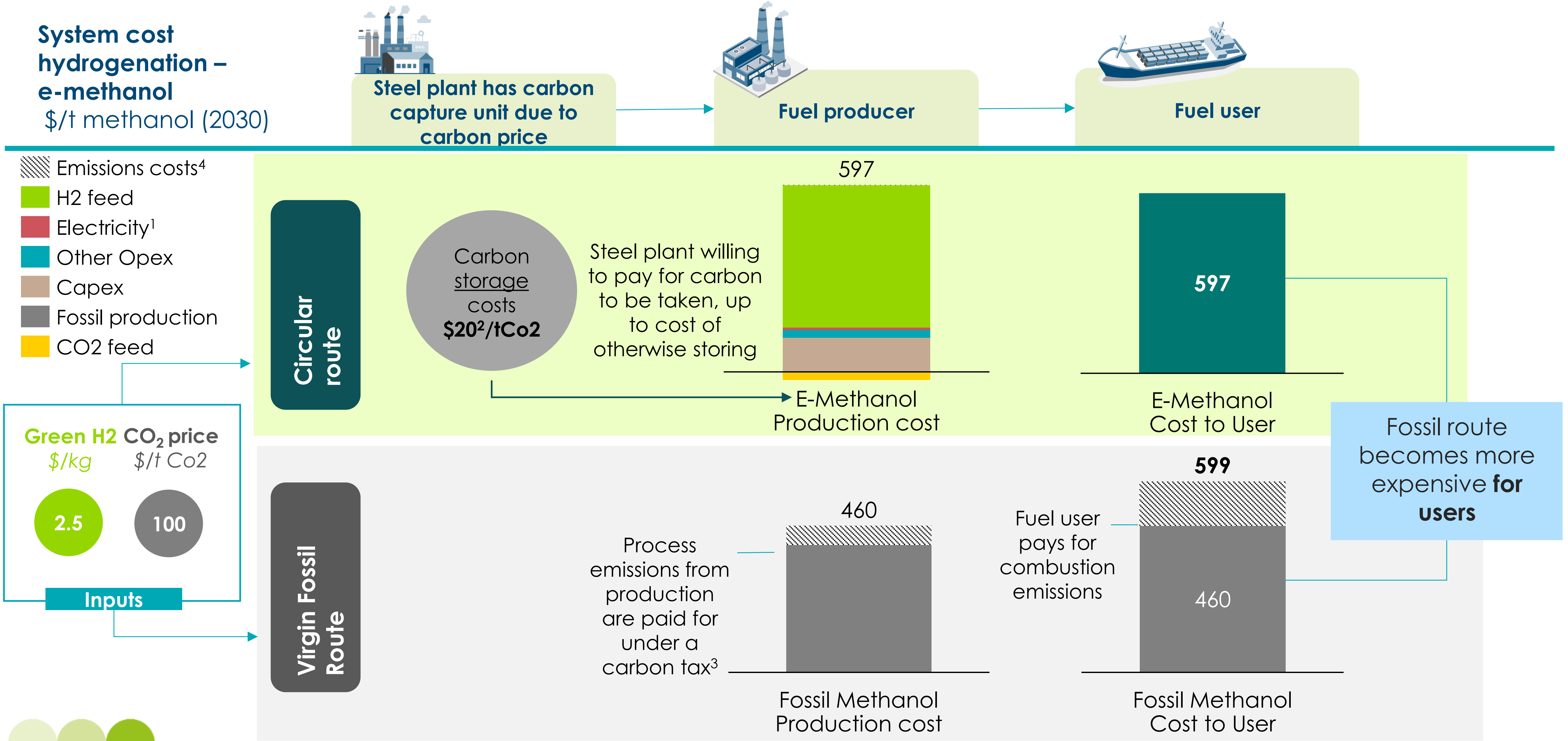
Scenario: A carbon price of \$100/t CO_2 with H_2 price of \$2.5/kg H_2 could make CCU pathways competitive with fossil

Illustrative

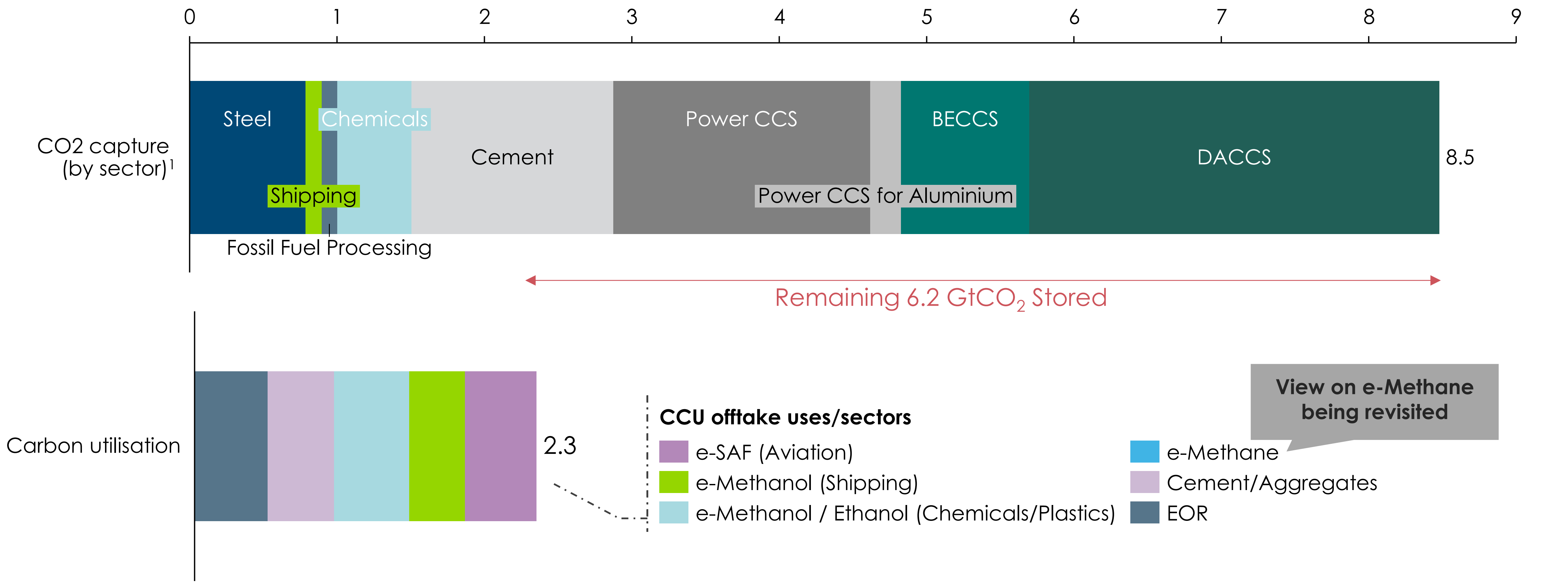


Source: Systemiq Analysis based on Planet Positive Chemicals (Systemiq, 2022), Carbon Footprint of Methanol (Methanol Institute, 2022). 1) Electricity cost of \$60/MWh 2) Cost of storage based on CCUS, ETC, 2022). 3) Process emission based on Methanol Institute 2022, small amount of emission are assumed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

GtCO$_2$ p.a.



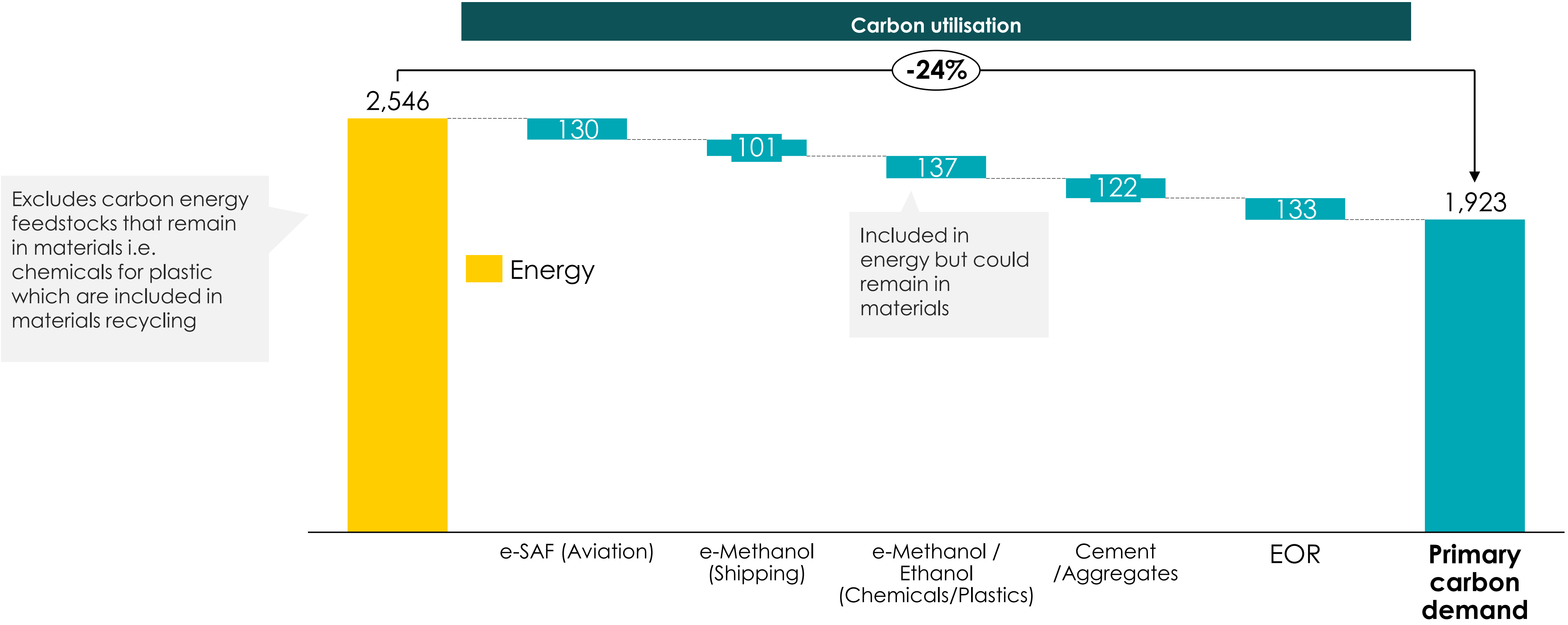
EOR = enhanced oil recovery. CCU = carbon capture and utilization. CCS = carbon capture and storage. DACCS = direct air carbon capture and storage. DACCU = direct air carbon capture and utilization. BECCS = bioenergy with carbon capture and storage. Note: 1) Volume shown refer to Accelerated But Clearly Feasible Scenario. Fossil Fuel Processing includes natural gas processing, oil products refining and production of high value petrochemicals.

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

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

Carbon utilization potential from energy sector carbon, 2050

Million tons of carbon (C)



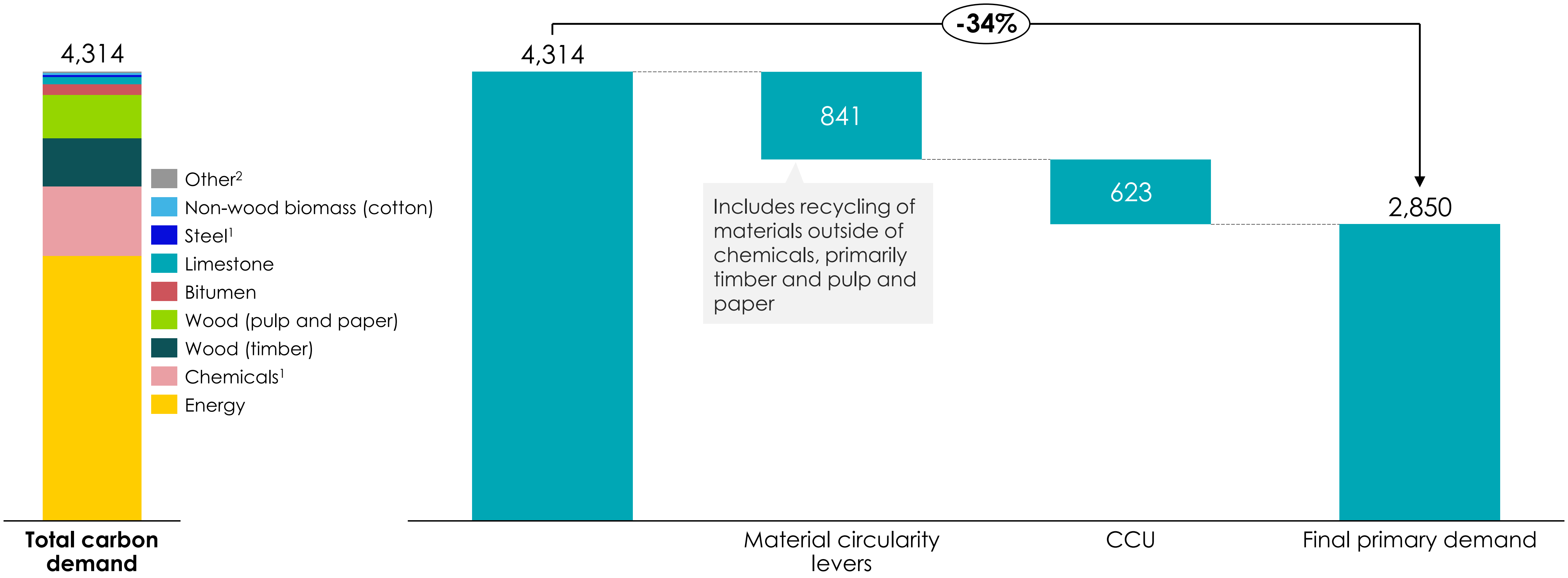
Sources: Energy: Systemiq analysis (2025), based on Fossil Fuels in Transition (ETC, 2023); Chemicals: Planet Positive Chemicals Report (Systemiq, 2022, BAU Net-Zero scenario), and Systemiq (2024) Plastic Treaty Futures.; 1) Excludes energy feedstocks used that remain in steel and chemicals, which are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

Next steps

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

Develop **innovation briefs** on key technologies

Phase 3 begins Q2