Energy
Transitions
Commission

ETC Carbon Molecules

ETC Representatives Meeting
20th February 2025

Agenda

Provide an update to the **ETC carbon molecules project** (supported by QCF)

Give overview the key findings from **Phase 1**

Provide an update on **Phase 2** and Share **next steps** and **opportunities** of offering **inputs**

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

Focus of today

Recap: Carbon molecules in the zero-emission economy: work programme

Pre-read

Question	Deliverables
1. How large a role can and should direct electrification play in a zero-emission economy?	• An extreme scenario which identifies how much of the economy could in principle be electrified if zero carbon electricity were available at a very low cost and on the required scale. • A revised version of our Possible but Stretching scenario which describes the optimal role of electricity in a world on target to limit global warming to 1.5oC. • A constrained clean electricity scenario, which would serve as a counter to the 'extreme scenario' which would be based on more conservative clean power build out (e.g. B EF's clean energy project pipelines) • A set of electrification innovation deepdives, covering technology, cost, barriers to deployment, impact on total electrification
2. The role of hydrogen and non-carbon H2 derivatives	• Updated set of scenarios for the role of hydrogen, exploring in particular the balance between hydrogen and non-carbon H2 derivatives relative to carbon and hydrocarbon molecules in different sectors
3. The potential to recycle and reuse carbon molecules	• Extreme scenario to explore how close to total recycling of all carbon molecules it would be possible to get, and with what implications for the primary supply of new carbon still required to support a prosperous global economy • A range of less extreme plausible scenarios for carbon source demands in a zero-emission economy
4. Sources of primary carbon: costs and sustainability	• Update (increasing or decreasing) of our past estimates of potentially sustainable bioresource supply • Description of the latest technology development and cost trends in point source capture and direct air capture of CO_2 (DACCS) • Brazil deepdive: assessment of the optimal decarbonisation path within Brazil's specific conditions

Agenda

Phase 1 the role of electrification and hydrogen

Phase 2 the potential to recycle and reuse molecules

Phase 1: evaluating the role of direct electrification, hydrogen and ammonia in a zero-emission economy

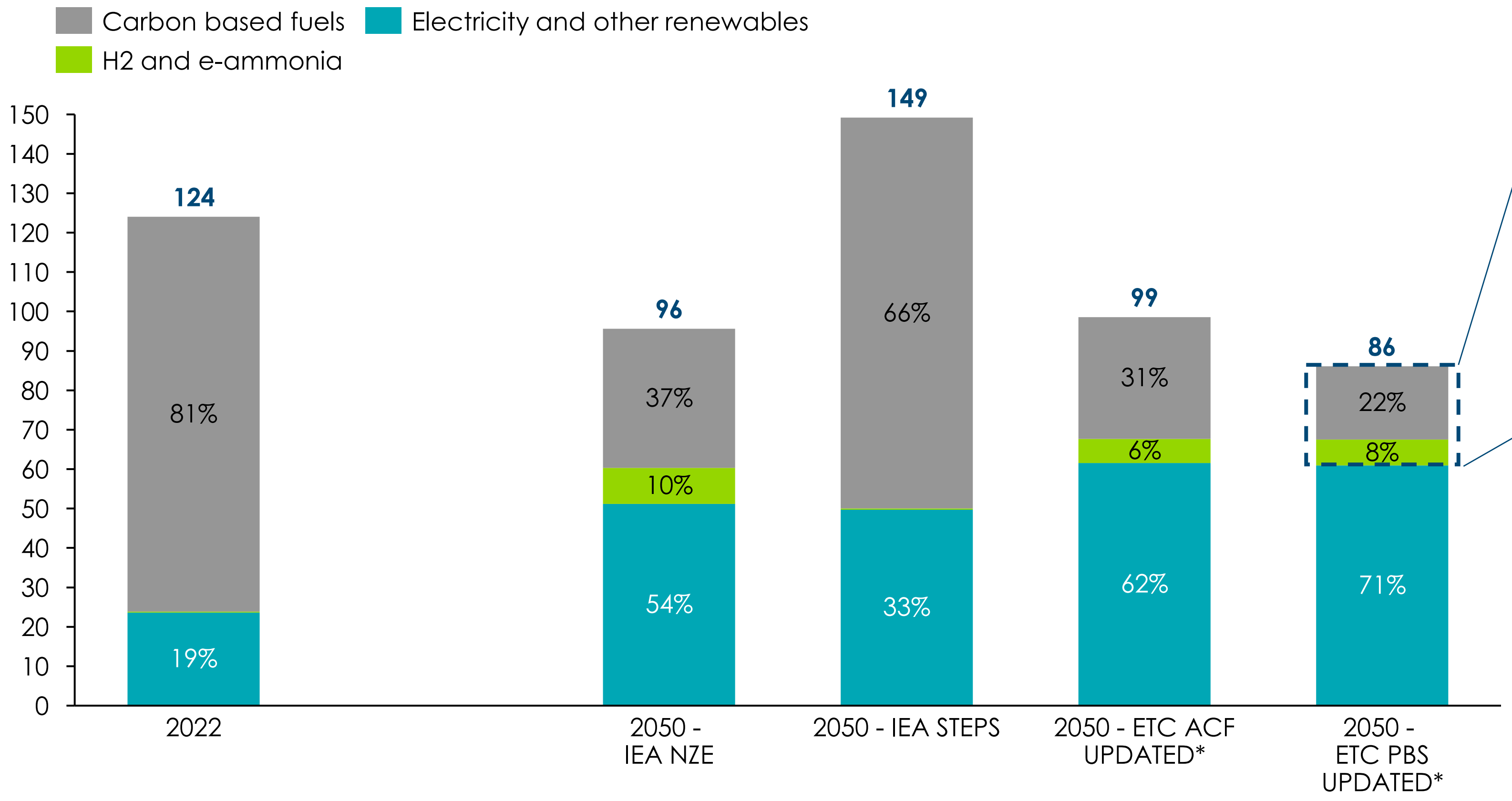
Integration in broader carbon molecule project

By sizing how much non-carbon technologies (electrification, hydrogen and ammonia) can deploy, we also assess the remaining need for carbon-based energy sources, which is the starting point of Phase 2 and 3.

	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	• Publication of the ETC report ahead of COP • A series of short innovation briefs for publication			
Key interactions	• 1 workshops with ETC Members • 1 session with ETC Commissioners	• Workshop • Report reviews • Report launch ahead of COP			

Our starting point: ETC's Fossil Fuel report forecast a high level of electrification in its scenarios, but still relying 30-40% on molecules

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



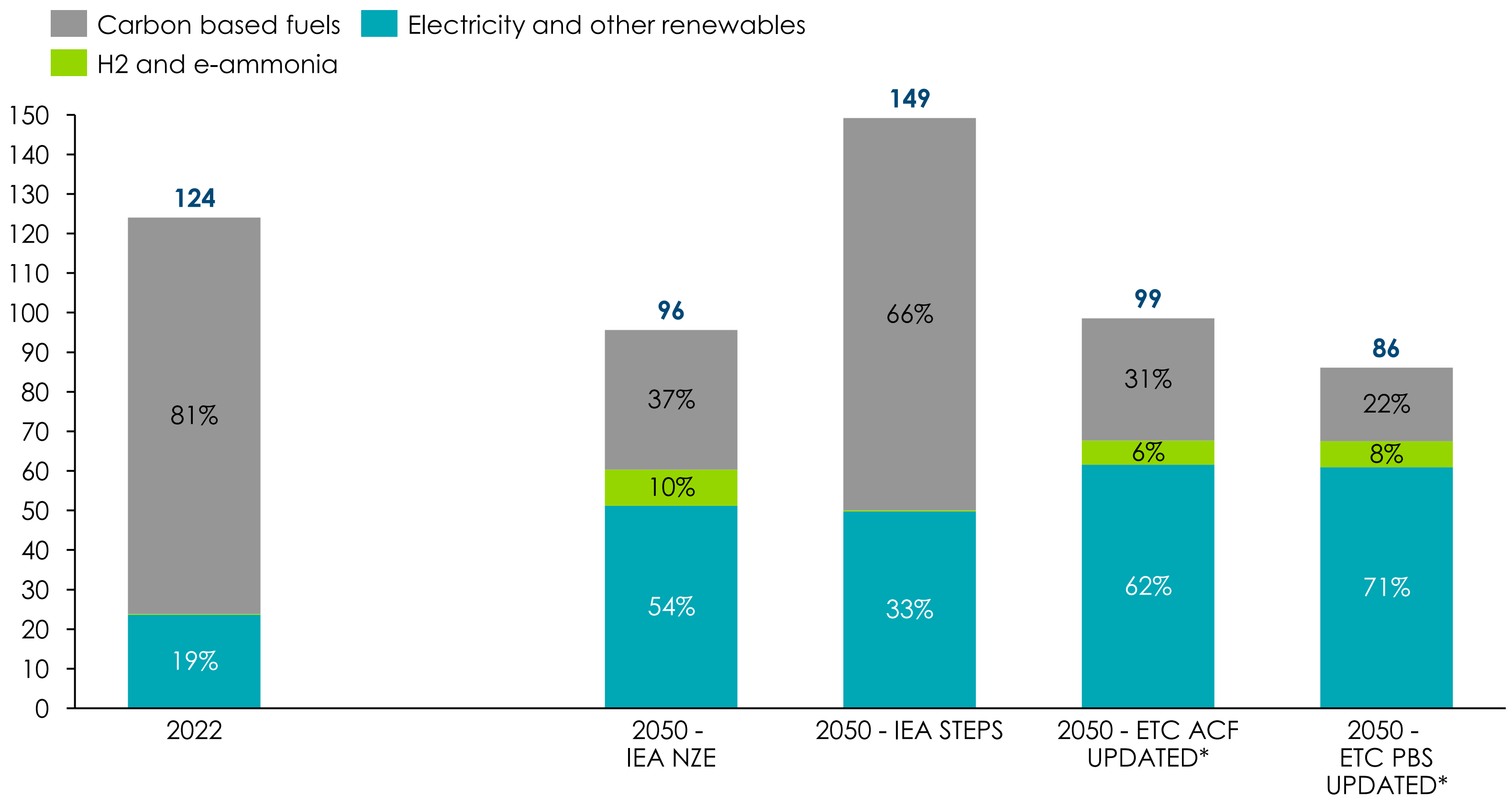
Role of Molecules:

- **~30-40% of overall Final Energy Demand**, of which:
  - 6-8% is **hydrogen or e-ammonia**
  - 20-30% are **carbon-based molecules**

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; IEA NZE, Taken from World Energy Outlook 2023 . *Minor updates from FIIT publication

Recap: We sought to develop two more scenarios – one with constrained electrification and one with electricity and H2 breakthroughs

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



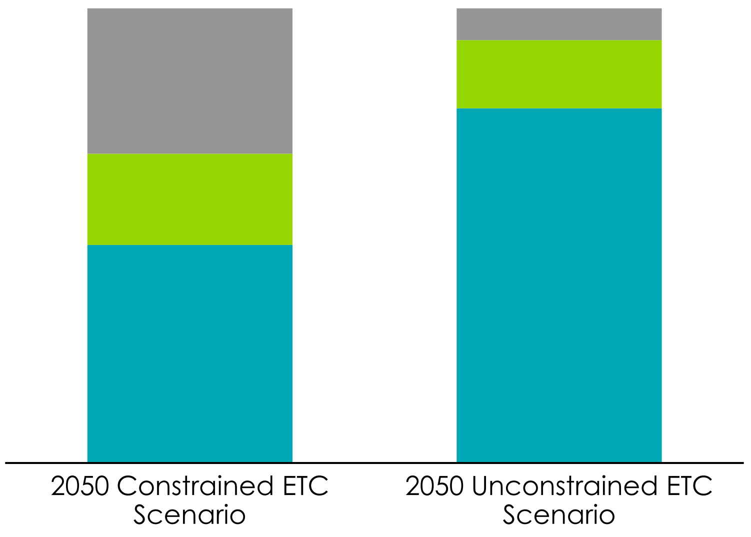
Global Final Energy demand in new ETC scenarios, Thousand TWh 2050

New Scenarios:

Constrained scenario based on conservative view of low emission power supply

Unconstrained scenario based on list of disruption allowing electrification/H2 breakthrough

Illustrative



Note: BNEF ZNS = BloombergNEF Net Zero Scenario; NZE = Net Zero by 2050; 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; IEA NZE, Taken from World Energy Outlook 2023

Eight potential disruptions were analysed that could increase the role of electrification and hydrogen further

Enablers | Hydrogen | Potential but less certainty | High potential

	Technology disruption	Key Conclusions	Sectors impacted
Sector specific	1 Industrial heat electrification (>600°C)	With **low cost-electricity prices**, can displace technologies such as conventional kilns for cement and steam-cracking with CCS for chemicals, however requires **24/7 clean power source**	(Heavy-) industry (cement)
	2 Electrical steam cracking		Chemicals
	3 Molten Oxide Electrolysis and Electrowinning	With cost-competitive electricity and technological advances could **electrify iron production**	Steel/iron production
	4 Li-ion solid state batteries	Steady advancements in battery technology could increase demand for electrons across all **road transport and even short-to-medium haul aviation and shipping**	Trucking; Shipping; Aviation
	5 Advanced Direct Air Capture (DAC) Revisit in phase 3	Advancements could significantly reduce the cost of DAC, but there is **uncertainty** whether these could materialize to be any lower than $100/t Co2 by 2050	Industry; Chemicals; Aviation; Power
Cross sectoral	6 Sodium-based battery technologies	Sodium further reinforces the scalability and economic viability of **battery storage** solutions to enable further renewable penetration in **power system**	Power; Industry; Mobility; Buildings
	7 Small Nuclear Reactors (SMR), Nuclear Micro Reactors (NMR)	Could see commercialization in late 2030s, but **remains highly uncertain.** Faces **competition with** decreasing cost of **renewables + battery**	Chemicals and other industry
	8 White hydrogen and optimizing electrolyzer system and balance of plant costs	Electrolyzers costs still expected to come down over time, but still higher than previous forecasts. **White hydrogen** is still **nascent**	Power; Chemicals; (Heavy-) industry

Four of the eight disruptions had higher certainty and potential to reduce molecules so were included in scenarios

Enablers | Hydrogen | Potential but less certainty | High potential

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	2 **Electrical steam cracking**		Chemicals
	3 **Molten Oxide Electrolysis and Electrowinning**	Cost-competitive electricity and technological advances could **electrify iron production**	Steel/iron production
	4 **Li-ion solid state batteries**	Steady advancements in battery technology could increase demand for electrons across all **road transport and even short-to-medium haul aviation and shipping**	Trucking; Shipping; Aviation — Focus next
	5 **Advanced Direct Air Capture (DAC)** Revisit in phase 3	Advancements could significantly reduce the cost of DAC, but there is **uncertainty** whether these could materialize to be any lower than $100/t Co2 by 2050	Industry; Chemicals; Aviation; Power
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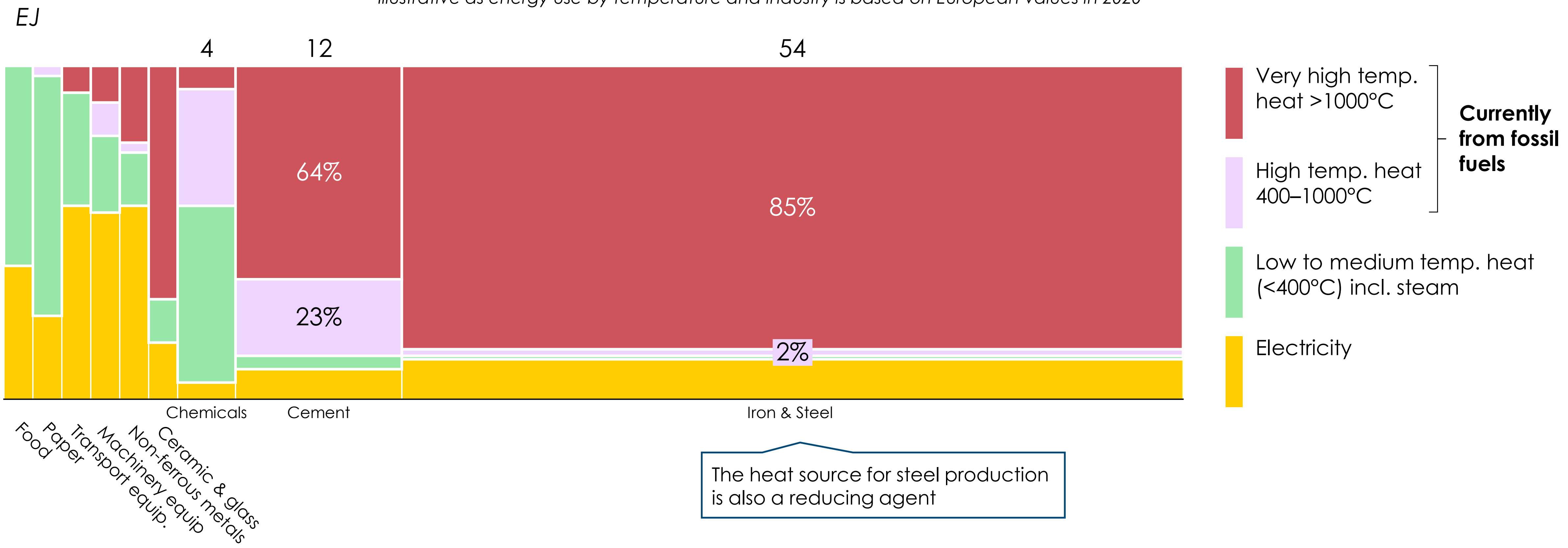
High temperature industrial heat: demand for high temperature heat in industrial sectors present a big opportunity

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



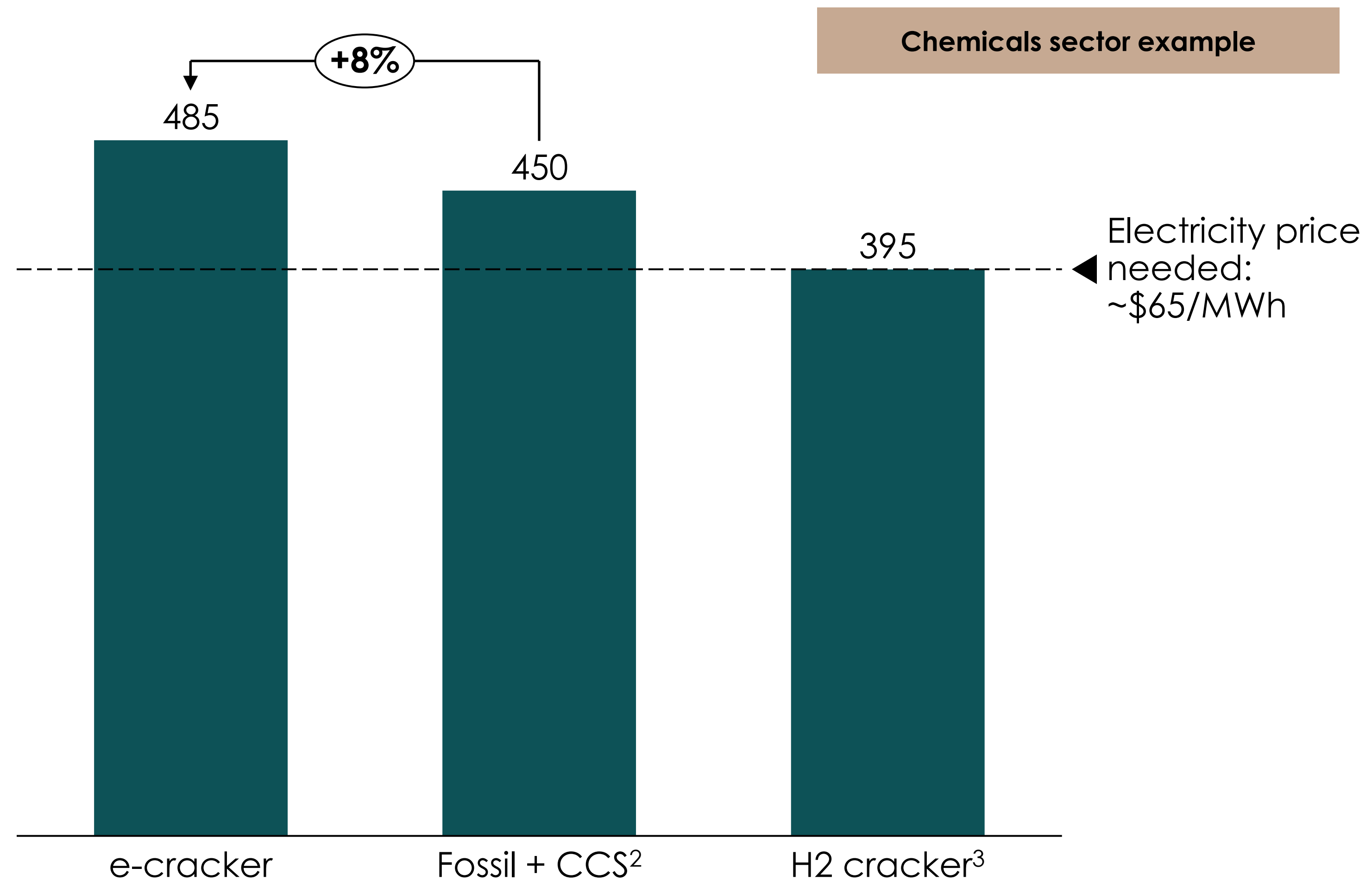
Notes: 1. Data representing energy split by temperature in EU across the sectors applied to a global level based on a study from Madeddu (20220) with adaptions for the chemical sector to include plastics from Coolbrook (2024).

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

Low electricity prices could see high temperature industrial heat become competitive with alternatives, but barriers exists to scaling

1 2

Levelised cost of heat in ethylene production in 2050[1], $/t ethylene



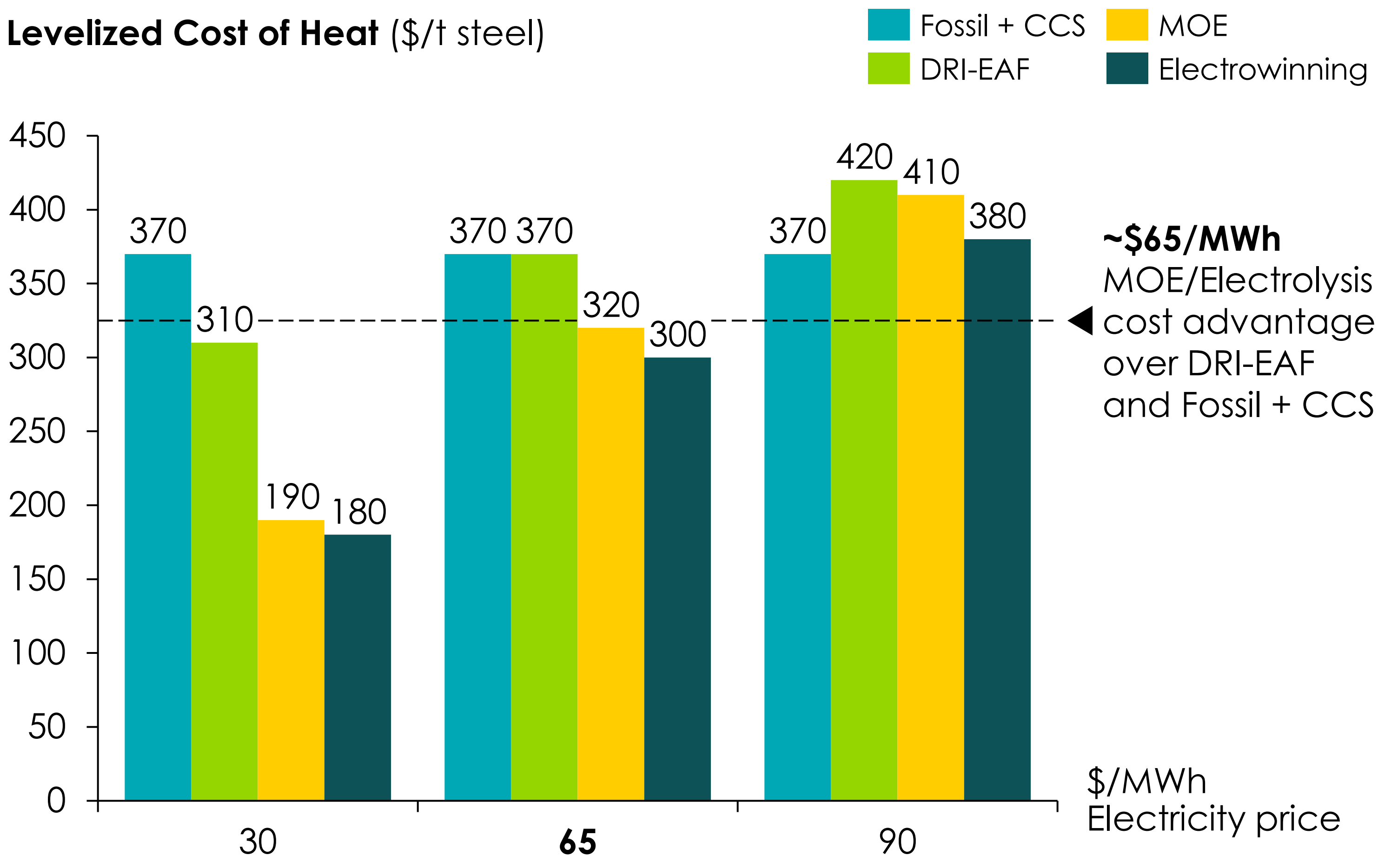
Potential barriers

- **Requires firm 24/7 clean power source:** energy-intensity cannot be easily ramped up/down without losses
- **Cost to convert** high-temp technology to existing assets could be high and disruptive to operations
- **Heat resistant materials** in the processes need to be able to reliably withstand extreme temperatures over operational lifetimes

Notes: 1. High value chemical; All values are based on a case example for a Naphtha cracker to produce Ethylene. E-cracker costs assume a capex of $1335 per tonne of high value chemical annualized over 10 years, average energy input of 4 MWh/t HVC at a price of $90/MWh 2. Assumes capex of a fossil naptha cracker of $1255 per tonne of HVC annualized over a period of 10 years. Input price for gas will include CCU/S assuming an emissivity factor of 0.2 t Co2/MWh and a cost of capture of $100/t Co2. Energy inputs are assumed at 5 MWh/t HVC with a gas price of $45/MWh. *3. Uses same capex and energy input requirement as fossil based cracker with a hydrogen price of $2/kg H2.*
Sources: Center for Global Commons & Systemiq (2022), *Planet Positive Chemicals, Tijani et al (2022) Review of Electric Cracking of Hydrocarbons*, Vasudev et al (2018) *Intensification fo Ethylene Production from Naptha and expert input*

Similarly for MOE and Electrowinning in steel/iron-making, electricity prices make both technologies competitive with other decarbonization alternatives

Sensitivity analysis of electricity price ($/MWh) on the levelized cost of heat ($/t steel) 2050



Potential barriers

- **Requires firm 24/7 clean power source: for MOE technology**, however electrowinning works with intermittent power supply
- **Cost uncertainty:** capex expected to come down, but currently high, O&M costs could be high due to material degradation
- **Material durability** equipment needs to withstand high temperatures and corrosive environments

Source: Systemiq analysis based on Mission Possible Partnership (2022), Making net-zero steel possible.
Notes: Annualized CAPEX: Assumed over 10 years, average over different electrification technologies and average BF-BOF capex assumed; for energy consumption 11.7 GJ/t steel for coking coal and 6.8 GJ/steel for lower-grade steel assumed; for CCU/S cost emissivity for best available technology assumed 1.8 tCO2/t steel and a capture price of $100/t CO2. Hydrogen price: $3/kg assumed from dedicated renewable electricity. Electricity price: based on assumed average grid electricity price. The 65 $/MWh represents the electricity cost to the factory gate.

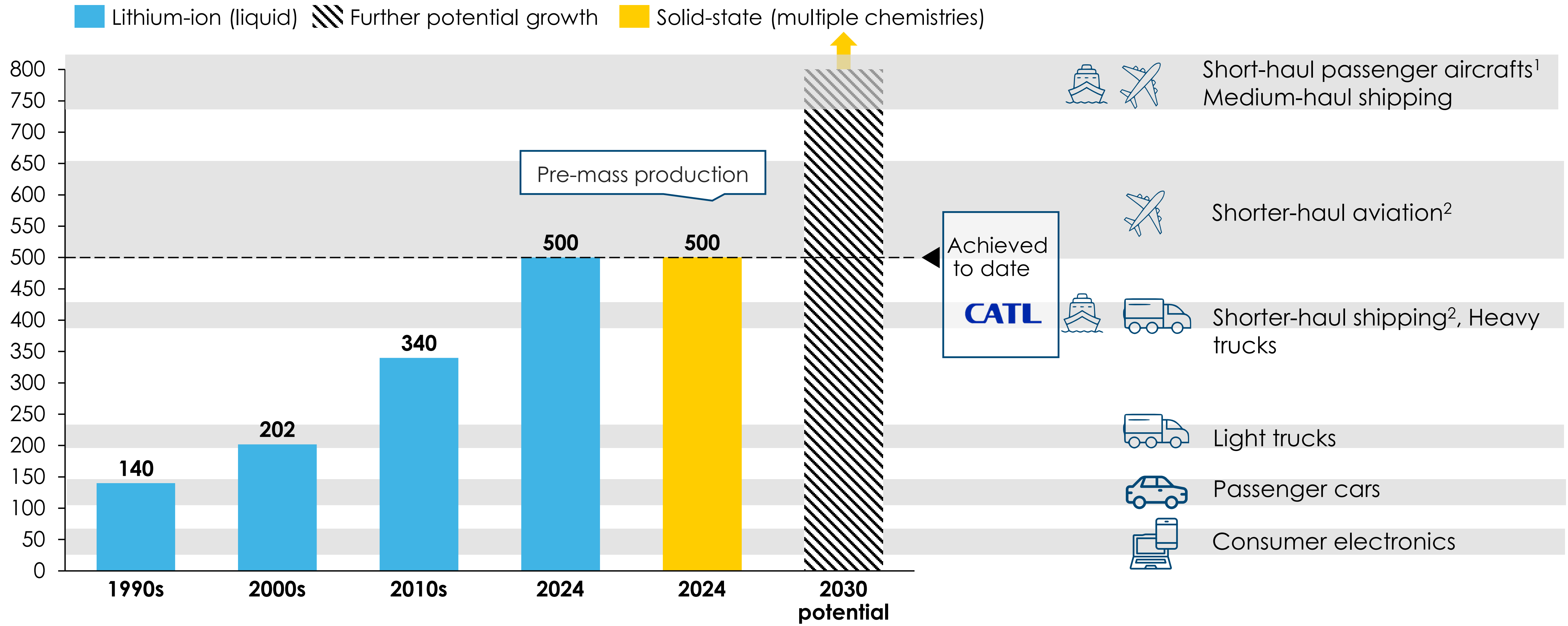
Solid-state batteries have the potential to further accelerate electrification in mobility by significantly enhancing energy density

Top-tier battery cell energy density by decade and today

Gravimetric densities, Wh/kg

Minimum viable energy density

Examples



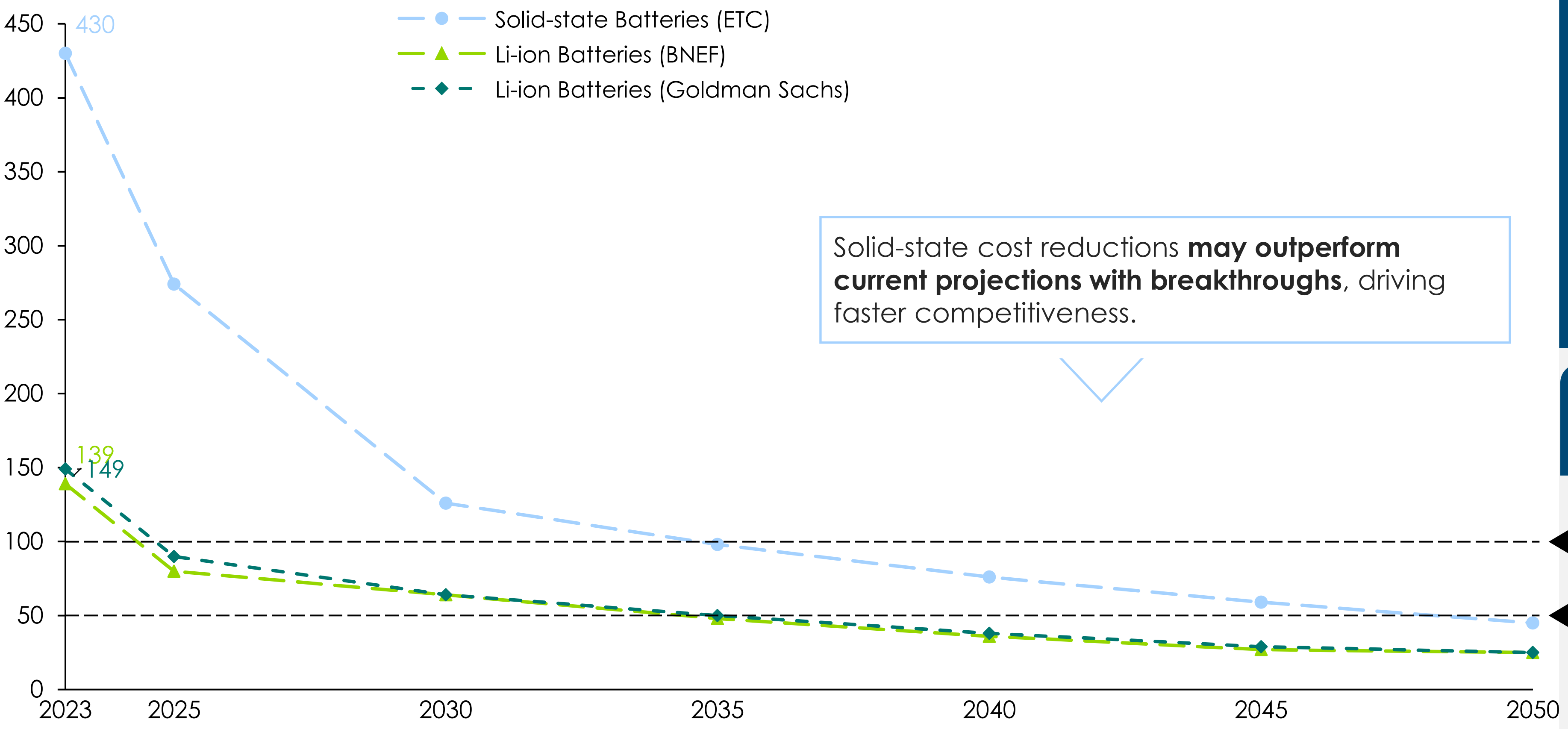
Notes: Currently dominant lithium-ion batteries use liquid electrolytes, current solid-state batteries predominantly use lithium, other ions (e.g., sodium) can be used; Minimum density at which first full battery-electric models are feasible, 1) Typical twin-engine narrowbody aircraft with a range of 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.

Rapid declines in battery costs could open a range of electrification pathways for mobility, potentially accelerating beyond anticipated levels

4

Average battery pack price
$/kWh, actuals and projections[1,2]



Potential barriers

- **Competition** with lithium-ion batteries innovation and R&D budgets across solid-state and other battery technologies
- **Scalability** of production due to technical requirements and existing factor infrastructure not currently fit for purpose

Mobility example
Battery pack price, shipping[3]

At $100/kWh battery-electric ships could compete with fuel oil ships for distances under 1,500 km

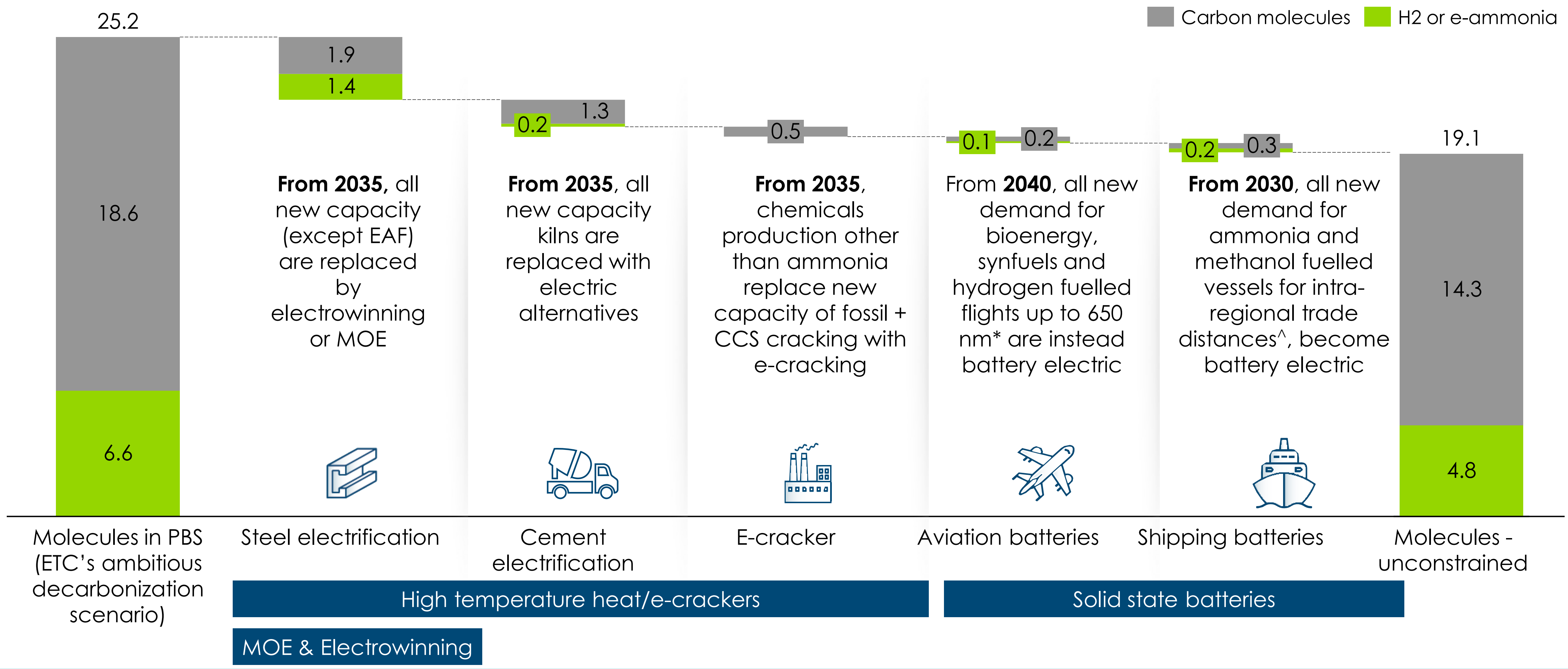
At $50/kWh battery-electric ships medium-range battery-electric ships (~3,000 km) could become economically viable.

1) Methodology for price projections: For solid-state based on Alkahidli et al (2024) projected cost improvement rate of 20% applied up to 2028, then 5% cost improvement rate applied up to 2050, for Li-ion price projections based on BNEF: price projection adapted from BNEF up to 2035: 6% cost improvement rate applied to years up to 2050: for Li-ion price projections from Goldman Sachs (GS): price projection adapted from GS up to 2030, thereafter 6% cost improvement rate applied to years up to 2050;

2) Sources: Goldman Sachs (2024) Electric vehicle battery prices are expected to fall almost 50% by 2026, based on company data, Wood Mackenzie, SNE Research, Goldman Sachs; BNEF (2024)Lithium-Ion Battery Pack Prices See Largest Drop Since 2017; Fraunhofer ISI (2024) Solid-state batteries roadmap 2035+, Alkahidli et al. (2024) Solid-state batteries, their future in the energy storage and electric vehicles market, RMI (2023) Xchange: Batteries The Battery Domino Effect based on Kersey et al (2022). Rapid battery cost declines accelerate the prospects of all-electric interregional container shipping, Nature energy

With key high-temperature industrial heat, iron/steel electrification and solid-state batteries, carbon and non-carbon molecules are can be reduced

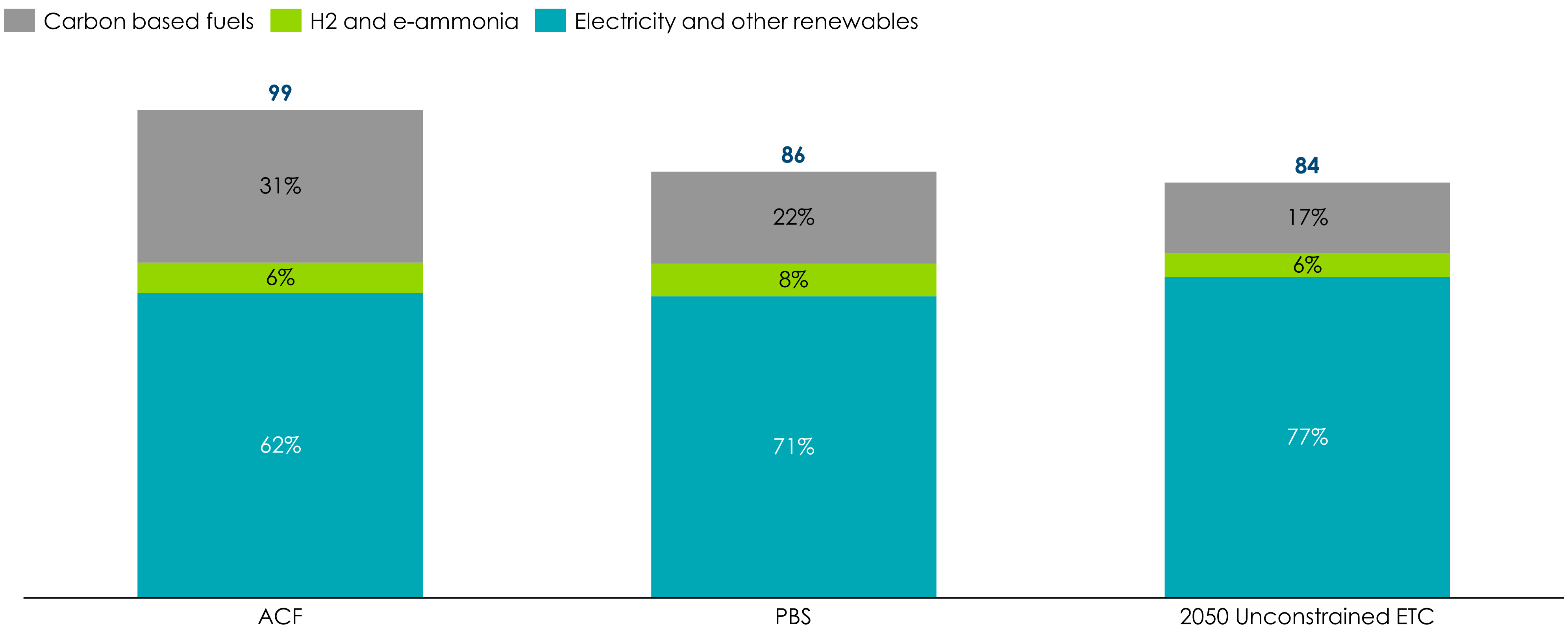
Molecules in the energy system – PBS to Unconstrained share
Final Energy Consumption, Thousand TWh



Source: ETC based on Systemiq analysis (2024)
Notes: PBS = Possible But Stretching ETC decarbonization scenario. *estimated at 15% of all nautical miles travelled, ^estimated at 20% of energy demanded

Final energy demand requiring carbon molecules can range between 20-30% between scenarios

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

Phase 1 the role of electrification and hydrogen

Phase 2 the potential to recycle and reuse molecules

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 workshops with ETC Members • 1 session with ETC Commissioners	• 1-2 workshop with ETC reps/ commissioners	• Workshop • Report reviews • Report launch ahead of COP		

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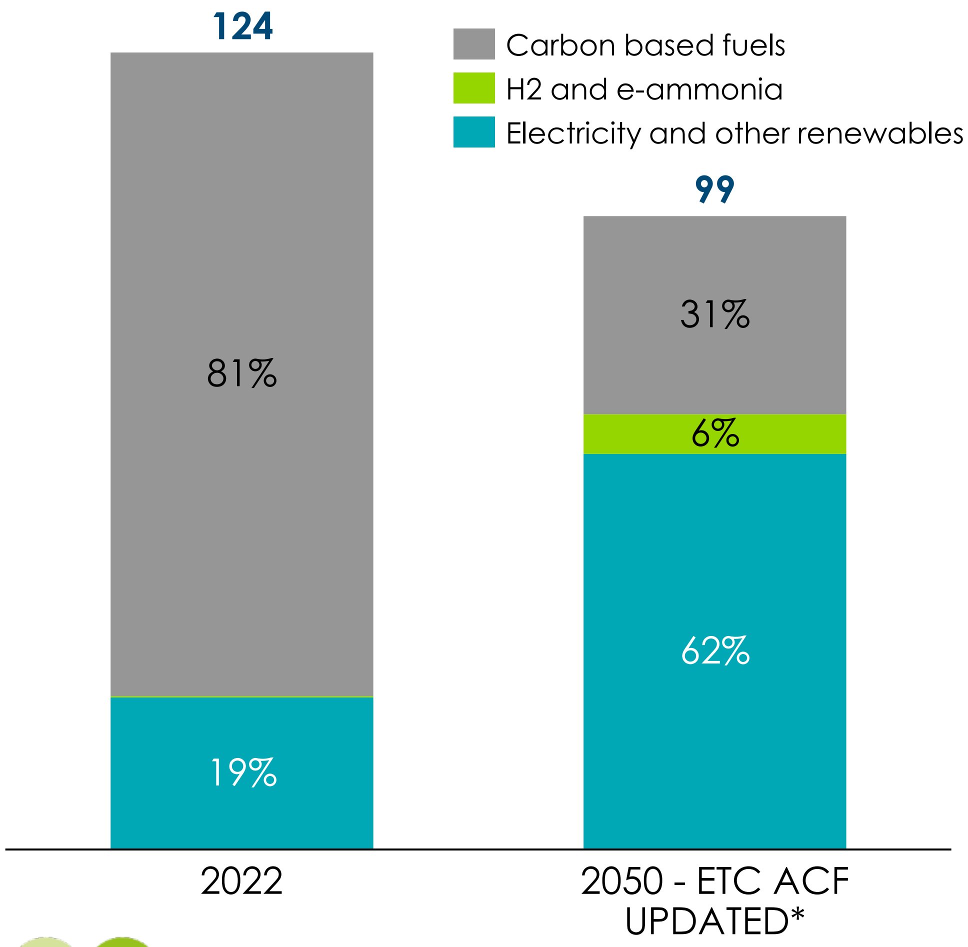
From Phase 1: The energy system demands ~11 Gt of carbon usage today, expected to decrease to 3.2 Gt by 2050 in a decarbonization scenario

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

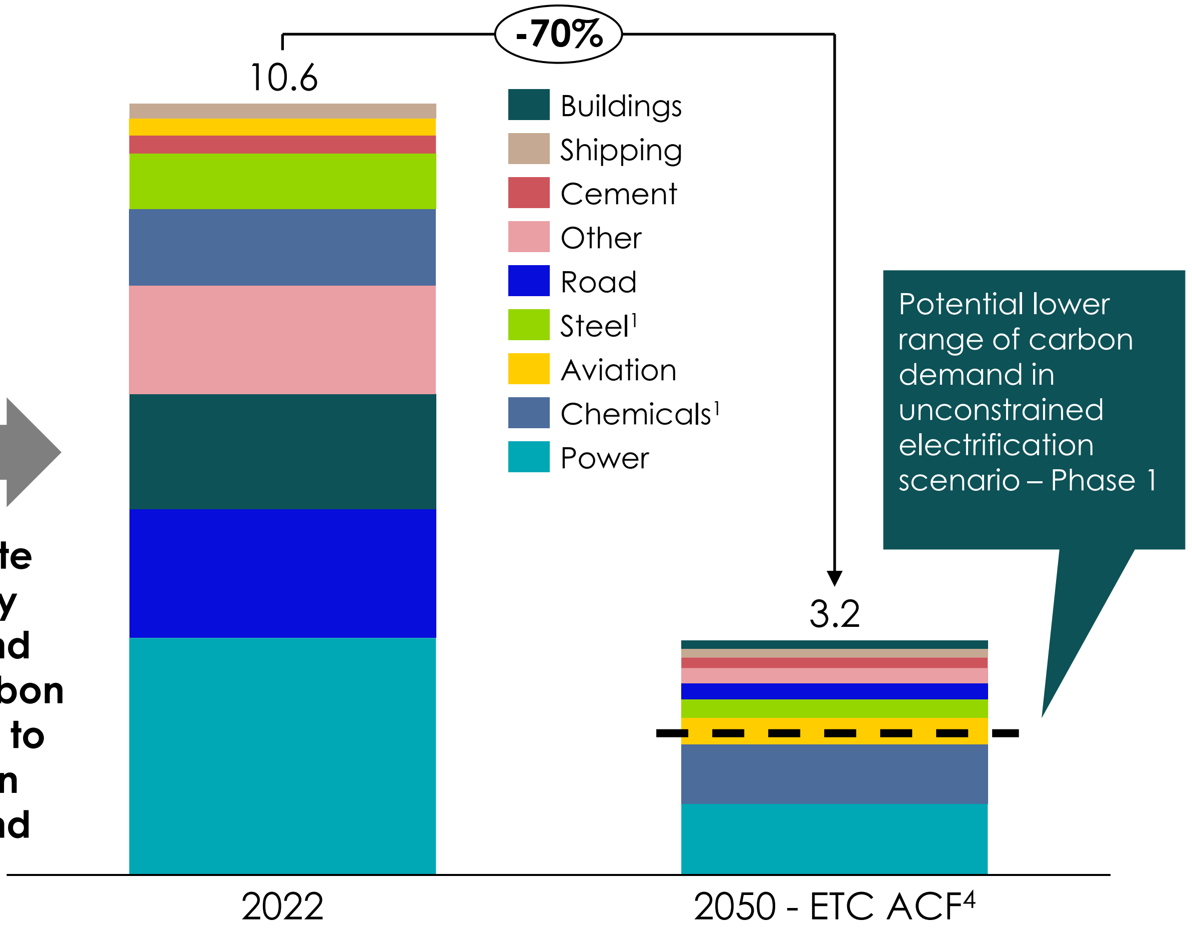
Thousand of TWh



Translate energy demand from carbon sources to carbon demand

Carbon Demand Across the Energy Sector

Giga tons of carbon (C)



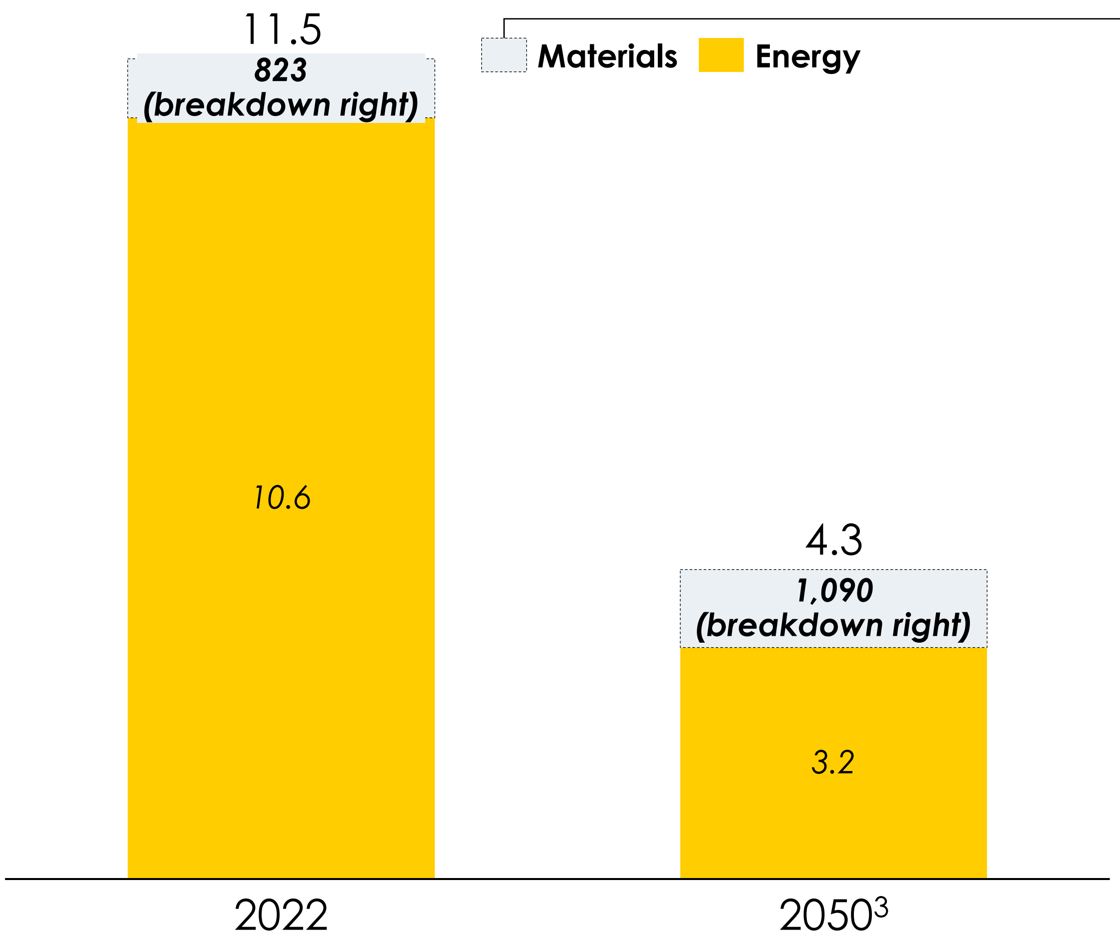
Sources: Energy: Systemiq analysis (2025), based on Fossil Fuels in Transition (ETC, 2023); Chemicals: Planet Positive Chemicals Report (Systemiq, 2022, BAU Net-Zero scenario); Biomass: ETC Bioresources report (2021); Steel: MPP STS (2022); Cotton, Bitumen and Soda Ash: Systemiq analysis (2025) Energy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

1. Include energy based carbon feedstocks, a proportion of which which end in the final products (e.g. chemicals for plastics and steel), and others end in process emissions

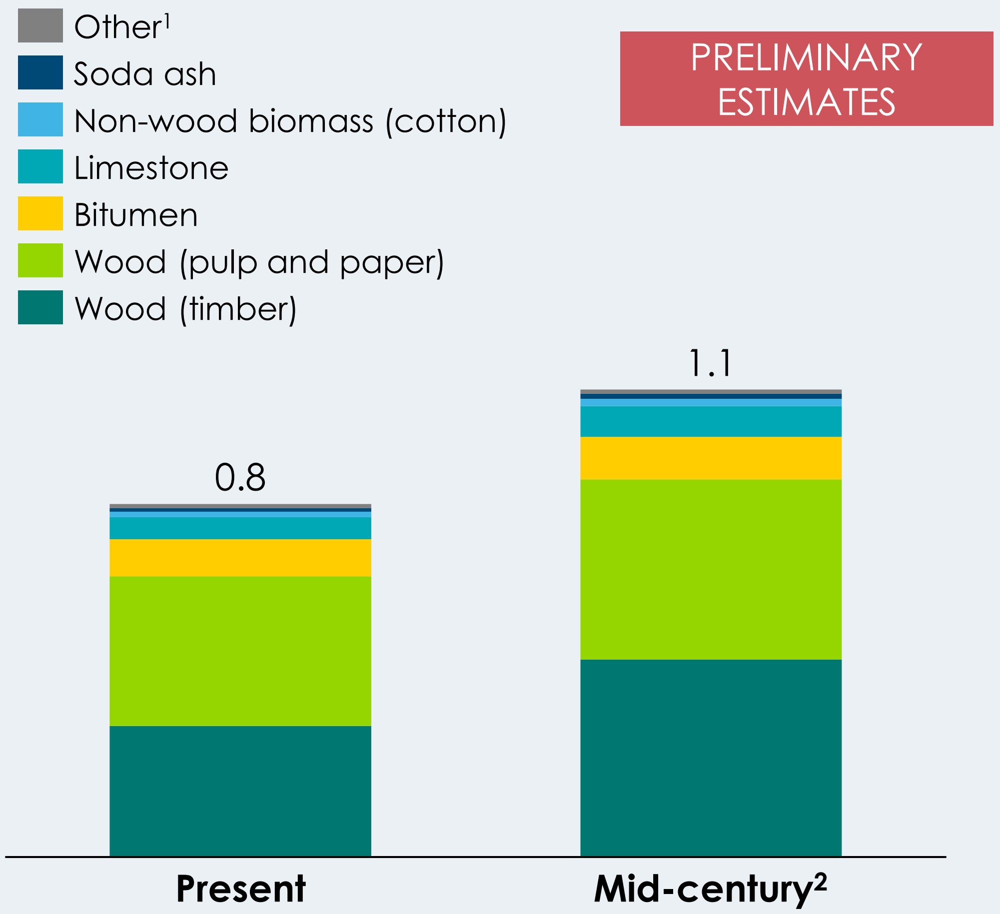
SYSTEMIQ

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
Giga tons of carbon (C)



Carbon Demand Breakdown Across Major Materials
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)
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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Two scenarios will be developed during this phase to show the potential range of primary molecules in demand

Technology assessments

Deep-dives on key technologies will be undertaken to inform scenarios including

- Key costs
- Key limitations and barriers
- Landscape analysis for drivers beyond costs

Scenarios

The technology assessments generate two scenarios

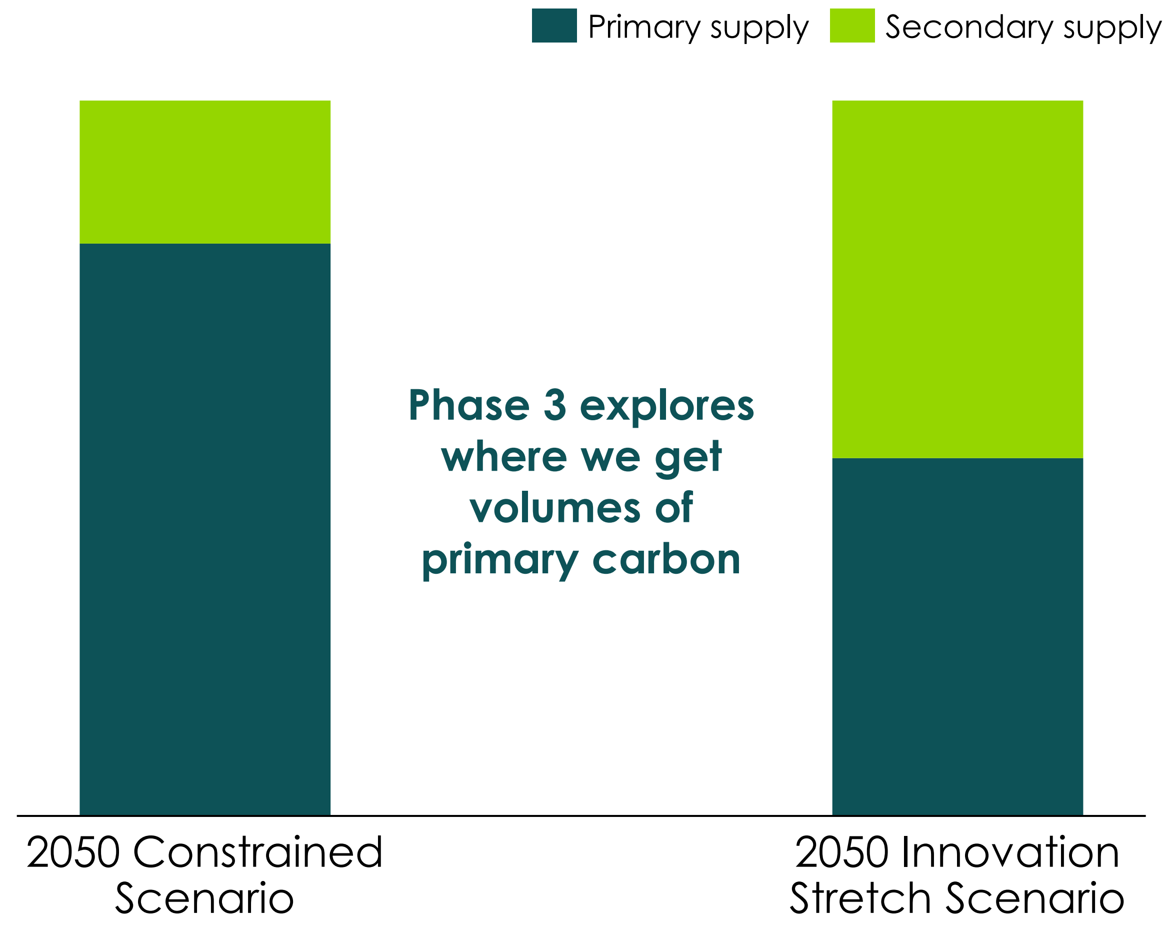
1. Innovation stretch

how close can we come to total recycling

2. Constrained

a more balanced mixture between circular and linear

Demand and supply for carbon molecules
(Illustrative), Million tons of carbon (C)



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

Material and carbon circularity solution set

Technology-deep-dives

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

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

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

Next steps

- Bilateral engagements with members and other experts
- Technology deep-dives and scenario development
- **Workshop 26th of February** – the potential to reuse and recycle carbon molecules