



Energy
Transitions
Commission

Emerging insights from the ETC's analytical work programmes

ETC Commissioners meeting
26 June 2025

Agenda

Evolution of energy demand: a growing, more efficient energy system dominated by electricity

Key messages from forthcoming report on power systems transformation

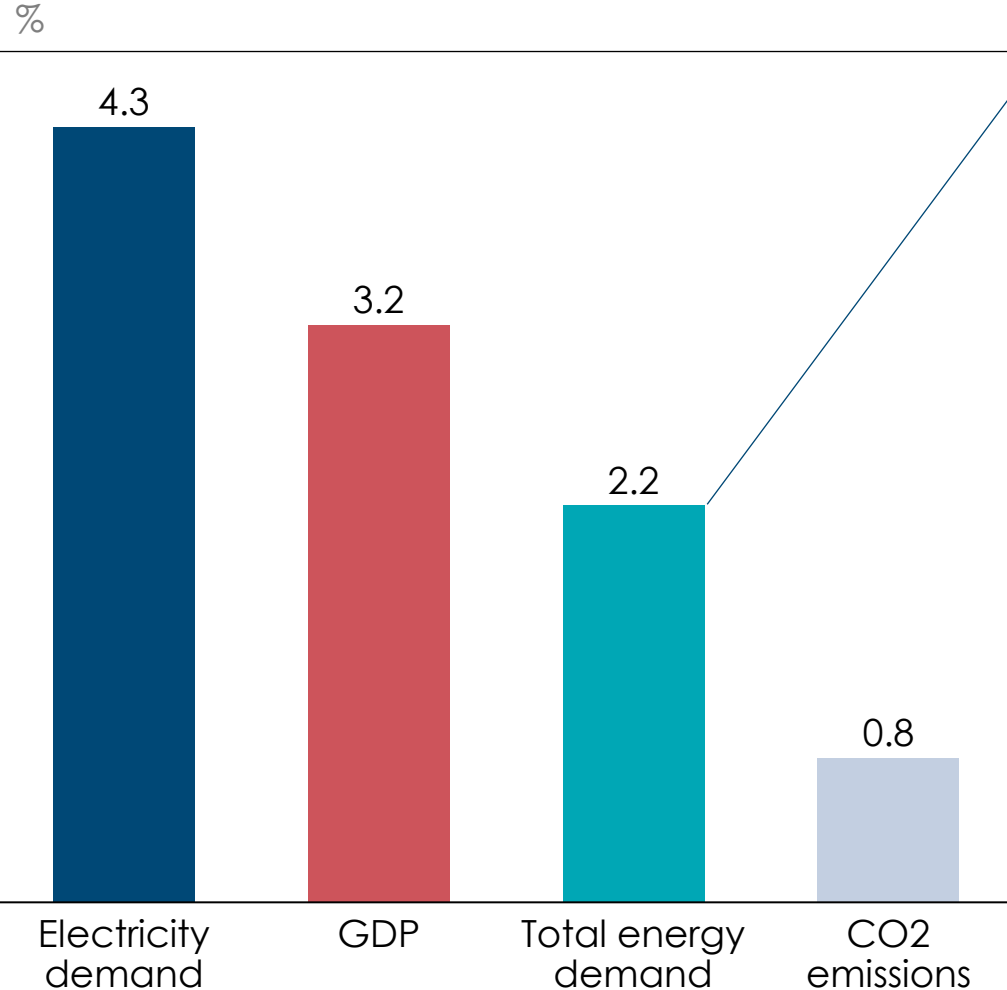
Decarbonising the last 20%
- the role of low-carbon molecules

Evolution of energy demand: a growing, more efficient energy system dominated by electricity

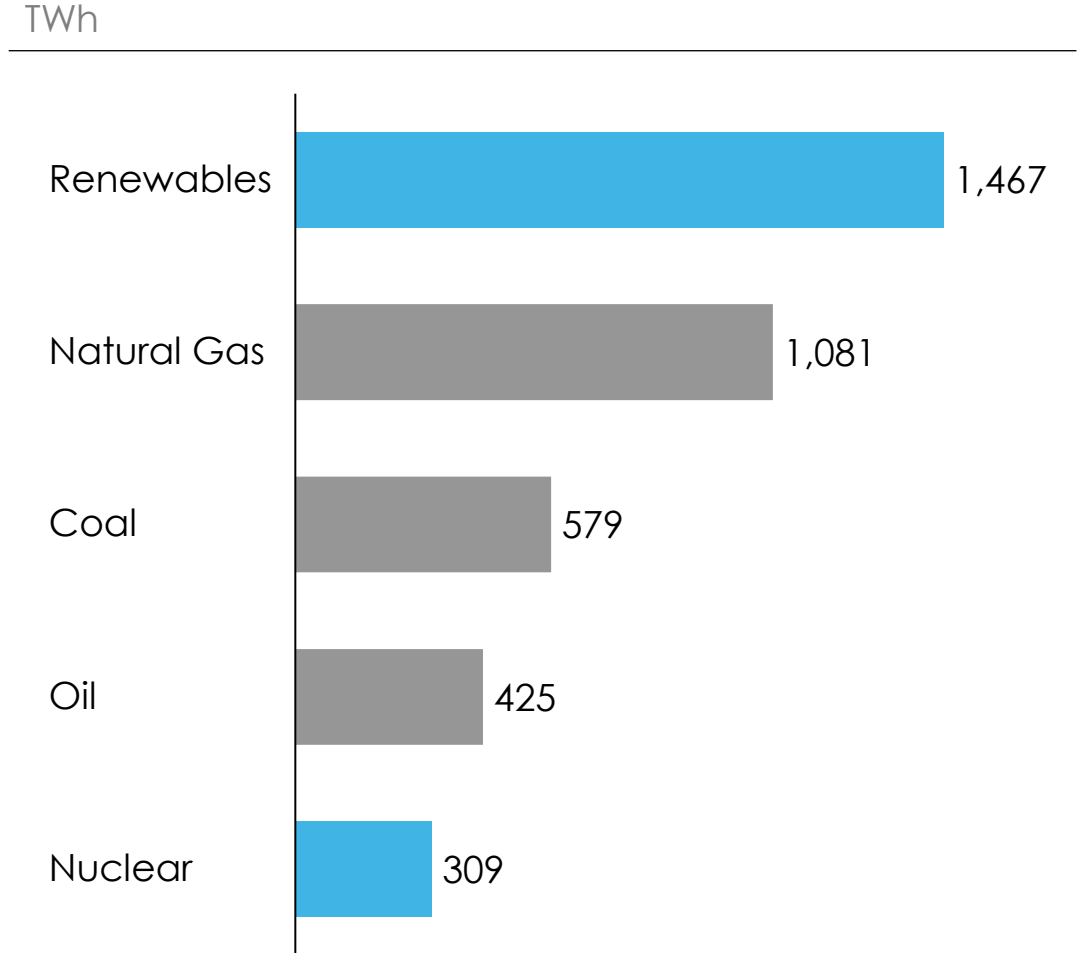


Energy demand continues to grow, with electricity demand soaring and most additional demand being met by low-carbon generation

Key global growth rates 2024



Total energy supply growth, 2024

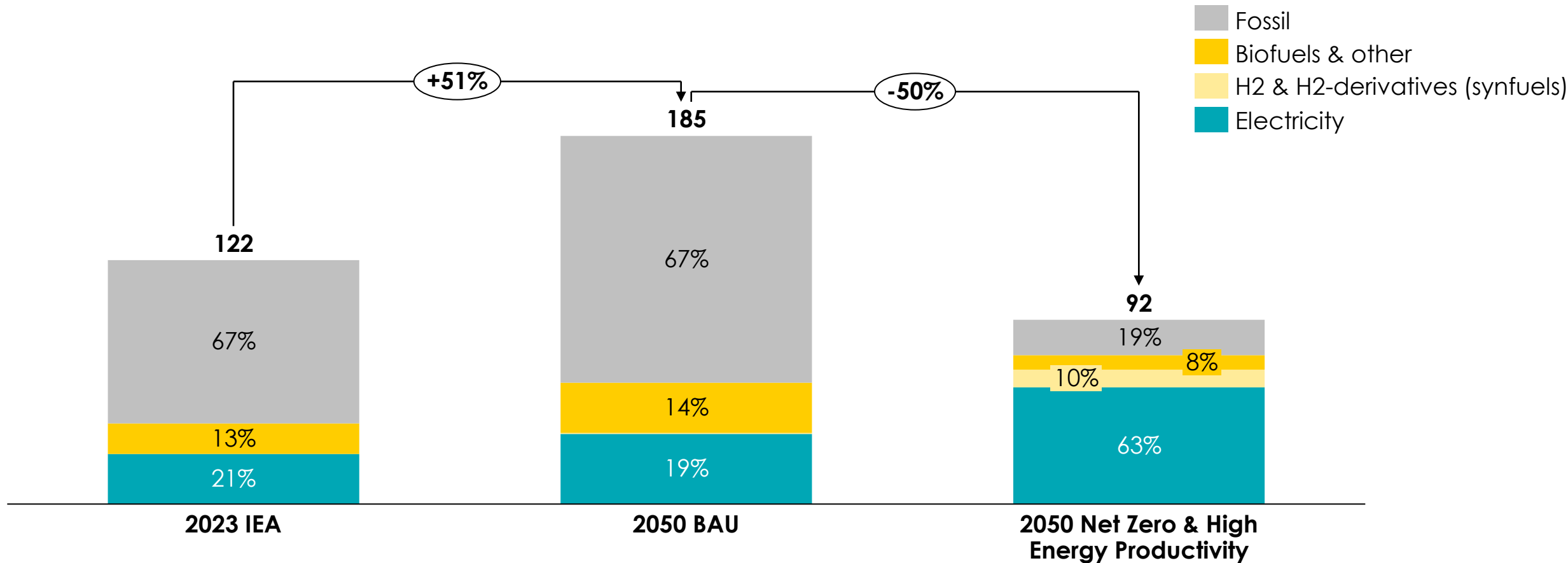


Source: IEA (2025) Global Energy Review

Towards the age of electrification: ETC net-zero pathway shows that final energy demand will need to shift from ~20% electricity to above 60% by 2050

Global Final Energy demand

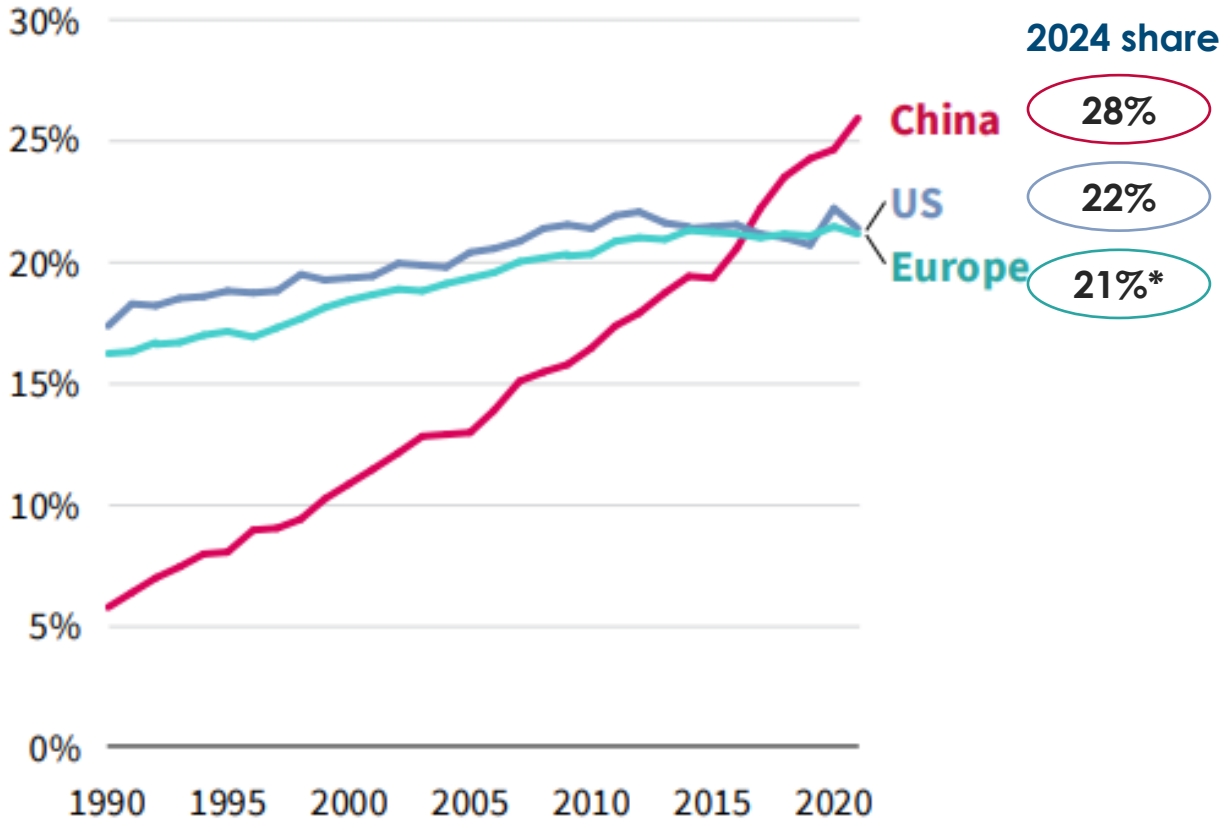
000 TWh



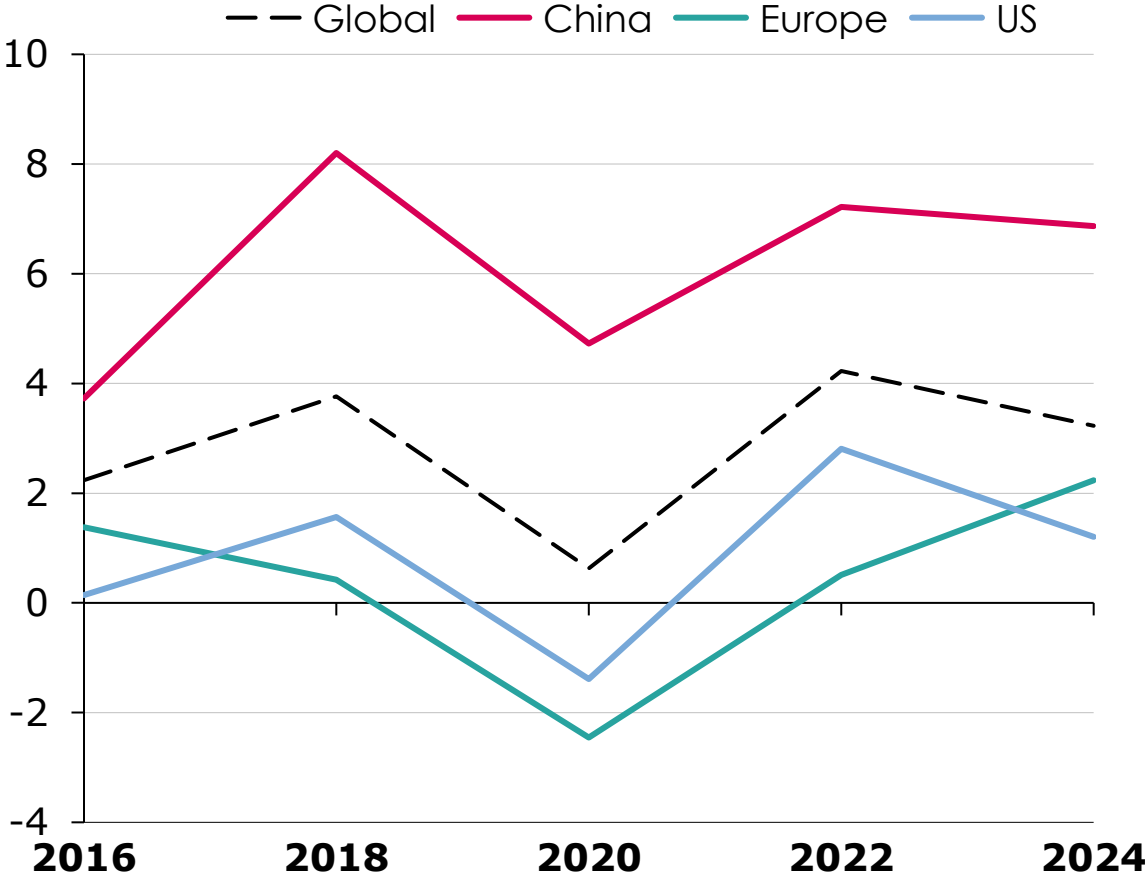
Source: IEA (2025) World Energy Outlook; MPP (2023) Hard-to-Abate Sector Transition Strategies; ETC (2025) Achieving Zero-Carbon Buildings; ETC(2023), Fossil Fuels in Transition; BNEF (2023) Vehicle Outlook; Systemiq analysis for ETC.

Electrification is under way, with very strong growth in China

Electricity share of total final energy consumption
%



Electricity demand growth rate
2-year CAGR (%/year)



* For European Union
Source: Our World in Data, Ember, RMI, IEA (2025) Electricity 2025, Sources: BNEF (2025), New Energy Outlook, Ember (2025), Global Electricity Review 2025

Three disruptions could reduce reliance on carbon molecules in the energy system, increasing the potential for electrification

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	

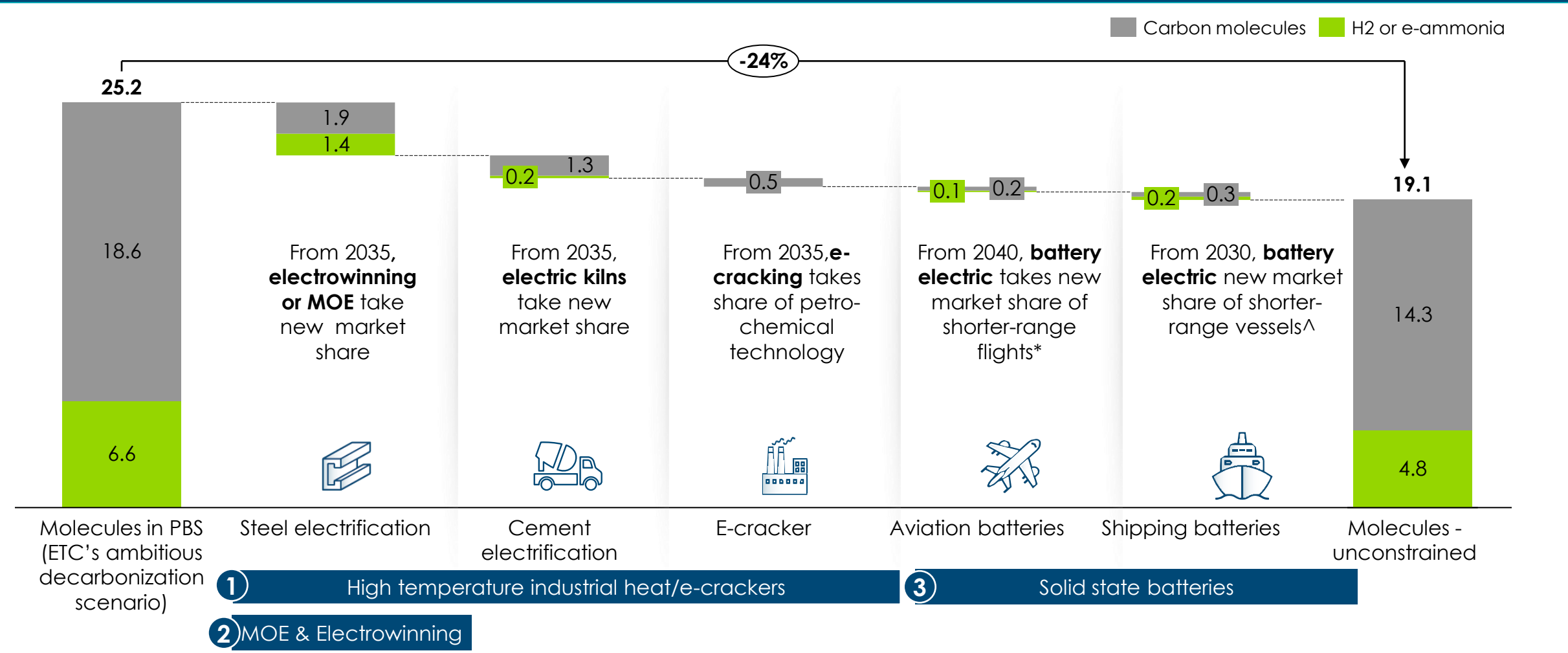
Source: Systemiq Analysis for ETC (2024) based on [Silvia Madeddu \(2020\)](#), [Fraunhofer ISI \(2024\)](#); [ARENA \(2024\)](#), [Agora Industry \(2024\)](#), [The Chemical Engineer \(2024\)](#), [Carbon Commentary \(2023\)](#), [Fast company \(2024\)](#), [IEA \(2024\)](#), [ETP Clean Energy Technology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



With 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

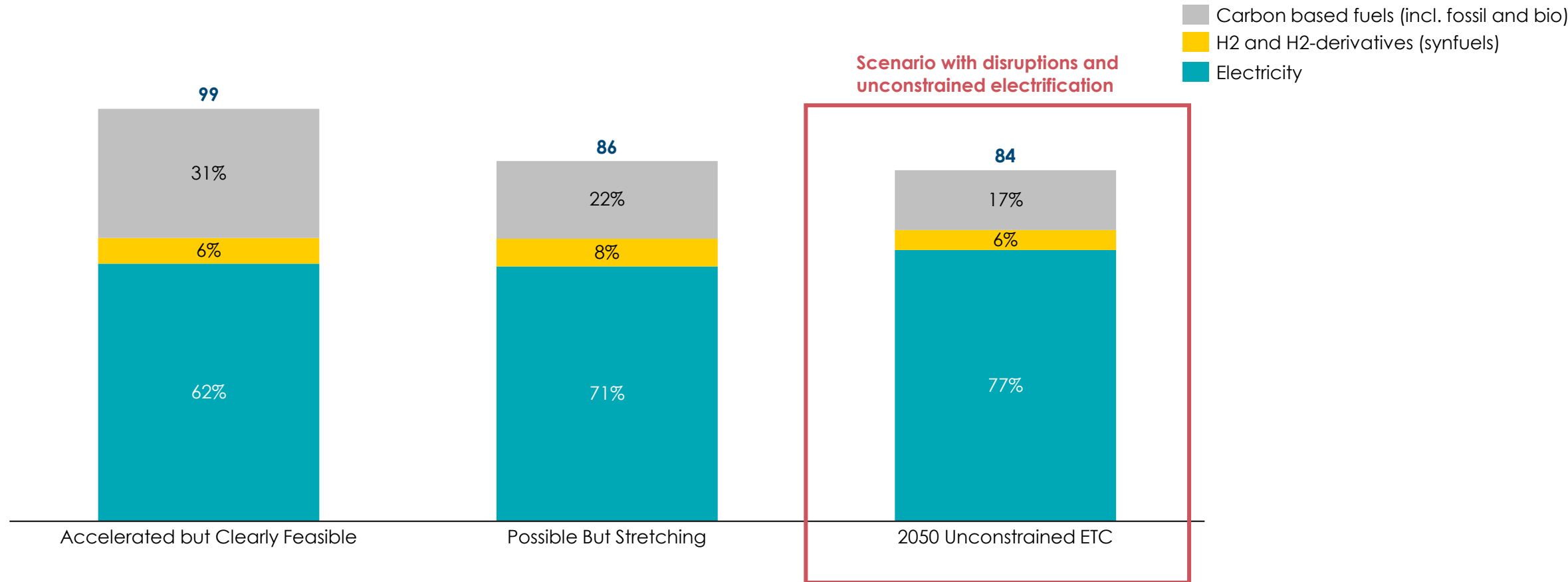


Source: Systemiq analysis for ETC (2024) based on Fossil Fuels in Transition (2023), Planet Positive Chemicals Report (Systemiq, 2022, BAU Net-Zero scenario); Steel: MPP STS (2022) Aviation: MPP STS (2022) Notes: PBS = Possible But Stretching ETC decarbonization scenario. *estimated at 15% of all nautical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

An “unconstrained electrification” scenario with these technology disruptions could reduce share of carbon molecules to ~15% of final energy demand

Global final energy demand by energy source and scenario, 2050

000 TWh

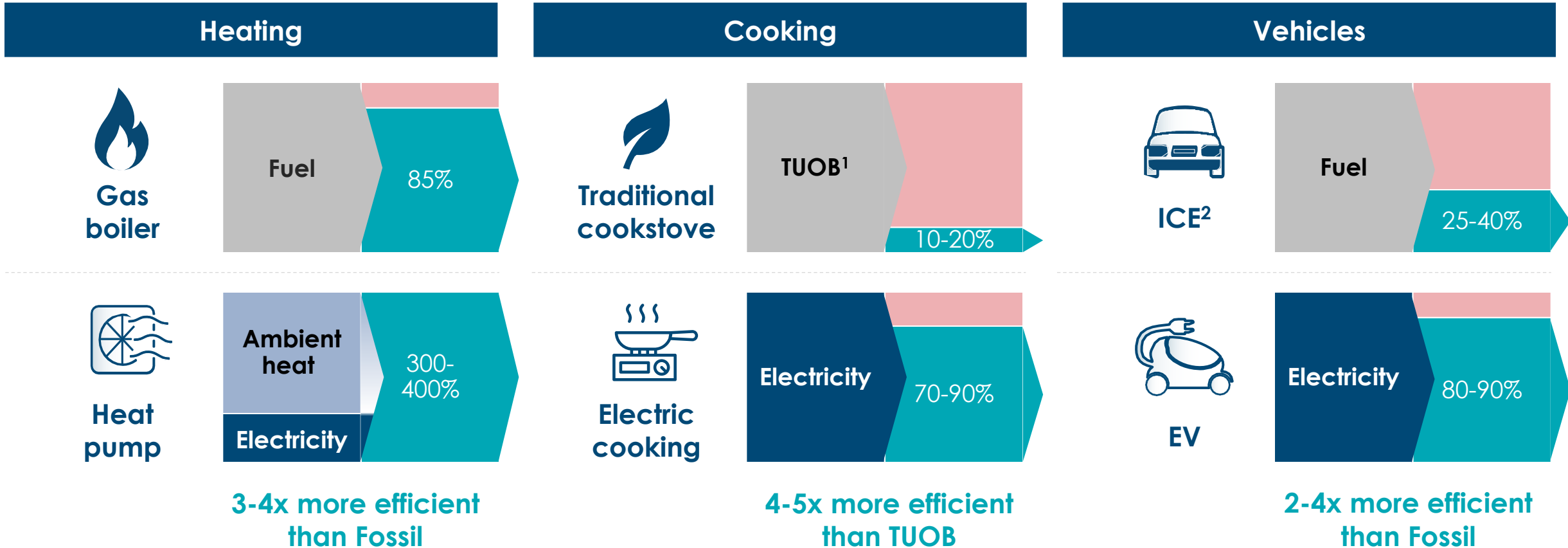


Note: STEPS = Stated Policies; ACF = Accelerated but Clearly Feasible; PBS = Possible but Stretching; *Remainder of electricity demand based on ACF scenario demand. CCS power assumes 30% energy penalty to power capture unit
Sources: 2022 scenario: Taken from ETC; ACF and PBS scenario: Taken from ETC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

Using molecules is more wasteful – shifting to electric technologies implies less energy needed overall

Average efficiency from appliances and vehicles incumbent fuel vs electric

Useful Energy Losses

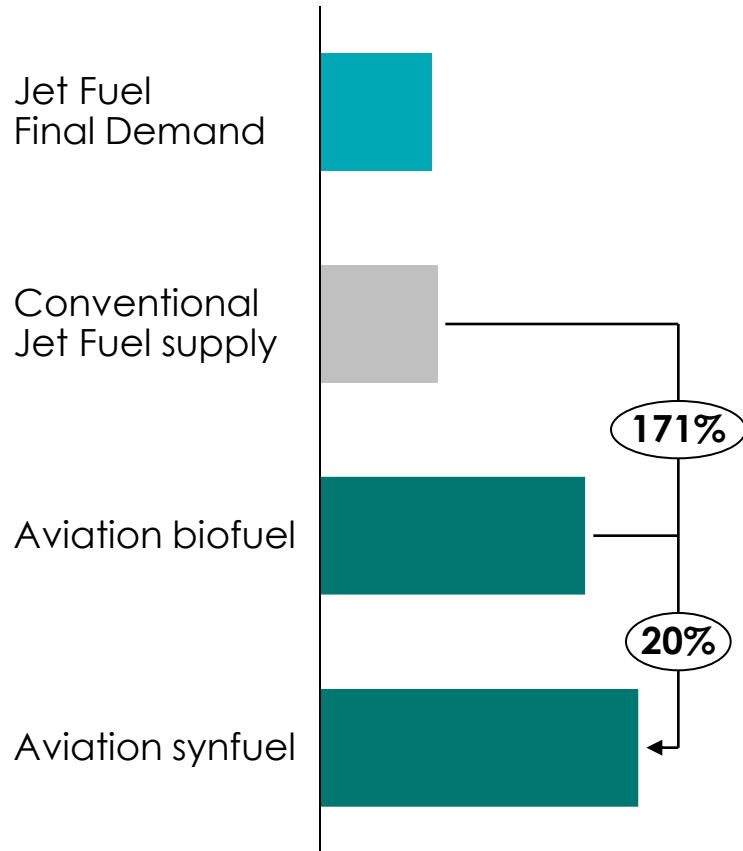


1. Traditional use of biomass; 2. Internal combustion engine
Source: RMI (2024), *Clean Tech Revolution*.

In some sectors, decarbonisation involves the use of molecules (through switching to new fuels and CCS) and increases primary energy needs

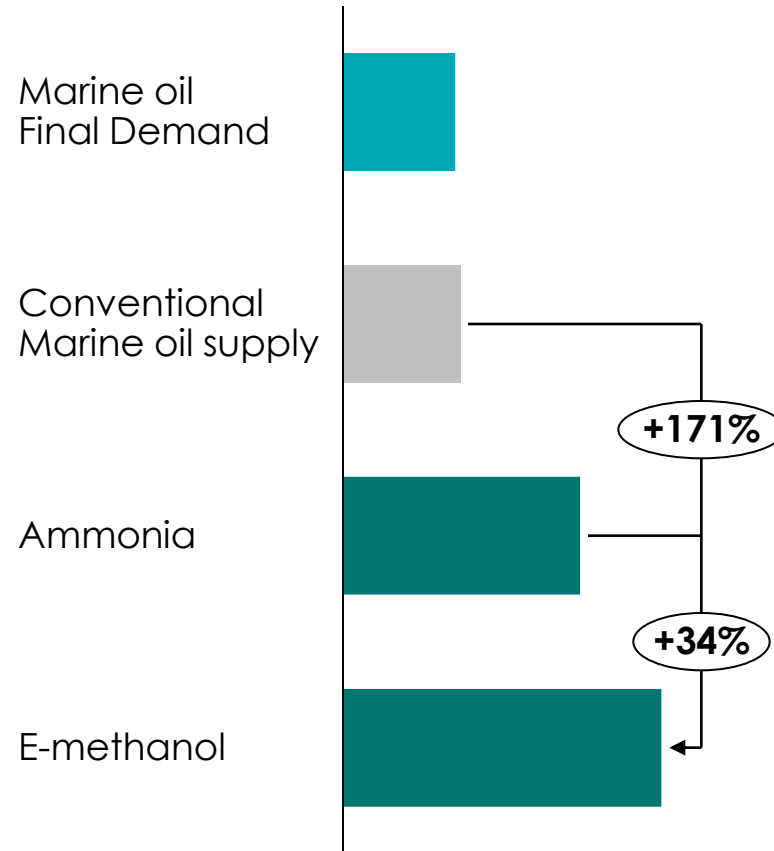
Aviation Case Study

TWh



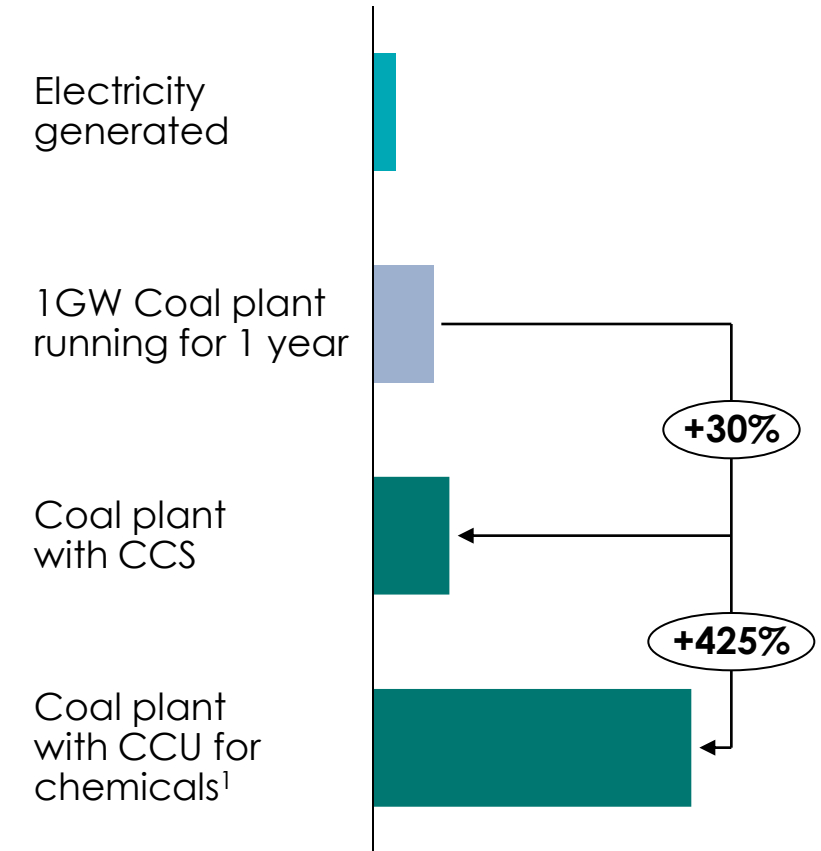
Shipping Case study

TWh



CCS Case study

TWh



¹ Additional steps for CCU include hydrogen production via electrolysis (50-55 kWh/kg of H₂), CO₂ capture and compression (0.5-1.5 kWh/kgCO₂) and methanol synthesis (1-2 kWh/kg MeOH); 100% capture and conversion to methanol is assumed (theoretical maximum)

Sources: Mission Possible Partnership (2023) Sector Transition Strategy, World Resources Institute (2022) 6 Things you Know About Direct Air Capture; IEA (2013). Technology Roadmap: Carbon Capture and Storage, IEA (2019). The Future of Hydrogen, ECN (2017). Techno-economic and environmental assessment of methanol synthesis using captured CO₂ and renewable hydrogen



Establishing a common language on energy efficiency is key to enable and coordinate action effectively

Key terms

Energy Productivity

The impact of reducing global energy consumption without compromising living standards (e.g. via using less/other goods, less/other materials)

Energy Efficiency

Is a part of productivity that focus on the energy input of production processes

How to measure progress?

- **Energy productivity**¹:
Energy input per unit of GDP

E.g. kWh/\$ GDP
- **Energy productivity improvement**:
Yearly change to energy productivity

$$\frac{\Delta \text{Energy productivity}}{\text{Energy productivity}_{t-1}} (\%)$$

Where we want action

Primary Energy

Energy before conversion, including losses during transformation and distribution

Energy consumed by end users, e.g. electricity or petrol

Final Energy

Energy to generate the desired output, e.g. move a vehicle

Energy Services

1: Energy productivity also referred as energy intensity by the IEA

Multiple levers to increase energy productivity

Target figure	Key lever	Guiding question	Reduced quantity	Example
Energy Productivity¹ (energy input per unit of GDP)	Technical energy efficiency	How can we decrease the energy input per (production) process?	Process energy	Shift to less energy-intense production technology (e.g. electrification), efficiency increase in incumbent technologies (e.g. appliances, EVs, buildings insulation), etc.
	Service efficiency	How can we decrease the demand without sacrificing living standard?	Demand (for specific service)	Streamline operations (e.g. route optimization, transport utilization rate), behavior changes , (e.g. switch to train vs plane, speed reduction)
	Product efficiency	How can we increase the utilization of the product?	Product	Reuse (e.g. reduce single use plastic), increased product lifetime (e.g. in buildings)
	Material efficiency	How can we decrease the material input per product?	Material	Recycling and use of recycled content (e.g. petro-chemicals, aluminum, and steel), reduce primary material use

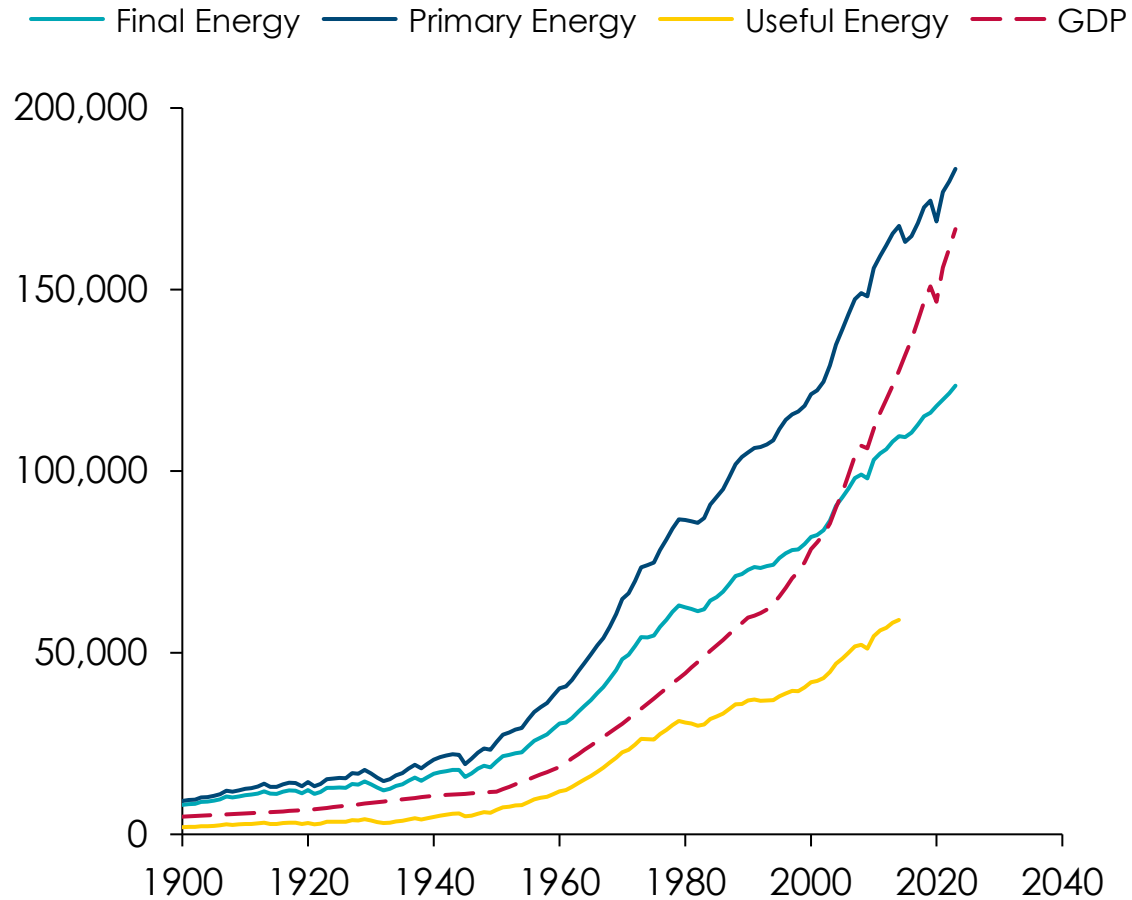


1: Energy productivity also referred as energy intensity by the IEA
 Source: Systemiq analysis for the ETC.

The world has made progress on increasing energy productivity over time

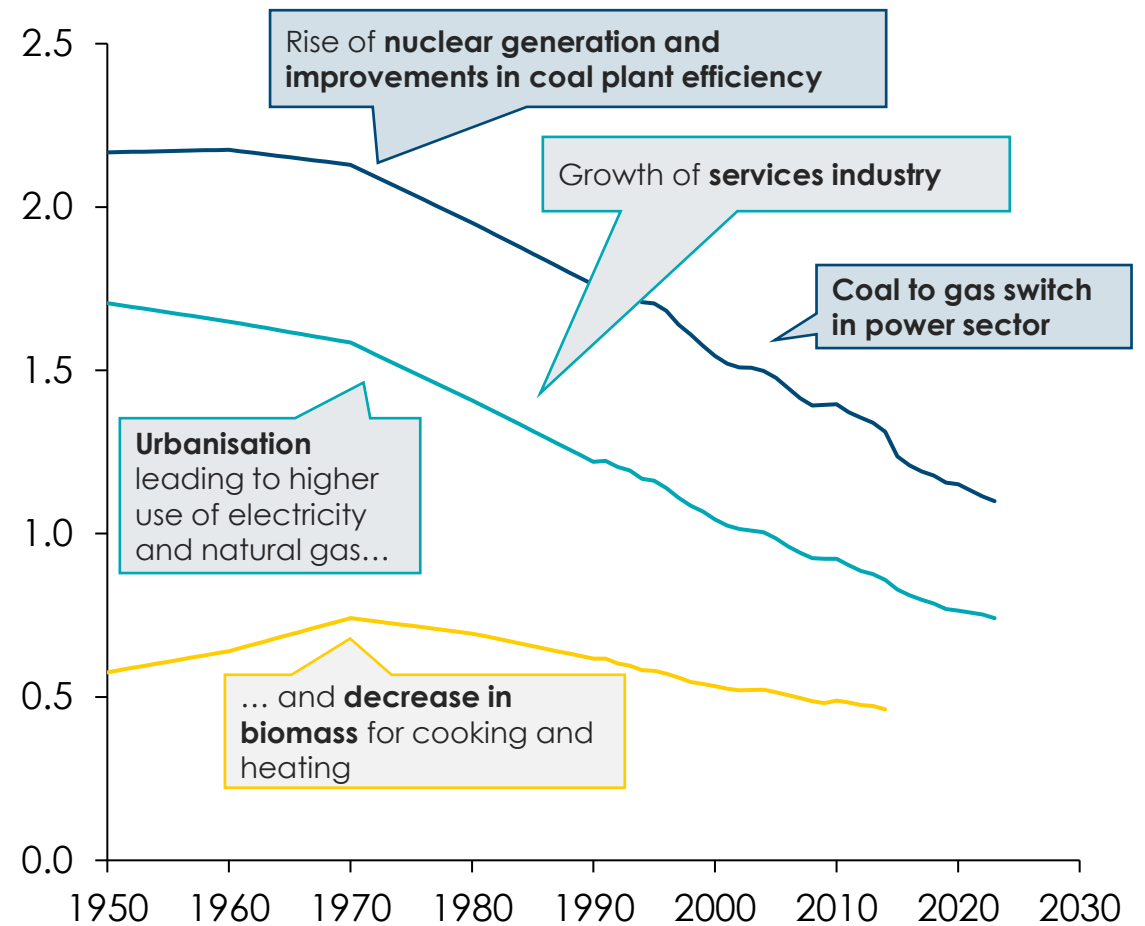
Total GDP vs. Energy Demand, 1900 - 2023

GDP in constant 2021 Bn.US\$, Energy Demand in TWh



Energy Productivity, 1950 - 2023

kWh/\$ 2021 PPP



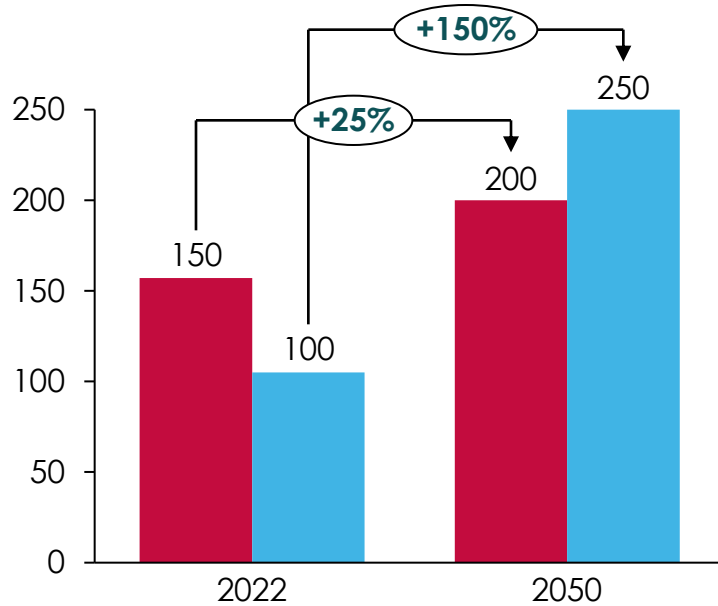
Looking ahead, greater energy services will be required, accounted for in ETC's Net Zero scenarios

Heated floor area vs. cooled floor area

Billion m²; IEA NZE Scenario; residential + commercial

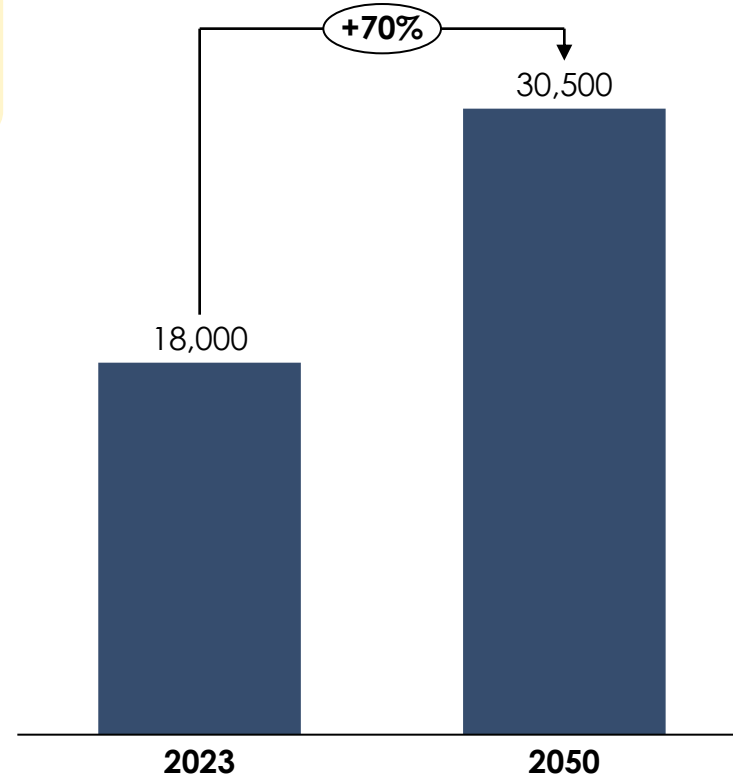
- Cooled floor area
- Heated floor area (space heating)

Cooled floor area is growing at a higher rate than heated, driven by 1) **GDP per capita growth**; 2) **increase in building floor area**, particularly in developing economies; 3) **warming climates**



Demand for passenger road transport

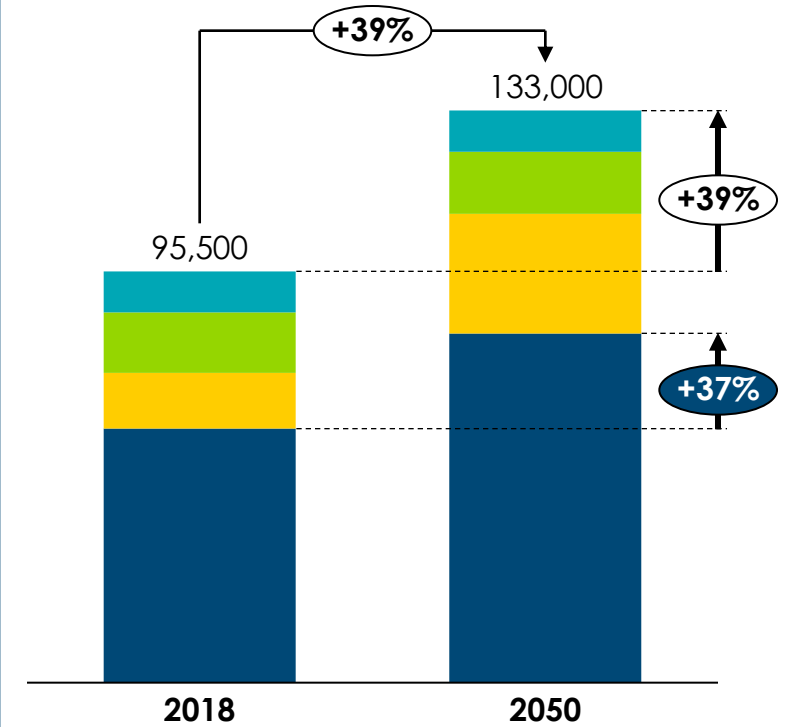
Billions of km; ETC ACF scenario



Shipping demand

Billions-tonnes miles

- Others
- Containers
- Tankers
- Bulk Carrier



Source: IEA (2023), *World Energy Outlook 2023*; Systemiq analysis for the ETC (2023), *Fossil Fuels in Transition; Committing to the phase-down of all fossil fuels*, available at <https://www.energy-transitions.org/publications/fossil-fuels-in-transition/>; Maersk Mc-Kinney Moller Center for Zero Carbon Shipping (2022), *We show the world it is possible*.

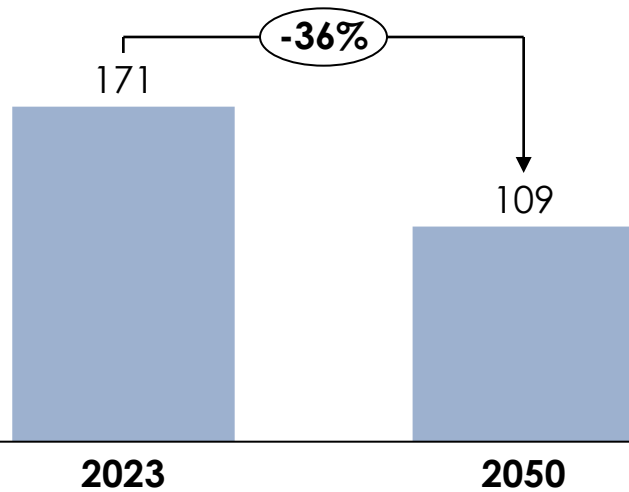
Even with rising energy services, primary and final energy demand can decline, due to electric technology's higher efficiencies

NZ Energy demand with Productivity levers

000 TWh

Shift away from Extraction....

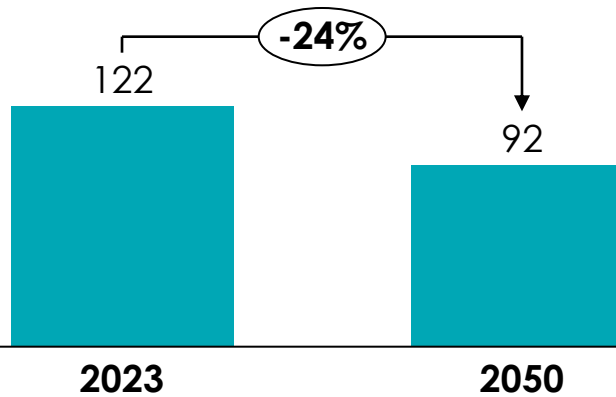
Fewer losses in transformation & distribution



PRIMARY ENERGY

Towards Electrification...

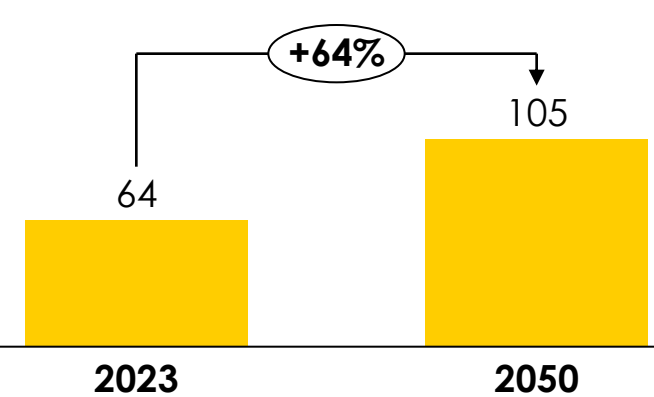
Fewer losses in conversion



FINAL ENERGY

For greater energy services

More energy end use



ENERGY SERVICES

Source: IEA (2025) World Energy Outlook; MPP (2023) Hard-to-Abate Sector Transition Strategies; ETC (2025) Achieving Zero-Carbon Buildings; ETC(2023), Fossil Fuels in Transition; BNEF (2023) Vehicle Outlook; Systemiq (2022); Planet Positive Chemicals; Systemiq analysis for ETC.

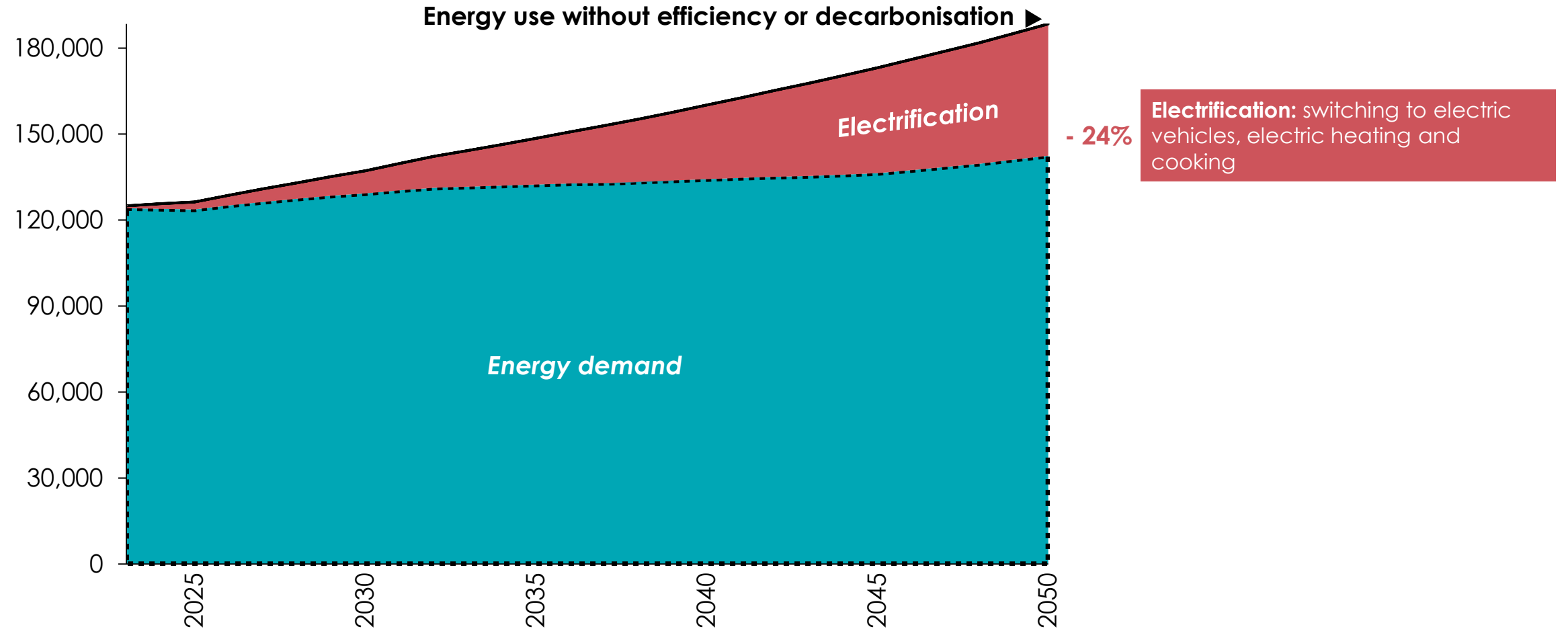
Overall, more electrification will be a critical driver of improving energy productivity

Final Energy demand vs. Productivity levers

TWh

% Reduction potential compared to 2050 Energy use without efficiency or decarbonisation

Key actions



Electrification: switching to electric vehicles, electric heating and cooking



Source: IEA (2025) World Energy Outlook; MPP (2023) Hard-to-Abate Sector Transition Strategies; ETC (2025) Achieving Zero-Carbon Buildings; ETC(2023), Fossil Fuels in Transition; BNEF (2023) Vehicle Outlook; Systemiq analysis for ETC.

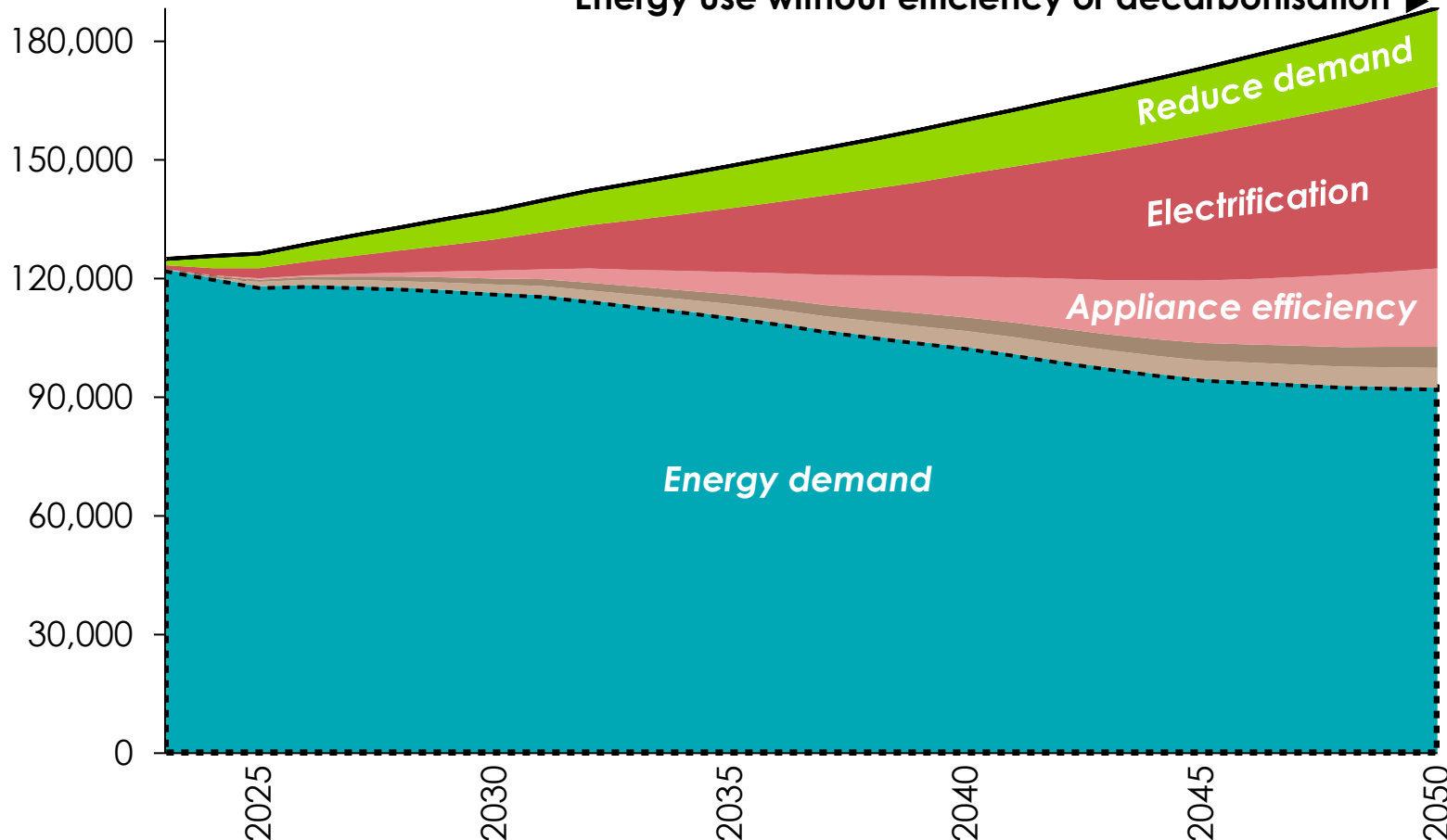
... but other levers are also critical for reaching maximum potential

Final Energy demand vs. Productivity levers

TWh

% Reduction potential compared to 2050 Energy use without efficiency or decarbonisation

Energy use without efficiency or decarbonisation



Key actions

Demand reduction: services (e.g. public transport), reducing & re-using (e.g. petro-chemicals) and better operations (e.g. aviation)

- 11%

Electrification: switching to electric vehicles, electric heating and cooking

- 24%

Improving efficiency of key electrical appliances: AC, heat pumps, EVs, lighting and other home appliances

- 10%

Better insulation in buildings: better buildings codes and fabric improvements

- 3%

Everything else – sector-specific interventions

- 3%

-51%



Source: IEA (2025) World Energy Outlook; MPP (2023) Hard-to-Abate Sector Transition Strategies; ETC (2025) Achieving Zero-Carbon Buildings; ETC(2023), Fossil Fuels in Transition; BNEF (2023) Vehicle Outlook; Systemiq analysis for ETC.

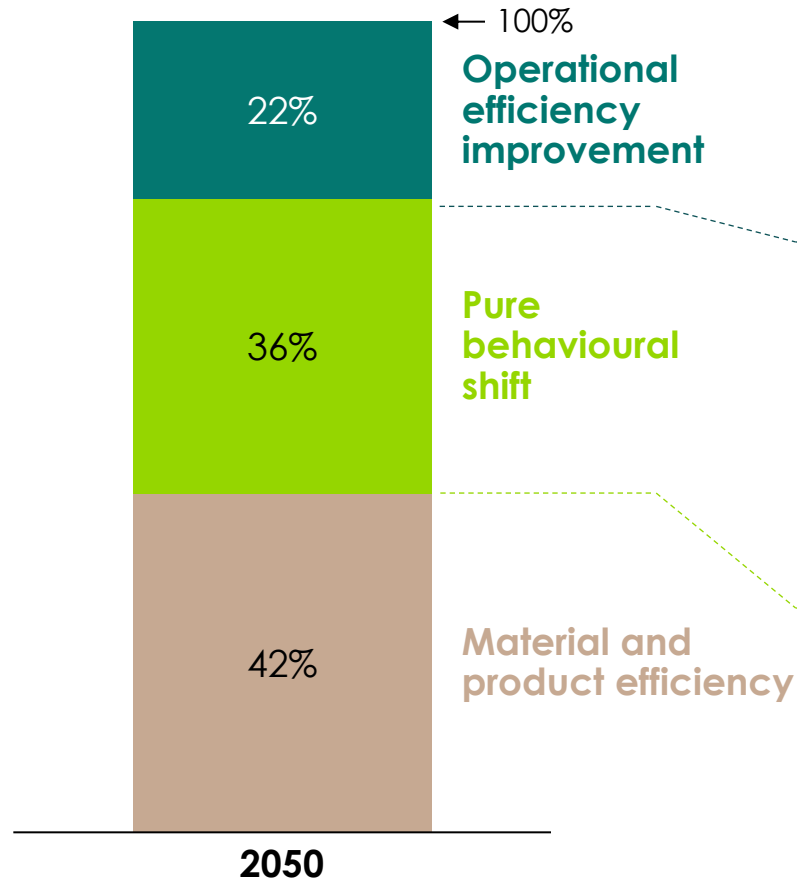
"Demand reduction" can be achieved in 3 ways , with about a third requiring some form of behaviour change

Demand reduction

Demand reduction deep-dive

%

Drivers



- **Streamline operations**
 - Aviation
 - Shipping
 - **Autonomous vehicles** in Road
 - **Energy management** in Buildings
-
- A share (50%) of **recycling** and **reduction** in:
 - Chemicals
 - Aluminum
 - **Speed reduction** in Road
 - Shifting to **alternative ways of transports** away from:
 - Cars
 - Planes (upside)
-
- Bulk of **recycling**, extended **product lifetime, reuse** and material efficiency in:
 - Cement
 - Aluminum
 - Steel
 - Chemicals



Source: Systemiq analysis for ETC

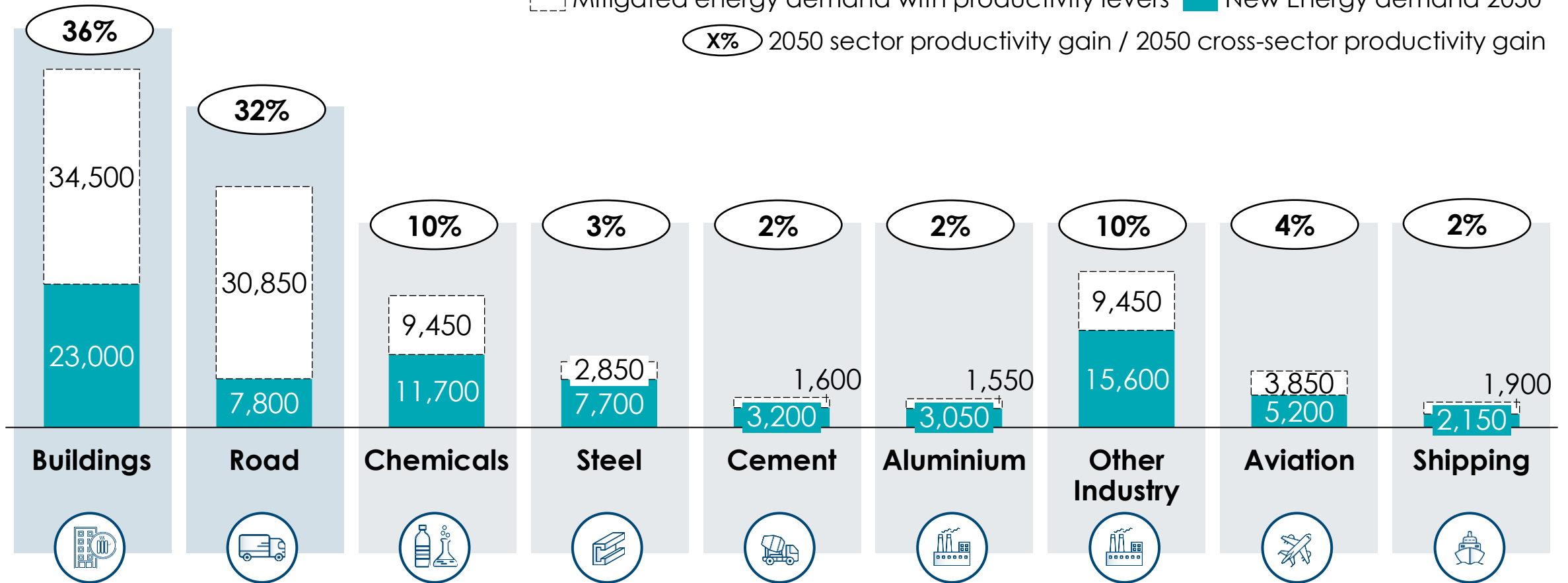
Buildings and road transportation hold the biggest opportunity: together they hold ~70% of the potential productivity gain in final energy demand

Final energy demand in 2050

TWh

 Mitigated energy demand with productivity levers
 New Energy demand 2050

X% 2050 sector productivity gain / 2050 cross-sector productivity gain



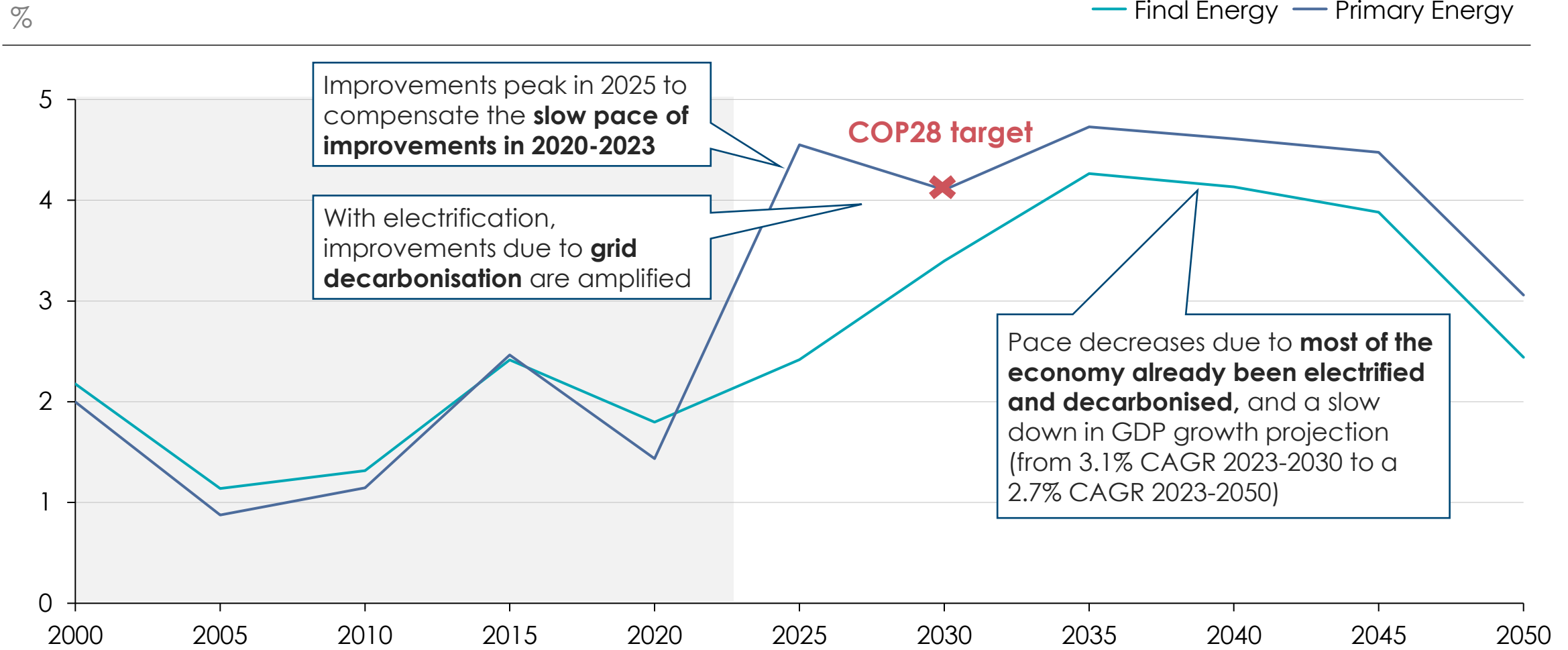
Note: Does not include fuel switch nor CCS for Net-Zero

Source: IEA (2025) World Energy Outlook; MPP (2023) Hard-to-Abate Sector Transition Strategies; ETC (2025) Achieving Zero-Carbon Buildings; ETC(2023), Fossil Fuels in Transition; BNEF (2023) Vehicle Outlook; Systemiq analysis for ETC.



A 4% improvement in energy intensity by 2030, aligned to COP28 targets, would depend on immediately accelerating efforts in energy productivity

5-Year CAGR Energy productivity improvement projection



Source: Systemiq analysis for ETC, Our World in Data, World Bank, IMF Real GDP Annual Growth, IEA World Energy Outlook 2024



Energy productivity through - and in addition to - electrification can ensure lower costs and impact on planetary boundaries and more energy security

Maximizing additional energy productivity *beyond* electrification can achieve:



Lower cost, by reducing annual energy & infrastructure investment **from \$3.5 to \$2.7 trillion / year**



Lower materials footprint, reducing cumulative end-use materials needed for energy transition by 2050 from 6.5 billion tonnes to as low as 4.6 billion tonnes; reducing cumulative **embodied carbon emissions** of these materials from **35 GtCO₂e to as low as 4.6 GtCO₂e**



Lower impact on planetary boundaries, reducing clean energy system requirements by for water and land use by 4%, or 4 billion m³ and 0.05 million km² respectively.

Maximising energy productivity *alongside* electrification can:



Increase energy security, reducing import needs and price volatility; e.g. in Germany primary energy imports in 2023 were ~70% of the country's energy demand, costing 80 billion euros. By 2035, with electrification and further energy productivity levers, **imports could drop 20%, reducing the import bill by 16 billion euros in 2023 prices.**

To maximise energy productivity levers, there are 5 priorities

	Main productivity levers	Energy saving (TWh/year)	Key technologies/solutions	Priorities
Final Energy	1 Electrification	17,400	<ul style="list-style-type: none"> EVs Heat Pumps Electric Cooking 	<ol style="list-style-type: none"> 1) Set national energy efficiency targets, integrated into national decarbonisation plans, and track progress 2) Lower upfront costs via subsidies and scrappage schemes 3) Raise awareness for financiers, SMEs, and consumers on the savings and business case for high-efficiency appliances 4) Align opex incentive: electricity at cost parity with gas and R&D for fuel saving in ships/planes. 5) Prepare the power grid for increased electrification and leverage demand shifts (EVs and buildings insulation)
	2 Appliance/vehicle efficiency improvement	8,700	<ul style="list-style-type: none"> Variable speed ACs Newer motors LEDs 	
	3 Reduced demand	7,400	<ul style="list-style-type: none"> Reduce & Re-use plastics Recycle steel & aluminium Digitalisation and automation 	
	4 Better insulation in buildings	2,900	<ul style="list-style-type: none"> Fabric improvement Building codes 	
	5 Everything else – sector-specific	3,300	<ul style="list-style-type: none"> Lightweight and aerodynamics 	
Primary Energy	6 Grid decarbonisation	60,000	<ul style="list-style-type: none"> Solar panels Utility size storage 	



Source: Systemiq analysis for ETC

Key messages from forthcoming report on Power Systems Transformation

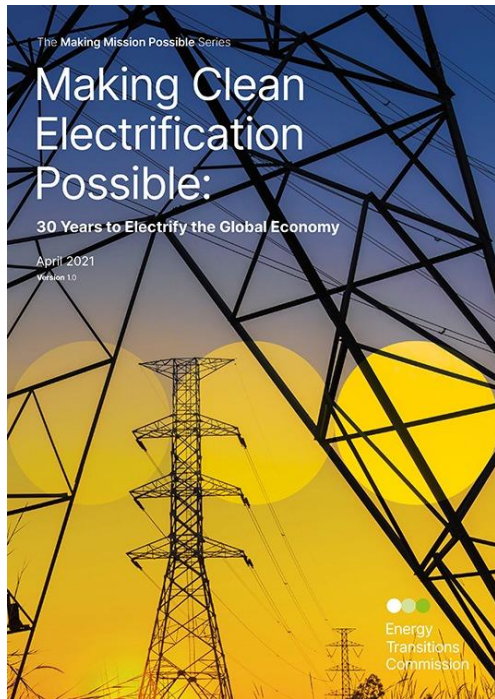


Delivering clean power systems: the ETC's body of work

2021

2022-2024

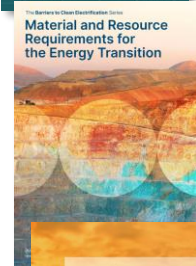
2024/25



Streamlining planning and permitting to accelerate wind and solar deployment



Better, Faster, Cleaner: Securing clean energy technology supply chains

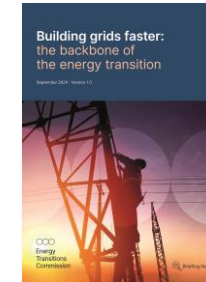


Material and Resource requirements for the Energy Transition



Overcoming Turbulence in the Offshore Wind Sector

Series and Major report on Power Systems transformation



Building Grids Faster: The backbone of the energy transition



Demand side flexibility – unleashing untapped potential for clean power



Long-distance cables: how greater transmission can accelerate the clean power transition
Coming in July



There are 3 key questions on power systems with high shares of wind and solar

1) Technical operation challenge

Can you operate an electricity system with high shares of wind and solar without technical challenges? Including issues with frequency regulation, voltage control, and system inertia?

8 May 2025

Iberian Peninsula blackout proves the need for grid resilience

2) Balancing systems at all durations

What to do when the sun does not shine and the wind does not blow? How can we balance supply and demand in a low carbon way across days, weeks, months, and years?

NEWS

UK confirms cap-and-floor mechanism for long-duration energy storage from 2025

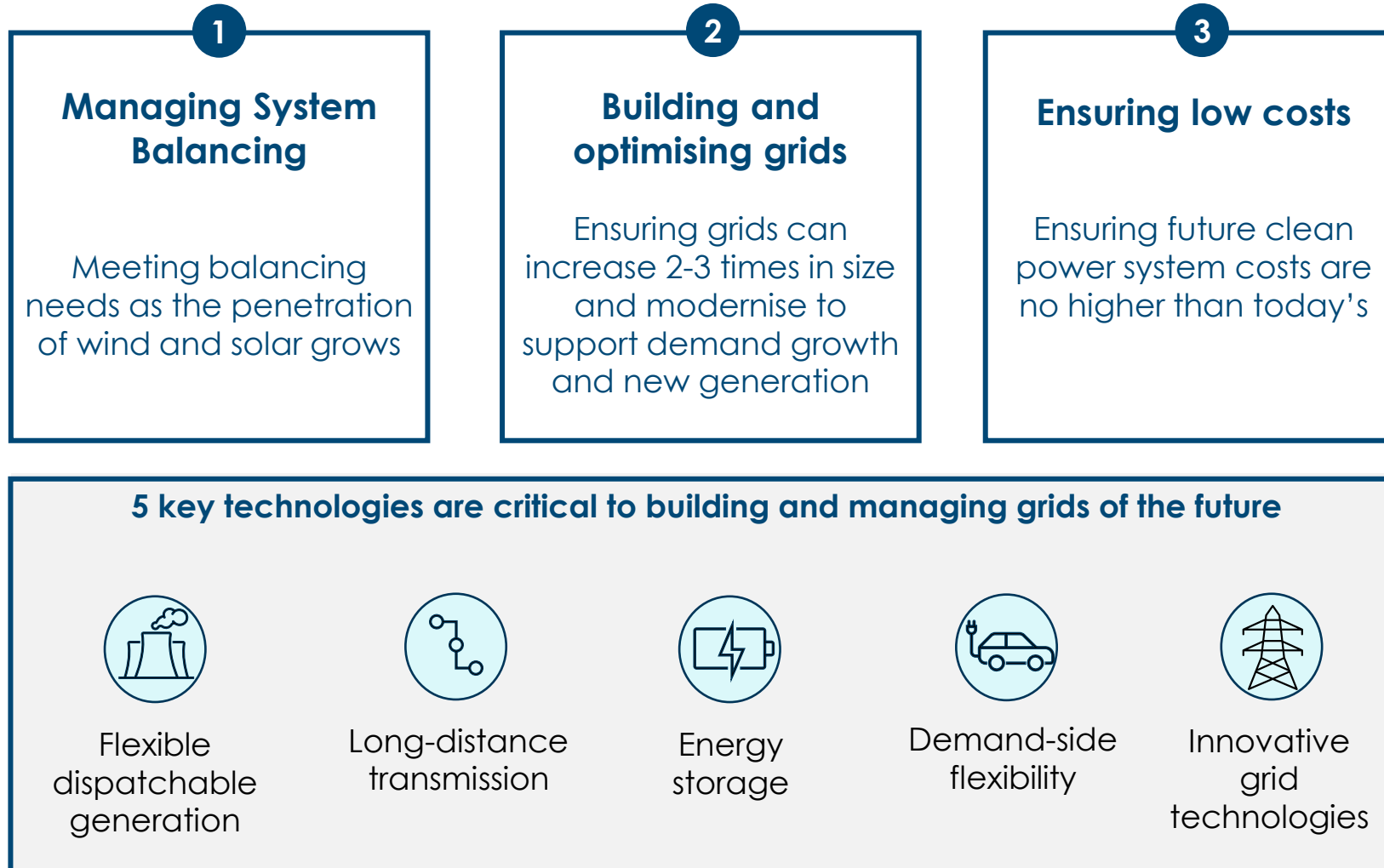
3) Cost concerns

Can the transition to a system based primarily on wind and solar be cost competitive, also including the expansion of the grid required?

Almost nine in ten Britons are concerned about energy prices



The ETC Power Systems Transformation report seeks to answer these questions, using the following structure



New insights from this report

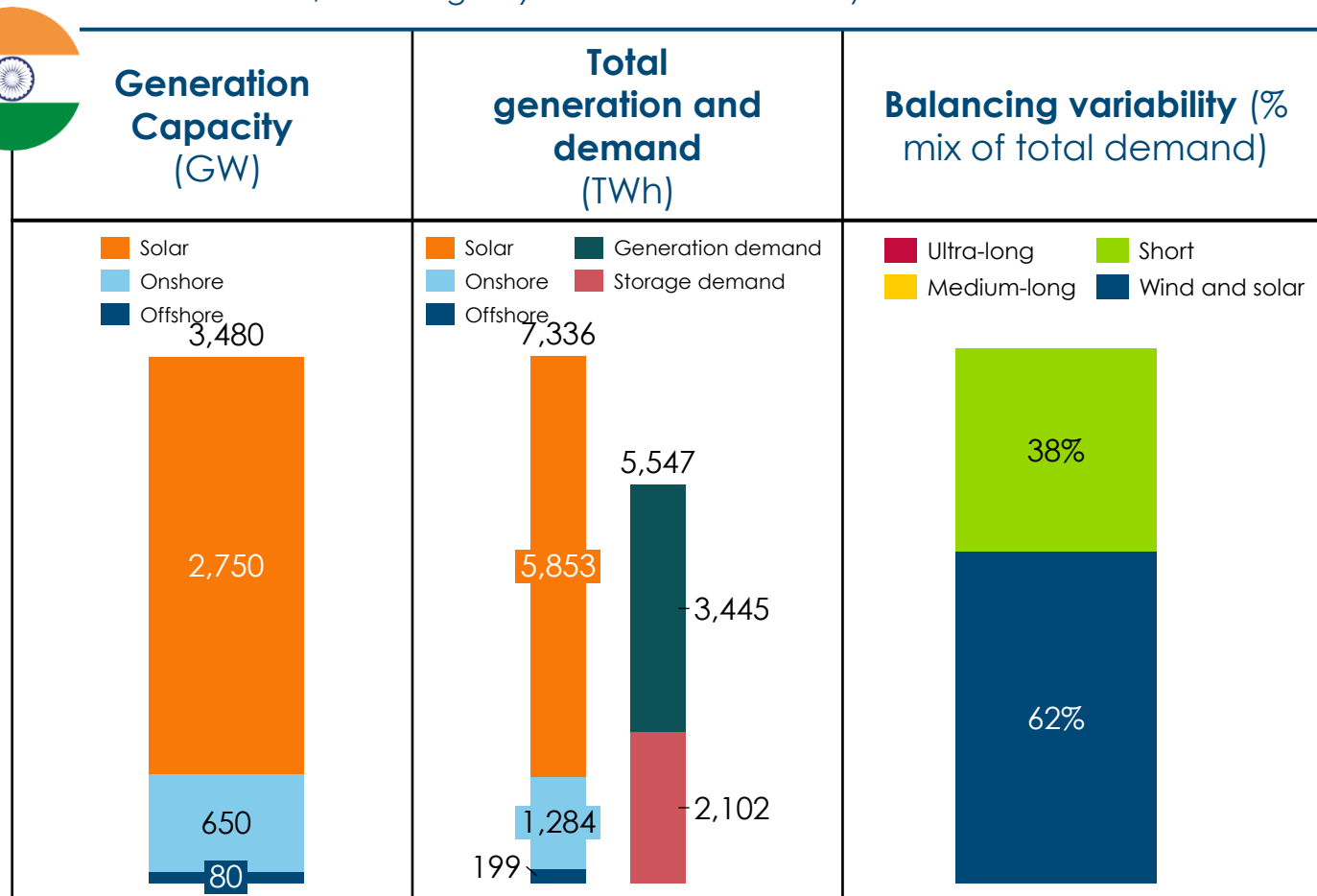
- 1** It is technically and economically possible to operate and balance power systems with high shares of wind and solar (e.g. 70-80%+) through technologies existing today. **The cost of each system varies significantly based on whether it is wind (“windbelt”) or solar (“sunbelt”) dominated**
- 2** **Wind dominated systems will require more ultra long duration balancing – where more gas turbine capacity could be required** (regardless of natural gas or hydrogen usage) within strict guidelines
- 3** **Up to 30% of all global power demand could be a flexible system asset (through demand-side flexibility)**, key bottleneck is how to incentivise deployment and adoption, and guarantee reliability
- 4** **Long-distance transmission from low-cost renewable regions can be a cost-effective source of flexibility where politically feasible**
- 5** **Grid costs per kWh are unlikely to materially change despite investments potentially increasing by 2-3x over the next 25 years**, as long as the user base expands in line with planning and innovative grid technologies and demand side flex are utilised. Need to ensure pace of electrification at same pace as decarbonisation.



The ETC conducted in-depth analysis for different regional archetypes; key features of the Tropical archetype show opportunity for sunbelt region

Generation and balancing mix results for tropical archetype (India Case Study)

Based on modelling matching demand (high electrification) and supply (based on variable renewables, including 30 years of weather data)



Generation

- Solar dominates (~80%)
- Solar overbuild is lowest-cost path
- Surplus solar buffers seasonal lulls (e.g. monsoons)

Balancing Mix

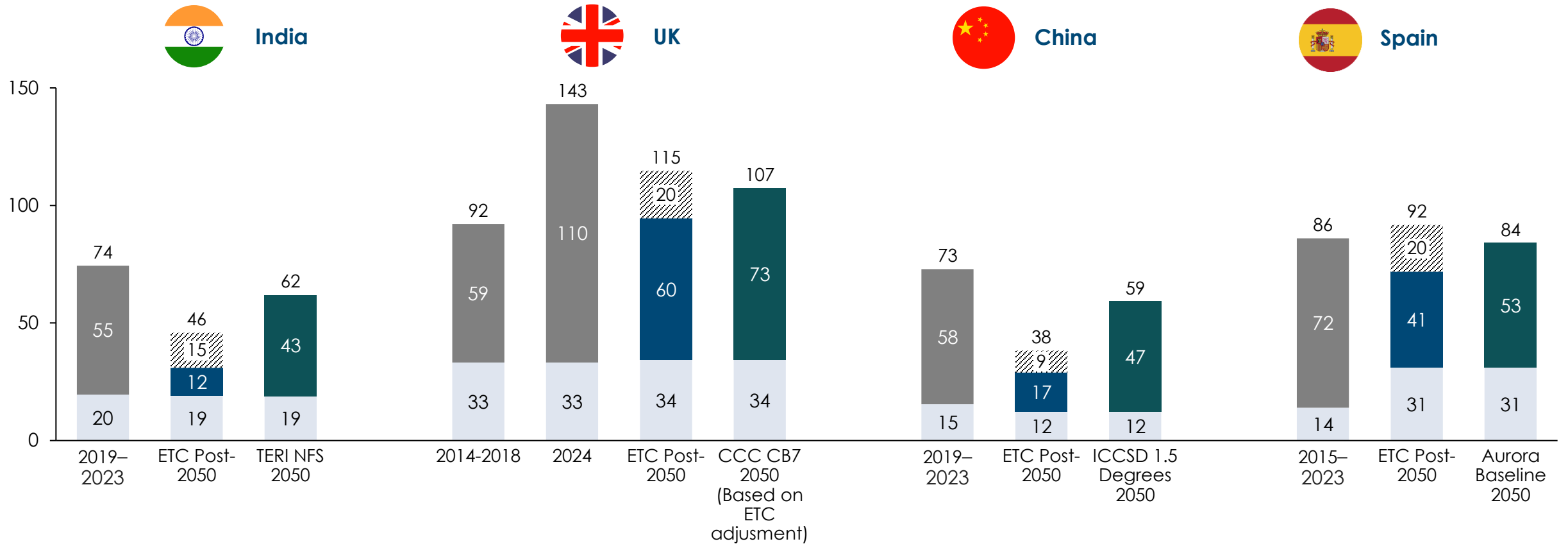
- 60% of demand met instantly; no storage needed
- 40% balanced via short-duration storage (daily), covered by batteries and demand side flexibility
- Low seasonality = minimal long-duration storage need
- Surplus solar could be absorbed via interconnectors, hydrogen, or flexible demand

Source: Systemiq analysis for the ETC;TERI (2024), *India's Electricity Transition Pathways to 2050: Scenarios and Insights*.

System generation, balancing, and grid costs could be competitive with current wholesale prices

Total system costs (generation, balancing, and grids), recent vs post-2050
\$/MWh (real 2024\$)

- Average wholesale power prices
- Dispatch model generation and balancing
- Cost of meeting balancing needs
- T&D costs (ETC est.)
- Wind/solar



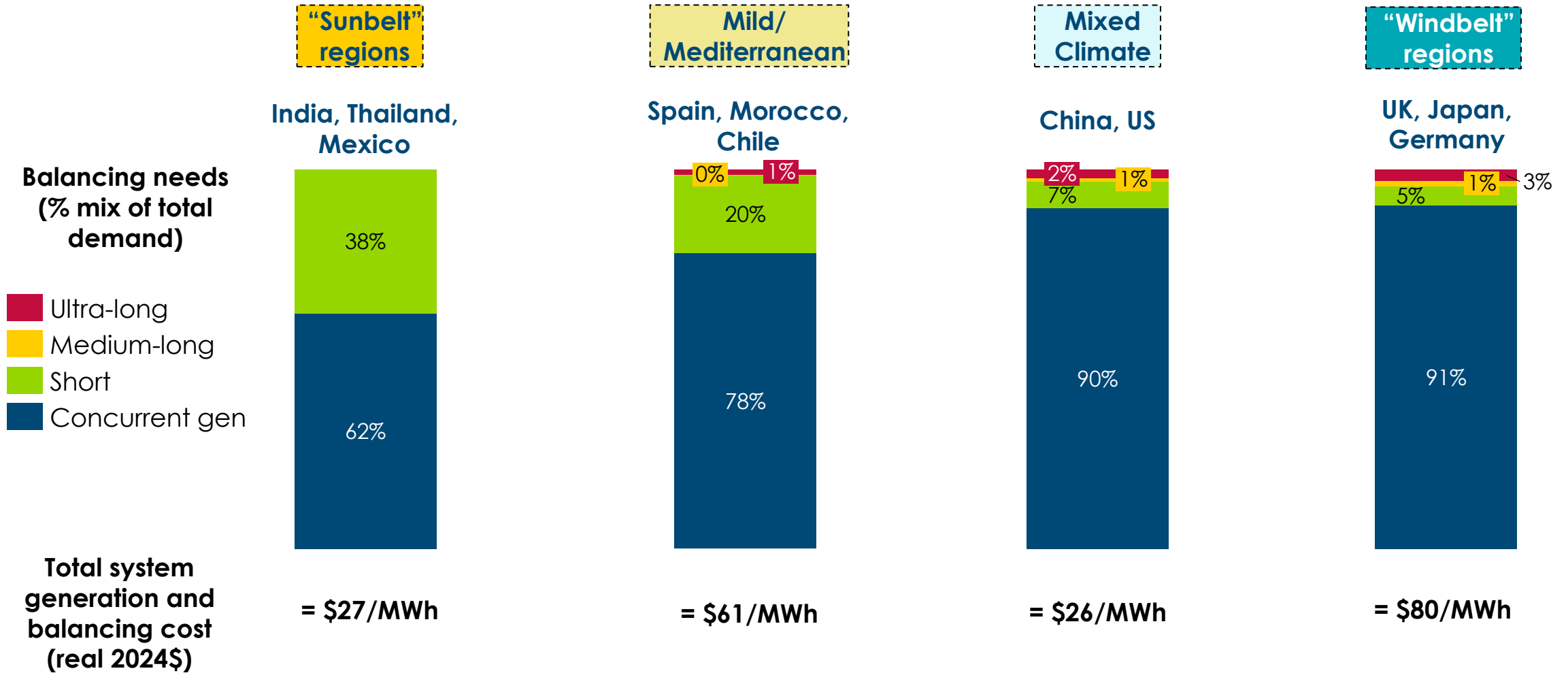
Note: T&D = Transmission and distribution. T&D costs per MWh have been assumed based on ETC modelling outlined in Chapter 2 across all presented here for consistency.

Source: Systemiq analysis for the ETC; BNEF (2025), LCOE: Data Viewer; Ofgem (2025), Wholesale market indicators – Electricity Prices: Forward Delivery Contracts – Weekly Average (GB); IEA (2023), Electricity Market Report – Update 2023; Statista (2024), Average electricity prices for enterprises in China from September 2019 to September 2024; Ember (2025), Wholesale electricity prices in Europe; CCC (2025), The Seventh Carbon Budget; TERI (2024), India's Electricity Transition Pathways to 2050: Scenarios and Insights; ICCSD (2022), China's Long-Term Low-Carbon Development Strategies and Pathways; Aurora (2023), Long Duration Energy Storage in Spain.



System balancing needs and costs differ in sunbelt vs. windbelt regions

Balancing needs and costs differ by region and resource type:


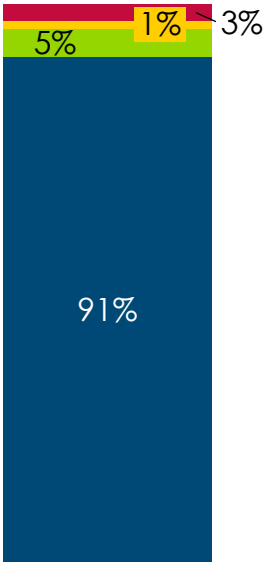



Source: Systemiq analysis for the ETC (2025)

Ultra-long duration balancing costs create significant additions to total system generation costs

Total system generation costs for a 2050 system, Northern Latitude

\$/MWh (real 2024\$)

Scenario	Balancing variability (% mix of total demand)	Generation and storage deployment and costs	System generation cost (\$/MWh, real 2024\$)
 Core scenario, UK	 <p> ■ Ultra-long ■ Short ■ Medium-long ■ Wind and solar </p>	<p>Generation: 778 TWh at \$45/MWh</p> <p>Short storage: 26 TWh at \$80/MWh</p> <p>Medium-long: 7 TWh at \$170/MWh</p> <p>Ultra-long: 16 TWh at \$460/MWh</p>	 <p> ■ Ultra-long ■ Short ■ Medium-long ■ Generation </p>

While ultra-long duration **only makes up 3%** of the balancing requirement in this archetype, **it makes a significant addition (\$14/MWh) to final generation costs**

Note: Generation costs are derived based on the generation mix using BNEF 2050 mid CAPEX and OPEX estimates, alongside capacity factors from the average weather year supply scenario (representing the long-term average), 30-year project lifetimes, and real WACC of 4%, 5%, and 6% for solar, onshore wind, and offshore wind, respectively. Storage costs are derived using the LCOS methodology outlined in this report, with the input electricity cost for all storage technologies set to be the archetype's generation cost per MWh. Efficiency losses for storage technologies are included (assumed efficiencies are 90% for short, 60% for medium-long, 40% for ultra-long). Surplus generation arises from overbuild required to meet balancing needs and is included in both energy and cost calculations. Cost estimates are in 2024 US\$/MWh and reflect levelised costs of generation and storage, including contributions from surplus energy. Source: Systemiq analysis for the ETC; BNEF (2025), LCOE: Data Viewer.

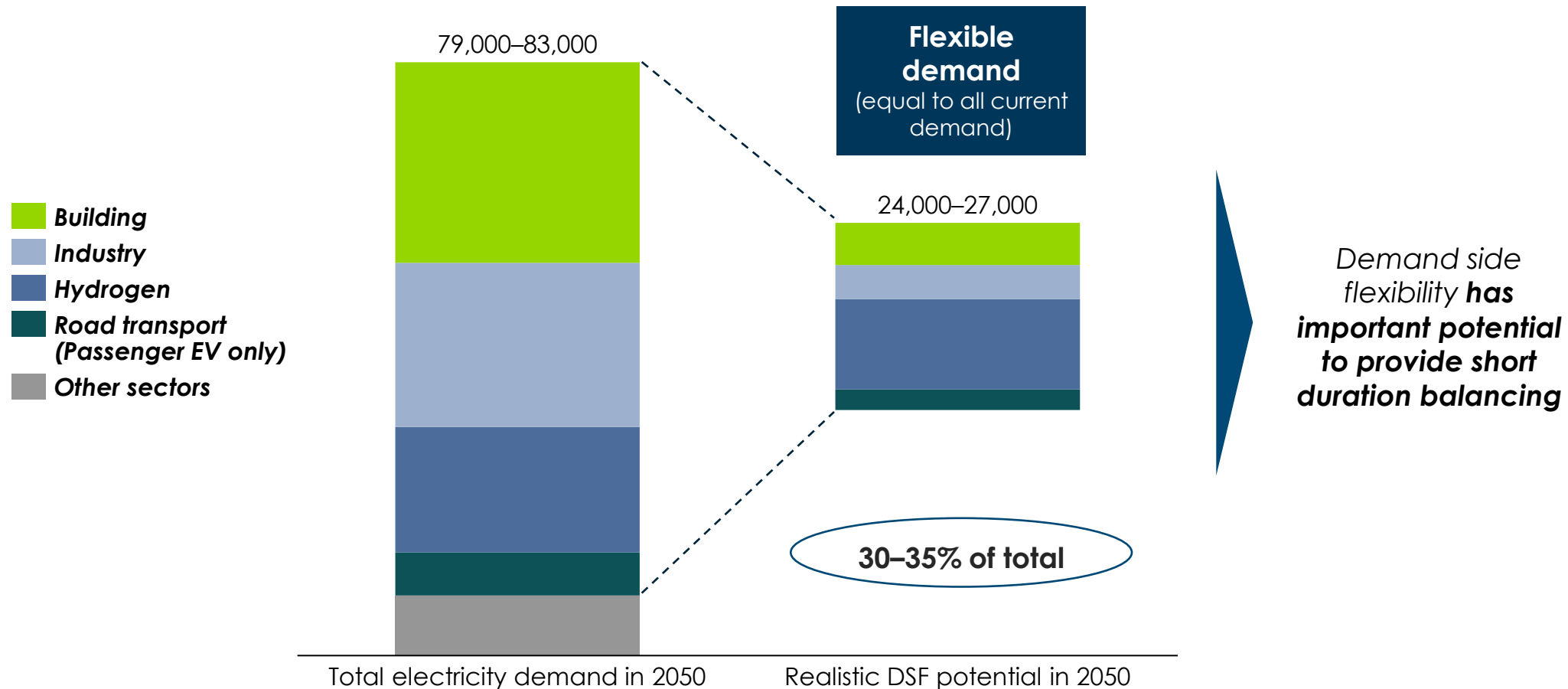


Around 30% of overall electricity demand in 2050 could be flexible

Global electricity demand and DSF potential, 2050

TWh

Ranges based on ETC scenarios ACF and PBS



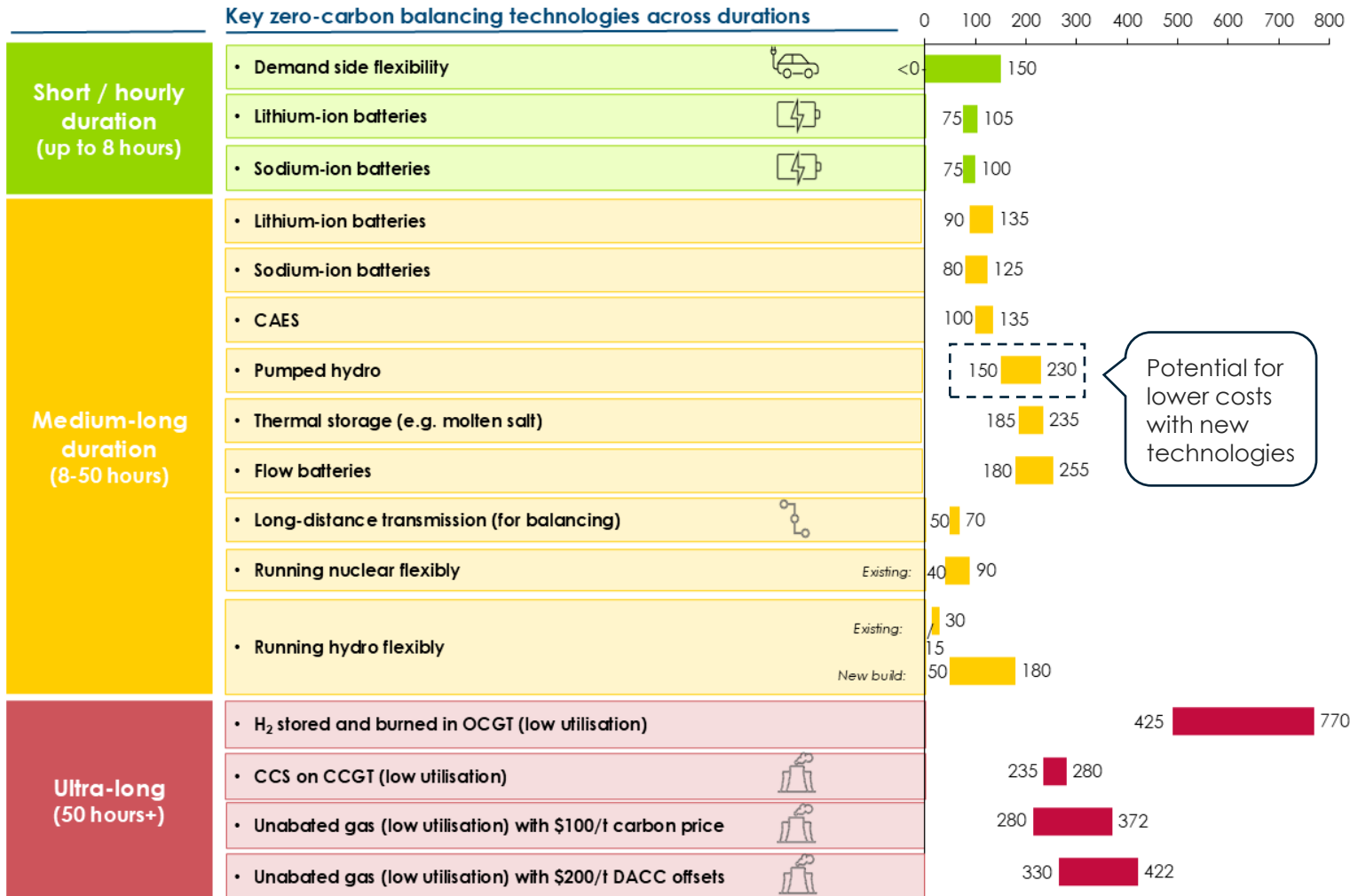
Note: To assess demand side flexibility (DSF) potential, we start by looking at theoretical potential—the maximum flexibility we could achieve if all technology and behaviour changes were fully adopted. Then, we evaluate realistic potential, which considers practical barriers including technological, economic, policy and behaviour. This approach helps us understand both the ideal possibilities and what can be realistically achieved in the near term.

Source: Systemiq analysis for the ETC; IEA (2024), *World Energy Outlook 2024*; RMI (2023), *Unlocking demand-side flexibility in China*; Macquarie (2020), *Flexibility of Hydrogen Electrolysers*; IEA (2024), *Global EV Outlook 2024*; World Electric Vehicle Journal (2019), *Flexibility of EV demand*.

Balancing can be met with different solutions, costs vary

Cost comparison of balancing technologies – \$40/MWh
\$/MW

Cost of delivered electricity in 2035



Key takeaways

- **Short duration:** Demand-side flexibility and lithium-ion batteries already cost competitive vs fossil in some cases
- **Medium-long duration:** mix of options, pumped hydro and long-distance transmission could be most competitive
- **Ultra-long duration:** Costly, as high capex assets at low utilisation; a restricted role for unabated gas with clear guidelines may be the most pragmatic near-term path.

Assumptions: The following assumptions are used for the following technologies: CCS on CCGT and unabated gas feature a utilisation rate of 5%. Hydrogen based on a 5% utilisation factor for OCGTs and a 20% electrolyser utilisation rate. Interconnectors: assume no electricity cost input. Source: Systemiq analysis for the ETC (2025); BNEF (2024) Energy Storage System Cost Survey; (2024) Long duration energy storage cost survey; PNNL (2025), Pumped Hydro Energy Storage; BNEF (2024), Electrolysis System Cost Forecast 2050: Higher for Longer, BNEF (2025), LCOE Data Viewer, Liu et al. (2021), Development status and prospect of salt cavern energy storage technology.

The ETC identified top 15 interconnector projects



Long distance transmission can help to deliver:

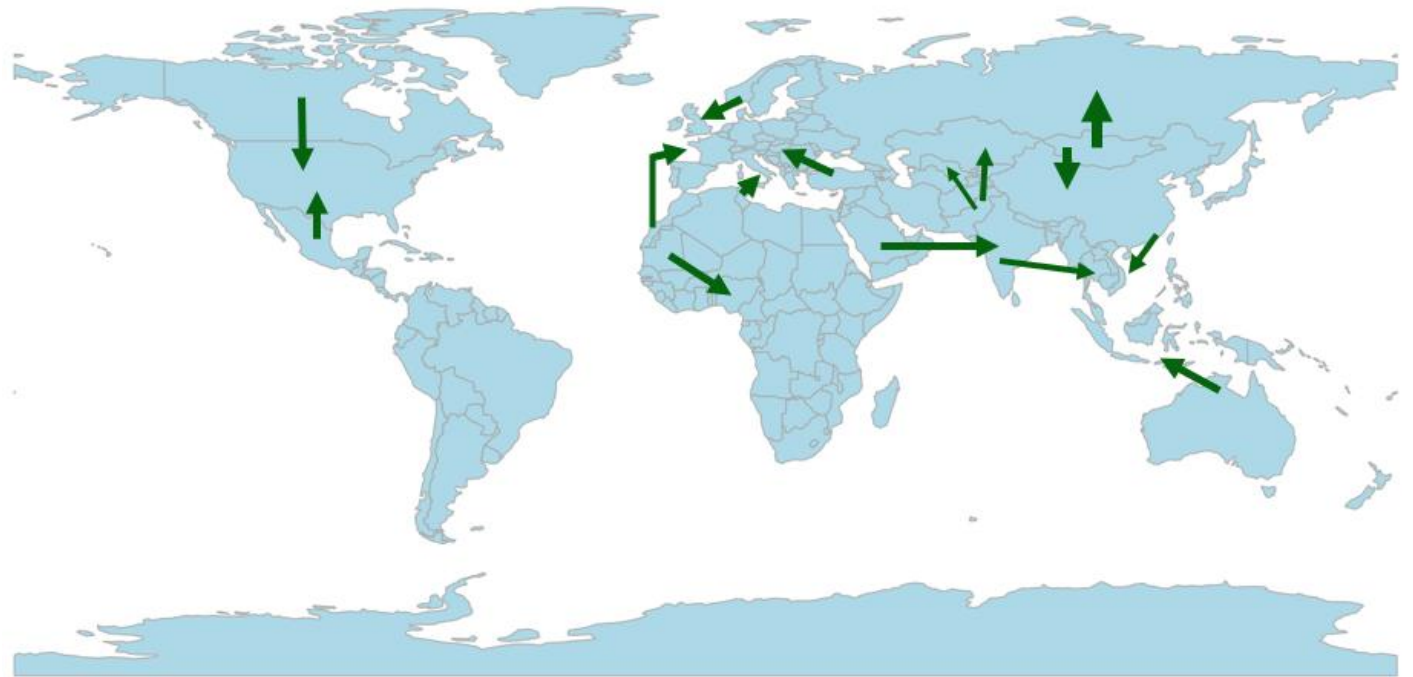
- Low-cost clean generation, from a low cost/high availability geography
- Balancing, Using non-correlated weather and demand including with storage at the export site



Overall modelling results suggest that a small number of high potential links could deliver by 2050:

- **15%** of 2024 global power demand
- **1.8 Gt** per annum carbon reductions (equal to 13% of global power sector emissions)
- **\$100bn** dollars of savings per year

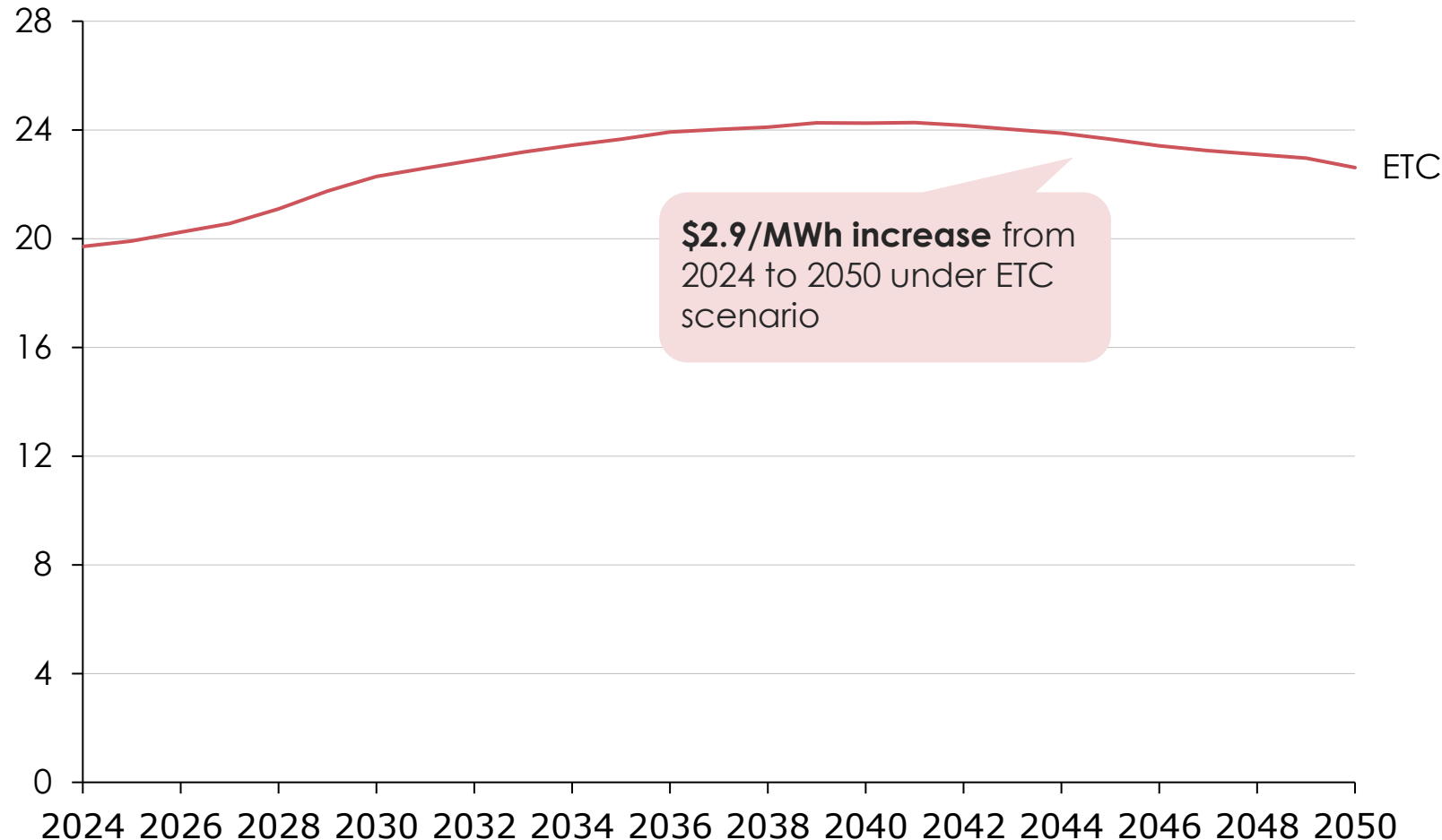
Overall modelling results: top 15 lines show potential for network 'megaprojects' such as Morocco and Australia as export hubs



Grids will need to expand, optimisation is key: costs per MWh will only increase slightly to 2050, but can be reduced if we maximise flexibility

Grid Capex costs (transmission & distribution) per demand unit, global, 2024–2050

\$/MWh (real 2024\$) for payments per electricity demand; interest rate = 5%; 30-year repayment timeline



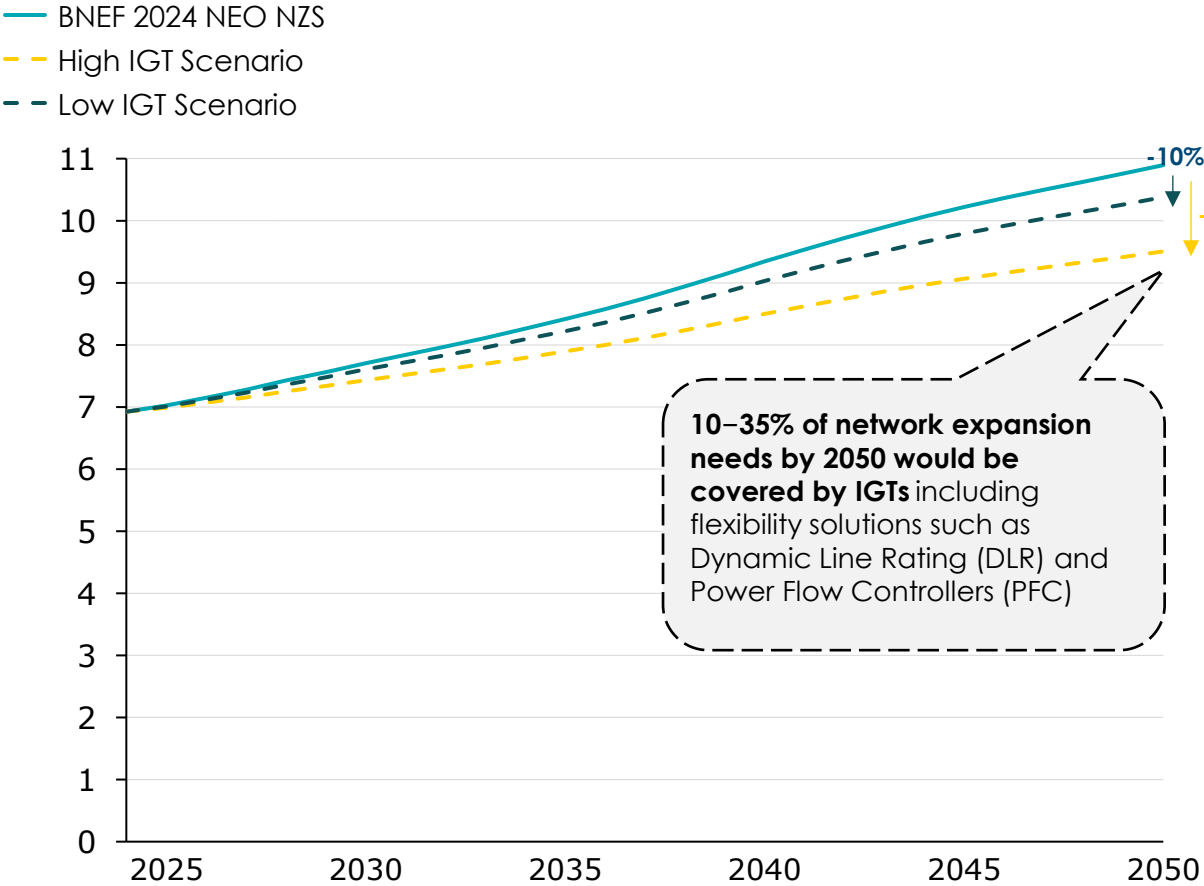
- **Grid capacity must grow by at least 50% by 2050** to meet electrification needs, even with all efficiency and optimisation measures in place
- The **initial increase in cost per unit of demand** is due to the upfront investments needed to build and reinforce the grid infrastructure in line with rising electricity demand.
- **The grid cost per unit of demand then decreases** because the fixed costs are spread over a larger volume of electricity consumption.
- **Grid optimization measures could further reduce** the need for additional grid build, lowering overall costs.

Source: Systemiq analysis for the ETC (2025), BNEF (2024) *New Energy Outlook 2024*

Innovative Grid Technologies could significantly reduce grid build & CAPEX

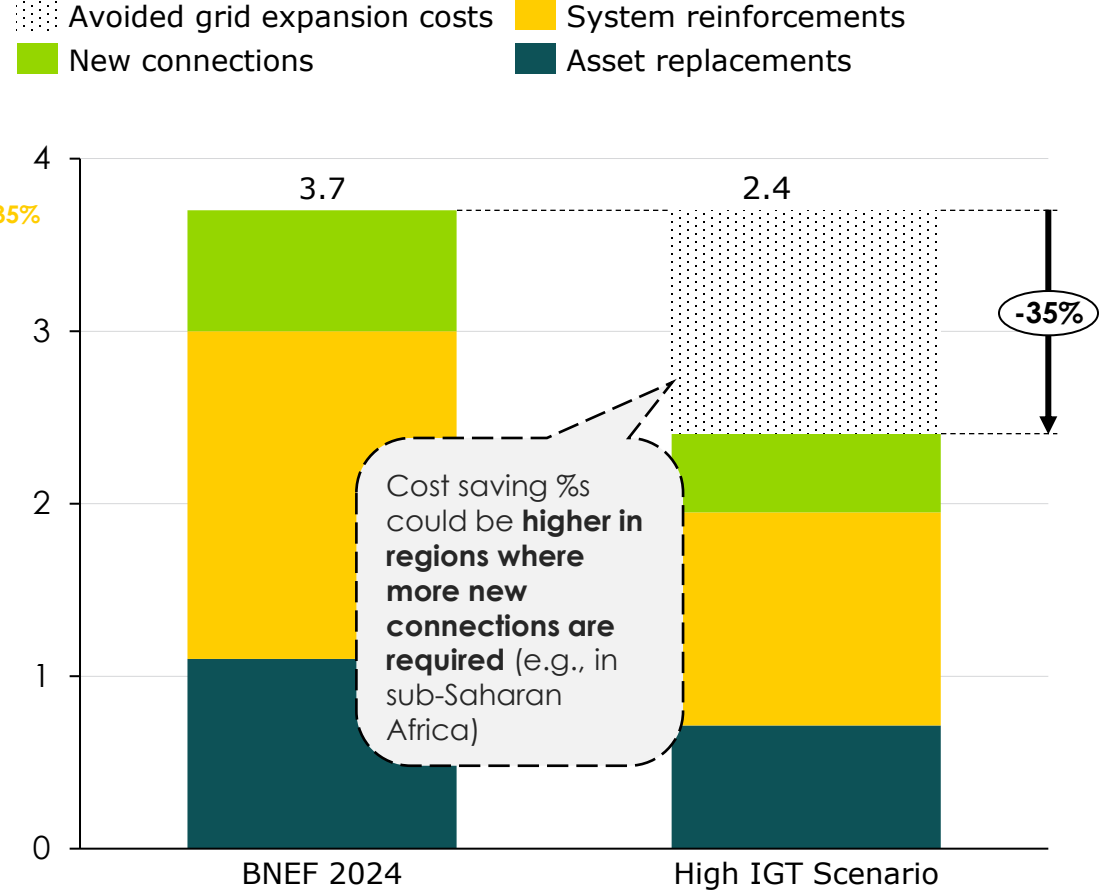
Benefits of IGTs compared to network expansion needs

Million km, Europe, 2024–2050



Cumulative investment in new power grid system, Europe

\$ trillion (real 2024\$), 2024–2050, based on BNEF



Note: We have assumed that IGTs impact all three investment categories: IGTs lower new connection needs by maximising existing and new infrastructure use (though some remote renewables still need connections, new connections leveraging IGTs will require fewer upgrades in future); IGTs delay system replacements by extending grid asset life; and IGTs reduce reinforcement requirements by improving line capacity and utilisation.

Source: Systemiq analysis for the ETC; CurrENT (2024), *Prospects for innovative power grid technologies*; BNEF (2024), *New Energy Outlook*.



Balancing electrification and decarbonisation: the risks of a mismatch

Developed Countries e.g. UK



UK territorial greenhouse gas emissions, 1850-2023

MtCO₂e

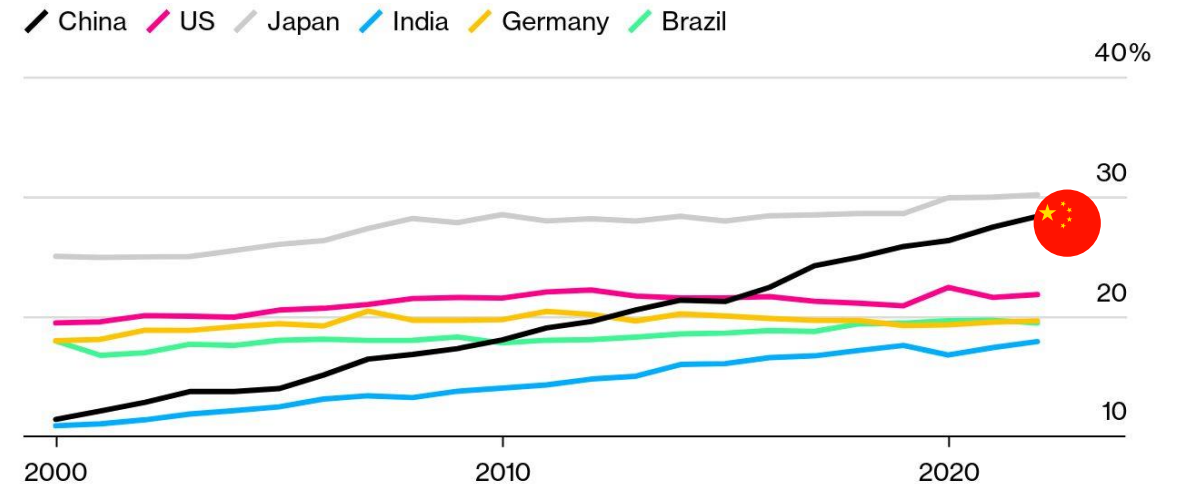


- **Decarbonisation occurring rapidly** in countries like the UK from 500g CO₂ per kWh in 2010 to 125g in 2025
- However, **electricity demand is stagnant** – from 360 TWh in 2010 to 320 TWh in 2024
- **The risk** – grid costs spread over fewer units, rising unit costs risk disincentivising electrification

Developing Countries e.g. China

Electricity's share of final energy consumption

%



- **Electrification rising** due to industrialisation and adaptation (e.g. rising AC use)
- But **supply is not yet decarbonised**, with China's power intensity remaining over 500g CO₂/kWh
- **The risk** – growing demand locks in high emissions unless supply transition accelerates

Six key enablers for power systems transformation

Strategic vision & planning

- **Smart targets for deployment** – including renewables, grids, energy storage, and flexibility.
- **Accurate models and forecasting** – to help set targets and enable integration of new technologies.
- **Political will for the transition** – To enable both phasing down of fossil, and plans for flexibility deployment (including across borders).
- **Anticipatory funding** – shifting from short-term reactive investment to anticipatory, long-term whole-system planning.



Market design

- Market access
- De-risked revenue streams
- Pricing signals (incl. locational pricing, carbon pricing)



Grid regulations

- Reform of grid fees
- Evolution of connection rules
- Modernisation and harmonisation



Data, AI and smart grids

- Data and AI modernisation
- Advanced metering and digitalisation



Supply chain and workforce

- Supply chain concerns
- Workforce education



Consumers

- Consumer engagement and trust-building



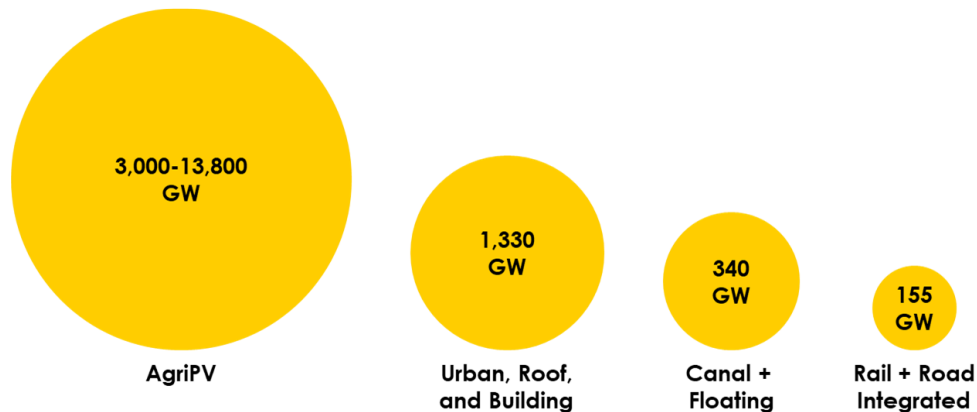
We will be looking into the solar potential in India and Indonesia



Assessing AgriPV's impact on India's power system

- Analysis will be done by TERI, seeking to answer outstanding questions on AgriPV around land availability, impact on local grid systems and best practices
- Three deliverables: briefing on land availability, technical paper on power system implications and integration, paper on 'Just Transition' elements

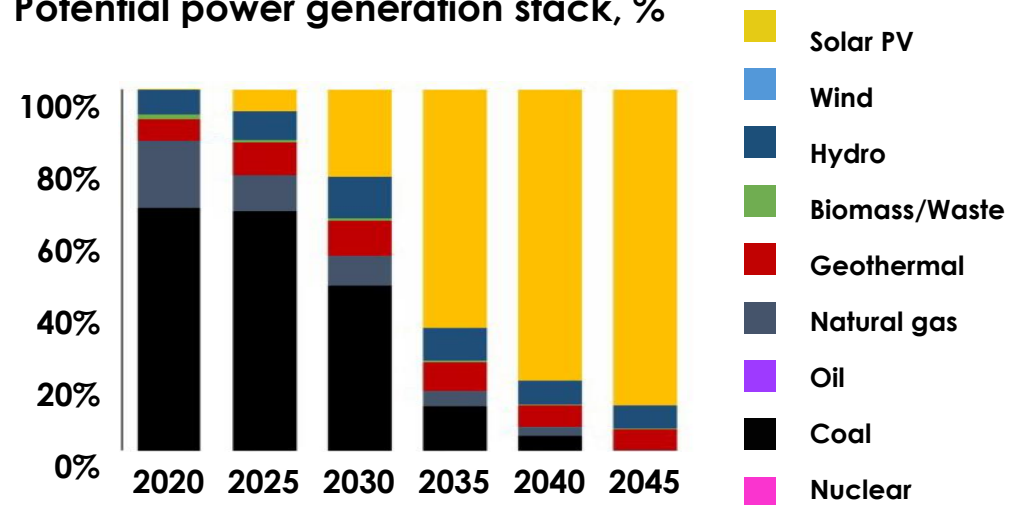
Estimates of potential capacity (GW)



Aligning renewable power as an enabler to Indonesia's economic growth

- Project will be reframing decarbonisation of the power sector as an economic growth lever – integrating the new power system with GVA, GDP and jobs impact numbers
- We will be organising convenings alongside the analysis, to target cross-ministerial support and liaising with ICGD and Kadin

Potential power generation stack, %



Impact of rooftop solar on Australian distribution networks

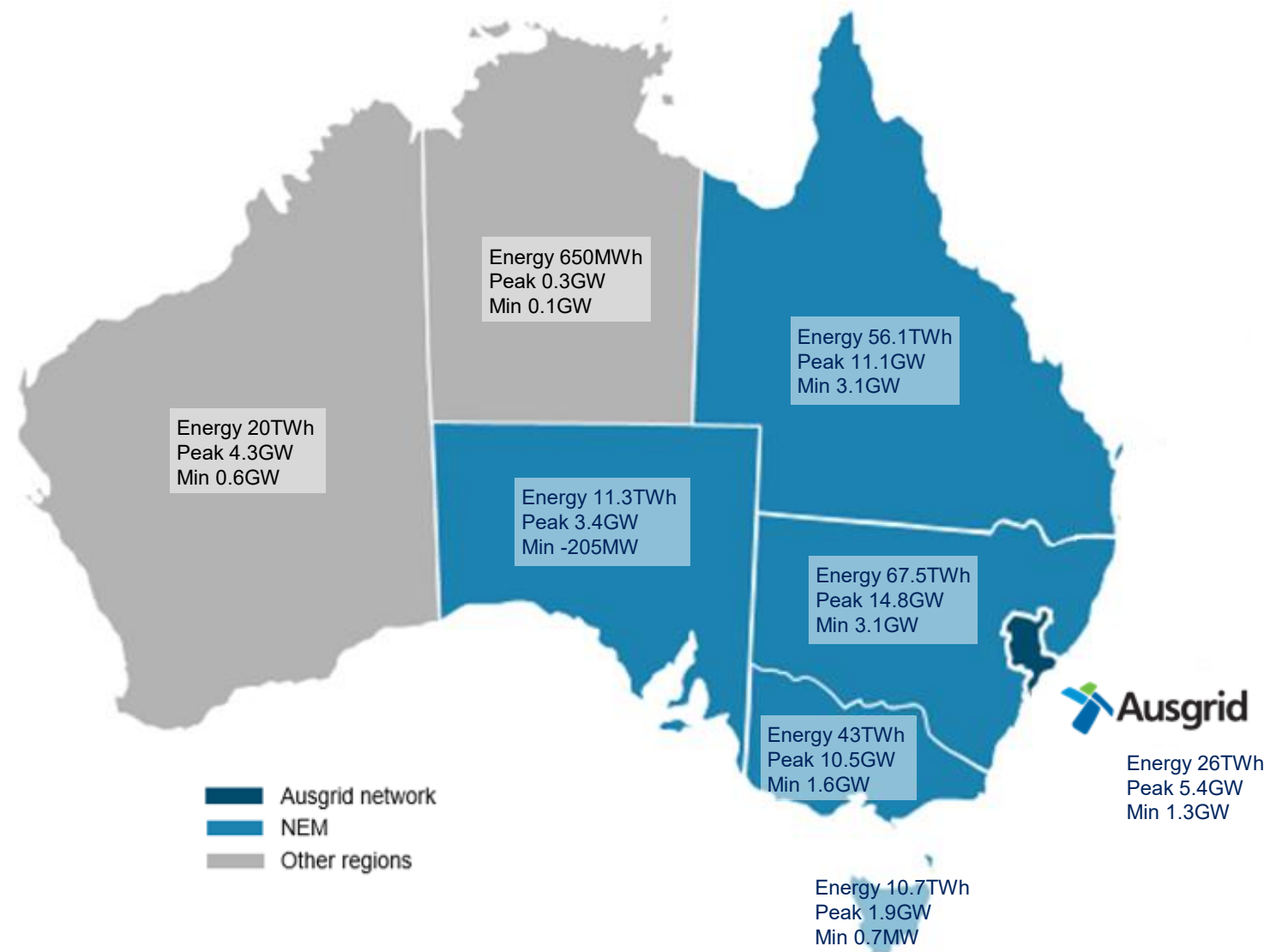
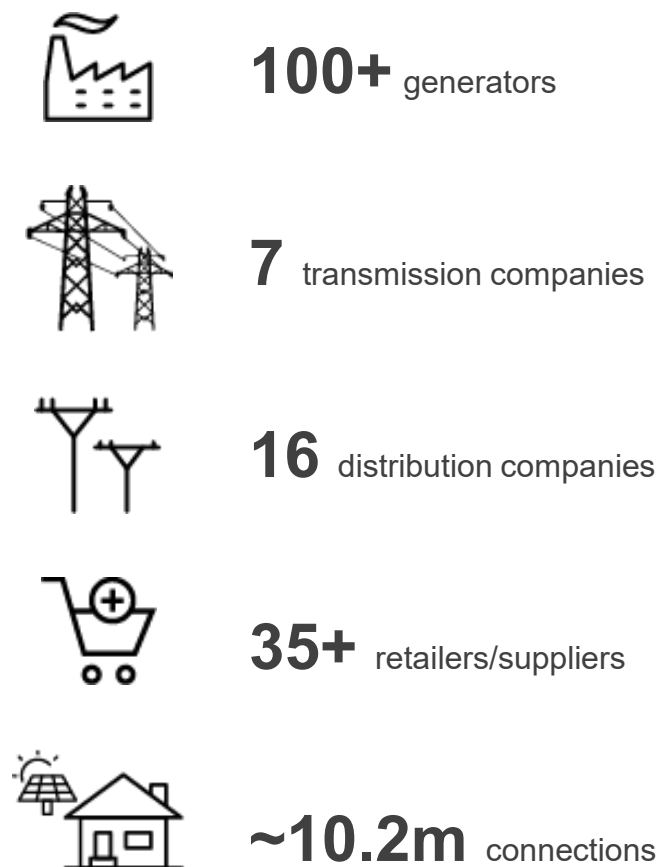
Tim Jarratt

Group Executive Market
Development & Strategy

June 2025



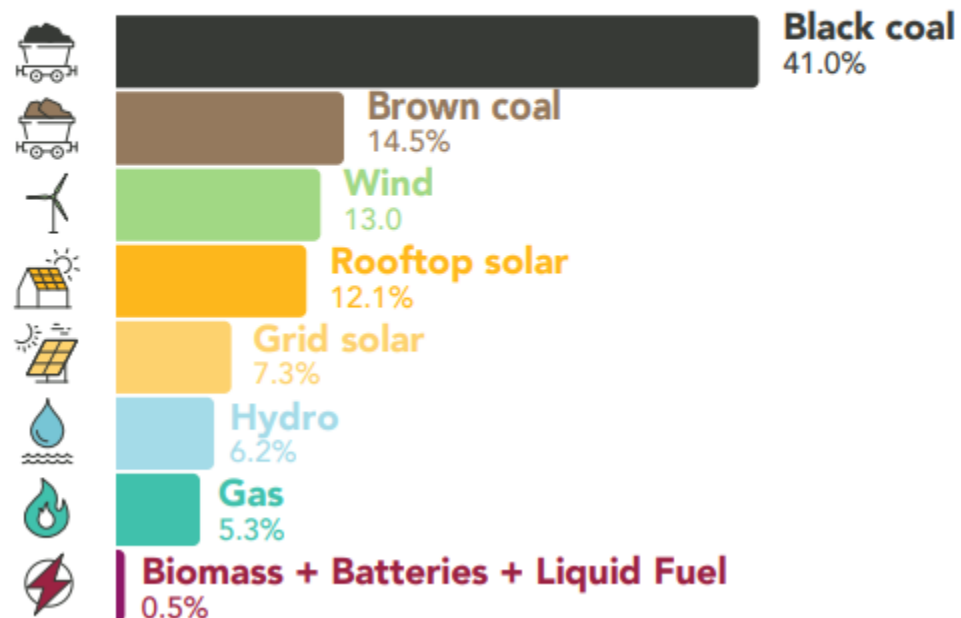
Electricity system in Australia



NEM generation still largely coal based today but rooftop solar now over 25% of capacity

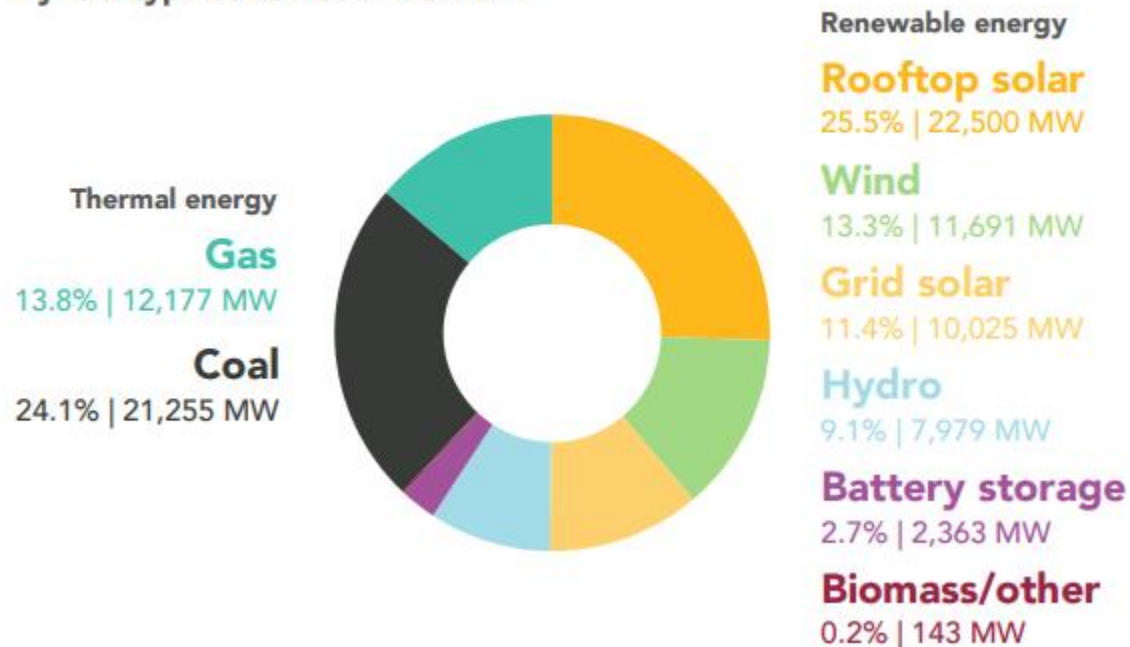
Generation supply mix

By fuel type as at December 2024



Generation capacity

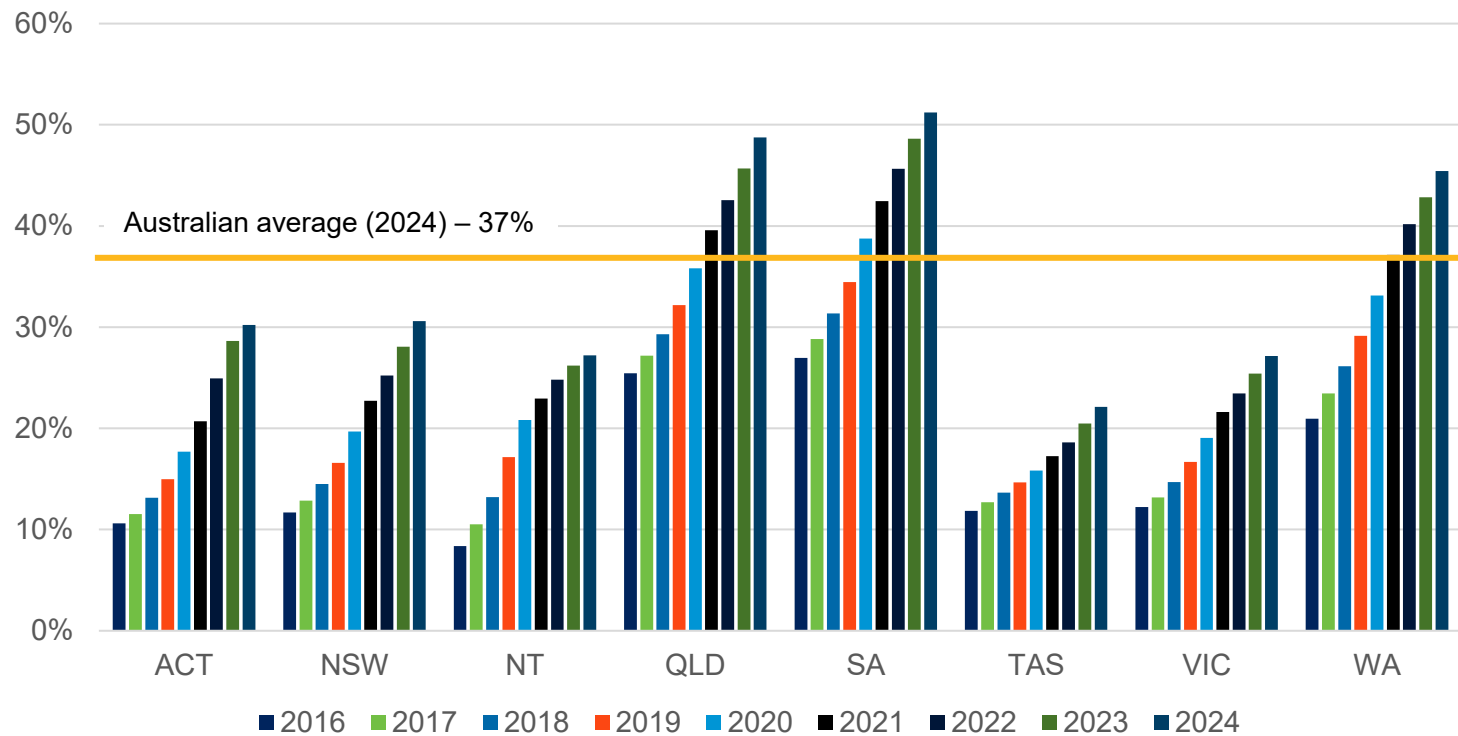
By fuel type as at December 2024



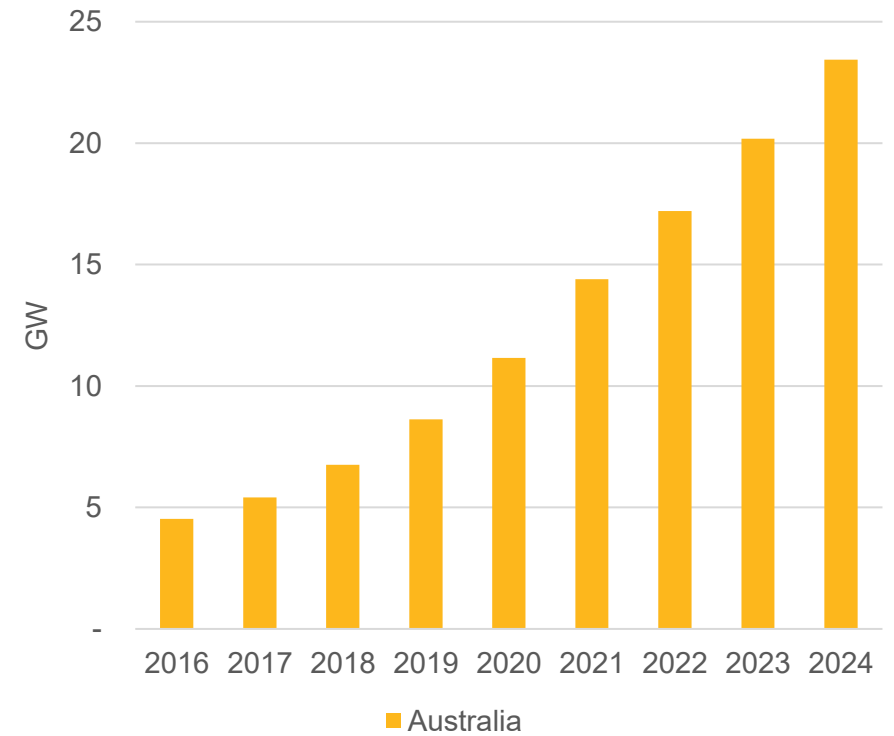
Source: <https://www.aemo.com.au/-/media/Files/Electricity/NEM/National-Electricity-Market-Fact-Sheet.pdf>

Over 1/3 of homes have rooftop PV...

Rooftop solar penetration by State



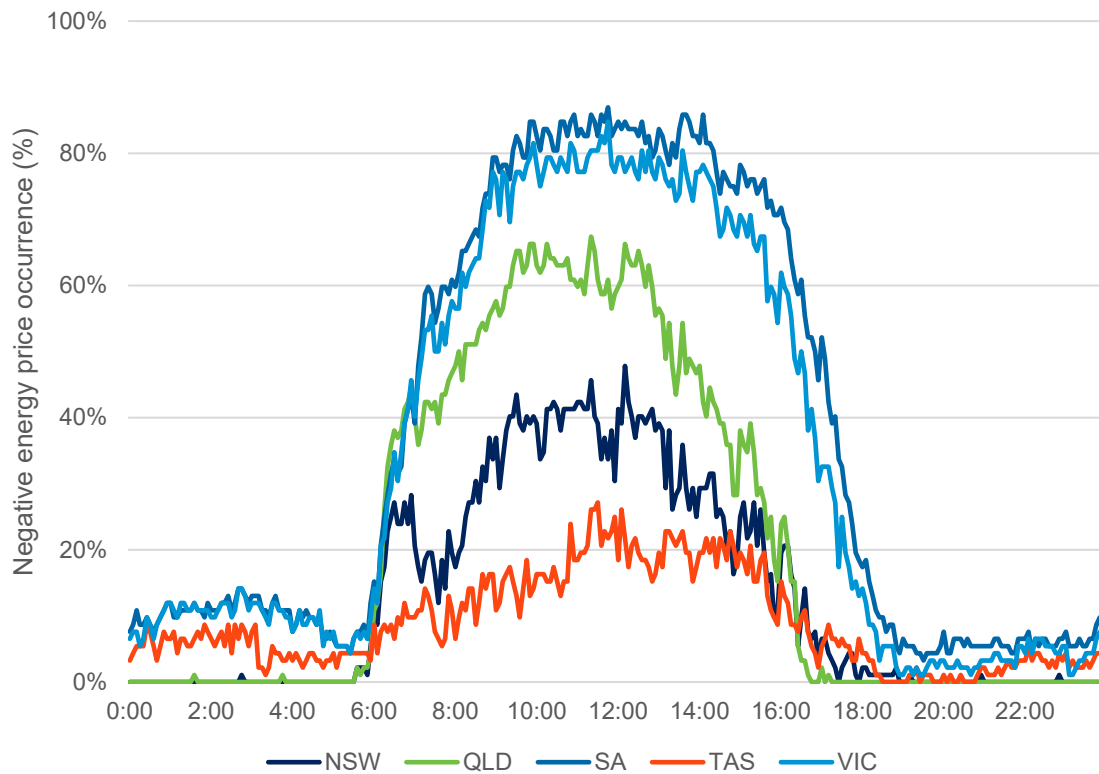
Installed rooftop solar capacity



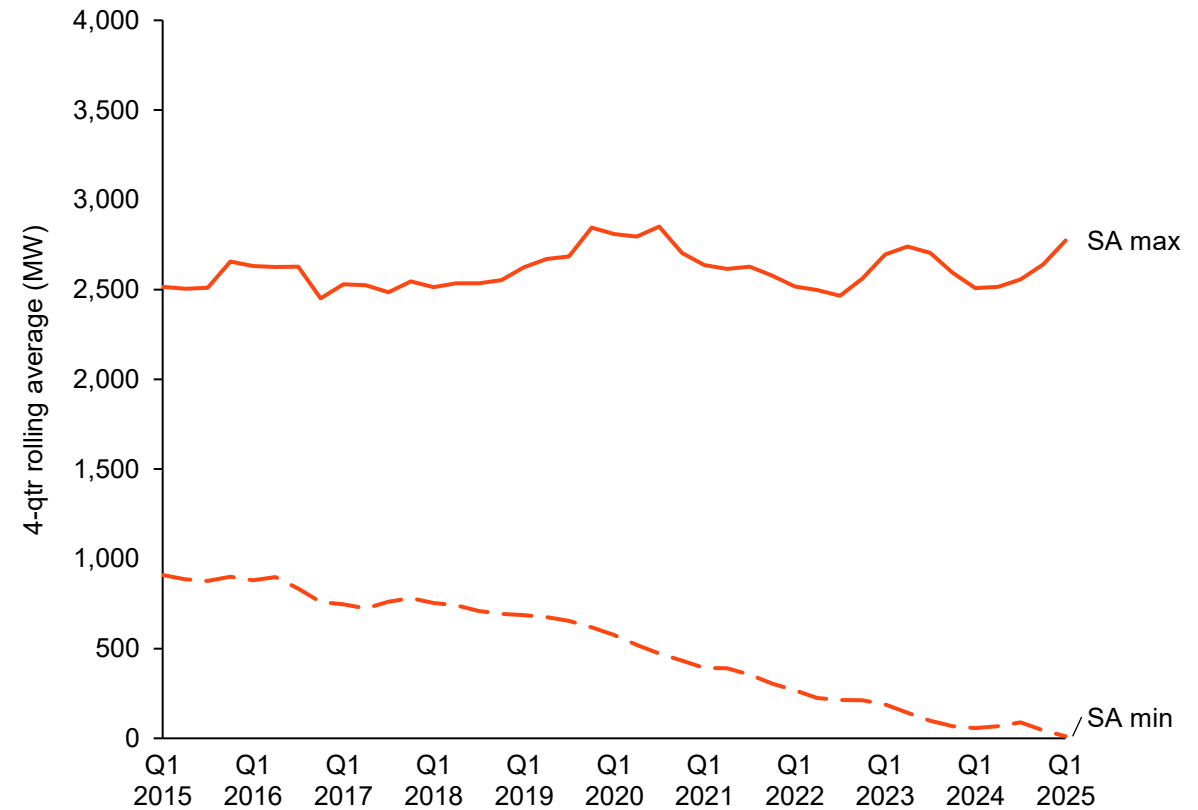
Source: <https://cer.gov.au/markets/reports-and-data/small-scale-installation-postcode-data>

...but excess solar PV causing grid stability issues

Negative price occurrence in the NEM in Q4 2024



SA Max and Min Operational Demand



Source: AEMO Quarterly Energy Dynamics reports



Today's solutions



Use

Encourage consumers to shift usage to the middle of the day through incentives (e.g. 'solar soak' and solar export tariffs, 'free power' offers)

Store

Soak up excess solar through energy storage at all levels in the system for use during peak hours (e.g. community batteries, VPPs)

Control

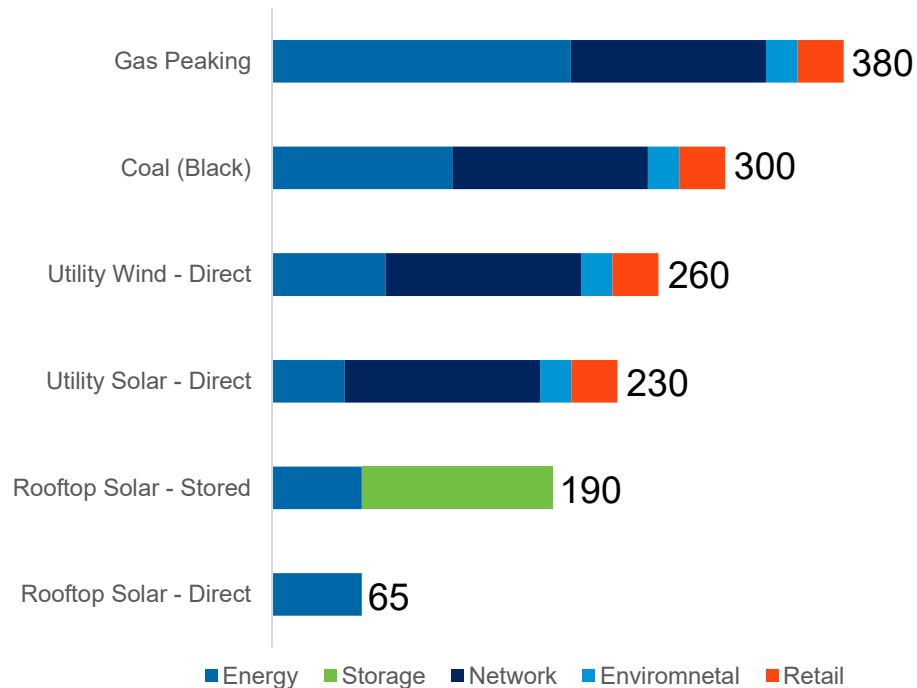
Reduce or prevent solar generation output during minimum load conditions (e.g. dynamic operating envelopes (DOEs), solar backstop)

Change needed to realise grid edge potential and address equity issues

Locally consumed solar is the cheapest power source available today...

...but large sections of society cannot directly access rooftop PV

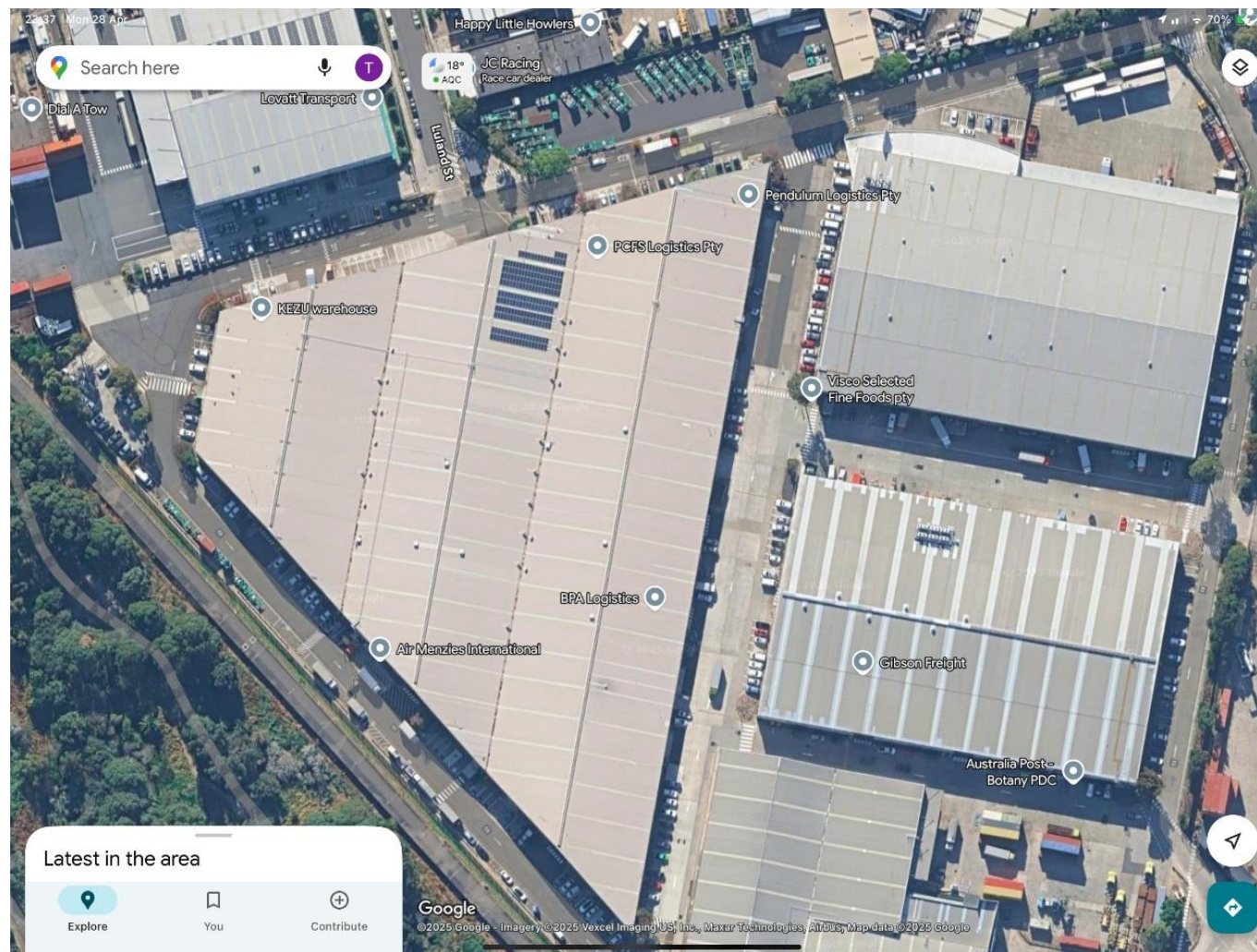
Levelised Cost Of Energy (A\$/MWh)



Source: CSIRO GenCosts 24-25, Energy Council & Ausgrid Analysis

- ~45% of residents in the Ausgrid territory live in apartments
- ~35% of customers in Greater Sydney are renters
- ~15% of households in Greater Sydney are classified as low income (<A\$650 p/w)

The opportunity: unused roof space in Australia could host 150+GW of extra solar



Commercial in Confidence





Decarbonising the last 20% - the role of low-carbon molecules



The Carbon Molecules workstream is completed over 3 phases

Overall objective of the carbon molecules workstream

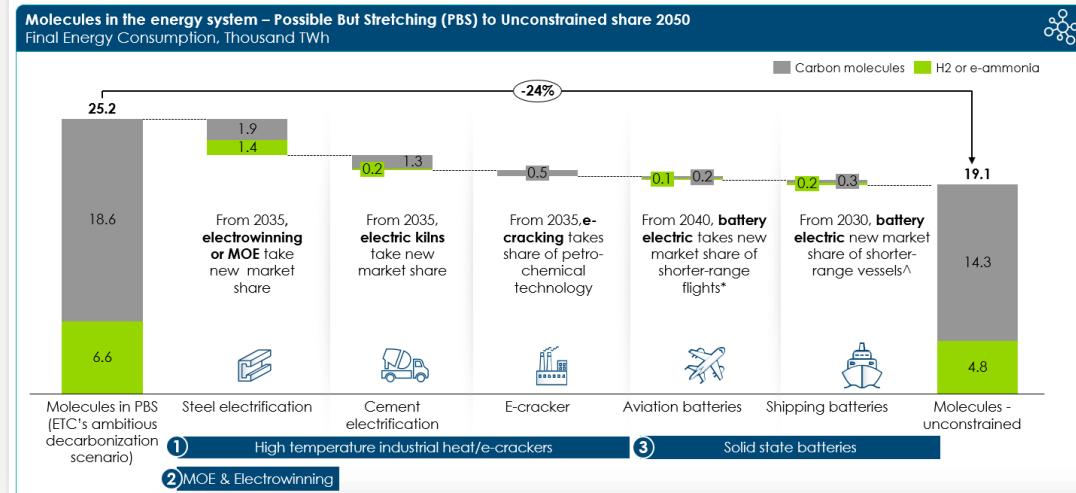
Understand the volume of carbon molecules demanded in a low-emission future for the energy and materials sectors, and how to supply that demand in an optimal and sustainable way.

	2024	2025			
	Q4	Q1	Q2	Q3	Q4
Workplan	<p>Phase 1A How large can and should the role of direct electrification be in a zero-emission economy</p> <p>Phase 1B The role of hydrogen and derivatives (i.e., ammonia) in a zero-emission economy?</p>	<p>Phase 2 The potential to recycle and reuse carbon molecules</p>	<p>Phase 3 Sources of primary carbon: costs and sustainability and end-of life carbon management</p>	<p>Phase 4 Report production and communication campaign running into COP30</p>	
Deliverables	<p>For each phase</p> <ul style="list-style-type: none"> • A 5-pager published externally • A series of short innovation briefs for publication 			<ul style="list-style-type: none"> • Publication of the ETC report ahead of COP • A series of short innovation briefs for publication 	
Key interactions	<p>For each phase</p> <ul style="list-style-type: none"> • 1-2 workshops with ETC Commissioners 			<ul style="list-style-type: none"> • Report reviews • Report launch at COP 	



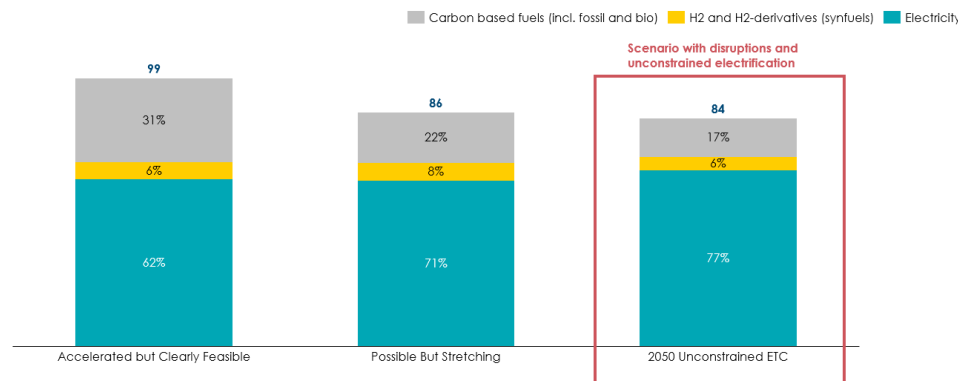
Phase 1A and 1B: Disruptive technologies for high temperature heat and iron/steel making potentially push electrification further

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



An “unconstrained electrification” scenario with these technology disruptions could reduce share of carbon molecules to ~15% of final energy demand

Global final energy demand by energy source and scenario, 2050
000 TWh



Key conclusion for achieving electrification disruptions



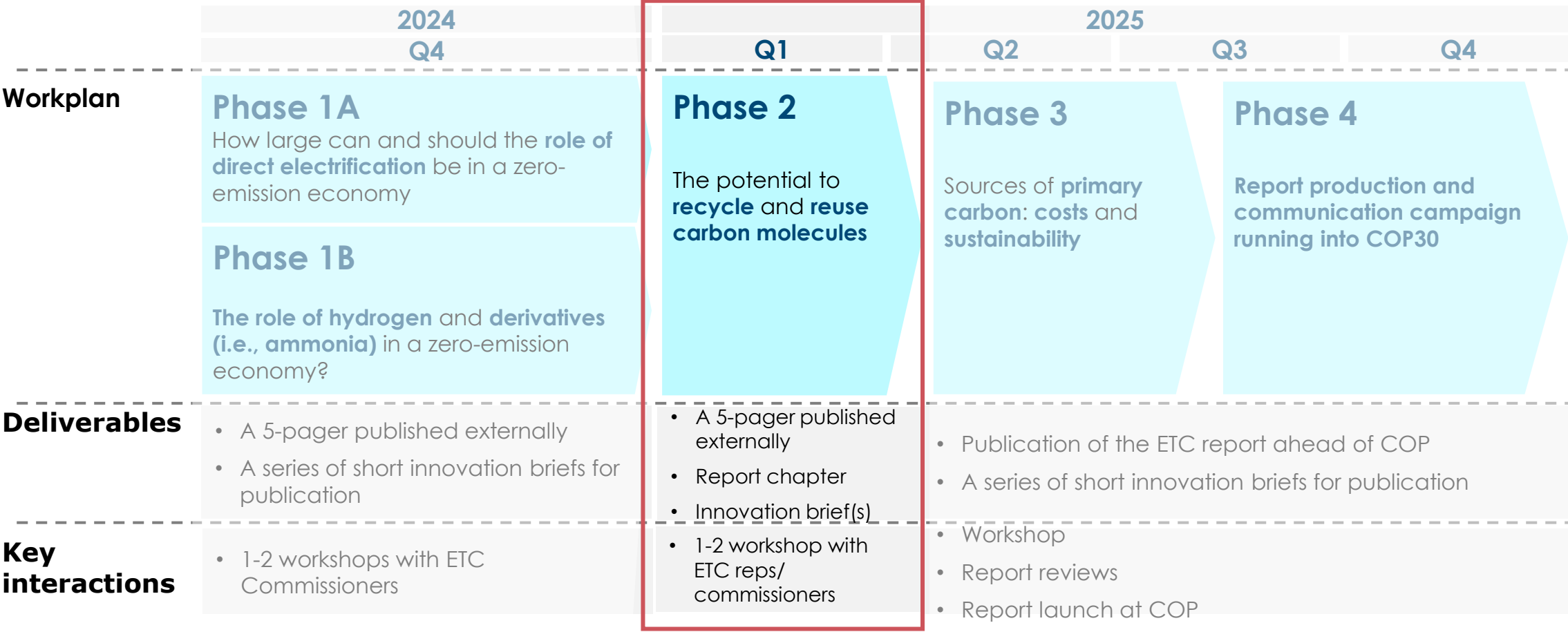
1. Largest opportunity for further electrification in steel and cement sectors
2. 24/7 clean power source required to allow high temperature technology viability
3. Potential challenges from retrofitting current operations and cost uncertainty
4. Solid state batteries expected to have performance spill-over effects, driving improvements across battery chemistries
5. Minimum carbon requirement, with disruptions to reduce share of carbon fuels in energy mix to 17%



Phase 2 focus: the potential to recycle and reuse carbon molecules - covering both plastics recycling and other opportunities

Integration in broader carbon molecule project

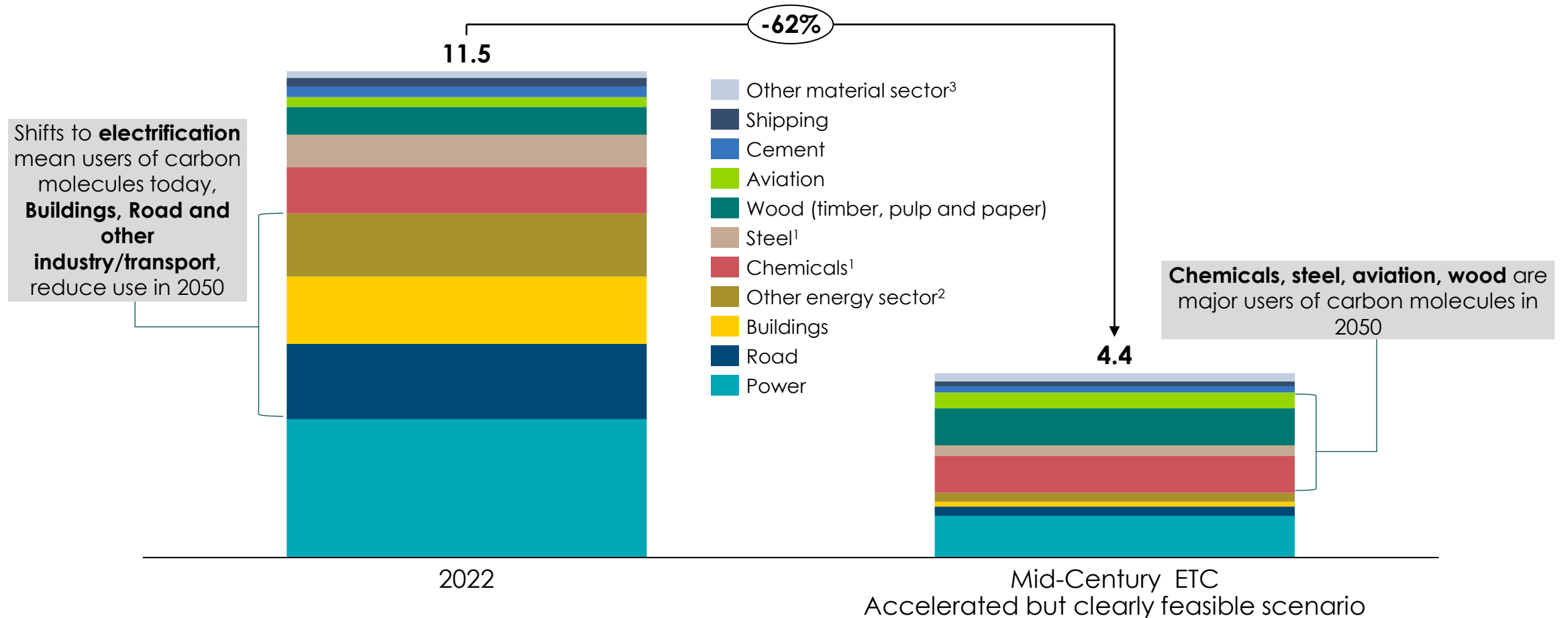
By sizing minimum and maximum volume of carbon molecules that can be reused and recycled (for energy and non-energy), we understand the implications for the primary supply of new carbon still required to support a prosperous global economy



The need for carbon molecules in our material and energy system will decline with decarbonization; up to 4.4 Gt will still be required by mid-century

Carbon Demand Across the Energy and Material Sectors

Gigatonns of carbon (C)



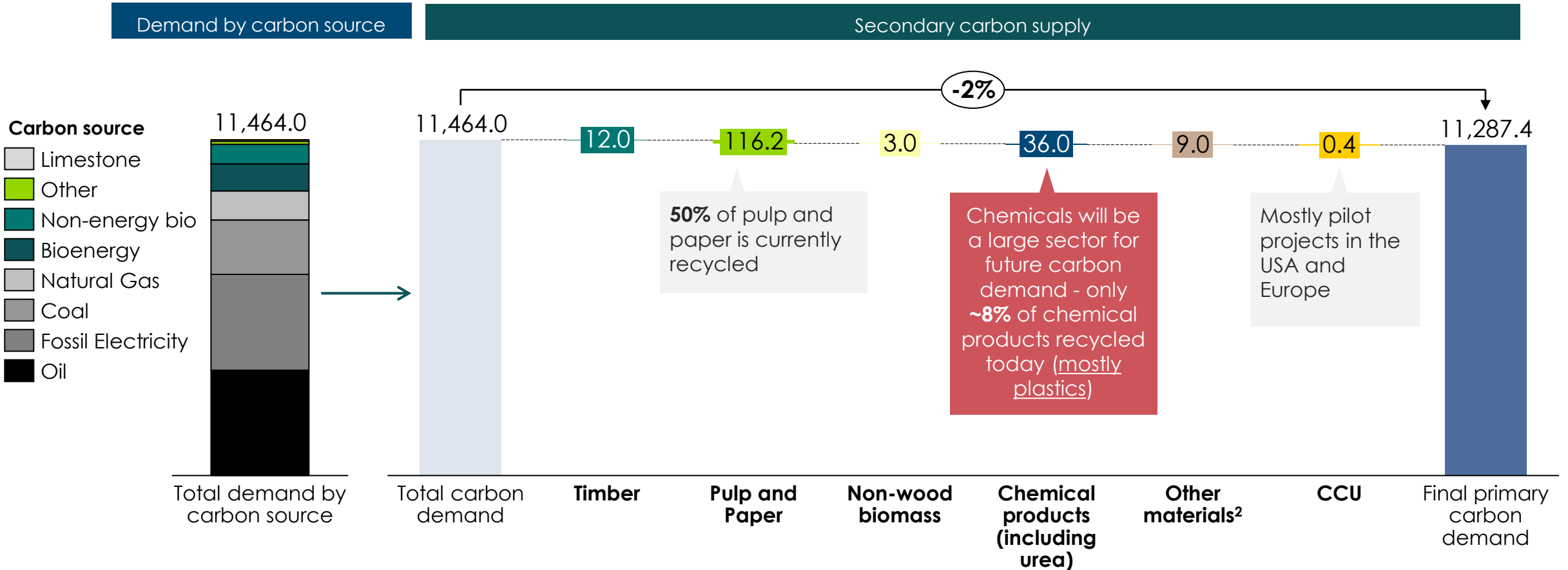
Notes: *ACF = Accelerated but Clearly Feasible scenario, based on ETC Fossil Fuels in Transition (2023) with minor updates. Sources: Chemicals: Planet Positive Chemicals Report (Systemiq, 2022, BAU Net-Zero scenario); Biomass: ETC Bioresources report (2021); Steel: MPP STS (2022); Cotton, Bitumen and 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. 3) Other material sectors include non-wood biomass, limestone, carbon ash, biochar, carbon fibre and charcoal. Carbon-based fuels include those fuels that also require carbon sources, e.g. e-methanol and synthetic aviation fuels.



Today, 98% of carbon molecules demanded are used once and major carbon users like the chemical sector recycle small amounts

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

Million tons of carbon (C)



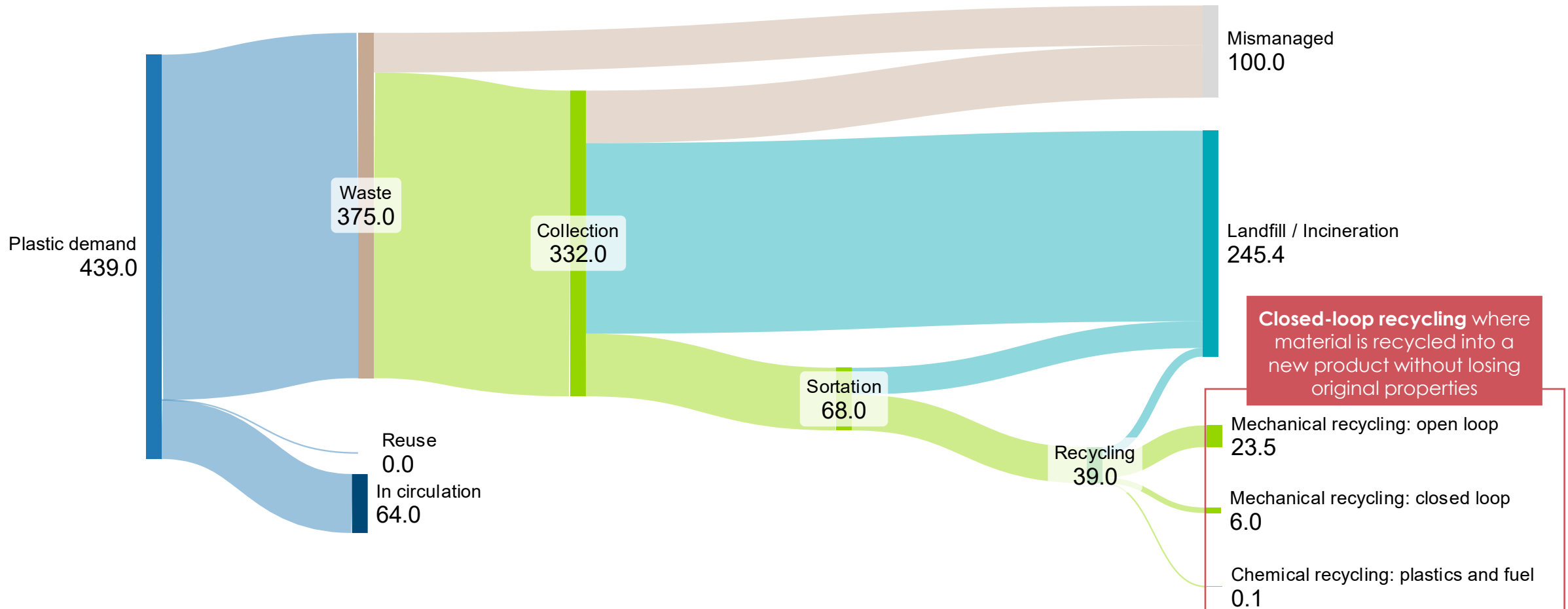
Sources: Energy: Systemiq analysis (2025), based on Fossil Fuels in Transition (ETC, 2023); Chemicals: Planet Positive Chemicals Report (Systemiq, 2022, BAU Net-Zero scenario); Biomass: ETC Bioresources report (2021); Steel: MPP STS (2022); Cotton, Bitumen and Soda Ash: Systemiq analysis (2025)

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.



Chemical sector in focus: 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



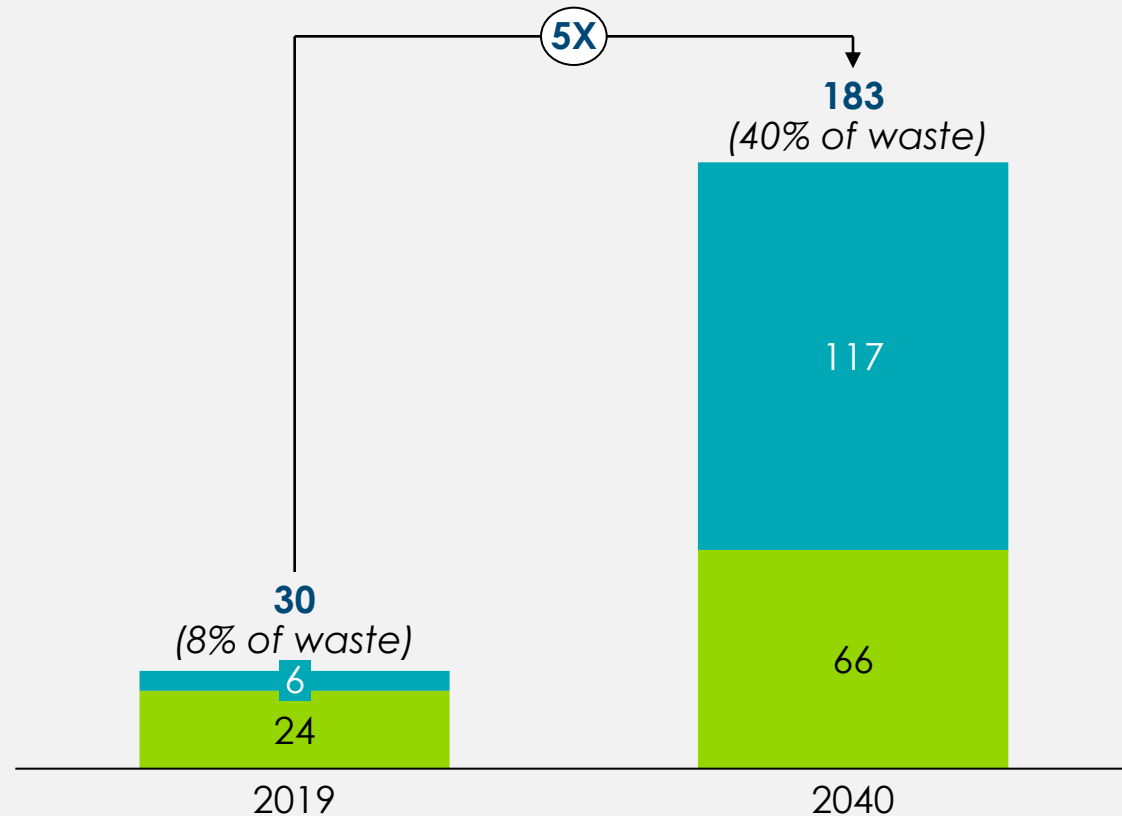
Source: Systemiq (2024) Plastic Treaty, BAU

Mechanical recycling of plastic material has economic challenges and technical limitations, but could increase under the right policy support




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.

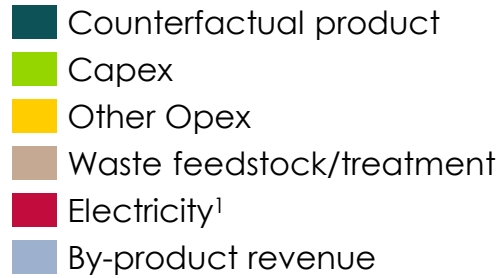
Chemical recycling could be complementary to mechanical recycling, but will need to overcome business case and reliable feedstock challenges

Levelised cost of production
\$/tonne (2025)

Depolymerisation
(PET)

Gasification (methanol
synthesis)

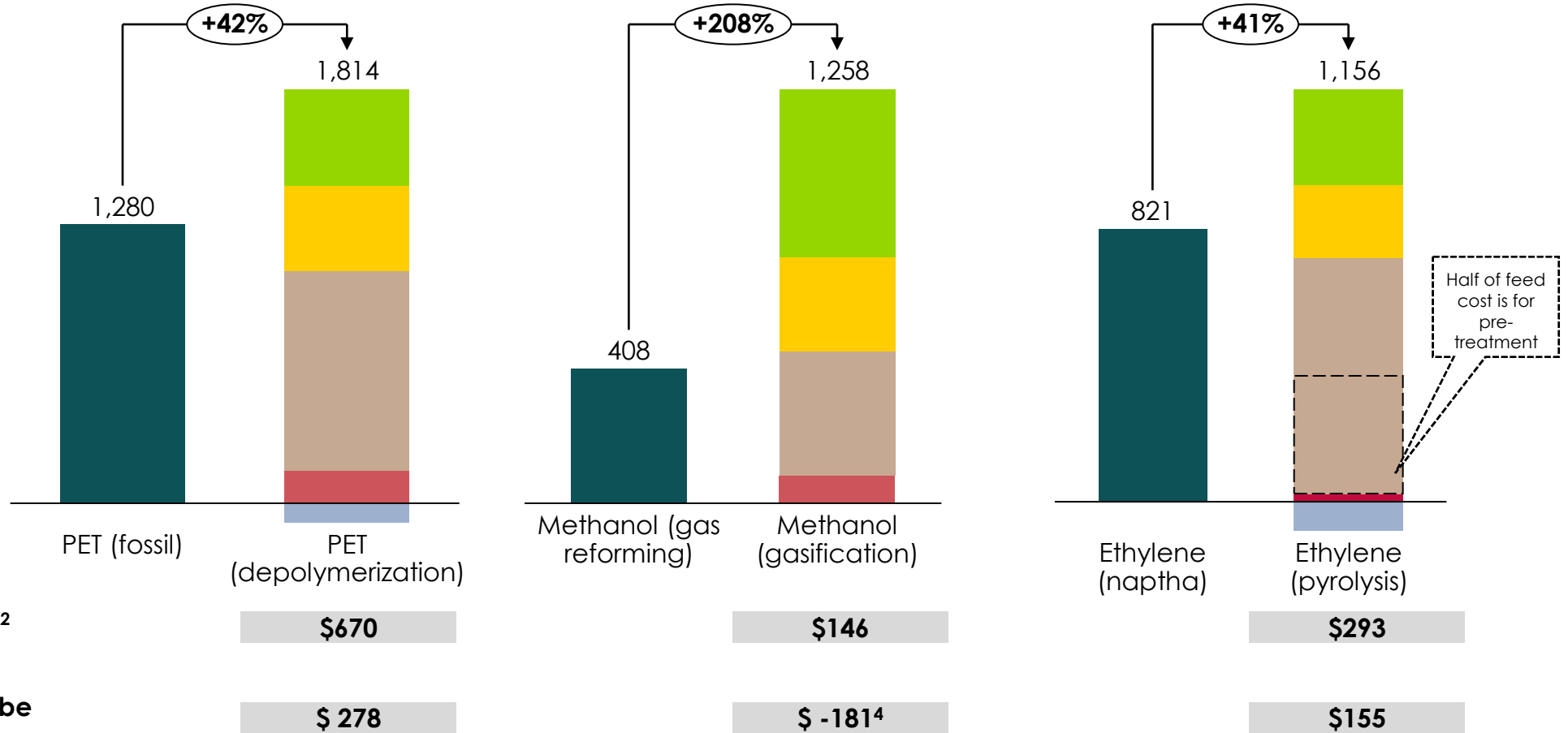
Pyrolysis
(ethylene cracking)



Beyond cheaper feedstock, cost parity could be achieved via incentives such as tax on incineration or credits for taking waste that would otherwise go to landfill

Feedstock cost assumed²

Feedstock cost needed to be competitive³



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

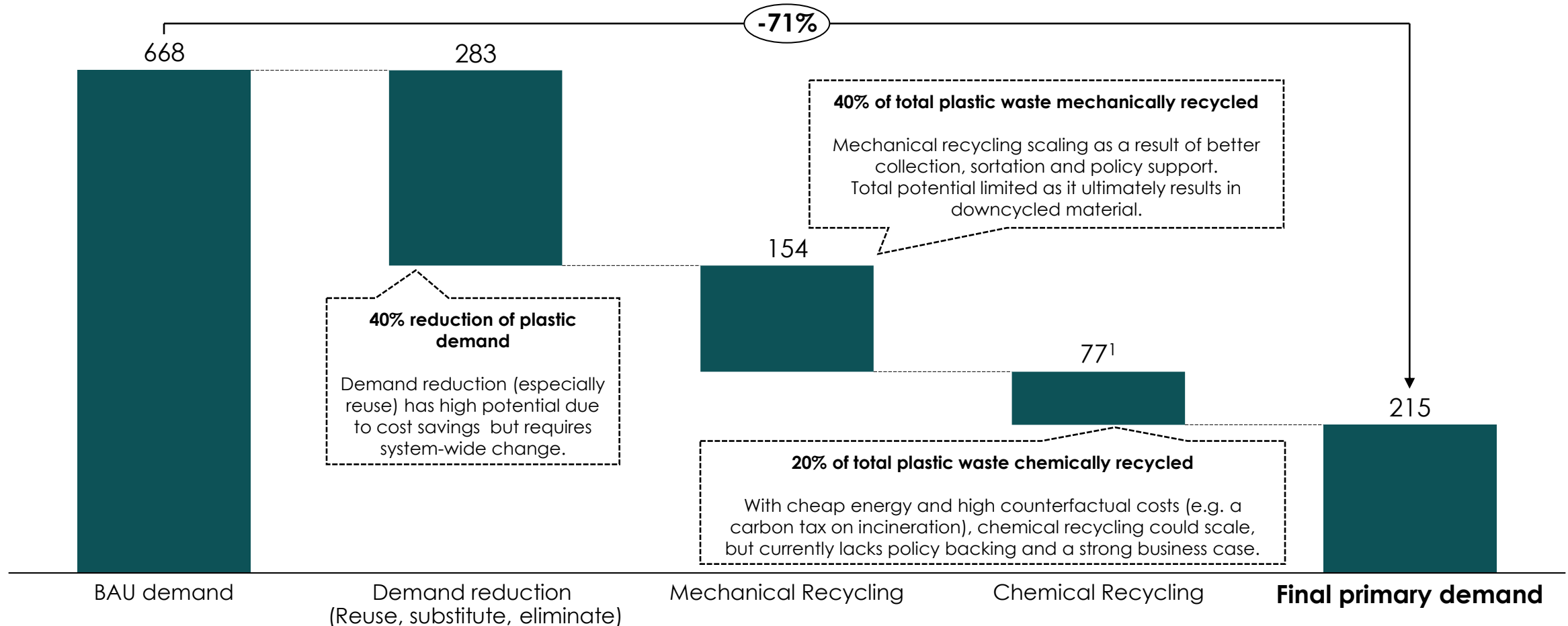
Notes: 1) Assumes baseload PPA power (~\$60/MWh). Midpoint of lower bound (~\$40/MWh) for low-cost H2 production region (Spain) and upper bound (~\$80/MWh) for high-cost region (Germany). 2) Gasification can take a variety of feedstocks from Municipal solid waste, mixed plastics are feedstocks for pyrolysis, cleaned PET flakes are feedstocks for depolymerization 3) Includes feedstock treatment costs 4) Negative feedstock cost required to make gasification competitive, as the main cost component with is capital costs



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

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) Upper bound estimate based on Systemiq reports and Chemical Recycling in a circular perspective (2023)

Phase 3 focus: Sustainable sources of carbon atoms and managing end of life carbon

Integration in broader carbon molecule project

































Having understood how maximum electrification and circularity of carbon to reduce reliance on primary carbon molecules, the last phase of work focuses on how we can meet the remaining demand for carbon molecules and manage end of life carbon

	2024		2025	
	Q4	Q1	Q2	Q3
Workplan	<p>Phase 1A How large can and should the role of direct electrification be in a zero-emission economy</p> <p>Phase 1B The role of hydrogen and derivatives (i.e., ammonia) in a zero-emission economy?</p>	<p>Phase 2 The potential to recycle and reuse carbon molecules</p>	<p>Phase 3 Sources of primary carbon: costs and sustainability and end-of life carbon management</p>	<p>Phase 4 Report production and communication campaign running into COP30</p>
Deliverables	<ul style="list-style-type: none"> A 5-pager published externally A series of short innovation briefs for publication 	<ul style="list-style-type: none"> A 5-pager published externally Report chapter Innovation brief(s) 	<ul style="list-style-type: none"> A 5-pager published externally Report chapter Innovation brief(s) 1-2 workshop with ETC reps/ commissioners 	<ul style="list-style-type: none"> Publication of the ETC report ahead of COP A series of short innovation briefs for publication Workshop Report reviews Report launch at COP
Key interactions	<ul style="list-style-type: none"> 1-2 workshops with ETC Commissioners 	<ul style="list-style-type: none"> 1-2 workshop with ETC reps/ commissioners 	<ul style="list-style-type: none"> 1-2 workshop with ETC reps/ commissioners 	<ul style="list-style-type: none"> Workshop Report reviews Report launch at COP



Multiple disruptions were explored on how we can effectively and sustainably source primary carbon

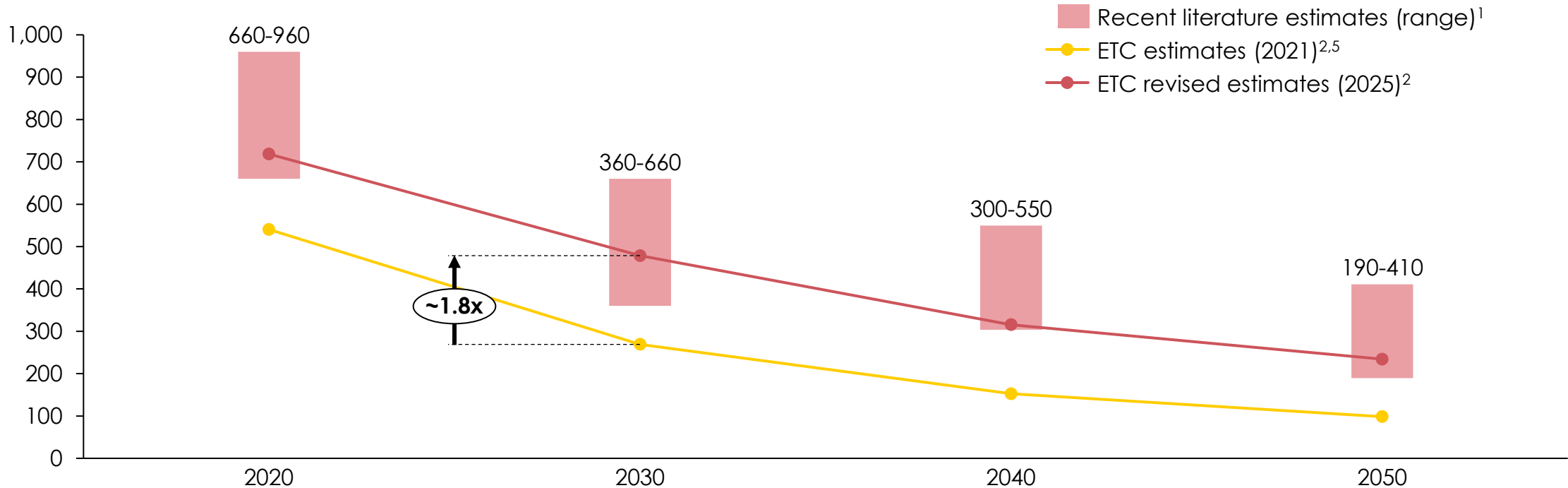
In focus today

Carbon source 	Technology disruption 	TRL 	Companies 
Direct Atmospheric	1 Direct air capture (advancements)	5-9	  Heirloom 
	Oceanic	2 Ocean based CDR	5-6
Biomass	3 Energy cane (incl degraded land)	6-9	   
	4 Alternative proteins	3-8	   
	5 Macro and Micro algae	7-9	   
	6 Advanced reactors and catalysts	6-9	   
Ground (fossil and limestone)	7 Carbon capture - Liquid/solid absorption (advancements)	7-9	    
	8 Carbon capture - Process modification	7	 
	9 Carbon capture - Calcium looping	6-7	 



1 Recent estimates of levelised cost of DAC are higher than previously predicted, which could hinder the technology's scale-up in the long-term

Levelised cost of CO₂ capture via DAC – projections 2020-2050
\$/tCO₂ (real 2025)



Key take-aways

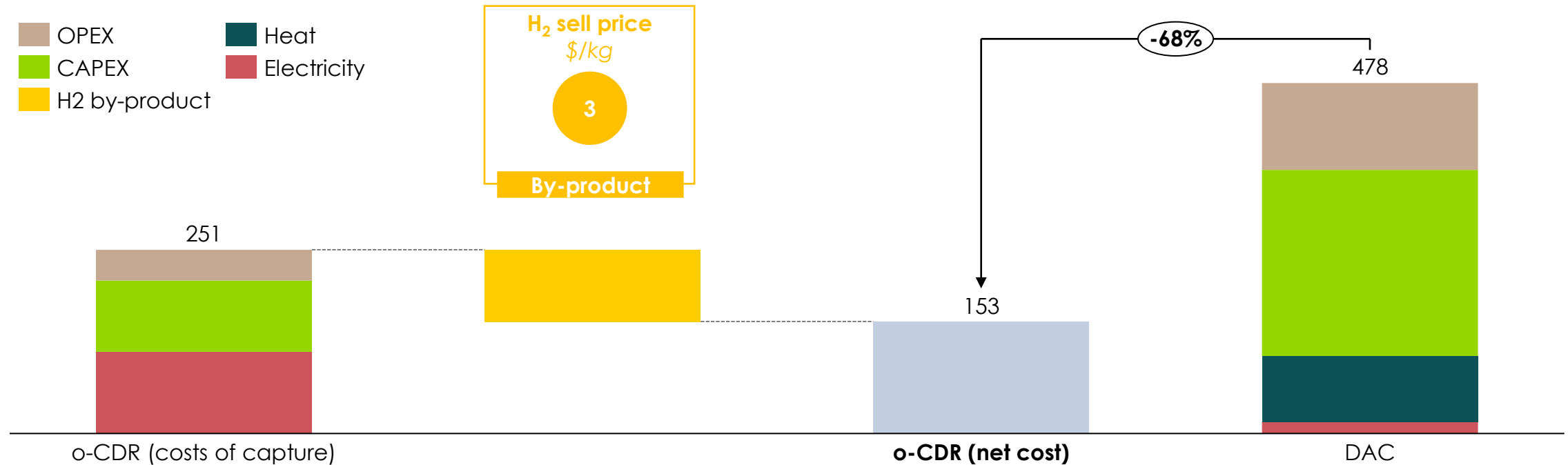
- Historical DAC cost projections have been optimistic with lower-than-realised capital costs and ongoing energy costs^{3,4}
- Recent credible publications predict higher costs of DAC until 2050¹, which could hinder the technology's scale-up

Sources/notes: 1) 2020 and 2030 estimates: Lorenzo Sani (2024) Bridging the gap between the UK's CCUS targets and reality. 2040 and 2050 estimates: Katrin Sievert et al. (2024); Manon Abegg et al. (2024); 2) Levelised cost of DAC refers to a fully electrified DAC system for 5,000 full load hours per annum. Assumes weighted average cost of capital of 7% and plant lifetime of 20 years, growing to 30 years by 2050. 3) Reality check on technologies to remove carbon dioxide from the air (MIT Energy Initiative, 2024). 4) Carbon Removal's Holy Grail Cost Cut Is Further Away Than It Seems (Bloomberg, 2024). 5) Adjusted for inflation (2025 real US dollars).

2 o-CDR is an emerging way to access oceanic carbon, and could become more economical than DAC by ~70%

Levelised cost of CO₂ capture for direct air and direct water capture in 2030

\$/tCO₂



Key takeaways

- Lower capex requirements and H₂ by-product could make o-CDR more economical than DAC. H₂ is only produced in electrolytic o-CDR routes that involve electrolysis
- Both DAC and o-CDR have high cost and scale-up risk, but DAC's stems from sorbent and thermal system uncertainty, while **o-CDR's depends on electrolyser cost** and renewable energy access.

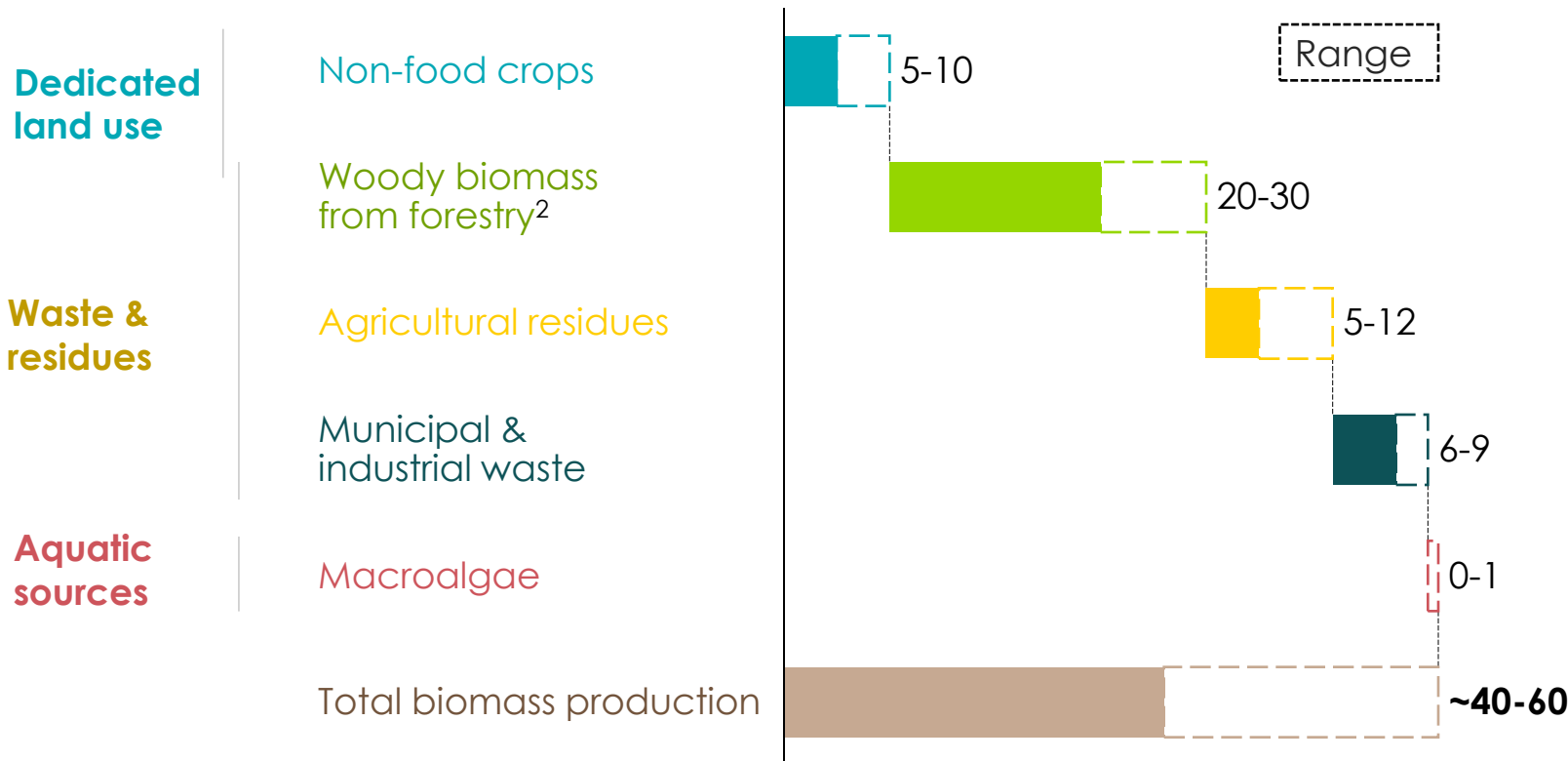
Notes: Uses electricity cost of \$50/MWh, electrolyzer utilization factor 50%, plant capacity of 110,000 tons Co₂/y, H₂ production of 3,600 tons H₂/y. Sources: 1) Patent US20220040639A1, 2) <https://www.equatic.tech/articles/equatic-to-build-north-americas-first-commercial-scale-ocean-based-carbon-removal-facility>

Bioresources – ETC has previously estimated prudent global supply of sustainable biomass at ~40-60 EJ/year, but disruptive innovation could change this

Global sustainable biomass¹ supply (2050) – illustrative scenario
EJ/year (primary energy)



Extra bioresource if radical change can happen



More productive land

In focus

More productive plants (traditional crops, algae) – **example Energy cane**

More available land

Dietary shifts from animal based-protein – **example Alternative proteins**

Less food waste

New sources

Development of macroalgae

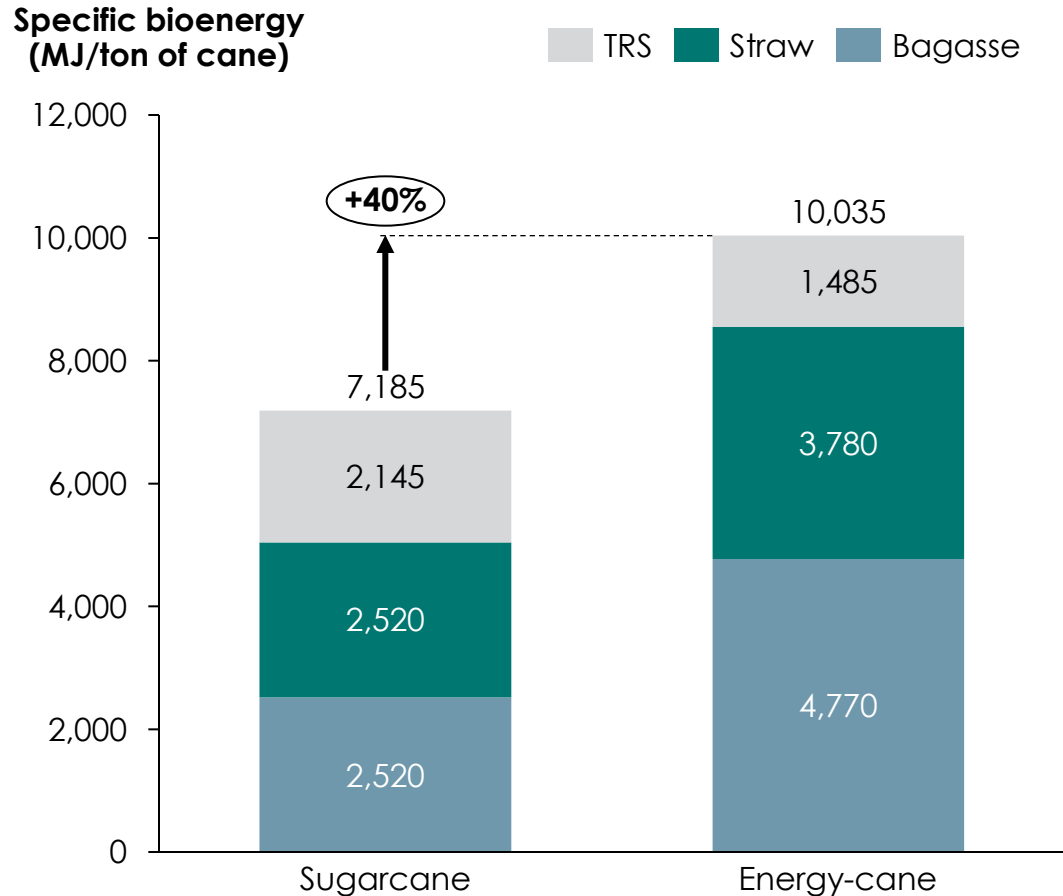
Increased collection to organic waste

Notes: The term 'sustainable biomass' is used to describe organic material that is renewable, has a lifecycle carbon footprint equal or close to zero (including considerations for the opportunity cost of land), and for which the cultivation and harvesting practices used are mindful of ecological considerations such as biodiversity and health of the land and soil. (2) Includes high-quality stemwood from forestry suitable for the timber and pulp & paper sectors (~10 EJ/year today, FAO Industrial Roundwood production less by-products used for energy). This category also includes residues from forestry but excludes traditional fuelwood (~25 EJ/year today, assumed to reduce with modernisation) due to collection and sustainability assurance challenges. (3) E.g., timber, pulp & paper. Based on current harvests from commercial forestry; additional high-quality stemwood could be made available if freed up land were dedicated to forestry. (4) Additional supply from recycled materials (~4 EJ/year today). Source: Systemiq analysis for ETC (2021).



3 4 Energy cane and alternative proteins are potential innovations where higher biomass supply could be realized

Energy-cane is a variety of sugar-cane that boosts primary bioenergy per kg of cane, as the higher energy content components (bagasse and straw) are maximized¹



Alternative protein technology can ease constraints on sustainable biomass supply by freeing up land used for animal feed and grazing

Innovations	Goal	Use case	Examples
Biomass fermentation (BF)	Produce whole protein-rich biomass	<ul style="list-style-type: none"> • Base ingredients in meat-like foods • e.g., mycoprotein (Quorn), fungal burgers 	
Precision fermentation (PF)	Make specific molecules for use as ingredients	<ul style="list-style-type: none"> • Functional ingredients for food production • e.g., egg white for baking, casein, rennet 	
Cultivated meat (CM)	Grow real meat tissue from animal cells	<ul style="list-style-type: none"> • Cuts of meat including muscle, fat and tissue • e.g., beef steaks, chicken breasts 	

Notes: 1) TRS (Total Recoverable Sugar): energy content = 16.5 MJ/kg (assuming TRS is composed only of saccharose), Bagasse calorific value = ~18 MJ/kg (dry); Straw calorific value = ~18 MJ/kg (dry). Middle values for composition taken from the comparative table. Sources (left): Sources: Silva, A. C. M. S (2018) Estudo da influência da umidade do bagaço da cana de açúcar na produção de energia em plantas de cogeração; Marques, T.A, Pinto, L. E. V (2013) Biomass energy from sugarcane under influence of hydrogel, vegetation cover and planting depth; Neves, L. C. G (2015) Biomass energy from sugarcane under influence of hydrogel, vegetation cover and planting

Crops such as 'energy cane' only have potential if cultivated on degraded or freed land, sparing housing, food, natural habitat, and climate needs

Options for 'new' land for sustainable biomass



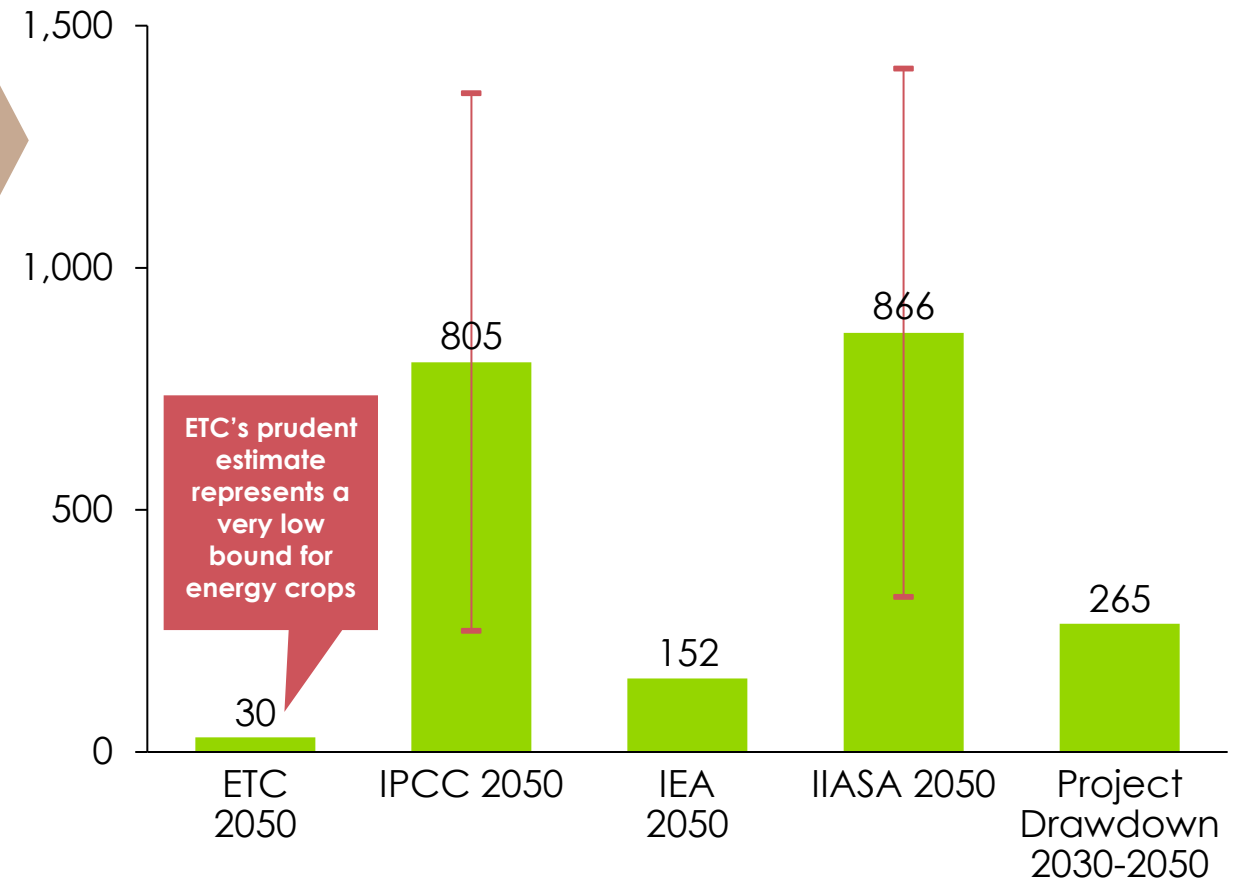
Still to be assessed:
potential perverse incentives created by being able to plant energy crops on "degraded land"

Use of degraded or marginal land for energy crops, and not competing with food requirements



Energy crops cultivated on land which is freed up through system change, including dietary shifts, higher yields and reduction in food losses

ETC's previous estimate for ha of degraded land for biomass use was conservative, Millions of ha

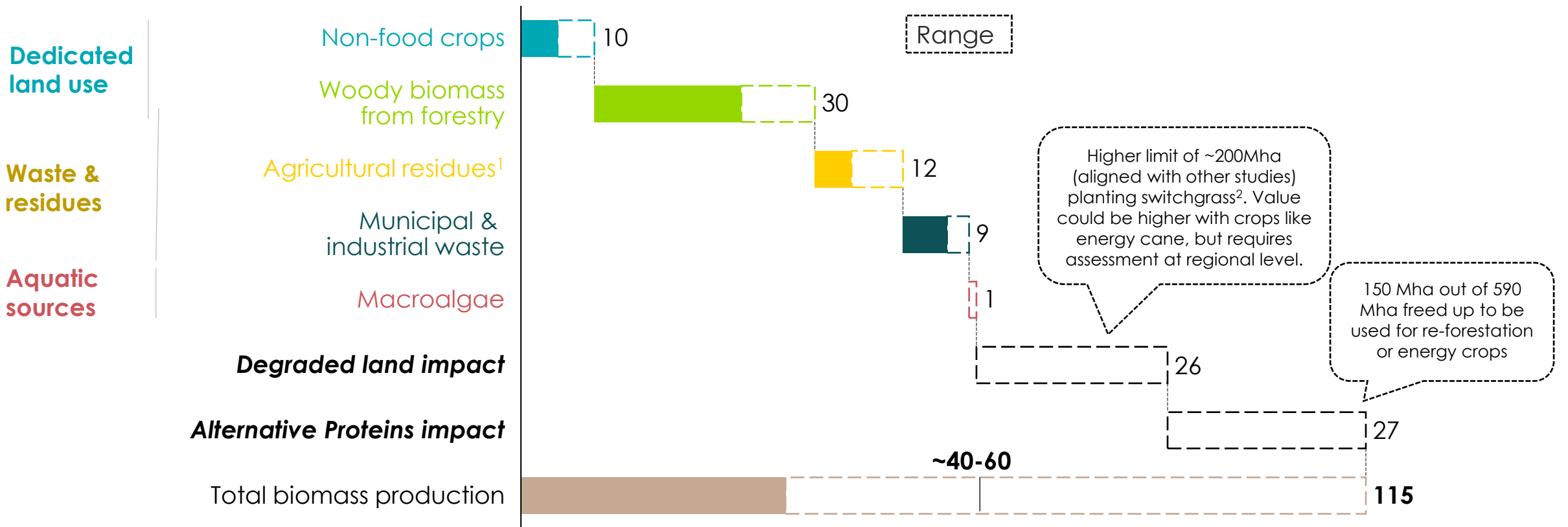


Sources: Food and Land-Use Coalition (FOLU) (2019) Growing Better, Global Environmental Facility (GEF) (2017) GEF-7 Replenishment Programming Directions, Potsdam Institute for Climate Impact Research (PIK) (2024) Transforming land management within planetary boundaries key to addressing global land use crisis. United Nations Convention to Combat Desertification (UNCCD) 2021 by Van der Esch et al The global potential for land restoration: Scenarios for the Global Land Outlook 2. PBL Netherlands Environmental Assessment Agency, The Hague. Food and Land Organization (FAO) 2024 Restoration of degraded agricultural lands.; IPCC (2022) Climate Change 2022: Mitigation of Climate Change; IEA (2024) Bioenergy



Innovations explored could increase the bioresources maximum potential scenario

Global sustainable biomass supply (2050) – illustrative scenario with prudent estimates and potential range of biotech innovation, EJ/year (primary energy)



Notes:1) Agricultural residues revised through a numerical approach by analyzing residues from top 10 most harvested crops. From total unprocessed residues, 70% are left on ground and a recoverability of ~50% is assumed. Production from 2023 is taken and extrapolated to 2050 using the same CAGR for the 2003 – 2023 period. 2) Switchgrass considered as a standard energy crop which is easy to grow across a wide variance in climates yielding 180 GJ/ha.
Sources: Systemiq Analysis (2025) using FAO data, ETC analysis; ETC (2021), Bioresources Within a Net-Zero Emissions Economy: Making a Sustainable Approach Possible.



Next steps



Calculate and compare a **scenarios** for primary supply sourcing



Explore the **trade-offs** between different scenarios



Develop **innovation briefs** on key technologies



Report draft to members in the summer

