Energy
Transitions
Commission

Emerging insights from the ETC's analytical work programmes

ETC Commissioners meeting

26 June 2025

Agenda

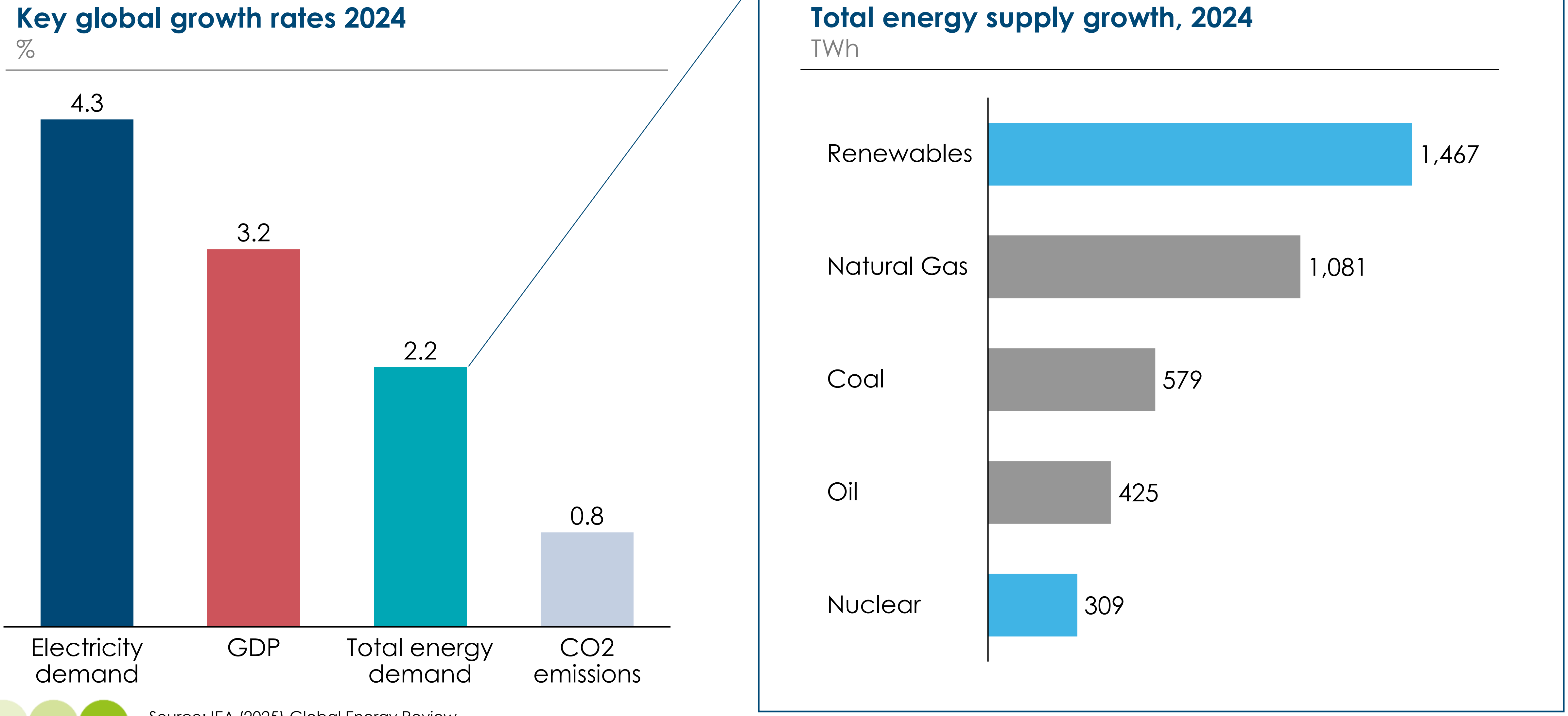
Evolution of energy demand: a growing, more efficient energy system dominated by electricity

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

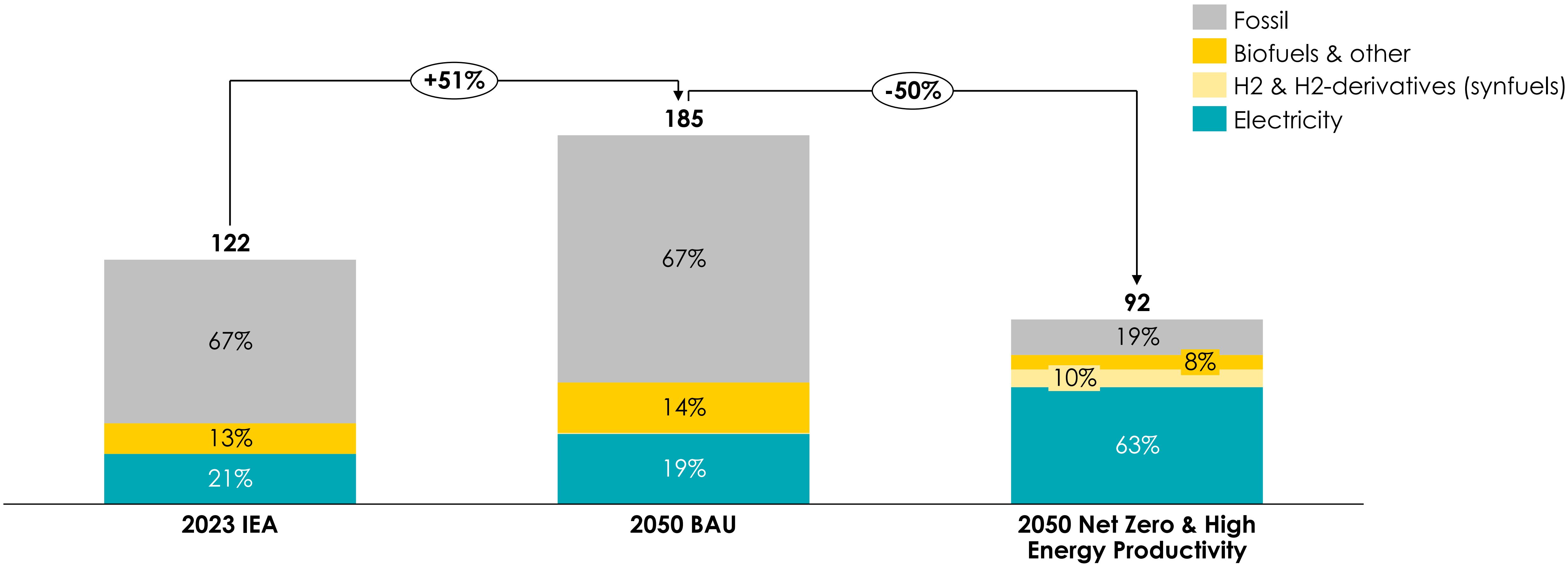


Source: IEA (2025) Global Energy Review

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

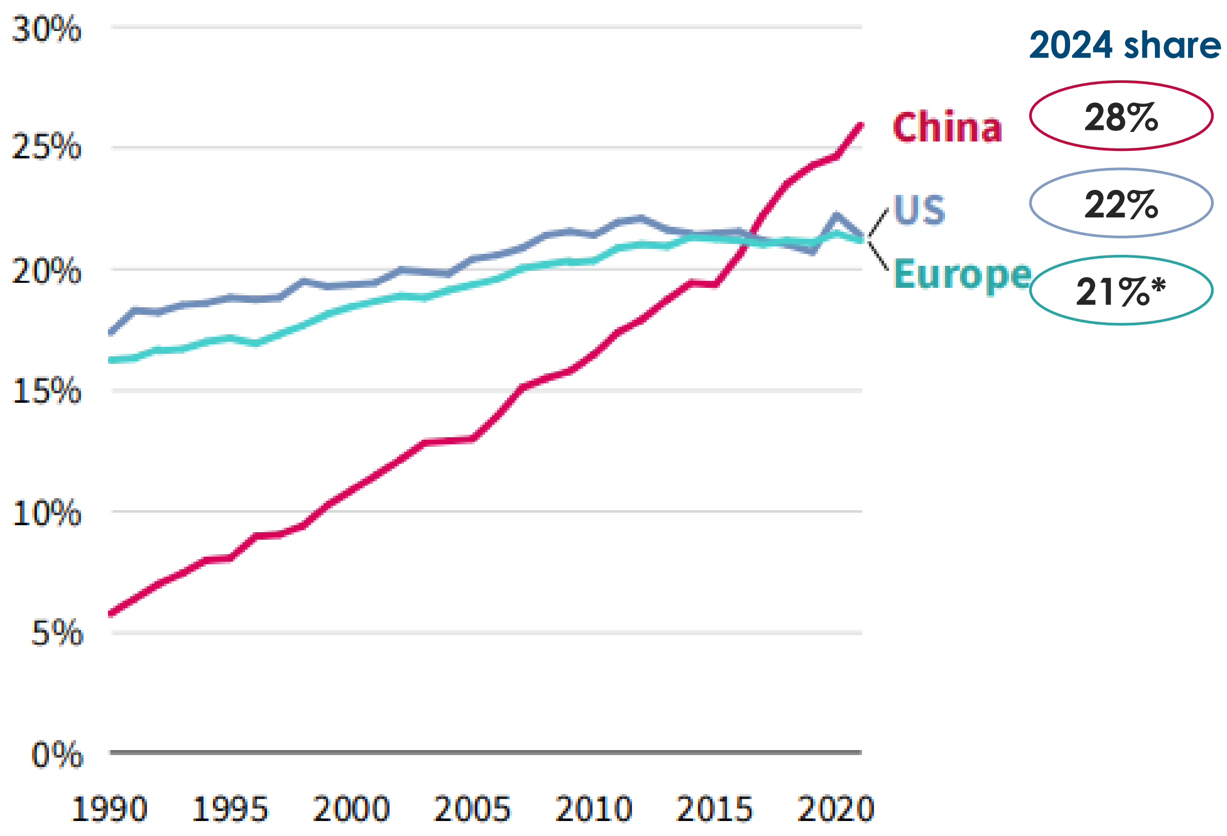
000 TWh



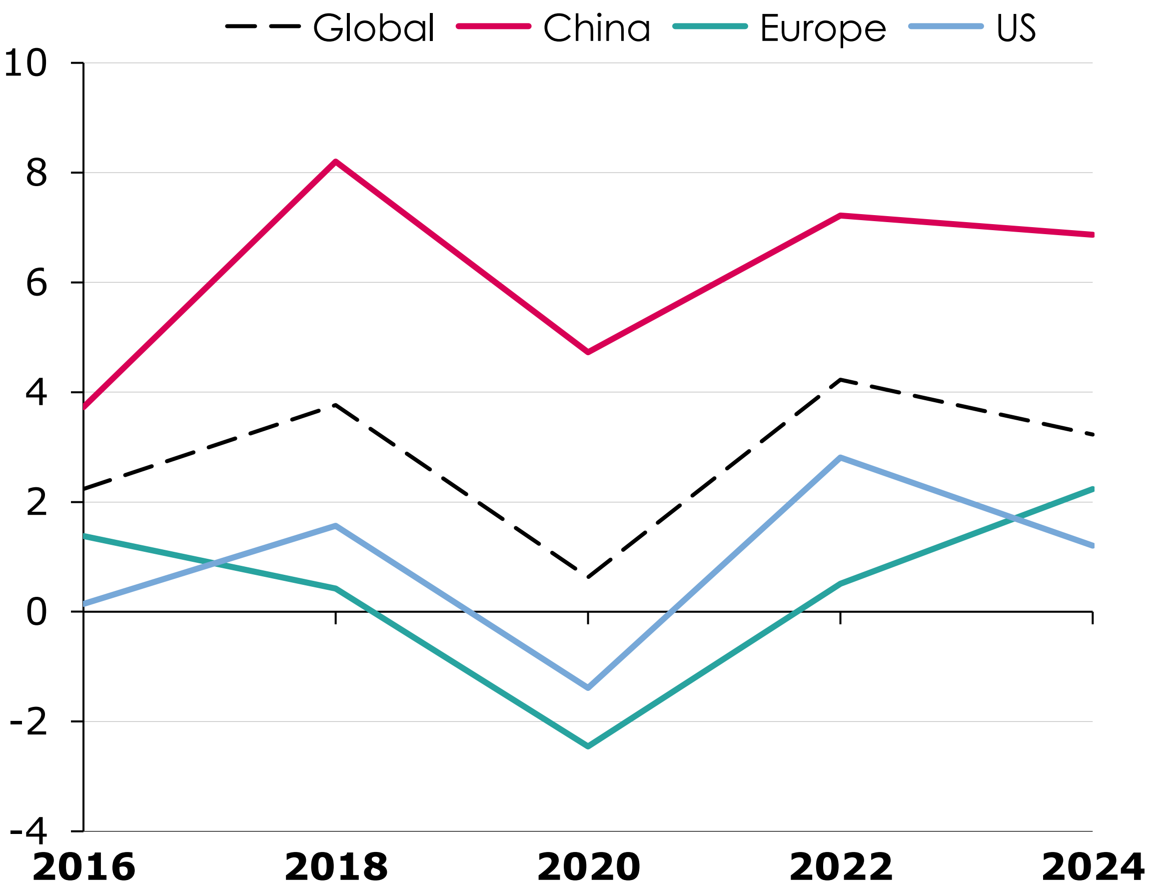
Source: IEA (2025) World Energy Outlook; MPP (2023) Hard-to-Abate Sector Transition Strategies; ETC (2025) Achieving Zero-Carbon Buildings; ETC(2023), Fossil Fuels in Transition; BNEF (2023) Vehicle Outlook; Systemiq analysis for ETC.

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)

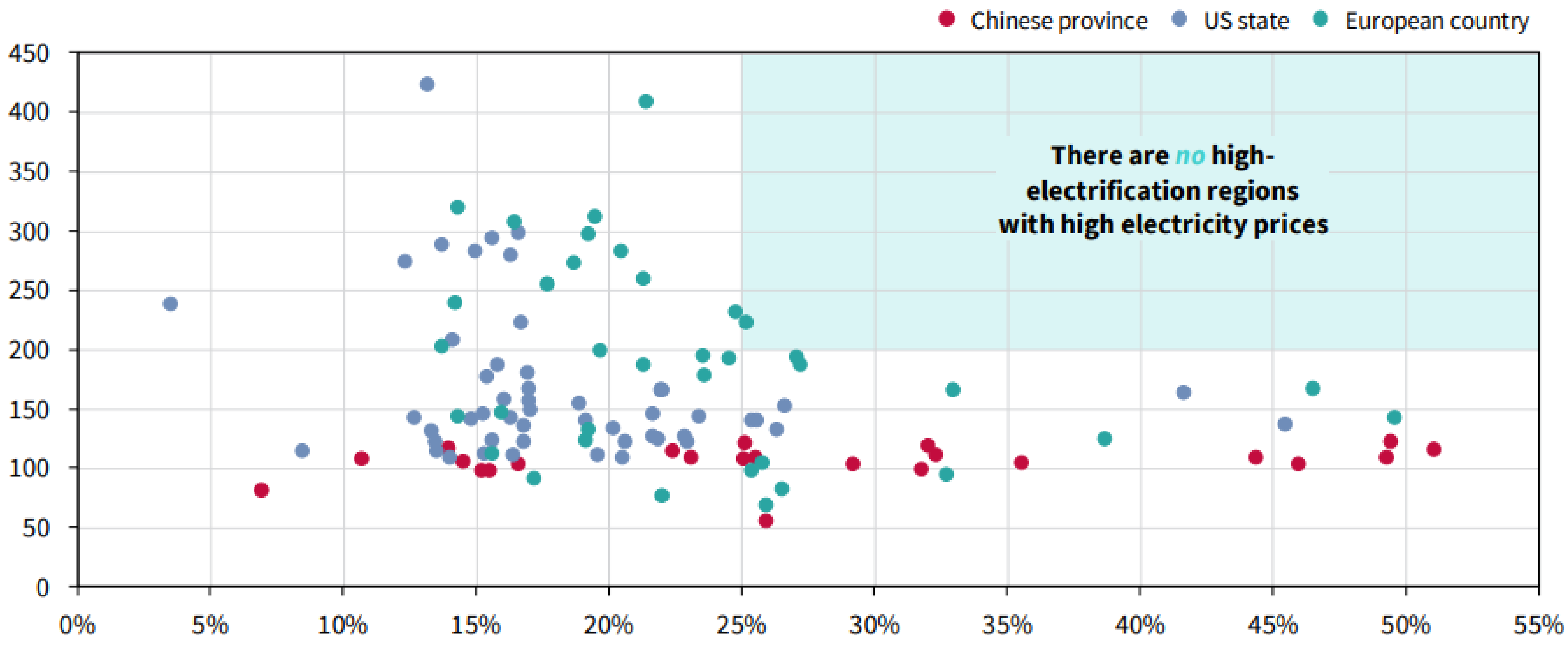


* For European Union
Source: Our World in Data, Ember, RMI, IEA (2025) Electricity 2025, Sources: BNEF (2025), *New Energy Outlook*, Ember (2025), *Global Electricity Review 2025*

Addressing electricity costs will be critical – no geography with high electrification has high energy prices

RMI analysis on consumer electricity price vs. electrification rate

USD/MWh (vertical); % of final energy consumption from electricity (horizontal)



Source: RMI (2024) Inside the Race to the Top

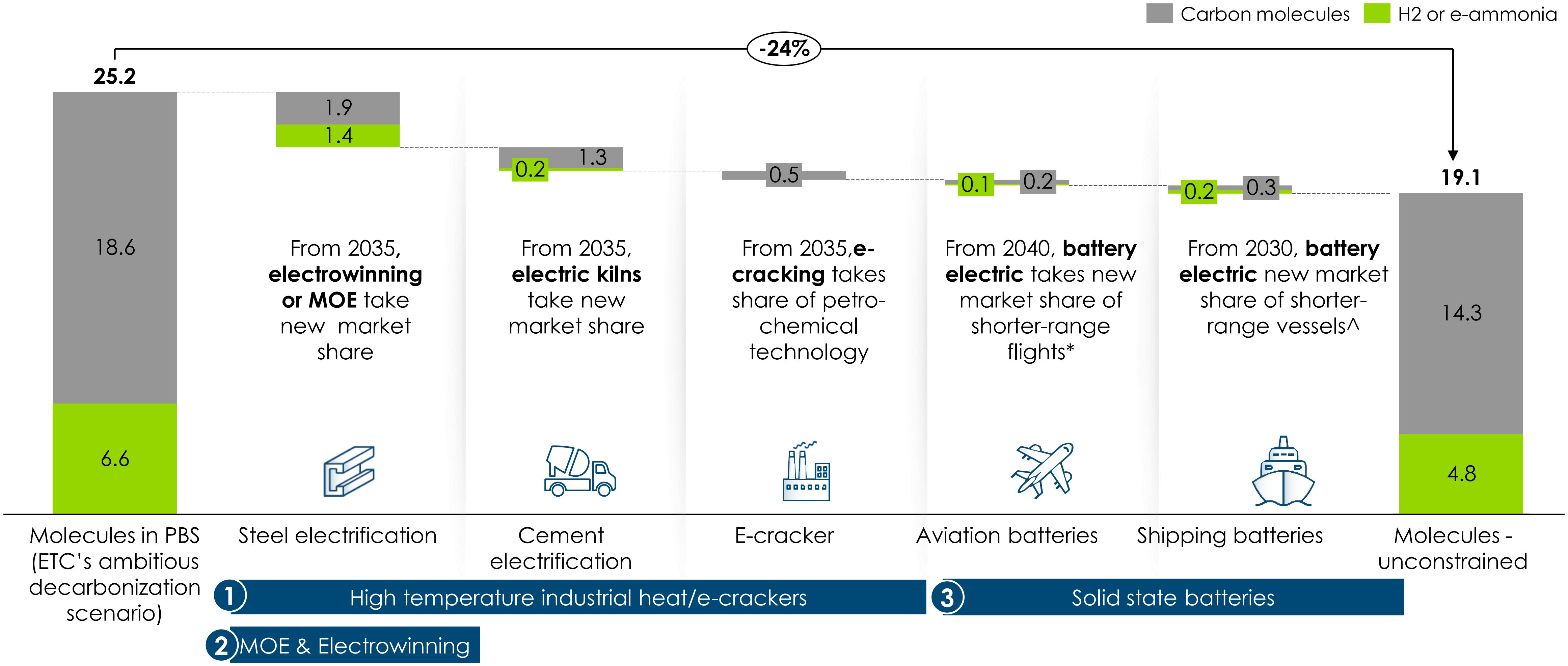
Three disruptions could reduce reliance on carbon molecules in the energy system, increasing the potential for electrification

Technology disruption	Sectors impacted		TRL	Companies
1 **Industrial heat electrification (>600°C), including e-crackers for chemicals**	(Heavy-) industry (cement), chemicals		6-9	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 ELEMENTZERO electra
3 **Li-ion solid state batteries**	Trucking	Shipping	7	CATL TOYOTA CALB Solid Power BYD LG Chem QuantumScape
	Aviation			

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)

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



From 2035, **electrowinning or MOE** take new market share

From 2035, **electric kilns** take new market share

From 2035, **e-cracking** takes share of petro-chemical technology

From 2040, **battery electric** takes new market share of shorter-range flights*

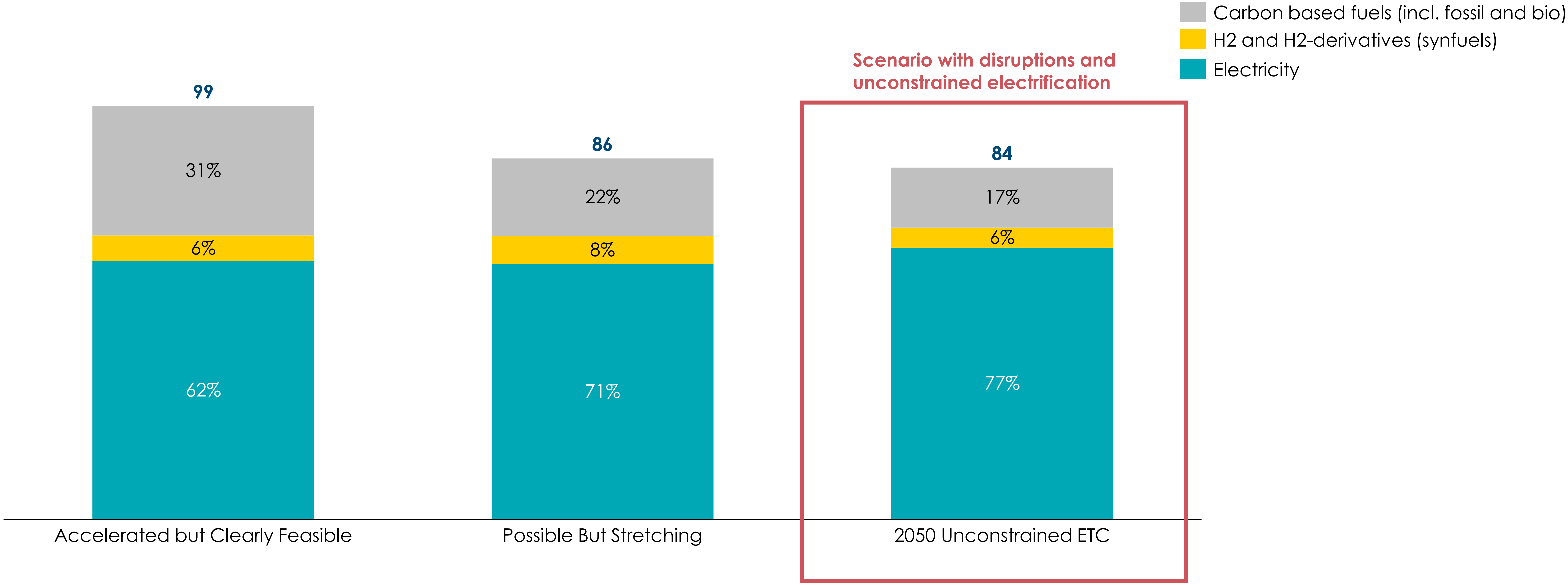
From 2030, **battery electric** new market share of shorter-range vessels^

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



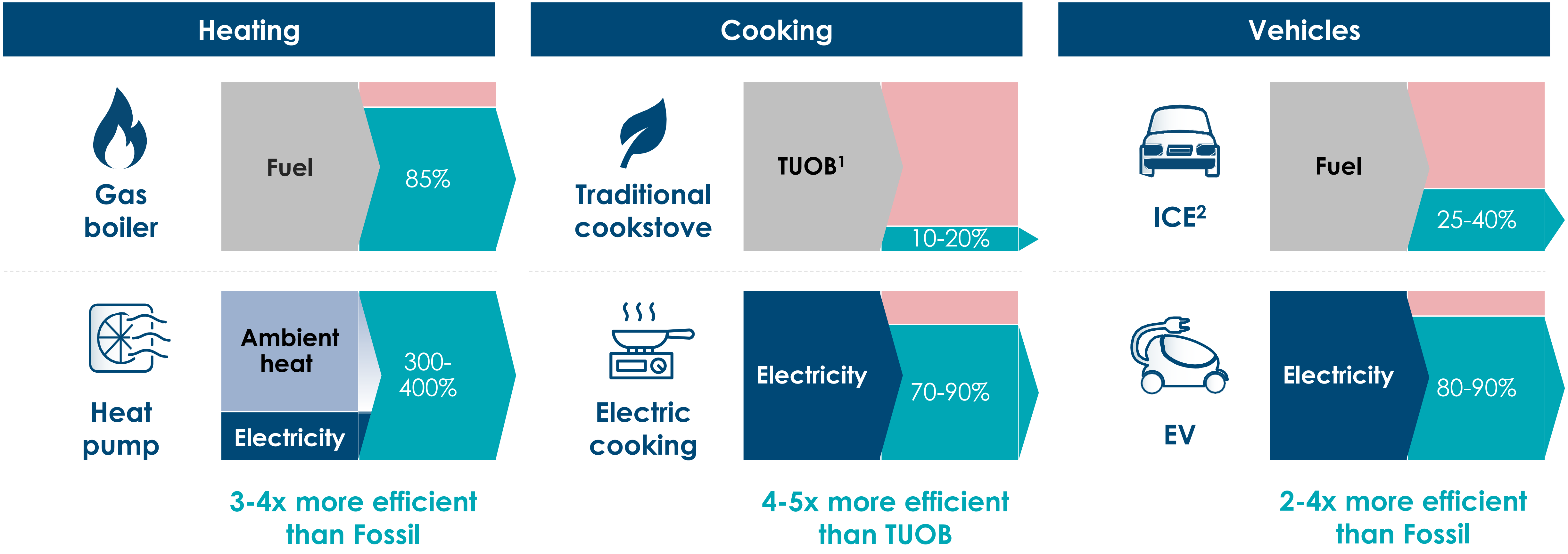
Note: STEPS = Stated Policies; ACF = Accelerated but Clearly Feasible; PBS = Possible but Stretching; *Remainder of electricity demand based on ACF scenario demand. CCS power assumes 30% energy penalty to power capture unit

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



Heating

Gas boiler

Fuel → 85%

Heat pump

Ambient heat + **Electricity** → 300-400%

3-4x more efficient than Fossil

Cooking

Traditional cookstove

TUOB[1] → 10-20%

Electric cooking

Electricity → 70-90%

4-5x more efficient than TUOB

Vehicles

ICE[2]

Fuel → 25-40%

EV

Electricity → 80-90%

2-4x more efficient than Fossil

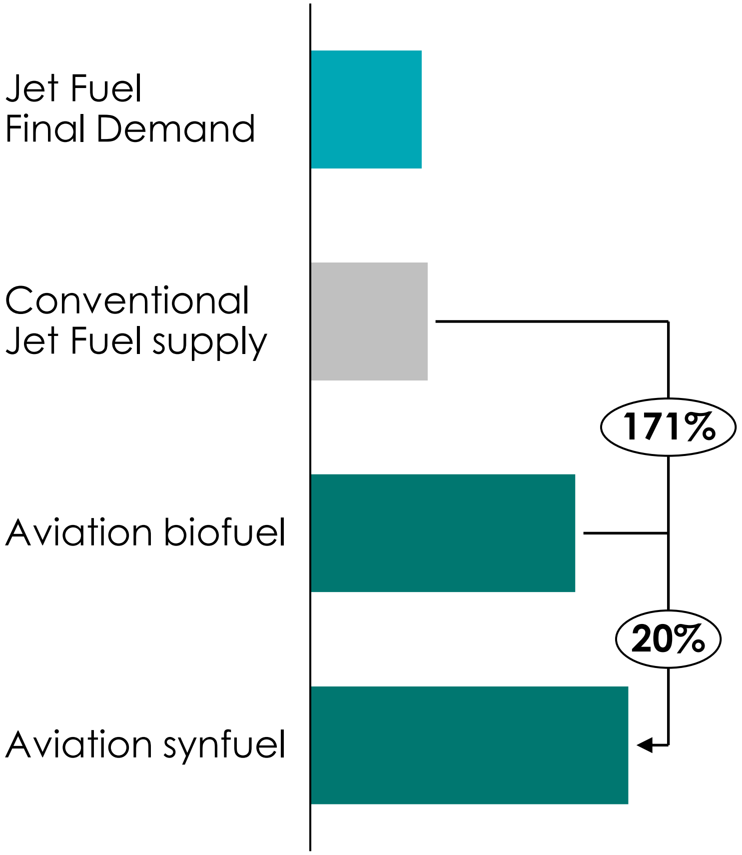
---

1. Traditional use of biomass; 2. Internal combustion engine

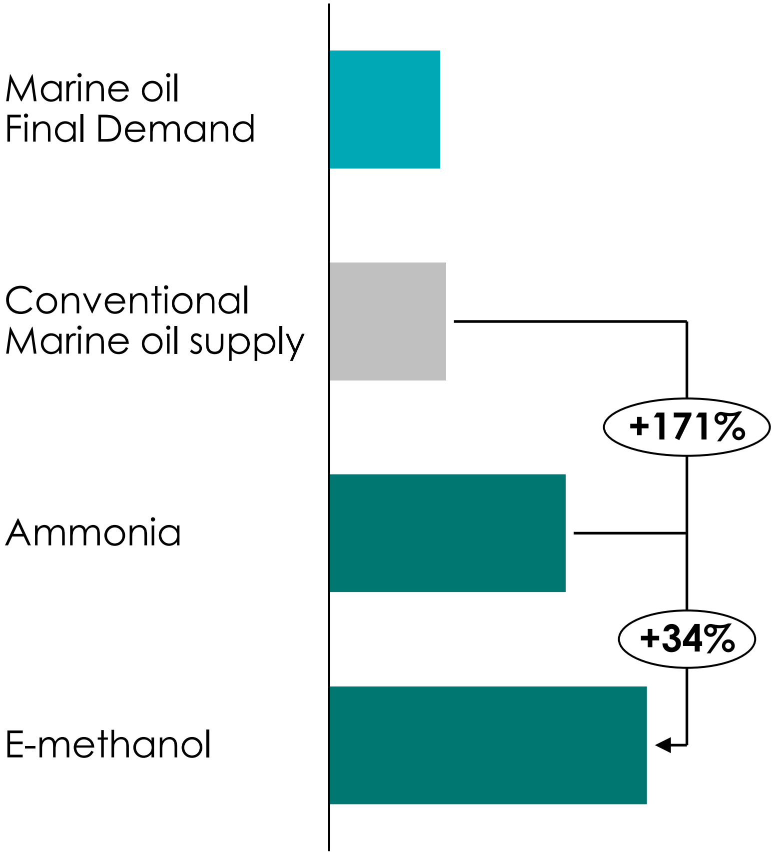
Source: RMI (2024), *Clean Tech Revolution.*

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

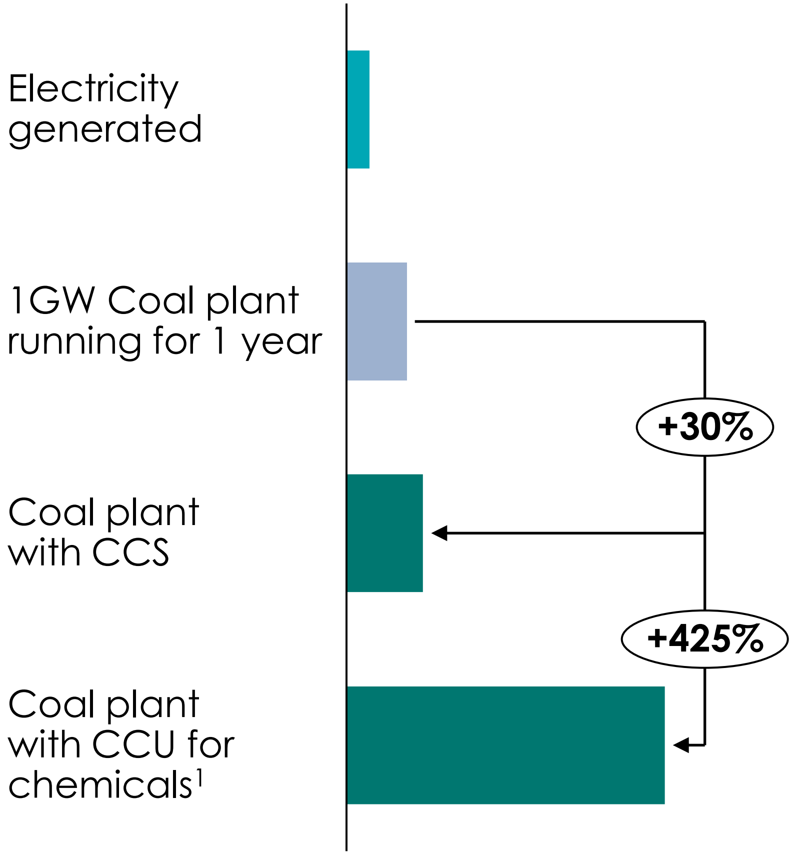
Aviation Case Study
TWh



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 CO_2 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

$$\frac{\Delta\, Energy\ productivity}{Energy\ productivity_{t-1}}\ (\%)$$

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

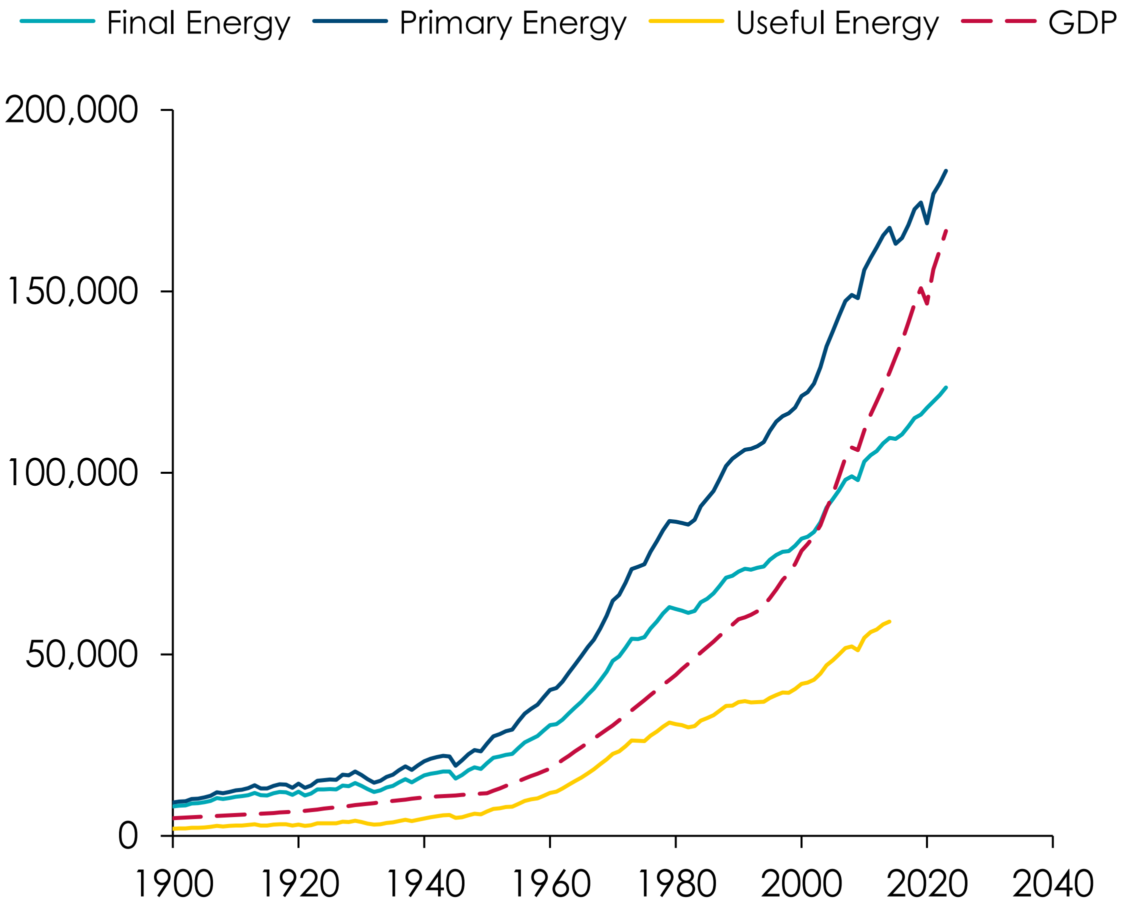
Target figure	Key lever		Guiding question	Reduced quantity	Example
Energy Productivity[1] (energy input per unit of GDP)	Technical energy efficiency		How can we decrease the energy input per (production) process?	Process energy	Shift to less energy-intense production technology (e.g. **electrification**), efficiency increase in incumbent technologies (e.g. **appliances, EVs, buildings insulation**), etc.
	Service efficiency	Demand 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 journey instead of airplane, road speed reduction)
		Product efficiency	How can we increase the utilization of the product?	Product	**Reuse** (e.g. reduce single use plastic), sharing of products, increased **product lifetime** (e.g. aluminum and steel 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 while maintaining specs of product (e.g. cement)

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

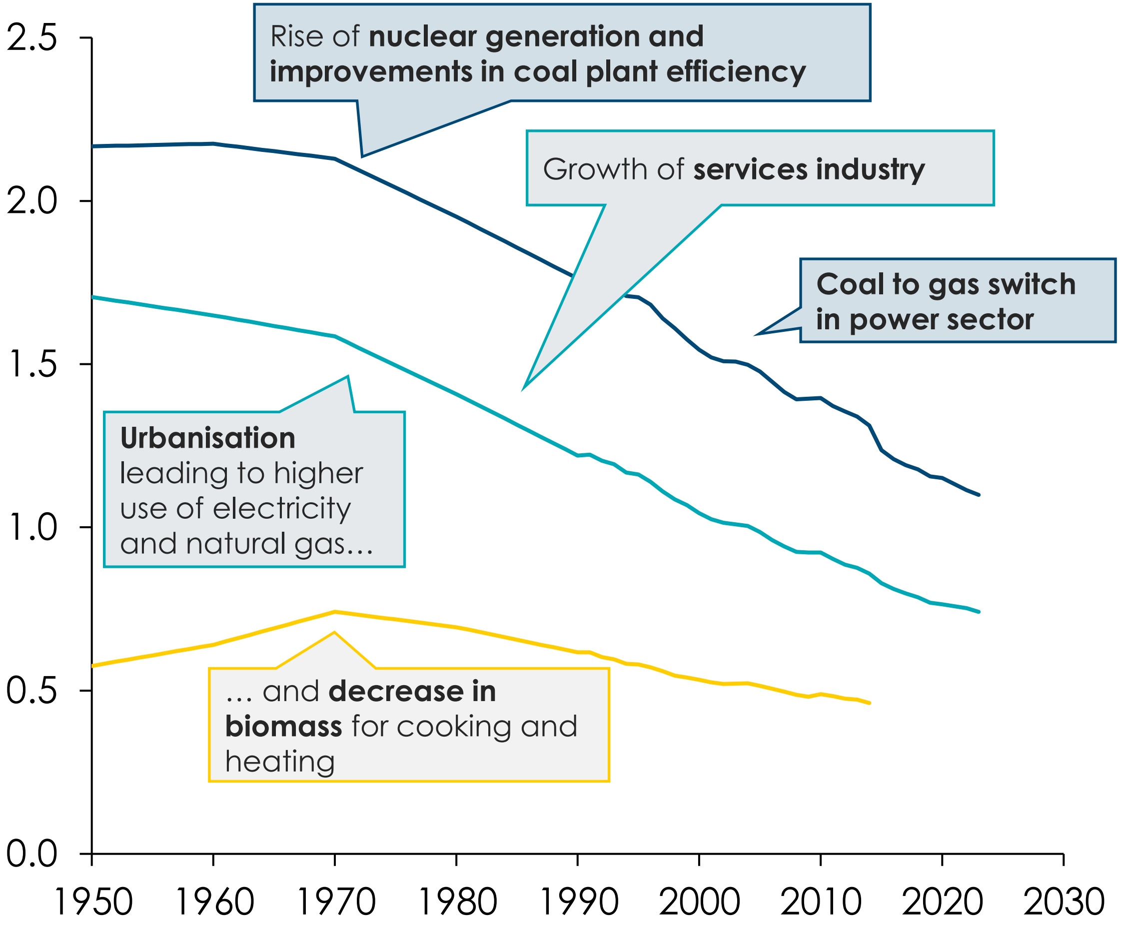
Total GDP vs. Energy Demand, 1900 - 2023

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



Energy Productivity, 1950 - 2023

kWh/$ 2021 PPP



Rise of **nuclear generation and improvements in coal plant efficiency**

Growth of **services industry**

Coal to gas switch in power sector

Urbanisation leading to higher use of electricity and natural gas…

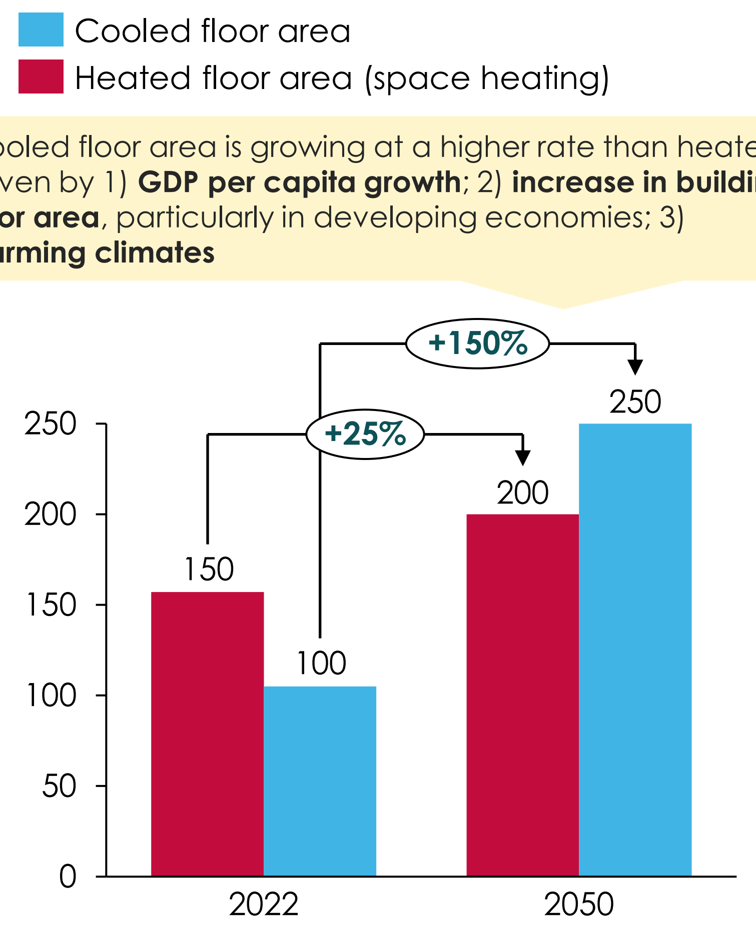
… and **decrease in biomass** for cooking and heating

Source: Systemiq analysis for the ETC; World Bank Group; Our World in Data; IEA (2024), *World Energy Outlook 2024; IIASA PFU Dataset*

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

Heated floor area vs. cooled floor area

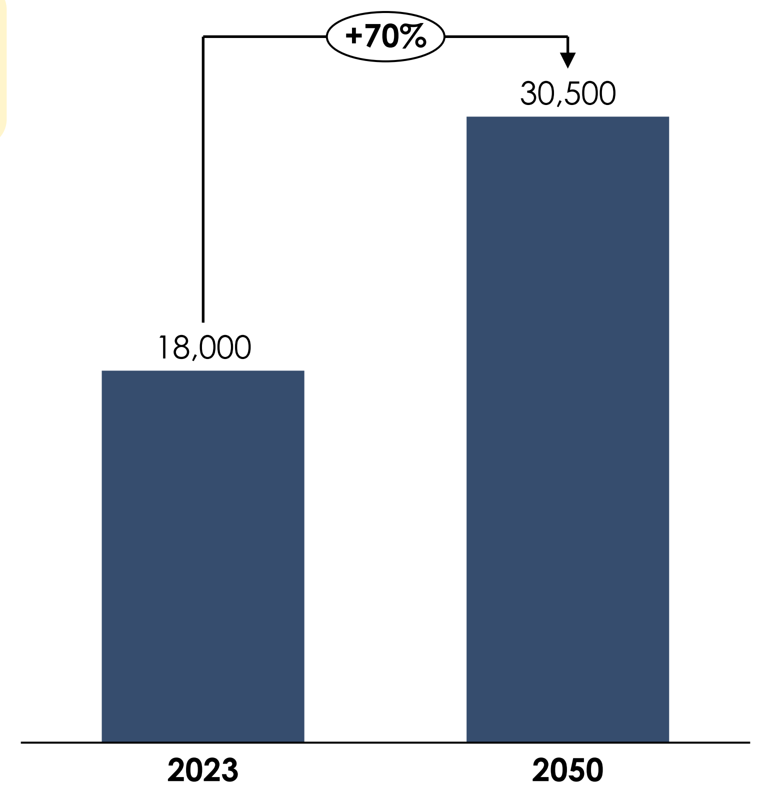
Billion m2; IEA NZE Scenario; residential + commercial



Cooled floor area 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**

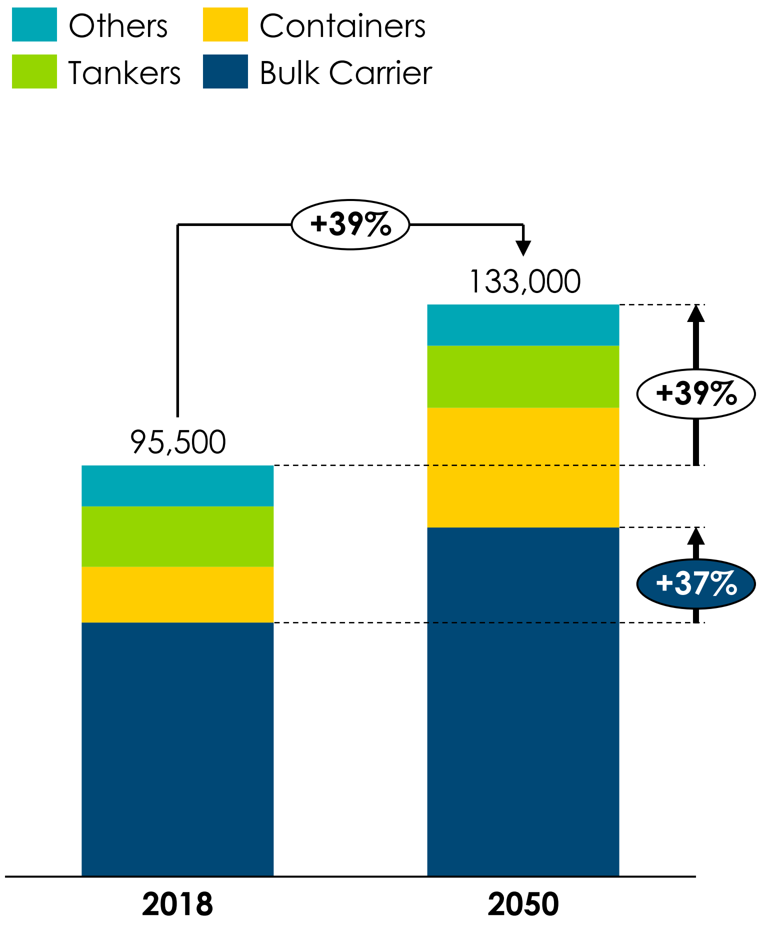
Demand for passenger road transport

Billions of km; ETC ACF scenario



Shipping demand

Billions-tonnes miles

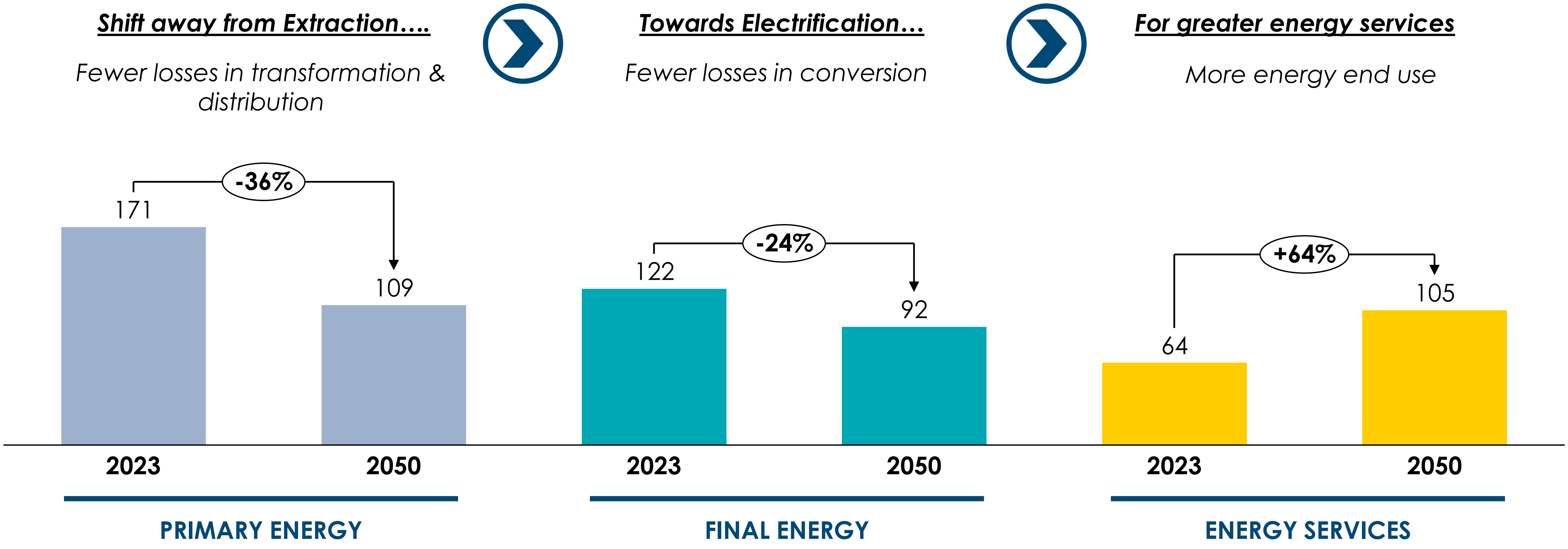


Source: IEA (2023), *World Energy Outlook 2023*; Systemiq analysis for the ETC (2023), *Fossil Fuels in Transition; Committing to the phase-down of all fossil fuels, available at* *https://www.energy-transitions.org/publications/fossil-fuels-in-transition/*; Maersk Mc-Kinney Moller Center for Zero Carbon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

Towards Electrification…

Fewer losses in conversion

For greater energy services

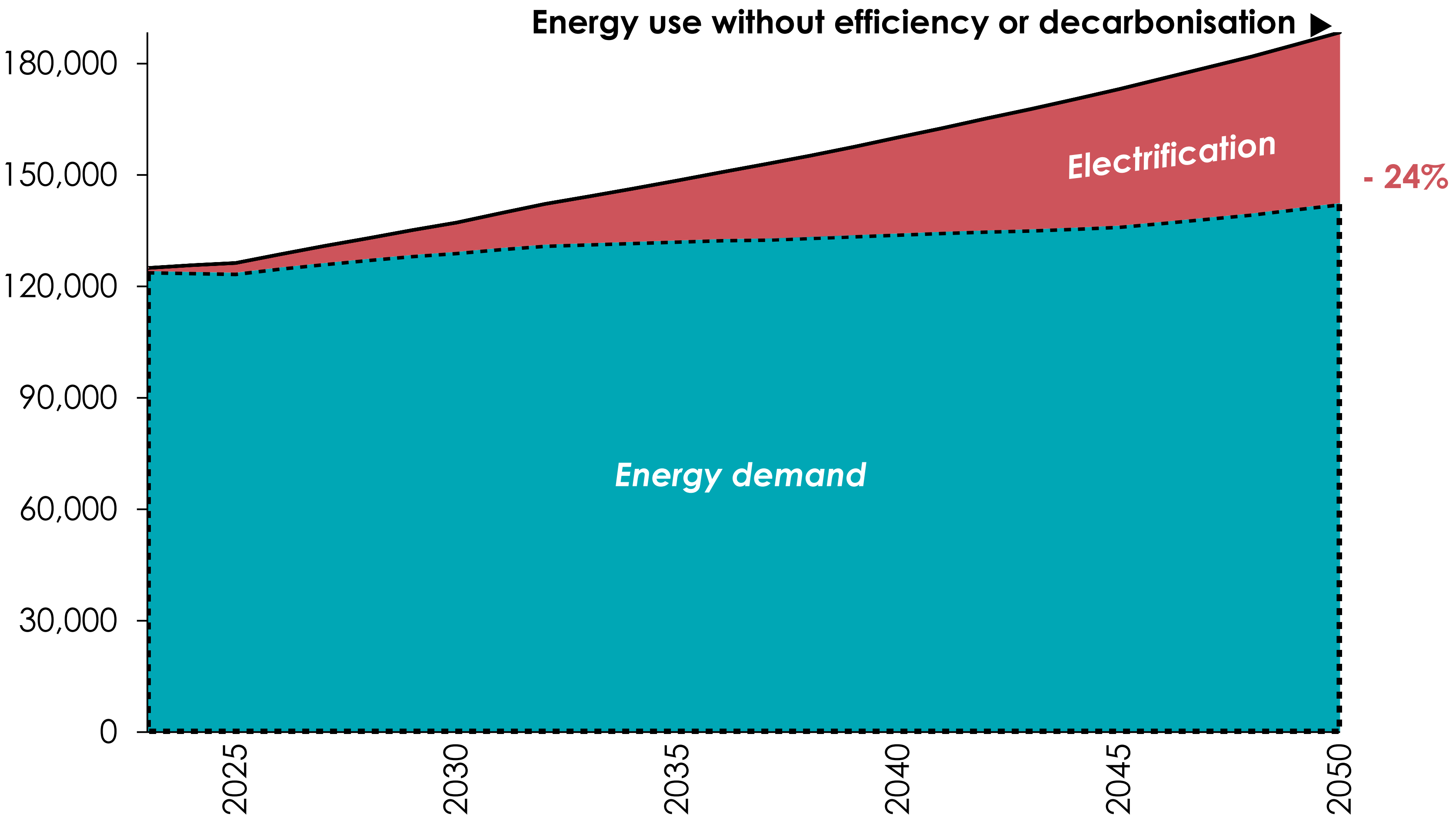
More energy end use

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

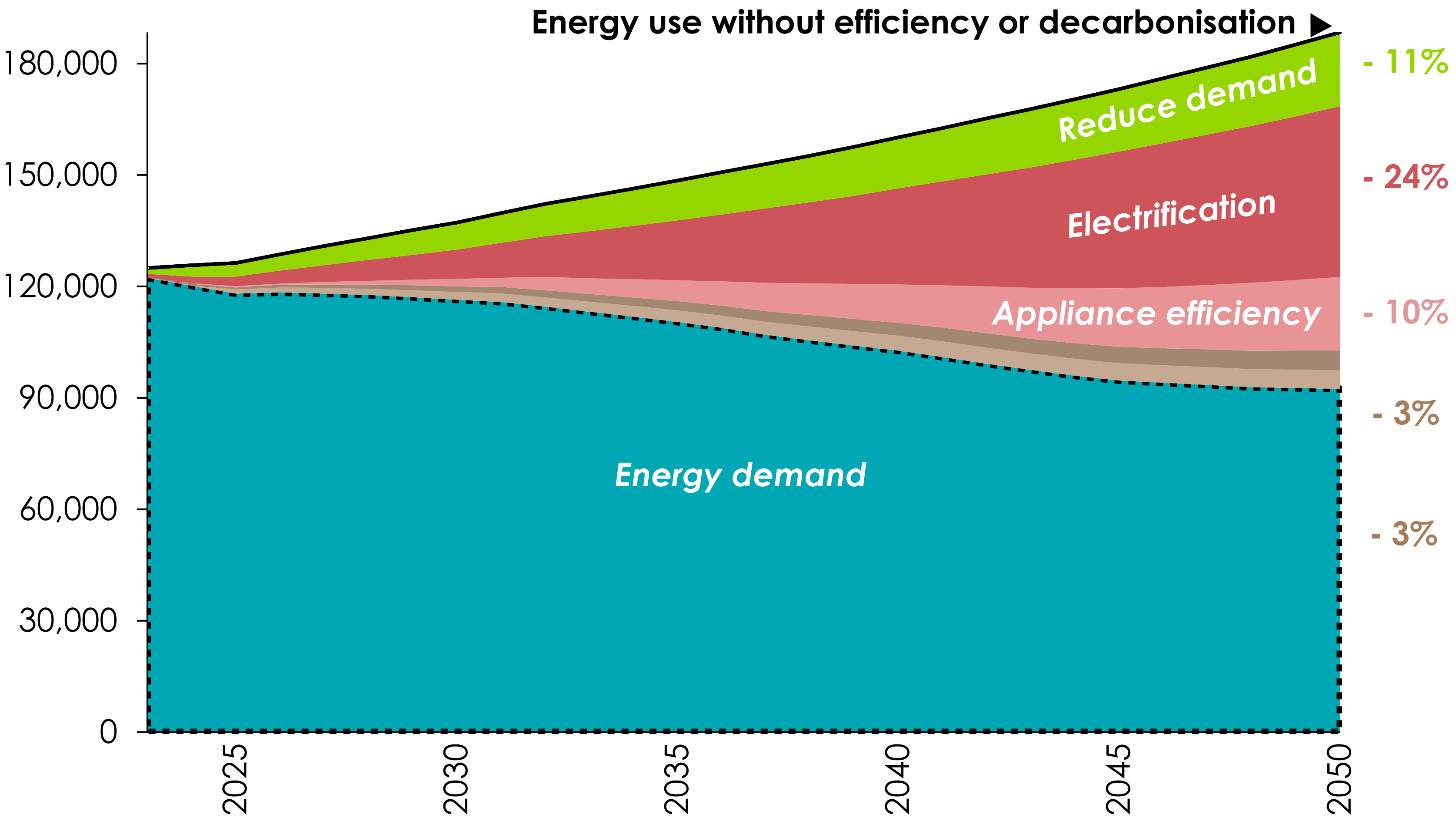
Electrification: switching to electric vehicles, electric heating and cooking

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 energy productivity

Final Energy demand vs. Productivity levers
TWh

% Reduction potential compared to 2050 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)

Electrification: switching to electric vehicles, electric heating and cooking

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

Better insulation in buildings: better buildings codes and fabric improvements

Everything else – sector-specific interventions

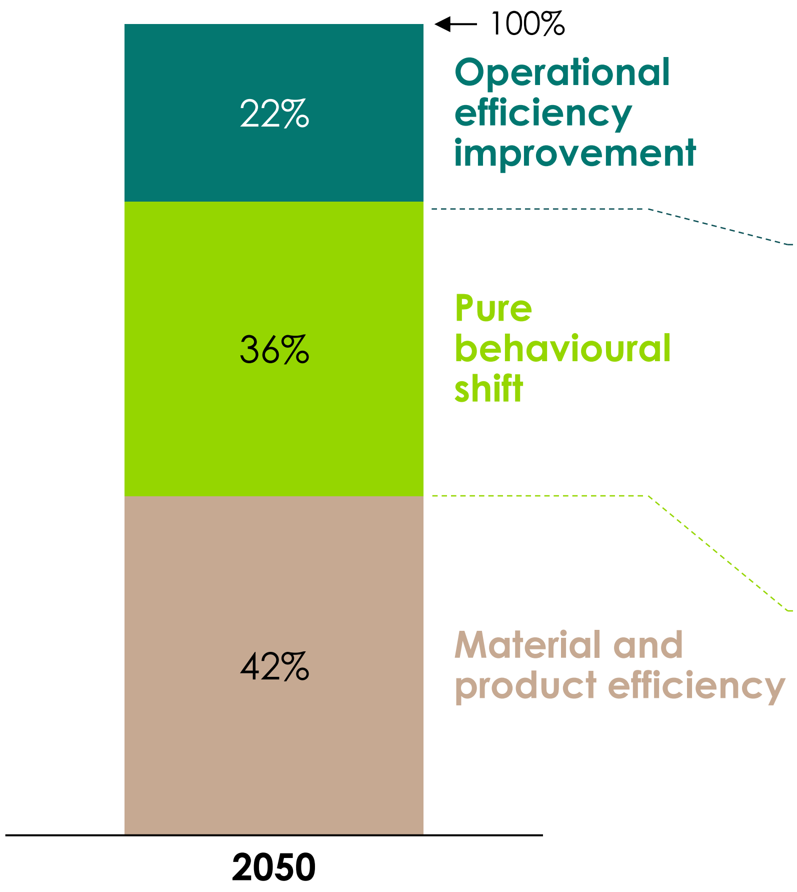
-51%

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 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)

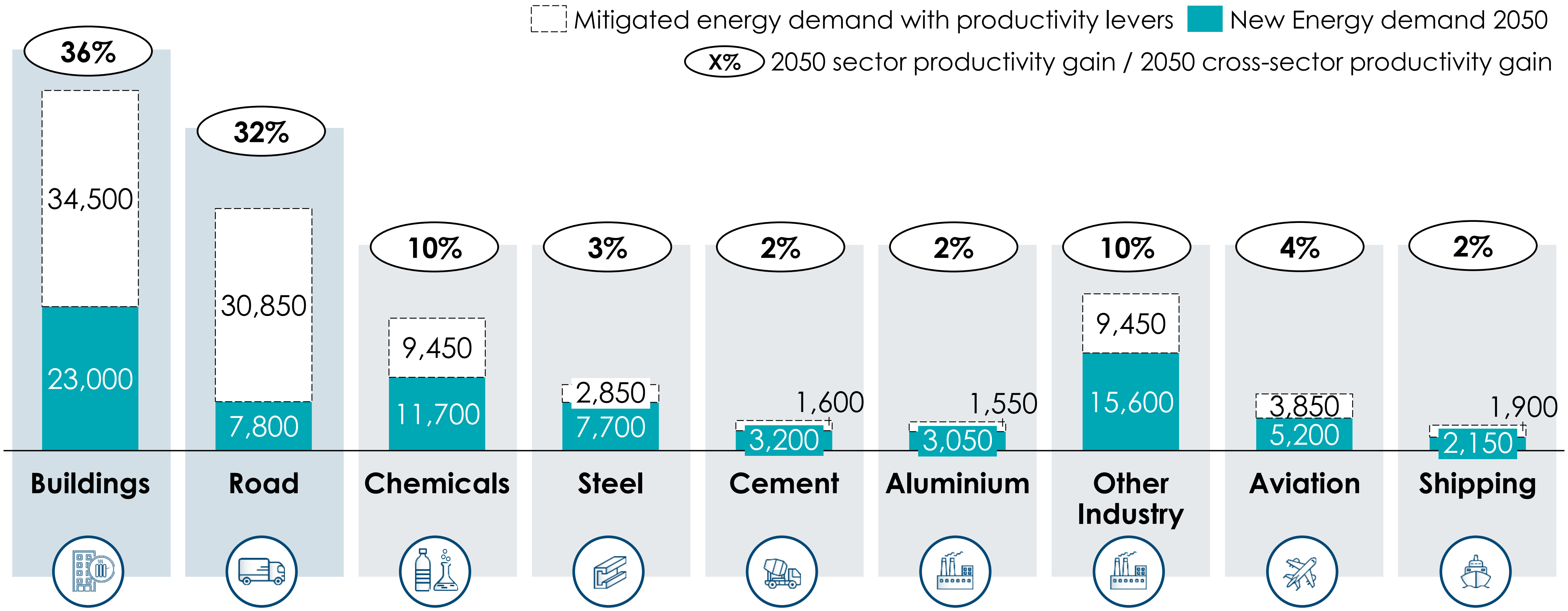
- Bulk of **recycling**, extended **product lifetime, reuse** and material efficiency in:
  - Cement
  - Aluminum
  - Steel
  - Chemicals

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

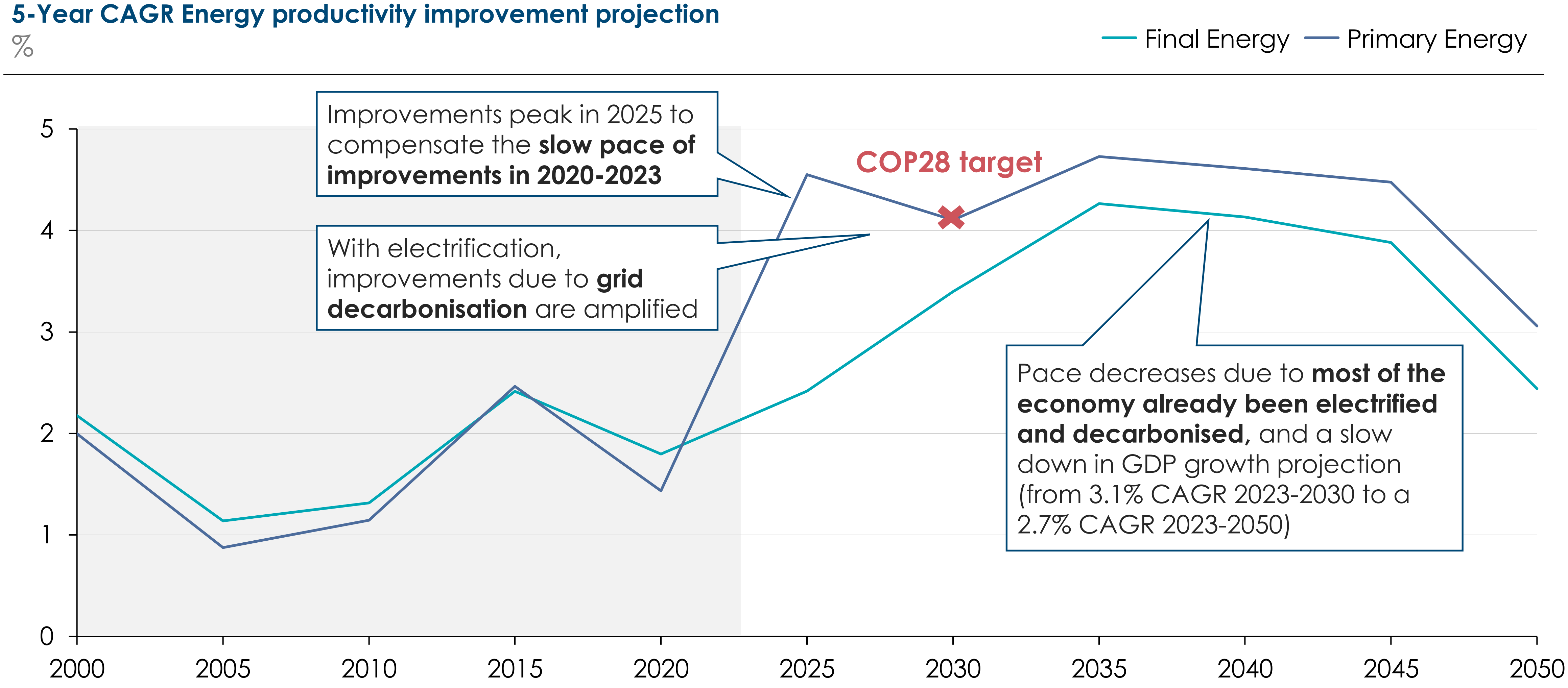
TWh



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

%

Improvements peak in 2025 to compensate the **slow pace of improvements in 2020-2023**

With electrification, improvements due to **grid decarbonisation** are amplified

Pace decreases due to **most of the economy already been electrified and decarbonised,** and a slow down in GDP growth projection (from 3.1% CAGR 2023-2030 to a 2.7% CAGR 2023-2050)

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 **from $3.5 to $2.7 trillion / year** the annual amount of energy infrastructure and investment needed

Lower materials footprint, by reducing the cumulative material requirements for the energy transition by 2050 down from 6.5 billion tonnes of end-use materials to as low as 4.6 billion tonnes and reducing the cumulative **embodied carbon emissions** of these materials from **35 $GtCO_2e$ to as low as 4.6 $GtCO_2e$**

Lower impact on planetary boundaries, by reducing clean energy system requirements by for water and land use by 4%, or 4 billion m^3 and 0.05 million km^2 respectively.

Maximising energy productivity *alongside* electrification can:

Increase energy security, reducing overall needs for energy can reduce needs for imports, reducing the impact of price volatility; e.g. in Germany primary energy imports in 2023 added up to around 70% of the country's energy demand at the cost of 80 billion euros. By 2035, with electrification and further energy productivity levers, **imports could drop by 20%, reducing the import bill by 16 billion euros in 2023 prices.**

Source: ETC (2023) Material and Resource Requirements for the Energy Transition; ETC (2025) Achieving Zero-Carbon Buildings; ETC (2025) The Road Ahead; ETC (2024) NDCs, NCQG, and Financing the Transition: Unlocking Flows for a Net-Zero Future; Eurostat; Clean Energy Wire (2025) Fossil fuel imports to Germany go down as costs increase

To maximise energy productivity levers, there are 5 priorities

	Main productivity levers	Energy saving *(TWh/year)*	Key technologies/solutions
Final Energy	1 **Electrification**	17,400	EVs Heat Pumps Electric Cooking
	2 **Appliance/vehicle efficiency improvement**	8,700	Variable speed ACs Newer motors LEDs
	3 **Reduced demand**	7,400	Reduce & Re-use plastics Recycle steel & aluminium Digitalisation and automation
	4 **Better insulation in buildings**	2,900	Fabric improvement Building codes
	5 **Everything else – sector-specific**	3,300	Lightweight and aerodynamics
Primary Energy	6 **Grid decarbonisation**	60,000	Solar panels Utility size storage

Priorities

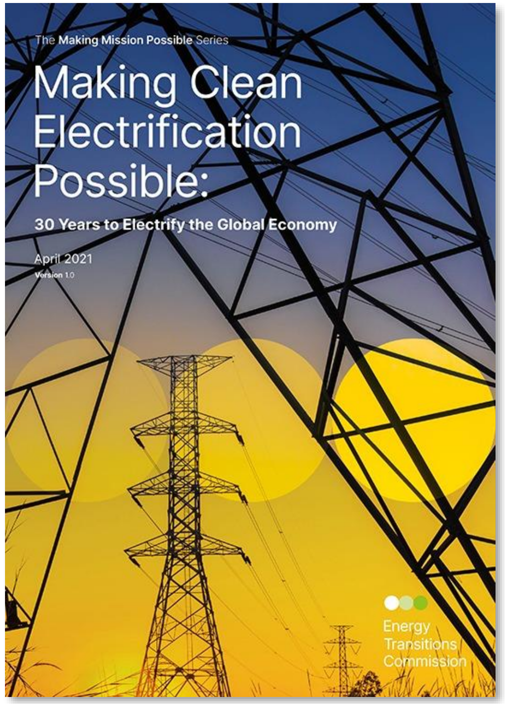
1) **Set national energy efficiency targets**, integrated into national decarbonisation plans, and track progress with key technologies and solutions
2) **Lower upfront costs** through targeted subsidies (e.g. heat pumps, scrappage schemes for faster stock turnover)
3) **Raise awareness for financiers, 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 aircrafts and vessels
5) **Prepare the power grid** for increased electrification and leverage demand shifts (EVs and buildings insulation)

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



The Making Mission Possible Series

Making Clean Electrification Possible:

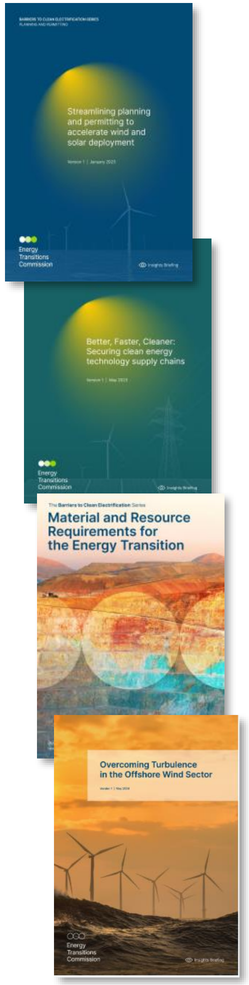
30 Years to Electrify the Global Economy

April 2021

Version 1.0

Energy Transitions Commission

2022-2024



Streamlining planning and permitting to accelerate wind and solar deployment

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

The Barriers to Clean Electrification Series

Material and Resource Requirements for the Energy Transition

Overcoming Turbulence in the Offshore Wind Sector

Energy Transitions Commission

Streamlining planning and permitting to accelerate wind and solar deployment

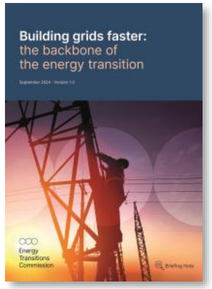
Better, Faster, Cleaner: Securing clean energy technology supply chains

Material and Resource requirements for the Energy Transition

Overcoming Turbulence in the Offshore Wind Sector

2024/25

Series and Major report on Power Systems transformation



Building grids faster: the backbone of the energy transition

Energy Transitions Commission

Building Grids Faster: The backbone of the energy transition

Briefing Note

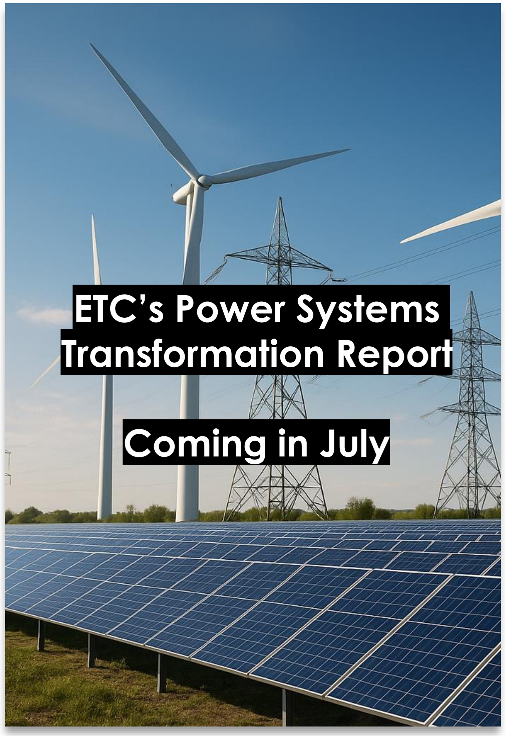
Demand side flexibility – unleashing untapped potential for clean power

A third of total electricity demand in 2050 could be flexible – roughly equivalent to today's entire electricity consumption.

Demand side flexibility – unleashing untapped potential for clean power

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

Coming in July



ETC's Power Systems Transformation Report

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

1

Managing System Balancing

Meeting balancing needs as the penetration of wind and solar grows

2

Building and optimising grids

Ensuring grids can increase 2-3 times in size and modernise to support demand growth and new generation

3

Ensuring low costs

Ensuring future clean power system costs are no higher than today's

5 key technologies are critical to building and managing grids of the future

- Flexible dispatchable generation
- Long-distance transmission
- Energy storage
- Demand-side flexibility
- Innovative grid technologies

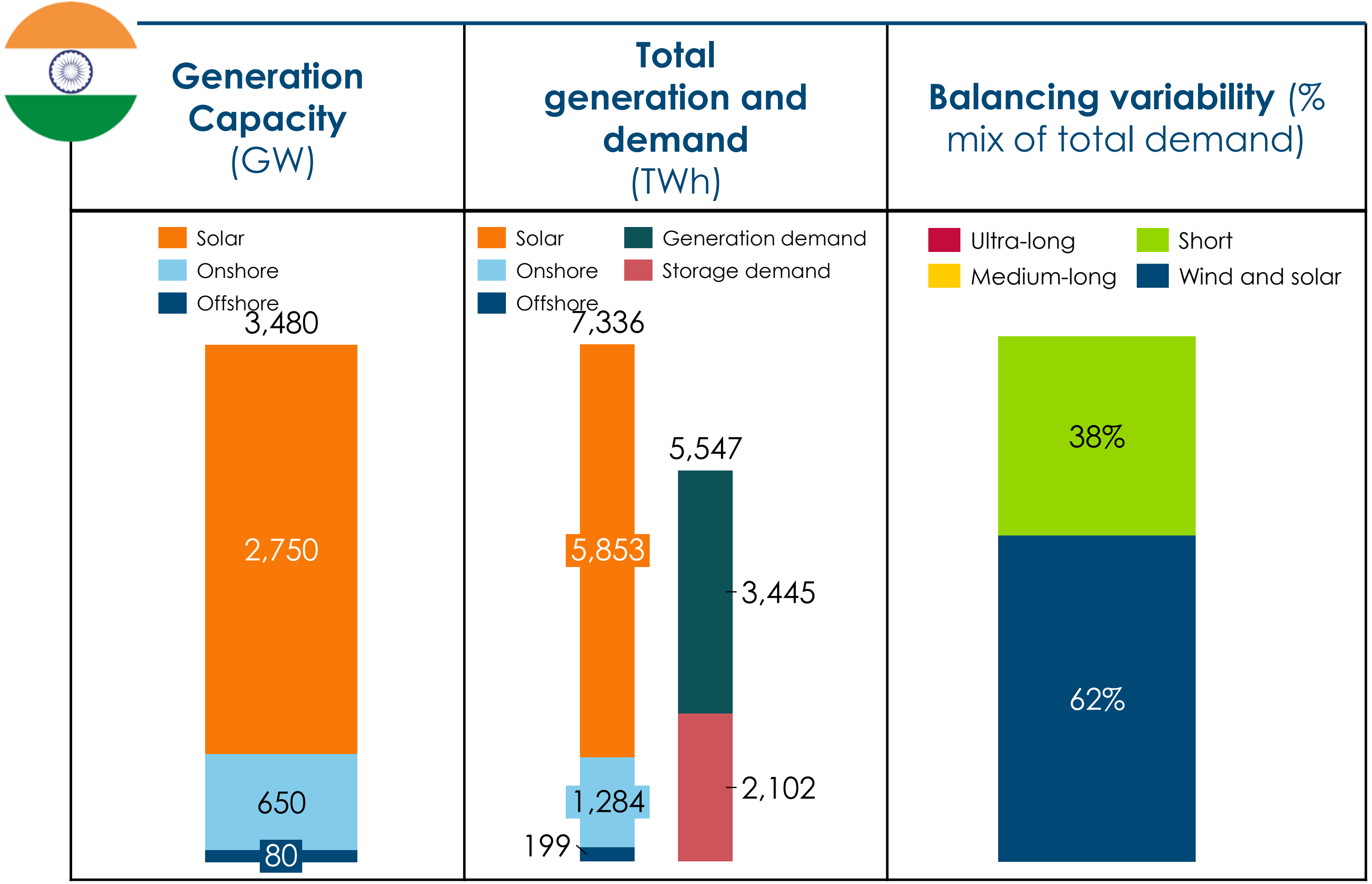
New insights from this report

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)**, the 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 Capacity (GW)

Total generation and demand (TWh)

Balancing variability (% mix of total demand)

Generation

- Solar dominates (~80%) due to high irradiation
- Solar overbuild is lowest-cost path to net-zero
- Surplus solar buffers seasonal lulls (e.g. monsoons)

Balancing Mix

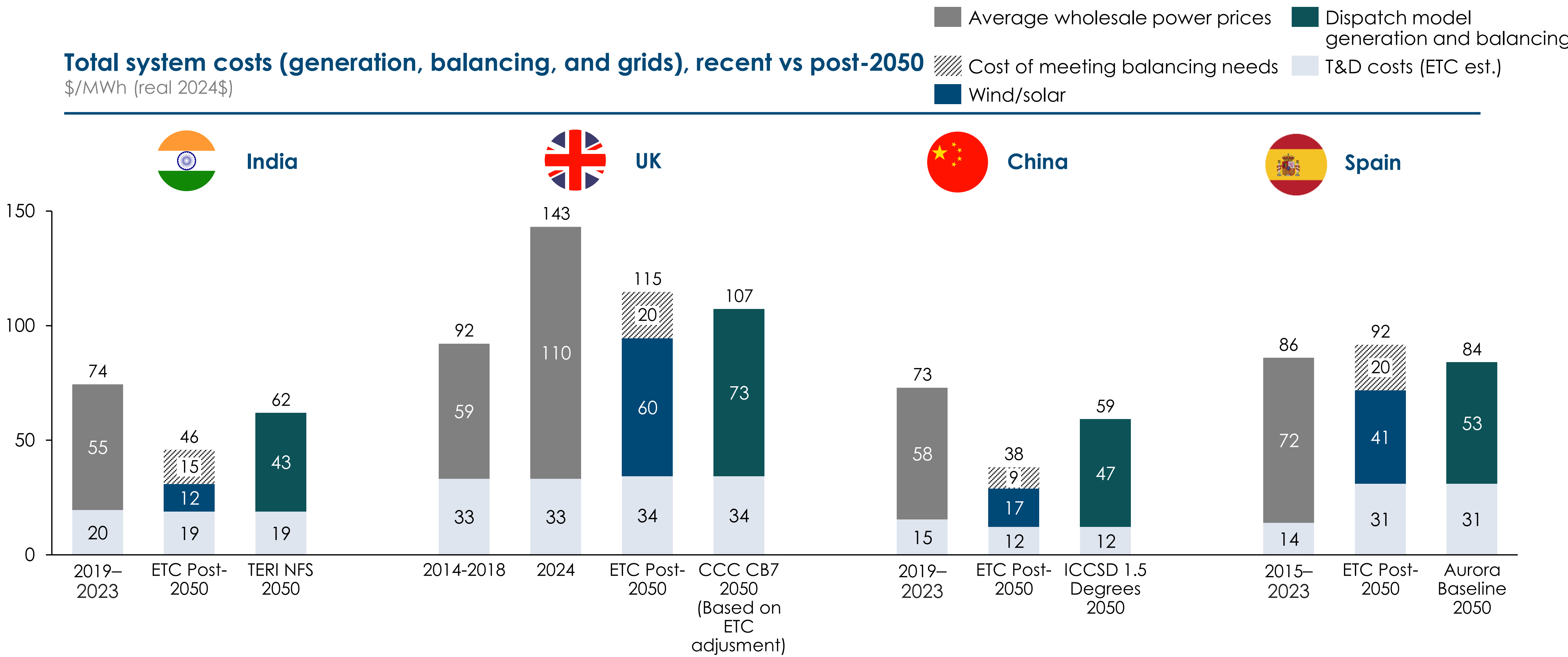
- 60% of demand met instantly – no storage needed
- 40% balanced via short-duration storage (daily)
- Low seasonality = minimal long-duration storage need
- Surplus solar absorbed via interconnectors, hydrogen, or flexible demand
- Night-time gaps covered by storage, demand-side response, grid optimisation

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

① System generation, balancing, and grid costs could be competitive with current wholesale prices

Total system costs (generation, balancing, and grids), recent vs post-2050

$/MWh (real 2024$)

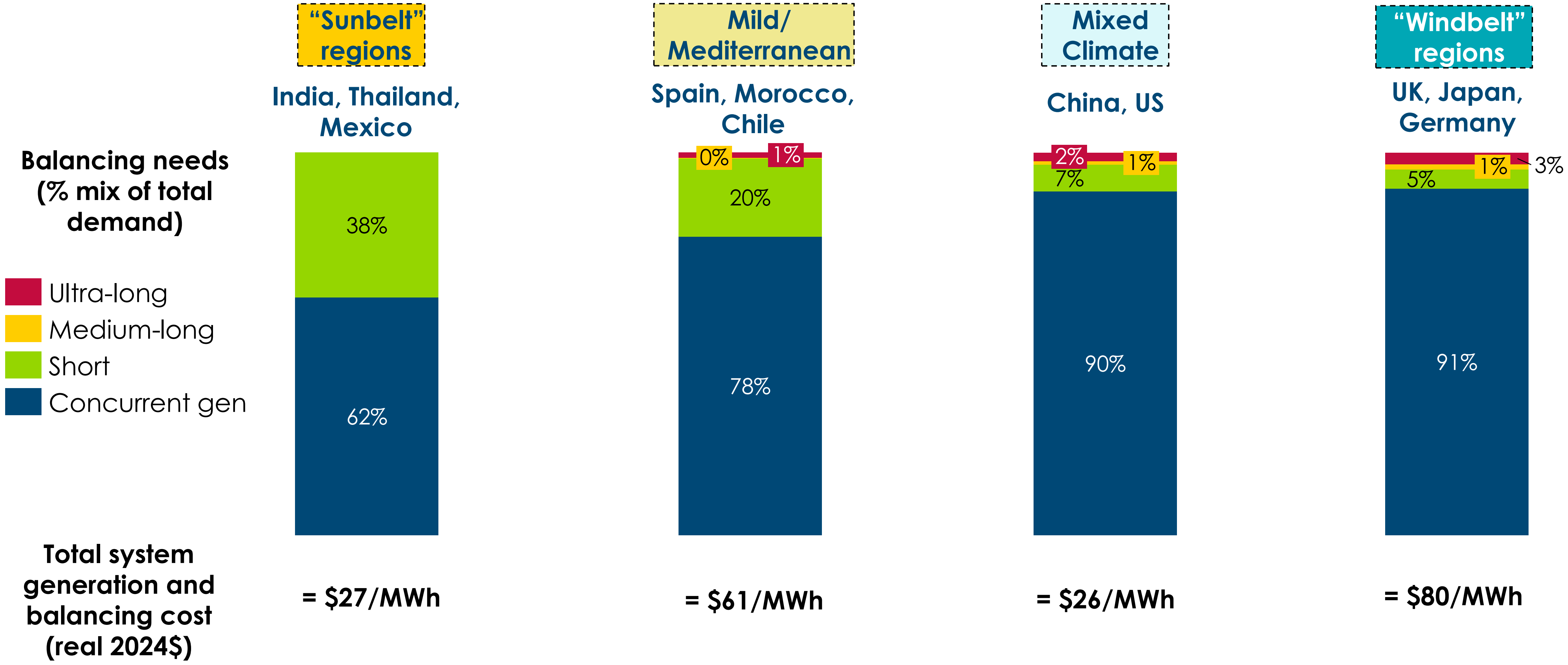


Note: T&D = Transmission and distribution. T&D costs per MWh have been assumed based on ETC modelling outlined in Chapter 2 across all presented here for consistency.

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:

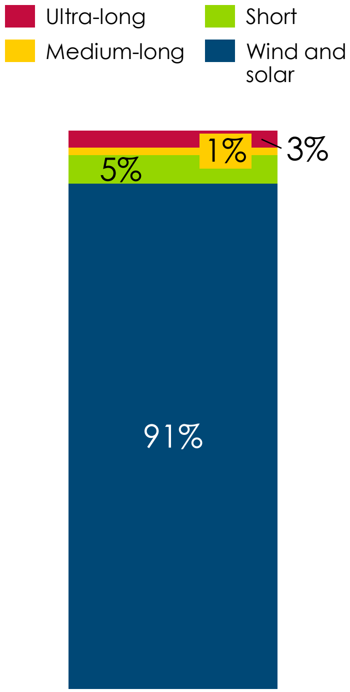
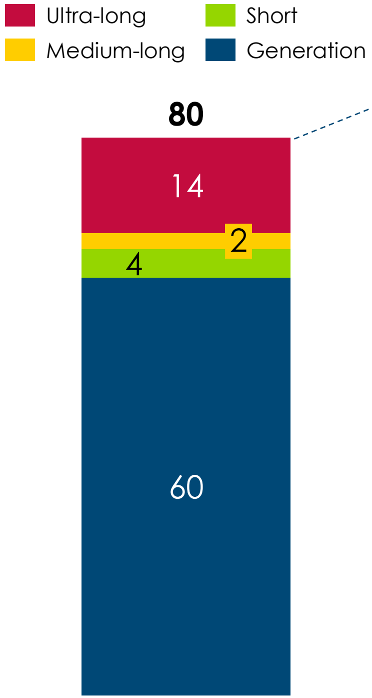


Source: Systemiq analysis fore the ETC (2025)

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		**Generation:** 778 TWh at **$45/MWh** **Short storage:** 26 TWh at **$80/MWh** **Medium-long:** 7 TWh at **$170/MWh** **Ultra-long:** 16 TWh at **$460/MWh**	

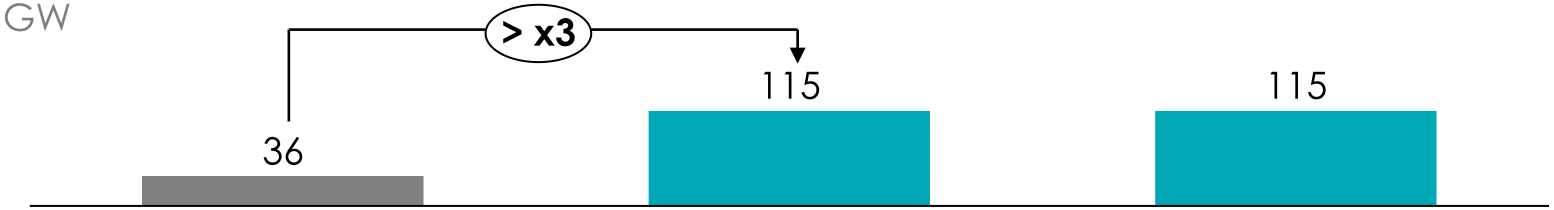
While ultra-long duration **only makes up 3%** of the balancing requirement in this archetype, **it makes a significant addition ($14/MWh) to final generation costs**

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.*

Illustrative example: meeting ultra-long duration balancing presents a significant addition to total system costs

Capacity today vs. capacity required in to fully meet max peak of ultra long-duration balancing

GW



	Gas capacity in UK in 2024	**H_2-ready OCGTs**	**Gas OCGTs**
Annual TWh of generation	101	15	15
Levelised cost ($/MWh)	N/A (existing)	740£/MWh	520£/MWh for new assets
Estimated impact on average household bill (based on 2024/5 household bill)	N/A	£125	£80
Annual emissions ($MtCO_2e$)	~40 $MtCO_{2e}$	~0 $MtCO_{2e}$	6 $MtCO_{2e}$

Cost vs. emissions trade off for "last mile" decarbonisation

Key takeaways

- Ultra-long duration balancing will be **costly**; decisions must prioritise cost-effectiveness given its small share of total demand
- **Hydrogen peaking** is the most expensive option, with costs >£700/MWh at low utilization
- **Unabated gas may be needed for rare peaks as lowest-cost option**, but must be clearly limited and regulated with guidelines

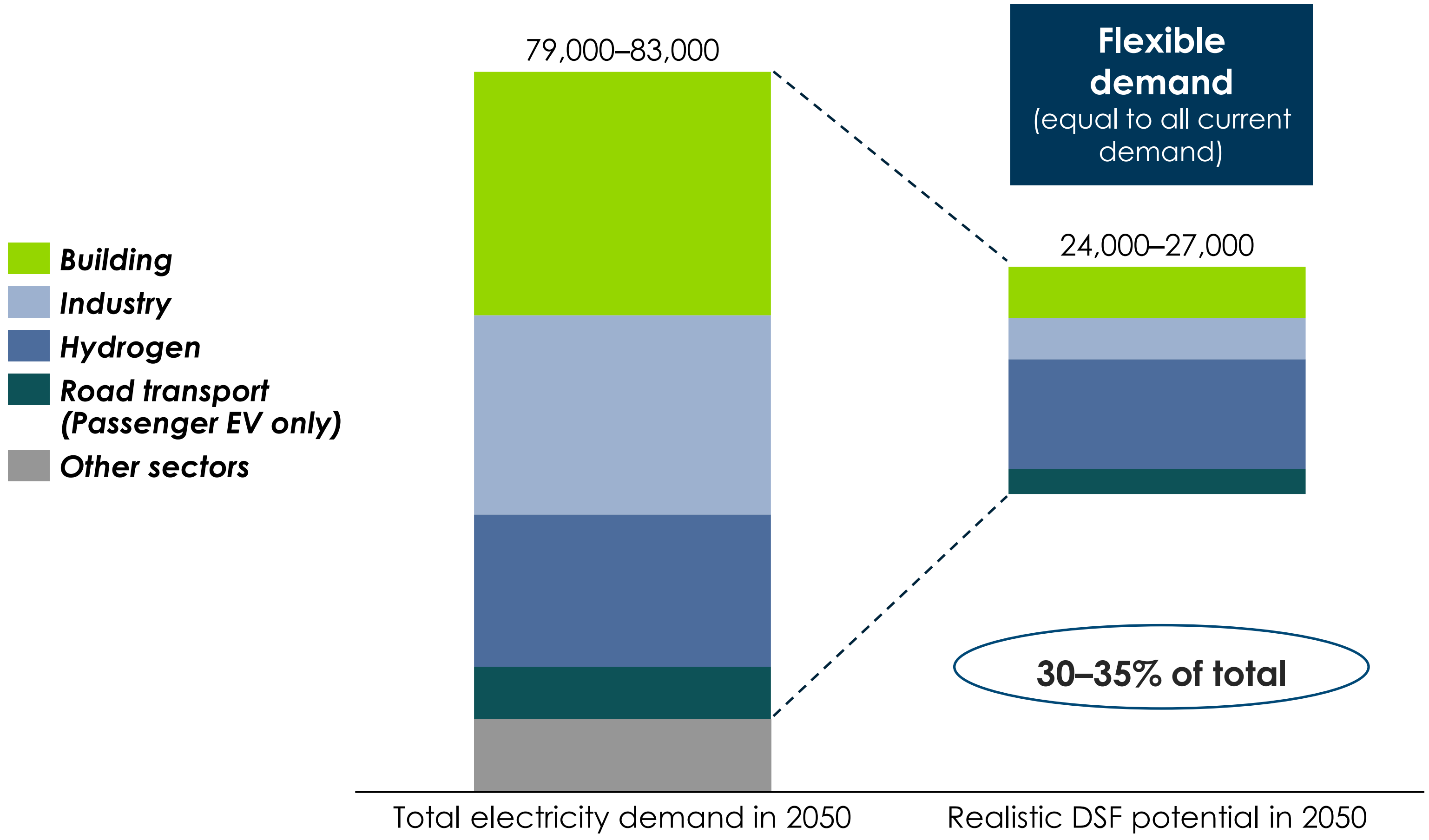
Note: **CCGT with CCS ruled out as unsuitable for very low utilisation because of high costs, slow ramping, and poor efficiency at low loads.** A 1.5% capacity factor is used to solve for minimum needed in both capacity and power. Emissions intensity of unabated gas assumed to be 0.394 $kgCO_{2e}$ per kWh as noted by the UK Department for Environment and Net Zero. H_2-ready peaker figure assumes a $2.70/kg cost of hydrogen in the UK in 2050 excluding storage. Based on 15 TWh of generation and 30 million households. Household bill figure calculated by pro-rating the increase in average wholesale cost due to "last-mile" peaking generation (e.g. H_2-ready peakers and unabated gas) over 15 TWh/year—equivalent to ~5% of UK annual generation. The resulting increase in wholesale price was applied to a representative 2024–25 household bill (£913), assuming the wholesale share remains at £311 (See Exhibit 3.4). Non-wholesale components (network, policy, other) were held constant to isolate the impact on total bills. Source: Systemiq analysis for the ETC; BNEF (2025), *Levelised Cost of Electricity 2025 Updates*; BNEF (2025), *LCOE Data Viewer*, Ben James (2025), *Electricity Bills;* Ofgem (2024), *Wholesale cost allowance methodology Annex 2;* Ofgem (2024); Ember (2025), Electricity Data Explorer

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



Flexible demand (equal to all current demand)

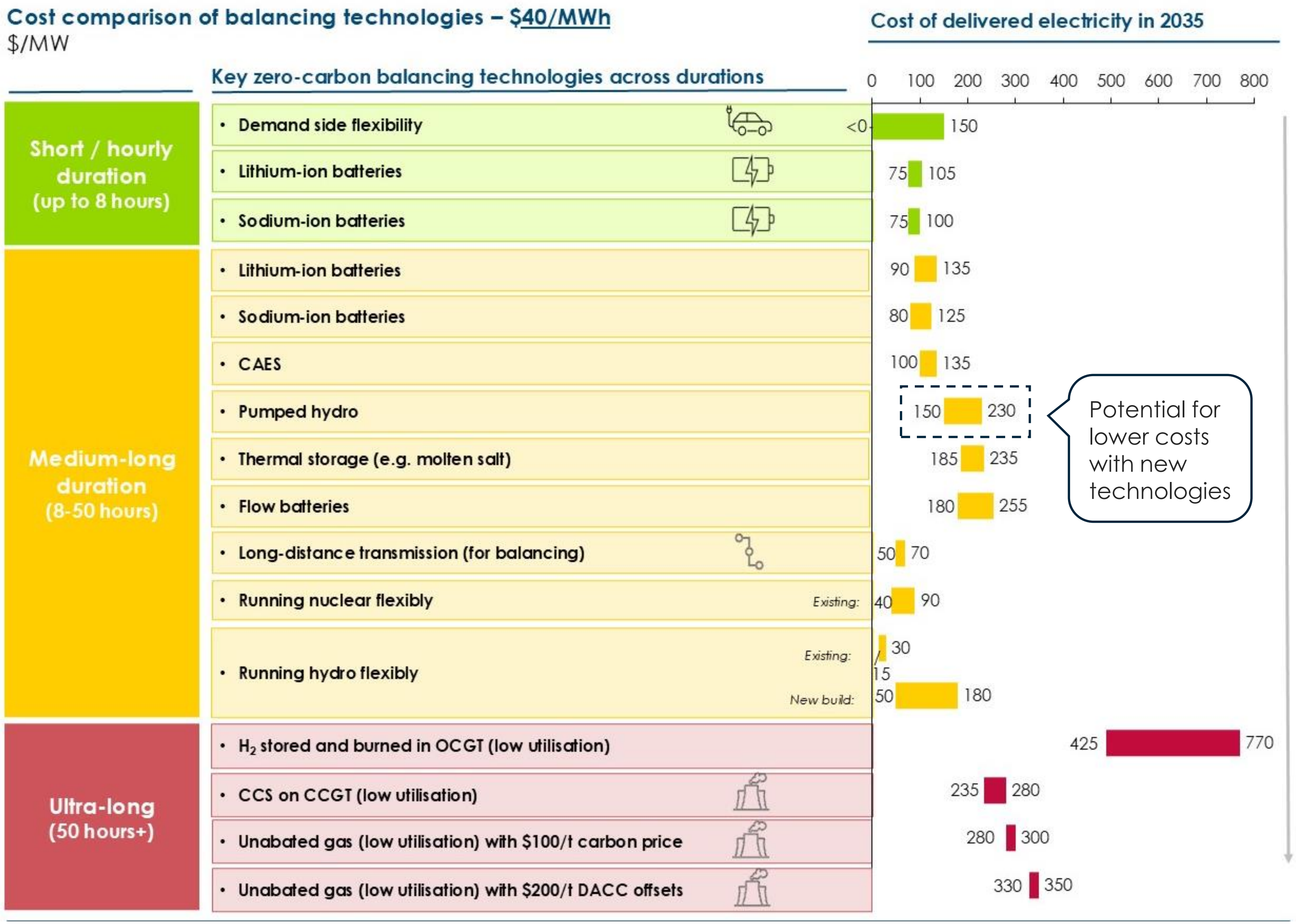
30–35% of total

*Demand side flexibility **has important potential to provide short duration balancing***

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

Duration	Key zero-carbon balancing technologies across durations		Cost of delivered electricity in 2035	
Short / hourly duration (up to 8 hours)	Demand side flexibility		<0	150
	Lithium-ion batteries		75	105
	Sodium-ion batteries		75	100
Medium-long duration (8-50 hours)	Lithium-ion batteries		90	135
	Sodium-ion batteries		80	125
	CAES		100	135
	Pumped hydro		150	230
	Thermal storage (e.g. molten salt)		185	235
	Flow batteries		180	255
	Long-distance transmission (for balancing)		50	70
	Running nuclear flexibly	*Existing:*	40	90
	Running hydro flexibly	*Existing:*	15	30
		New build:	50	180
Ultra-long (50 hours+)	H_2 stored and burned in OCGT (low utilisation)		425	770
	CCS on CCGT (low utilisation)		235	280
	Unabated gas (low utilisation) with $100/t carbon price		280	300
	Unabated gas (low utilisation) with $200/t DACC offsets		330	350

Potential for lower costs with new technologies

Key takeaways

- **Short duration**: Demand-side flexibility and lithium-ion batteries are the cheapest options for daily balancing.
- **Medium-long duration**: Technologies like pumped hydro and long-distance transmission offer cost-effective solutions for 8-50 hours balancing duration.
- **Ultra-long duration**: All options are 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

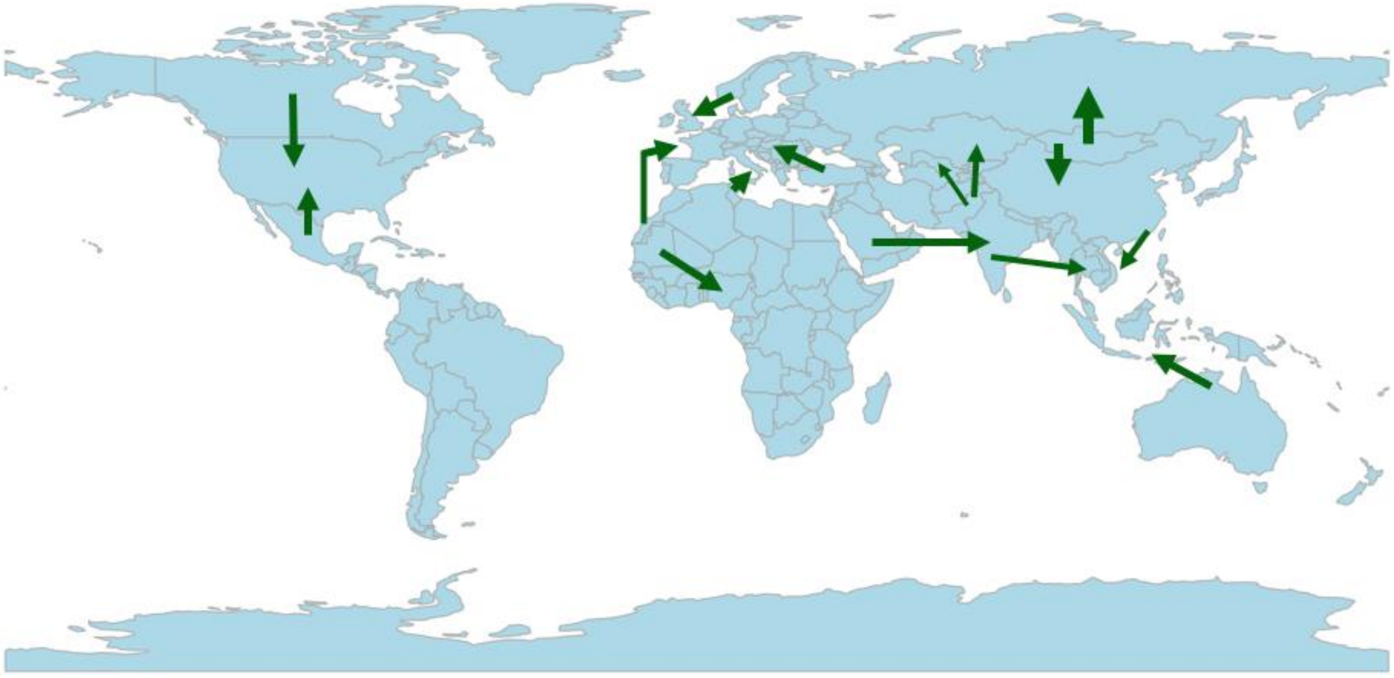
Long distance transmission can help to deliver:

- 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

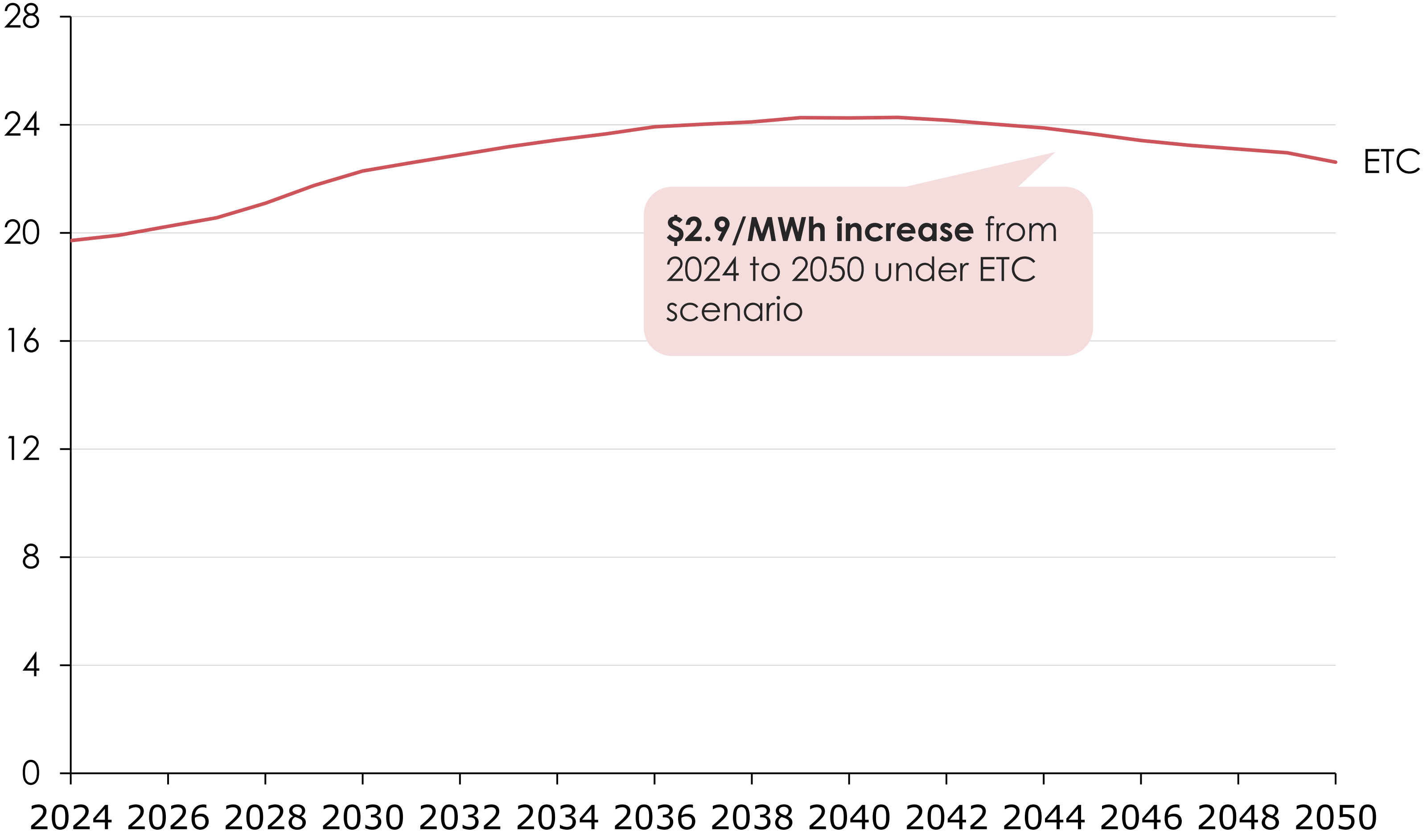
Overall modelling results: top 15 lines show potential for network 'megaprojects' such as Morocco and Australia as export hubs



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



$2.9/MWh increase from 2024 to 2050 under ETC scenario

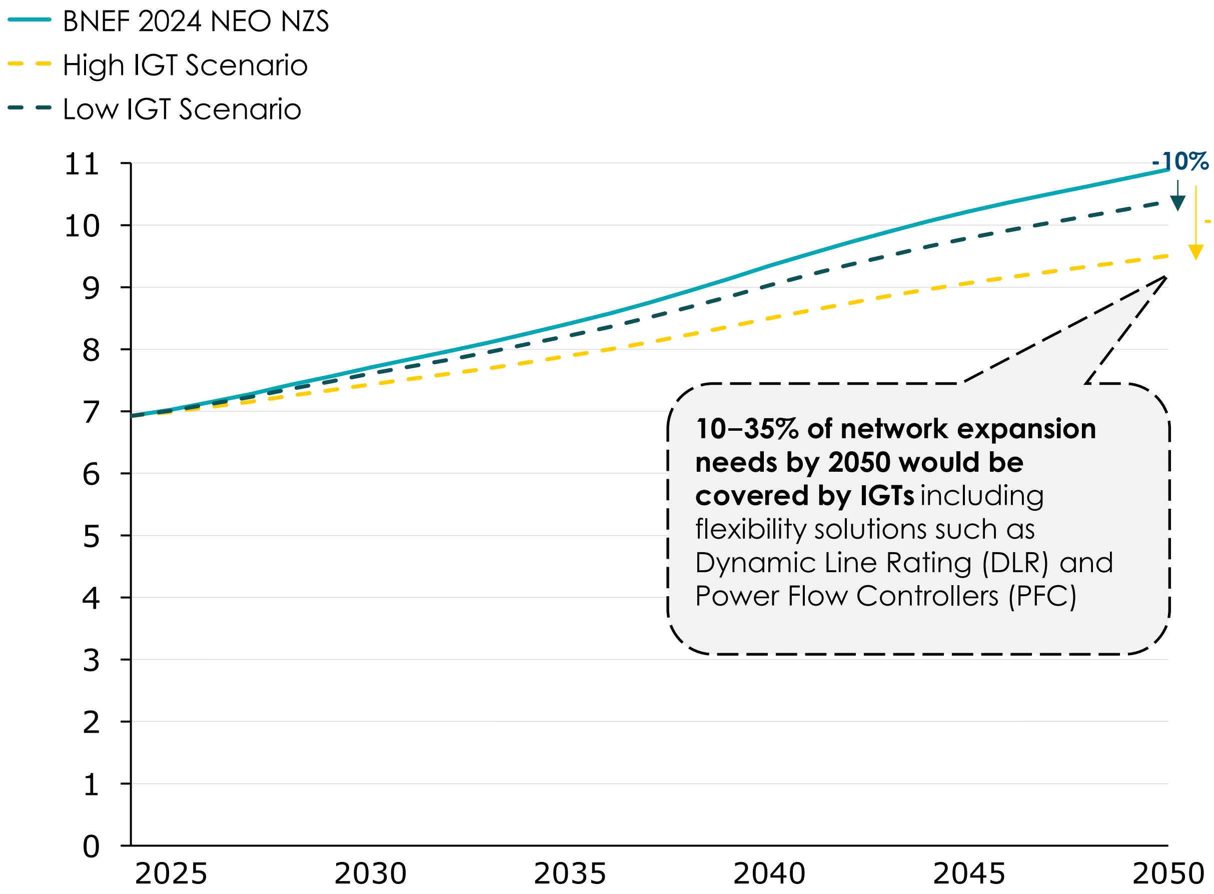
Source: Systemiq analysis for the ETC (2025), BNEF (2024) *New Energy Outlook 2024*

- **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.

Innovative Grid Technologies could significantly reduce grid build & CAPEX

Benefits of IGTs compared to network expansion needs

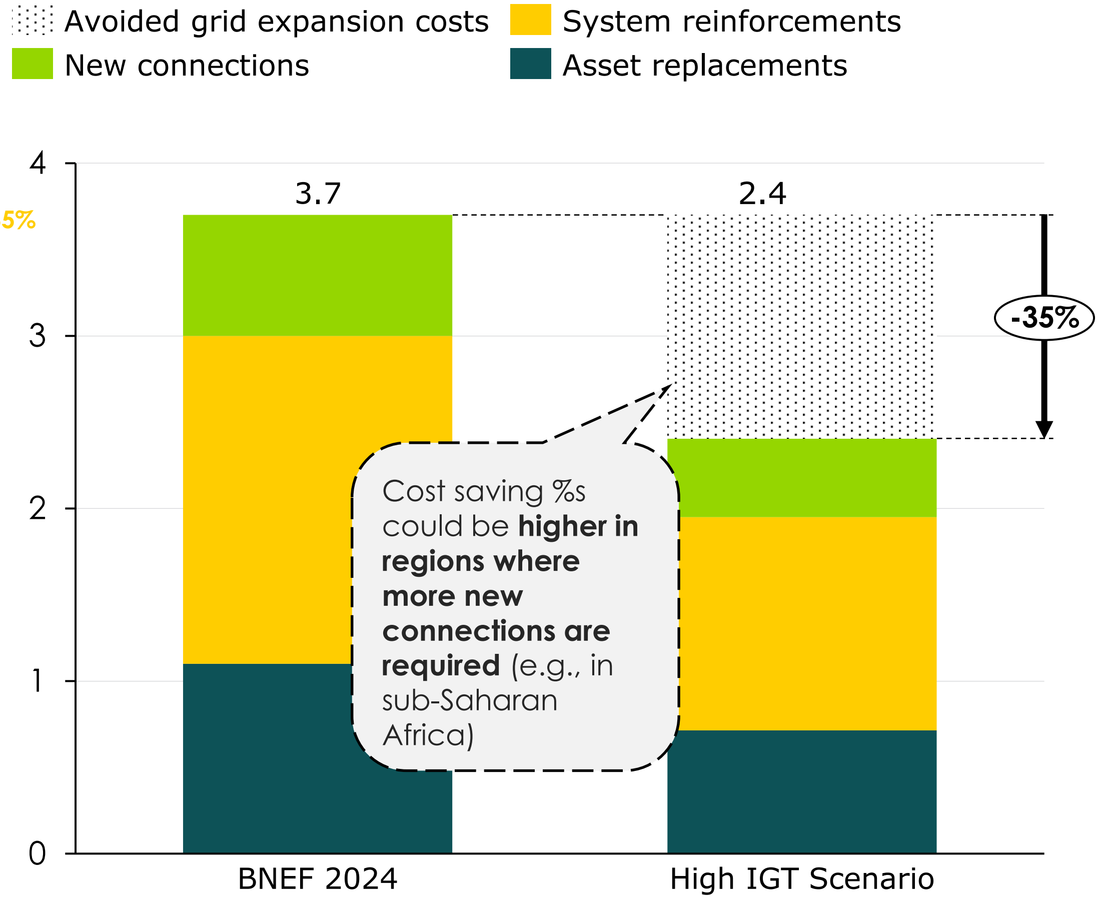
Million km, Europe, 2024–2050



10–35% of network expansion needs by 2050 would be covered by IGTs including flexibility solutions such as Dynamic Line Rating (DLR) and Power Flow Controllers (PFC)

Cumulative investment in new power grid system, Europe

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



Cost saving %s could be **higher in regions where more new connections are required** (e.g., in sub-Saharan Africa)

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.

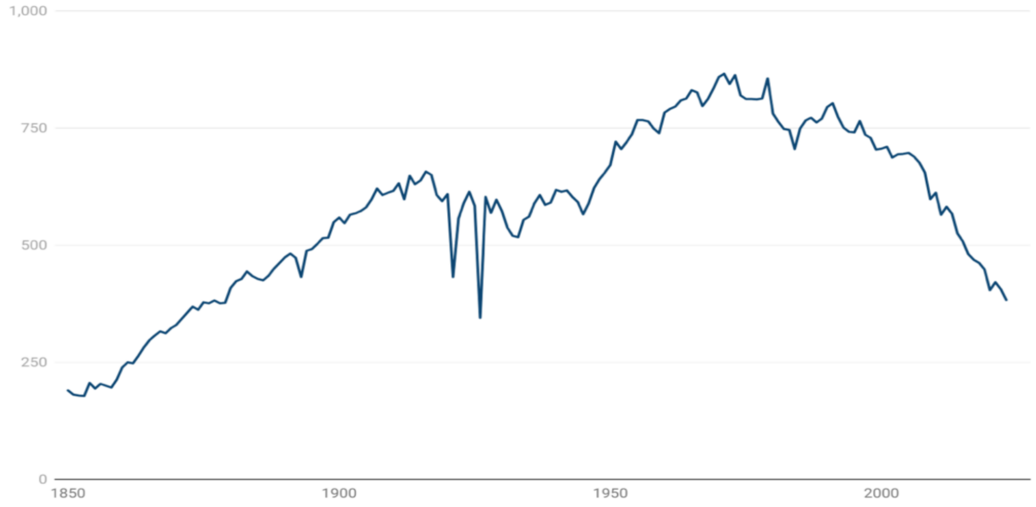
Source: Systemiq analysis for the ETC; CurrENT (2024), *Prospects for innovative power grid technologies*; BNEF (2024), *New Energy Outlook*.

Balancing electrification and decarbonisation: the risks of a mismatch

Developed Countries e.g. UK

UK territorial greenhouse gas emissions, 1850-2023

MtCO2e

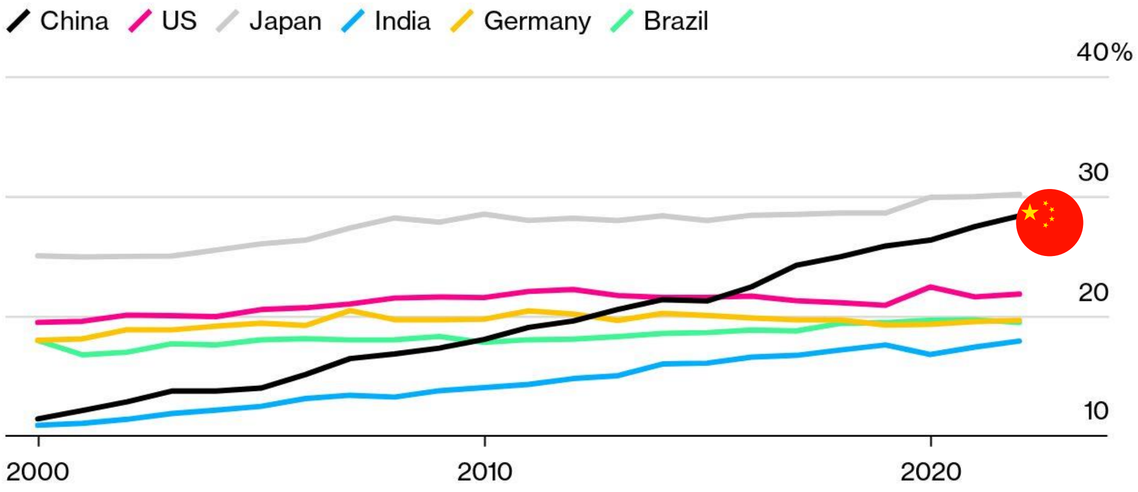


- **Decarbonisation occurring rapidly** in countries like the UK from 500g CO_2 per kWh in 2010 to 125g in 2025
- However, **electricity demand is stagnant** – from 360 TWh in 2010 to 320 TWh in 2024
- **The risk** – grid costs spread over fewer units, rising unit costs risk disincentivising electrification

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 CO_2/kWh
- **The risk –** growing demand locks in high emissions unless supply transition accelerates

Source: Jones et al (2023) and Carbon Brief analysis of figures from DESNZ, BNEF (2024), China's Soaring Power Demand Raises Questions About Coal, Renewables

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

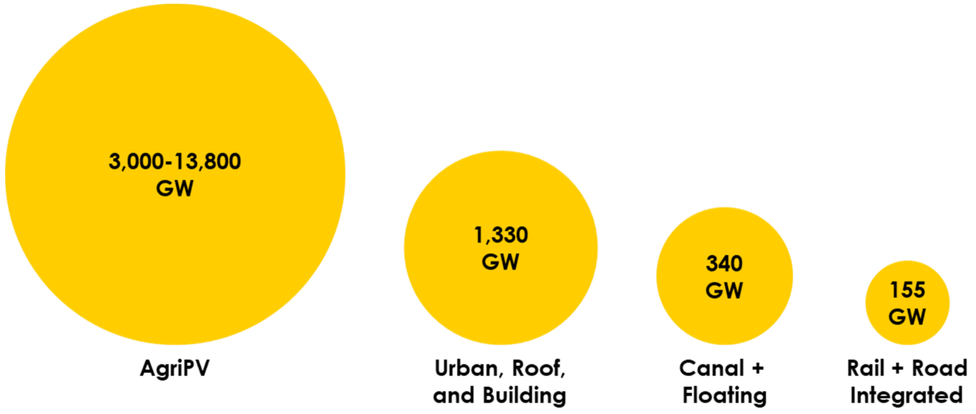
- Consumer engagement and trust-building

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 pper on power system implications and integration, paper on 'Just Transition' elements

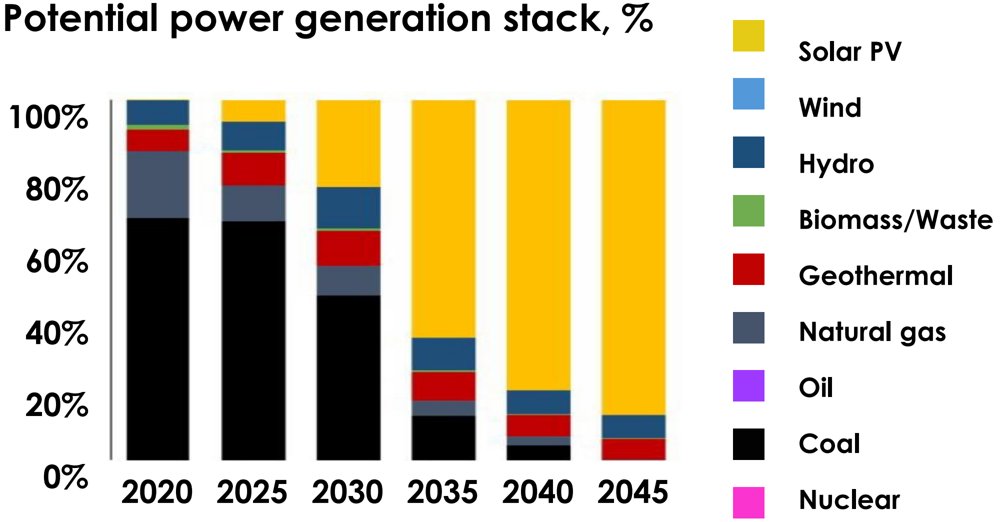
Estimates of potential capacity (GW)



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 liasing with ICGD and Kadin

Potential power generation stack, %



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

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** and **end-of life carbon management**

Phase 4
Report production and communication campaign running into COP30

Deliverables

For each phase

- 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

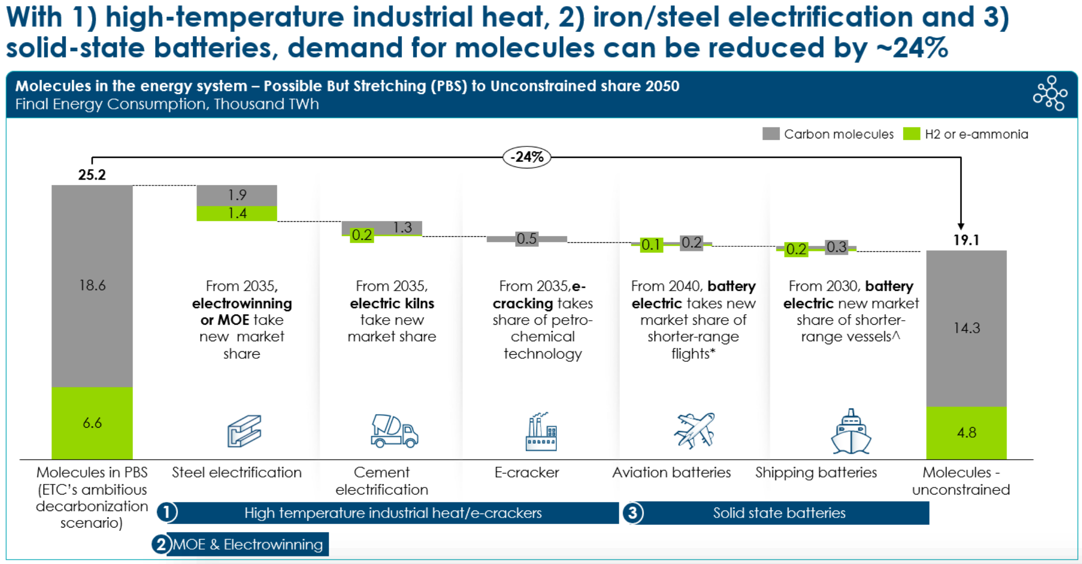
Key interactions

For each phase

- 1-2 workshops with ETC Commissioners

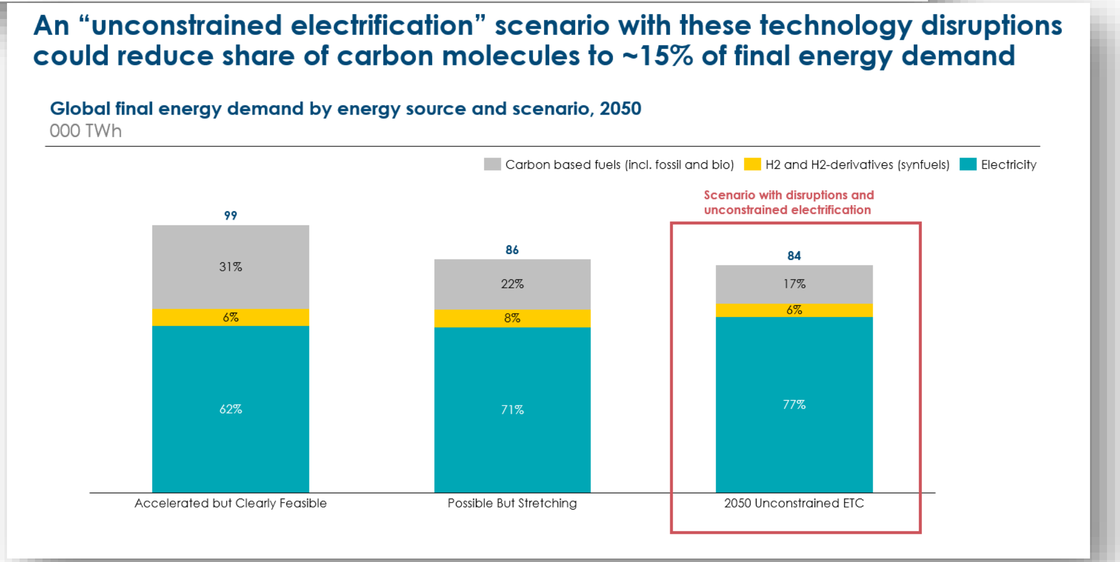
- Report reviews
- Report launch at COP

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%

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



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

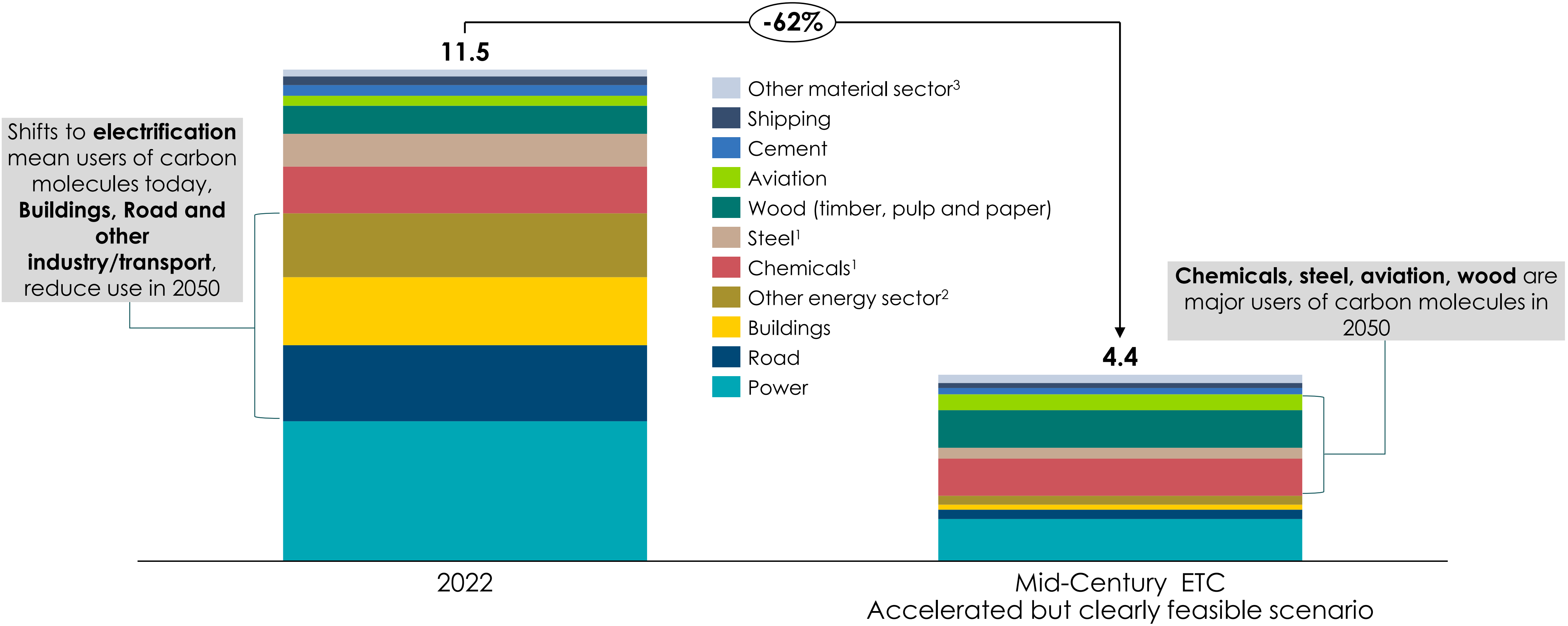
By sizing minimum and maximum volume of carbon molecules that can be reused and recycled (for energy and non-energy), we understand the implications for the primary supply of new carbon still required to support a prosperous global economy

	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		

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

Gigatons of carbon (C)



Shifts to **electrification** mean users of carbon molecules today, **Buildings, Road and other industry/transport**, reduce use in 2050

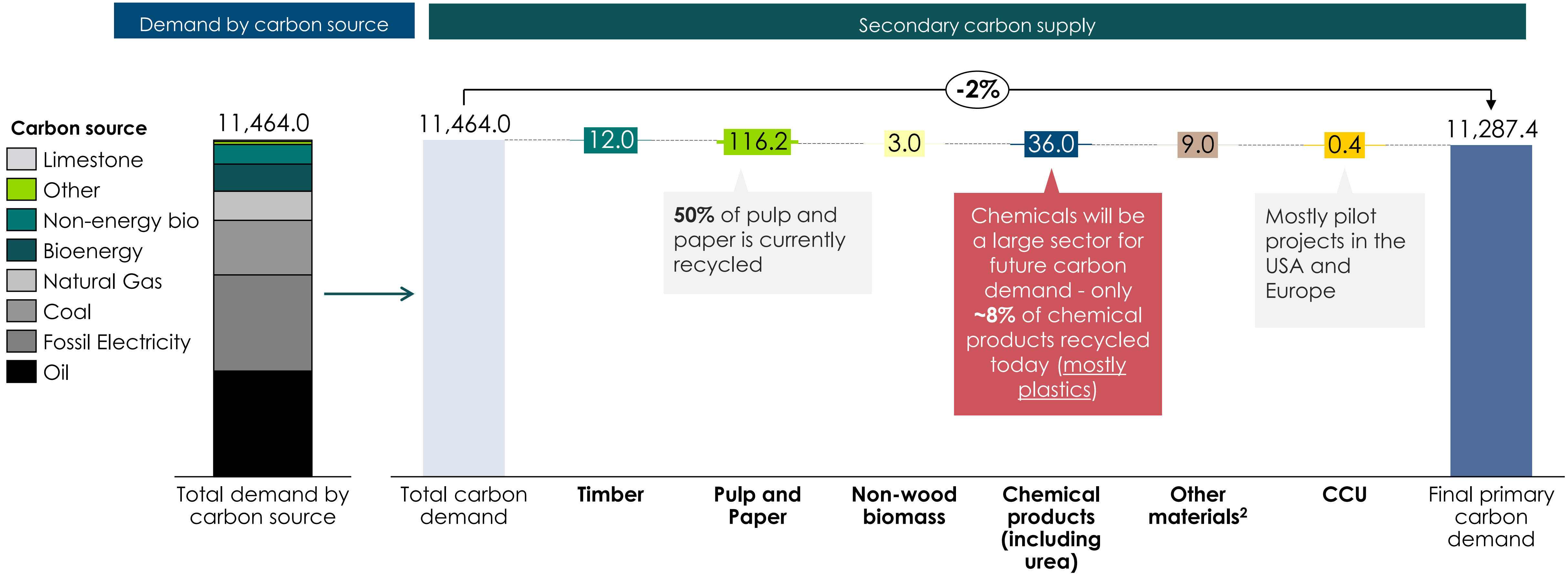
Chemicals, steel, aviation, wood are major users of carbon molecules in 2050

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)



50% of pulp and paper is currently recycled

Chemicals will be a large sector for future carbon demand - only **~8%** of chemical products recycled today (mostly plastics)

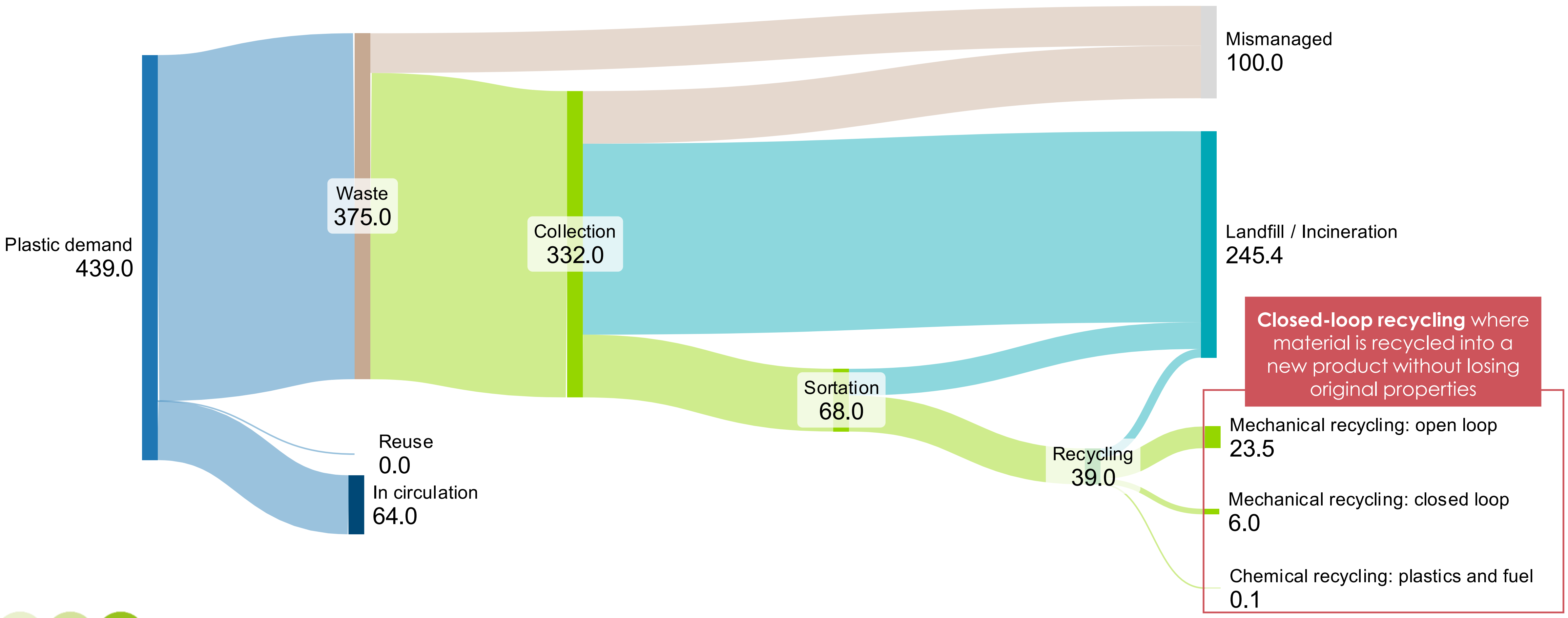
Mostly pilot projects in the USA and Europe

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*

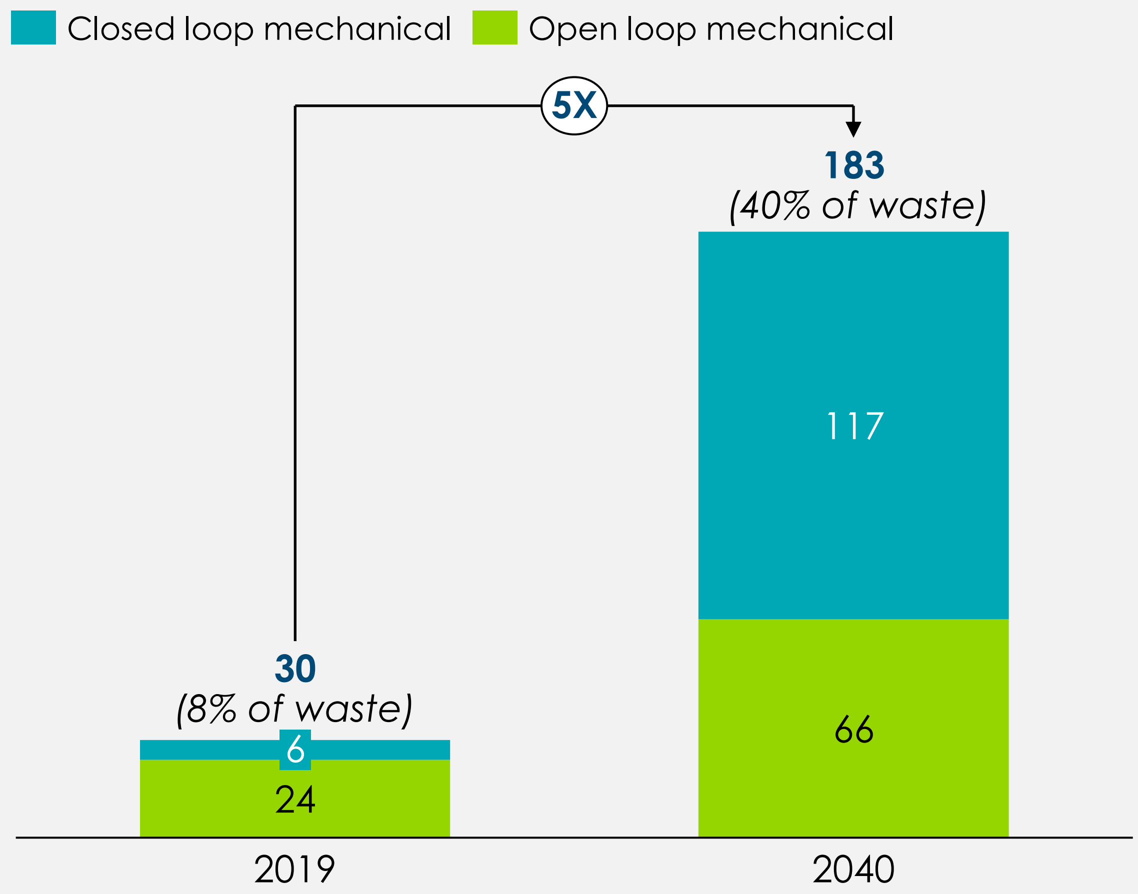


Closed-loop recycling where material is recycled into a new product without losing original properties

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 (%)



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

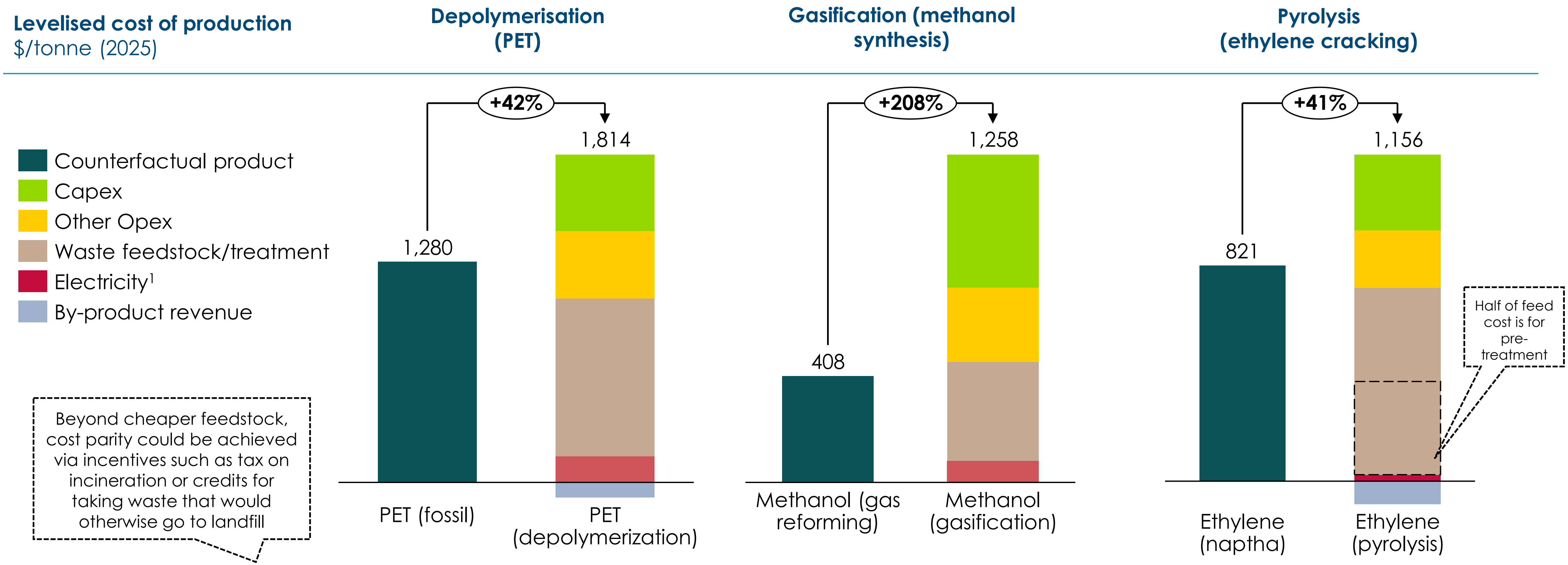
Source: Systemiq Plastic Treaty (2024). List provided is a subset interventions in the Global Full Lifecycle Scenario that related to increase recycling.

Key technologies explored in Phase 2 focused on how carbon-using sectors, like chemicals, could recycle in the future

In focus today

Lever	Technology disruption	TRL	Companies
Reduce demand	1 New re-use technologies and delivery models	7-9	cupclub Loop Vinted Uber
Recycle carbon *(chemical recycling of material and thermos conversion)*	2 Depolymerisation	5-8	Syre revalyu CARBIOS EASTMAN
	3 Pyrolysis	6-8	OMV BRIGHTMARK agilyx BASF We create chemistry
	4 Gasification	7-8	SunGas RENEWABLES Sumitomo SHI FW OMNI CONVERSION TECHNOLOGIES
Recycle carbon *(utilise waste CO_2)*	5 Hydrogenation to methane/methanol	7-8	IHI thyssenkrupp JM Johnson Matthey Inspiring science, enhancing life CARBON RECYCLING INTERNATIONAL
	6 Electrochemical reduction	5-8	sunfire twelve TOPSOE
	7 Reverse water gas shift	7-8	OXCCU MAN Energy Solutions
	8 Biocatalysis	8-9	LanzaTech synata bio
Enablers	9 Advanced AI and robotics sorting	8-9	greyparrot AMP ROBOTICS TOMRA

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



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

	Depolymerisation (PET)	Gasification (methanol synthesis)	Pyrolysis (ethylene cracking)
Feedstock cost assumed[2]	$670	$146	$293
Feedstock cost needed to be competitive[3]	$ 278	$ -181[4]	$155

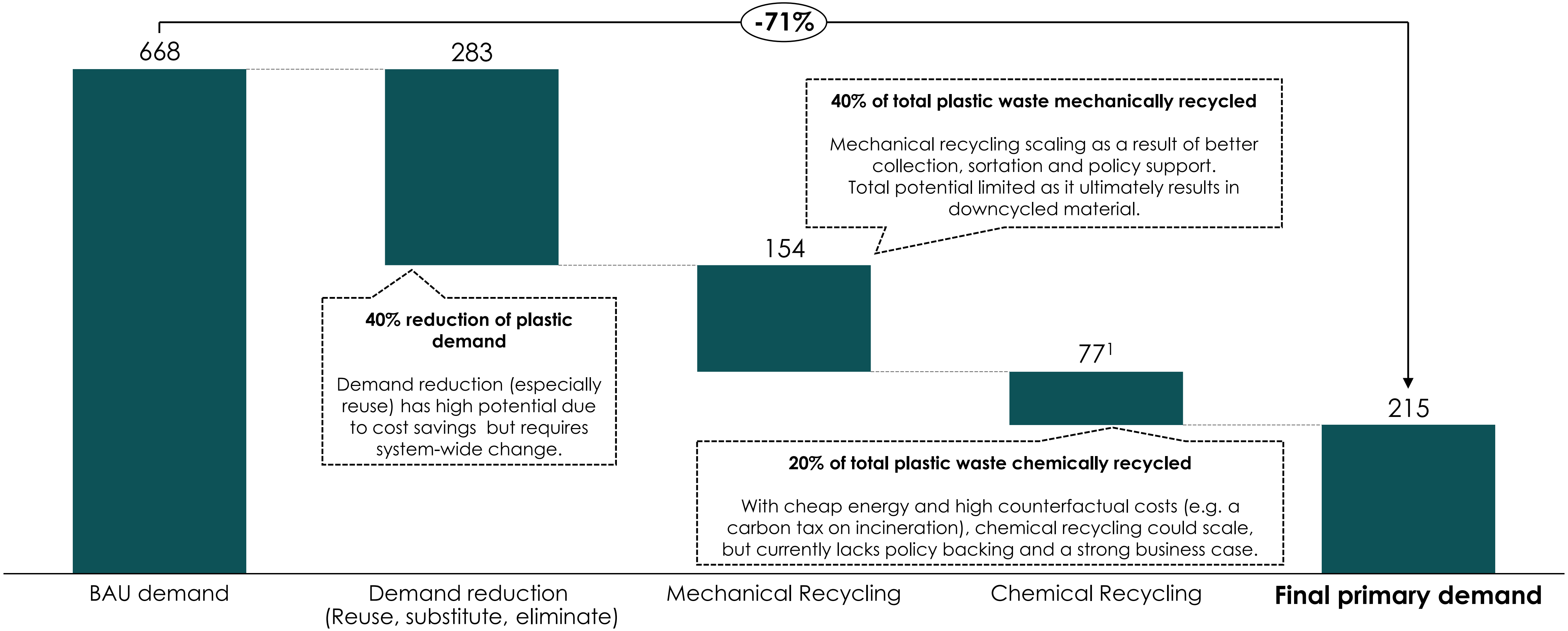
Sources: Depoly estimation is based on published data: Singh et al. (2021). Gasification and pyrolysis based on BEIS, NREL and Systemiq PCC model.

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)



40% reduction of plastic demand

Demand reduction (especially reuse) has high potential due to cost savings but requires system-wide change.

40% of total plastic waste mechanically recycled

Mechanical recycling scaling as a result of better collection, sortation and policy support. Total potential limited as it ultimately results in downcycled material.

20% of total plastic waste chemically recycled

With cheap energy and high counterfactual costs (e.g. a carbon tax on incineration), chemical recycling could scale, but currently lacks policy backing and a strong business case.

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

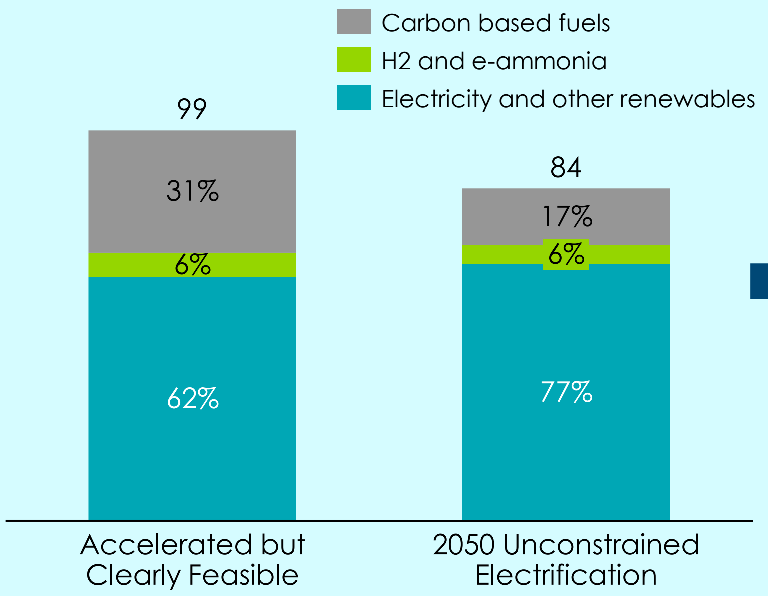
	2024	2025			
	Q4	Q1	Q2	Q3	Q4
Workplan	**Phase 1A** How large can and should the **role of direct electrification** be in a zero-emission economy **Phase 1B** **The role of hydrogen** and **derivatives (i.e., ammonia)** in a zero-emission economy?	**Phase 2** The potential to **recycle** and **reuse carbon molecules**	**Phase 3** **Sources** of **primary carbon: costs** and **sustainability** and **end-of life carbon management**	**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)	• 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	• 1-2 workshop with ETC reps/ commissioners	• Workshop • Report reviews • Report launch at COP	

Phase 3 of the carbon molecules analysis focuses on primary carbon, end of life management and cross-cutting insights

Phase 1
How much can we reduce carbon energy by maximising electrification

Final Energy Demand for ETC's ACF scenario in 2050

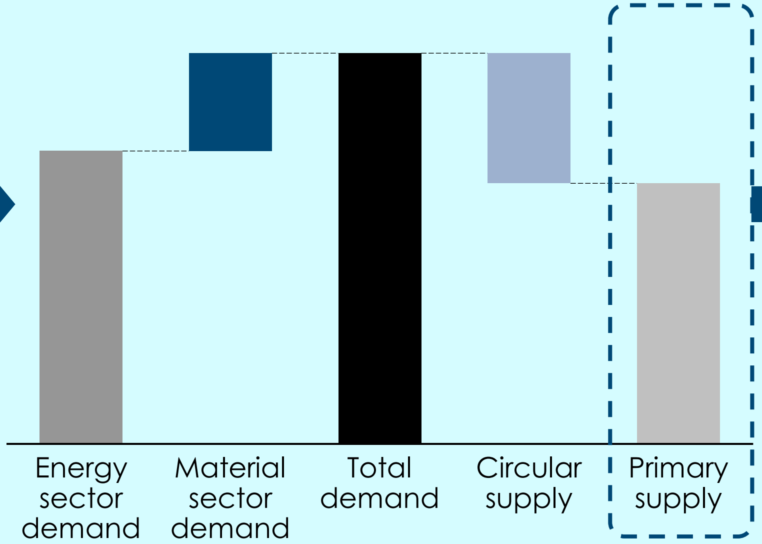
Thousand of TWh



Phase 2
What is total carbon demand and how much of it can be circular

Carbon demand and supply, 2050

Gigatons of carbon (C)

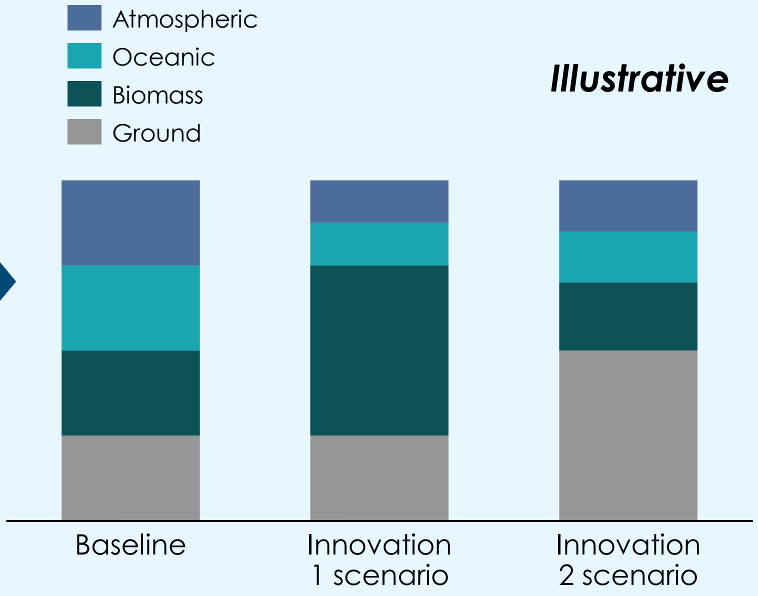


Phase 3
How do we sustainably source primary carbon & manage carbon at end of life

Scenarios for sourcing primary carbon supply

Gigatons of carbon (C)

Illustrative



Cross cutting trade-off analysis

Examples conclusions →

- Pushing circularity as far as we can will saving X million tonnes of primary carbon
- This will save DAC requirements of X tonnes of CO2/y
- Investment requirements for such as system are X

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

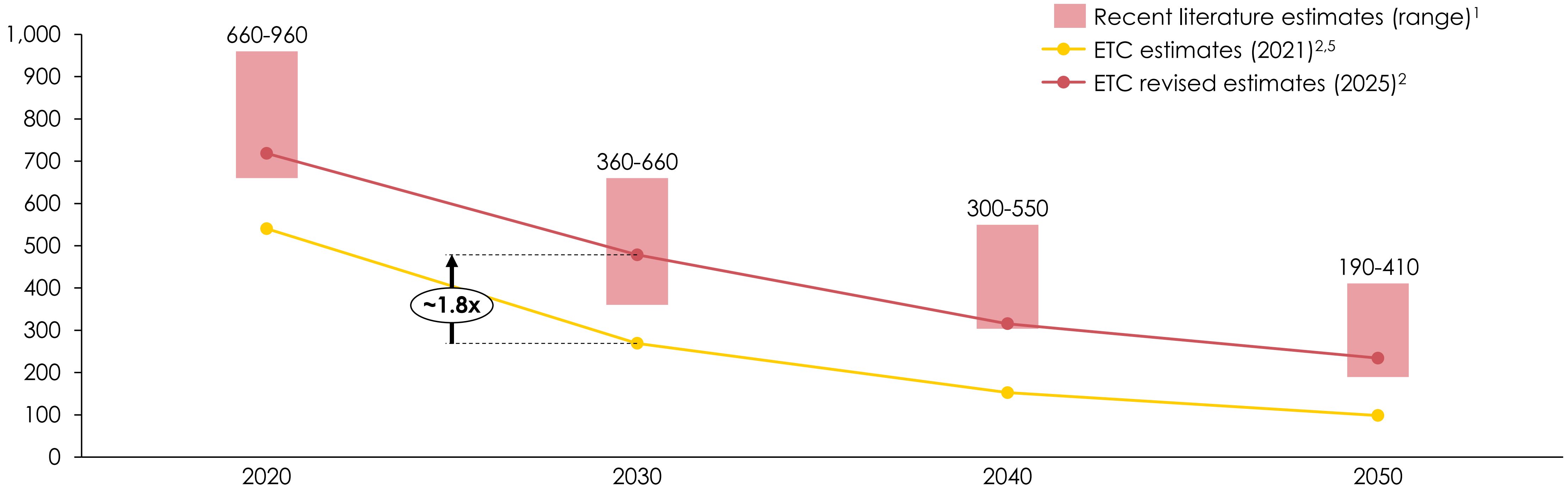
In focus today

Carbon source	Technology disruption	TRL	Companies
Direct Atmospheric	1 Direct air capture (advancements)	5-9	Carbon Engineering Heirloom climeworks
Oceanic	2 Ocean based CDR	5-6	captura Equatic SeaO$_2$
Biomass	3 Energy cane (incl degraded land)	6-9	raízen nuseed Nufarm Unilever
	4 Alternative proteins	3-8	Quorn SOLAR FOODS Mosa Meat air protein
	5 Macro and Micro algae	7-9	ATLANTIC SEA FARMS OCEANIUM Allmicroalgae natural products ALGAMA
	6 Advanced reactors and catalysts	6-9	novozymes TOPSOE VELOCYS VEOLIA
Ground (fossil and limestone)	7 Carbon capture - Liquid/solid absorption (advancements)	7-9	Shell AKER CARBON CAPTURE Svante INVENTYS RESEARCH FOR GOOD carbon clean
	8 Carbon capture - Process modification	7	8 RIVERS NETPOWER
	9 Carbon capture - Calcium looping	6-7	AIR PRODUCTS ExxonMobil

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 CO_2 capture via DAC – projections 2020-2050

$/t$CO_2$ (real 2025)



Key take-aways

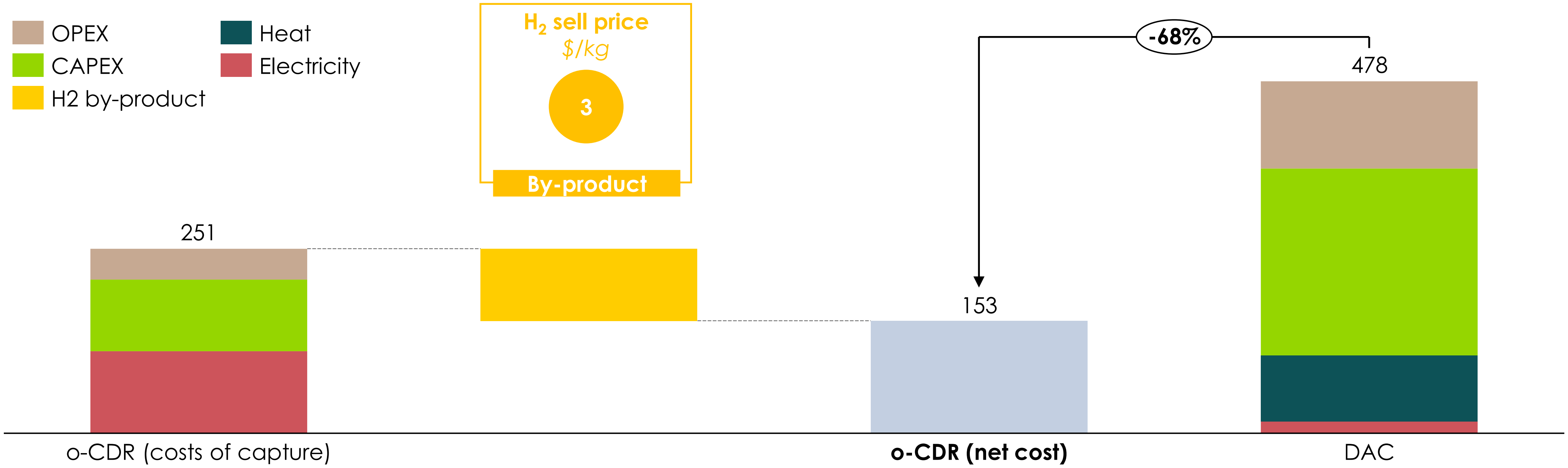
- Historical DAC cost projections have been optimistic with lower-than-realised capital costs and ongoing energy costs[3,4]
- Recent credible publications predict higher costs of DAC until 2050[1], which could hinder the technology's scale-up

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 CO_2 capture for direct air and direct water capture in 2030

$/t$CO_2$



Key takeaways

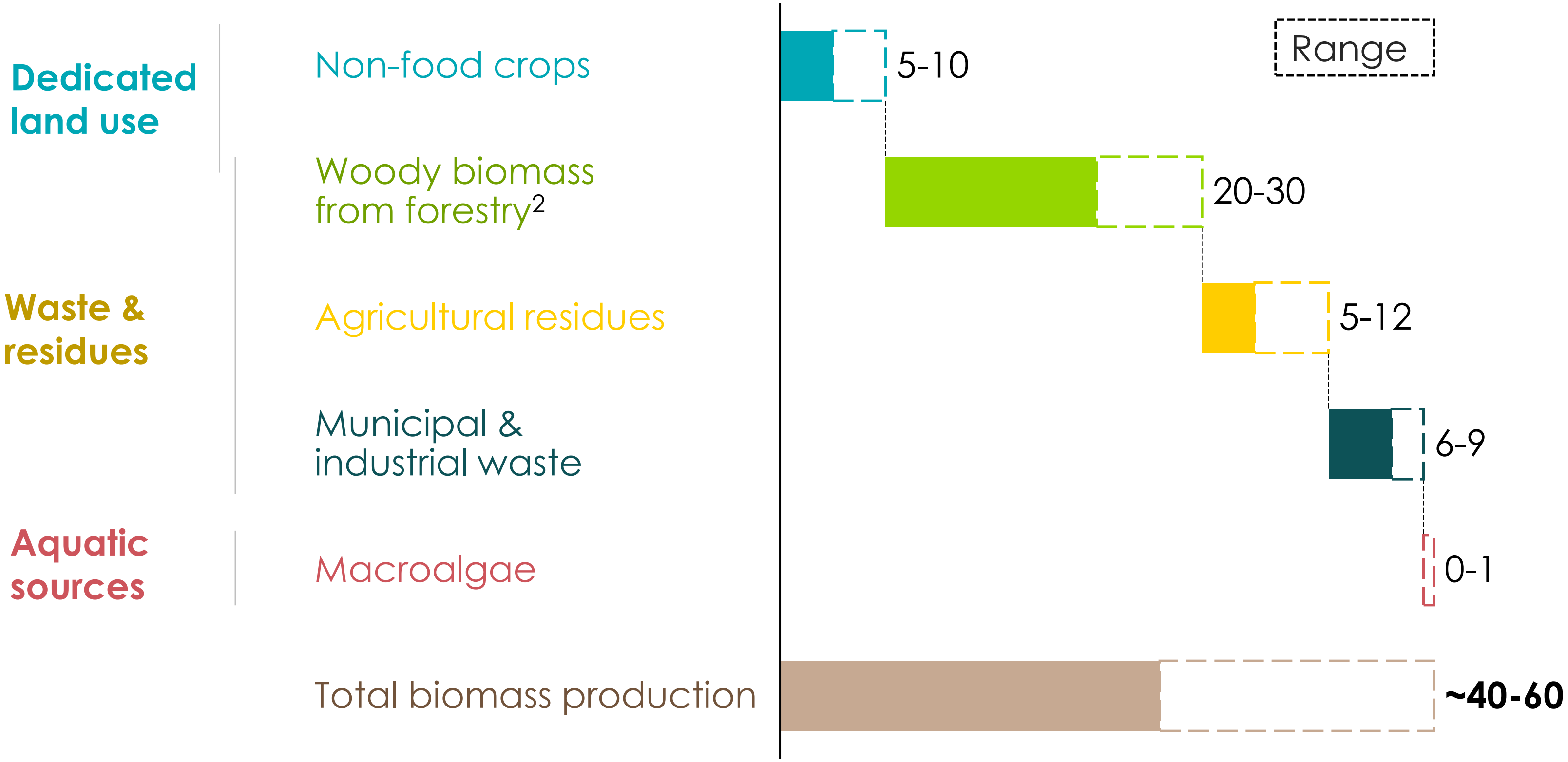
- Lower capex requirements and H_2 by-product could make o-CDR more economical than DAC. H_2 is only produced in electrolytic o-CDR routes that involve electrolysis
- Both DAC and o-CDR have high cost and scale-up risk, but DAC's stems from sorbent and thermal system uncertainty, while **o-CDR's depends 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 biomass[1] supply (2050) – illustrative scenario

EJ/year (primary energy)



Extra bioresource if radical change can happen

In focus

More productive land

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

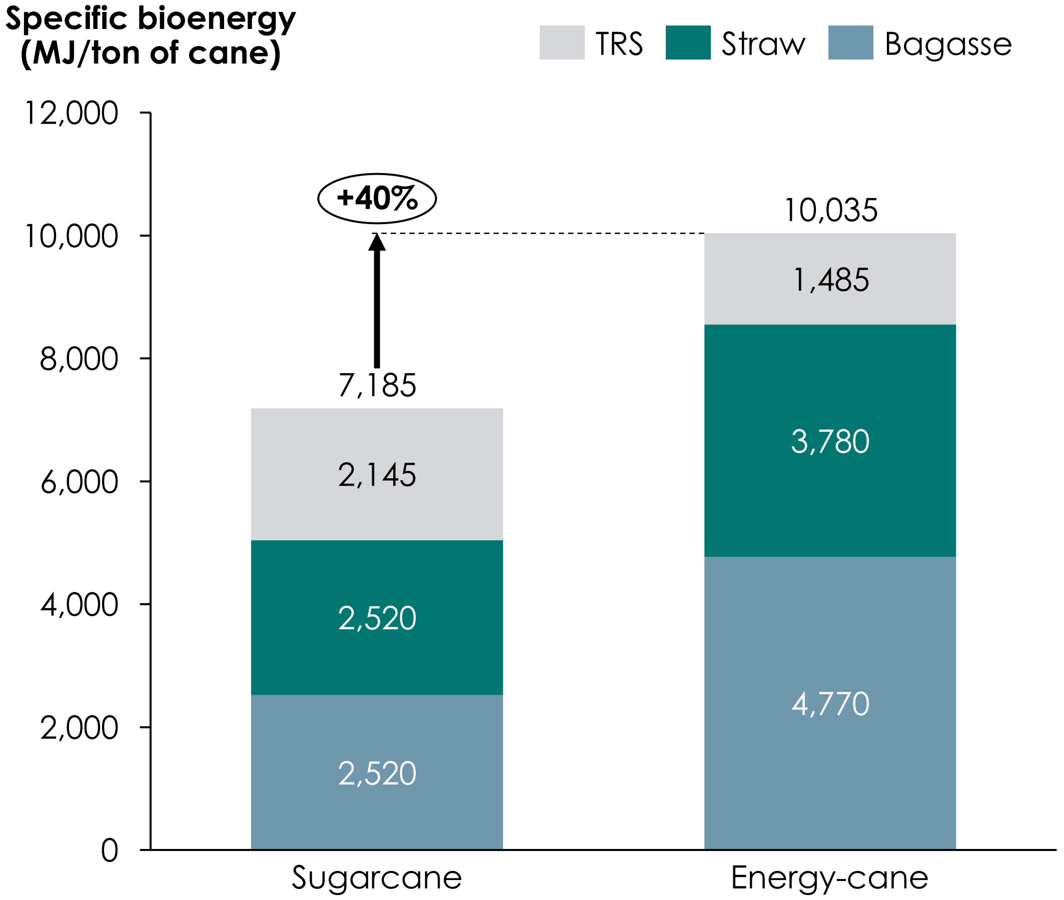
Development of macroalgae

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).

③④ 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 maximized[1]



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**	• **Base ingredients in meat-like foods** • e.g., mycoprotein **(Quorn)**, fungal burgers	
Precision fermentation (PF)	Make **specific molecules** for use as **ingredients**	• **Functional ingredients** for food production • e.g., **egg white** for baking, casein, rennet	
Cultivated meat (CM)	**Grow real meat** tissue from animal cells	• **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

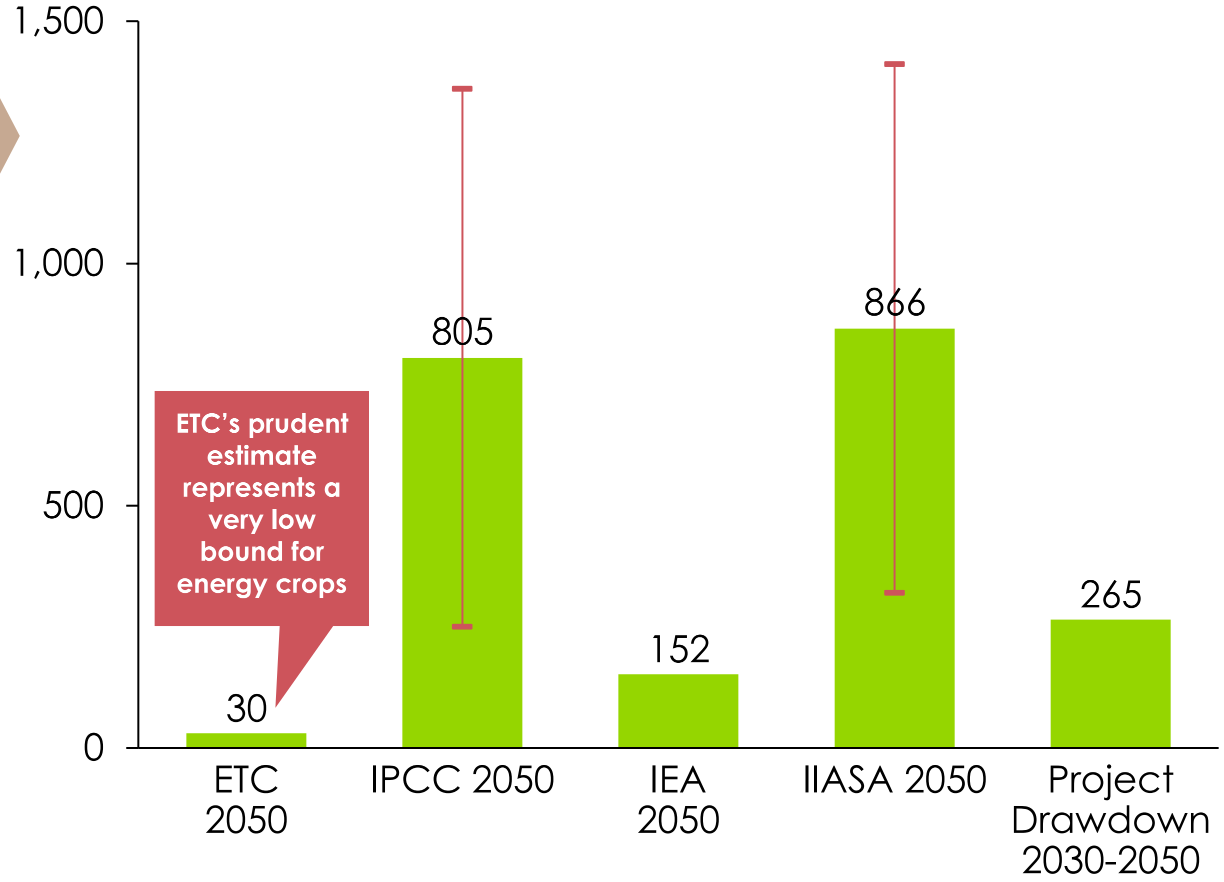
Options for ‘new’ land for sustainable biomass

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

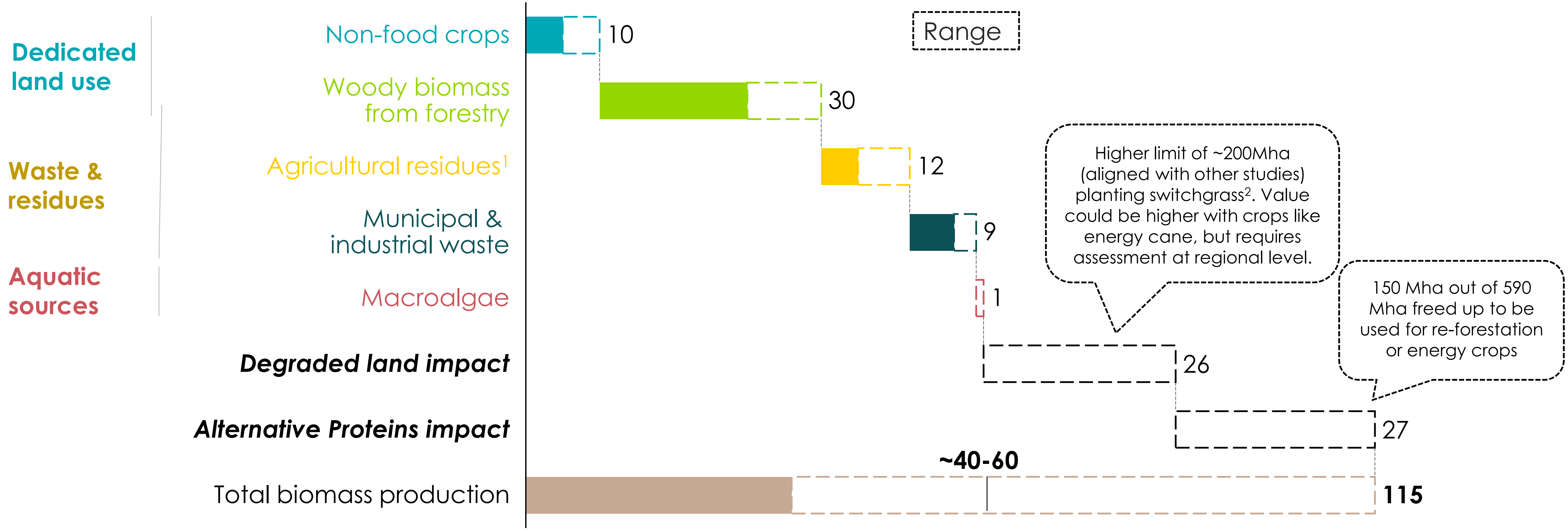


ETC’s prudent estimate represents a very low bound for energy crops

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)



Higher limit of ~200Mha (aligned with other studies) planting switchgrass[2]. Value could be higher with crops like energy cane, but requires assessment at regional level.

150 Mha out of 590 Mha freed up to be used for re-forestation or energy crops

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