Energy
Transitions
Commission

Transforming Power Systems: emerging insights

ETC Representatives Meeting

20th February 2025

Power work timeline and report

	Date	Deliverable
Workshop 1: Grid build challenge	March 26th 2024	Briefing note published in September 2024
Workshop 2: Key technologies to balance the system : *dispatchable generation, storage assets*	June 18th	
Workshop 3: Key technologies to balance the system: *demand side flexibility*	Oct 9th	Briefing Note published in February 2025
Workshop 4: Sizing the system balancing challenge	Oct 24th	
Workshop 5: Potential of long distance cross-border transmission	Dec 9th	Insights Briefing to be published in 2025
Workshop 6: Key enablers	Feb 3rd 2025	
Power systems transformation report ★	Q2 2025	Report publication

Report structure & agenda for today

The structure of this presentation follows that of the upcoming Power Report

1. Context on importance of clean electrification; challenges around running future power systems; role of emerging technologies
2. Managing the system balancing challenge
3. Building and optimising grids
4. Costs: how do these pathways influence costs
5. Key enablers to unlock the power system of the future

Agenda

1. Context on importance of clean electrification; challenges around running future power systems; role of emerging technologies
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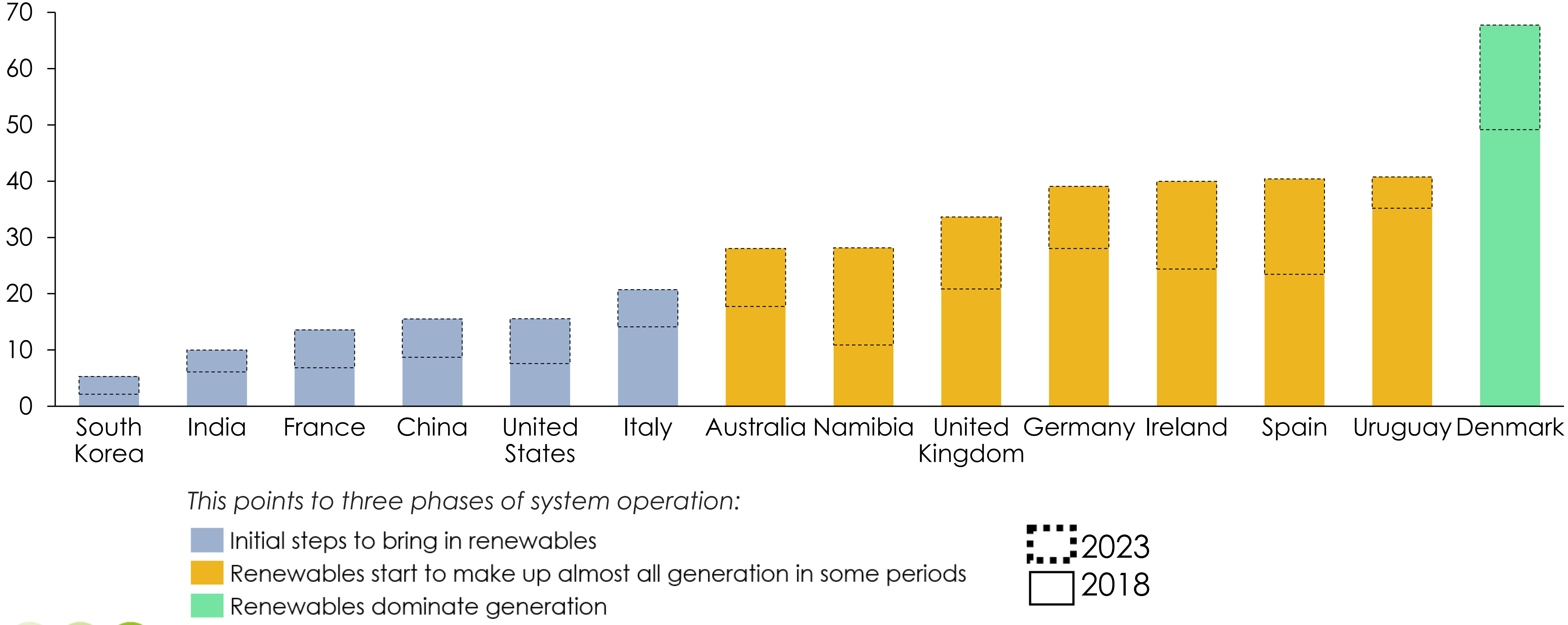
Wind and solar are growing as share of global power generation

Annual wind and solar share and corresponding system integration phase in selected countries

% Wind and solar annual electricity generation, 2018, 2023



Source: Ember (2024), *Electricity Data Explorer, featuring latest available data (2023)*

There are two key focus issues for power systems transformation

	"Build"		*"Optimise"*	
Building and optimising grids	**Tx: Grow the transmission network**	**Dx: Reinforcing existing & building new network infrastructure**	**Tx: Optimising use of existing assets via new technologies**	**Dx – Spreading peak load to increase grid utilisation & balance the system**

Grids – e.g. interconnectors and long-distance transmission can – in part – help to solve balancing challenge

Storage and flexibility deployed to solve system balancing can – in part - reduce the grid build needed & help to optimise

Managing the system balancing challenge (in high variable renewable systems)	**Ix / Tx – balancing the system via interconnection / long distance transmission**	**Balancing the system via storage, flexibility & generation technologies**

To meet the two challenges, role of several emerging technologies is critical

Build & optimise grids

Need to build vast amounts of new grids, as well as optimise new and existing grids for maximum efficiency.

Manage system balancing

Need to manage the system balancing challenge, which arises as the penetration of wind and solar grows

Innovative grid technologies

Flexible dispatchable generation

Energy storage

Heat storage

Demand side flexibility

Long distance interconnection

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System balancing occurs across different durations

A high-renewable power system must be able to meet several challenges…

Seconds
Minutes
Hours
Days
Weeks
Months

'System operation'
Inertia, frequency response, voltage control, fault ride through

Short duration balancing (up to 8 hours)

- Predictable daily: e.g. large daytime solar output but significant demands during the evening
- Unpredictable daily: Deviations from average generation patterns (e.g.. cloudy days in summer)

Medium-Long duration (8 hours to 50 hours)
Variations (e.g. seasonal) driven by either :

- Demand (e.g. winter heating peak in Europe, A/C peak in southern China or India in summer)
- Or supply (e.g. Indian wind during monsoon , European sun in summer)

Ultra Long (50+ hours)
Primarily unpredictable variations driven by:

- Demand (e.g. above normal AC peak from heatwaves; cold period heating demand)
- Anticyclone wind drought

Challenge that existed in fossil system, but now needs to be met with new technologies

New challenges that must be met for high-renewables power systems due to intermittent nature of generation

There are a set of balancing options across durations

			System operation	Short duration	Medium duration	Security of supply
Dispatchable generation	Other zero carbon	Hydro, nuclear[1]	✓	✓	✓	(✓)
	Fossil	Fossil (or bioenergy) + CCS	✓	✓	✓	✓
		Fossil – low/very low utilisation	✓	✓	✓	✓
Long distance transmission		Accessing complementary weather patterns and time shifting generation	(✓)	(✓)	(✓)	(✓)
Energy storage		Pumped hydro	✓	✓	✓	(✓)
		Lithium ion battery[2]	✓	✓	(✓)	
		Other technology (i.e. CAES, liquid air, etc.)[3]	✓	✓	✓	(✓)
		Power-to-X (i.e. H2)[4]	✓	✓	✓	✓
Heat storage		Heat battery		✓		
Demand side flexibility		EV (smart charging, V2G)		✓		
		Heating load[5]		✓		
		Industrial load[6]		✓	✓	

Notes: 1. Limited nuclear capacity for flexible ramping. 2. Li-ion storage is utility-scale and behind-the-meter. 3. Emerging tech night include gravitational storage and molten sands storage. 4. Examples of Power-to-X include the production of H2 from electrolysis and re-conversion of hydrogen in power via gas turbines or fuel cells. 5. Residential and commercial standard heating needs6. Including hydrogen electrolysis, where production can be shifted to optimal times. Source: Adapted from Climate policy Initiative for the Energy Transitions Commission (2017), *Low-cost, low-carbon power systems*

Short-duration flexibility "ladder" highlights key opportunities

High priority
Low cost, low barriers, high efficiency, potential for automation

	Demand-side flexibility (DSF) solutions: Shedding	Demand-side flexibility (DSF) solutions: Shifting	Demand-side flexibility (DSF) solutions: Storage	Other solutions
A Virtually free solutions	**Home smart systems** (actions either combined or separate): Dynamic temperature adjustment (heat pump/AC)	Pre-heating /cooling in well insulated homes; Smart appliances; EV smart charging (residential)		
B Low-cost, easy-to-implement solutions	**Commercial building management systems**: Lighting sensors; Centralised, dynamic HVAC systems	Crypto mining; Shifting (some) data centre demand[1]	Hot water storage	Grid scale lithium-ion batteries; Existing flexible hydro; Existing interconnectors
C Moderate-cost and/or automated solutions	Running aluminium electrolysis flexibly; Timing "batch" production processes (e.g., paper, food)	Running industrial maintenance flexibly	Industrial heat battery-boilers (e.g. heat storage); Distributed energy storage (e.g., batteries)	
D High-potential but capital-intensive solutions		Running H2 electrolysers flexibly	Residential Vehicle to Grid (V2G)	New interconnectors; Medium-duration storage[2]
E Sector-specific, high-cost solutions	Flexible manufacturing (continuous) processes (e.g., chemicals)			
F Expensive, low-priority solutions	Strategic industry shutdowns			
G Undesirable	Rolling blackouts			

Low priority / Undesirable
High cost, high barriers

Notes: Ladder concept based on Michael Liebreich's Hydrogen Ladder
[1]Non-critical data processes, such as AI training, can be **postponed or shifted** to low-demand periods without real-time constraints. Flexibility also exists when companies run computing centres across different countries / regions to allow **load shifts over geographies**
[2]Medium-duration storage (including pumped hydro) **is less competitive for short-duration balancing** than batteries, driven by the higher round-trip efficiency of batteries.

ETC analysis on long-distance transmission links highlights high potential

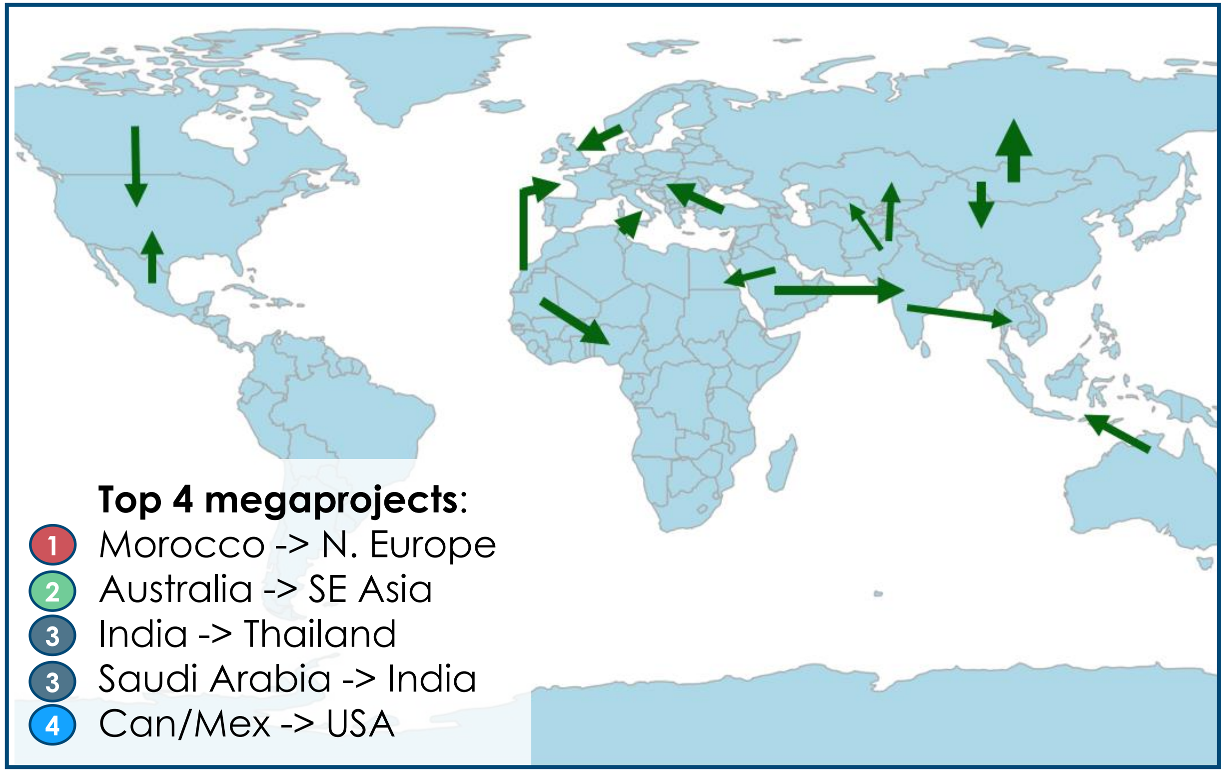
Long distance transmission can help to deliver:

- 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

ETC analysis, using a global optimisation model of wind and solar supply and demand, suggests a small number of high potential links could deliver in 2050:

- 15% of global power demand,
- 1.8 Gt per annum carbon reductions (equal to 13% of global power sector emissions),
- $90bn dollars of savings per year

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



Notes: Top 10 lines based on results across all metrics, amended for political feasibility (trading power between allied nations, not crossing excessive country borders). Largest line shown = India to Thailand, at 480 TWh; smallest shown Mexico to USA at 170 TWh.
Source: Systemiq analysis for the ETC.

The costs associated with different balancing durations vary significantly

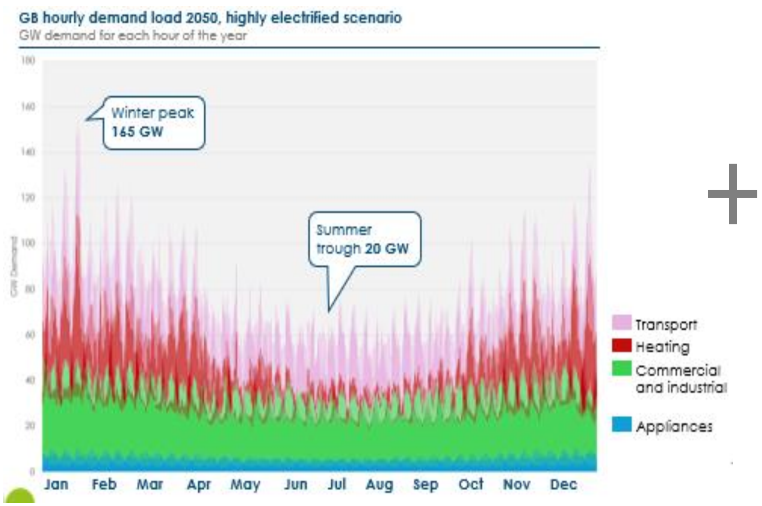
Balancing needs	Key zero-carbon balancing technologies across durations		Cost of delivered electricity cost in 2035[1] $/MWh (real 2024$)
Short / hourly duration (up to 8 hours)	Demand-side flexibility		<0 – 50
	Lithium-ion and sodium-ion batteries		160 – 200
	Heat storage		75 – 150
Medium-Long duration (up to 50 hours)	Energy storage (pumped hydro, compressed air, batteries)		40 – 380
	Long-distance transmission (for balancing)		50 – 70
	Running nuclear flexibly	*Existing:*	40 – 90
		New build:	60 – 480
	Running hydro flexibly	*Existing:*	15 – 30
		New build:	50 – 180
Ultra-long (50 hours+)	H2 in CCGT, CCS on CCGT (low utilisation)		180 – 435
	Unabated gas (low utilisation)		90 – 200

[1] The DSF range assumes that DSF can reduce total system costs at the lower end (through reducing overall demand) and that upgrades to smart, DSF-capable systems incurs a net cost at the upper end. LCOS calculations assume electricity input cost of $0.06/kWh. All batteries are full LCOS calculations including cost of electricity usage. Heat storage source based on Rondo heat battery LCOS and BNEF thermal LCOS figures for solid state and molten salt storage. Other figures are based on ETC analysis.

We have compared supply and demand patterns to quantify the balancing challenge for 100% wind and solar generation systems

This has been carried out for India, UK, and China archetypes and will also be carried out for Spain.

Demand



Detailed 2050 hourly load profiles obtained from expert forecasters which are reflective of high electrification and specific peak profiles (i.e. UK ESO, TERI in India)

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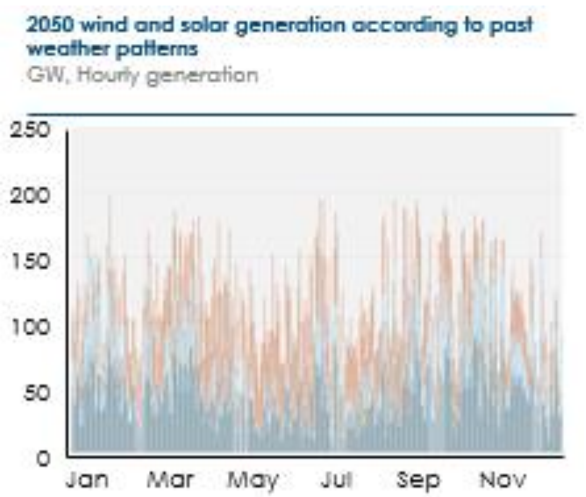
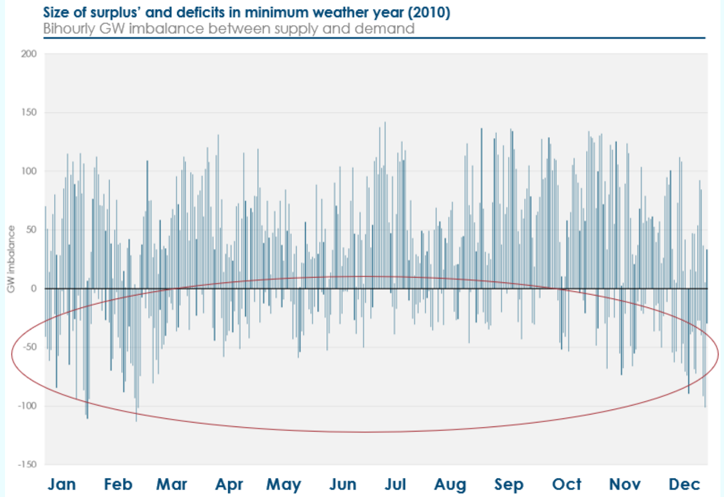
Supply (wind + solar)[1]



Bihourly weather data obtained for past 30 years (1994-2023); assumed wind and solar deployment for each country; weather patterns applied to renewables to provide generation across low-high scenarios)

Balancing



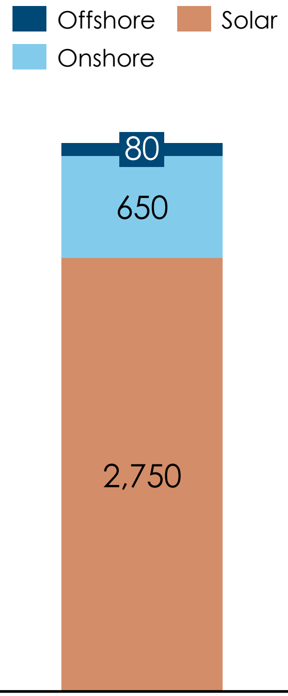
Matching at bi-hourly level across demand and supply to assess periods of wind & solar generation excess/shortfall relative to demand. Charging/discharging rates and efficiencies were used to prioritise short-, medium- and long-duration storage options to optimally balance the system.

[1] Baseload low-carbon might replace some wind and solar as low-cost generation (if lowest-cost), but wind and solar generation on the system would still lead to a balancing challenge. Therefore, this analysis does not embed any low-carbon baseload mix into "sizing" the challenge; it focuses on assessing the "full" balancing challenge in an 100% wind and solar system.

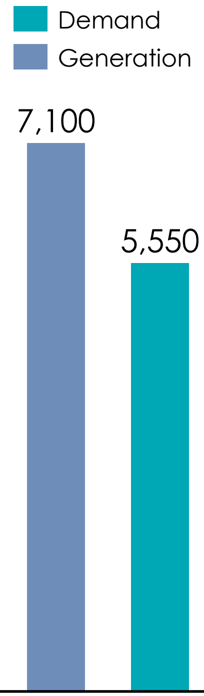
India: 2050 generation and storage mix will drive total system generation cost

Scenario: Core scenario, India

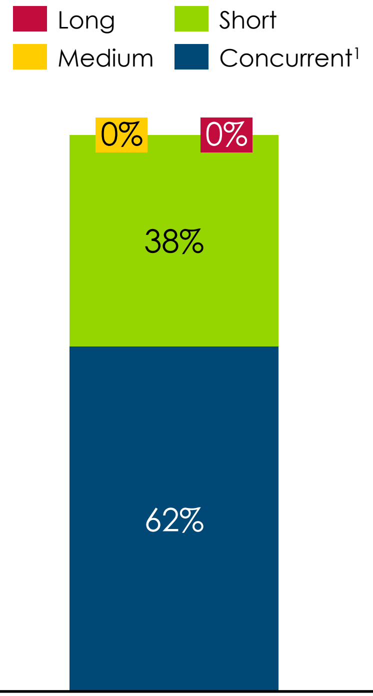
Generation Capacity (GW)



Total generation[2] and demand (TWh)



Balancing variability (% mix of total demand)



Generation and storage deployment and costs

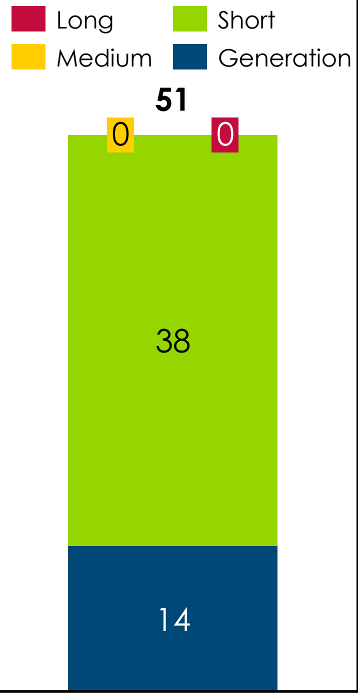
Generation:
7,100 TWh
@ **$15/MWh**

Short storage:
2100 TWh
@ **$100/MWh**

Medium:
0 TWh
@ **$120/MWh**

Long:
0 TWh
@ **$240/MWh**

System generation cost ($/MWh, real 2024$)



Considerations

- Balancing through **short storage** – significant battery capacity required.
- **Higher solar-to-wind ratio** covers extended lulls in monsoon generation.
- Localised distribution helps manage daily fluctuations.
- Short-duration balancing makes a significantly higher contribution to the total system generation cost than wind/solar generation.

- System generation costs are derived by multiplying total system generation/storage requirements (in TWh) by assumed costs (in $/MWh).
- These cost assumptions are representative of projects commencing in 2050, therefore the system cost is for a future, steady state system (post-2050).

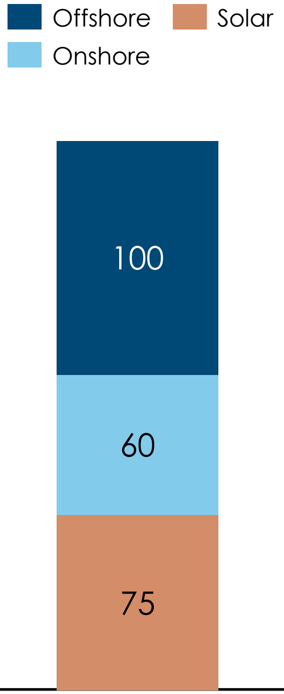
[1] Wind/solar supply and demand are concurrent, meaning that no storage is required during these times. [2] Surplus generation (the difference between demand and generation) is either curtailed or used in electrolysers.
Source: Systemiq analysis for the ETC (2024)

UK: 2050 generation and storage mix will drive total system generation cost

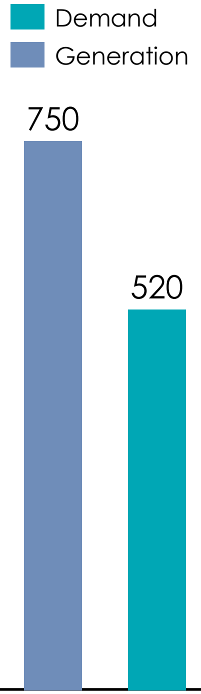
Scenario

Core scenario, UK

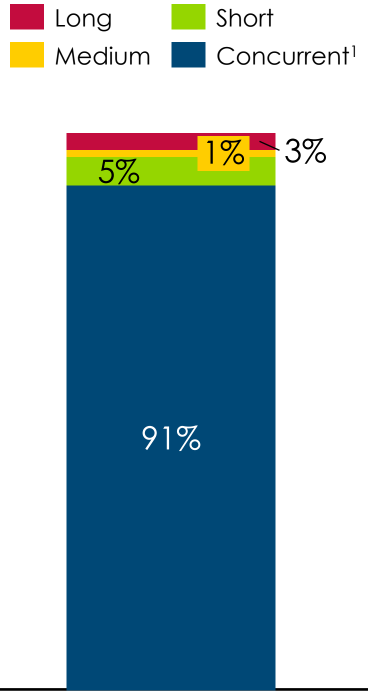
Generation Capacity (GW)



Total generation[2] and demand (TWh)



Balancing variability (% mix of total demand)



Generation and storage deployment and costs

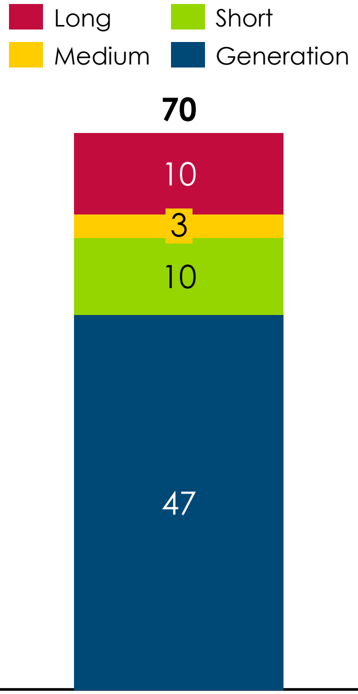
Generation:
750 TWh
@ **$35/MWh**

Short storage:
30 TWh
@ **$190/MWh**

Medium:
10 TWh
@ **$230/MWh**

Long:
20 TWh @
$340/MWh

System generation cost ($/MWh, real 2024$)



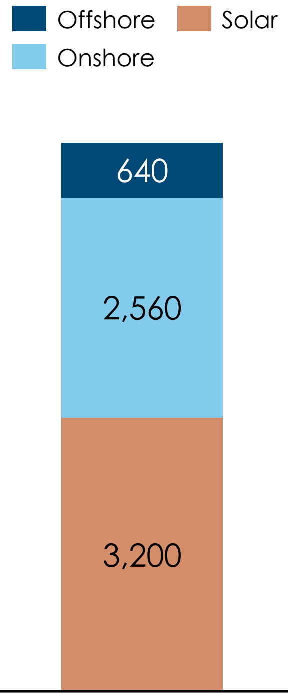
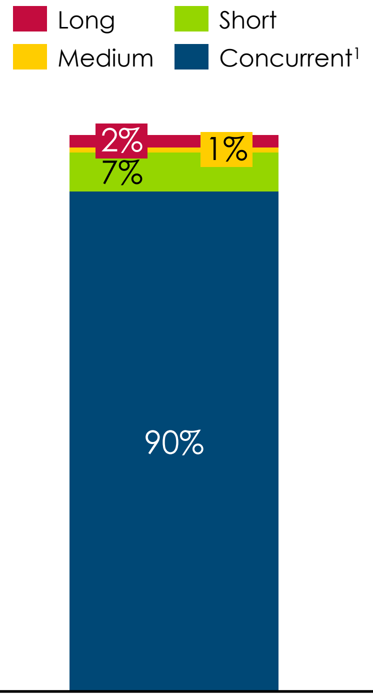
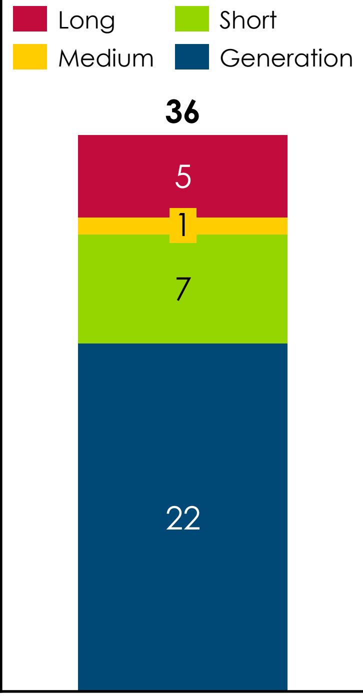
Considerations

- Balancing through **all types of storage**
- Presence of long duration storage diminishes role for medium duration.
- Generation patterns vary across regions, requiring long storage to handle prolonged deficits.
- Generation makes the highest contribution to the total system generation cost, with short/long-duration storage making up most of the balancing costs.

- System generation costs are derived by multiplying total system generation/storage requirements (in TWh) by assumed costs (in $/MWh).
- These cost assumptions are representative of projects commencing in 2050, therefore the system cost is for a future, steady state system (post-2050).

[1]Wind/solar supply and demand are concurrent, meaning that no storage is required during these times. [2]Surplus generation (the difference between demand and generation) is either curtailed or used in electrolysers.
Source: Systemiq analysis for the ETC (2024)

China: 2050 generation and storage mix will drive total system generation cost

Scenario	Generation Capacity (GW)	Total generation[2] and demand (TWh)	Balancing variability (% mix of total demand)	Generation and storage deployment and costs	System generation cost ($/MWh, real 2024$)	Considerations
Core scenario, China 				**Generation:** 18,300 TWh @ $20/MWh **Short storage**: 1050 TWh @ $100/MWh **Medium**: 130 TWh @ $120/MWh **Long**: 330 TWh @ $240/MWh		• Balancing through **all types of storage** • Generation patterns vary across regions, requiring long storage to handle prolonged deficits • Generation makes the highest contribution to the total system generation cost, with short- and long-duration storage making up the bulk of the balancing costs.

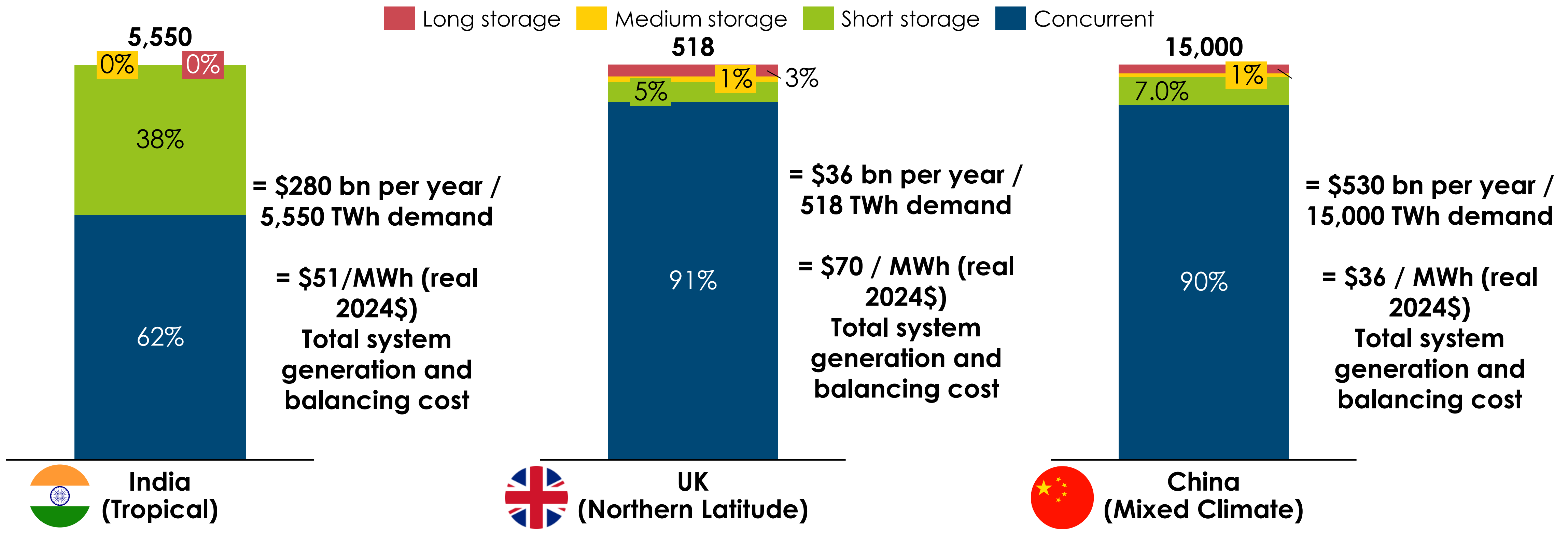
- System generation costs are derived by multiplying total system generation/storage requirements (in TWh) by assumed costs (in $/MWh).
- These cost assumptions are representative of projects commencing in 2050, therefore the system cost is for a future, steady state system (post-2050).

[1] Wind/solar supply and demand are concurrent, meaning that no storage is required during these times. [2] Surplus generation (the difference between demand and generation) is either curtailed or used in electrolysers.
Source: Systemiq analysis for the ETC (2024)

Balancing needs and total system costs will across regional archetypes

Balancing variability for India, UK, and China in systems with high shares of wind/solar

% of TWh of annual demand provided by specified generation/storage



Primarily a diurnal challenge

Balancing required across short, medium and long durations

Source: Systemiq analysis for the ETC (2024)

Agenda

1. Context on importance of clean electrification; challenges around running future power systems; role of emerging technologies
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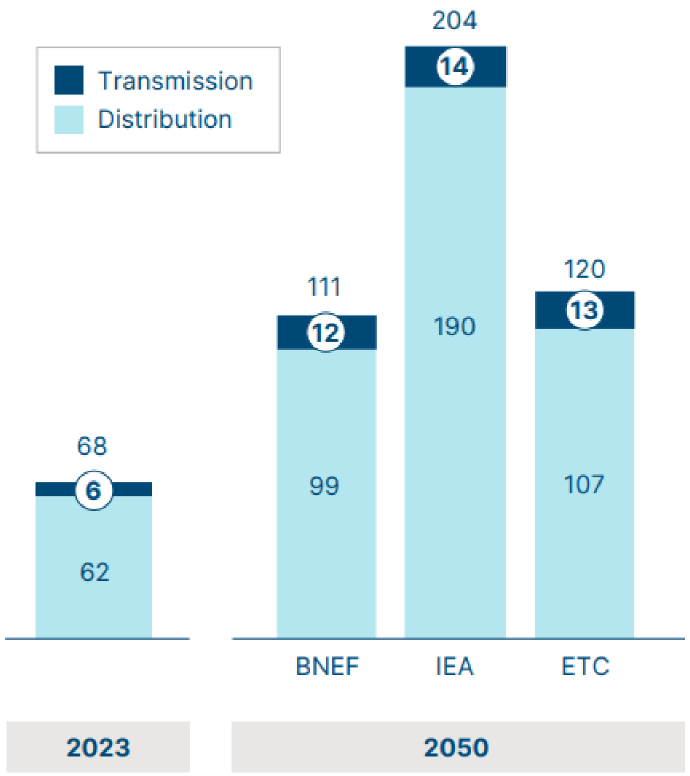
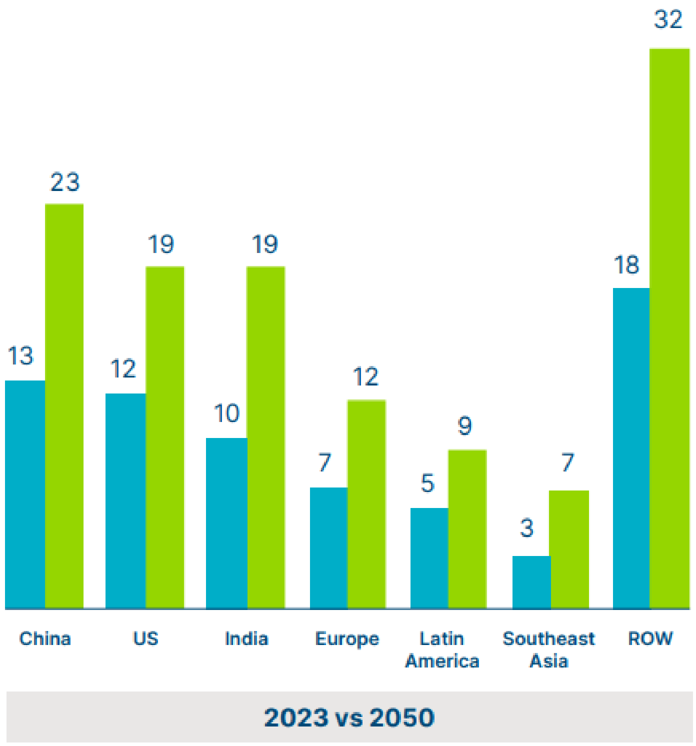
Transmission and distribution network build will have to increase drastically across regions

Estimated wires required under various assumptions
Million km



Significantly more transmission and distribution wires are needed

Estimated wires required from 2023 to 2050
Million km



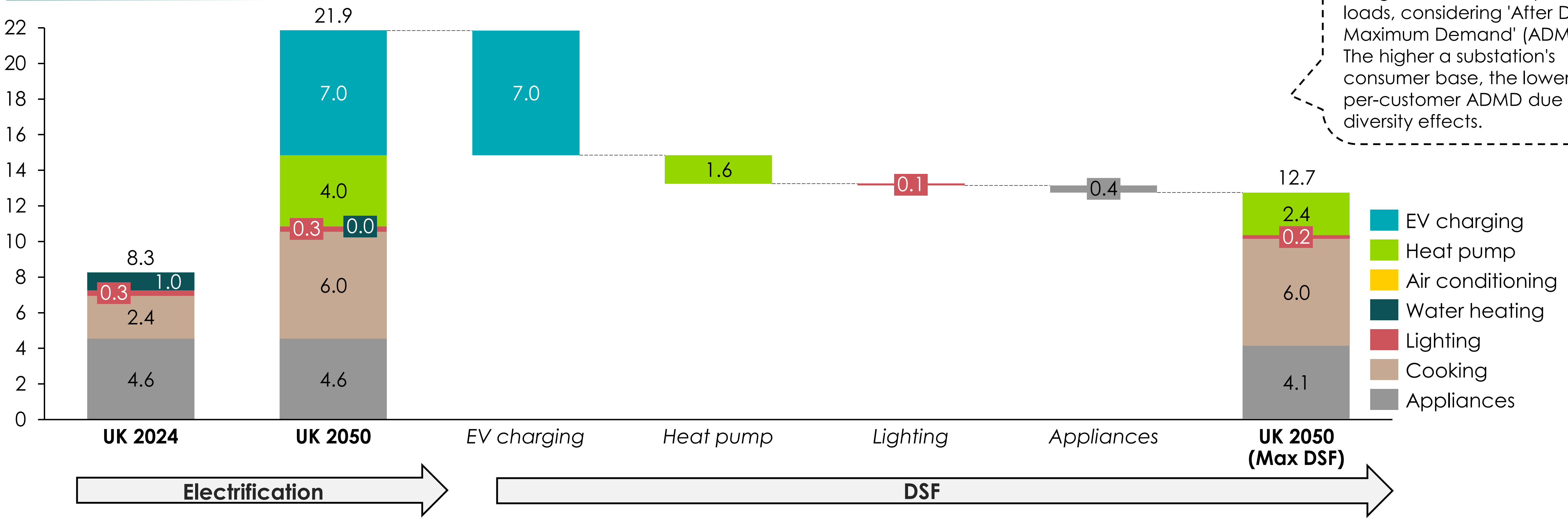
All regions will have to increase their estimated wire build substantially under a net-zero scenario

- **Grid growth should aim to optimise the system**, reducing total build required by deploying:
  - 1)**Innovative grid technologies** that increase the efficiency of power flows
  - 2) **increasing storage and flexibility** and
  - 3) use of **long-distance interconnectors**.
- **However, even full deployment of all optimisation routes will not eliminate the need to build new grids**

Increases in household-level peak power demand are expected, although DSF can offset some peak demand increase

Typical UK household demand impacts driven by electrification and DSF

Potential Winter Peak (kW)



Local distribution networks are designed to cater for peak loads, considering 'After Diversity Maximum Demand' (ADMD). The higher a substation's consumer base, the lower the per-customer ADMD due to load diversity effects.

Electrification

- Heat pumps will draw approximately 4 kW, driving the potential peak increase.
- Electric vehicle (EV) charging could contribute around 7 kW to the peak demand (1/3 of the total).

DSF

EVs: EVs could be fully shifted assuming price mechanisms which incentivise shifting (requiring automation).

Heat pumps: 50-60% of peak demand can be shifted / shed[1].

Lighting: Lighting loads could be reduced 14-23% via DSF solutions in UK and India.

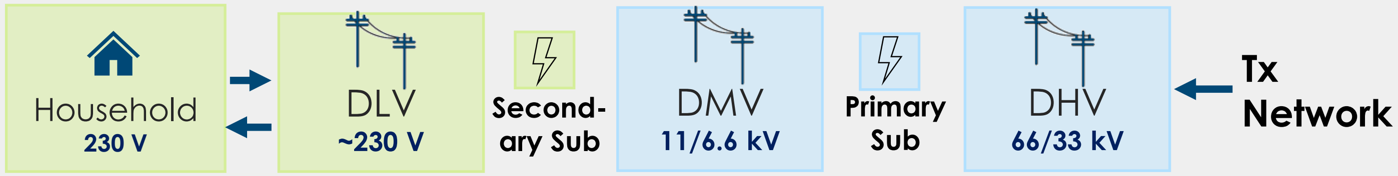
Appliances: 10% DSF during peak demand assumed for other appliances in UK and India, however this is ess critical for grid flexibility.

[1]Heat pump DSF assumptions based on DSF workshop: peak demand reduced via: load shift: 3-14% using thermal inertia; 25% shifting heating loads to off-peak using TES; load shed: 5% thermal inertia, 20% lowering room temp set-point.

Future consumer demand increases will affect the upgrade requirements of each stage of the distribution network

Country	2050 household peak demand increase (vs 2024) (%)	DSF household & secondary sub. peak reduction (vs 2050 w/o DSF) (%)	2050 primary sub. demand increase (vs 2024) (%)	DSF primary sub. peak reduction (vs 2050 w/o DSF) (%)	DSF aggregated upgrade costs impacts per primary sub. (vs 2050 w/o DSF) (%)
UK urban archetype case study[1]	↑ 165%	↓ -40%	↑ 630%	↓ -25%	↓ -60%
India urban archetype case study[2]	↑ 530%	↓ -40%	↑ 250%	↓ -30%	↓ -45%

Dx network schematic:



Key Considerations

- We have simplified the significant variations across demand zones (including ADMD patterns).
- A key potential impact of DSF is the potential to buy more time for grid upgrades.
- DSF could reduce redundancy requirements.
- There are increasingly blurred lines between voltage levels.

[1]**UK assumptions:** 117 final customers per secondary sub. with 336 kW existing capacity; 17,500 final customers per primary sub. with 15 MW existing capacity.
[2]**India assumptions:** 500 final customers per secondary sub. with 126 kW existing capacity; 30,000 final customers per primary sub. with 3.3 MW existing capacity.

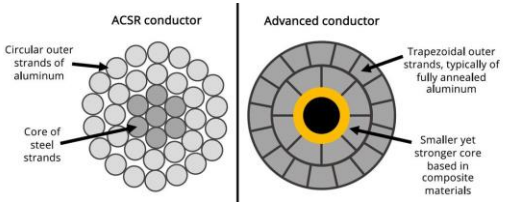
Innovative Grid Technologies (IGTs) can improve grid efficiency through changes to pylons and wires, reducing buildout and local opposition

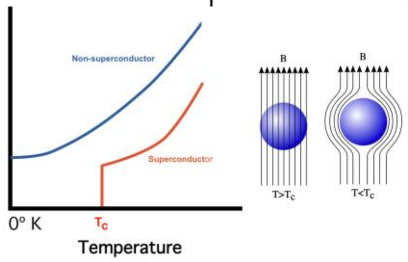
Changes to pylons and wires

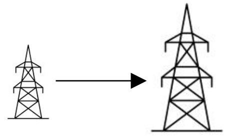
Direct capacity improvement compared to conventional technologies

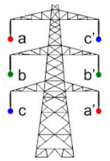
Digital twins, flexibility software management solutions

Technology options:	Method to increase grid capacity:	Network capacity increase*
Advanced conductors	Improved versions of traditional metal conductors, reinforced with composite materials, allowing for higher capacities per line.	**100%**
Superconductors	Superconductors eliminate electrical resistance, allowing for zero energy loss during transmission.	**400 - 1000%**
Voltage upgrade (via larger pylons)	High voltages reduce losses, enabling higher power transfer, improving stability, and optimizing infrastructure use.	**400+%[1]**
Double circuiting	Two transmission circuits per corridor doubles the power-carrying capacity of a transmission line compared to a single circuit.	**100%**
Storage as transmission asset (SATA)	Backup batteries can override the N-1 criterion, which ensures that the power system remains stable after a failure without exceeding security limits.	**40%**









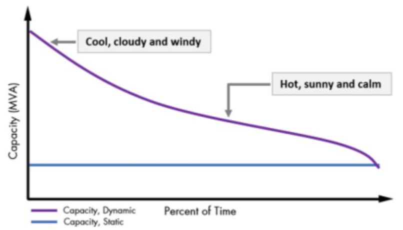
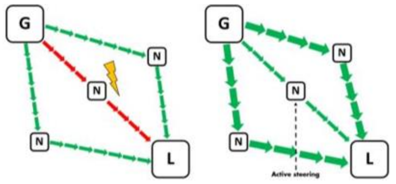
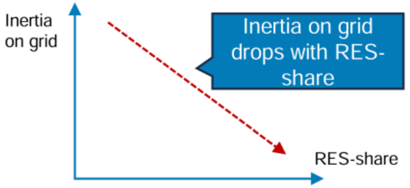
Total network capacity improvement, via changes to pylons and wires and optimising wires and networks: 10 - 40%

[1] Capacity increase depends on the voltage upgrade.
Note: * Network capacity increase = **increase (% of line capacity):**
Source: CurrENT (2024) *Prospects for innovative power grid technologies.*

IGTs can also improve efficiency by optimising current wires and networks, reducing buildout and local opposition

Optimising wires and networks
Improving the monitoring and control of power flows

Digital twins, flexibility software management solutions

Technology options:	Main methods to increase grid capacity:	Network capacity increase*	
Dynamic Line Rating	**Better understanding of actual line limits** • Improves efficiency by giving system operators better visibility and enabling them to respond to real-time temperature and sag of power lines. • Dynamic ratings exploit natural line cooling	**30%**	
Flexible AC Transmission systems (FACTS)	**Dynamically controlling power flows on the grid** • Power flows through a network are often limited by its weakest line • By dynamically controlling power flows (e.g., like road traffic management), more capacity is unlocked on the existing grid	**30%**	
Grid inertia measurements	**Better understanding of actual inertia limits/stability limits** • Inertia on the grid decreases with more renewables in the system, which may cause stability issues and curtailment. • Precise inertia measurement in real-time enables targeted inertia procurementa and minimises curtailment.	**30%[1]**	

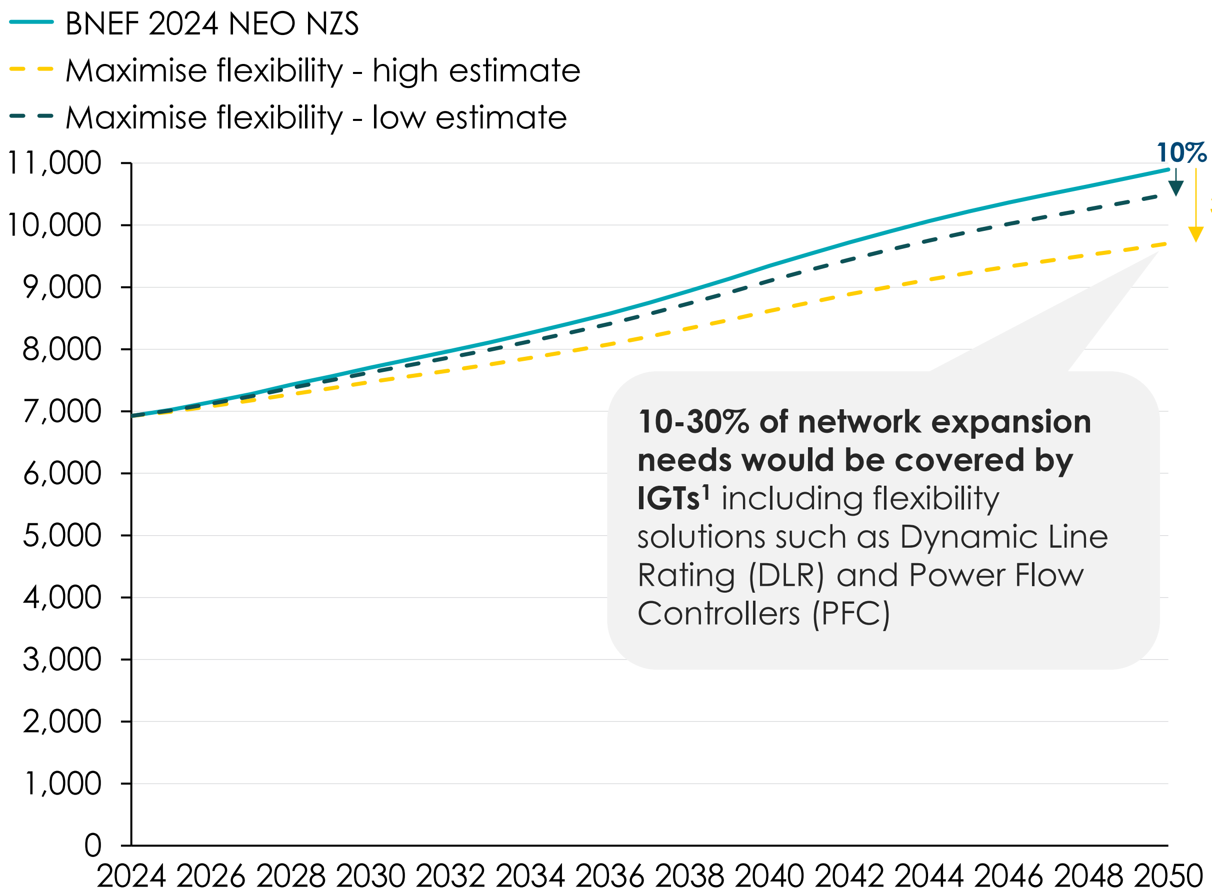
Total network capacity improvement, via changes to pylons and wires and optimising wires and networks: 10 - 40%

[1] Reduction in renewables output due to 30% higher inertia compared to conventional lines.
Note: **(% of line capacity):** Source: CurrENT (2024) *Prospects for innovative power grid technologies.*

IGTs could significantly reduce grid build and reduce CAPEX spending

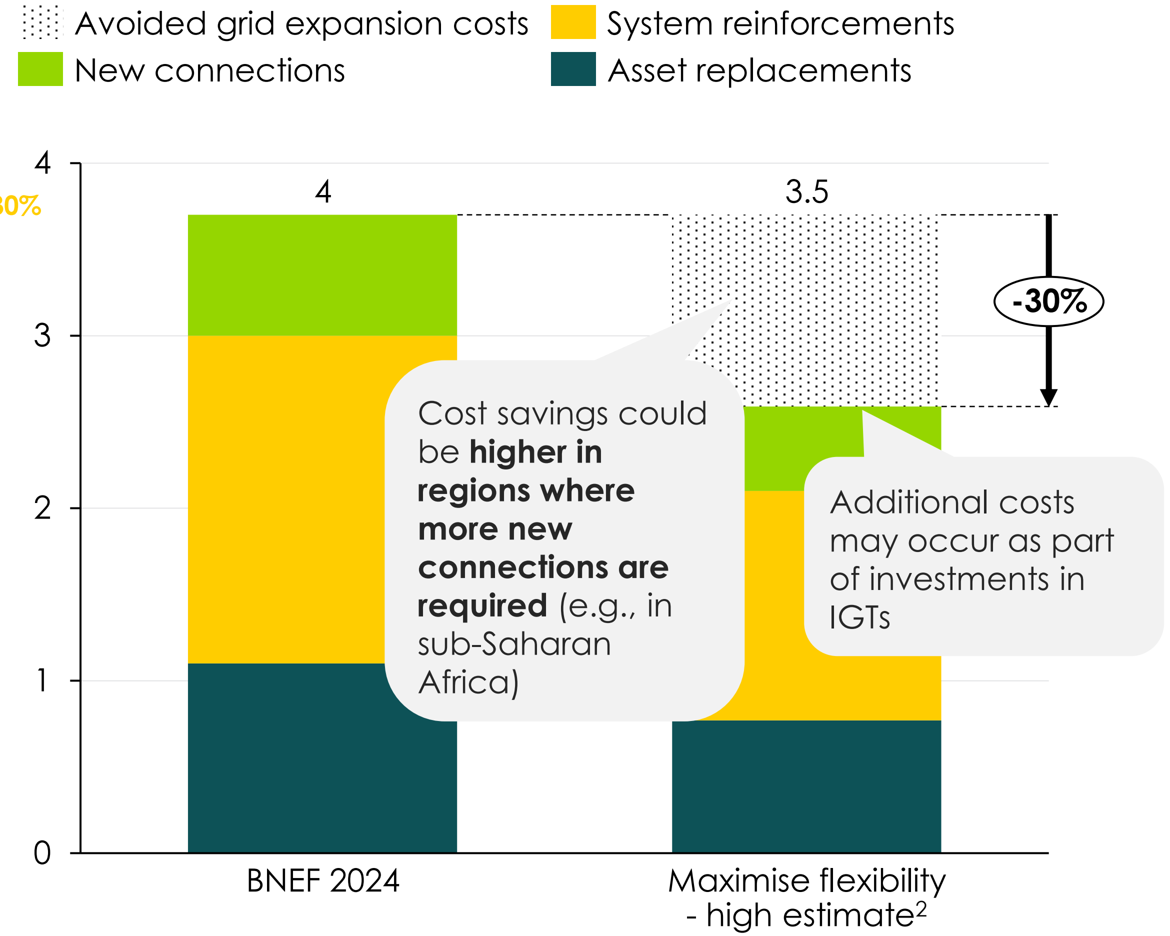
Benefits of IGTs compared to network expansion needs

1,000 km, Europe, 2024–2050



Cumulative investment in new power grid system, Europe

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



[1] Accounting for the inclusion of some flexibility in BNEF's 2024 estimate, hence the lower impact estimate than the 10-40% range on the IGT slides.
[2] It has been assumed that the 30% avoided costs apply to new connections, system reinforcements, and asset replacements.
Source: CURRENT (2024), Prospects for innovative power grid technologies; BNEF (2024); BNEF (2023)

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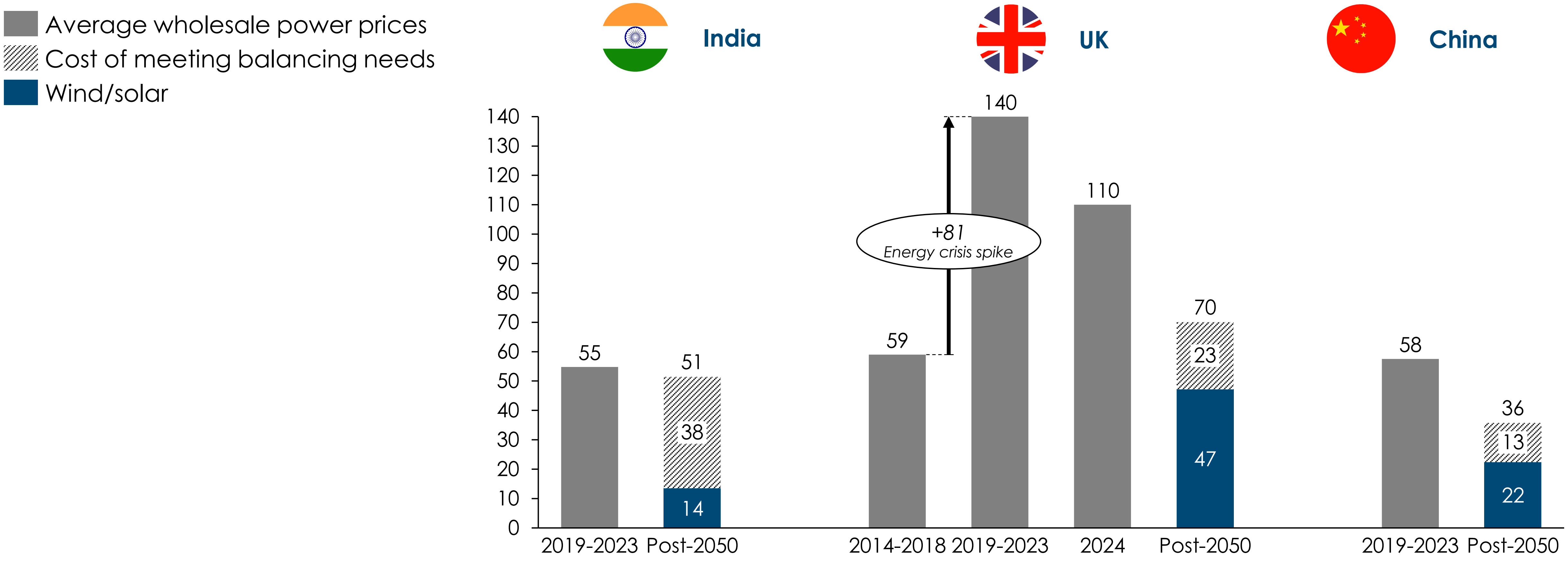
Total system generation costs of clean systems could be competitive with today's systems

Total system generation costs, today vs post-2050 system

$/MWh (real 2024$)

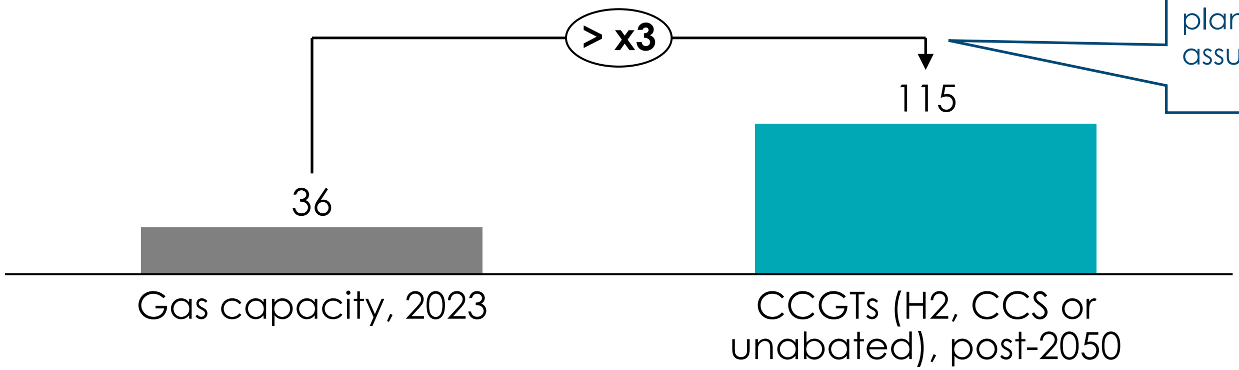


Source: Systemiq analysis for the ETC (2025); BNEF (2023), 2H 2023 LCOE: Data Viewer v.1.0; BNEF (2024) *CLIMATESCOPE*; Ember (2025) *European Wholesale Electricity Price Data*; Ofgem (2025) *Wholesale market indicators.*

Meeting long duration storage peak need (in min year) via CCGTs would require over 3x today's turbine capacity, but at very low average utilisation

UK gas capacity today vs capacity required in to fully meet max peak of long-duration balancing[1]

GW



This would mean going from ~50 gas plants today to ~164 gas plants, assuming average plant size of 700 MW

	Gas capacity, 2023	CCGTs (H2, CCS or unabated), post-2050
Annual TWh of generation	**101**	**15***
Annual total potential of TWh from fleet	315	1000
Annual hours running	2,800	136
Annual fleet capacity factor	32%	1.6%
Annual TWh of total demand	317	518
% of total demand met	32%	3%

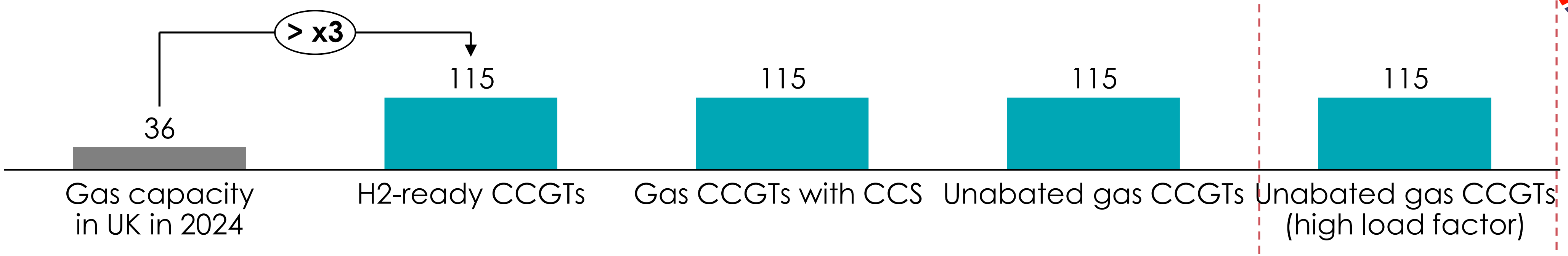
Sizing gas fleet to meet peak deficit periods for balancing **would require massive built of new low-carbon assets** – a fully renewable system could therefore actually require more (though much lower utilization, low carbon) turbine capacity

[1]Based on max long duration balancing need in 'Sizing the Balancing Challenge' modelling. Source: Systemiq analysis for the ETC (2024).

Ultra-low utilization assets to meet long duration peak involve high costs

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

GW



Cost vs emissions trade off for "last mile" decarbonization

	Gas capacity in UK in 2024	H2-ready CCGTs	Gas CCGTs with CCS	Unabated gas CCGTs	Unabated gas CCGTs (high load factor)
Annual TWh of generation	101	15	15	15	50
Levelised cost ($/MWh)	n/a (existing)	300 $/MWh	430 $/MWh	200 $/MWh for new, but some existing	90 $/MWh for new, but some existing[1]
Additional annual cost for UK households (on typical household bill of $2000/year)	n/a	~ $ 80	~ $ 110	~ $ 40	~ $ 20
Annual emissions (MtCO2e)	~19 MtCO2e	~ 0 MtCO2e	~ 0 MtCO2e	3 MtCO2e	9 MtCO2e

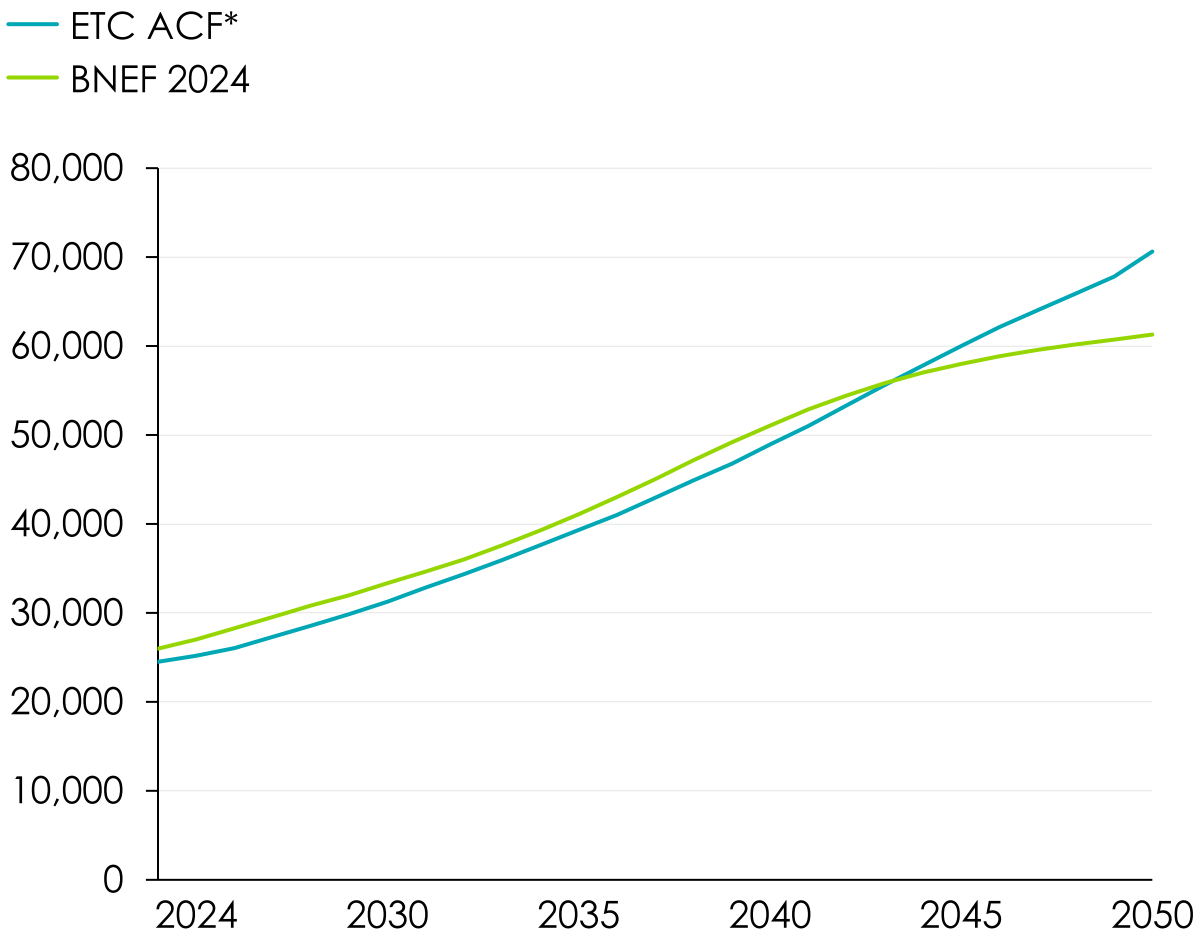
Portfolio of options best way to deliver lowest cost last mile decarbonization?

[1]New build cost is lower due to higher utilization factor. Note: Annual capacity factors based on assumption that total TWh annually generated from CCGTs is 26 TWh. Emissions intensity of unabated gas assumed to be 0.1829 kg CO2e per kWh. LCOEs assume $3/kg cost of hydrogen and 1000 $/kw cost of plant, 20 years lifetime. Household costs based on 26 TWh of generation and 30 million households. Systemiq analysis for the ETC (2024).

As electricity demand rises globally, CAPEX investments will be needed to build and reinforce grids

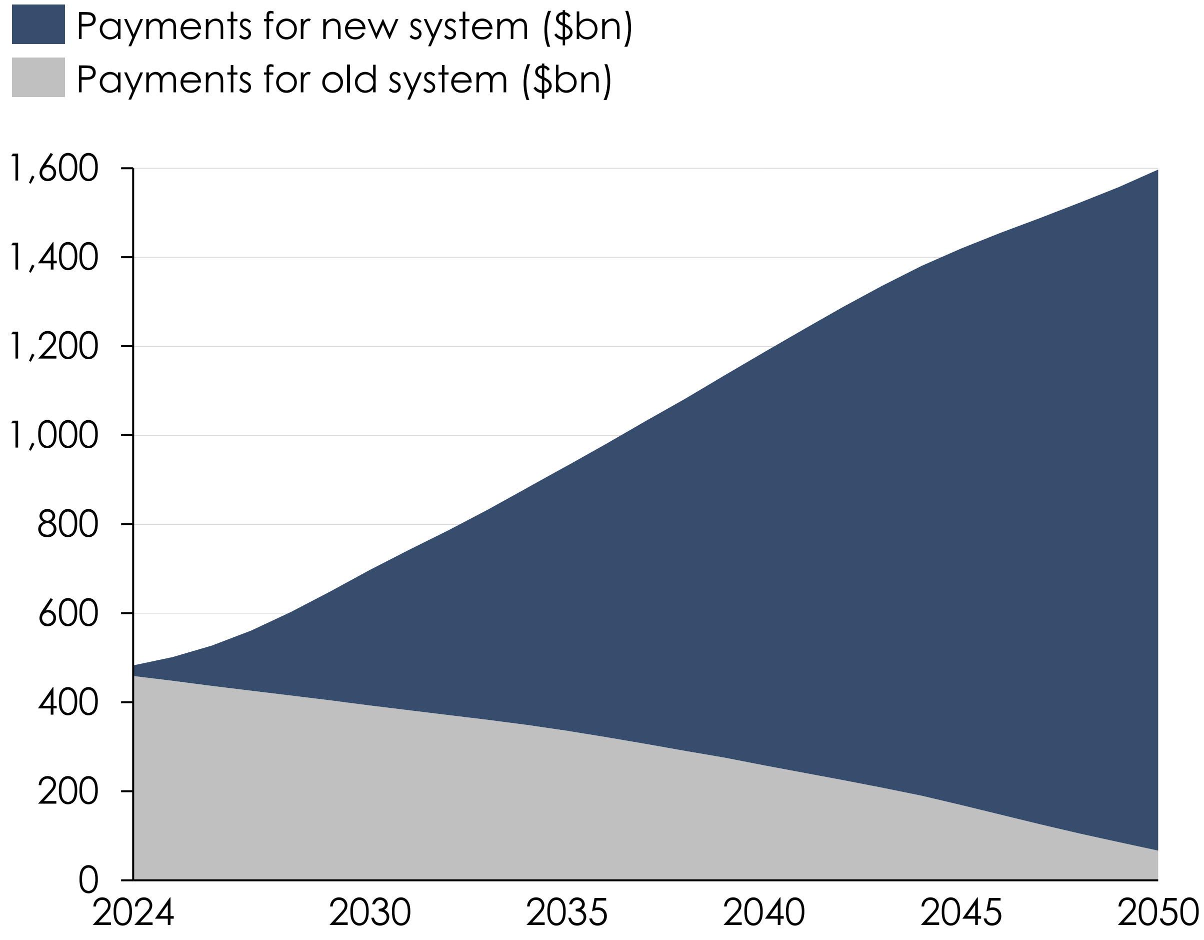
Annual electricity demand, global, 2024–2050

TWh



Annual payments in power grid, global, 2024–2050

$ bn (real 2024$)

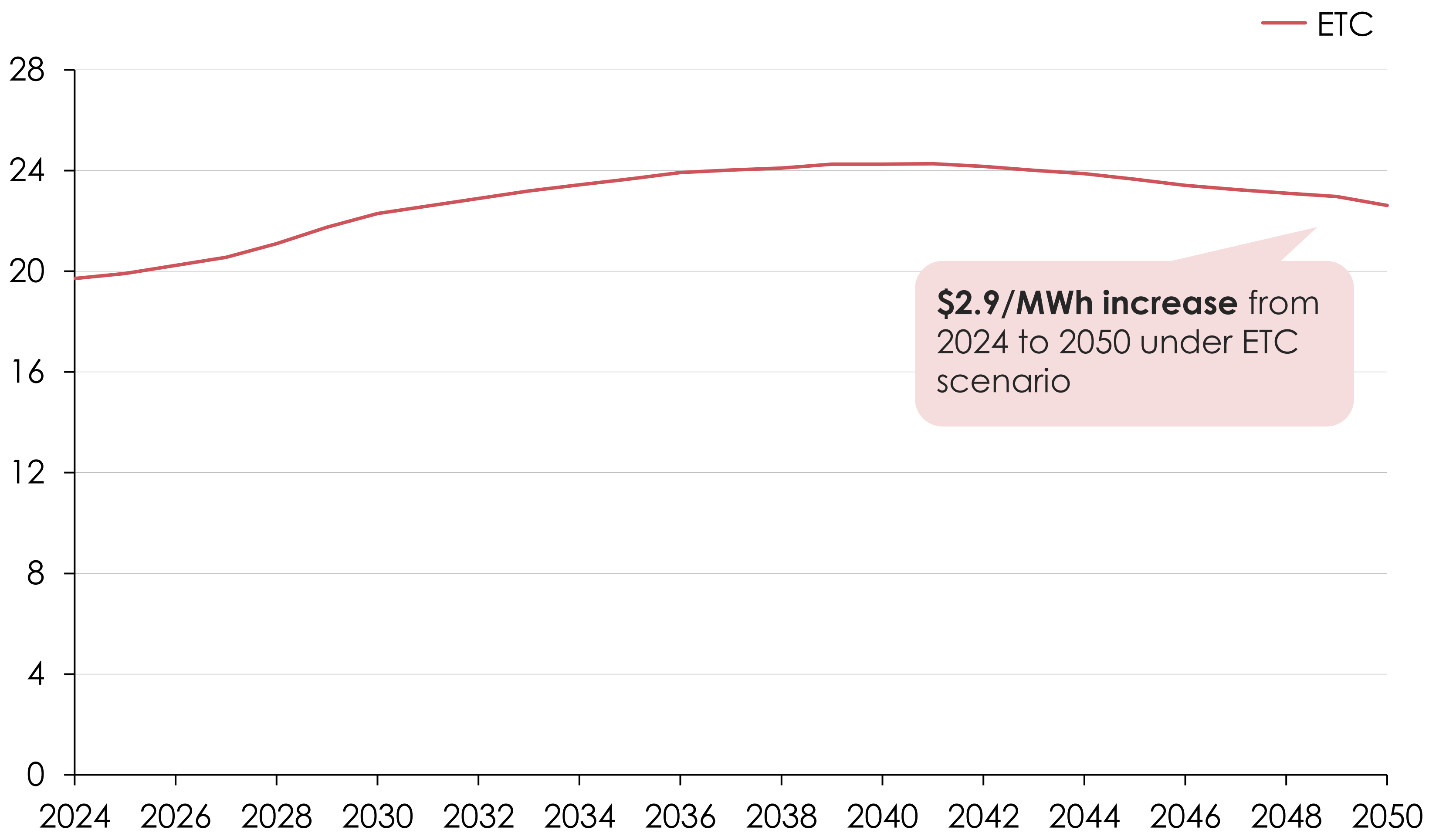


Note: *Only 50% of indirect use for hydrogen production is counted

Grid 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

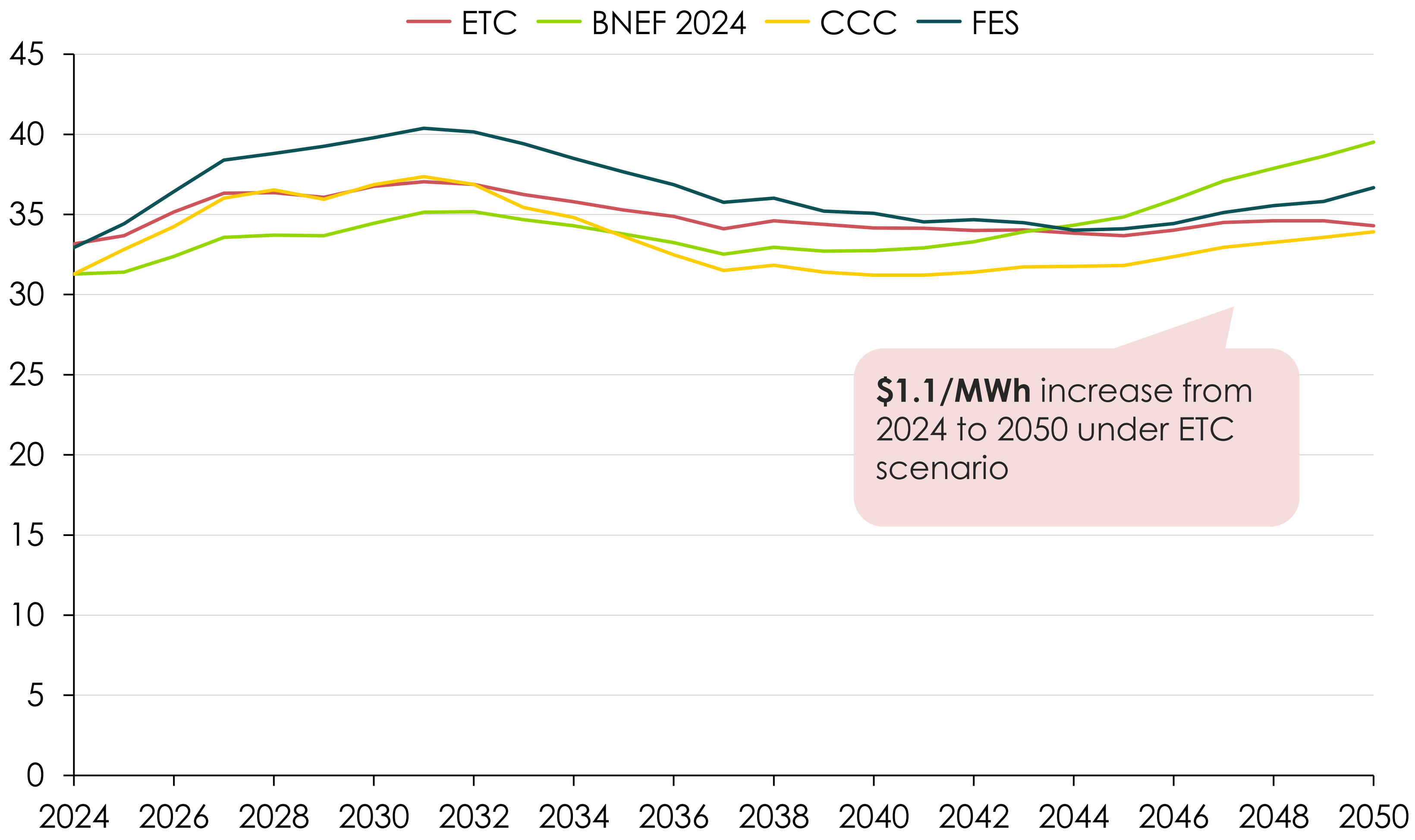


- The **initial increase in cost per unit of demand** is due to the upfront investments needed to build and reinforce the grid infrastructure in line with rising electricity demand.
- **The grid cost per unit of demand then decreases** because the fixed costs are spread over a larger volume of electricity consumption.
- **Grid optimization measures could further reduce** the need for additional grid build, lowering overall costs.

UK 2050 grid capex costs could be slightly above today's levels

Cost per unit of demand, UK, 2024–2050

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

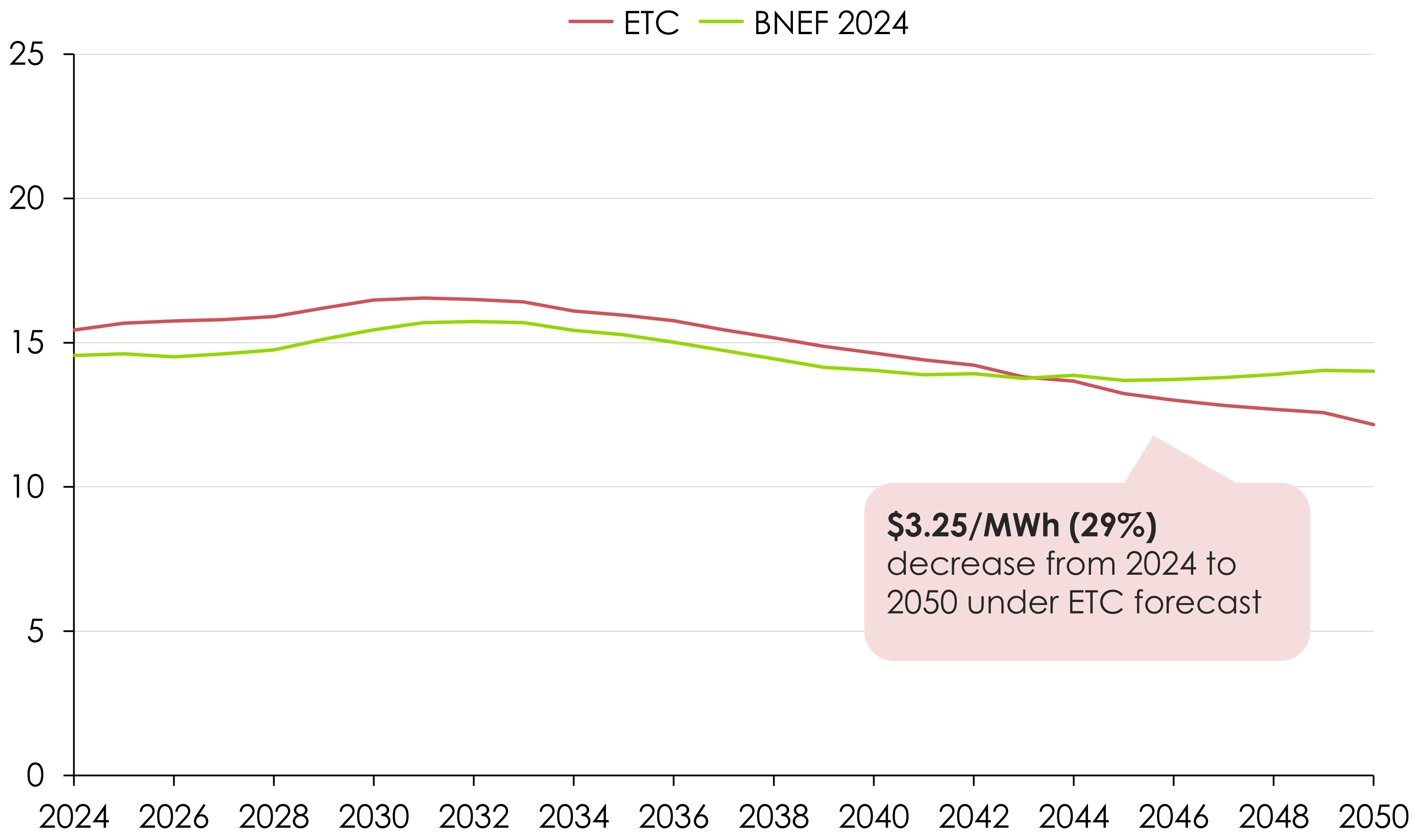


- The **initial increase in cost per unit of demand** is due to the upfront investments needed to build and reinforce the grid infrastructure.
- **The grid cost per unit of demand decreases** as demand increases faster than the rate of grid repayment from around 2030-2044, and
- Demand rises more slowly after 2040, causing the subsequent **increase in grid cost per unit of demand**.

By contrast, China's 2050 grid capex costs could be below today's levels

Cost per unit of demand, China, 2024–2050

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

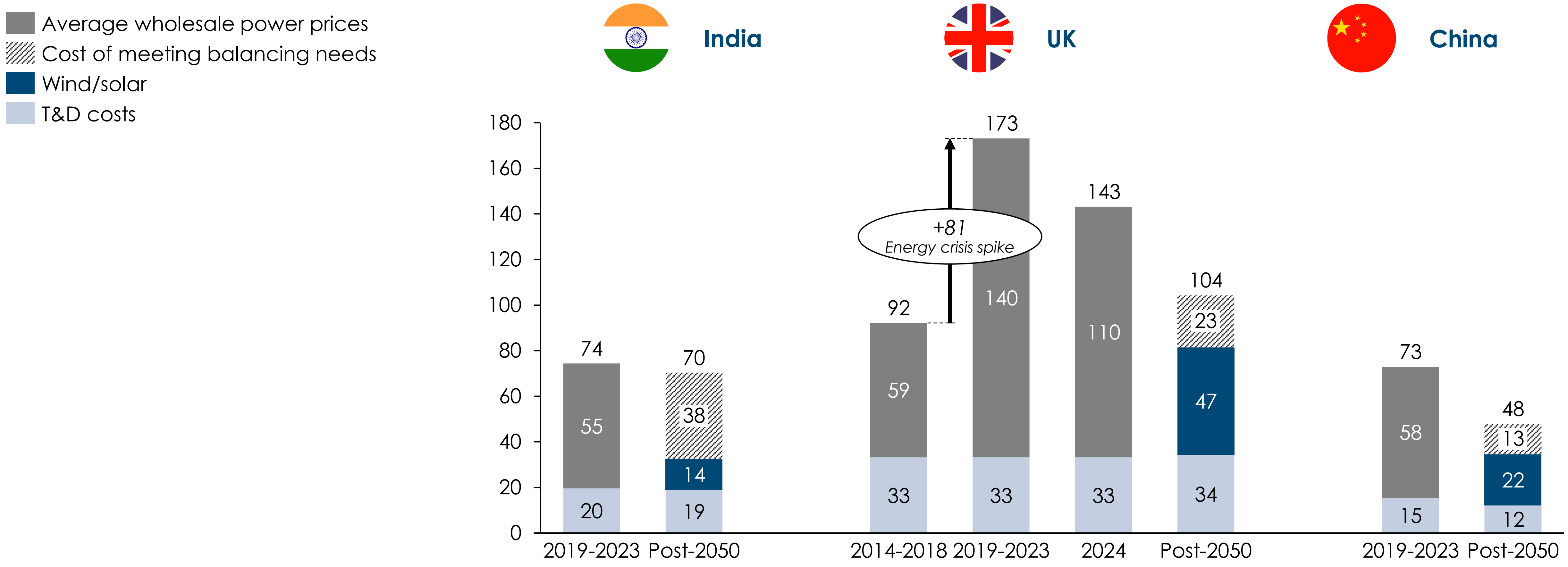


- China's annual **grid investments ramp up quickly** until around 2030, before slowing down as grid build out slows.
- China's **demand is expected to continue to increase** at a constant rate until 2050, driven by further electrification and growth.
- Therefore, **the grid cost per unit of demand decreases** beyond 2030, as demand growth outpaces grid investments.

Total system generation and transmission costs less than current wholesale prices

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

$/MWh (real 2024$)

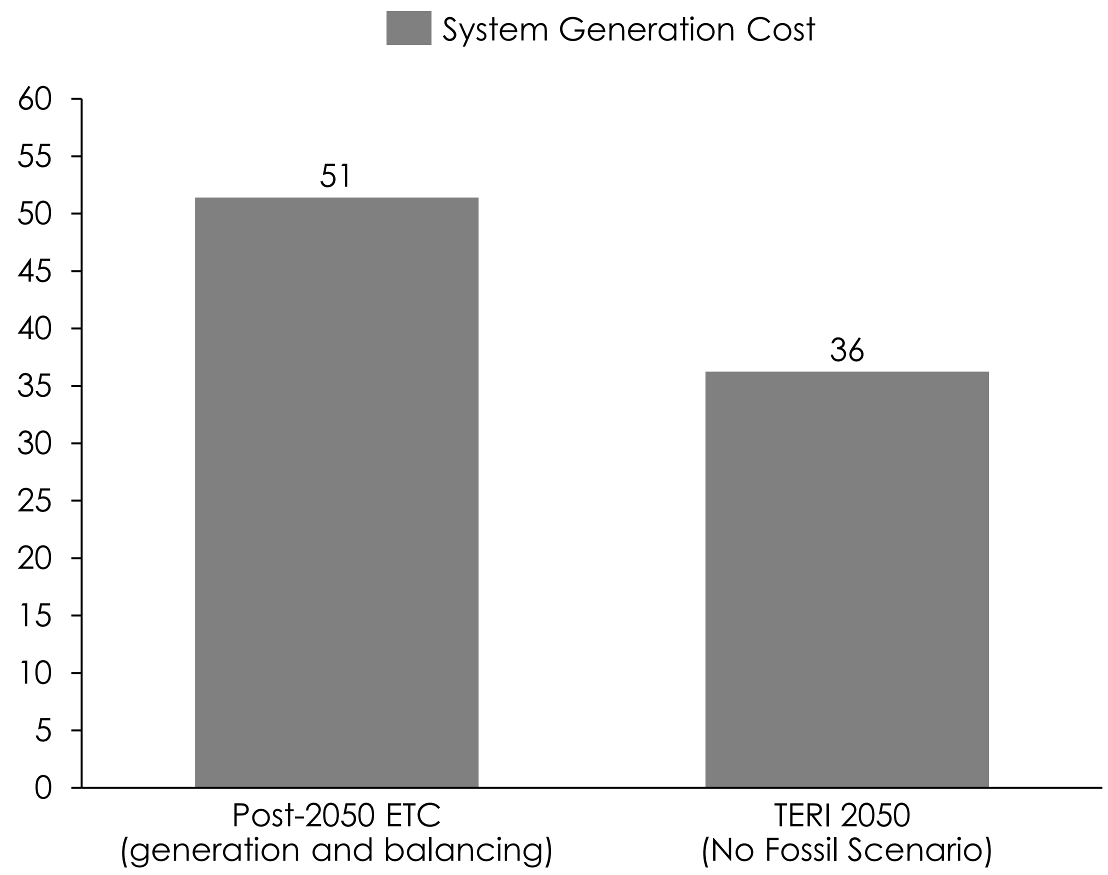


Source: Systemiq analysis for the ETC (2025); BNEF (2023), 2H 2023 LCOE: Data Viewer v.1.0; Ofgem (2025), *Wholesale market indicators – Electricity Prices: Forward Delivery Contracts – Weekly Average (GB)*; IEA (2023), *Electricity Market Report – Update 2023*; Statista (2024), *Average electricity prices for enterprises in China from September 2019 to September 2024*

Next steps: we will compare our modelling with detailed dispatch models and consider the future impacts on consumer bills

Comparison of our system generation cost outputs with TERI's 2050 forecasts[1]

$/MWh (real 2024$)



Assumption differences

- We assume different future technology cost declines
- TERI include dispatchable sources including nuclear and hydro
- Excluding these in our analysis results in significant wind/solar overbuild
- More wind/solar capacity results in more battery capacity in our modelling

Considerations for our analysis

- Our assumed system with maximised wind/solar is oversimplified leading to an overreliance on batteries to shift supply
- Accounting for dispatchable low carbon sources could decrease overall system costs, in line with TERI's analysis
- Evaluating impacts on consumer bills will require these sources to be incorporated in more realistic scenarios

[1]Comparison of generation and balancing costs, excluding transmission costs. TERI's costs are in base year 2020 so we have converted to 2024$.
Sources: TERI (2024), *Power Sector 2050*

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Enablers across five key areas will be needed to scale the balancing and grid solutions required for future, renewables-dominated systems.

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)

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, workforce and financing regimes

- Supply chain concerns
- Workforce education
- Anticipatory financing

Consumers

- Consumer engagement and trust-building

Technology: