




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



Agenda

Context on importance of clean electrification; challenges around running future power systems; role of emerging technologies

Managing the system balancing challenge

Building and optimising grids

Costs: how do these pathways influence costs

Key enablers to unlock the power system of the future



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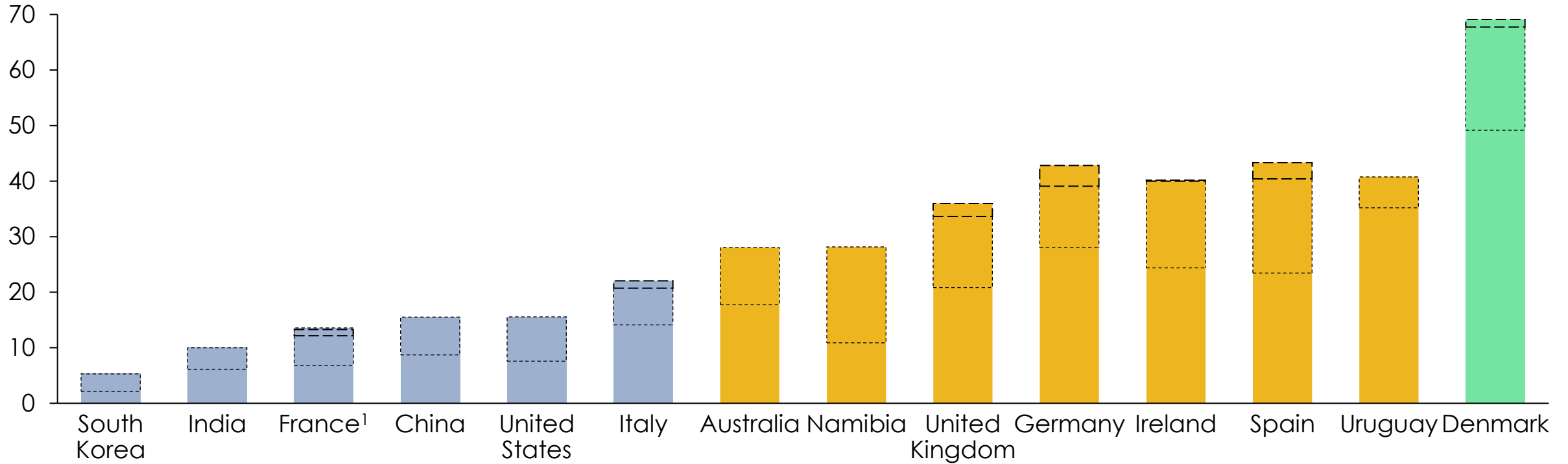
Key enablers to unlock the power system of the future



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, 2024



This points to three phases of system operation:

■ Initial steps to bring in renewables

■ Renewables start to make up almost all generation in some periods

■ Renewables dominate generation

□ 2024

□ 2023

□ 2018

¹France's wind and solar share dropped from 14% in 2023 to 12% in 2024 due to increased nuclear and hydro contributions to the electricity generation mix in 2024.

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



There are two key focus issues for power systems transformation

Building and optimising grids

“Build”

“Optimise”

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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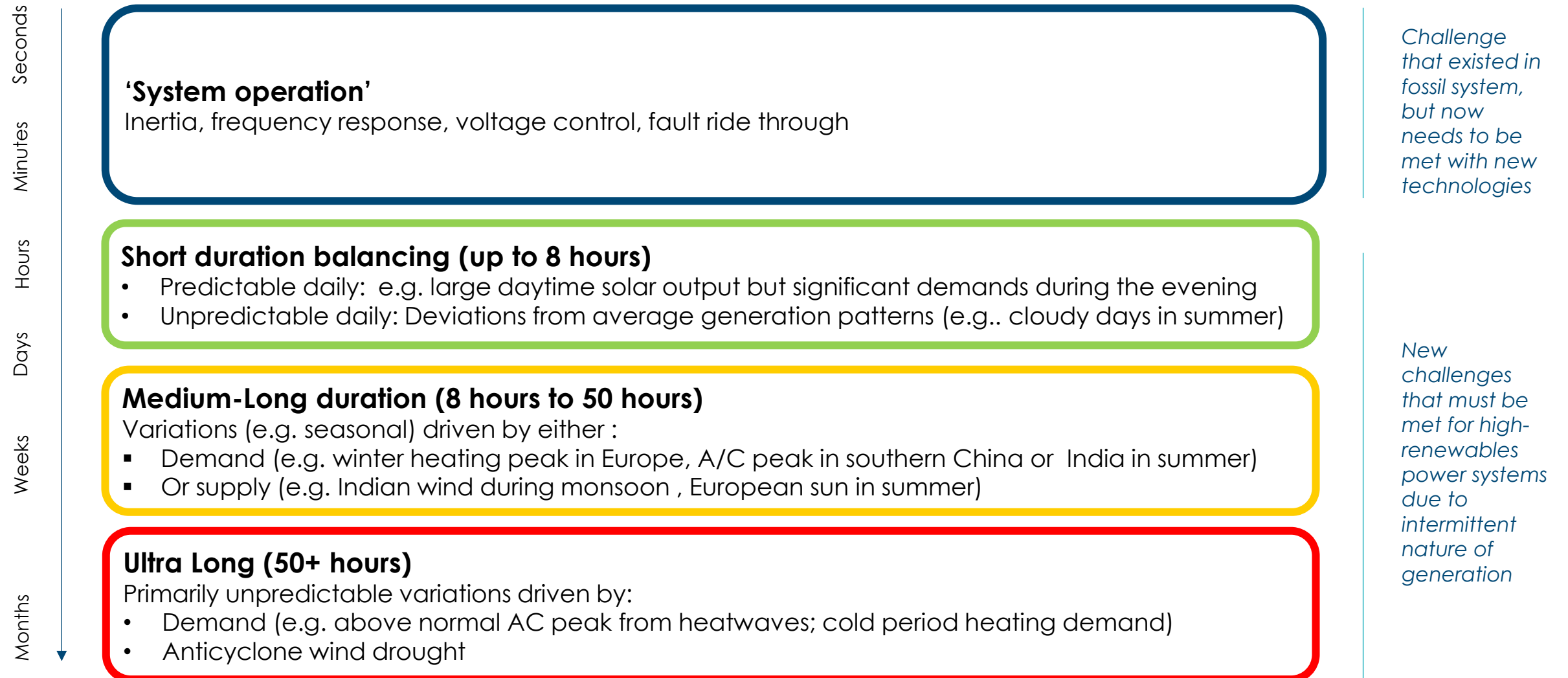
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System balancing occurs across different durations

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



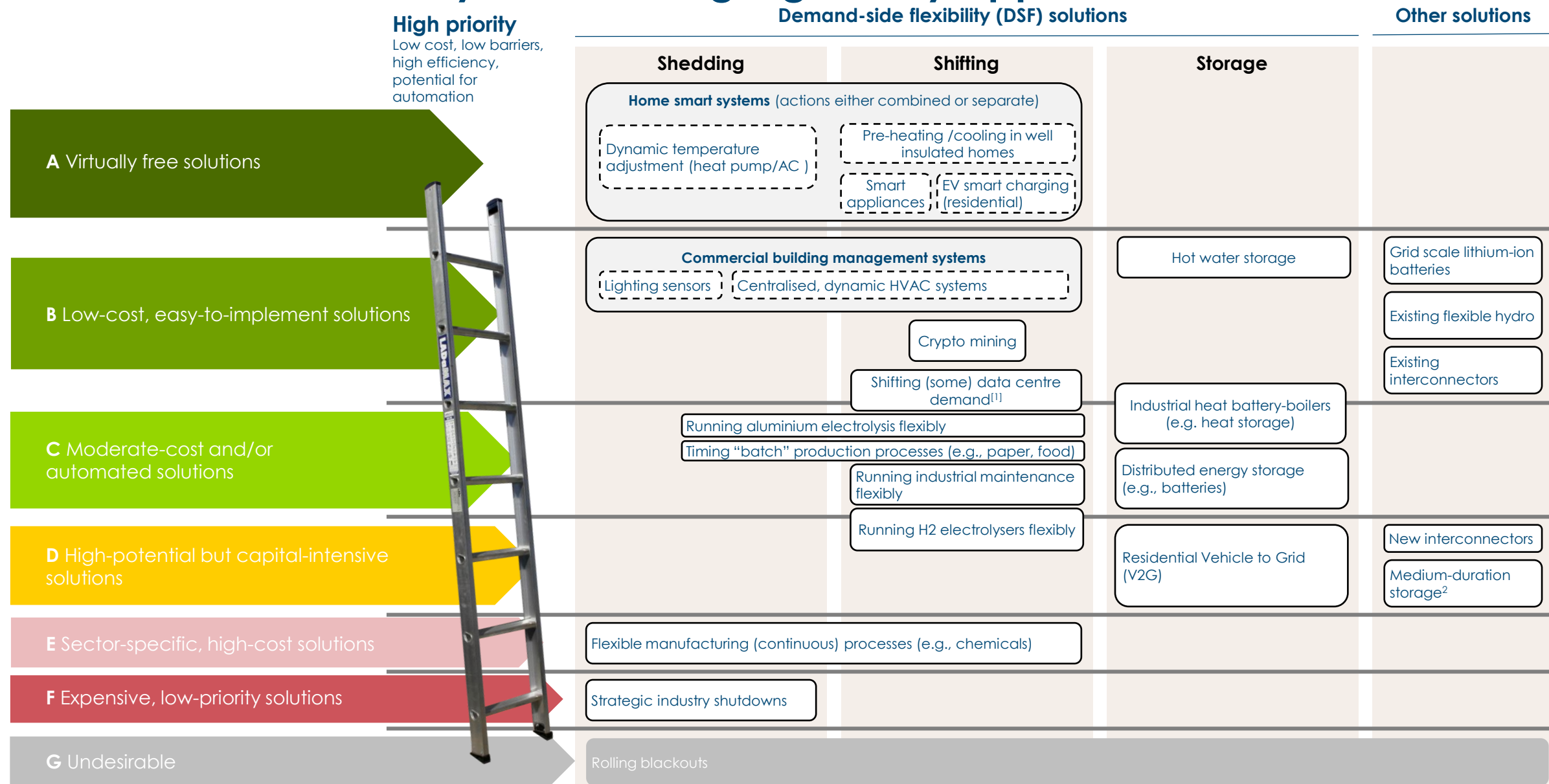
There are a set of balancing options across durations

			System operation	Short duration	Medium-Long duration	Ultra-Long
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. H ₂) 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 might 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 needs. 6. 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

Low priority / Undesirable
High cost, high barriers

Notes: Ladder concept based on Michael Liebreich’s Hydrogen Ladder
¹Non-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**
²Medium-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:

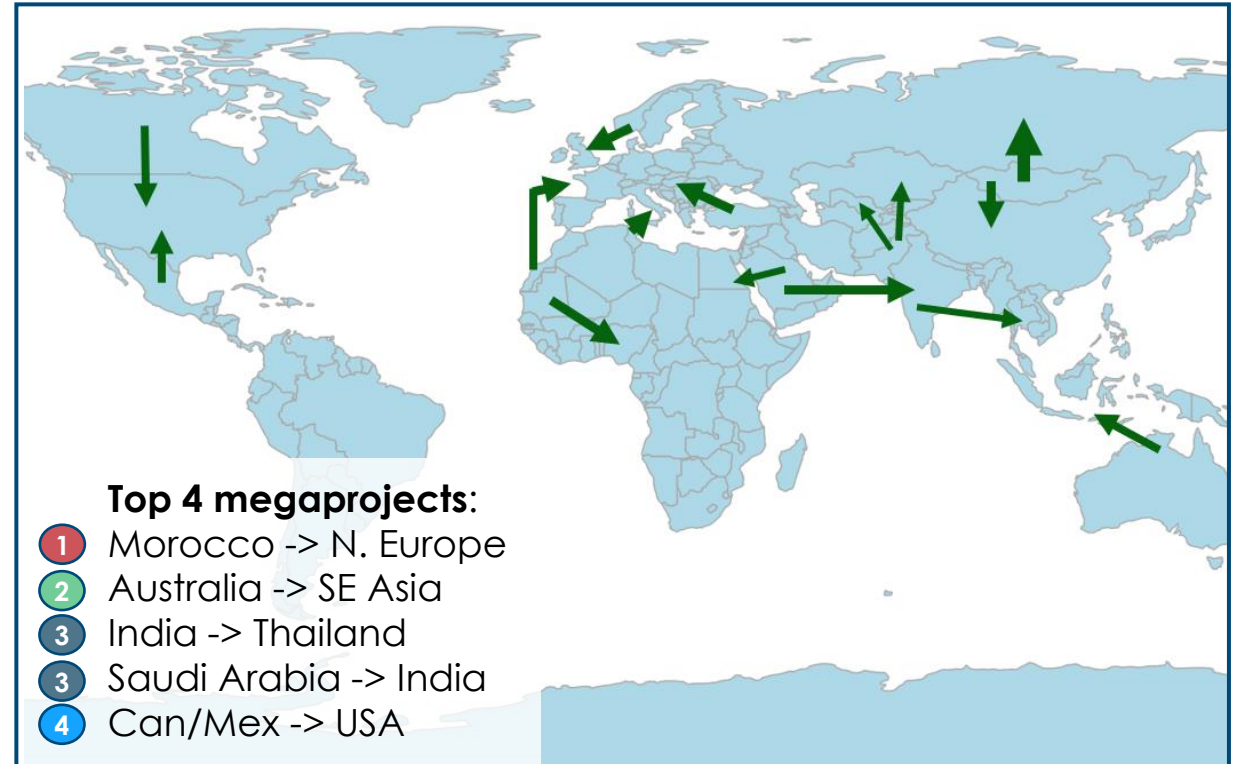
- Low-cost clean generation, from a low cost/high availability geography
- Balancing, Using non-correlated weather and demand including with storage at the export site



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:

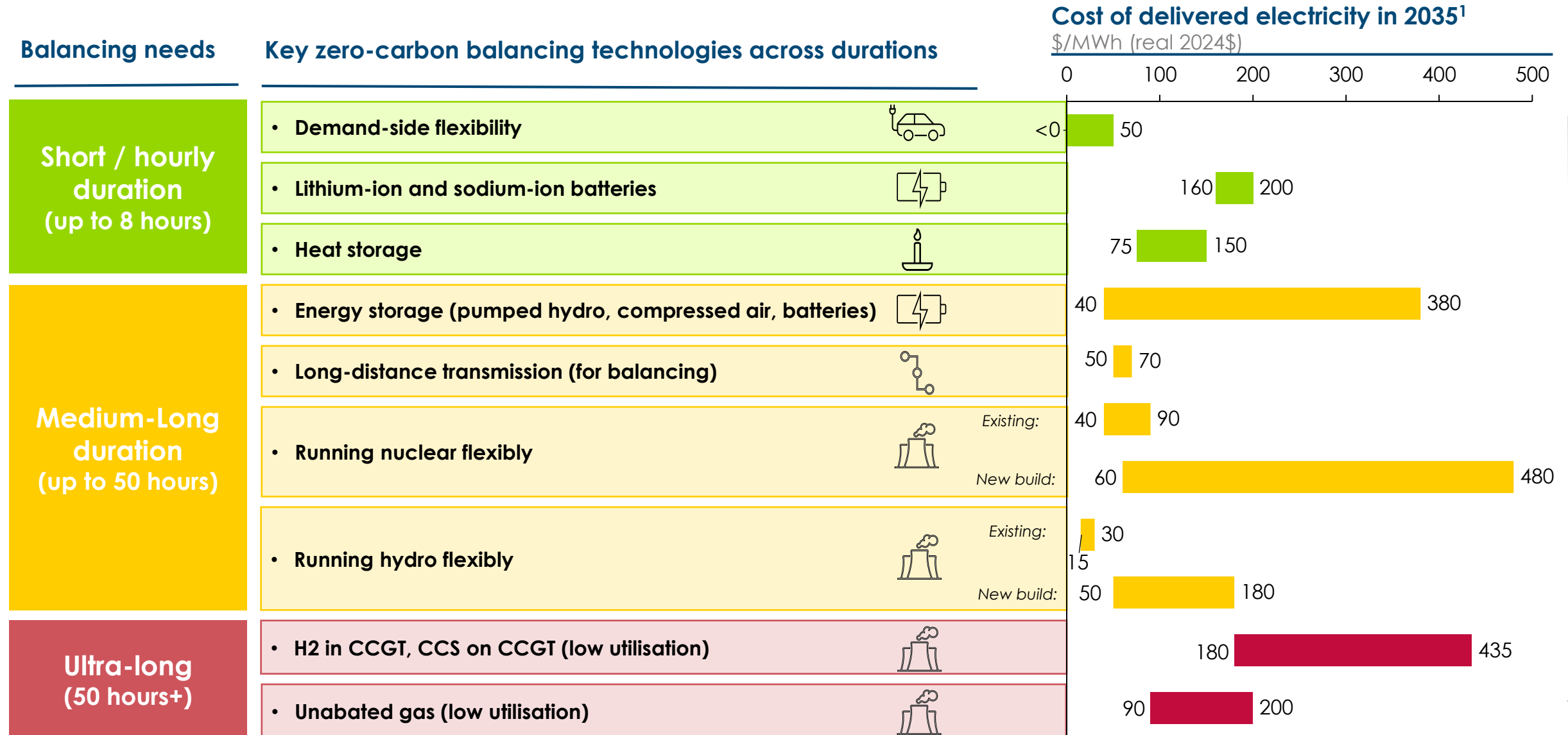
- 15% of global power demand,
- 1.8 Gt per annum carbon reductions (equal to 13% of global power sector emissions),
- \$90bn dollars of savings per year

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



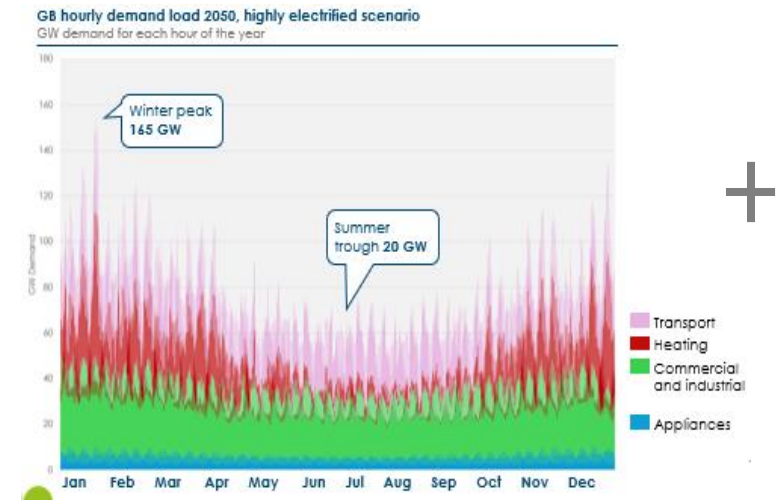
[1] The DSF range assumes that DSF can reduce total system costs at the lower end (through reducing overall demand) and that upgrades to smart, DSF-capable systems incurs a net cost at the upper end. LCOS calculations assume electricity input cost of \$0.06/kWh. All batteries are full LCOS calculations 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

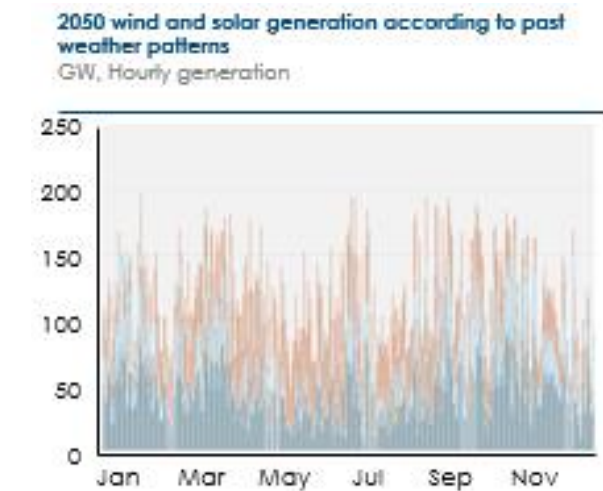
This has been carried out for India, UK, and China archetypes and will also be carried out for Spain.

Demand



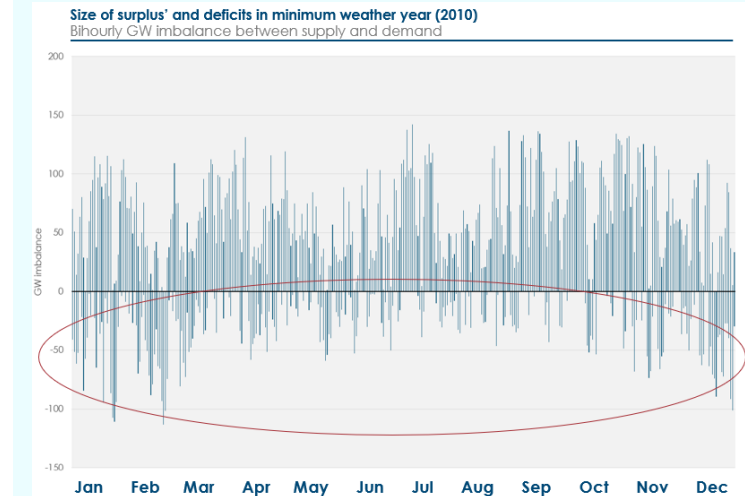
Detailed 2050 hourly load profiles obtained from expert forecasters which are reflective of high electrification and specific peak profiles (i.e. UK ESO, TERI in India)

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


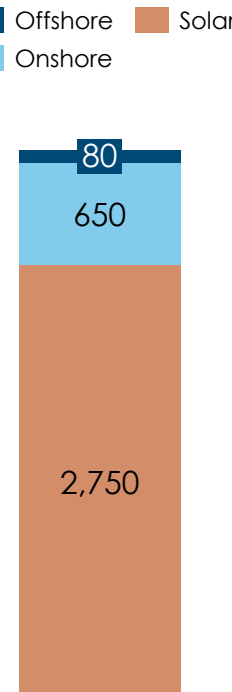
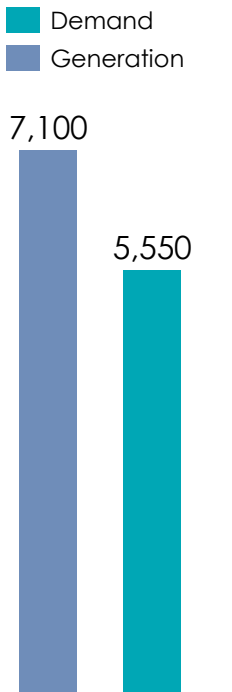
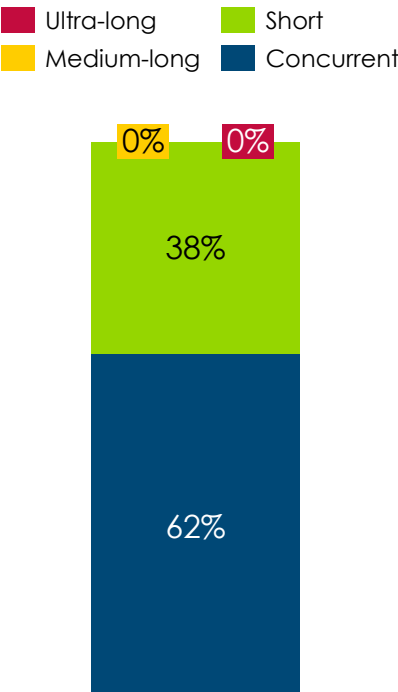
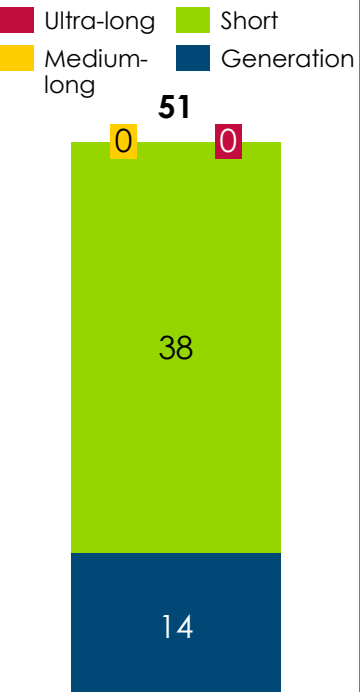


Matching at bi-hourly level across demand and supply to assess periods of wind & solar generation excess/shortfall relative to demand. Charging/discharging rates and efficiencies were used to prioritise short-, medium- and long-duration storage options to optimally balance the system.



¹Baseload 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	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
 <p>Core scenario, India</p>	 <p>Offshore 80 Onshore 650 Solar 2,750</p>	 <p>Demand 5,550 Generation 7,100</p>	 <p>Ultra-long 0% Short 38% Medium-long 0% Concurrent¹ 62%</p>	<p>Generation: 7,100 TWh @ \$15/MWh</p> <p>Short storage: 2100 TWh @ \$100/MWh</p> <p>Medium: 0 TWh @ \$120/MWh</p> <p>Long: 0 TWh @ \$240/MWh</p>	 <p>Ultra-long 0 Medium-long 0 Short 38 Generation 14</p>	<ul style="list-style-type: none"> 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).

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

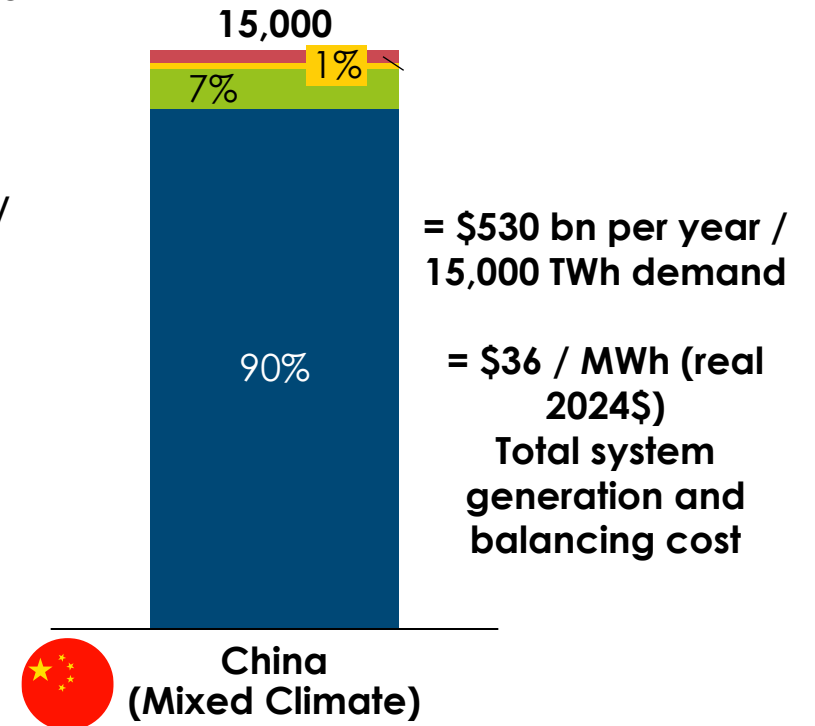
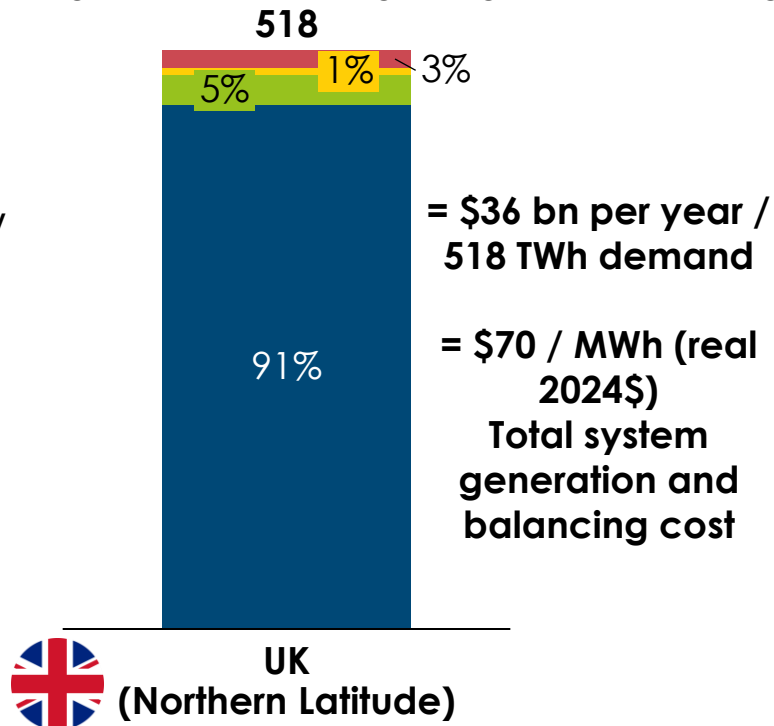
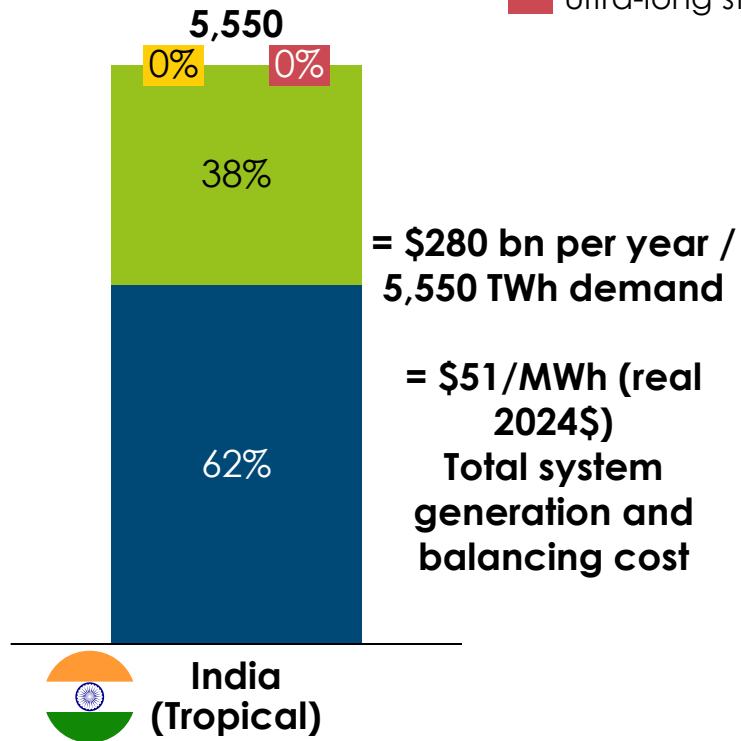


Balancing needs and total system costs will across regional archetypes

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

■ Ultra-long storage ■ Medium-long storage ■ Short storage ■ Concurrent



Primarily a diurnal challenge

Balancing required across short, medium and long durations



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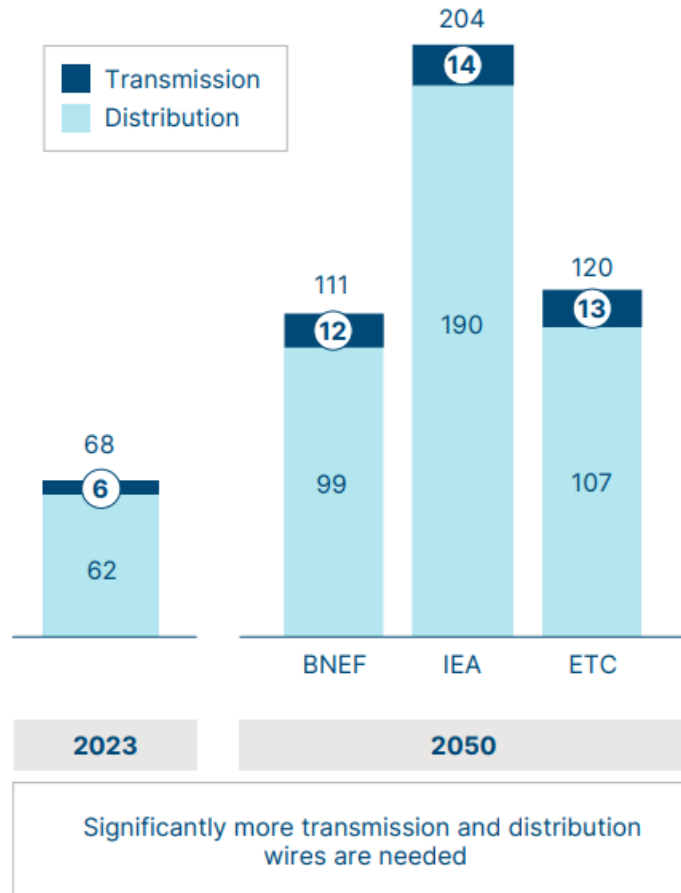
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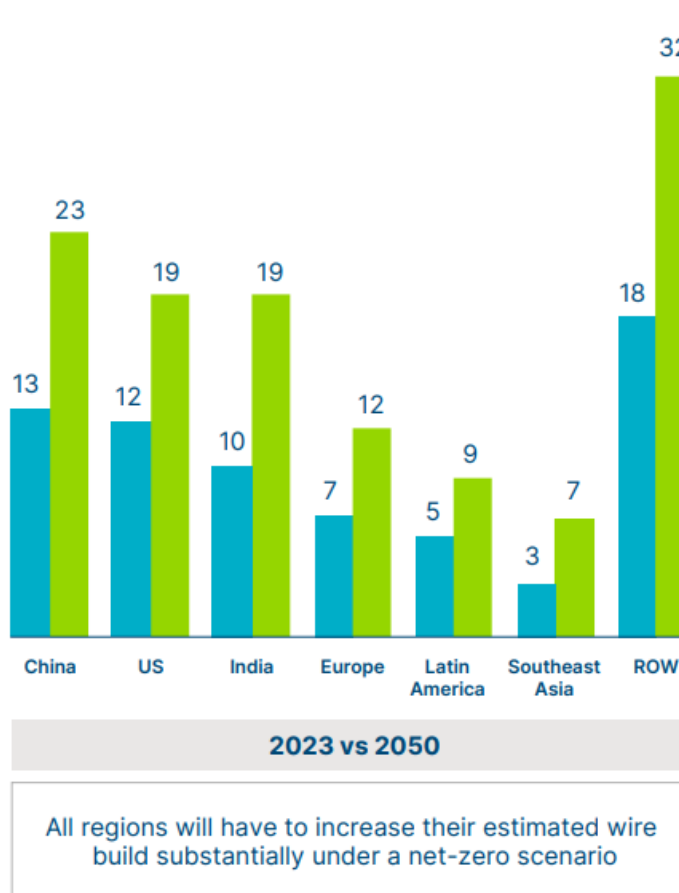


Transmission and distribution network build will have to increase drastically across regions

Estimated wires required under various assumptions
Million km



Estimated wires required from 2023 to 2050
Million km



- **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**.

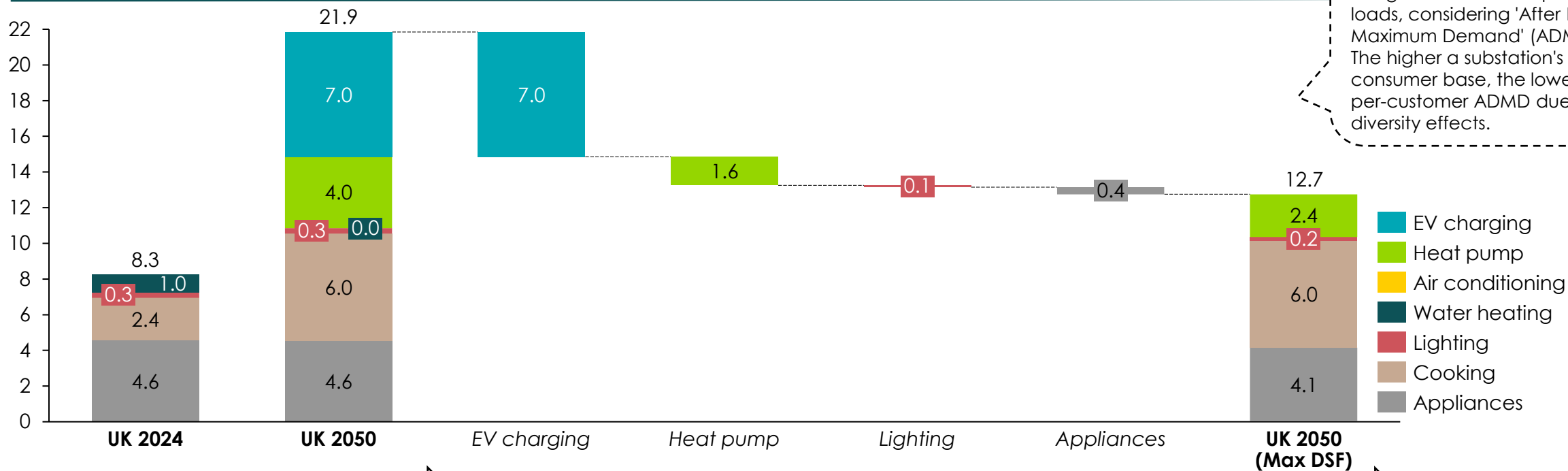
- **However, even full deployment of all optimisation routes will not eliminate the need to build new grids**



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 / shed¹.



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 essential for grid flexibility.

¹Heat 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.

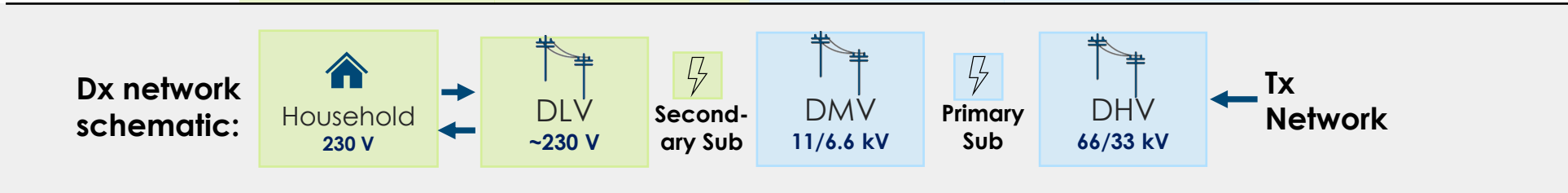


Future consumer demand increases will affect the upgrade requirements of each stage of the distribution network

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%

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.



¹UK assumptions: 117 final customers per secondary sub. with 336 kW existing capacity; 17,500 final customers per primary sub. with 15 MW existing capacity.

²India 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.

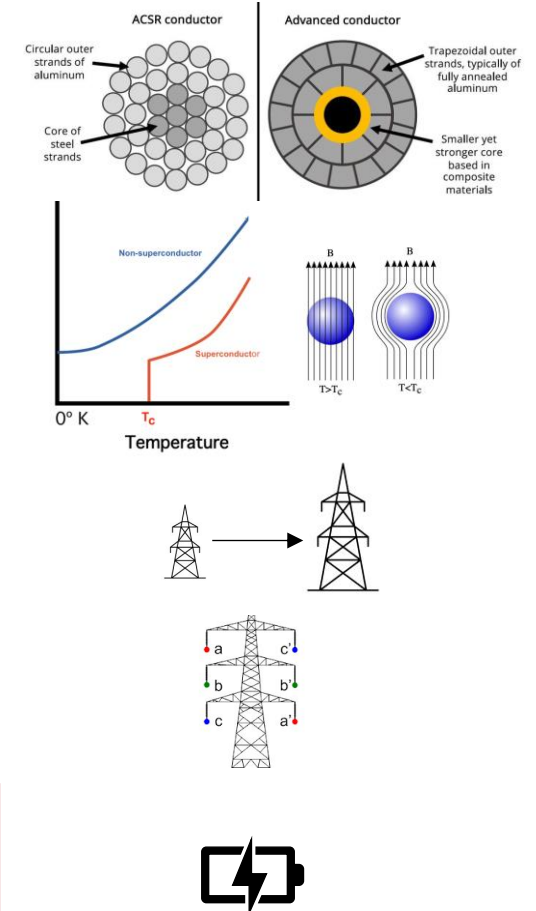


Innovative Grid Technologies (IGTs) can improve grid efficiency through changes to pylons and wires, reducing buildout and local opposition

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%

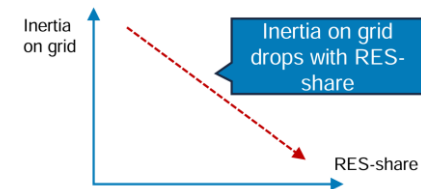
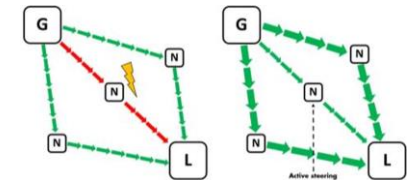
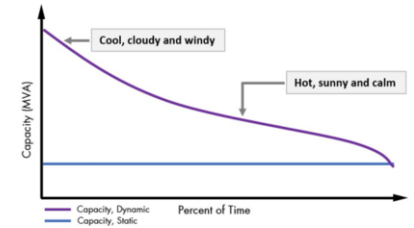


¹ Capacity increase depends on the voltage upgrade.
 Note: * Network capacity increase = **increase (% of line capacity)**:
 Source: CurrENT (2024) *Prospects for innovative power grid technologies*.

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

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

	Technology options:	Main methods to increase grid capacity:	Network capacity increase*
Optimising wires and networks <i>Improving the monitoring and control of power flows</i>	Digital twins, flexibility software management solutions	Dynamic Line Rating <ul style="list-style-type: none"> Better understanding of actual line limits <ul style="list-style-type: none"> 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) <ul style="list-style-type: none"> Dynamically controlling power flows on the grid <ul style="list-style-type: none"> 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 <ul style="list-style-type: none"> Better understanding of actual inertia limits/stability limits <ul style="list-style-type: none"> 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 procurement and minimises curtailment. 	30% ¹



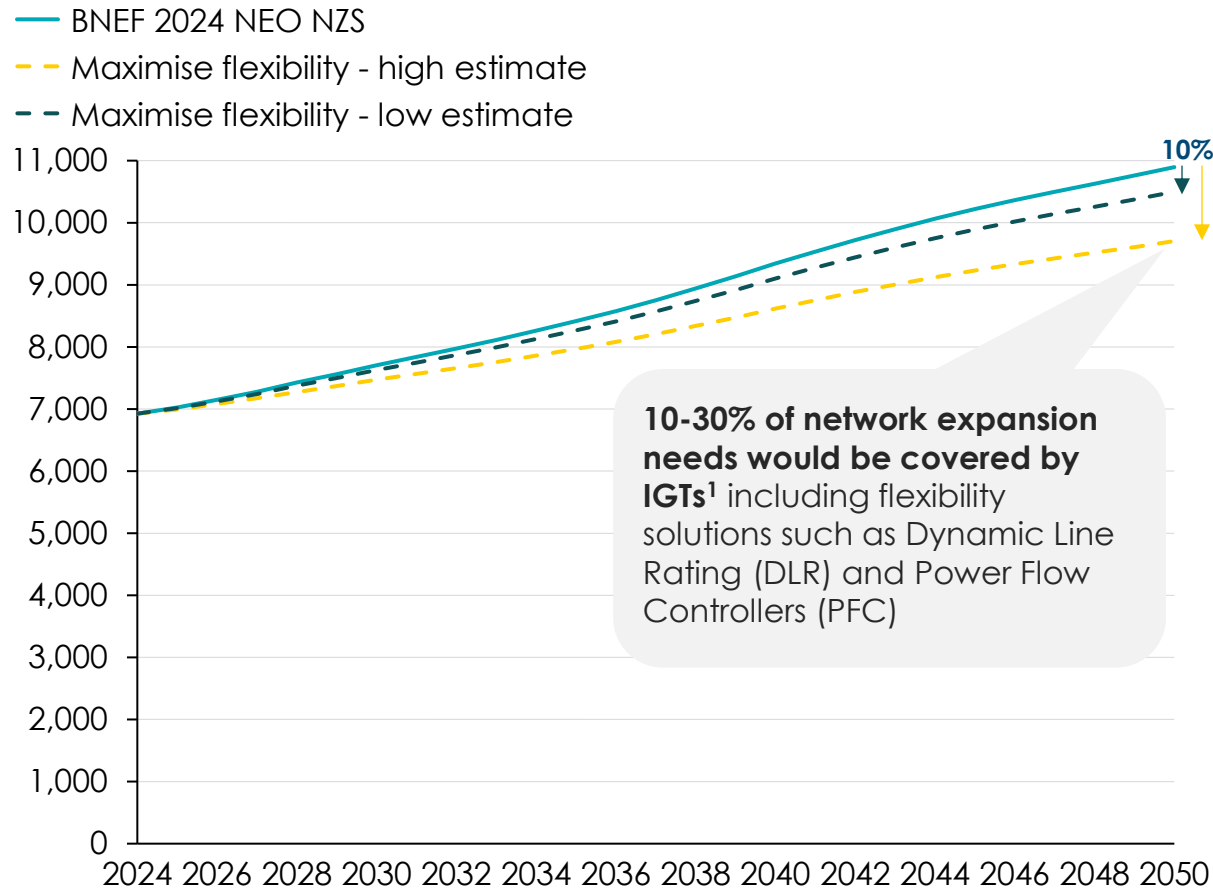
¹ Reduction in renewables output due to 30% higher inertia compared to conventional lines. Note: (% of line capacity): Source: CurrENT (2024) *Prospects for innovative power grid technologies*.

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

IGTs could significantly reduce grid build and reduce CAPEX spending

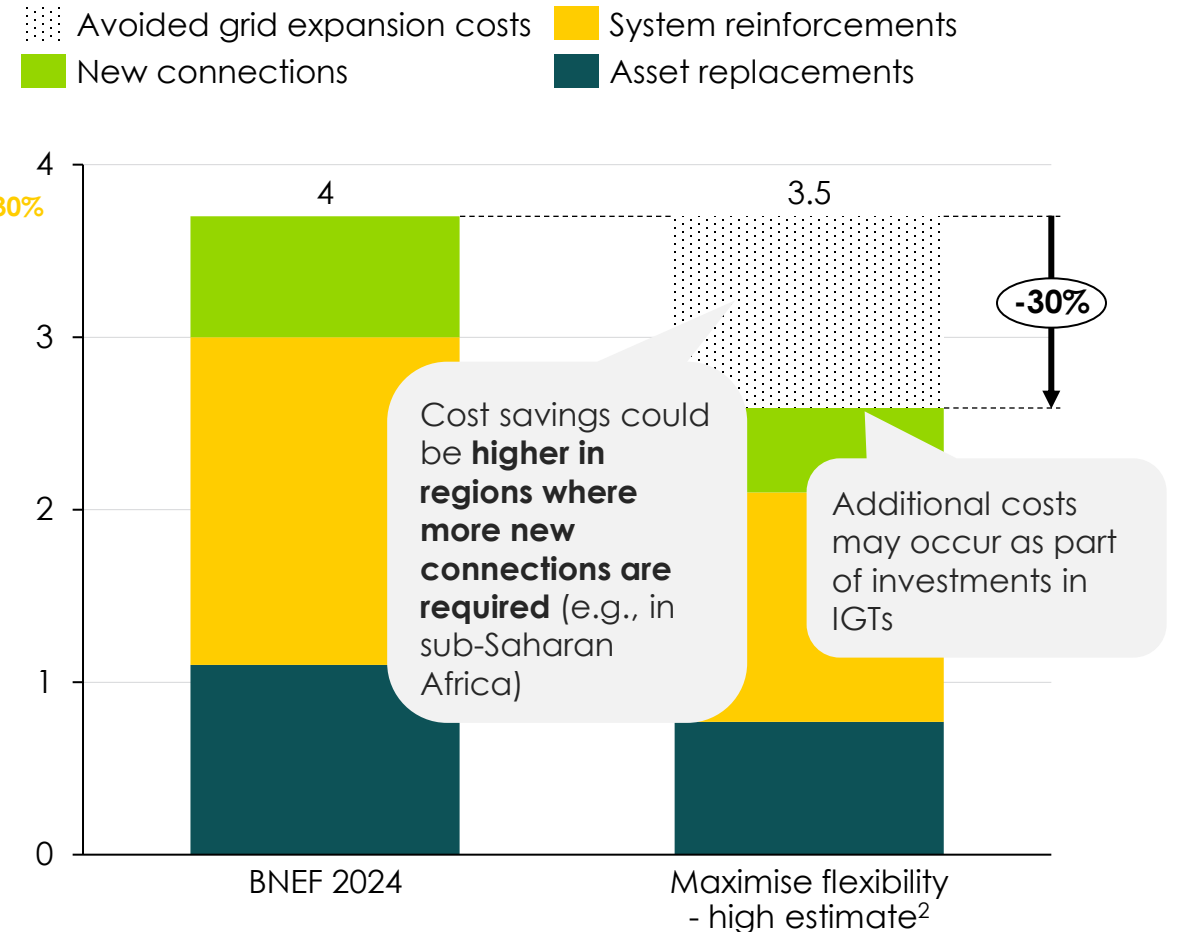
Benefits of IGTs compared to network expansion needs

1,000 km, Europe, 2024–2050



Cumulative investment in new power grid system, Europe

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



¹Accounting 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.

²It 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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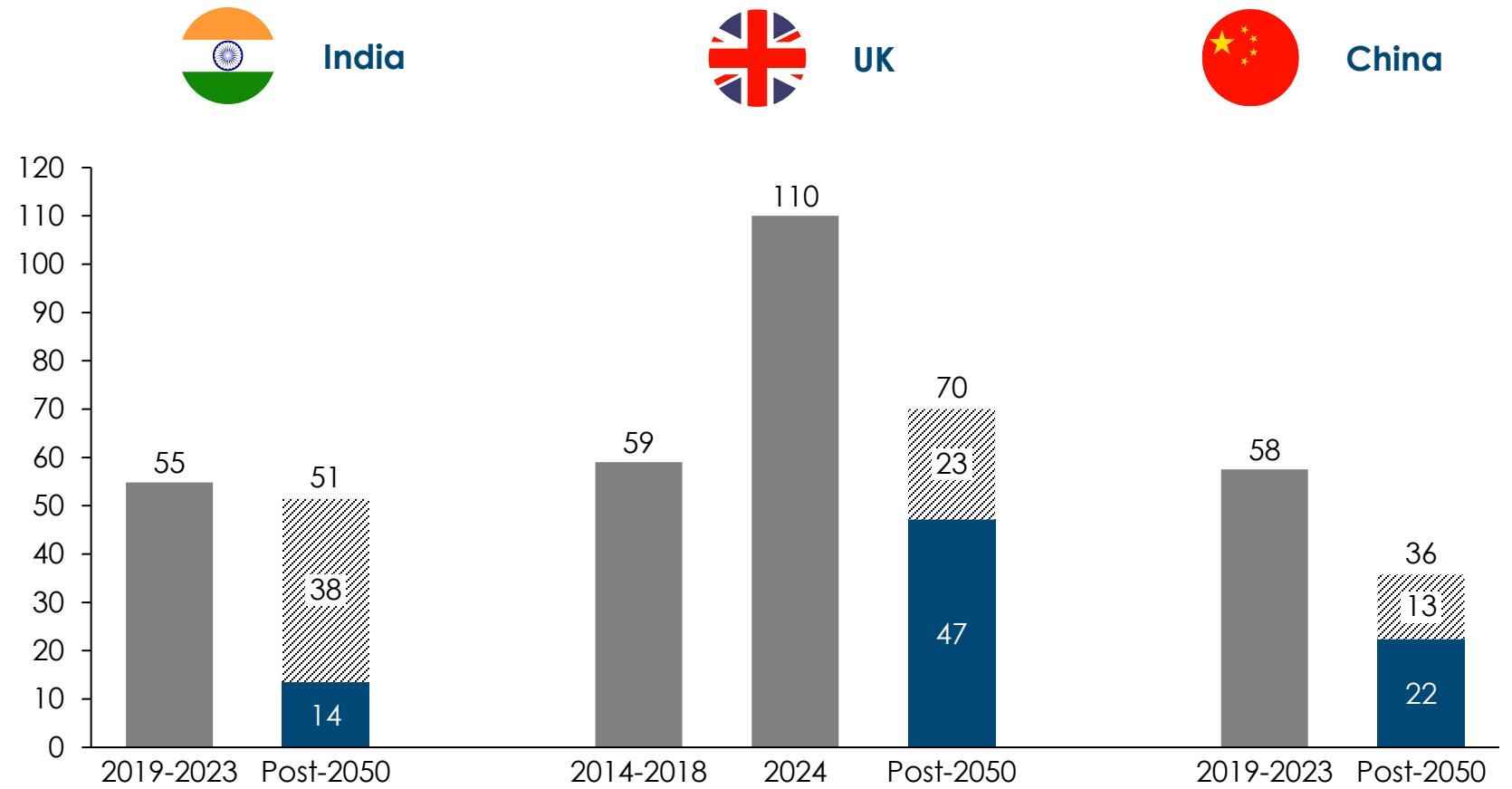


Total system generation costs of clean systems could be competitive with today's systems

Total system generation costs, today vs post-2050 system

\$/MWh (real 2024\$)

- Average wholesale power prices
- Cost of meeting balancing needs
- Wind/solar

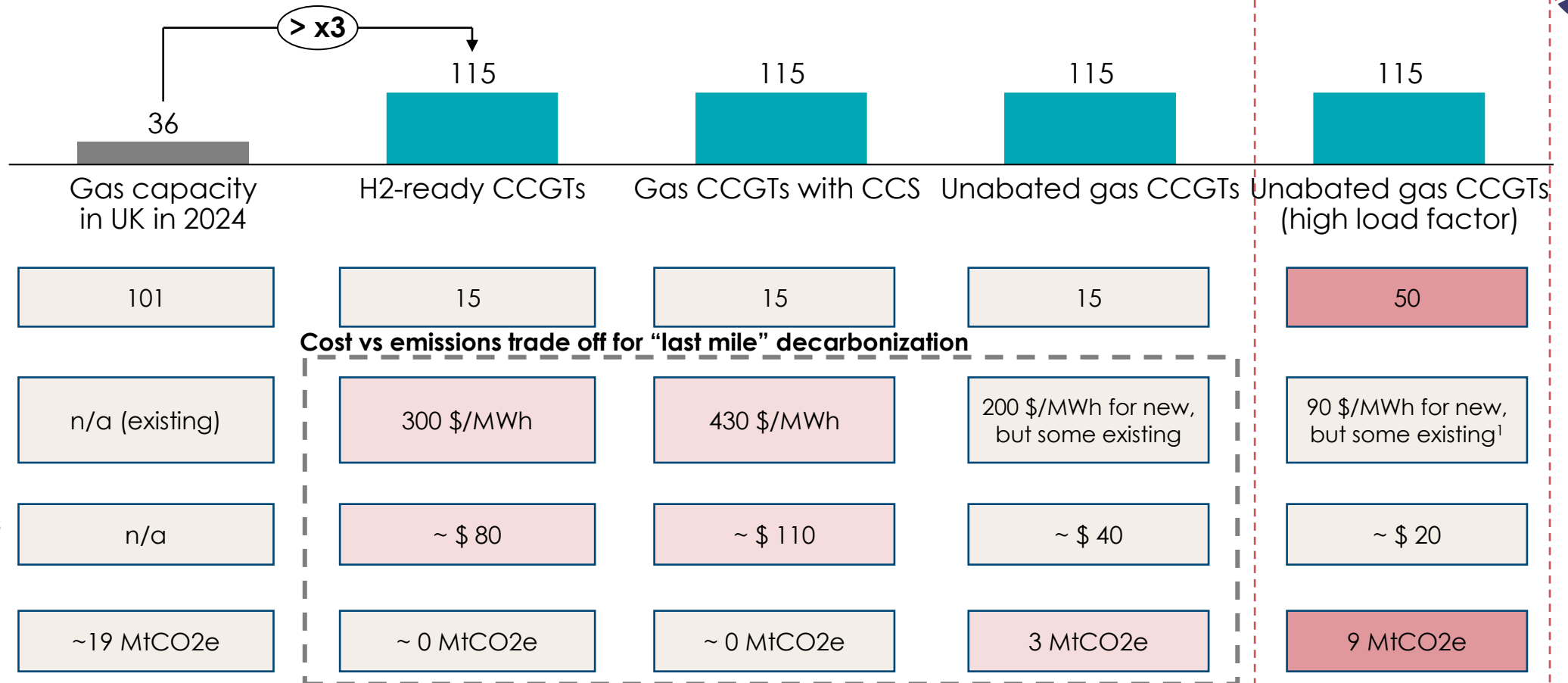


Source: Systemiq analysis for the ETC (2025); BNEF (2023), 2H 2023 LCOE: Data Viewer v.1.0; BNEF (2024) CLIMATESCOPE; Ember (2025) European Wholesale Electricity Price Data; Ofgem (2025) Wholesale market indicators.

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

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

GW



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

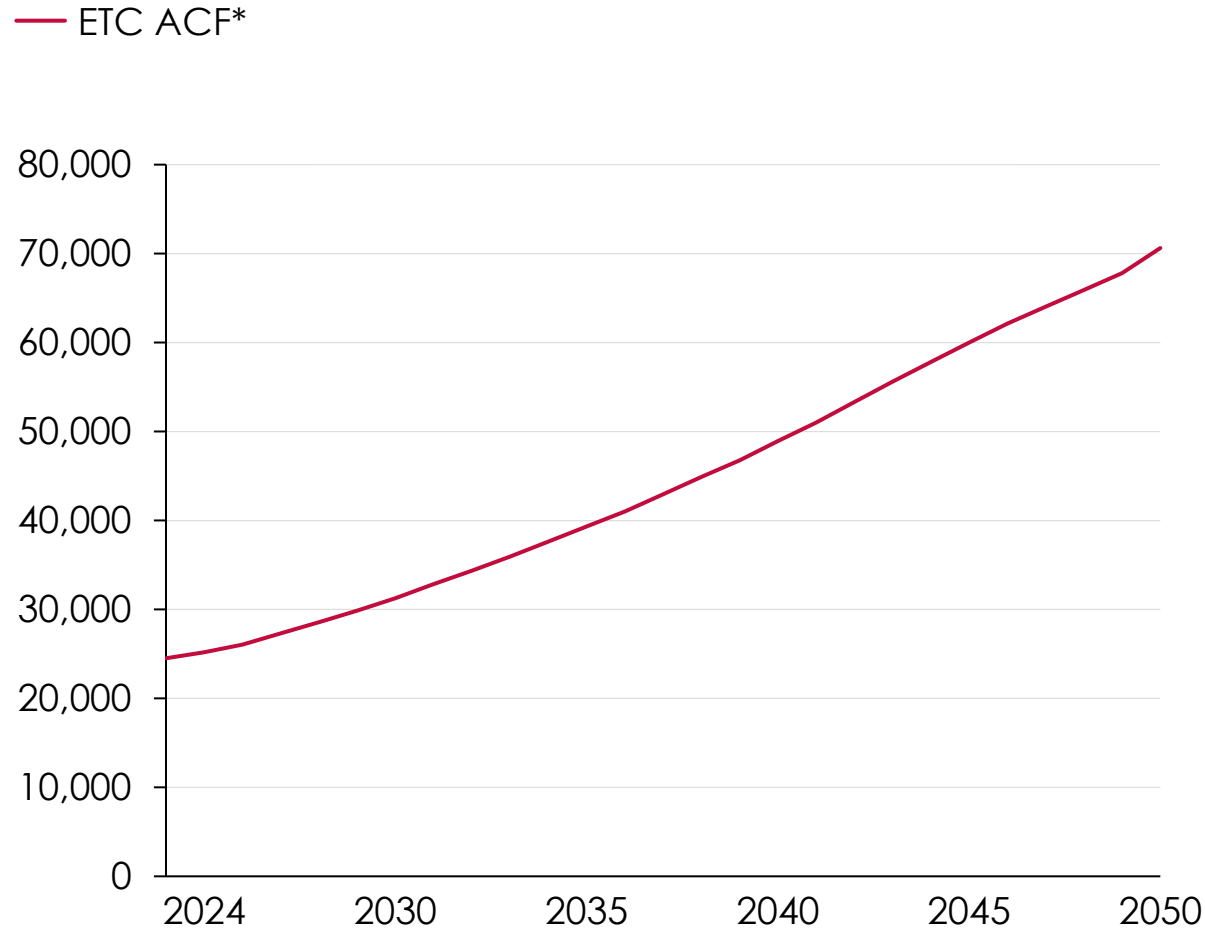
¹New build cost is lower due to higher utilization factor. Note: Annual capacity factors based on assumption that total TWh annually generated from CCGTs is 26 TWh. Emissions intensity of unabated gas assumed to be 0.1829 kg CO2e per kWh. LCOEs assume \$3/kg cost of hydrogen and 1000 \$/kw cost of plant, 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

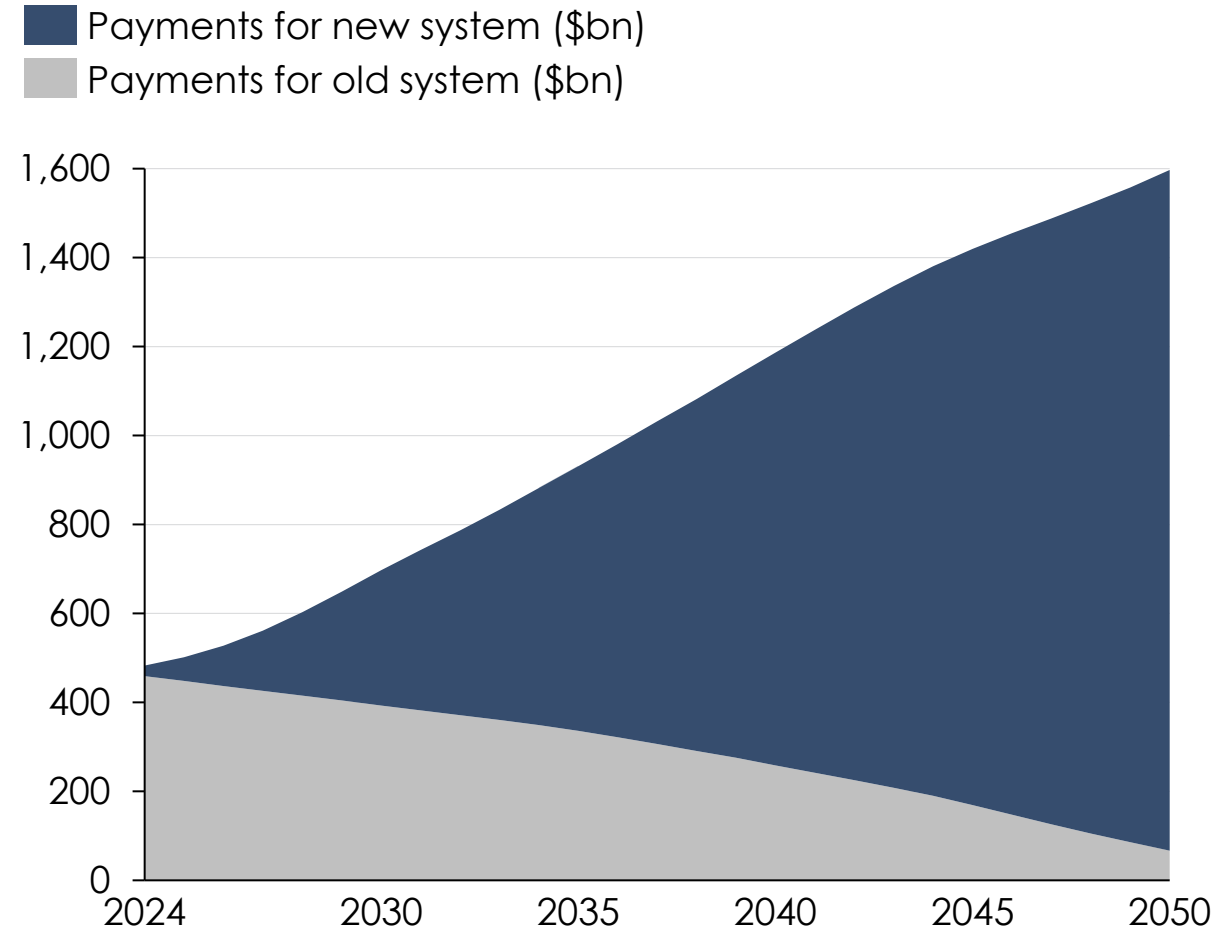
Annual electricity demand, global, 2024–2050

TWh



Annual payments in power grid, global, 2024–2050

\$ bn (real 2024\$); interest rate = 5%; 30-year repayment timeline



Note: *Only 50% of indirect use for hydrogen production is counted
 Source: IEA (2023), *Investment in transmission and distribution grids in selected countries, 2015-2022*; BNEF (2024); BNEF (2023)

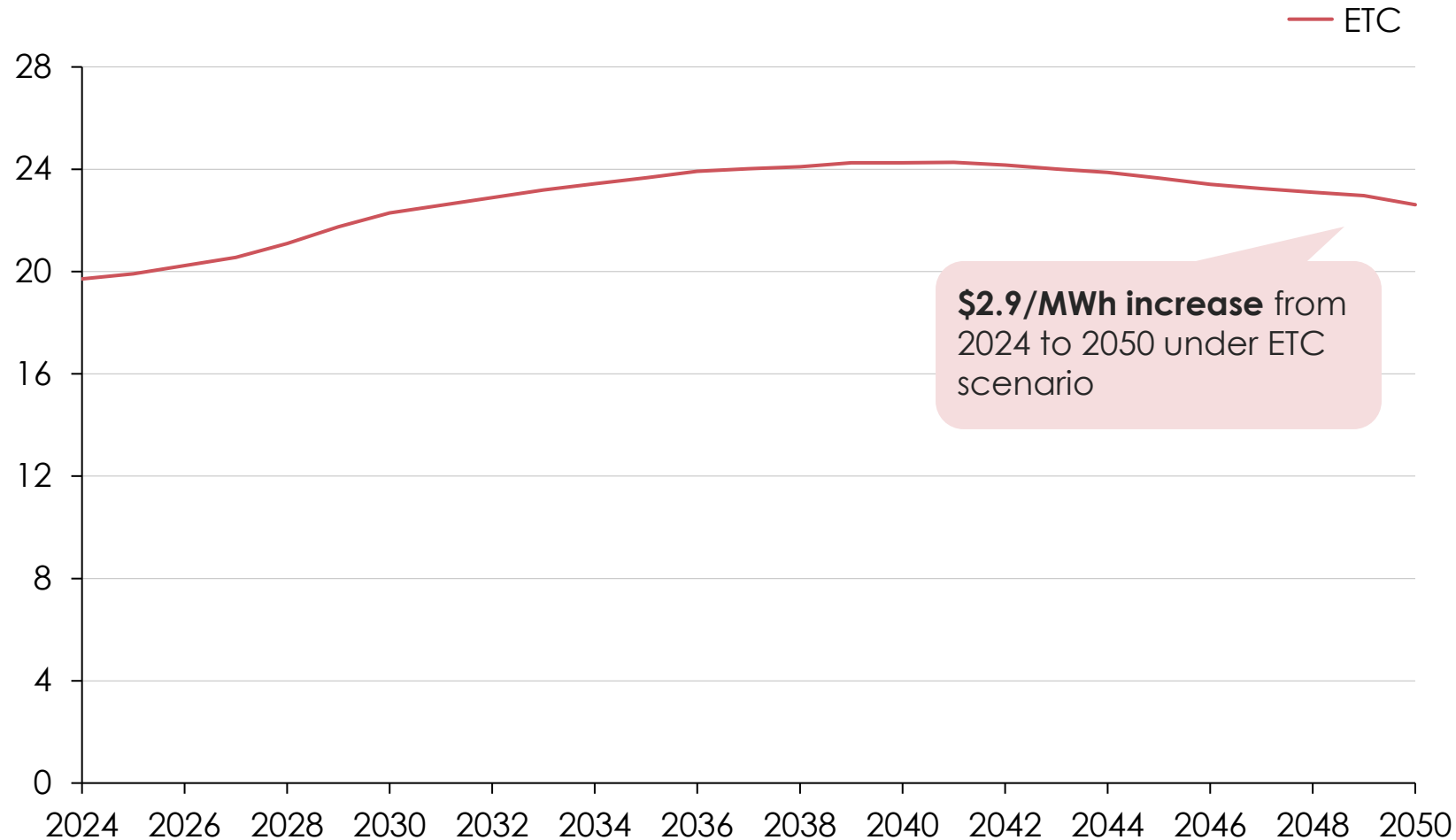




Grid costs per MWh will only increase slightly to 2050, but can be reduced if we maximise flexibility

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



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





- 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.

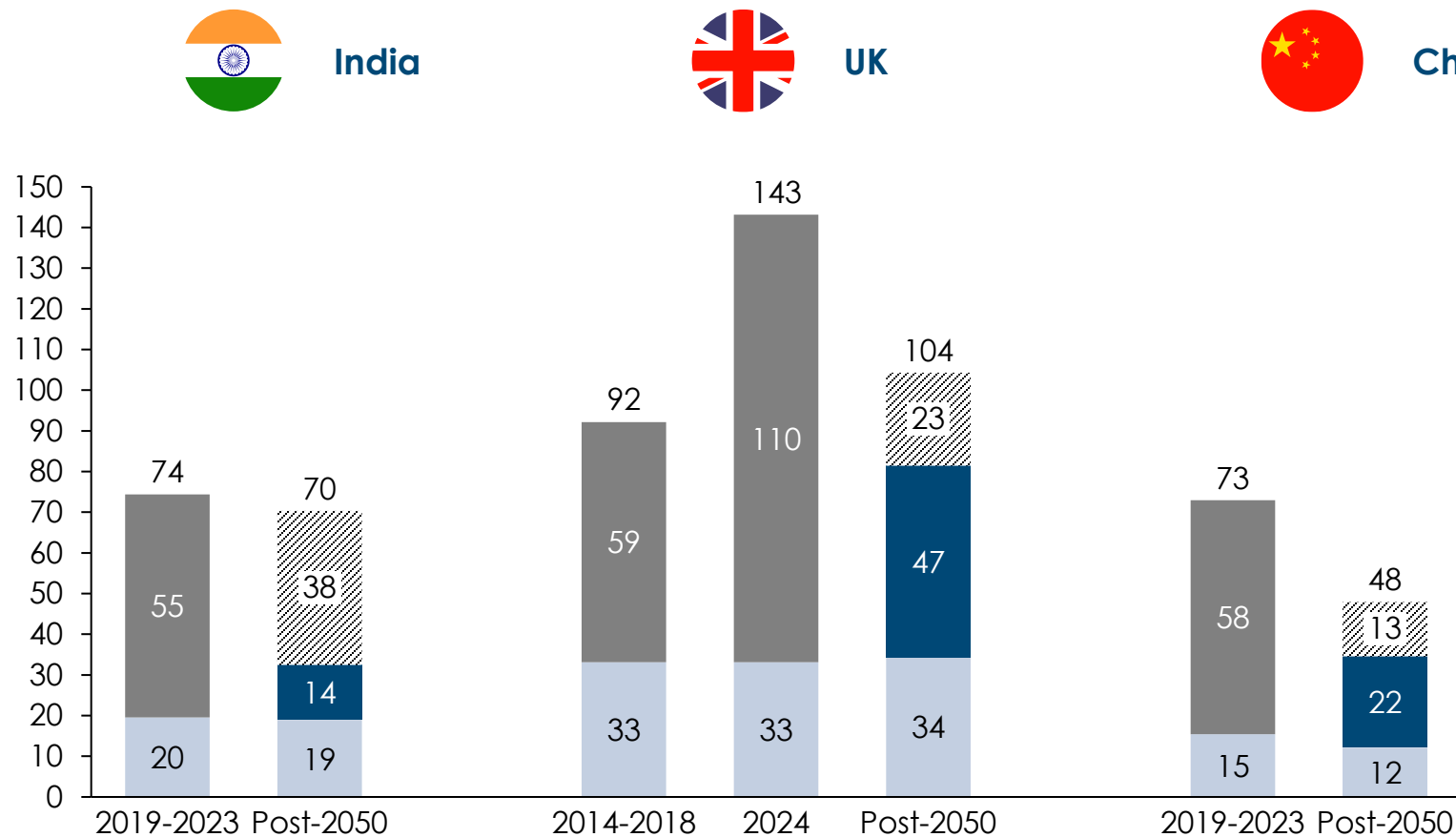


Total system generation and transmission costs less than current wholesale prices

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

\$/MWh (real 2024\$)

-  Average wholesale power prices
-  Cost of meeting balancing needs
-  Wind/solar
-  Transmission & distribution costs



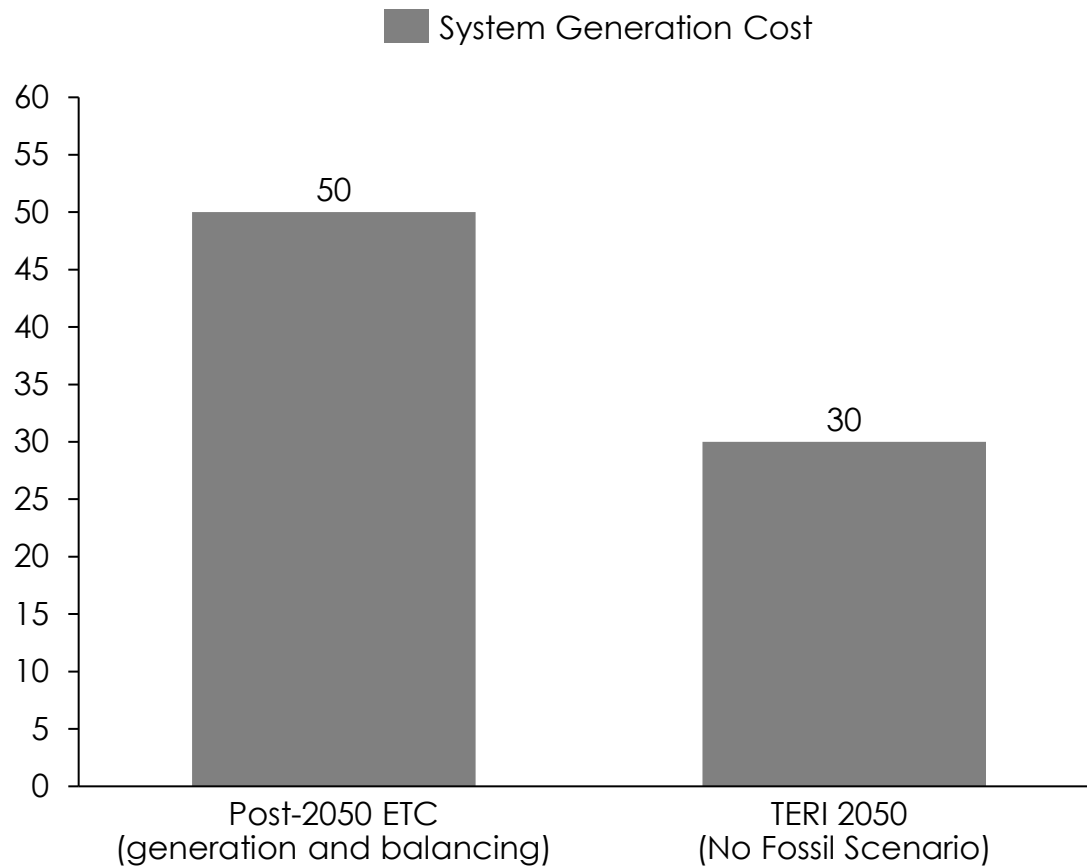
Source: Systemiq analysis for the ETC (2025); BNEF (2023), 2H 2023 LCOE: Data Viewer v.1.0; Ofgem (2025), Wholesale market indicators – Electricity Prices: Forward Delivery Contracts – Weekly Average (GB); IEA (2023), Electricity Market Report – Update 2023; Statista (2024), Average electricity prices 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 forecasts¹

\$/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



¹Comparison of generation and balancing costs, excluding transmission costs. Sources: TERI (2024), *Electricity Transition Pathways to 2050*

Agenda

Context on importance of clean electrification; challenges around running future power systems; role of emerging technologies

Managing the system balancing challenge

Building and optimising grids

Costs: how do these pathways influence costs

Key enablers to unlock the power system of the future



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

