Energy
Transitions
Commission

Power systems balancing: integrated view from this year's work on grids and power storage

ETC Commissioners Meeting

27th June 2024

Overview

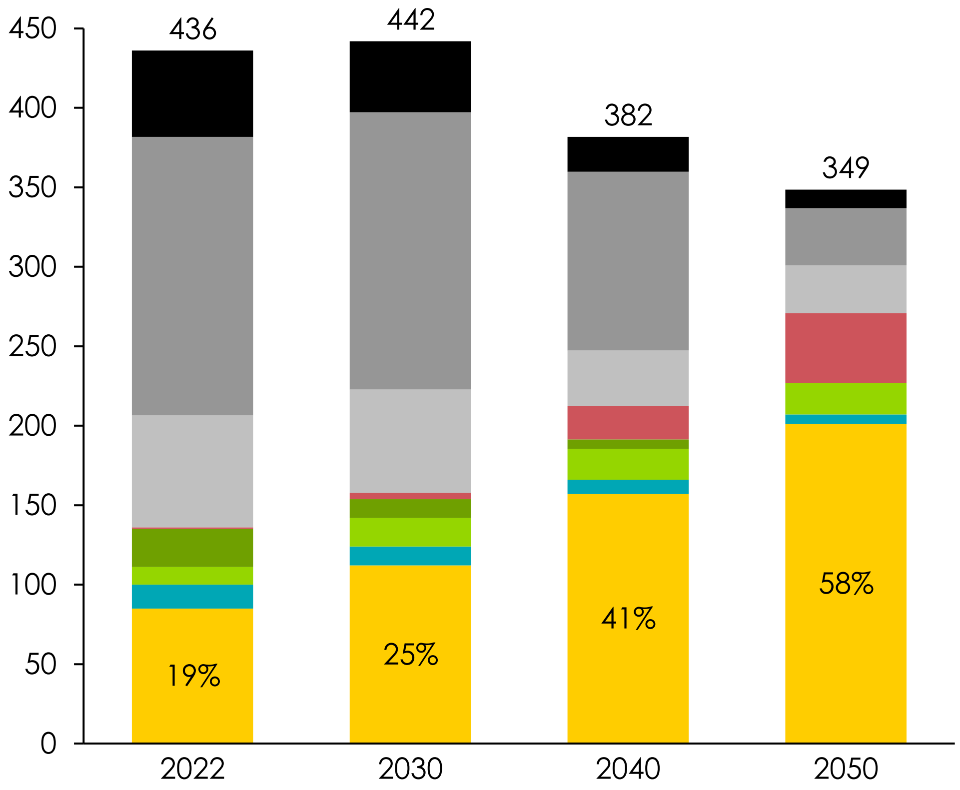
- Re-cap on Power systems transformation workplan
- Building + optimising grids: emerging conclusions
- Managing the system balancing challenge: emerging conclusions
- Reminder on workstream next steps

Re-cap on Power systems transformation workplan

Reminder: ETC scenarios see clean electrification going to 70% by 2050

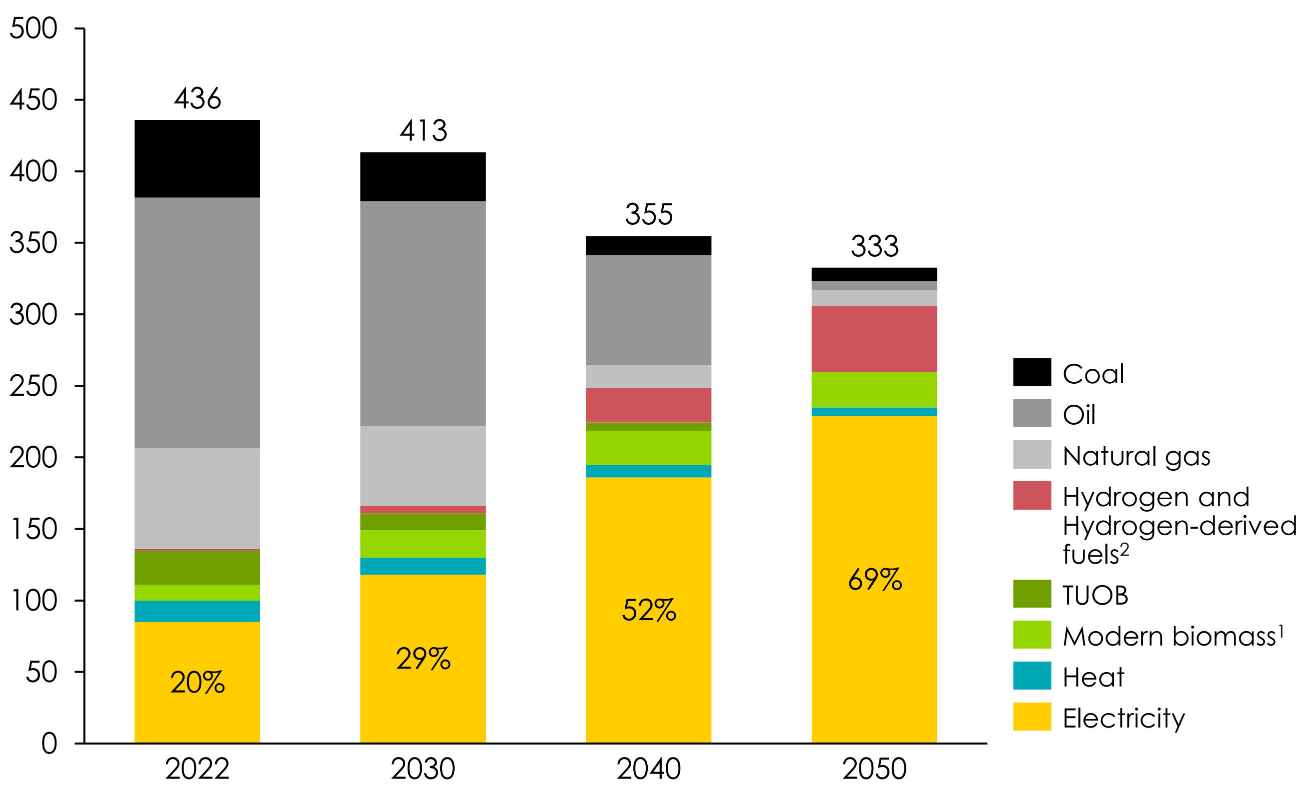
ACCELERATED BUT CLEARLY FEASIBLE

EJ/year



POSSIBLE BUT STRETCHING

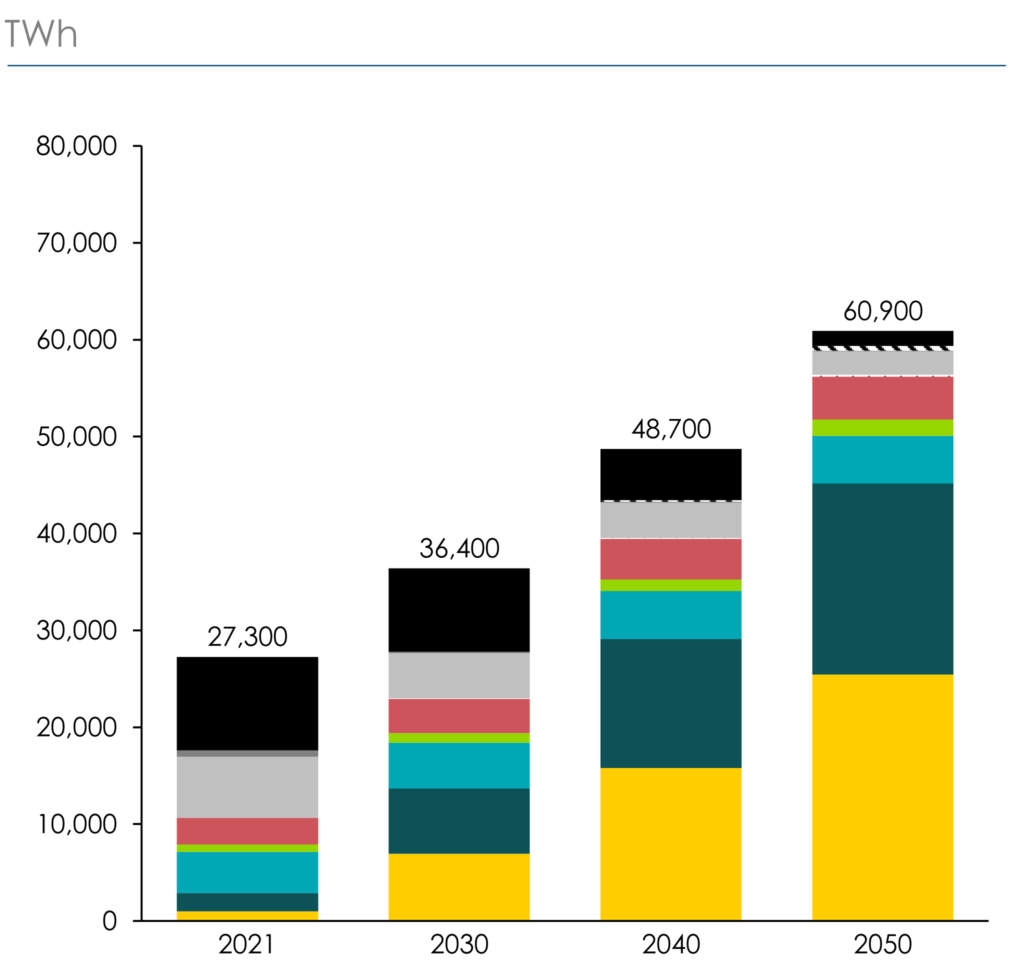
EJ/year



Note: [1]Final energy demand from Modern biomass to be finalized. Excludes wood products, pulp and paper. [2]Mainly from green sources.
Source: Systemiq analysis for the ETC (2023).

Reminder: generation to grow significantly to 2050, wind + solar ~70% by 2050

ACCELERATED BUT CLEARLY FEASIBLE



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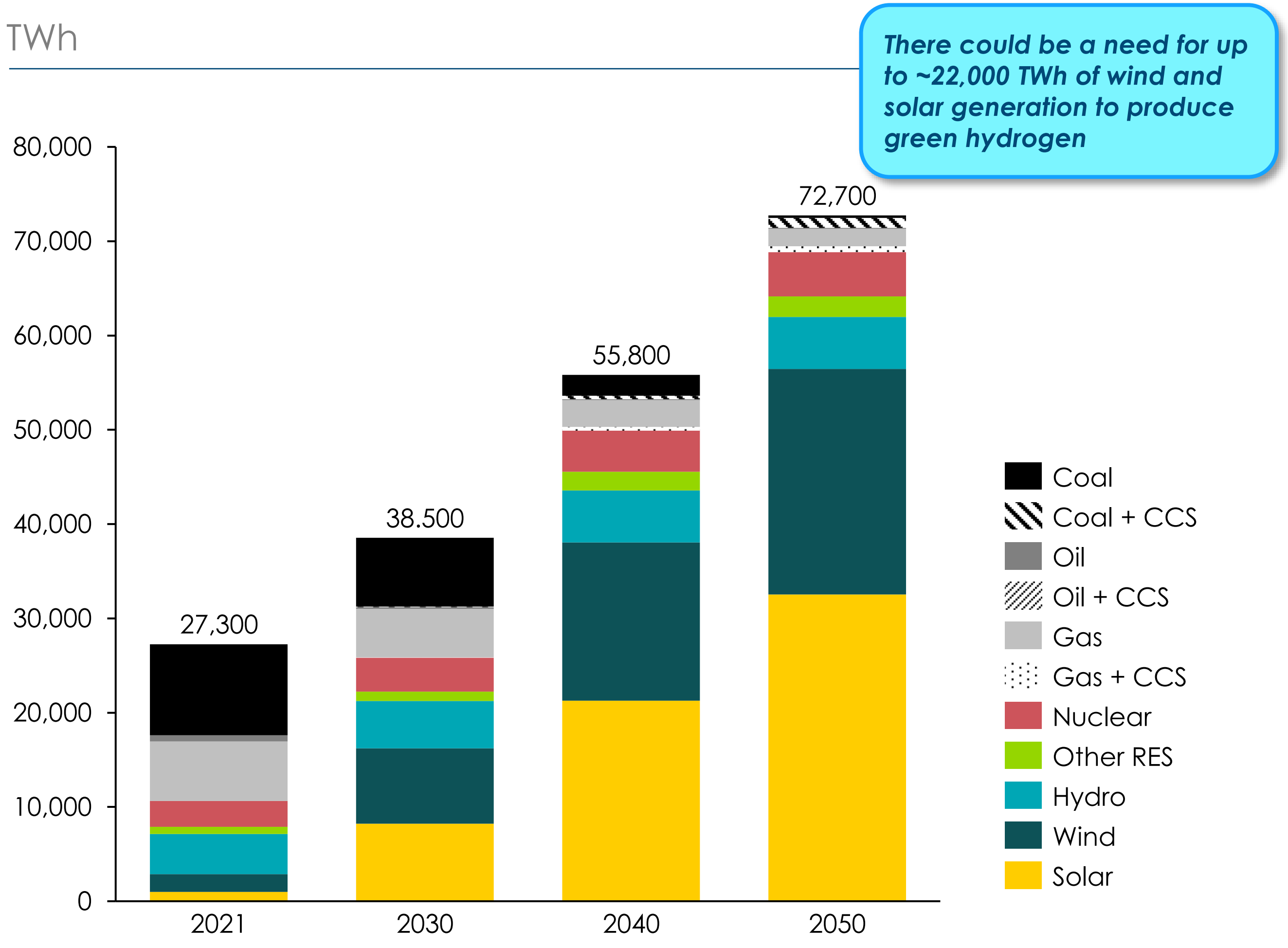


Note: figures include power demand from DACCS from 2030 onwards.
Source: Systemiq analysis for the ETC (2023).

ETC 2024 Power systems transformation work is focused on 3 pillars

How can we enable power flows for the future system?

What is changing?

- *Electricity consumption growth*
- *Dispersed generation*
- *Economy wide-electrification*
- *Intermittent generation*

Core challenge areas

	1 Grids: addressing the build challenge	2 Sweating legacy and new assets	3 Managing the system balancing challenge
Why?	Grid must meet the needs of • A larger system • A more distributed system (generation and consumption)	Optimizing the grid to reduce build needs and costs • Spreading peak load • Maxing utilisation of existing (& new) assets	Balancing a renewables dominated system system across minutes, hours, weeks and months
What?	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	Ix / Tx – balancing the system via interconnection / long distance transmission Balancing the system via storage, flexibility & generation technologies

Related to power grids

Related to energy storage & flexibility

"Sweat assets" to minimise level of build needed
Build new assets to maximise system efficiency

Build more storage and interconnection in the right locations to minimise domestic network build required

There are therefore two fundamental & interrelated key areas for power systems which the ETC is looking at this year

A

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

B

Managing the system balancing challenge

Ix / Tx – balancing the system via interconnection / long distance transmission	Balancing the system via storage, flexibility & generation technologies

Building + optimising grids

Building & optimising grids – key questions

A

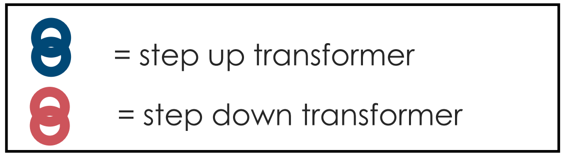
Building and optimising grids

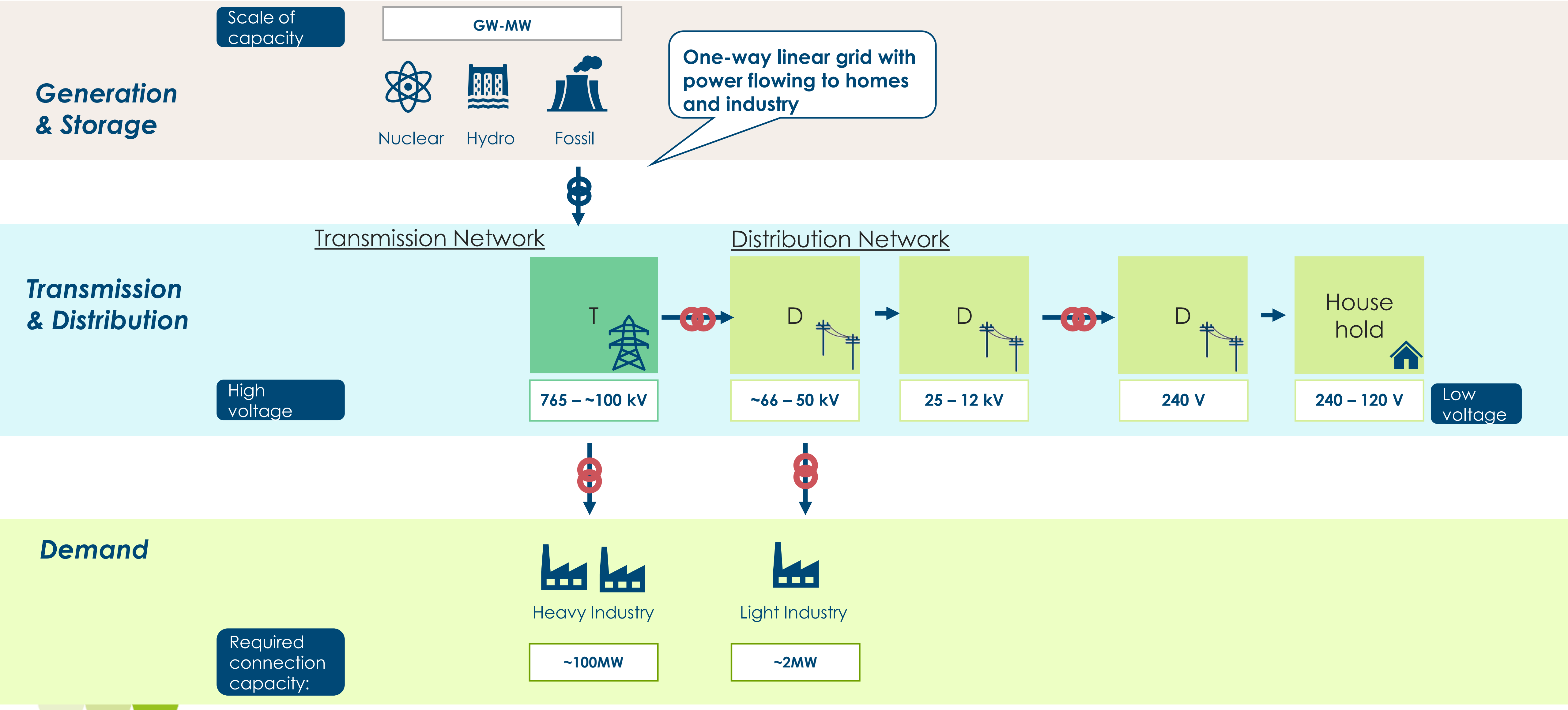
Tx: Grow the transmission network	Dx: Reinforcing existing & building new network infrastructure	Tx: Optimising use of existing assets via new technologies	Dx – Spreading peak load to increase grid utilisation & balance the system

Key questions

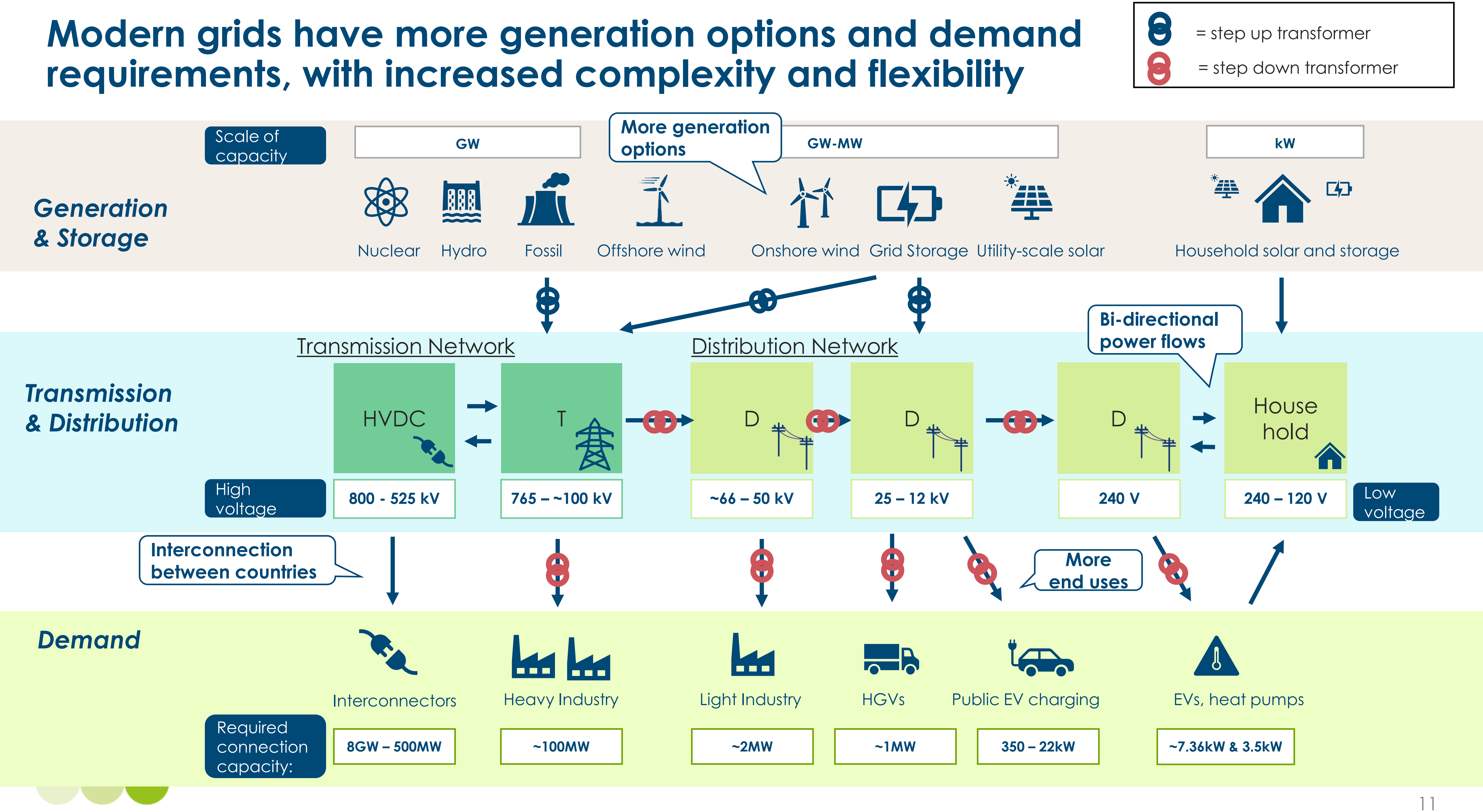
- What does the future grid look like – type of grid, size of the grid, investment needed into the grid? How does this differ by region? What are the key enablers to unlock grid build?
- How can we minimize the transmission build challenge and make the system more efficient? E.g. use of technologies
- How can we minimize the distribution build challenge and make the system more efficient? E.g. solving the peak demand challenge

Fossil dominated systems are linear, with plants located close to demand centres and connected via transmission





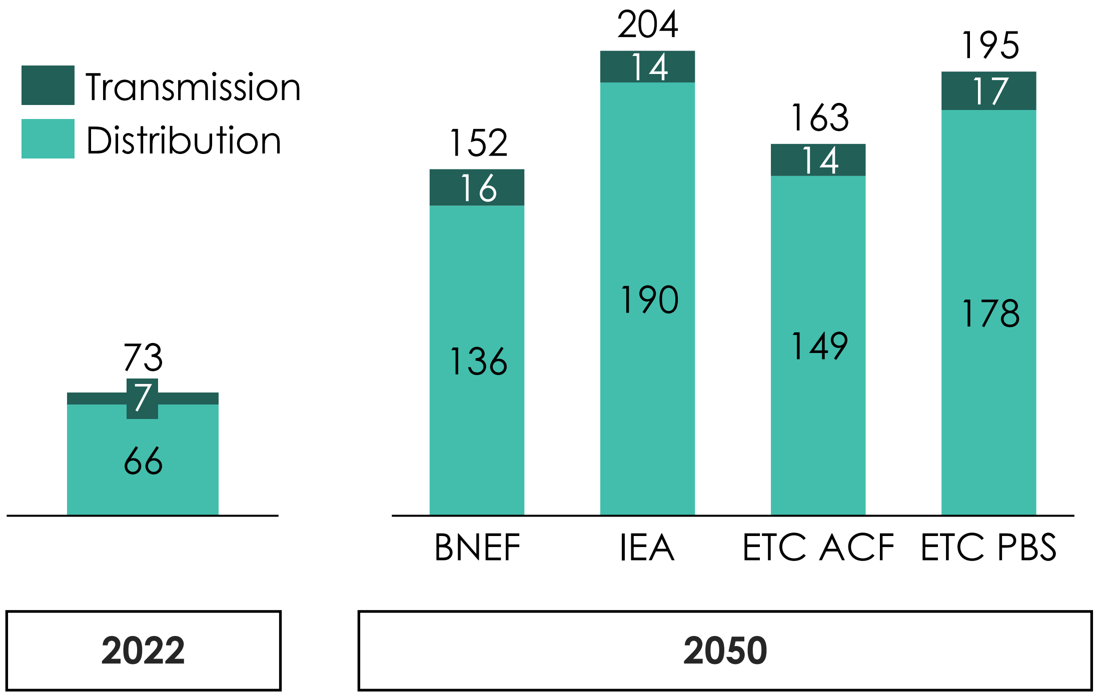
Modern grids have more generation options and demand requirements, with increased complexity and flexibility



Preliminary

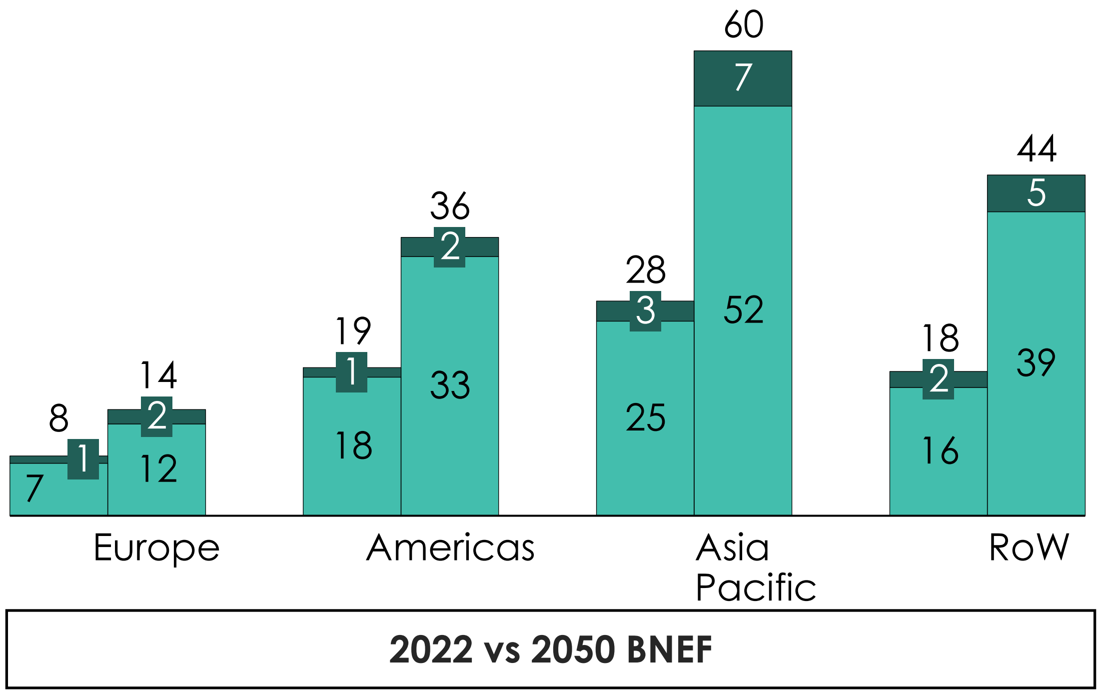
Network build will have to increase dramatically across regions

Estimated wires required under various assumptions
Million km



Significantly more wires are needed

Estimated wires required (BNEF Net Zero Scenario)
Million km



Key regions will have to increase their estimated wire build substantially under a Net zero scenario

Note: BNEF data used represents NZS (Net Zero Scenario). The ETC Accelerated but Clearly Feasible scenario (ACF): is clearly technically and economically feasible, but in some sectors will require more forceful policy support than currently in place. If combined with significant carbon removals, this scenario would be broadly compatible with limiting global warming below 2°C (specifically to 1.7°C) but would not deliver a 1.5°C limit. The ETC Possible But Stretching scenario (PBS): is also technically and economically feasible but would require significant strengthening of current commitments and policies. Combined with significant carbon removals, this scenario would come close to delivering a 50% chance of limiting global warming to 1.5°C in 2050, and a level below 1.5°C in 2100 if removals could continue in the second half of the century

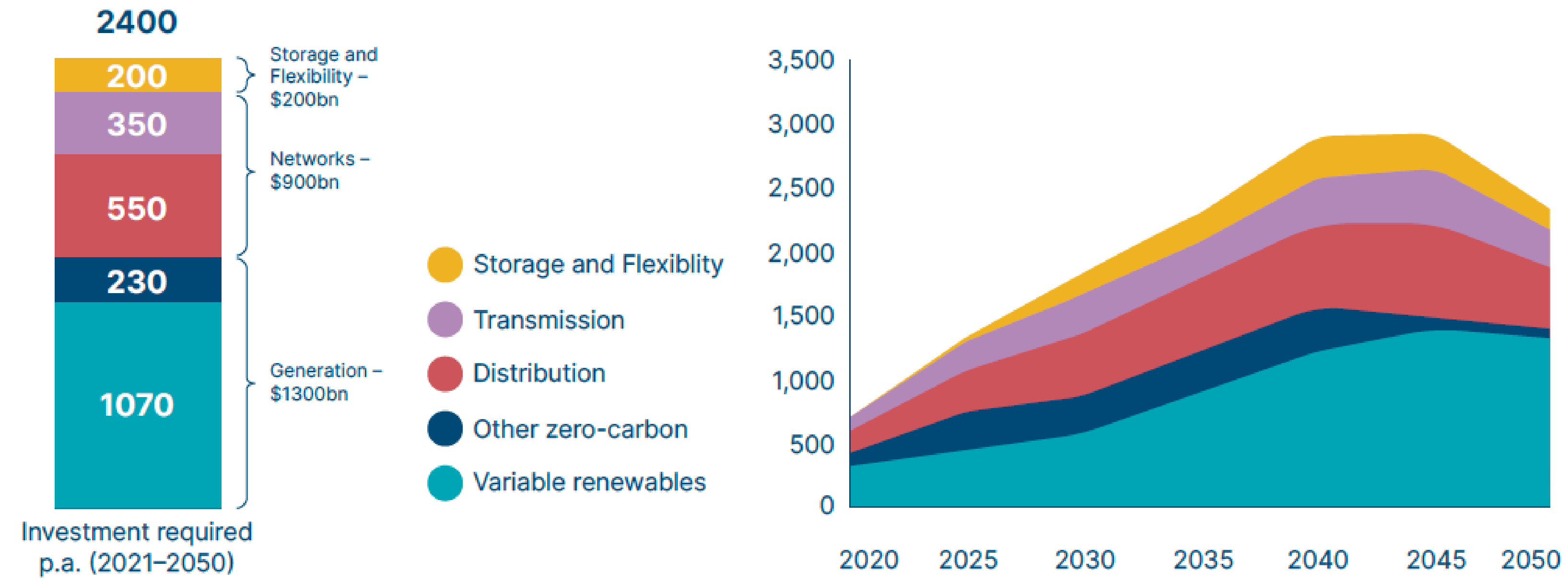
Source: BNEF (2023) NEO grids; BNEF (October 2023) NEO data viewer; IEA (2023) *Electricity Grids and Secure Energy Transitions; IEA (2023) Electricity Grids and Secure Energy Transitions; Systemiq analysis for the ETC (2024)*

Grid spend to triple from ~$320 billion p.a. today to ~$900 billion p.a. in 2050

Preliminary

Global annual investment

$ billion p.a.

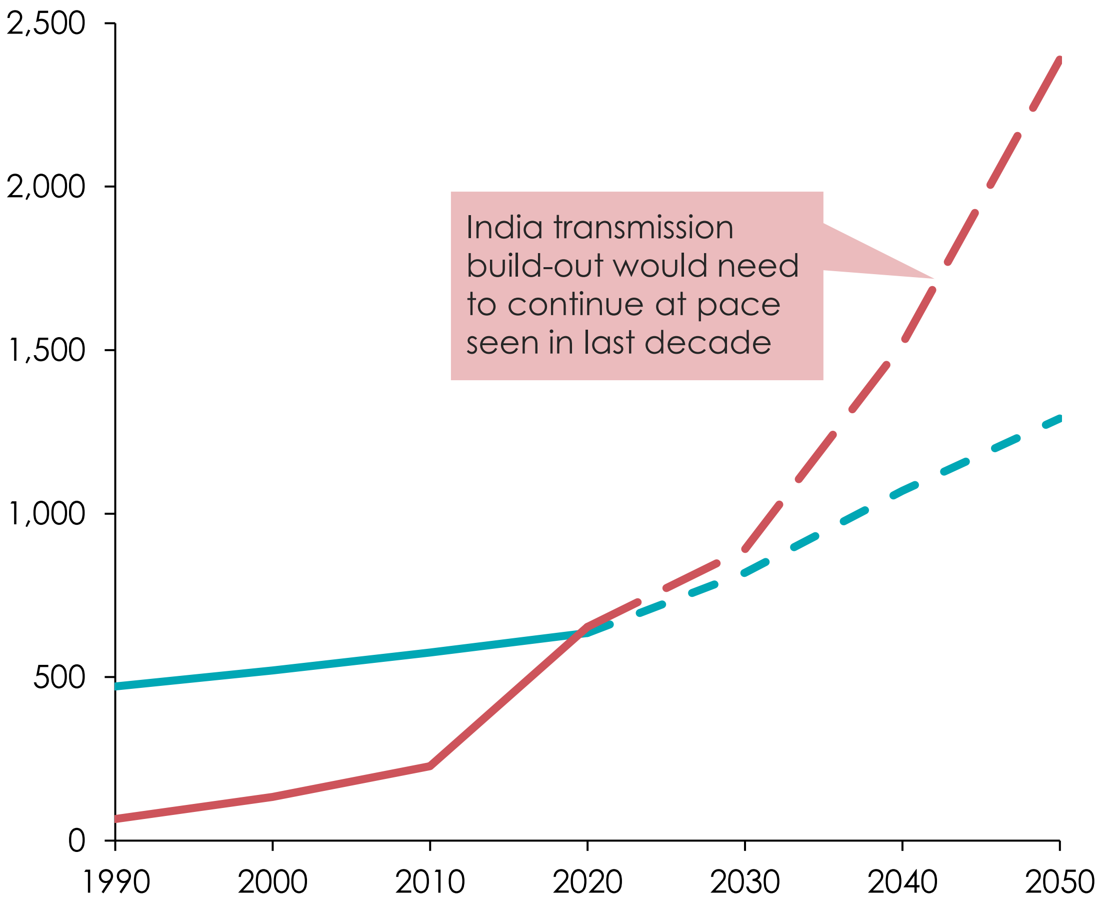


- **$900bn per year in transmission and distribution networks**: required to underpin significant increases in electricity demand and enable the integration of variable renewable generation.
- Cumulatively, this would equate to over $25 trillion between 2022-2050

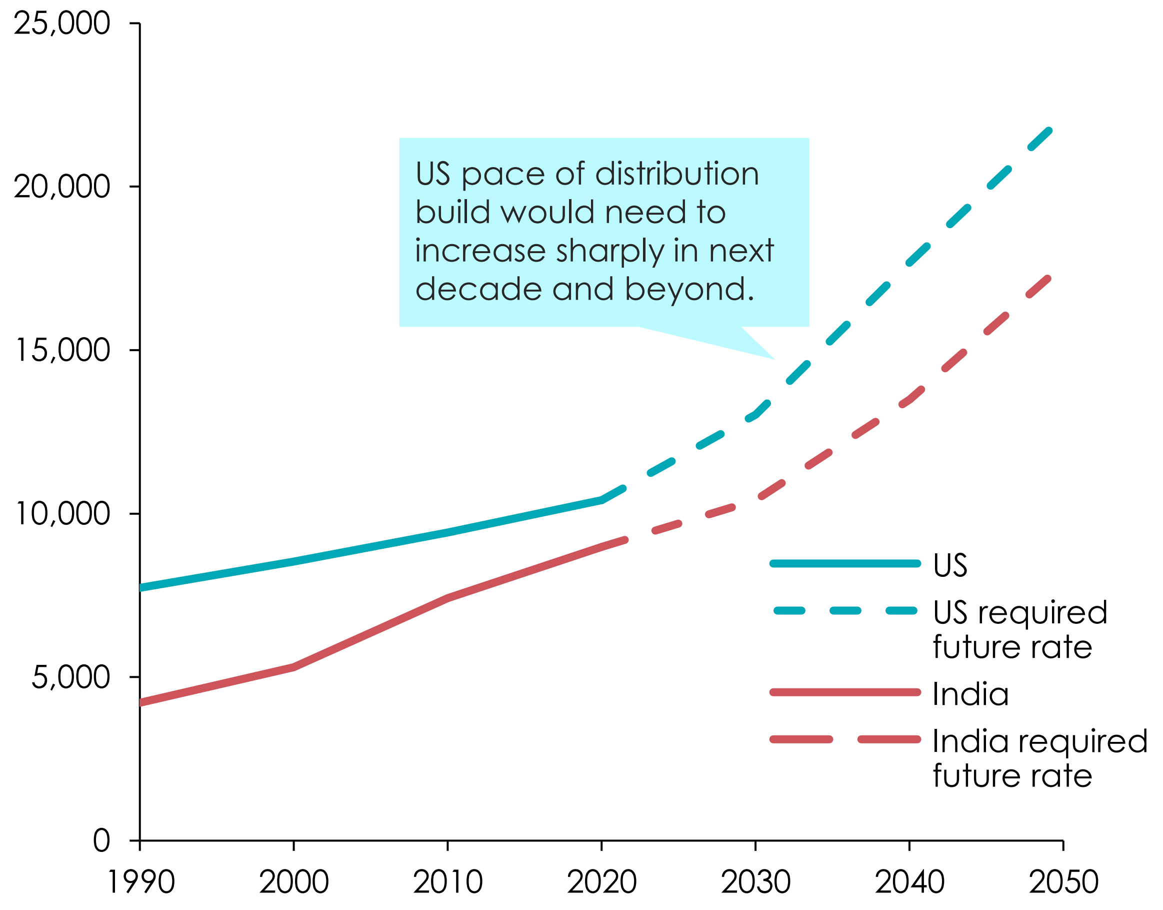
Note: Includes investment in clean electricity generation required to produce green hydrogen.
Source: ETC (2023) *Financing the Transition*

Grid growth will need to accelerate in many countries

Historical and forecast transmission build rate, US and India
Thousand km of wires



Historical and forecast distribution build rate, US and India
Thousand km of wires

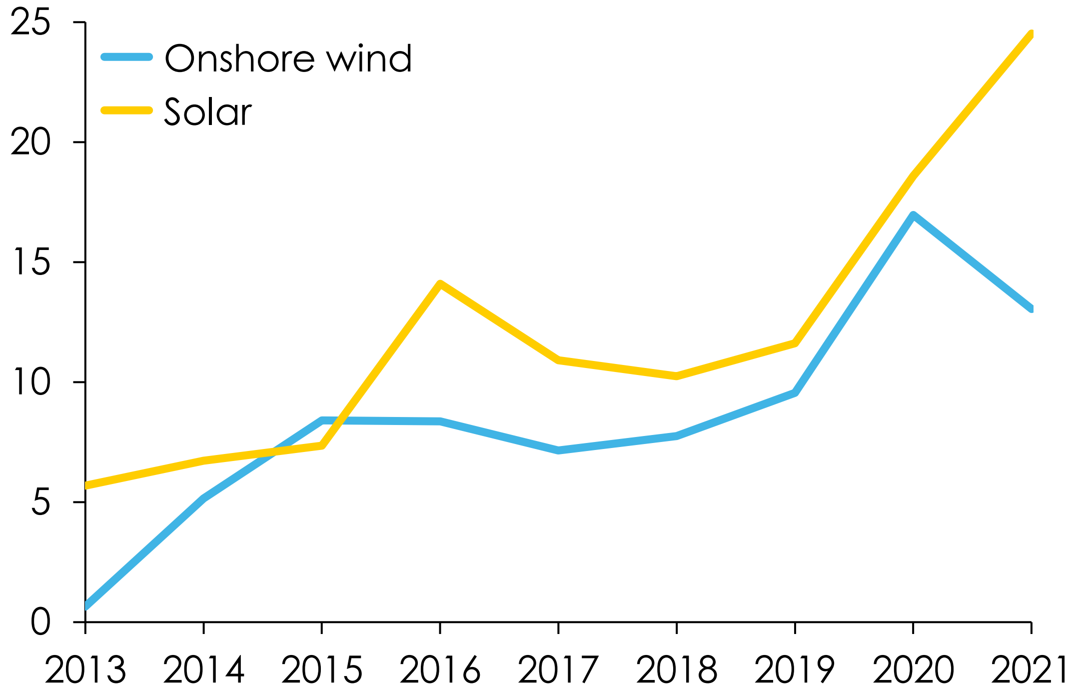


Notes: US historical build rate calculated on assumption of 1% grid growth in transmission and distribution per year from 1990 – 2022; Princeton modelling outlines that from 2013 to 2020 transmission lines have expanded at only 1% per year. Source: BNEF (2021) Power Grid Long Term Outlook 2021; BNEF (2023) New Energy Outlook Grids; Princeton Zero Lab (2022) *Preview: Final REPEAT Project Findings on the Emissions Impacts of the Inflation Reduction Act and Infrastructure Investment and Jobs Act*

Grid expansion is not keeping pace with renewable deployment

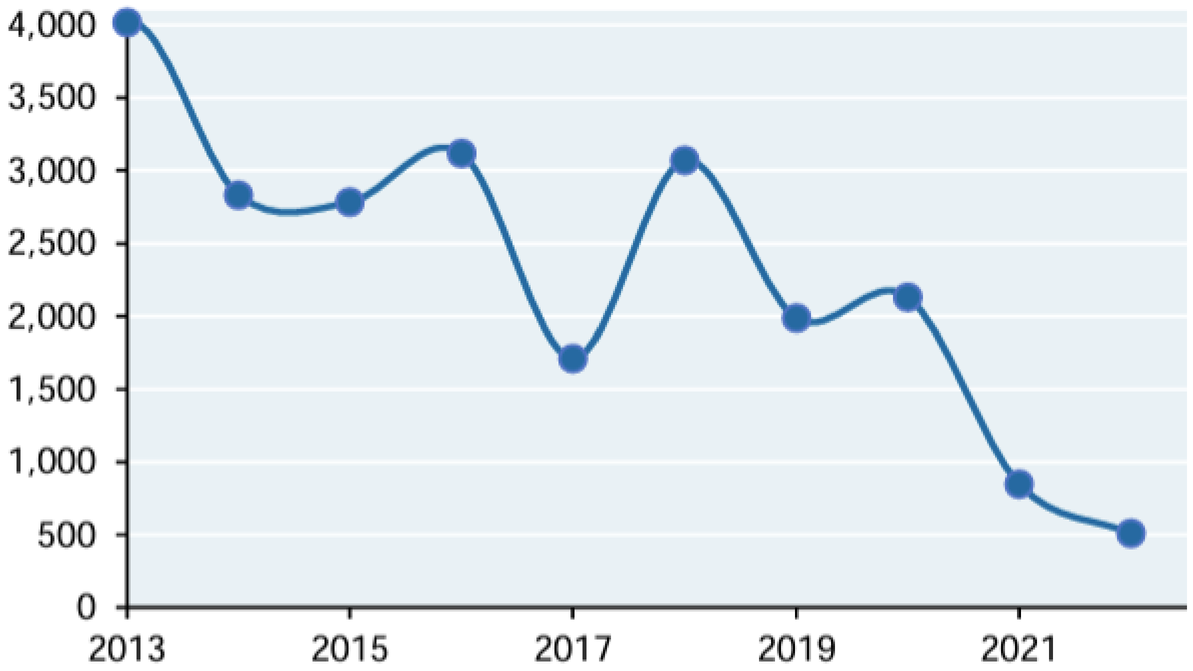
US Wind and solar capacity growth

New build Installed capacity (GW/year)



US transmission line growth

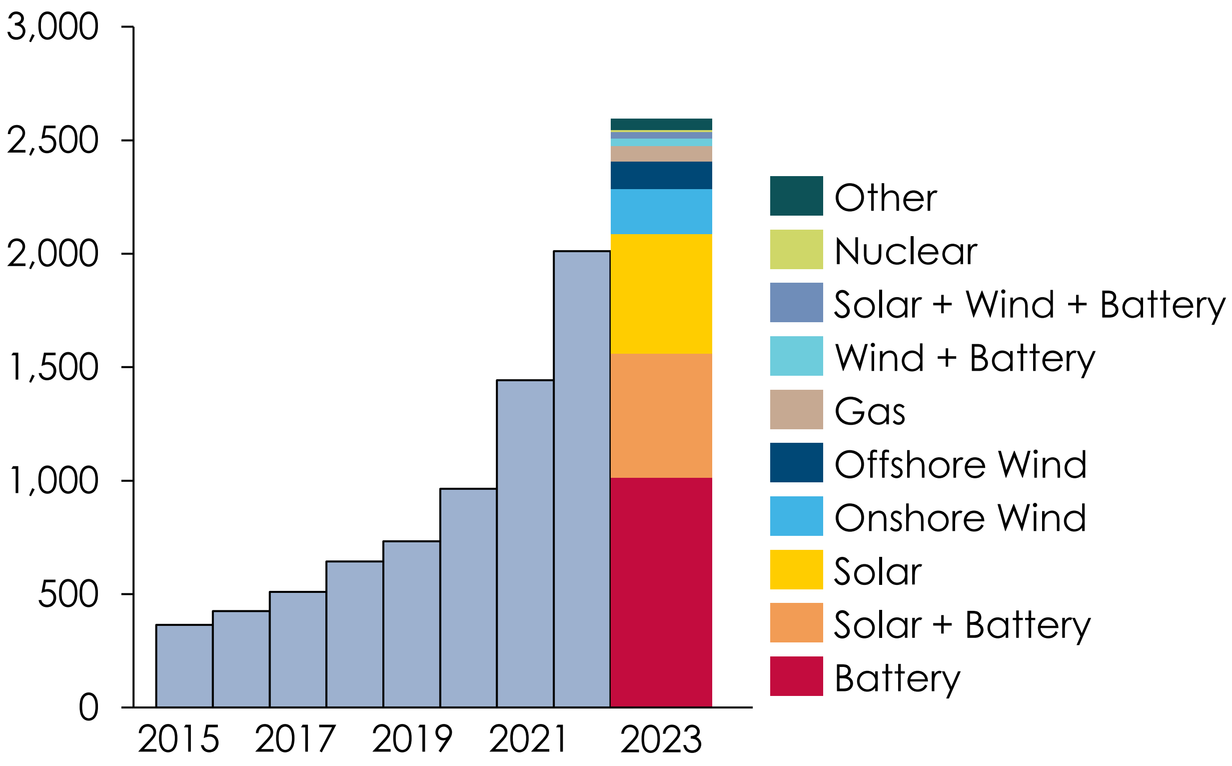
Miles added per year (Transmission lines > 100kV)



Source: S&P Global (2024), *JPMAM;* BNEF (2024), *Capacity & Generation*

Lack of grid build is already leading to connection queues, which are growing each year

US Grid connection queue sizes (2015-2023)
GW



Projects in queues are growing, in **2023 the US had 1450 GW** of wind and solar capacity in queue (equal to 50% current global wind and solar capacity).

Source: Berkeley Lab (2024) *Queued Up: Characteristics of Power Plants Seeking Transmission Interconnection*

Lack of grid build also leading to increases in congestion payments

Congestion payments are typically paid to renewable generators to avoid them producing when networks are congested

Windpower Monthly

Grid constraints cost UK £1 billion per year in wasted wind power generation

Aurora Energy Research

Grid Overload: The Impact of the Electricity Grid on the Dutch Energy Transition

Aurora Energy Research

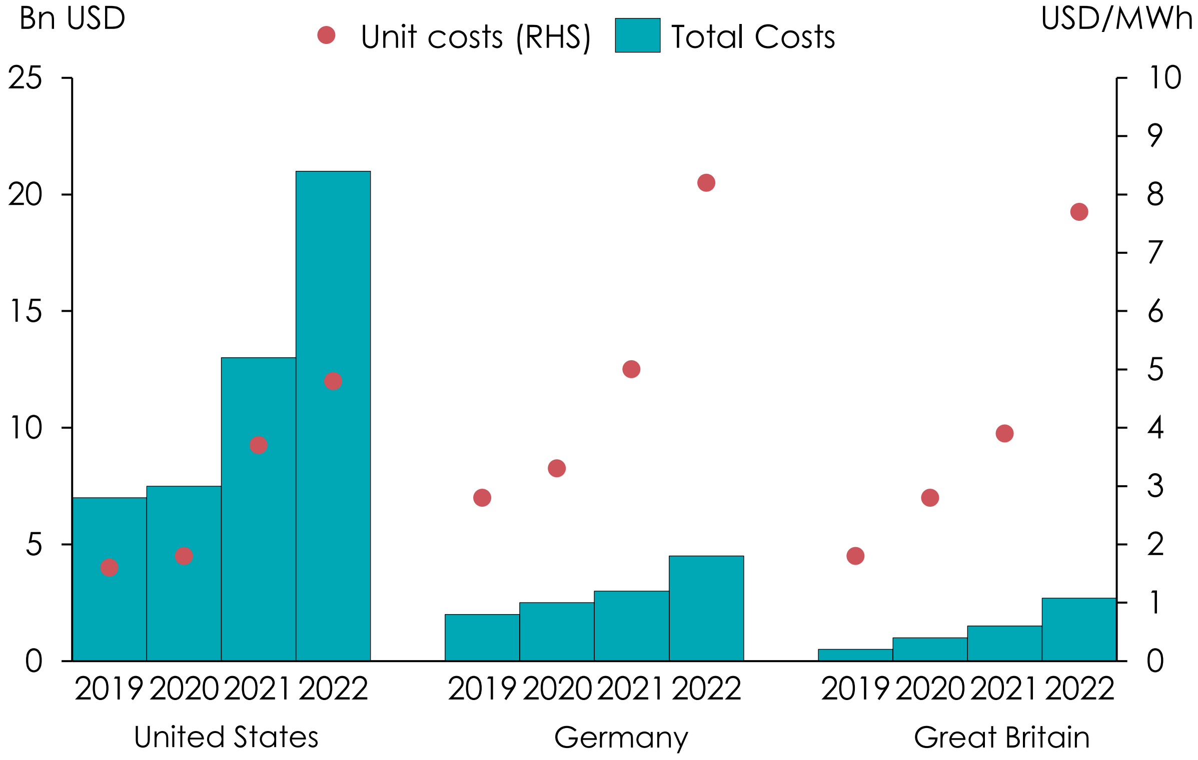
Grid management challenges costing Spanish energy consumers

Scottish Daily Express

Two Scottish offshore wind farms paid £100m a year to switch off their turbines

Annual transmission grid congestion estimates in select regions

Bn USD and USD/MWh



Lack of grid connection is causing congestion power systems, with associated costs totalling in billions for some regions

Source: IEA (2023), *Electricity Grids and Secure Energy Transition*

Four areas address grid build challenge

1 Implement a strategic vision coordinated across key stakeholders & supported by clear data

Ensuring grid plans are:

1. Aligned with **decarbonisation targets** and **planning horizons**
2. Integrated with plans for **generation siting**
3. Developed across as **wide a geographic area as possible** (e.g. across regions, countries)
4. Targeted to develop a **coordinated expansion approach for distribution** networks

2 Address slow **permitting & approvals and societal acceptance**

- Regulatory and legislative reform to address **regulatory and administrative blockages** (e.g. slow consenting, multiple authorities in charge/ lack of resources)
- **Improve societal support** via actions to increase community buy-in and reduce opposition

3 Address skill, component and materials gaps

Rapidly and sustainably scale up supply and coordination across key stakeholders for:

- **Specific materials**, such as copper
- **Specific components**, such as transformers, subsea cables, and cable-laying vessels
- **Skills**, particular for linesmen; power engineers; planners; etc.

4 Reform financing structures & increase access to finance

- **Reform existing investment approach** to enable anticipatory investment ahead of need
- Improve routes to provide **sufficient financing for grid assets in developing countries**

Efforts to address grid build priorities are underway in key regions

Key new initiatives

- Reforms to US FERC planning process, e.g. for all TSOs to have **20-year transmission planning processes**.
- **DOE roadmap to accelerate grid connections**, via open data, targets, and tools for speeding queues.
- DOE proposal for **10 National Interest transmission corridors** to have streamlined permitting & financing

- **National Grid outlined £60bn investment plan** between 2025-30, in in a "switch away from yield to growth".
- New "**Future Systems Operator" to begin operations in 2024**, responsible for coordinating energy system and the entire gas and electricity networks.

- **EU Action plan on grids launched**, with actions including better finance, long-term planning, regulatory incentives, implementing 'projects of common interest'.
- **EU Council approves conclusions** for a coordinated, interconnected and integrated European network.

US Department of Energy has proposed 10 National Interest Transmission Corridors with expedited permitting

Source: Lexology (2024), *Order No. 1977: FERC Siting Permits for Interstate Electric Transmission Facilities - FERC Finalizes Backstop Transmission Siting Reforms*

Building & optimising grids – key questions

A

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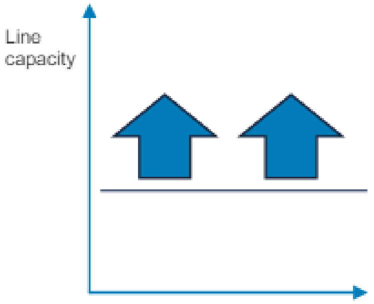
Innovative Grid Technologies (IGTs) allow for a better use of the grid

Main methods to increase grid capacity:

Existing rights of way
Changes to pylons and wires

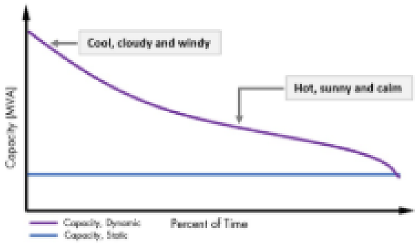
Capacity increase for a given line



- Direct capacity improvement compared to conventional technologies

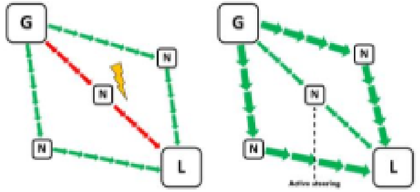
Existing wires and networks
No changes to pylons and wires

Better understanding of actual line limits



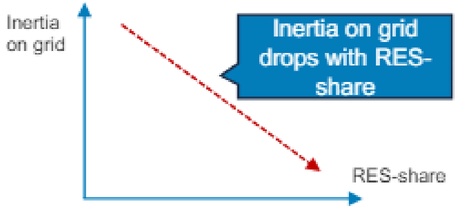
- A static limit must be very conservative, to not overload lines in adverse (hot) conditions;
- Dynamic ratings exploit natural line cooling

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

Better understanding of actual inertia limits/stability limits



- Inertia on the grid decreases with more RES in the system, which may cause stability issues and RES curtailment
- Precise measurement of inertia allows curtailment to only happen when necessary

Technology options:

- **Advanced conductors**
- **Superconductors**
- **Voltage upgrade** (via larger pylons)
- **Double circuiting**
- **SATA** (Storage as transmission asset)

- **Dynamic Line Rating**

- **APFC** (Advanced Power Flow Control)
- **FACTS** (Flexible AC Transmission systems

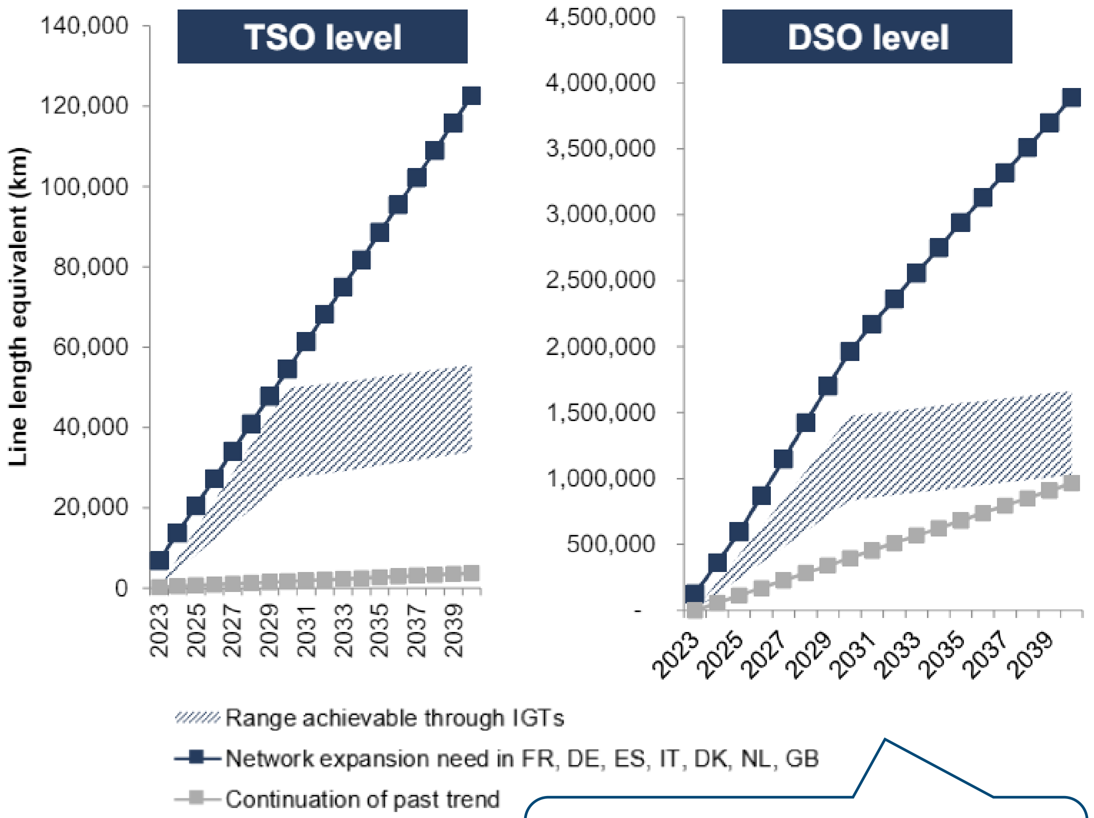
- **Grid inertia measurements**

- **Digital twins, Flexibility software management solutions**

Notes: The term "Grid Enhancing technologies" can also be used to describe technologies that "maximise the transmission of electricity across the existing system through a family of technologies that include sensors, power flow control devices, and analytical tools". This theoretical framework does not provide an exhaustive classification of IGTs, and of their effects. Other technologies and effects could potentially be considered. Substations and switching stations must be upgraded in tandem with grid capacity upgrades to manage the additional power in the system, key solutions here include gas-insulated switchgear and superconducting transformers. Source: *CURRENT (2024), Prospects for innovative power grid technologies.*

Innovative Grid Technologies could meet substantial portion of network expansion needs

Benefits of IGTs compared to expansion needs and past trends
Line length equivalent, FR, DE, ES, IT, DK, NL and GB



Over 40% of network expansion needs can be met by IGTs, accelerating expansion by 4-8 years

- A 2024 CURRENT study concluded **potential for current capacity/line lengths to increase 20%-40%** from Innovative Grid Technologies on the wider network
- Key enablers need to be enacted to help rollout:
  - **Regulatory incentives for non-capex-intensive solutions** (current capex bias via regulated returns)
  - **New approach to T/DSO investment doctrine**, taking a technology neutral approach
  - **Better access to funding** for IGT deployment

Notes: Charts take conservative assumption of 10-20% capacity increase out of potential 20-40%. TSO = Transmission System Operator, DSO = Distribution System Operator. European countries included in study include France, Germany, Spain, Italy, Denmark, Netherlands, Great Britain. Source: *CURRENT (2024), Prospects for innovative power grid technologies.*

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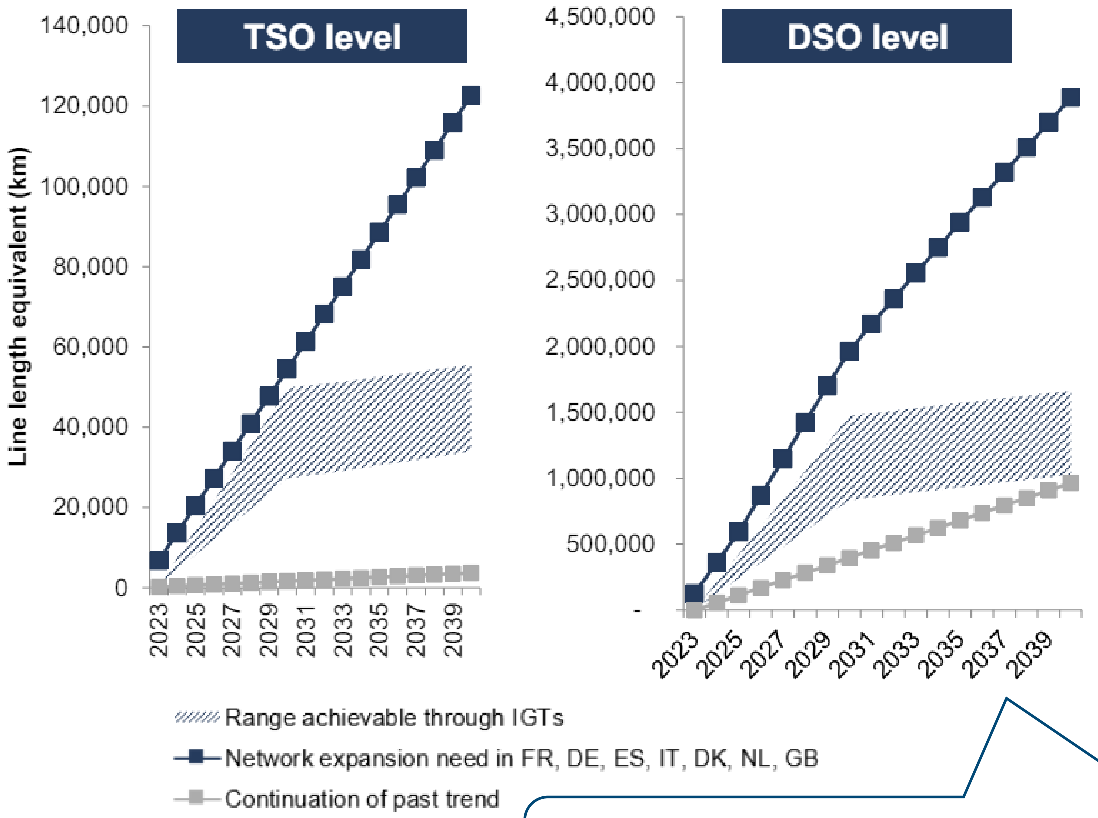

Over 40% of network expansion needs can be met by IGTs on existing networks, accelerating expansion compared to need by ~4-8 years

- A 2024 CURRENT study concluded **potential for current capacity/line lengths to increase 20%-40%** from Innovative Grid Technologies on the wider network.
- Conservatively assuming that this could lead to 10-20% expansion of the current network, a large portion of required increases can be met.
- Key enablers need to be enacted to help rollout:
  - **Regulatory incentives for non-capex-intensive solutions** (current capex bias via regulated returns)
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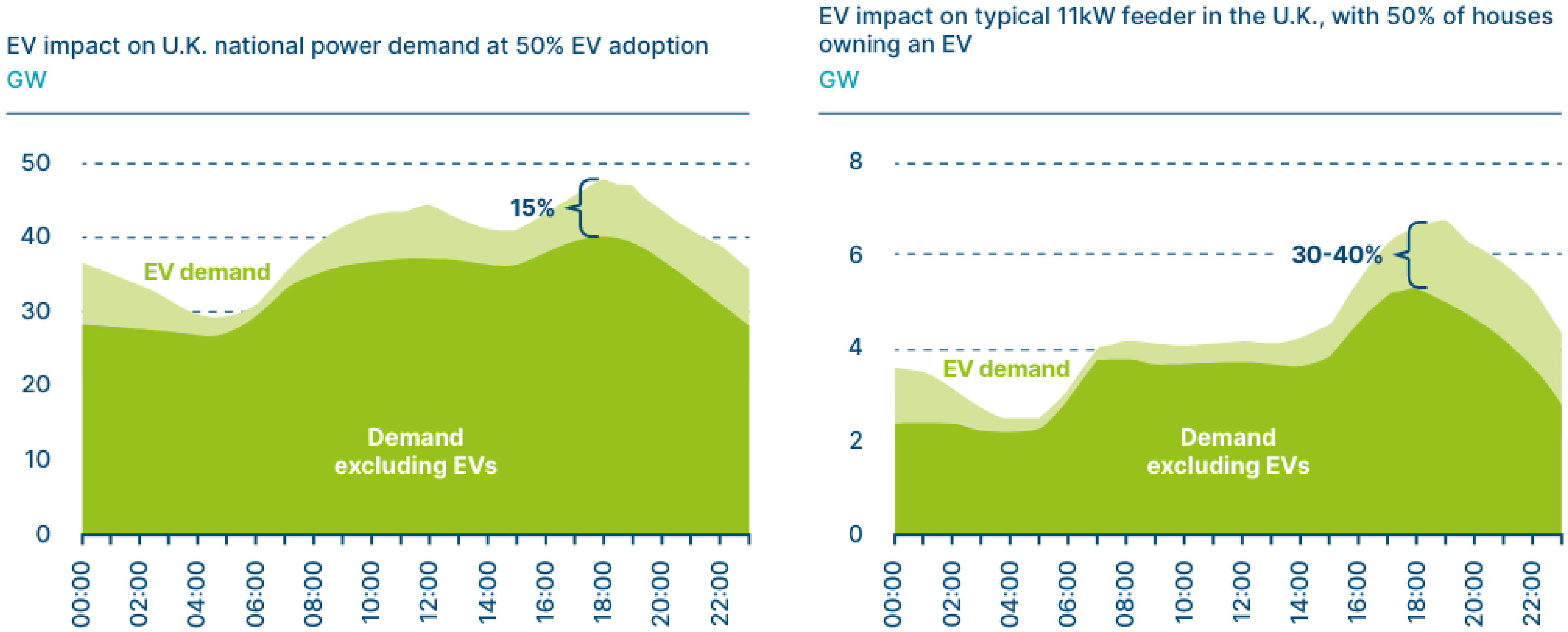
Distribution: challenge of 'peak load' at local level

Peak demand at local level could be double that of national level, due to highly localised EV adoption

Illustrative examples



Peaks will need to be mitigated through grid management solutions at Dx level:

- *Digitalisation*
- *Smart charging*
- *Time-of-use tariffs*
- *Greater energy storage*

Notes: EV charging curve = combination of passenger and commercial EVs. Winter day. Assumes all EVs are BEVs charging at 7kW. Source: BNEF (2020), Sector Coupling in Europe: Powering Decarbonisation

Managing the system balancing challenge

Managing the system balancing challenge – key questions

B

Managing the system balancing challenge

Ix / Tx – balancing the system via interconnection / long distance transmission

Balancing the system via storage, flexibility & generation technologies

Key questions

- What is the system balancing challenge? How much storage and flexibility will be required across different durations for key countries?
- What are the technologies to meet the balancing challenge? What will they cost? What are the key enablers we need to make sure we can bring the required storage & flexibility onto the system?

Different aspects of the 'balancing' challenge

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

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

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)

Predictable seasonal variations in 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)

Unpredictable week-by-week variations

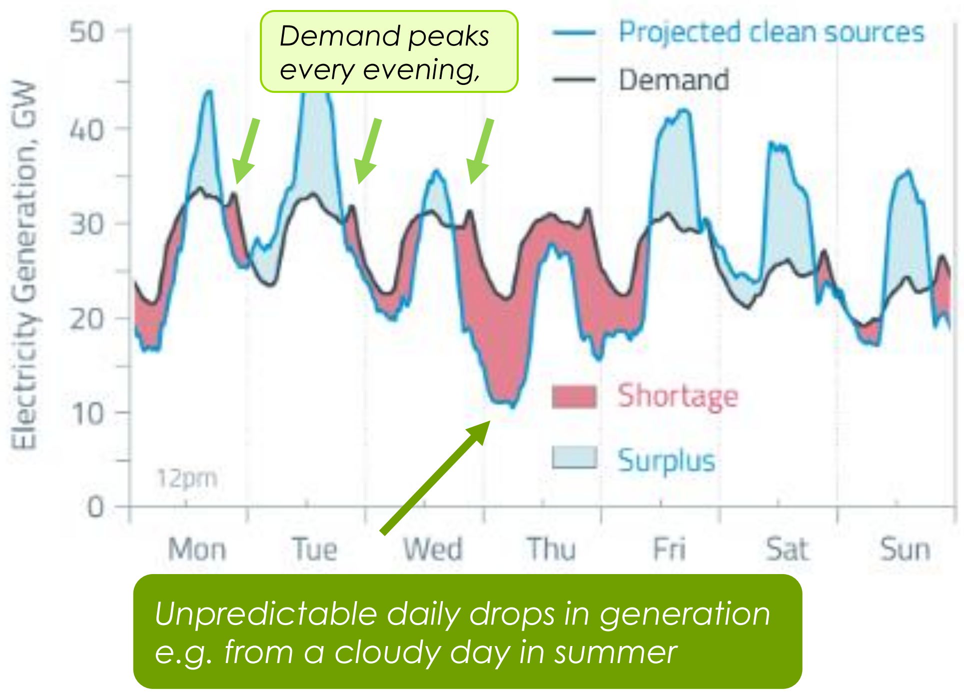
- Demand (e.g. above normal AC peak from heatwaves; cold period heating demand)
- Anticyclone wind drought

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

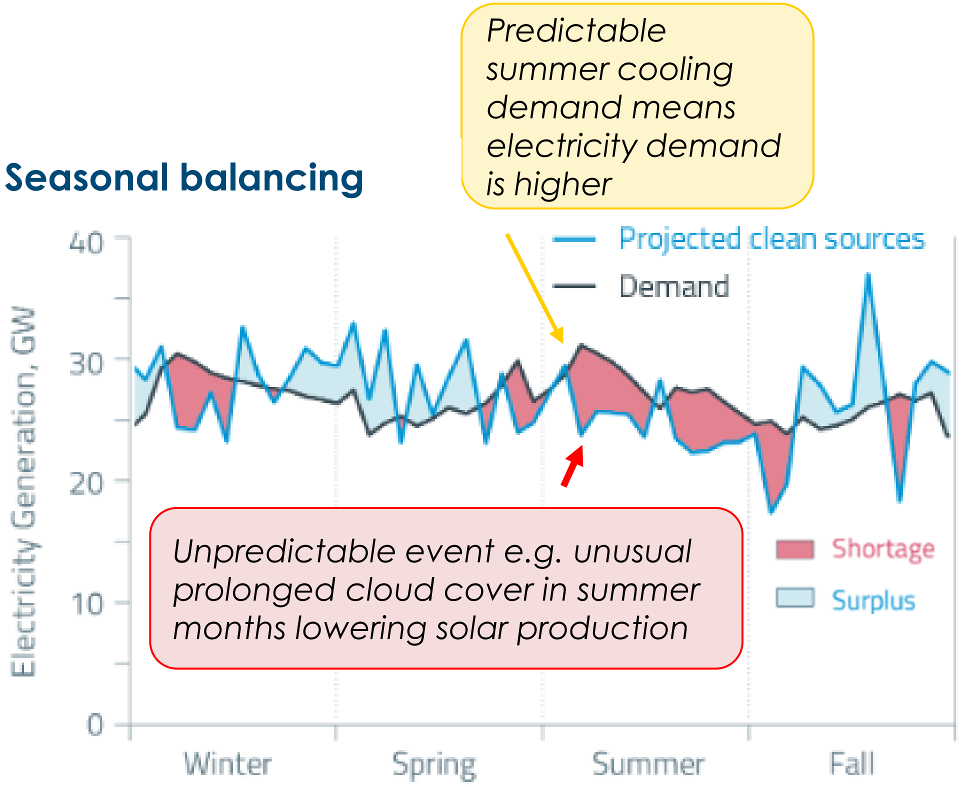
System view: daily, seasonal, & week-by-week unpredictable challenges

Example: Spain in 100% decarbonised electricity system

Hourly, daily balancing



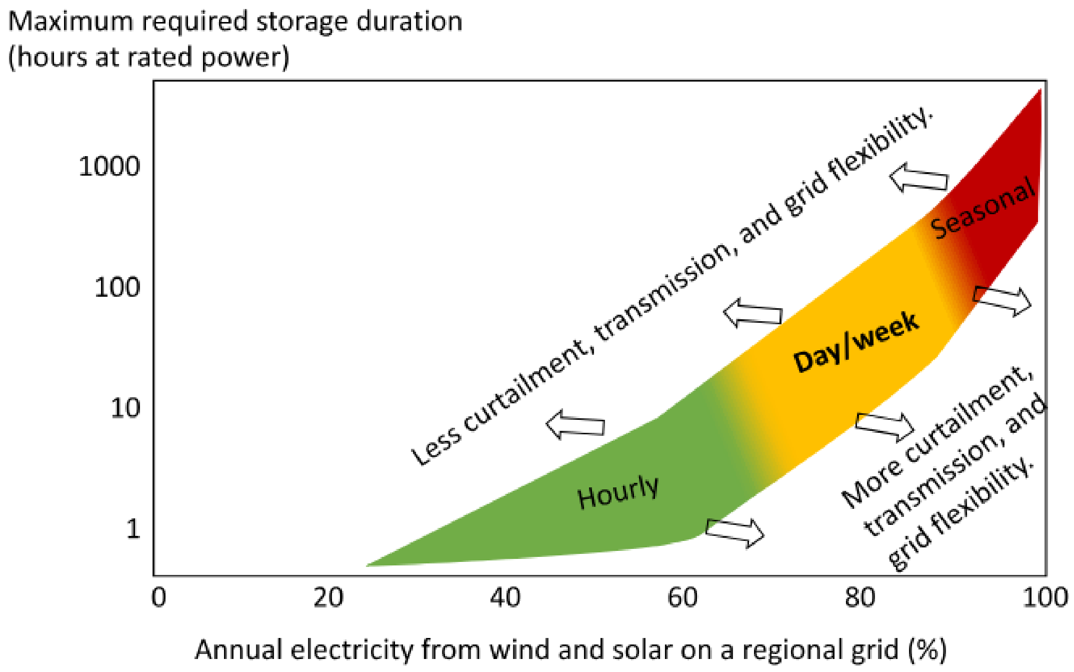
Seasonal balancing



Note: Based on hypothetical scale-up of Spain's clean power production based on 2022's weather patterns, using data from Spanish electrical grid when wind and solar reached 37% of total generation, and clean sources overall (including hydropower and nuclear) reached 63%. The "Projected clean sources" area was computed by adding enough extra wind and solar generation on top of current clean generation to substitute all fossil-based electricity (the remaining 37%), such that average clean generation equals average demand over the period of interest. Source: FCA - https://fcarchitects.org/content/the-basic-the-gaps-ldes/

Longer duration of storage required as wind and solar penetration increases

Maximum duration of electricity storage needed at differing wind and solar penetration rates
Hours at rated power, %



The amount of storage required depends on percentage of annual electricity from wind and solar:

- **~20-50%** – **Little storage needed** until higher fractions are reached, especially in regions with optimised blends of wind and solar
- **50-80%** – Can be reached with storage durations of **up to 10 hours**
- **70-90%** – Longer durations are needed, of between **10 to the low 100's** of hours
- **->100%** – storage durations are required in the **seasonal and inter-year realm**

Utilising **a suite of generation technologies**, with some that are dispatchable and/or provide baseload, **can be more economical and reduce storage need**

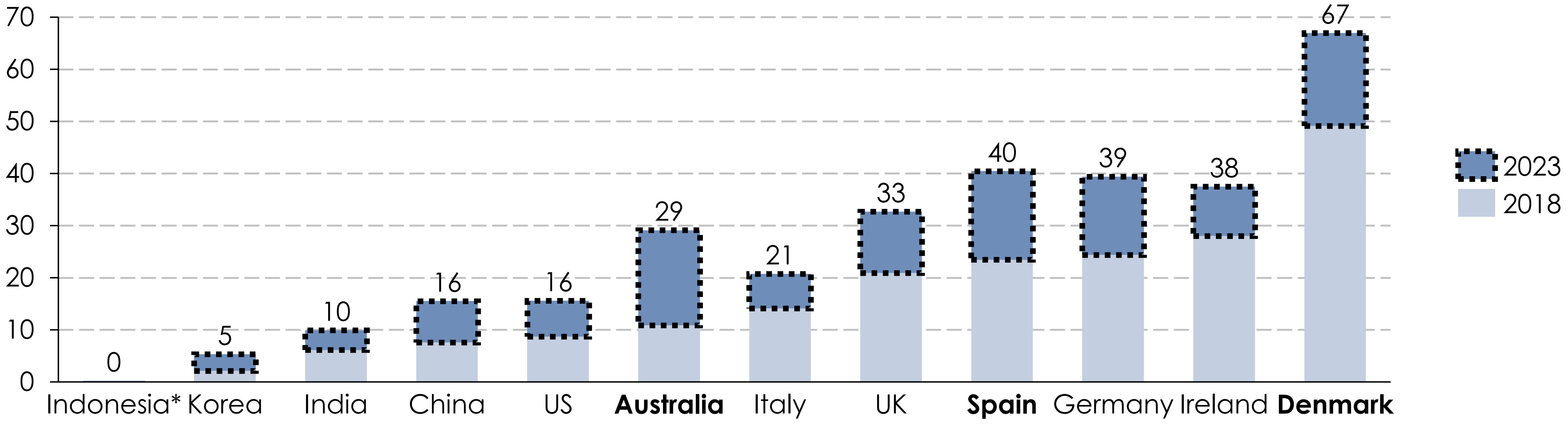
Notes: Differences between percentages depends on key characteristics (e.g., quality of solar and/or wind resource, transmission system capabilities, amount of natural gas versus low ramp rate resources, etc.) Source: Albertus et al. (2020), *Long-Duration Electricity Storage Applications, Economics, and Technologies*

Above 50% wind and solar share of electricity generation could be possible through primarily running fossil flexibly

- It is possible to get to high percentages of wind and solar generation without large scale deployment of additional storage, with prior analysis suggesting India and China could achieve ~30% with no new fossil generation capacity.
- Denmark is a low-gas, low-hydro system which has reached 67% variable renewable generation without significant development of new storage solutions; wind and solar are running alongside 8% coal and 21% bioenergy and 9 GW (~25% of total capacity) of interconnectors.

Wind and solar annual electricity generation, 2018, 2023

%

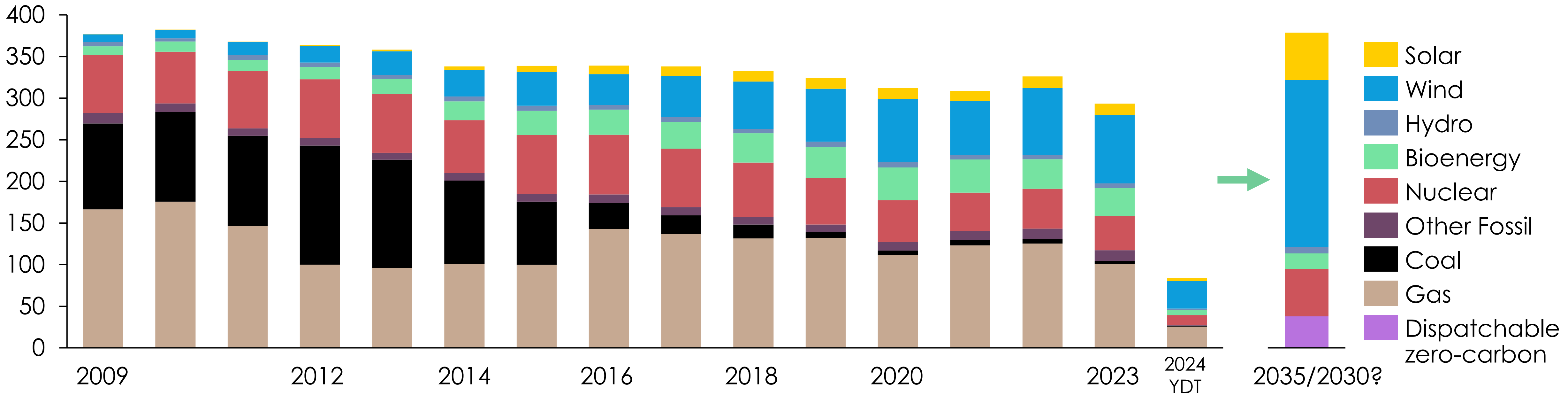


Notes: 2022 data used for Indonesia
Source: Ember (2024), *Electricity Data Explorer*

UK electricity generation nearing coal obsolescence, nearing final phase for 2035 zero-carbon target

Electricity generation 2009-2023, by technology
TWh

2035 zero-carbon electricity system
%



Annual gCO_2/ kWh	2009	2012	2014	2016	2018	2020	2023	2024 YDT	2035/2030?
	440	500	420	270	210	170	150	130	~0

Phase 0
Primarily coal to gas switching
500 to ~300 gCO_2e/kWh

Phase 1
Low share of renewables + gas
~300 to ~200 gCO_2e /kWh

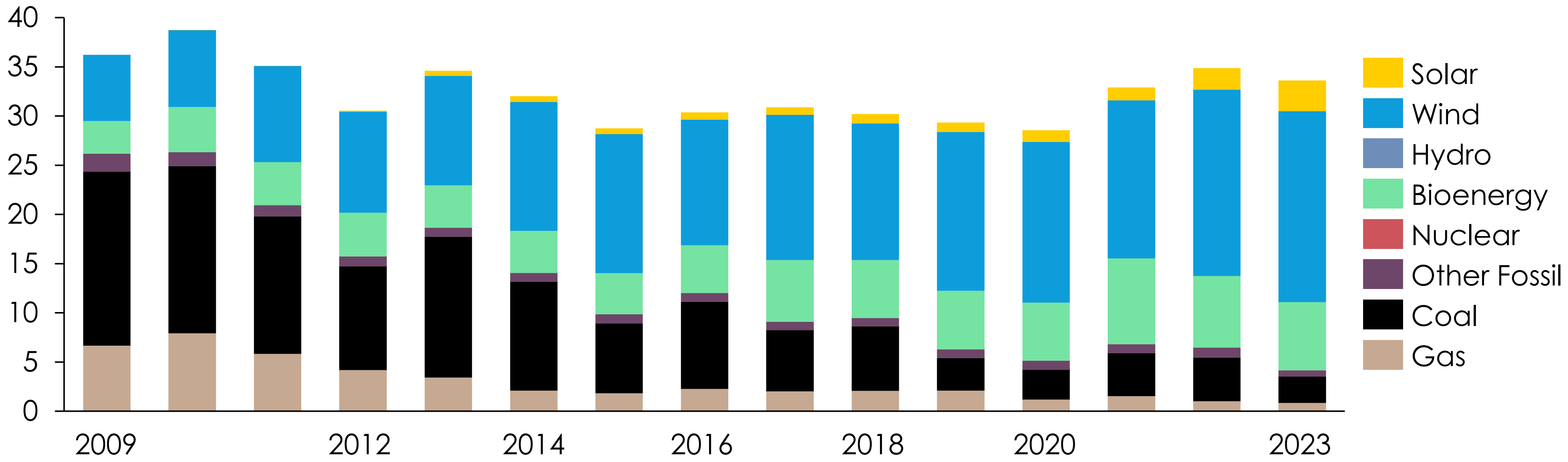
Phase 2
Increasing share of renewables, evolving grid operation (e.g. new ancillary services)
~200 to ~100 gCO_2e /kWh

Phase 3
Last mile decarb, no unabated fossil; suite of storage tech (i.e. batteries, PHES, H2, CCS)
~100 towards 0 gCO_2e /kWh

Note: Opposition pledges for 2030 zero-carbon electricity system; 2024 YTD = Jan-Apr 2024. GB grid intensity data used as a proxy for UK, data from National Grid ESO; illustrative 2035 mix assumed. PHES = Pumped Hydro Storage, H2 = Hydrogen Storage, CCS = coal or gas with CCS at high capture rates.
Source: Ember (2024), *Electricity data explorer*, ESO (2024), *ESO's Carbon Intensity Dashboard*. UK Government (2024), *Energy White Paper*.

Denmark on track to make coal obsolete, transitioning towards the final phase of achieving a zero-carbon electricity target by 2030

Electricity generation 2009-2023, by technology
TWh



Denmark targets fossil independent electricity system 2030.

Annual gCO_2e/kWh	2009	2012	2014	2016	2018	2020	2023	2030
	583	431	401	361	297	189	152	~0

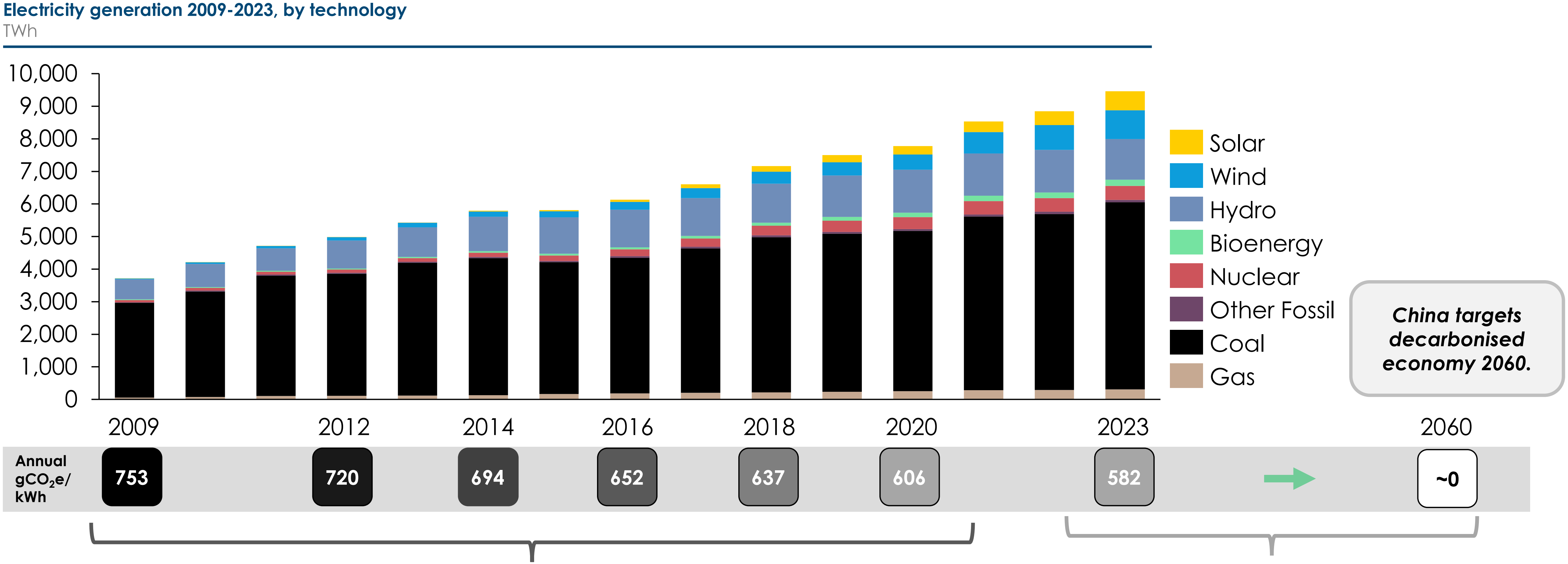
Phase 1
Low share of renewables + gas ***~300 to ~200 gCO_2e /kWh***

Phase 2
Increasing share of renewables, evolving grid operation (e.g. new ancillary services)
~200 to ~100 gCO_2e /kWh

Phase 3
Last mile decarb, no unabated fossil; suite of storage tech (i.e. batteries, PHES, H2, CCS)
~100 towards 0 gCO_2e /kWh

Note: PHES = Pumped Hydro Storage, H2 = Hydrogen Storage, CCS = coal or gas with CCS at high capture rates; intensity data in carbon equivalent.
Source: Ember (2024), *Electricity data explorer,* ESO (2024), *ESO's Carbon Intensity Dashboard.* Danish Government (2024), *Clean Energy – Denmark is a laboratory for green solutions.*

China remains heavily reliant on coal and has only just begun its transition toward achieving a zero-carbon electricity system by 2060

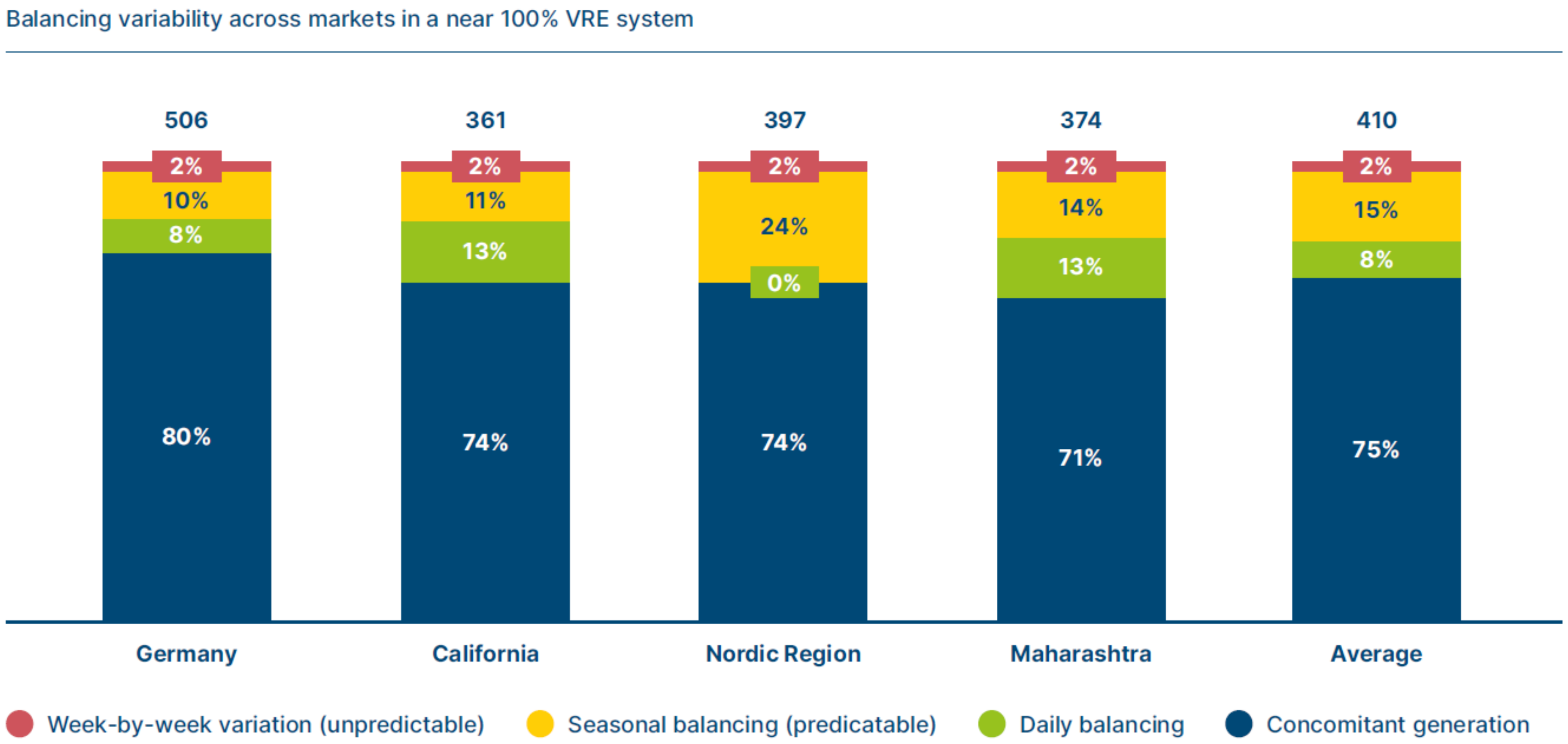


Phase 1
Low share of renewables + gas ***~800 to ~200 gCO_2e /kWh***

Phase 2 + 3
Increasing share of renewables -> last mile decarb, no unabated fossil; suite of storage tech (i.e. batteries, PHES, H2, CCS) ***towards 0 gCO_2e /kWh***

Note: PHES = Pumped Hydro Storage, H2 = Hydrogen Storage, CCS = coal or gas with CCS at high capture rates. Intensity data in carbon equivalent.
Source: Ember (2024), *Electricity data explorer*, ESO (2024), *ESO's Carbon Intensity Dashboard;* Climate Action Tracker (2024), *Net-zero targets – China.*

Scale of balancing challenge will vary by region, as indicated in 2017 CPI analysis used in Making Clean Electrification Possible



*ETC to **refresh the view of sizing of balancing challenge across key regional archetypes** in 2024, assessing weather data over time for wind/solar generation & 2050 demand profiles*

NOTE: 2% week-by-week variation is approximate, and range will vary by market. Generation scaled up to meet 100% demand based on current VRE ratio: Wind (64%), solar (34%) and run of river hydro (2%). SOURCE: Adapted from Climate Policy Initiative for the Energy Transitions Commission (2017)

Managing the system balancing challenge – key questions

B

Managing the system balancing challenge

Ix / Tx – balancing the system via interconnection / long distance transmission

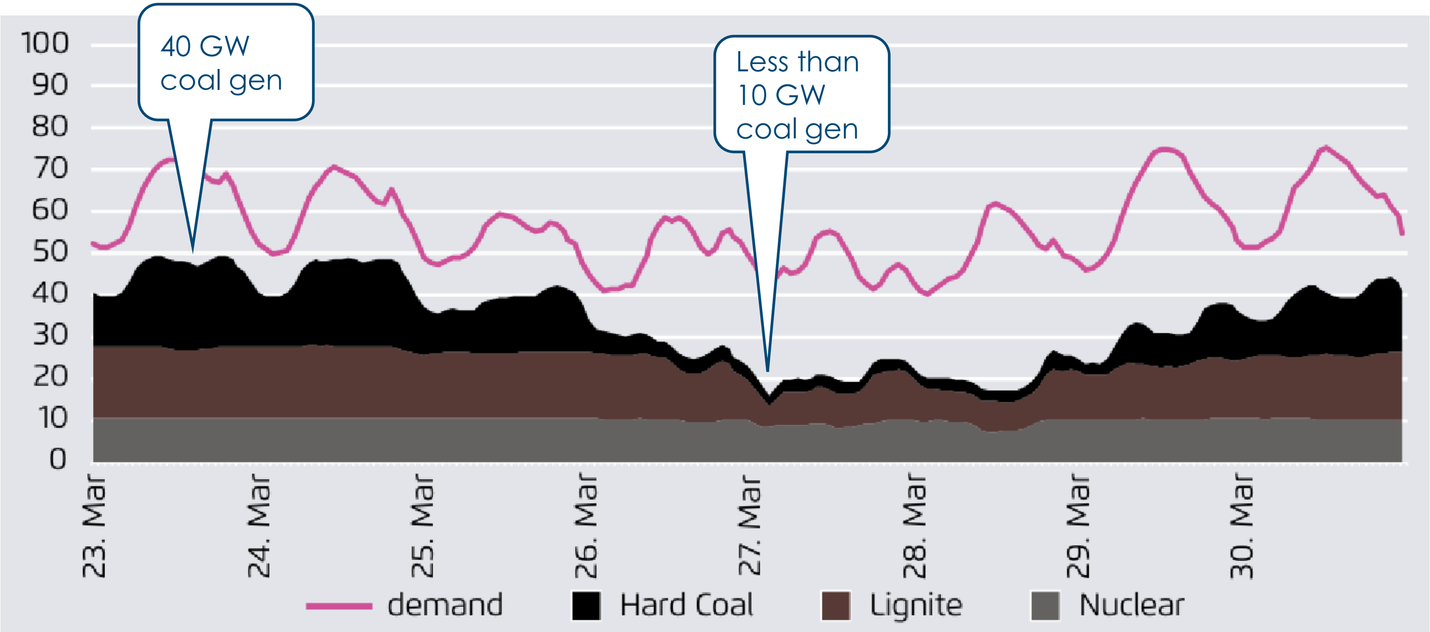
Balancing the system via storage, flexibility & generation technologies

Key questions

- What is the system balancing challenge? How are countries facing this challenge today, and how will they be facing it as they decarbonize power systems further?
- What are the technologies to meet the balancing challenge? What will they cost? What are the key enablers we need to make sure we can bring the required storage & flexibility onto the system?

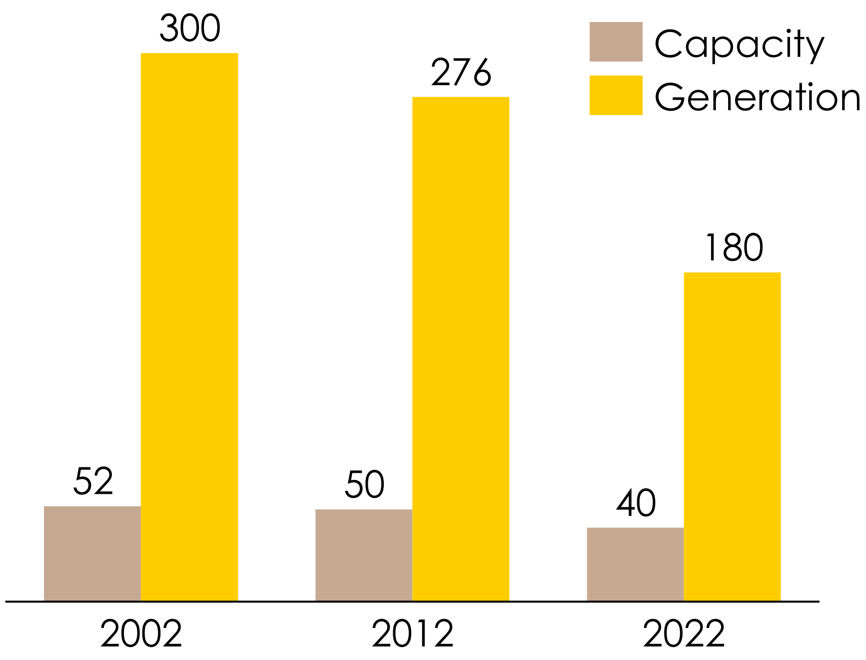
Coal: Some countries have already been very successful in retrofitting plants, with Germany a leader in flexibility

Power supply from nuclear and coal plants and demand in Germany, March 2017
GW



- Coal plants are already providing significant flexibility in Germany, operating in 15-minute intraday markets.
- Hard coal has proven to be particularly flexible, reducing generation by 10 GW in 3 hours.

German coal capacity and generation, 2002-22
Capacity GW, Generation TWh

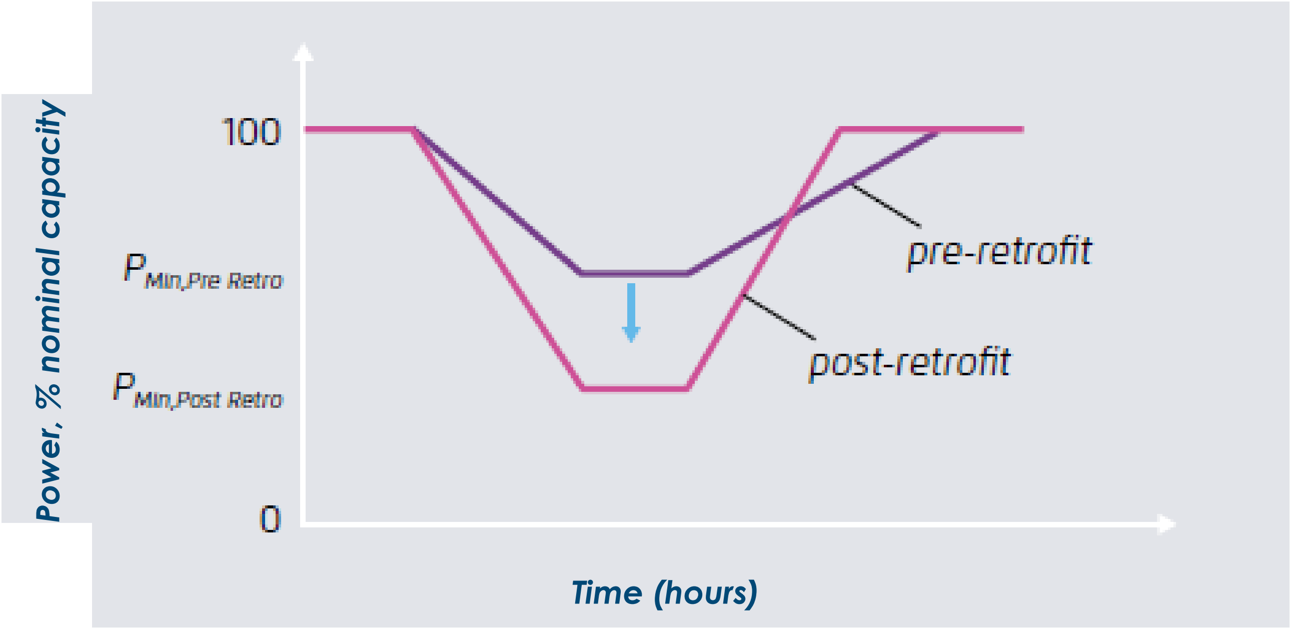


- Coal is running more flexibly as time passes, with a decrease in generation of 40% compared to 25% decrease in capacity.

Source: Agora (2017), *Flexibility in thermal power plants*; Ember (2024), *Electricity Data Explorer*

Coal: At the German Neurath Block E plant, light retrofits have enabled cost-effective substantial increases in flexibility

Load curves for pre- and post-retrofit of German Neurath Block E coal plant
% of nominal capacity



€70m (~10% of initial project capex) was invested into retrofitting a 600 MW turbine within the lignite plant over **2.5 months** (~120$/kW).

This upgraded plant control technology and certain components (i.e. condenser and cooling tower) which:

- **Extended life** of 35-year-old plant by 10 years
- **Increased efficiency** by 0.6%
- **Reduced minimum load** from 70% to 48% (420 MW->290 MW)
- **Increased ramp rate** from 0.7%/min to 2.4%/min (4.2->14.2 MW/min)
- **Shortened start-up time** from 4 ¼ hrs to 3 ¼ hrs

Source: IESR (2022), *Flexibility Thermal Power Plant*

Coal: China has set out a clear strategy for coal

- **By 2025, China have stringent flexibility targets:**
  - **24%** of power generation capacity to be "flexible power sources" (720/3000 GW)
  - At least **200 GW** of existing coal power to undergo flexibility retrofits (~20% of 2023 coal fleet)

- Retrofits involve **dropping minimum loads** from 40-50% -> 15%; **increasing ramp rates** and **cutting start up times**

- Meeting targets primarily relies on overcoming market barriers:
  - **Technical barriers** are limited as all retrofit options are possible, even on ultrasupercritical plants.
  - **Market barriers**: key factor as limited current remuneration options for flexible operation & intraday power trading. Costs of RMB 500-1500/kW ($70-$200/kW) are equivalent to 10-30% of overall plant costs so it is hard to make a business case attractive.

2022-2023

- **Change in emissions from coal:** Increased

Contributing factors:
- **Electricity increase** – 6.7%
- **Increase in renewables**
- **Large hydro drop** (droughts)

2024

- **Change in emissions from coal:** Likely neutral

Contributing factors:
- **Electricity increase forecast** – 6%
- **Increase in renewables**
- **Hydro to return to normal**

2025

Change in emissions from coal: Potential transition to permanent decline

Contributing factors:
- **Electricity increase forecast** – ~6%
- **Increase in renewables**
- **Uncertain additional hydro**

Notes: China's 14th Five-Year Plan talks of strengthening coal's role as a guarantee of energy security, with coal planned to be used flexibly. All plants may be retrofit including ultrasupercritical plants which make up majority of Chinese fleet. Assumes $700/kW for cost of new Chinese coal plant.
Source: Oxford Institute of Energy Studies (2022), *Guide to Chinese Climate Policy 5: Coal*; Ember (2024), *Electricity data explorer;* ETC call with experts

Achieving balance: options to meet different challenges

			System operation	Predictable Daily	Unpredictable Daily	Seasonal	Unpredictable week by week
Dispatchable generation	Other zero carbon	Hydro, nuclear[1]	✓	✓	✓	✓	✓
	Fossil	Fossil (or bioenergy) + CCS	✓	✓	✓	✓	✓
		Fossil – low/very low utilisation	✓	✓	✓	✓	✓
Interconnection		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*

ETC has conducted review of energy storage tech landscape

Very early-stage technology

	Electrochemical	Chemical	Mechanical	Thermal / Electrothermal
Short-Duration (< 8-10h)	*Lithium & sodium battery storage* • Lithium-ion (mostly LFP) • Lithium-ion solid state • Sodium-ion • Lithium-air *Flow batteries* • Vanadium redox flow • Iron redox flow battery Zinc-air Aluminium-air		Flywheel Gravity-based (A)CAES - Compressed Air - ad/dia	Molten salt storage Heat storage in bricks
Long-Duration (> 10h)	Vanadium redox flow Aluminium-air (potentially cut)	*Hydrogen* • Hydrogen in CCHT/OCHT • Hydrogen in fuel cell • Hydrogen based synthetic fuels (LOHC, ammonia, methanol and synthetic natural gas in CCGT	Gravity-based (A)CAES - Compressed Air - ad/dia Pumped hydro Liquid Air Energy Storage - LAES	Hot water/water pit storage Molten salt storage Heat storage in bricks Ice storage (potentially cut)
Very long-Duration (> 50h)	Iron-air	*Hydrogen* • Hydrogen in CCHT/OCHT • Hydrogen based synthetic fuels (LOHC, ammonia, methanol and synthetic natural gas in CCGT	Gravity-based (A(CAES) Compressed Air –ad/dia Pumped hydro Liquid Air Energy Storage - LAES	
Early development	Lignin based battery Concrete battery Nickel zinc battery	Clean circles	Liquid CO2 - LCES Liquid Nitrogen	Carnot batteries

Sources: ETC analysis (2024), IEA (2024), *ETP Clean Energy Technology Guide*

ETC work so far has focused on subset of key techs

ETC deep dives*
Very early-stage technology

	Electrochemical	Chemical	Mechanical	Thermal / Electrothermal
Short-Duration (< 8-10h)	*Lithium & sodium battery storage* • Lithium-ion (mostly LFP) • Lithium-ion solid state • Sodium-ion • Lithium-air *Flow batteries* • Vanadium redox flow • Iron redox flow battery Zinc-air Aluminium-air		Flywheel Gravity-based (A)CAES - Compressed Air - ad/dia	Molten salt storage Heat storage in bricks
Long-Duration (> 10h)	Vanadium redox flow Aluminium-air (potentially cut)	*Hydrogen* • Hydrogen in CCHT/OCHT • Hydrogen in fuel cell • Hydrogen based synthetic fuels (LOHC, ammonia, methanol and synthetic natural gas in CCGT	Gravity-based (A)CAES - Compressed Air - ad/dia Pumped hydro Liquid Air Energy Storage - LAES	Hot water/water pit storage Molten salt storage Heat storage in bricks Ice storage (potentially cut)
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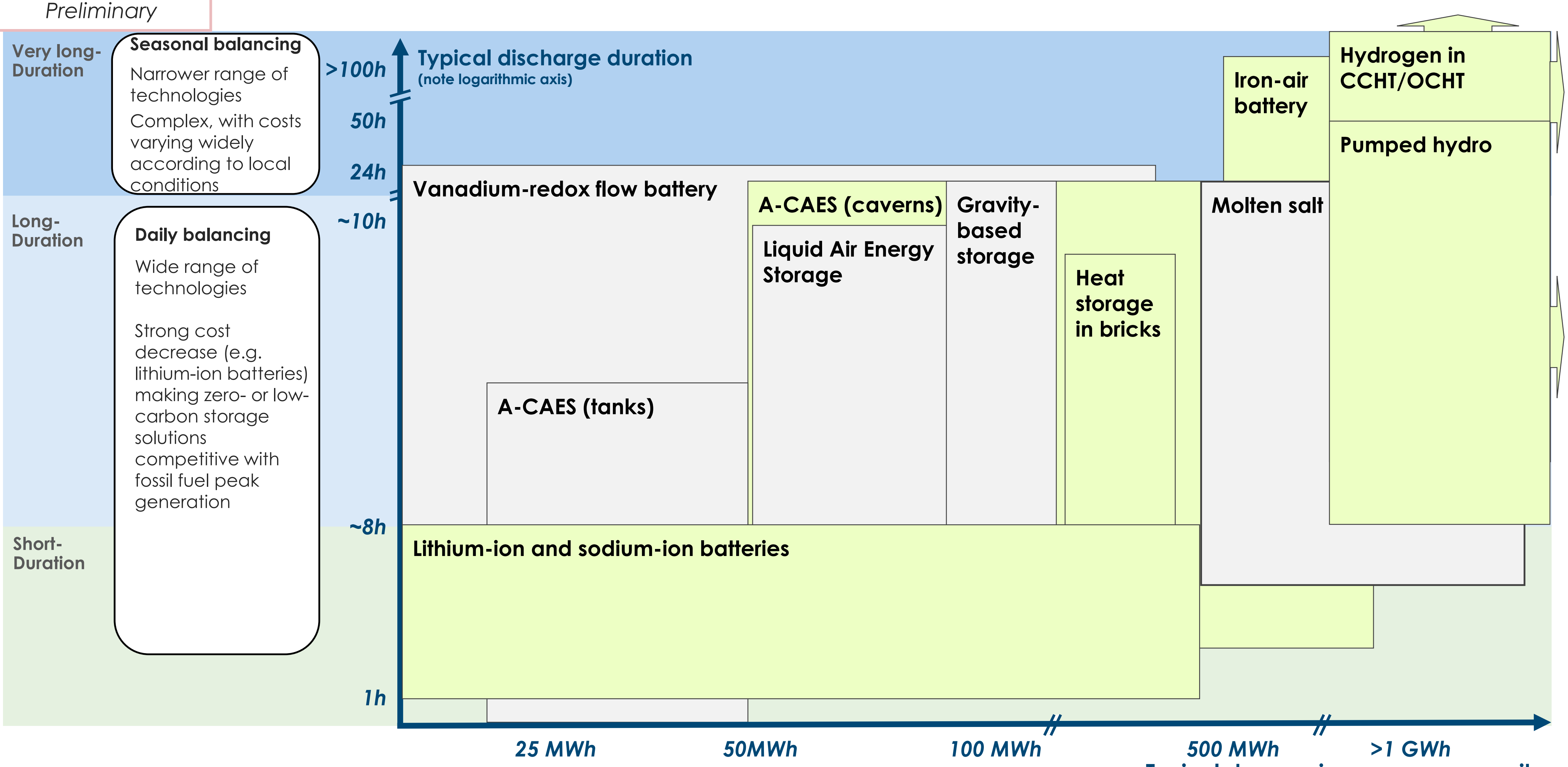
Early development	Lignin based battery Concrete battery Nickel zinc battery	Clean circles	Liquid CO2 - LCES Liquid Nitrogen	Carnot batteries

ETC deep dives selected based on current scale of technology, scale-up and funding progress, and level of coverage/citation across key sources.

Sources: ETC analysis (2024); IEA (2024), *ETP Clean Energy Technology Guide*

ETC assessment points to several key techs at given durations/storage sizes

Preliminary



Source: Data from BNEF (2024), *2024 long-duration energy storage cost survey;* Pacific Northwest National Laboratory (2023), *Energy Storage Cost and Performance Database*; IEA (2024), *ETP Clean Energy Technology Guide;* others from sources on deep dive slides;.
Note: Simplified visual description for improved readability.

Emerging conclusions, key set of technologies to solve balancing challenge

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)

Predictable seasonal variations in either :

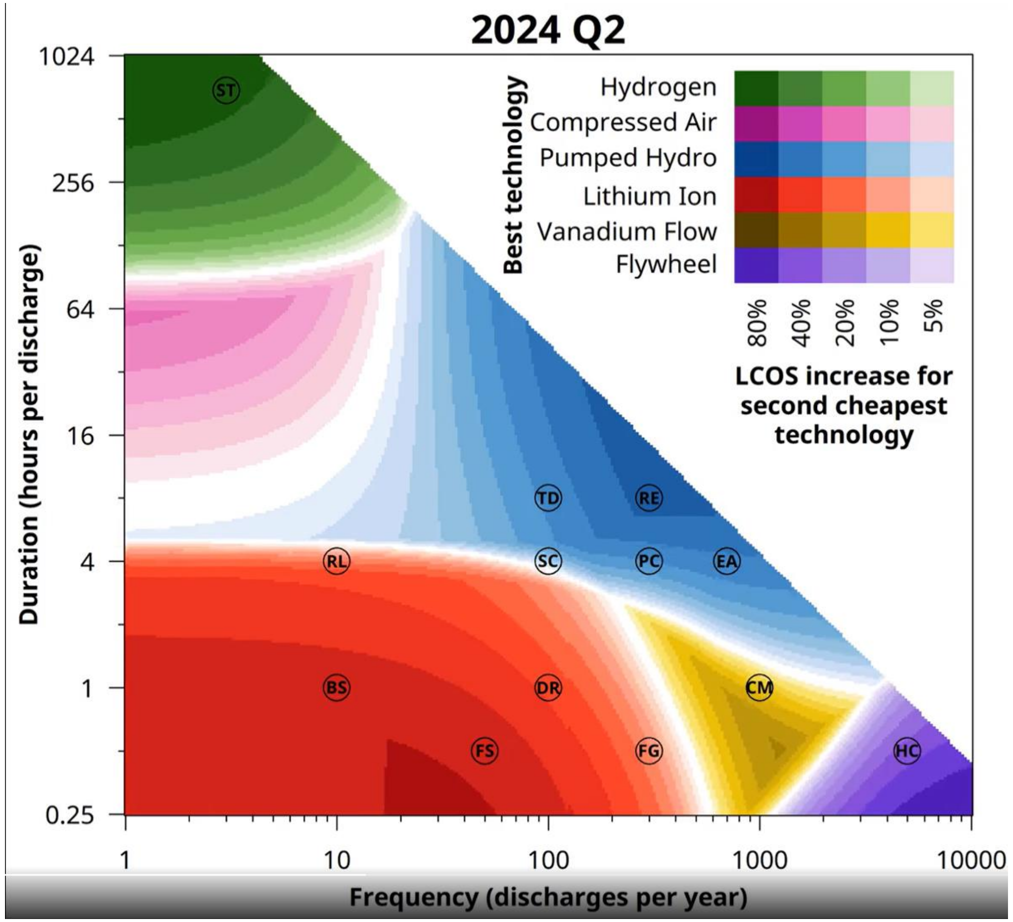
- Demand (e.g. winter heating peak in Europe, A/C peak in southern China or India in summer)
- Or supply (e.g. Indian wind during monsoon , European sun in summer)

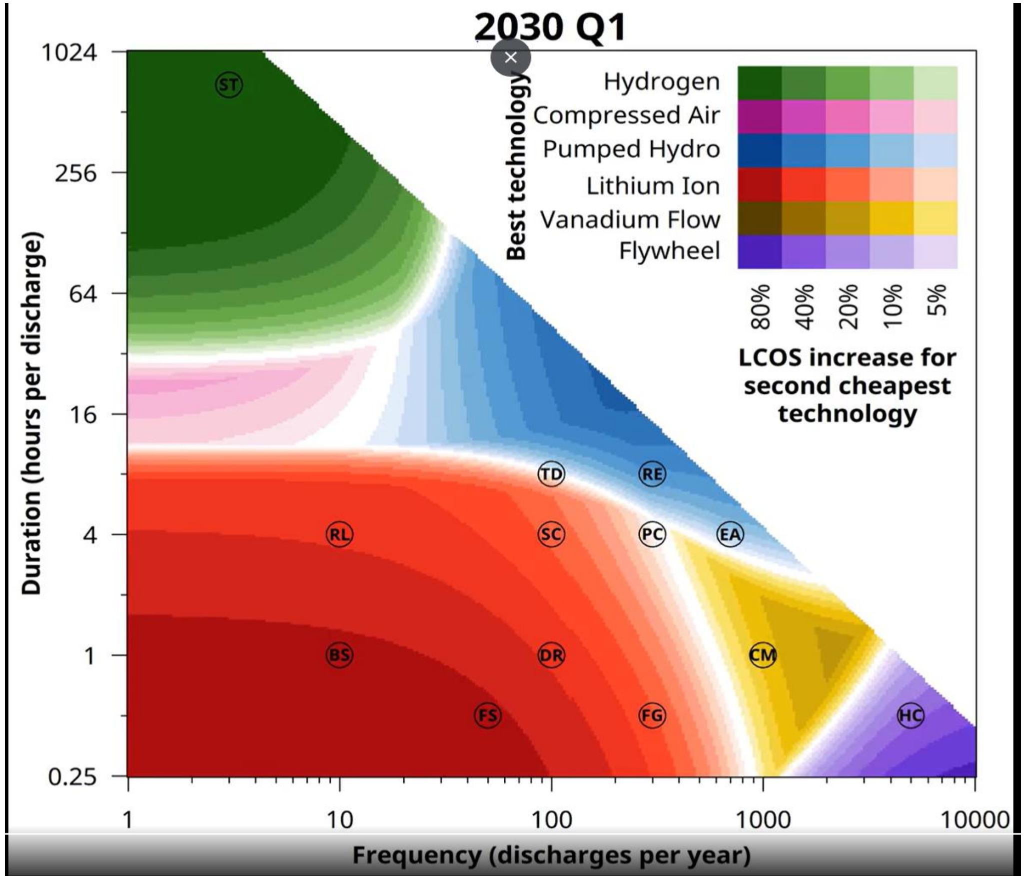
Unpredictable week-by-week variations

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

- **Li-ion likely to dominate short duration.** Cost reductions could mean it can play at longer duration and different cycling profiles.
- **For medium duration, there is an increasing set of players, particularly notable are A-CAES and heat storage in bricks,** as well as pumped hydro which already plays a role.
- **Very long-duration storage is likely to be met via H2 (or via CCS in the dispatchable route),** although developments around Iron-Air could also make a contribution at higher durations.

Imperial College cost modelling in 2023 suggests large role for Li-ion + H2



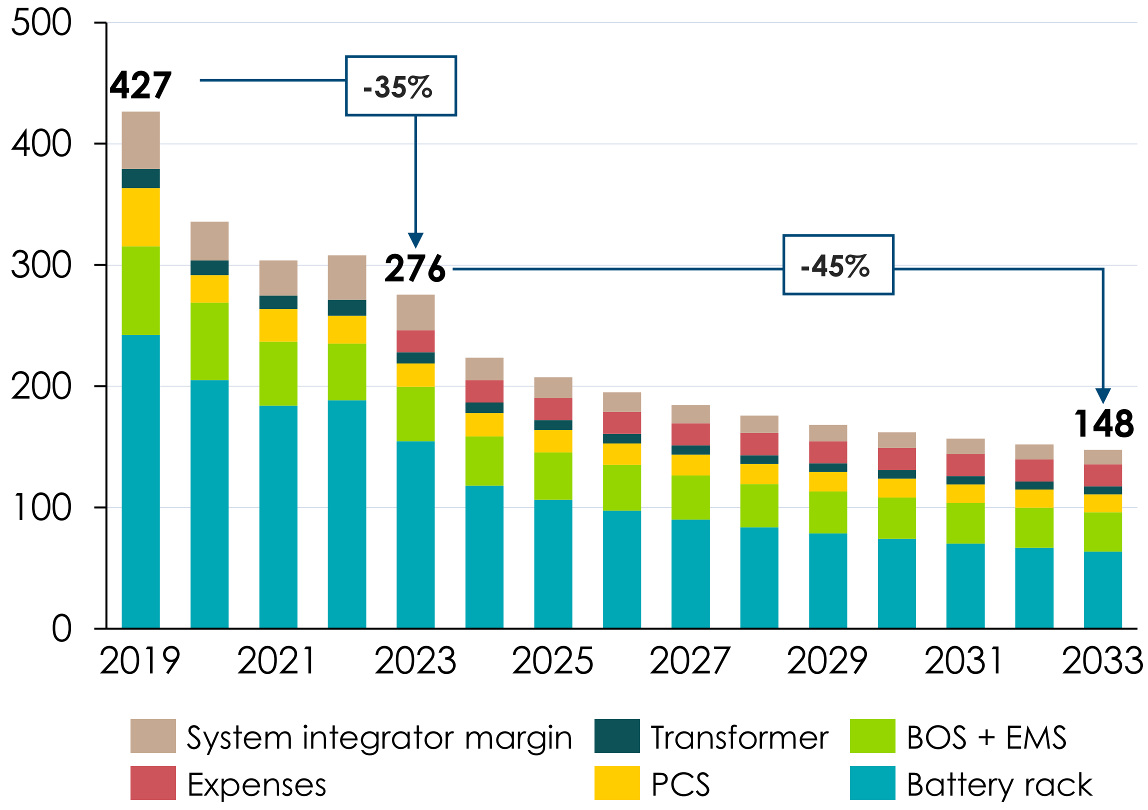


- Colours represent technologies with **lowest lifetime cost**
- Axes show **duration** and **cycling frequency**
- **Shading indicates how strong the cost advantage is over the second cheapest technology**

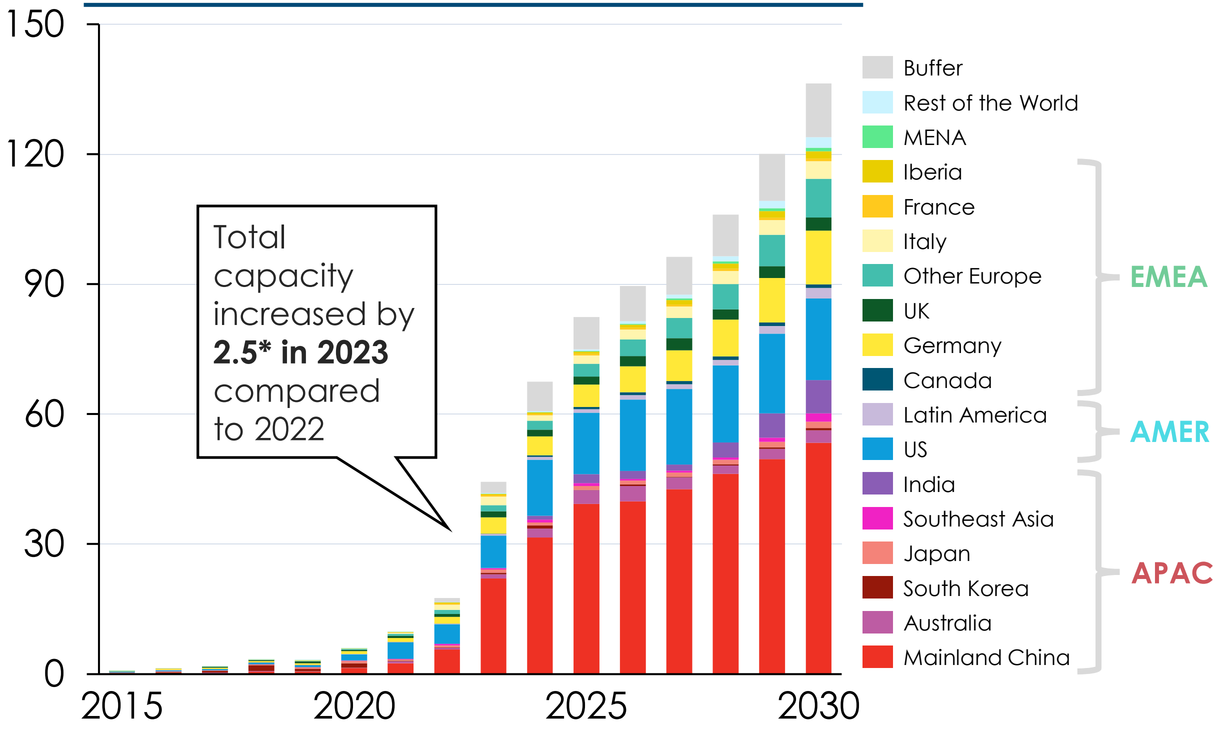
Source: Schmidt & Staffell (2023), *Monetizing Energy Storage – a toolkit to assess future cost and value.*

Globally, li-ion battery storage prices continue to fall, deployment is growing

Two-hour duration large AC energy storage system
$/kWh



Global gross energy storage additions by market
GW

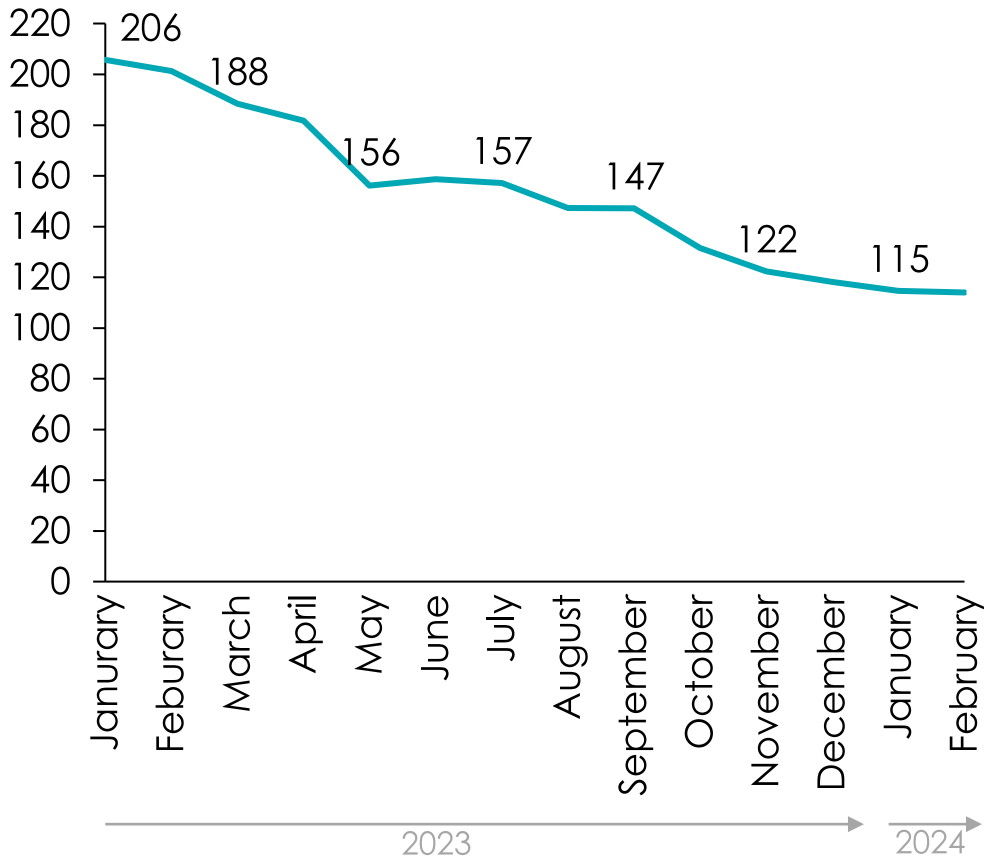


Notes: BOS + EMS = balance of system and energy management system. Excludes warranty costs, which are often paid annually rather than as part of the initial capital expenditure. Costs do not explicitly include taxes. Excludes grid connection costs as these are very location-specific. Historical figures adjusted using US CPI index to convert to real 2023$. Buffer = headroom not explicitly allocated to an application. Costs provided are for a full energy storage project.
Source: BNEF (2024), *1H 2024 Energy Storage Market Outlook*

Rapid price decline of Chinese battery storage systems leads to multiplier effect, pulling down price bids at Indian auctions for battery storage systems

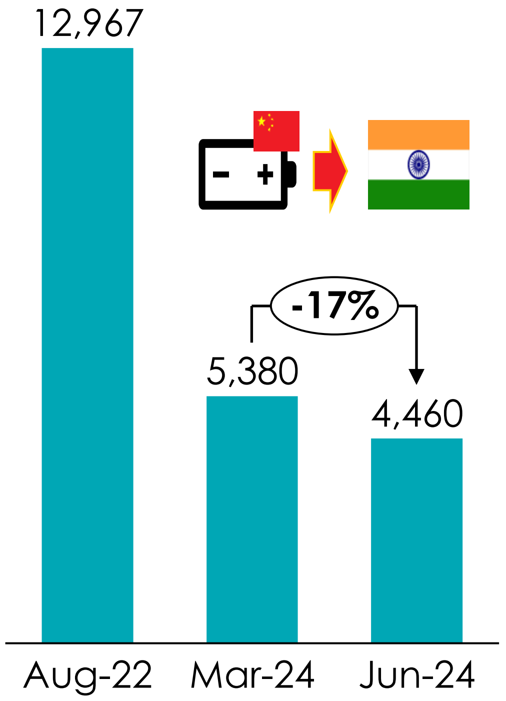
Price decline of battery systems from China…

$/kWh – for two-hour energy storage: turnkey system



…leads to bid price drop at Indian auctions for standalone battery storage

$/MW per month – lowest bid prices at auctions



3 standalone battery auctions so far

Drivers for bid-price decline:

- **Large-scale imports of inexpensive Chinese batteries,** which dominate global market.
- **Increasing competition** among developers/bidders.

Consequences for future auctions

- **Further aggressive bids expected** for battery storage capacity commitments.
- **Auctioned projects expected to boost India's energy storage** capacity.


BloombergNEF
Battery Costs Down 17% in Three Months, India Bids Show
Published on Wed, Jun 12, 2024

…since previous, 2nd round, in March 2024

Note: August 2022 auction refers to auction organized by Solar Energy Corporation of India (SECI) auction: for 500 MW/1,000 MWh of standalone BESS. 17% bid price drop refers to 2024 March and June auctions, organized by Gujarat Urja Vikas Nigam Ltd.: for 250 MW/500 MWh of standalone BESS. Must discharge twice daily and maintain 95% availability. Source: BNEF (2024), *1H 2024 Energy Storage Market Outlook*; BNEF (2024), *Bidding Frenzy Paints Bright Future for India's Batteries*; BNEF (2024), *Battery Costs Down 17% in Three Months, India Bids Show.*

Lithium and sodium battery landscape – relevance for energy storage

Lithium-ion

High relevance
Boosted by recent Lithium ferrous phosphate (LFP) development breakthroughs and shift away from Nickel Manganese Cobalt, boosting deployment at lower costs.

Lithium-ion solid state

Lower relevance
As higher performance on energy density and charging speed is less relevant for stationary.

Sodium-ion

Increasing relevance
Driven by lower material costs and lower supply chain risks.

Lithium-air

Lower relevance
Stemming from remaining technology challenges and high energy density potential that make it more suitable for mobility use case, e.g. aviation.

Source: BNEF (2024), 2024 long-duration energy storage cost survey; Pacific Northwest National Laboratory (2023), Energy Storage Cost and Performance Database; IEA (2024), *ETP Clean Energy Technology Guide;* others from sources on deep dive slides.
Pictures from: from Allianz (n.a.), *Tech Talk 26;* EEPower (2023), *Sodium-aluminum Battery Heats Up Grid Storage;* AZO Materials (2020), *Boosting Lithium-Air Battery Performance with Catalysts*

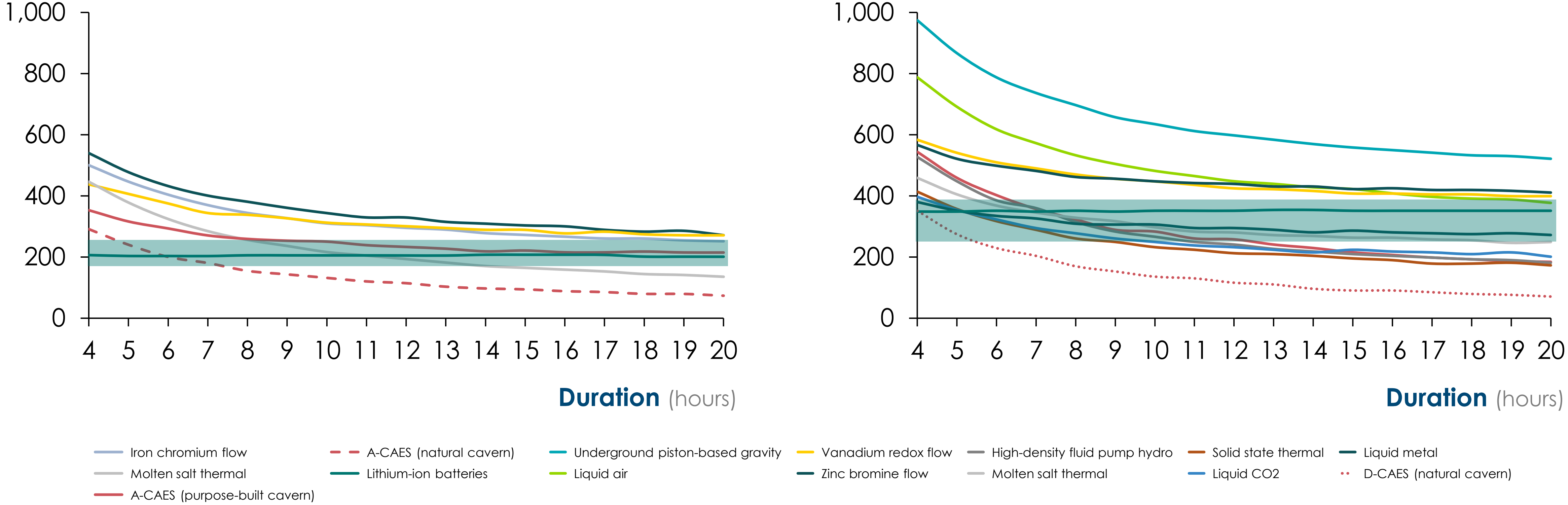
BNEF: Long duration energy storage technologies outcompete li-ion storage after 8+ hours

Modeled capex of fully installed energy storage systems as a function of duration, China 2018-24

$/kilowatt-hour (real 2023)

Modeled capex of fully installed energy storage systems as a function of duration, non-Chinese markets 2018-24

$/kilowatt-hour (real 2023)



However, for accurate comparison of costs across technologies need to factor in other factors (e.g. efficiency, cycling profile), need to determine a view of 'levelized cost'

Notes: Does not include cost data for technologies delivered post 2024. The cost data shows the upfront capital expenditure required for a fully installed energy storage system at the beginning of the project lifetime. D-CAES = diabetic compressed air energy storage. Source: BNEF (2024), *2024 Long-duration energy storage cost survey*.

However, full comparison requires going beyond capex to 'levelized cost'

Illustrative Levelised Cost of Storage

For a fixed/given duration

$$\text{Cost per kWh charged and discharged (or 'levelized cost')} = \frac{\left[\underbrace{\text{Capital cost per kWh (\$/kWh)}}_{1} + \text{Opex (\$/kWh)}\right] \times \text{Annualization factor (\%)}^{[1]}}{\underbrace{\text{\# of cycles per annum}}_{2}} + \underbrace{\left(1 - \text{Lifecycle efficiency (\%)}\right)}_{3} \times \underbrace{\text{Cost of electricity input}^{[2]}}_{4}$$

1. **(Annualised) capital cost per kWh**
2. **Number of cycles per annum**
3. **Lifecycle efficiency**
4. **Cost of electricity input**

→ ***Key variables to determine cost of storage***

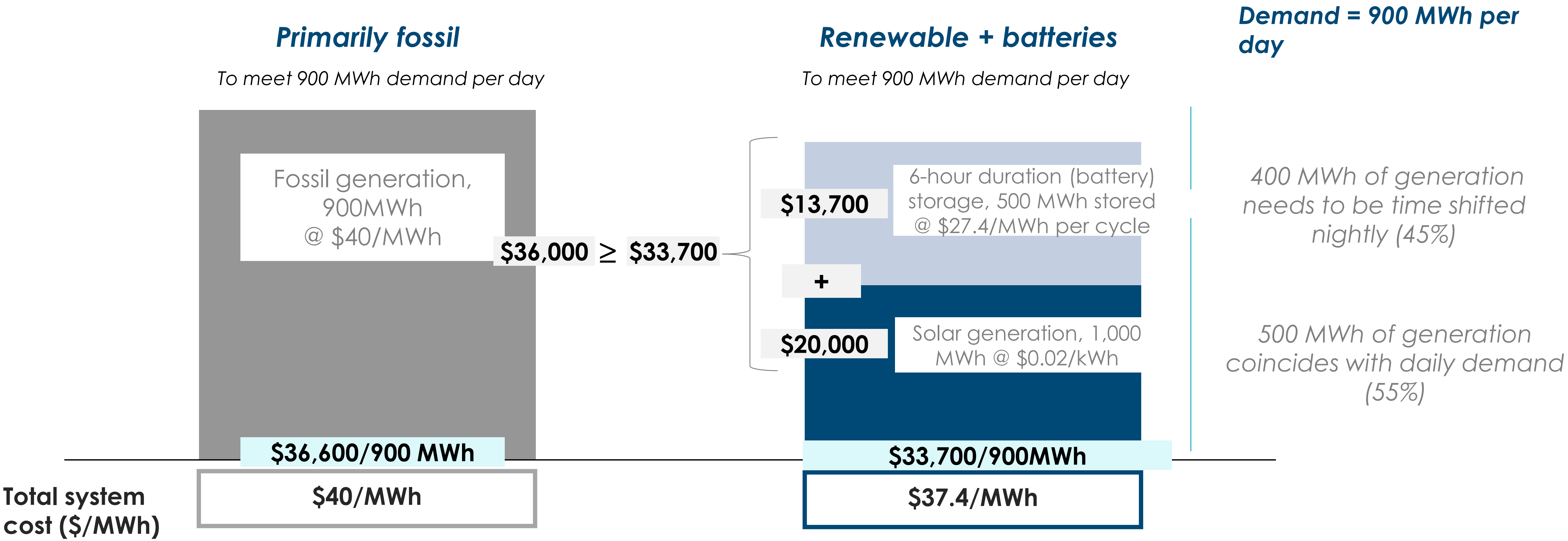
[1] Annualization factor (%): depends on cost of capital, as well as lifetime expectancy of technology [2] Cost of electricity input: will likely be below average price as storage will fill at times of low prices

Impact on total system costs could be cheaper than current system

Example 1: Geography with primarily daily balancing challenge

Illustrative generation profile and LCOE

Total generation stack with balancing needs, $/MWh



Notes: Supply and demand at 900 MWh per day, of which 500MWh is during sunshine hours, 400MWh at night. Supply can be met by either:

- Dispatchable gas producing 900 MWh per day;
- Solar producing 1,000 MWh per day, of which 500 MWh consumed simultaneously, and 500 MWh stored in a battery, with 80% life cycle efficiency, discharging 400 MWh overnight

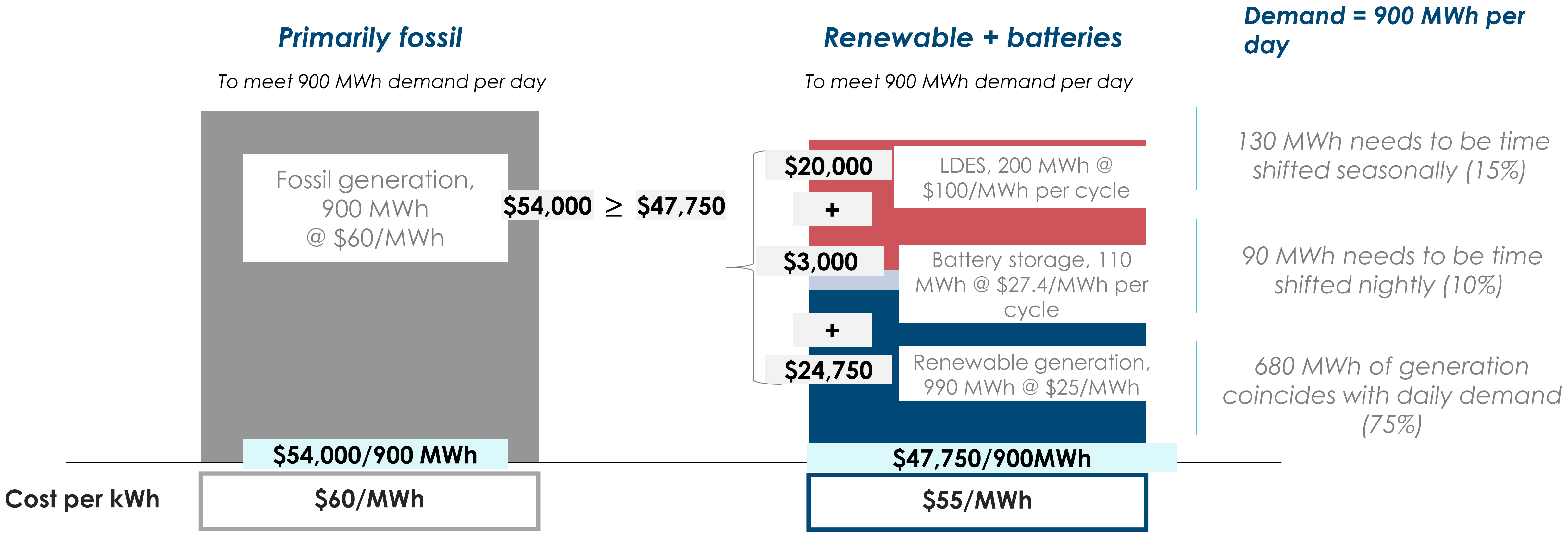
Cost of gas generation is $0.04 per kWh, Solar is $0.02 per kWh. Battery capex $100 per kWh: $10 per kWh annualized; $2.74 per cycle at 365 cycles per annum .

Impact on total system costs could be cheaper than current system

Example 2: Geography with daily and seasonal balancing need

Illustrative generation profile and LCOE

Total generation stack with balancing needs, $/MWh



Notes: Supply and demand at 900 MWh per day, of which 680 MWh is during wind and solar generation hours, 220 MWh when renewables not generating. Supply can be met by either: Dispatchable gas producing 900 MWh per day; Wind and solar producing 1,060 MWh per day, of which 680 MWh consumed simultaneously, 110 MWh stored in a battery, with 80% life cycle efficiency, discharging 90 MWh overnight, and 200 MWh stored in LDES, with 65% life cycle efficiency, discharging 130 MWh daily equivalent. Cost of gas generation is $0.06 per kWh, Solar and wind at $0.25 per kWh. Battery capex $100 per kWh: $10 per kWh annualized; $2.74 per cycle at 365 cycles per annum. LDES capex @ $200: $10 per kWh annualized, $0.1/kWh per cycle at 100 cycles per annum.

Future low-carbon system costs are likely the same, or cheaper, than today's

Emerging ETC conclusions suggest total system costs are likely the same as today's fossil without a carbon price

Other studies reinforce this:

The UK Climate Change Committee estimates suggests that total decarbonisation with variable renewables rising to 80% of generation will reduce UK electricity system costs in 2050 by an amount equal to 0.16% of GDP.

Estimates of total system cost in China made by the **Energy Research Institute of the NDRC** suggest that 2050 costs per MWh for a "below 2 degrees" trajectory with 73% wind and solar generation in 2050 will be 19% below today's level.

India's TERI estimates suggest that a 100% variable renewable power system could in 2050 deliver power at total system costs per MWh about 5% below today's level.

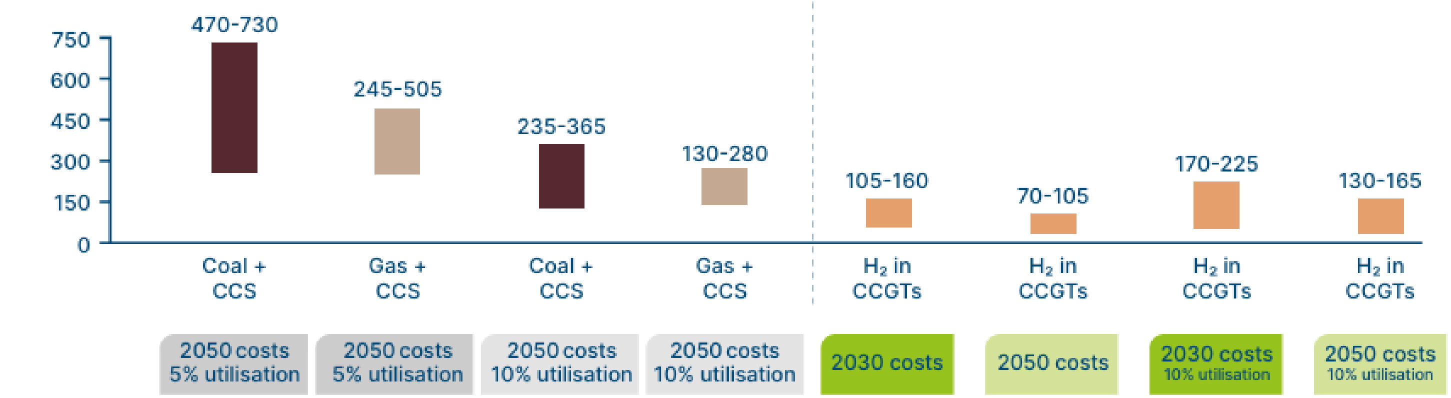
A **study for the United States by UC Berkeley** looking at reaching 90% clean electricity in the United States by 2035 concluded that electricity costs would fall to 4.6 cents per kWh under a base case, about 10% lower than the 5.1 cents per kWh in 2020.

Source: UK Climate Change Committee (2020), *Sixth Carbon Budget;* CNREC (2018), *China Renewable Energy Outlook (CREO 2018);* TERI/ETC (2024), *The Role of Hydrogen in India;* UC Berkely (2020), *The Report;* Flags from World Flag Database (2024), *World Flag Database.*

For very long duration balancing, CCS and Hydrogen are the key routes

H_2 in CCGTs could be most cost-effective zero-carbon way to meet unpredictable week-by-week variations

Indicative levelised cost of electricity (LCOE), $/MWh



	Coal + CCS / Gas + CCS	H_2 in CCGTs (2030 costs, 2050 costs)	H_2 in CCGTs (2030 costs 10% utilisation, 2050 costs 10% utilisation)
CCS Capex	Yes (new asset)	n/a	
Generation Plant Capex	No (existing asset)	No (existing asset with no retrofit cost, assumes H_2-compatible gas turbine)	Yes (new asset, H_2-compatible gas turbine)

NOTES: High/Low ranges determined by CCS capex cost ($2490-4770/KW for coal CCS and $1620-3560/KW for gas), fuel costs ($2-7/MMBtu for gas, coal fuel costs assumed to be negligible in 2050), and costs of hydrogen production ($1.5-2.5/kg in 2030, and $0.9-1.5/kg in 2050). Hydrogen T&S cost assumed to be $0.2/kg. Assuming 50% conversion efficiency in CCGTs for hydrogen. Hydrogen-ready CCGT capex is assumed to be $1000/KW in 2050 and $1080/KW in 2030. Assumed 20-year asset lifetimes.

SOURCE: S. Budinis, S. Krevor et al, (2018), *Energy Strategy Reviews*, "An assessment of CCS costs, barriers and potential." BloombergNEF(2020), *Hydrogen: The Economics of Power Generation*, SYSTEMIQ analysis for the Energy Transitions Commission (2021).

Choice between the two will depend on:

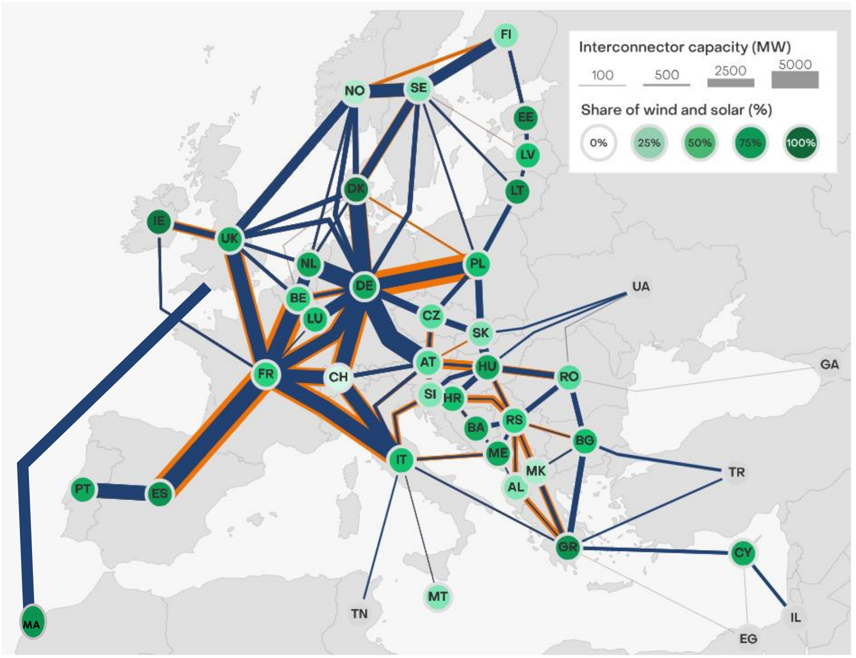
- Relative costs, e.g. capex for CCS unit and for electrolysers as well as H2-compatible CCGTs
- Performance factors, e.g. minimum efficient load factors if both options are present, e.g. gas + CCS needs a minimal load of ~20% so should be run first where present

Emerging conclusions on reaching highly decarbonised power systems

- **Confidence that it is possible to deeply decarbonise the power system**, including
  - **Possibility to reach at least 30% wind and solar penetration, possibly much more, by running existing fossil more flexibly – even in a coal-based system (incl. via cost-effective retrofits to improve flexibility) with minimal storage and limited interconnection**
  - **Reaching high shares of wind and solar penetration (e.g. >70%) by deploying available suite of storage options and increasing interconnection capacity**
- **Confidence that we can build zero-carbon electricity systems primarily based on wind and solar generation with total system in costs in line with those of the system today**
- **This will require bringing on a set of key enablers, specifically across power market design & grid access**

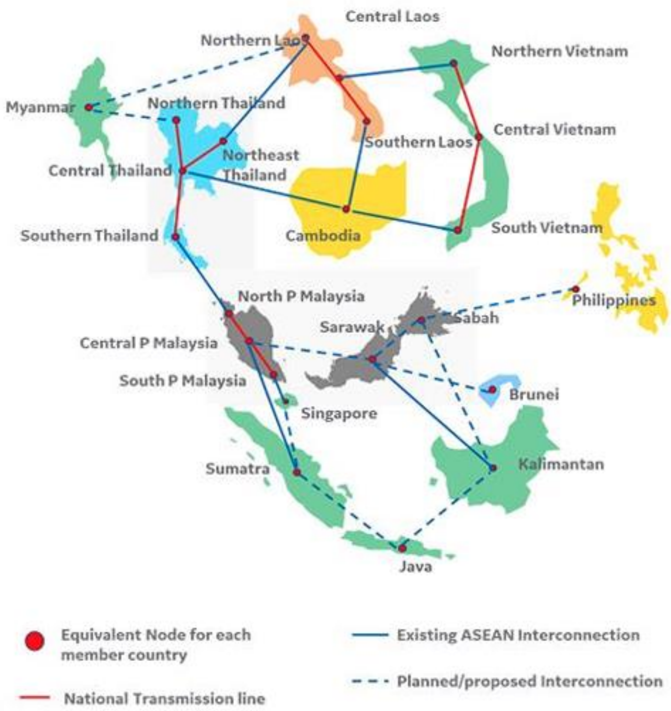
The system will also critically be balanced through interconnection, which will be critically important in Europe and South-East Asia – to be explored in next phase of research

Ember: forecast evolution of Europe's interconnected grid



Europe is already the world's largest interconnected grid, with over **400 interconnectors** linking **600 million citizens.** Europe must **double** its interconnection capacity over the next 15 years to deliver on energy targets.

Proposed ASEAN interconnected system (ASEAN Centre for Energy)



Vast potential for interconnecting ASEAN grids to balance systems and bring on more renewables equitably. Must overcome key challenges including grids running on **different frequencies and voltages**.

Source: Ember (2023), *Breaking borders: The future of Europe's electricity is in interconnectors*; ASEAN Centre for Energy (2021) Regional Power Grid Connectivity: The ASEAN Power Grid

Three key enablers for energy storage

Overall vision for power system and storage targets
- Energy storage technologies must be considered in wider power system planning
- Countries set out capacity targets for energy storage alongside renewable deployment targets

Enabling power market design
- Market mechanisms must effectively remunerate flexible operation of existing dispatchable fleet
- Energy storage projects must be supported in many cases by different regulatory mechanisms, including providing long-term revenue stability and derisking (i.e. rewarded through capacity markets and given ability to ‘revenue stack’)

Faster grid connection
- Energy storage projects must be treated differently in queues than generation given potential to alleviate grid congestion
- Repurposing existing grid connected sites for storage should have expedited permitting (i.e. old coal plants)
- Renewable generation projects combined with storage could be preferred to help balancing

Market design: for all energy storage market / contract design options will be critical

- Explicit system operator contracts for ancillary services
- Free market: arbitraging big variations in price per kWh
- Explicit system operator contracts for capacity
- "Round the clock" renewables contracts (e.g. India)
- …other?

Reminder on workstream next steps

Reminder: next steps across power systems transformation workplan

Report: Building and optimising grids

Report : Balancing challenge

Grid build challenge

Briefing note to be published summer 2024

March 26th

System balancing challenge: key technologies to balance the system
Technology, costs, & other suitability criteria

June 18th

System balancing challenge: key focus on sizing balancing needs across key regions

Sept/ Oct

Optimising the Dx system (the peak load challenge)
Summary of conclusions on optimizing the Tx system (grid technology focus)

End 2024

Backup

Target dates for full power grid decarbonization across key geographies

National **renewable energy target of 82%** in power generation by 2030

Fully decarbonised grid by 2035

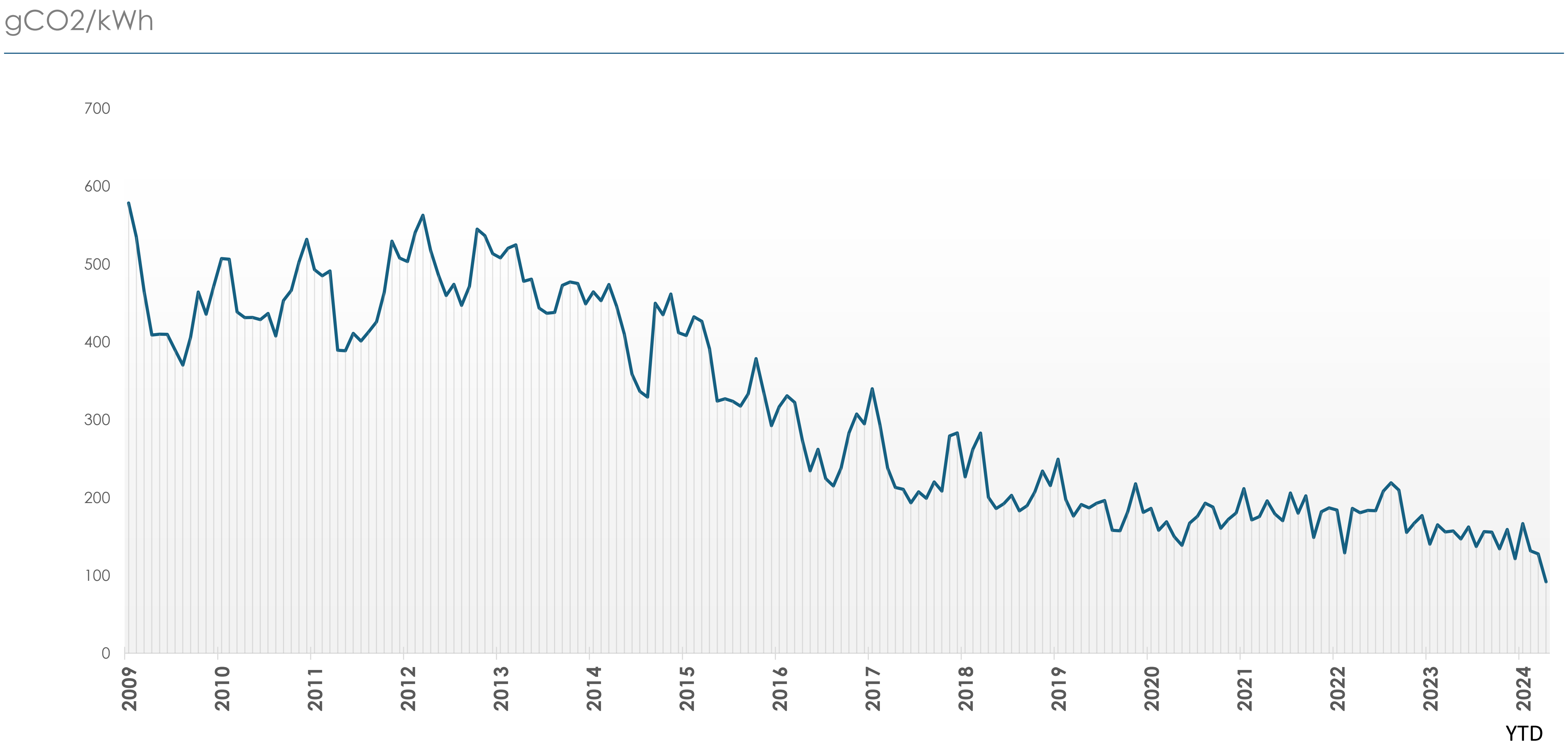
Fully decarbonised grid by 2040 across member states

Fully decarbonized grid by 2035, although Labour Party plans to bring forward to 2030

Fully decarbonised grid by 2035

Sources: Australian Government (2024), *Go Green with Australia;* Government of Canada (2024), *Canada Electricity Advisory Council – Interim Report;* EU-LEX (2024); *Communication from the Commission;* The Labour Party (2024), *Make Britain a Clean Energy Superpower;* US Department of Energy (2023), *On The Path to 100% Clean Electricity;*

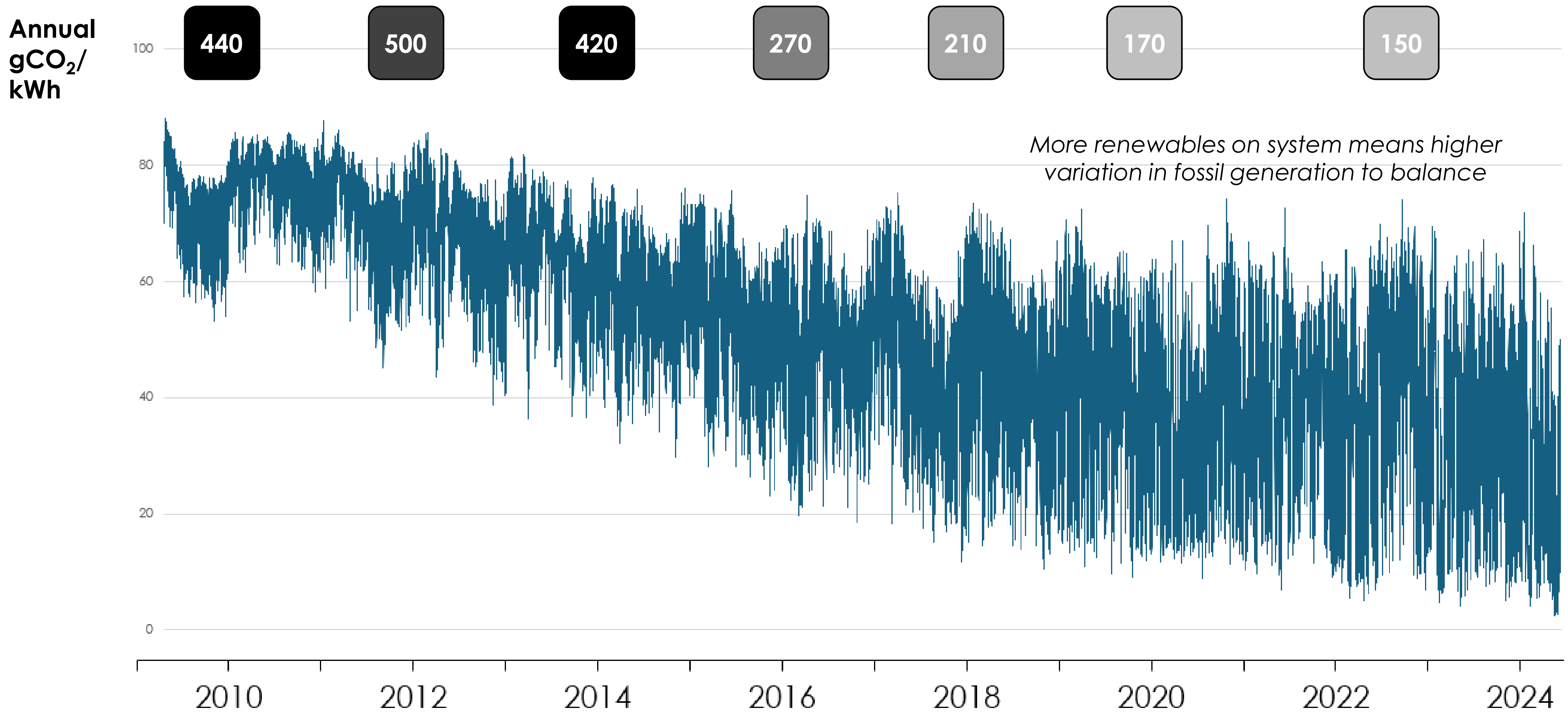
UK electricity system carbon intensity 2009-2024



Share of Great Britain electricity from fossil fuels in each half hour period

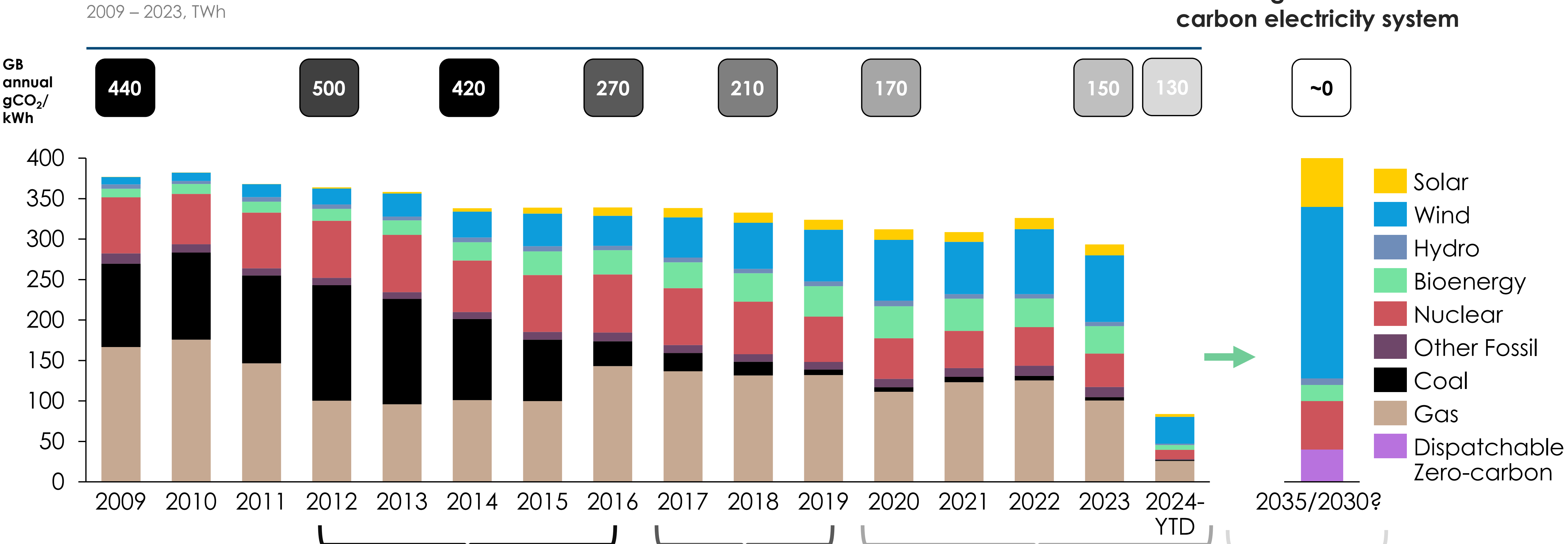
%, ESO (2024), *historic generation mix and carbon intensity*

Generation from fossil fuels, %



Source: ESO (2024), historic mix and carbon intensity

UK electricity generation by technology



Phase 0
Primarily coal to gas switching
500 to ~300 gCO_2/kWh

Phase 1
Low share of renewables + gas
~300 to ~200 gCO_2/kWh

Phase 2
Increasing share of renewables, evolving grid operation (e.g. new ancillary services)
~200 to ~100 gCO_2/kWh

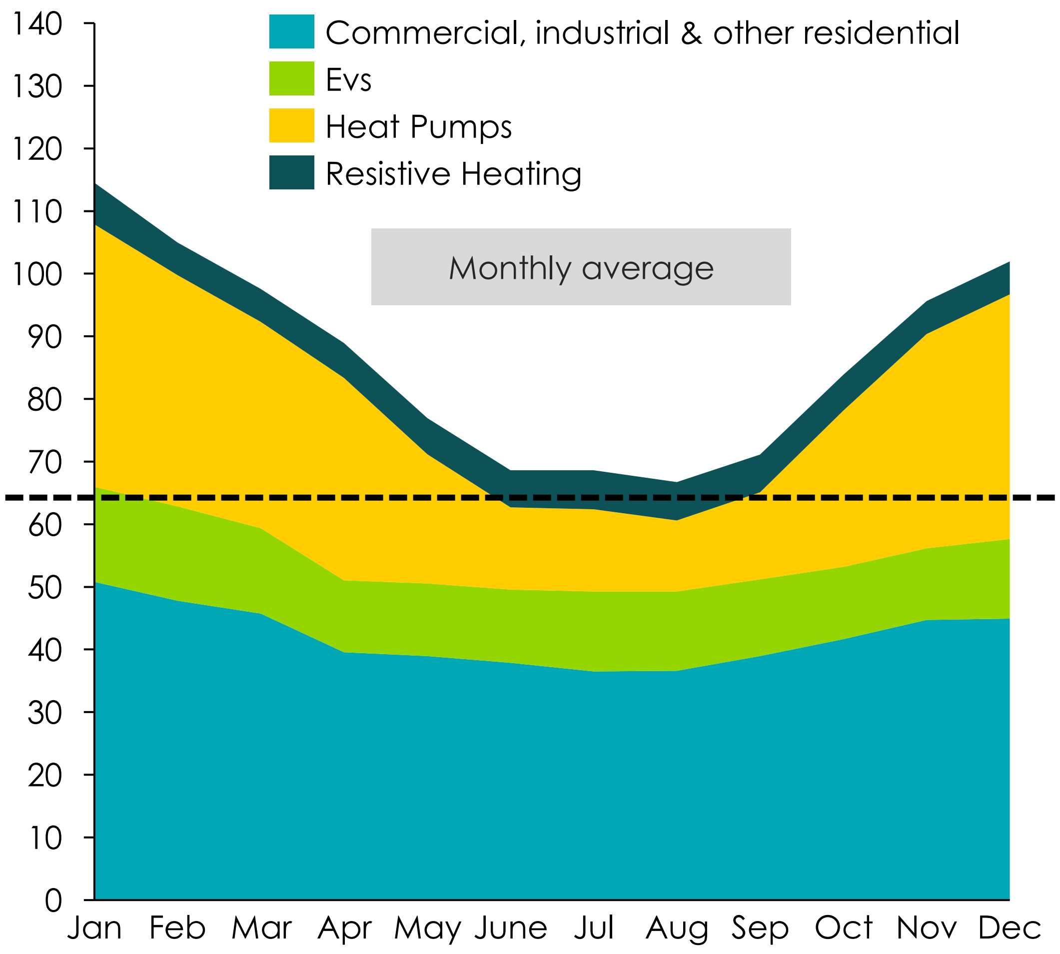
Phase 3
Last mile decarb, no unabated fossil; suite of storage tech (i.e. batteries, PSH, H2, CCS)
~100 towards 0 gCO_2/kWh

Note: 2024 YTD = Jan-Apr 2024. GB grid intensity data used as a proxy for UK, data from National Grid ESO; illustrative 2035 mix assumed. PSH = Pumped Hydro Storage, H2 = Hydrogen Storage, CCS = coal or gas with CCS at high capture rates. Source: Ember (2024), *Electricity data explorer*, ESO (2024), *ESO's Carbon Intensity Dashboard*.

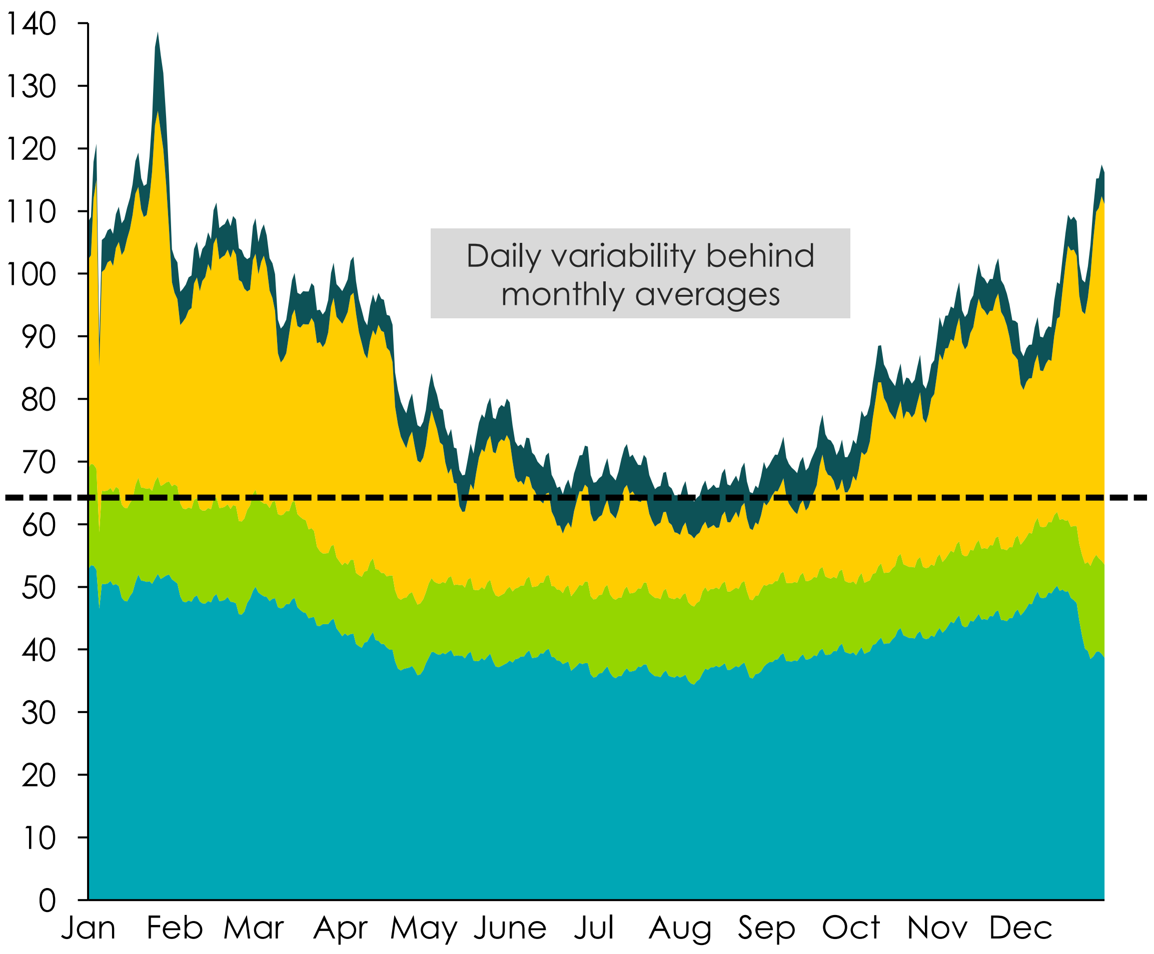
Projected UK power demands 2050

Demand for electricity, averaging daily demand across the month
GW

Largest amount of electricity used at peak time on a cold day to date to date



Demand for electricity, daily demand
GW



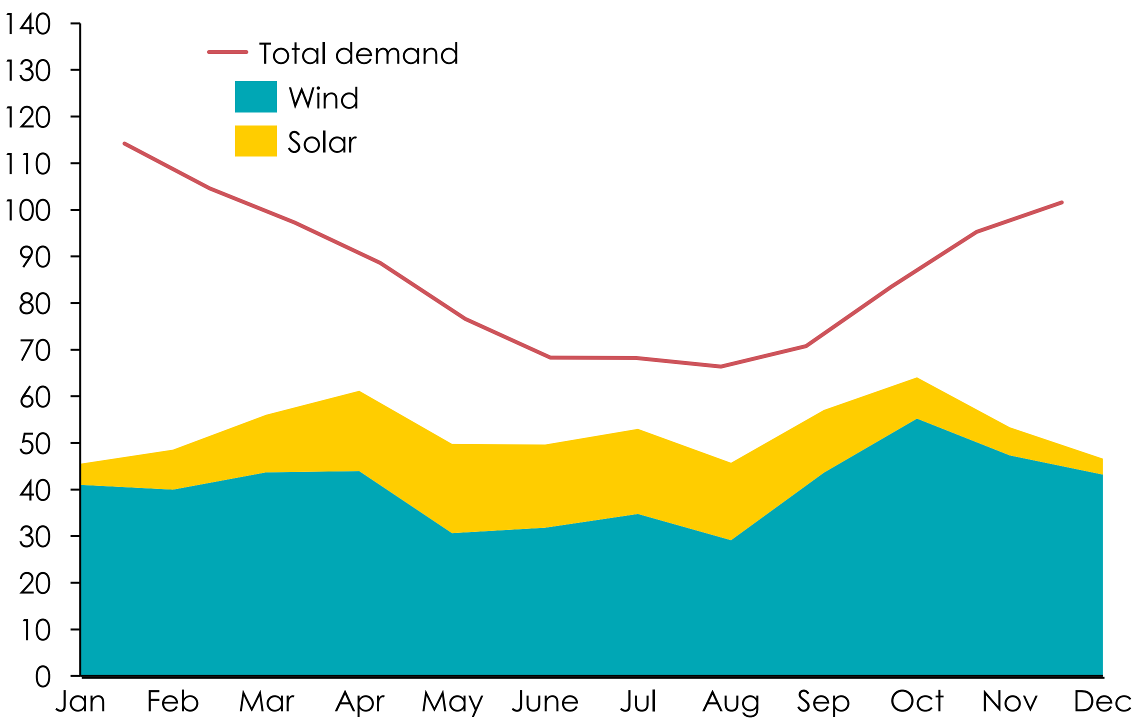
Source: Imperial College (2018) *Alternative Heat Decarbonization Pathways* – showing the demand from the Electric heating decarbonization scenario

At the system level, meeting demand requires solar and wind capacity to be complemented with system levers like dispatchable generation and interconnection

UK case study, assuming all heating is electrified using a combination of heat pumps and resistive heating. Uses historical temperature data with a few consecutive days of modified demand to simulate extreme weather events, i.e. very cold days with low output of renewable energy, for 2050

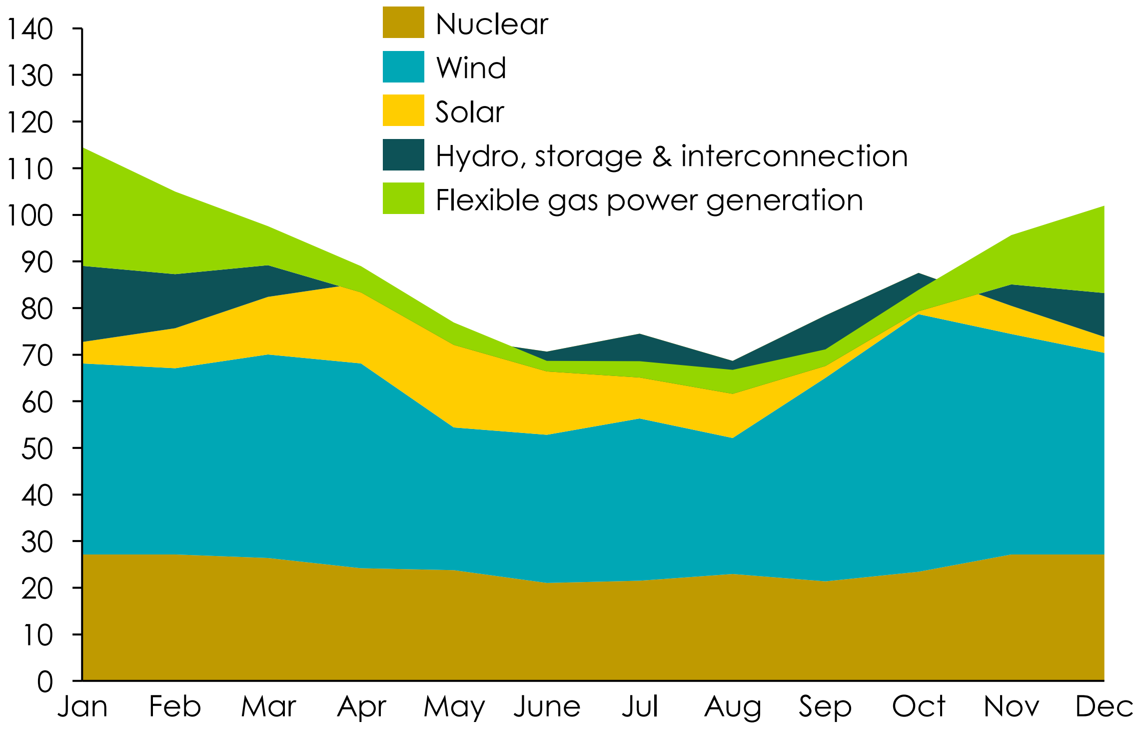
Variability in wind and solar supply……

Potential scenario seasonal supply (wind and solar) 2050 (UK)
GW



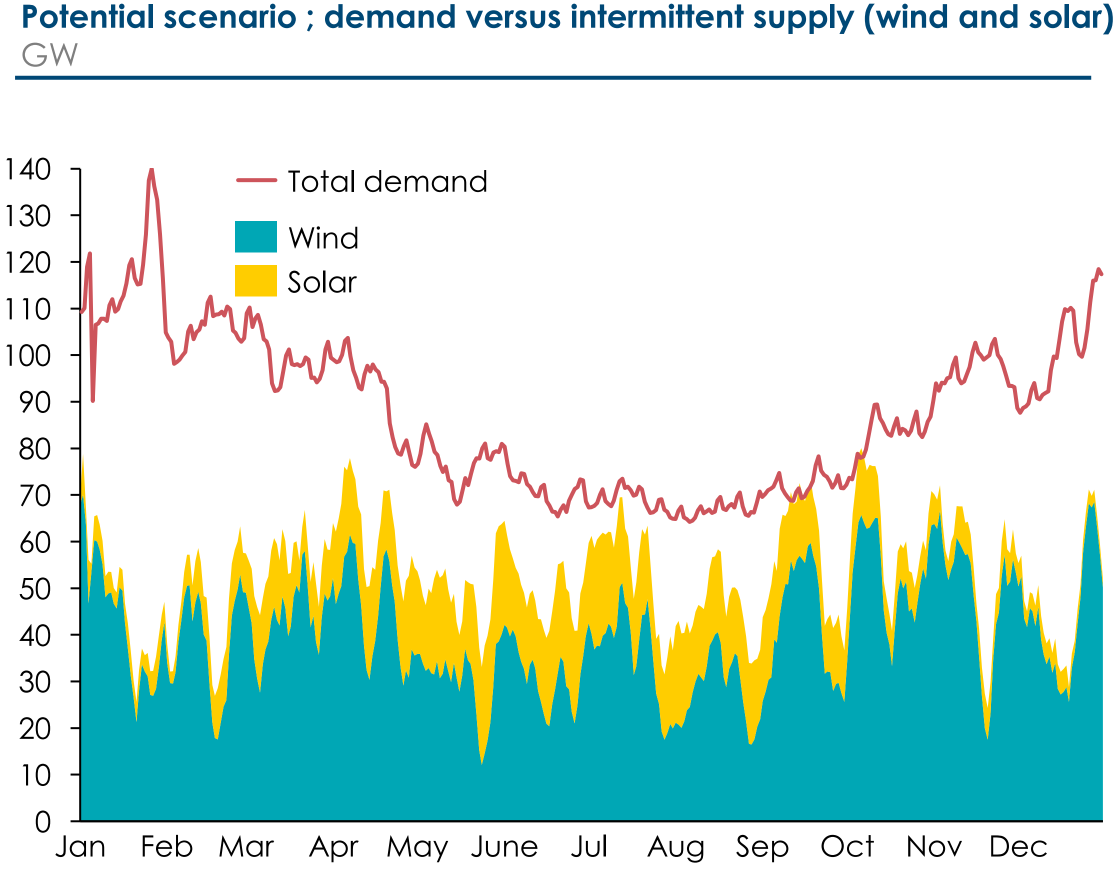
Will need to be complemented with other energy sources

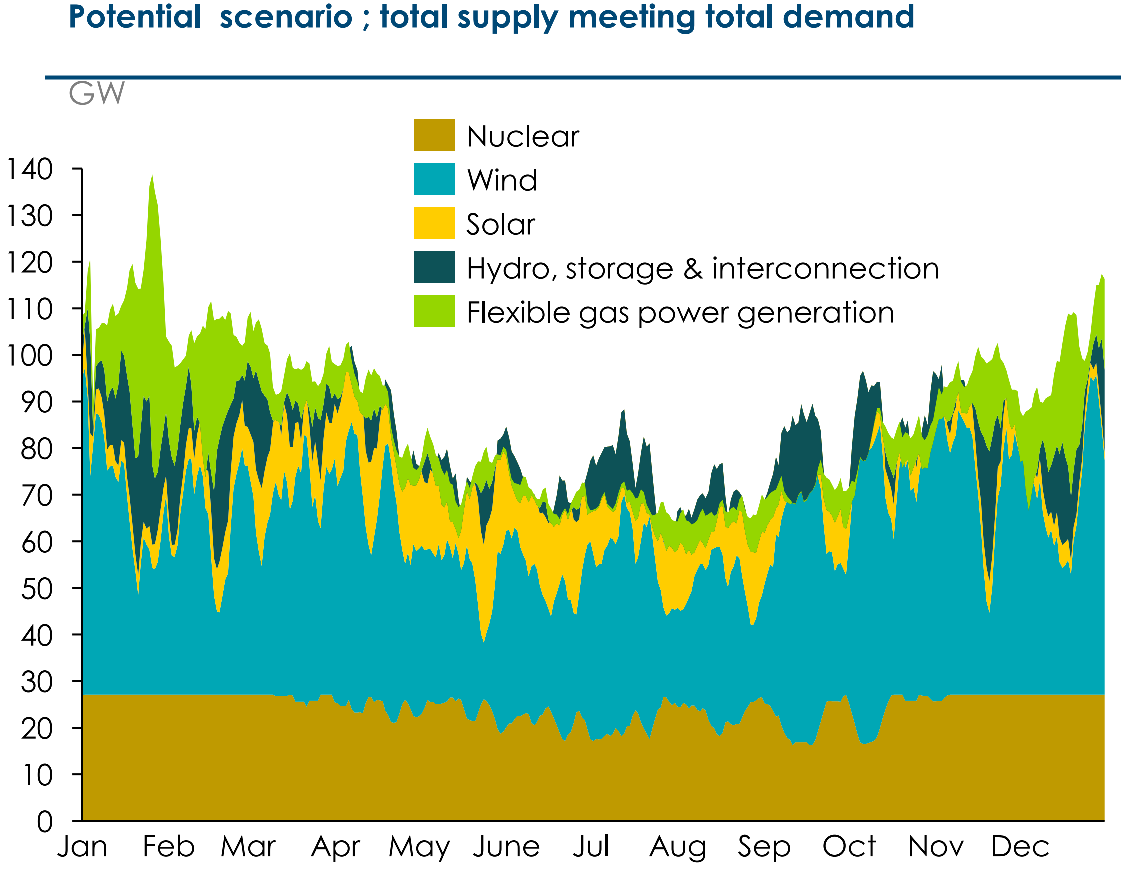
Potential scenario daily power supply by source 2050 (UK)
GW



Source: ETC based on Imperial College (2018) *Alternative Heat Decarbonization Pathways*

Potential supply demand balances UK 2050 ; daily variation



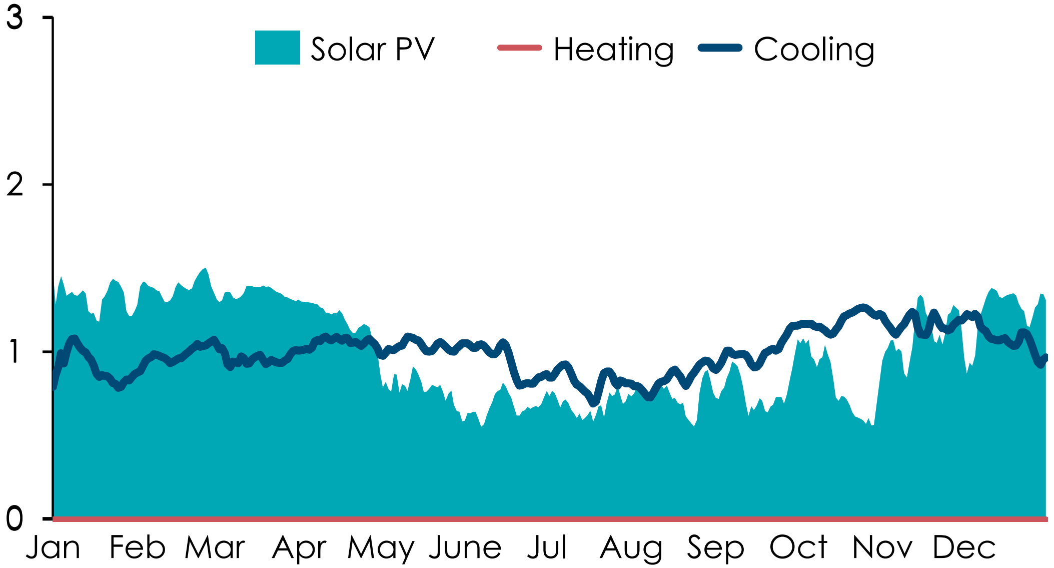


UK case study, assuming all heating is electrified using a combination of heat pumps and resistive heating. Uses historical temperature data with a few consecutive days of modified demand to simulate extreme weather events, i.e. very cold days with low output of renewable energy, for 2050

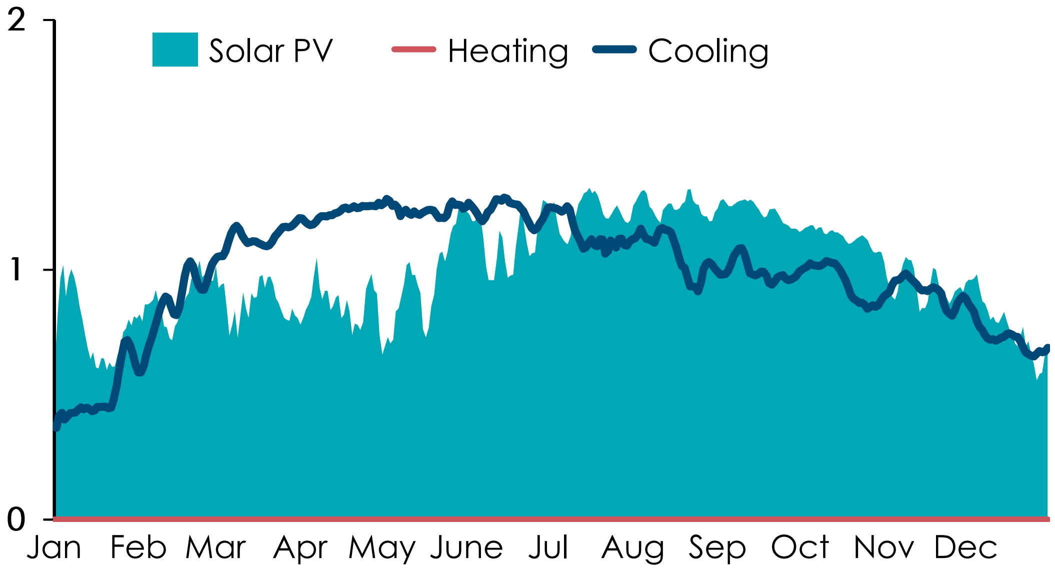
Source: Imperial College (2018) *Alternative Heat Decarbonization Pathways*

Balancing solar source versus cooling demand

Renewables potential and heating and cooling demand (India[c]) Index*



Renewables potential and heating and cooling demand (Indonesia[d]) Index*



Potential heating and cooling demand patterns based on temperature and weather in 2019.

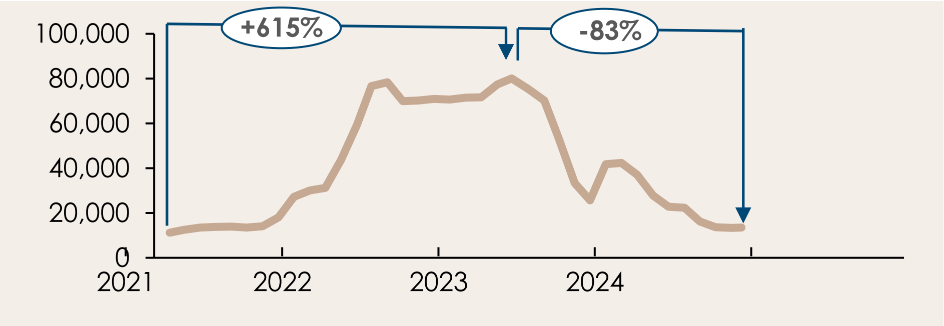
Variations in solar PV supply patterns can vary significantly from the cooling demand patterns across different regions

Note: graphs do not refer to total volumes of generation supply/ demand. Gaps between supply and demand should not be interpreted as a gap in generation.

*Wind and solar potential indexed to 2019 yearly average potential, based on five-day rolling averages. Cooling and heating indexed to 2019 daily average potential, based on five-day rolling averages. a. Brazil figures based on Rio De Janeiro. b. Italy figures based on Rome. c. India figures based on Chennai. D. Indonesia figures based on Jakarta: Renewables Ninja 2024

Mineral prices: the supply constraint that disappeared?

Lithium, $/tonne

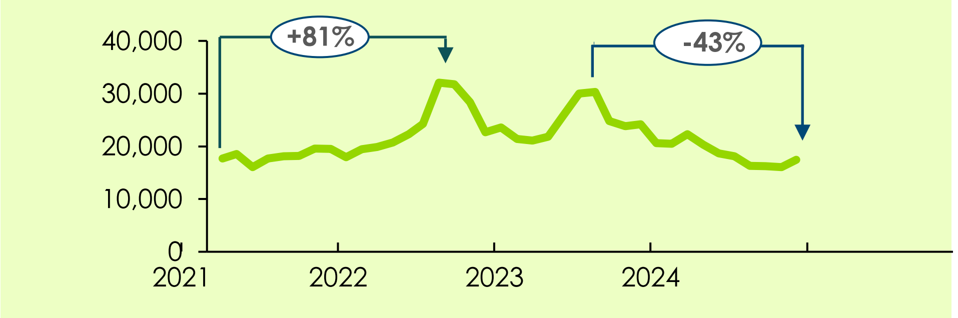


Slowdown in EV demand relative to very high expectations

New projects announced in EU , US , Australia, Chile …..

Some subsequently postponed
New technology Direct Lithium Extraction(DLI) from brine

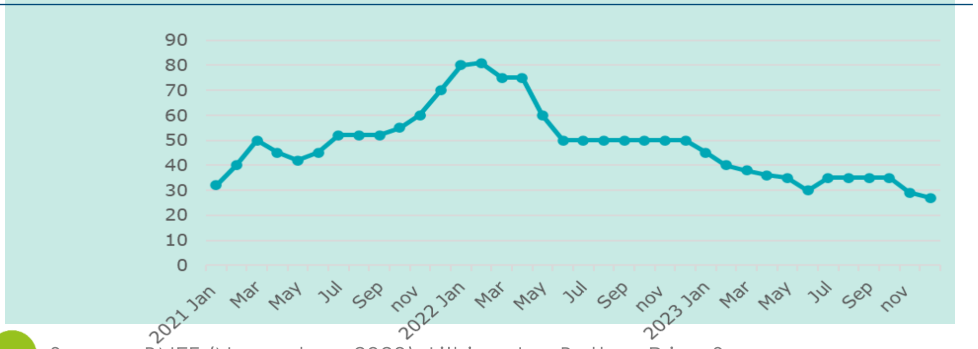
Nickel, $/tonne



Shift towards nickel-free LFP batteries

Massive expansion of Indonesian supply (Chinese owned)

Cobalt, 1,000$/tonne



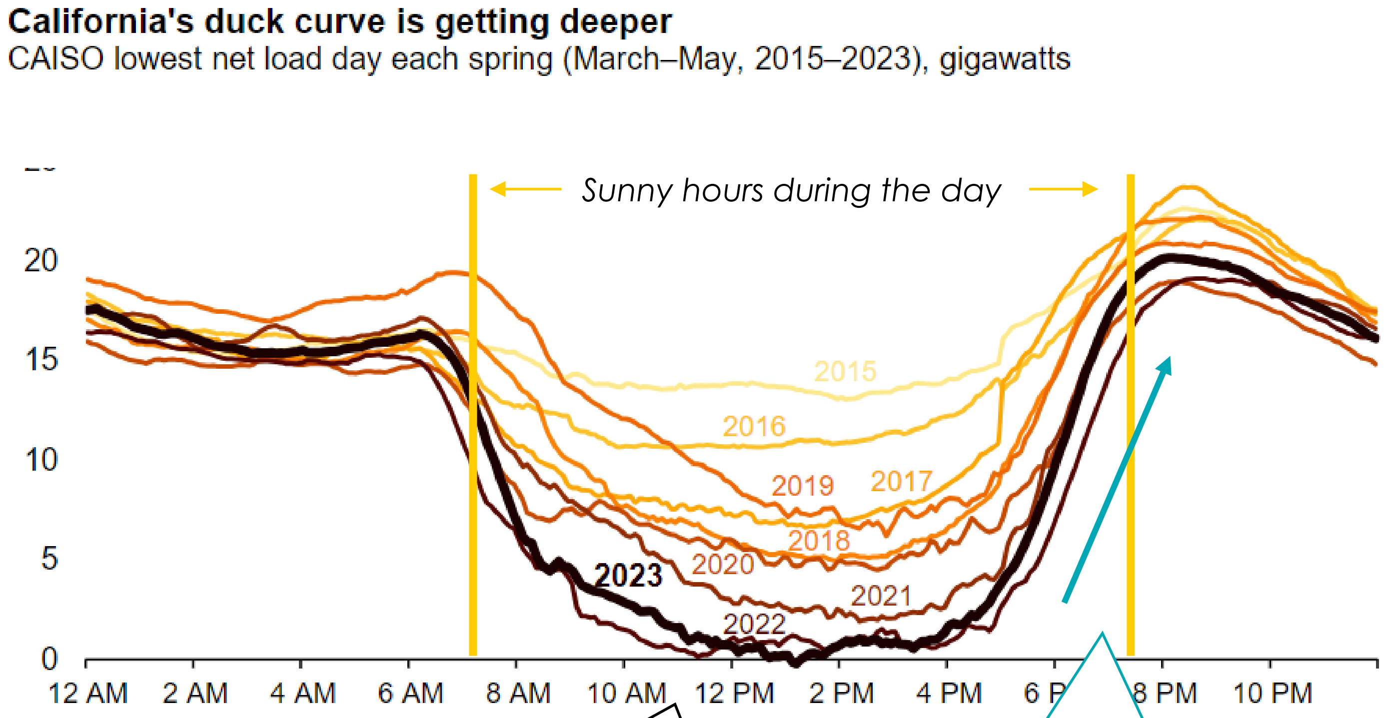
Reduction of Co proportion within NMC batteries

Shift towards nickel and cobalt free LFP batteries

By product of nickel development in Indonesia

Source: BNEF (November, 2023), Lithium-Ion Battery Price Survey.

California's 'Duck curve' - higher solar leads to significant ramping/daily balancing need



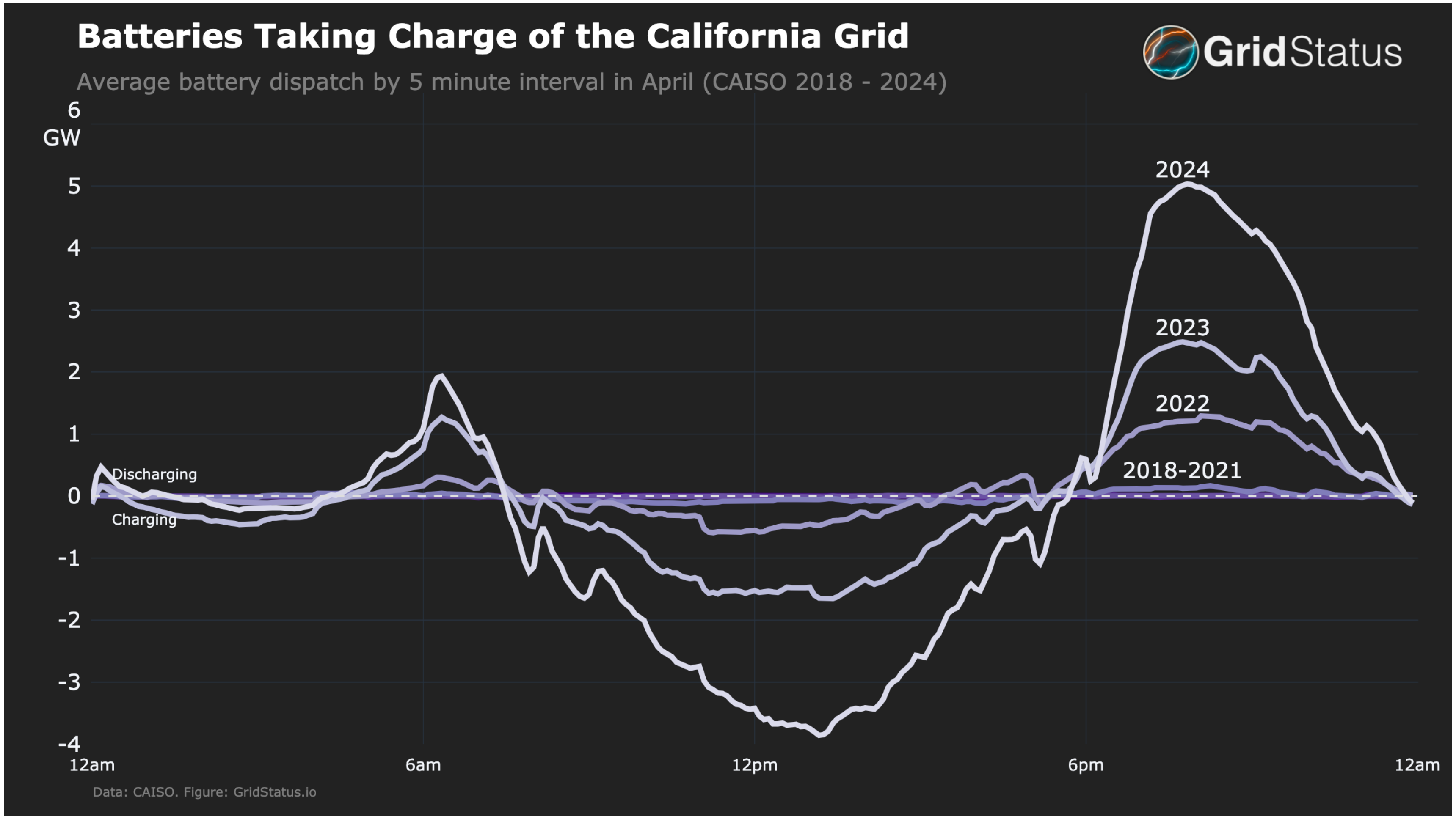
Higher solar penetration means solar can meet almost all load requirements at peak hours since 2022

With more generation from solar, need for alternative source to meet peak evening load means steeper ramp-up challenge

- Net load is total electricity demand minus wind and solar generation levels
- **Solar % of generation grew from 10% in 2015, to 28% in 2023.**
- **Until recently, gas has mostly been used to balance the system**, i.e. provide ramp-up capacity in the evening.

Notes: California electricity mix 2023: 38% gas, 28% solar, 13% hydro, 8% nuclear, 6% wind, 5% other renewables, 2% bioenergy, 1% other fossil.
Source: CAISO, California Energy Commission (2023), *New Data Shows Growth in California's Clean Electricity Portfolio and Battery Storage Capacity;* Ember (2024), *Electricity Data Explorer.*

‘End of the duck curve?’ Growing role for batteries



Source: Grid Status (2024), *Is California finally moving away from natural gas?*