Energy
Transitions
Commission

Power Systems Transformation workshop

Sizing the system balancing challenge

24/10/2024

Workshop agenda

1) Context and past ETC work

- Overview of past ETC work
- This year's focus

2) Methodology and key results

- What determines the size of the balancing challenge?
- Approach to analysis
- Demand: an electrified system vision
- Supply: bringing together 30 years of weather data for wind and solar
- Balancing challenge: bringing it all together

3) Implications on meeting the system balancing challenge

- Key implications for Tropical archetype (India)
- Key implications for Northern Latitude archetype (GB)
- Step back: macro considerations from this analytical approach

Workshops

Grid build challenge

Briefing note published in September 2024

March 26th

Key technologies to balance the system: *dispatchable generation, energy storage, heat storage*

June 18th

Key technologies to balance the system: *demand side flexibility*

Oct 9th

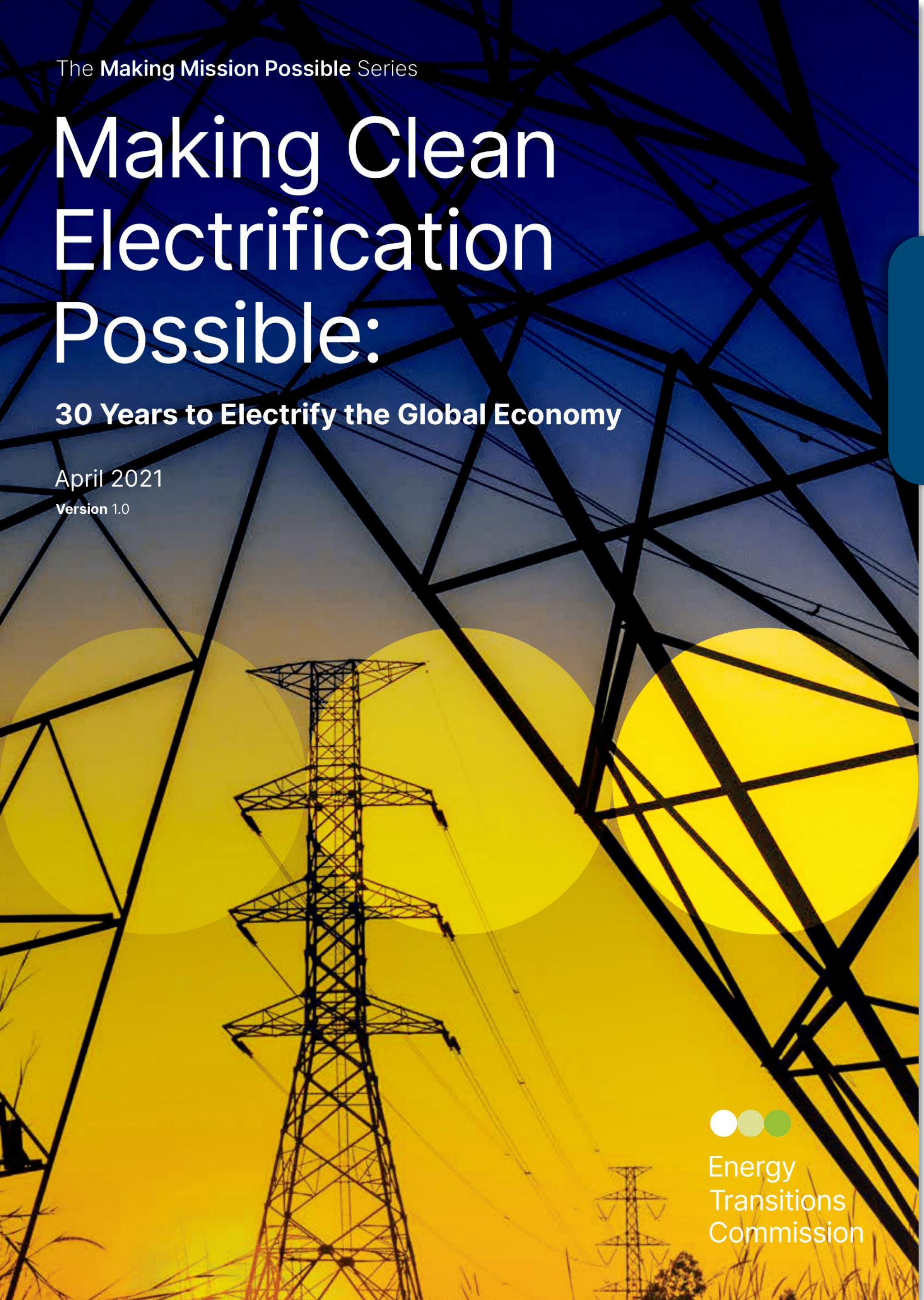
Sizing the system balancing challenge

Oct 24th

Role of interconnectors
Key enablers

End 2024 / early 2025

Overview of past ETC work



The **Making Mission Possible** Series

Making Clean Electrification Possible:

30 Years to Electrify the Global Economy

April 2021
Version 1.0

Energy
Transitions
Commission

Making Clean Electrification Possible: 30 Years to Electrify the Global Economy (2021)

In MCEP we set out the vision for the clean electrification of the global economy and demonstrating that it is feasible for electricity to represent 70% of final energy demand by 2050

Key points:

- Electricity to account for **70% of final energy demand by 2050,** requiring a scale up of 3-5x today's electricity systems.
- **Wind and solar can provide 75-90% of total electricity** in most regions, at the **same or lower cost than today's fossil power** systems.
- Outlined the near term actions required to ensure **rapid enough scale-up** – across generation, balancing, networks and consumption.

Impact:

- Continued to push others (e.g. IEA, BNEF, IRENA) to consider **even larger** future global power systems.
- **Clarified the system development** needed to deliver low cost VRE dominated systems.

Balancing challenge: MCEP presented different needs across key archetypes

Scale of seasonal balancing needs differs across regions

Balancing variability across markets in a near 100% VRE system

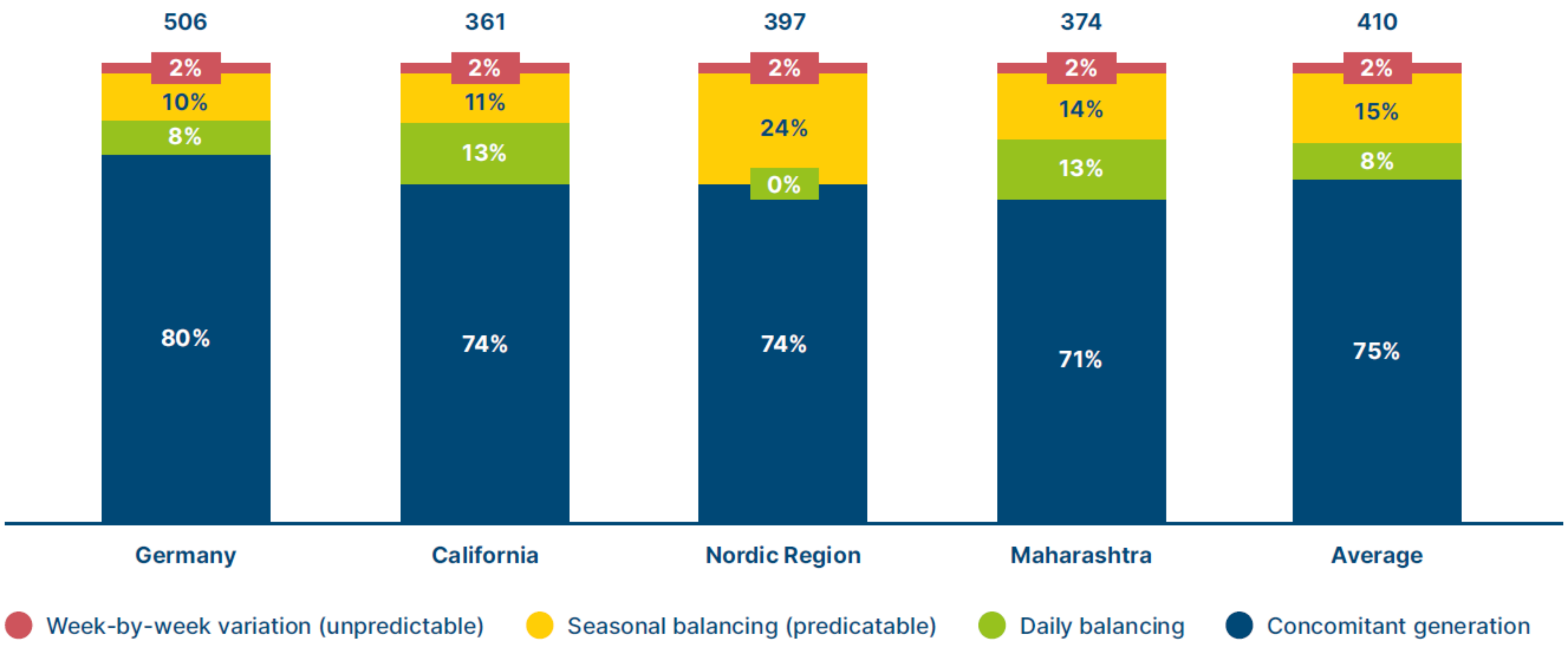


Exhibit 2.9

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)

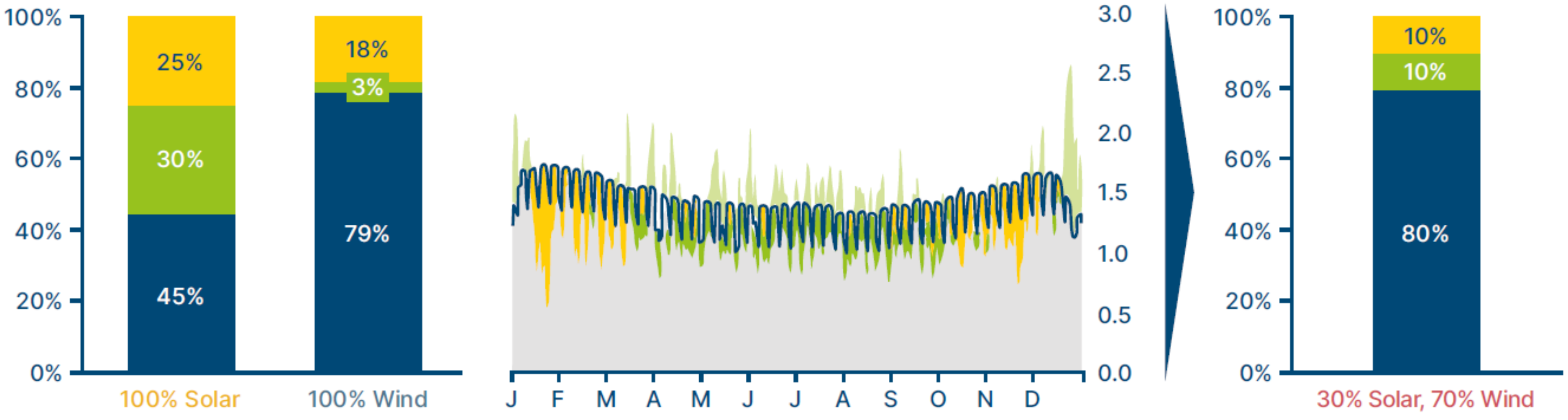
Modelling by CPI in 2017 to derive balancing mix looked at optimization between wind/solar production to minimize storage gap needed

Optimal mix of VRE resources can minimise balancing challenges

Germany storage 'gaps' – with 100% solar or wind

German yearly power demand profile in a near 100% VRE system, Daily TWh

Germany storage 'gap' with optimal mix



	100% Solar	100% Wind
Seasonal gap	25%	18%
Daily gap	30%	3%

- Seasonal balancing
- Daily balancing
- Concomitant generation

- Daily electricity demand
- Renewable energy generation used in the same hour it is produced
- Daily shortfall of renewable energy production, potentially met by daily shifting
- Daily surplus of renewable energy production that can be shifted
- Seasonal shortfall

	30% Solar, 70% Wind
Seasonal gap	10%
Daily gap	10%

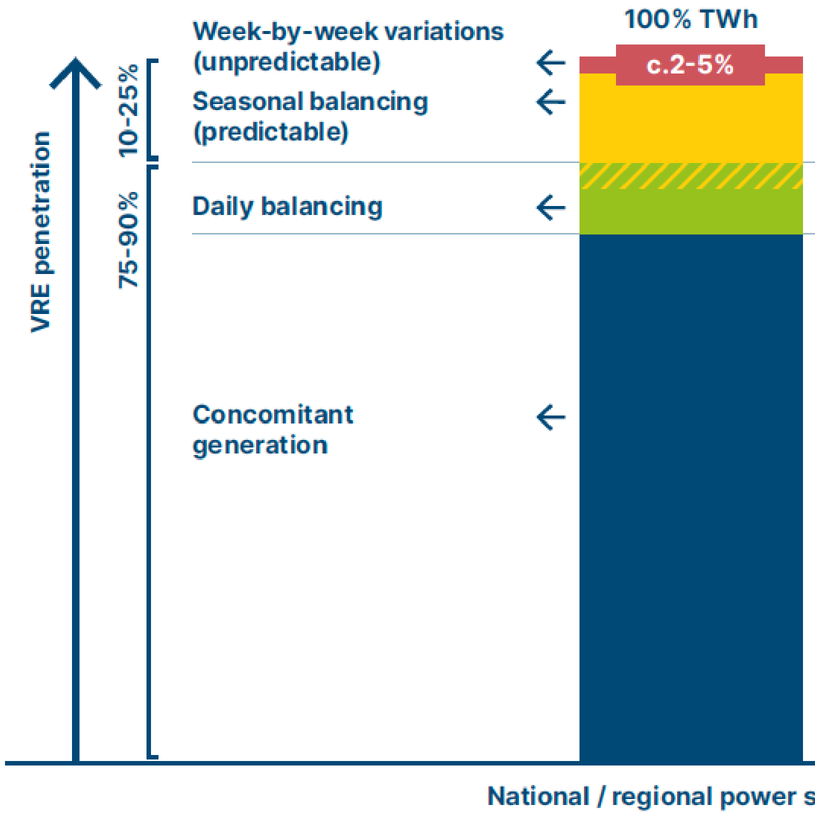
Exhibit 2.8

SOURCE: Adapted from Climate Policy Initiative for the Energy Transitions Commission (2017)

For each generation / balancing need, we considered tipping points between fossil and zero-carbon sources

Exhibit 2.11

The cost impact of increasing VRE penetration and optimal mix of balancing solutions deployed will be influenced by cost “tipping-points”



	Cost “tipping points” vs unabated fossil:	Cost “tipping points” vs abated fossil (zero carbon option)
Week-by-week variations (unpredictable) Seasonal balancing (predictable)	• H_2 < natural gas (¢/kWh) • VRE LCOE x 2 < gas marginal cost	• H_2 < existing fossil + CCS • VRE LCOE x 2 < existing fossil + CCS
Daily balancing	• VRE + storage < existing fossil • VRE + storage < new fossil	• VRE + storage < existing fossil • VRE + storage < new fossil
Concomitant generation	• VRE < existing fossil • VRE < new fossil	

SOURCE: SYSTEMIQ analysis for the Energy Transitions Commission (2021)

MCEP outlined set of zero-carbon technologies to meet balancing challenge

Exhibit 2.10

Range of dispatchable generation, energy storage, demand-side flexibility options

			Daily	Seasonal (predictable)	Week-by-week (unpredictable)
Dispatchable generation	Other zero carbon	Hydro, nuclear[1]	✓	✓	✓
	Fossil	Fossil (or bioenergy) + CCS	✓	✓	✓
		Fossil – very low utilisation	✓	✓	✓
Energy storage		Pumped hydro	✓	✓	✓
		Lithium ion battery[2]	✓		
		Emerging technologies	✓		
		Power-to-X-Power[3]	✓	✓	✓
Demand side flexibility		EV (smart charging, V2G)	✓		
		Heating load	✓		
		Industrial load[4]	✓	✓	

NOTES: [1] Limited nuclear capacity for flexible ramping. [2] Li-ion storage is utility-scale and behind-the-meter. [3] Examples of Power-to-X-Power include the production of hydrogen from electrolysis and re-conversion of hydrogen into power via gas turbines or fuel cells. [4] 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*

This year’s focus

This year, we have returned to issues around balancing the system

Building and optimising grids

**Tx:
Grow the transmission network**

Dx: Reinforcing existing & building new network infrastructure

Tx: Optimising use of existing assets via new technologies

Dx – Spreading peak load to increase grid utilisation & balance the system

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

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

Managing the system balancing challenge (in high variable renewable systems)

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

Balancing the system via storage, flexibility & generation technologies

On managing the system balancing challenge, what have we done so far and what is changing in our thinking?

Revisit power system transformation trajectory

- **Until ~50% penetration of wind and solar, balancing challenge can primarily be met by running existing fossil more flexibly**

☆ ***Focus today***

Revisit shape of the balancing challenge

- **Understanding the mix of daily/weekly/seasonal balancing** needed in different regions

Revisit role of different routes to meet balancing challenge

- **For short-duration storage, renewed confidence in the role of lithium-ion batteries**
- **Increasing number of technology options for medium-duration storage, set of options to meet long duration storage is more limited**
- **High potential for demand-side flexibility**
- **Heat storage opportunities** for industrial heat provision

Upcoming focus

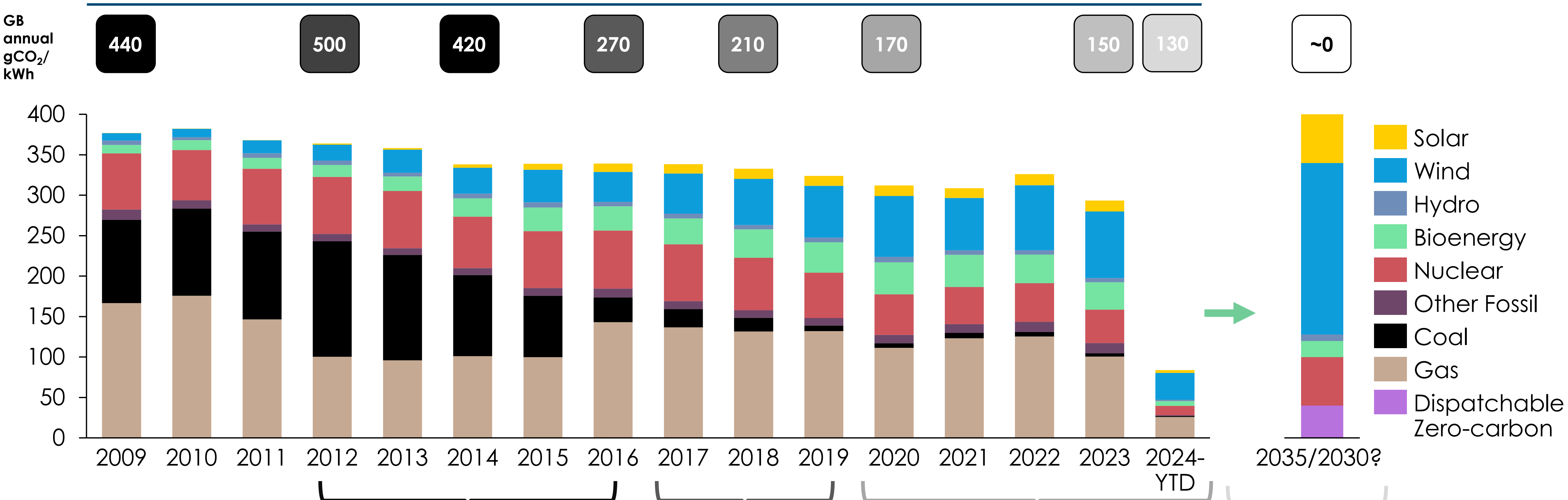
Revisit power market design & key enablers for balancing needs

- **Market design needs to evolve to provide revenue certainty for storage**
- **Role of locational pricing** is critical

UK example: significant power decarbonisation can be accomplished by running fossil flexibly

2009 – 2023, TWh

UK target 2035 zero-carbon electricity system



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

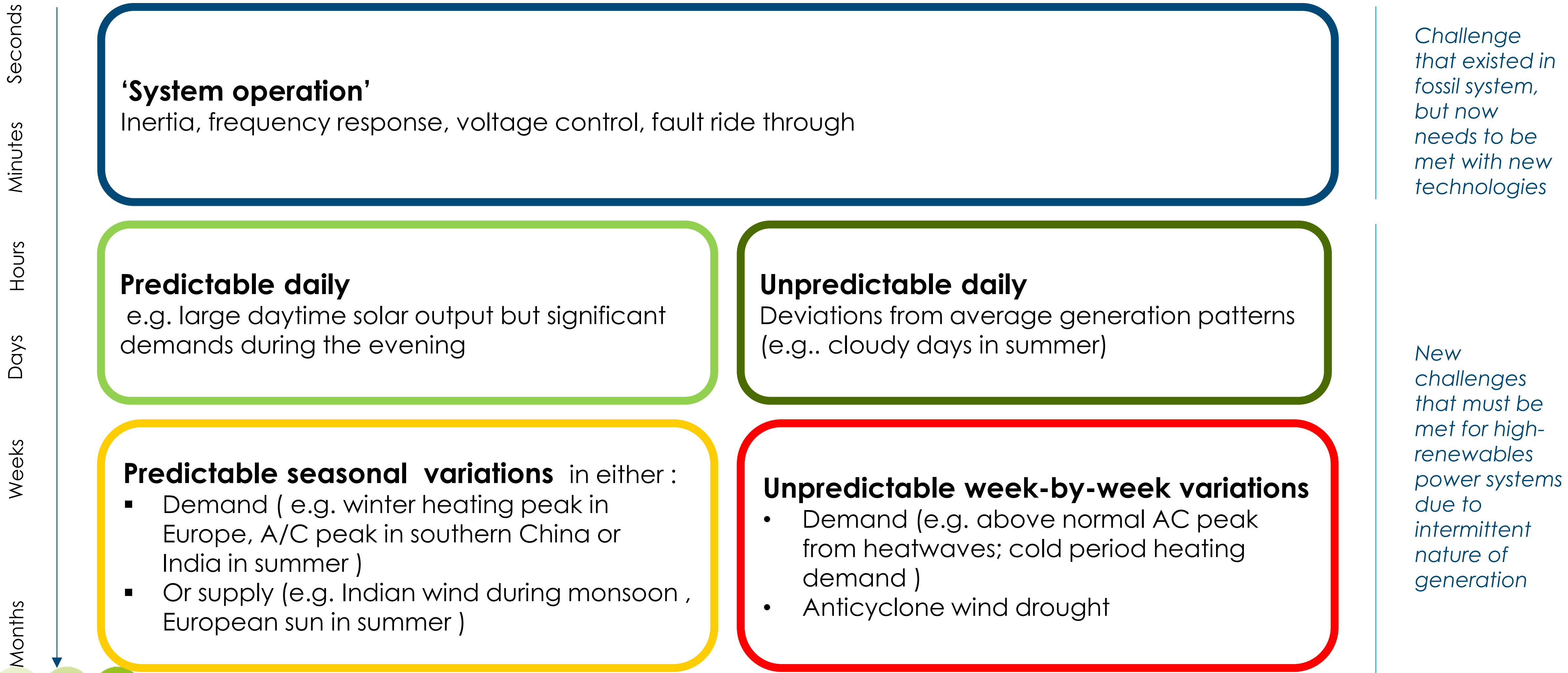
Phase 1
Low share of renewables + gas
~300 to ~200 gCO_2/kWh

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

Defining different aspects of the 'balancing' challenge

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



'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

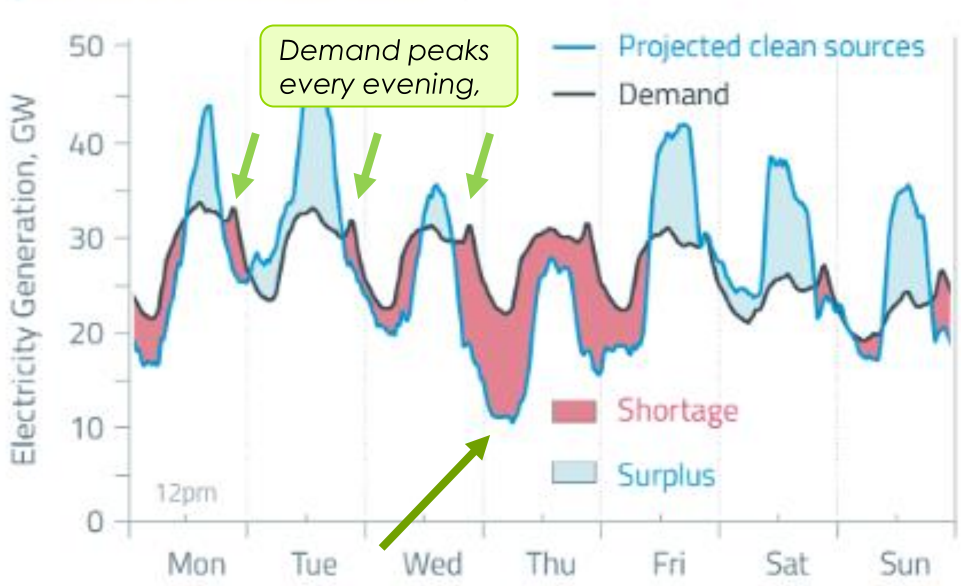
- Demand (e.g. above normal AC peak from heatwaves; cold period heating demand)
- Anticyclone wind drought

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

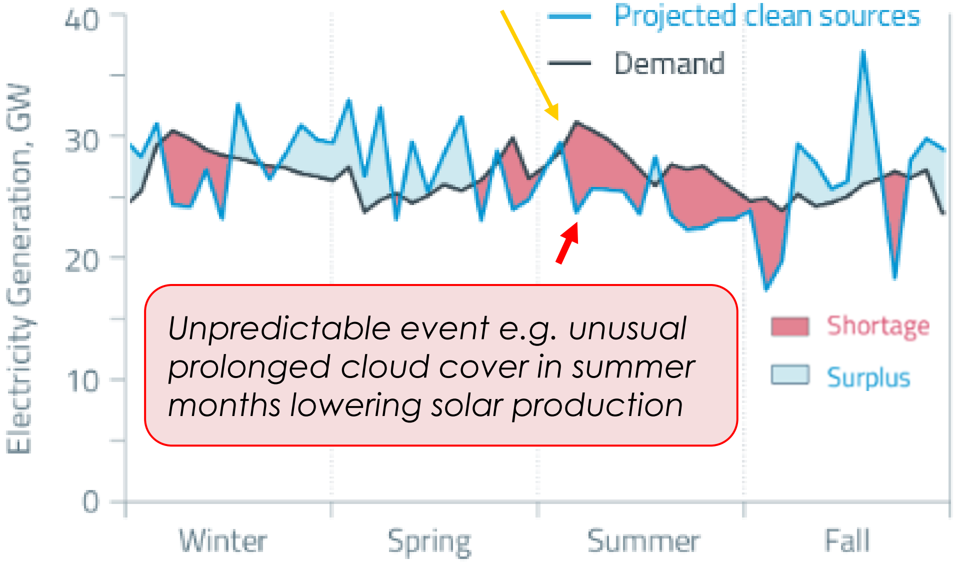


Demand peaks every evening,

Unpredictable daily drops in generation e.g. from a cloudy day in summer

Seasonal balancing

Predictable summer cooling demand means electricity demand is higher



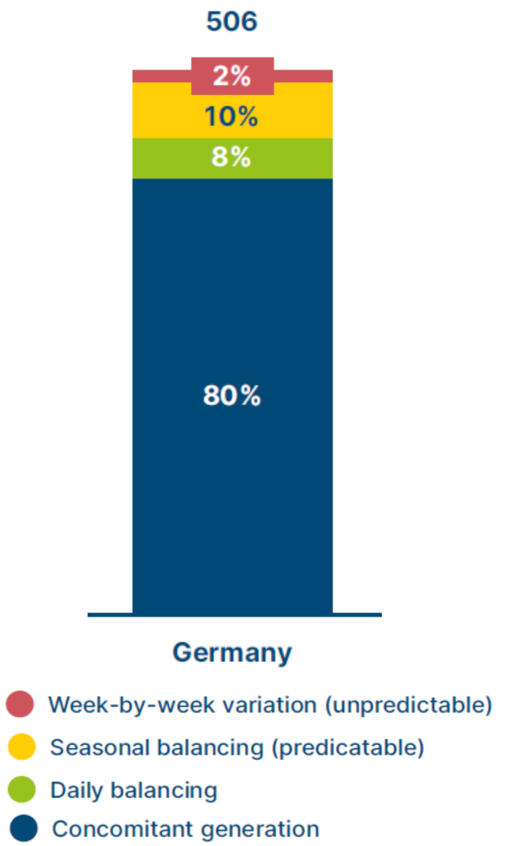
Unpredictable event e.g. unusual prolonged cloud cover in summer months lowering solar production

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/

In variable renewable dominated systems, critical question: how big is the balancing challenge?

Existing ETC work – 2017 analysis

Balancing variability across markets in a near 100% renewable system



New analysis for 2024

Updated ETC analysis will assess 2050 energy balance requirements based on:

- **Supply,** via realistic 2050 wind and solar generation profiles, which will be derived using weather data from the past 30 years to create minimum, average and maximum scenarios over 2 hourly generation periods.
- **Demand,** via 2050 hourly demand forecasts obtained from expert models (i.e. Imperial College for UK), accounting for new loads (e.g. EVs, heat pumps) and load patterns.

Supply & demand will be matched to determine balancing requirements across time periods (daily, weekly, and seasonal needs), for key country archetypes.

What will this approach improve?

- Considers 30 years of historical weather data to give greater understanding of storage needs in low-variable renewable output years
- Ability to revise and flex assumptions of wind/solar capacity installed, and the relative mix (e.g. reflecting renewed confidence in sola generation)
- Refresh of assumptions of changing demand curve in highly electrified systems

Notes: 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%). Potential countries in scope are: UK, India, Indonesia, USA, Germany, China, Chile, Colombia, Australia, Kenya.
Source: Adapted from Climate Policy Initiative for the Energy Transitions Commission (2017)

Methodology & key results

What determines the size of the balancing challenge?

Key factors determine the size of the balancing challenge

Key factor	How is this assessed?
Penetration of wind and solar	Model assumes 100% of electricity requirements are generated by wind and solar
Split of wind and solar mix	Assumed most likely technology mix based on literature, targets and sensitivities
Level of electrification of demand	Utilise best 2050 scenarios including electrified transport, heating and industry electrification
Level of Demand Side Response	Some embedded DSR assumed, (but not max scenario, which would reduce peakiness and scale of challenge)
Local weather and climate	Variation across climactic region archetypes; variations over years are a source of uncertainty

Deepdive on next slide

Local weather and climate: how does it impact electricity demand & supply?

Local weather and climate

Significant variation & unpredictability which must be taken into account:

- **Predictable daily variation** (e.g. large daytime solar output but none during evening when demand is high)
- **Unpredictable daily deviations in average generation** (e.g. cloudy days in Summer)
- **Predictable seasonal variations in either demand** (e.g. Europe Winter heating peak, US Summer A/C peak) and supply (e.g. India lack of sun and increased wind during monsoon season)
- **Unpredictable weekly/monthly drops in some seasons** (e.g. dunkelflaute, and annual "low wind" years)

View of historical weather data is critical to capture possible peaks across these variations

We use 4 archetypes with distinctive characteristics on demand and supply to illustrate global balancing needs

Key characteristics	**Archetype 1:** Northern latitude Case study: GB	**Archetype 2:** Low latitude/tropical Case study: India	**Archetype 3:** Mild/mediterranean Case study: Spain	**Archetype 4:** Mixed climate Case studies: USA, China, Chile
Solar irradiance:	Relatively low	High with moderate seasonality (e.g. monsoon season lower)	Plentiful Summer, less Winter	Varied, high in places
Wind speed:	Generally high & consistent	Mixed, high in places	Relatively high & consistent	Varied, high in places
Heating need:	Winter peak	Generally low	Generally low, some in Winter	High in Winter, large variation
Cooling need:	Generally low	High throughout year	High in Summer	High in Summer, large variation
What does archetype represent?	*Representative of most northern countries: North Europe, Canada, etc.*	*Representative of many tropical countries: Thailand, Vietnam, etc.*	Representative of many milder climates: Italy, Morocco, Türkiye, etc.	Representative of very large varied countries: Argentina, Mongolia, etc.

Focus of this workshop is on Archetypes 1 and 2 - GB & India as case studies

Key characteristics	**Archetype 1:** Northern latitude Case study: GB	**Archetype 2:** Low latitude/tropical Case study: India	**Archetype 3:** Mild/mediterranean Case study: Spain	**Archetype 4:** Mixed climate Case studies: USA, China, Chile
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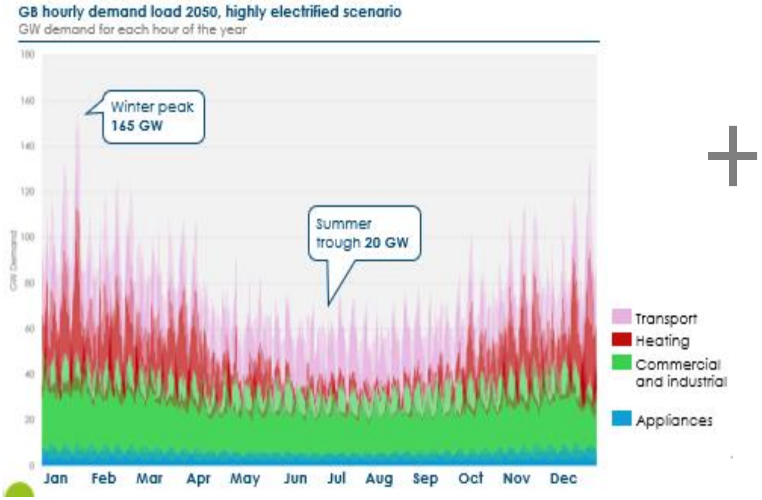
Approach to analysis

Approach to this analysis

For each archetype

Demand



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

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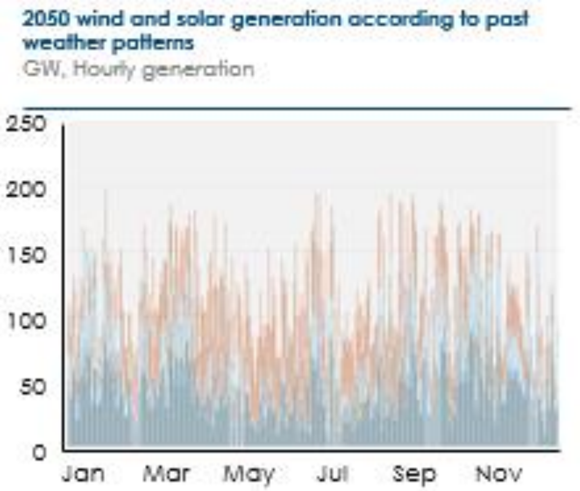
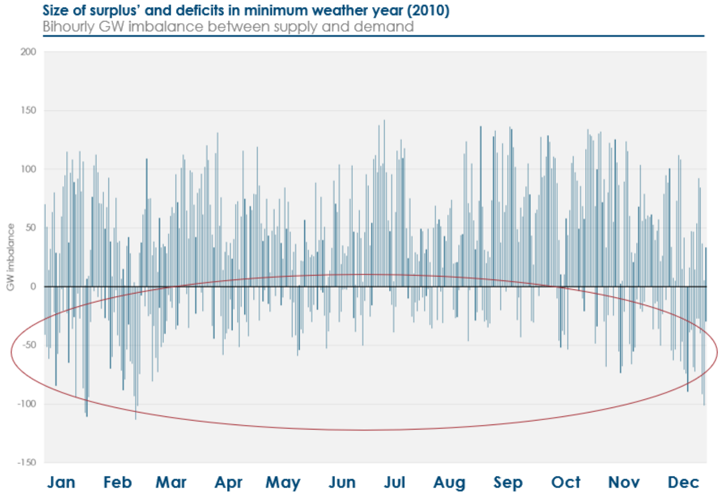
Supply (wind + solar)



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

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*Installed solar PV, onshore wind and offshore based on deployment ratio of solar/onshore/offshore broadly consistent with existing government targets and/or relevant literature

Low-carbon baseload wouldn't eliminate balancing challenge; in this approach, we consider balancing need for 100% wind and solar systems

Role of low-carbon baseload (e.g. nuclear, geothermal, hydro)

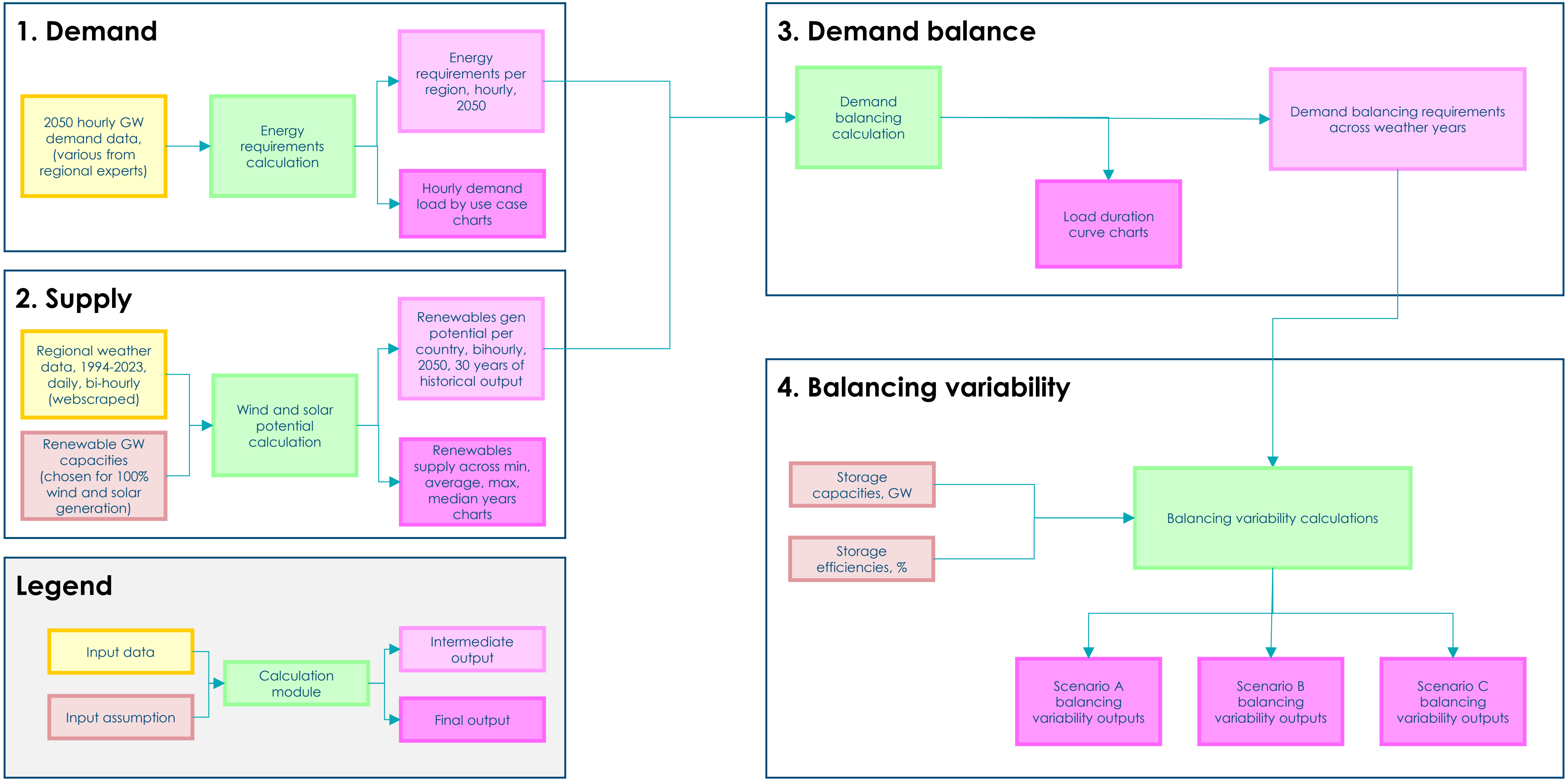
- **Existing or new low-carbon generation, <u>if run as baseload, would not solve</u> the balancing challenge**
  - Baseload low-carbon might replace some wind and solar as low cost generation (if lowest-cost), but wind and solar generation on the system would still lead to a balancing challenge
  - **Therefore, this analysis does not embed any low-carbon baseload mix into "sizing" the challenge; it focuses on assessing the "full" balancing challenge in an 100% wind and solar system**

- **However, low-carbon baseload technologies (e.g. hydro, nuclear), if run as flexible assets in the power system, can <u>help to solve some of the</u> balancing challenge**
  - This requires power market design to reflect different value to the system
  - There is a variation in technical capabilities of low-carbon generation to run flexibly (ramp up/down rates, etc)

- **Our view is that low-carbon generation can play a role to solve balancing challenge, provided it would be cost competitive vs renewables + flex provision (E.g. wind/solar + storage, demand side flex)**

- **ETC will look further into low-carbon baseload as part of next year's work programme**

Model structure



1. Demand

2050 hourly GW demand data, (various from regional experts)

Energy requirements calculation

Energy requirements per region, hourly, 2050

Hourly demand load by use case charts

2. Supply

Regional weather data, 1994-2023, daily, bi-hourly (webscraped)

Renewable GW capacities (chosen for 100% wind and solar generation)

Wind and solar potential calculation

Renewables gen potential per country, bihourly, 2050, 30 years of historical output

Renewables supply across min, average, max, median years charts

Legend

Input data

Input assumption

Calculation module

Intermediate output

Final output

3. Demand balance

Demand balancing calculation

Load duration curve charts

Demand balancing requirements across weather years

4. Balancing variability

Storage capacities, GW

Storage efficiencies, %

Balancing variability calculations

Scenario A balancing variability outputs

Scenario B balancing variability outputs

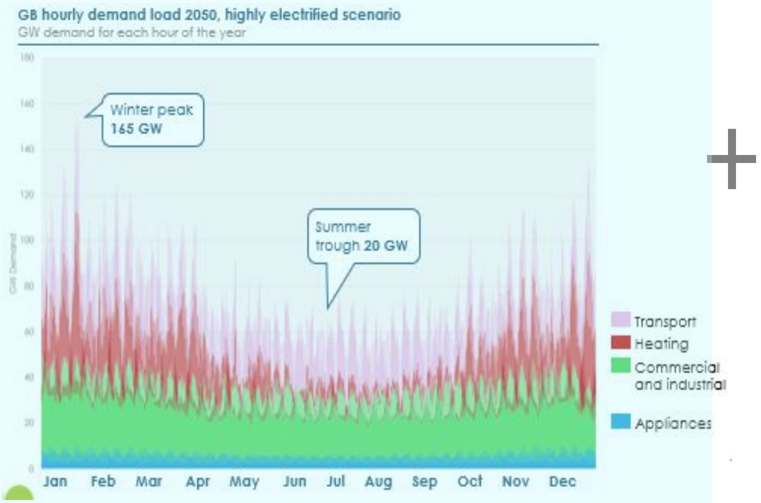
Scenario C balancing variability outputs

Demand: an electrified system vision

Approach to this analysis

For each archetype

Demand



GB hourly demand load 2050, highly electrified scenario

GW demand for each hour of the year

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

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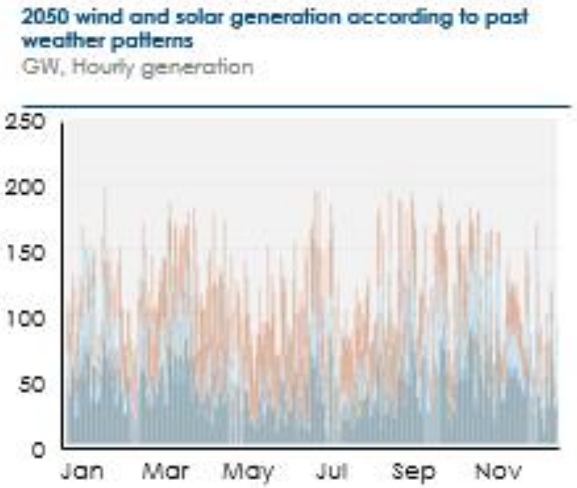
Supply (wind + solar)

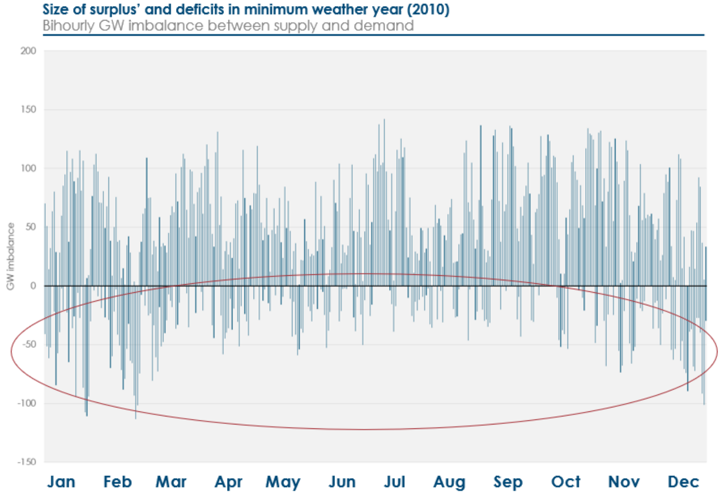


2050 wind and solar generation according to past weather patterns

GW, Hourly generation

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



Size of surplus' and deficits in minimum weather year (2010)

Bihourly GW imbalance between supply and demand

Matching at bi-hourly level across demand and supply to assess periods of wind & solar generation excess/shortfall relative to demand

What would our demand curves ideally incorporate?

Key assumptions	**Ideal inputs for modelling**	**Inputs for ETC modelling**
Representative 2050 demand curve for case study countries		
Baseline assumptions	• Precise assumptions on heating and transport (e.g. uptake of heat pumps, EVs) based on S-curve uptake	• Some uncertainty over precise assumptions on technology pathways
Breakdown by load type	• As specific as possible	• Varying levels of specificity
Role of demand-side flexibility	• Clearly stated and quantified, to understand how much of potential flexibility is already embedded and reducing peak shapes	• Some uncertainty over precise level of demand side flexibility employed
Granularity (time)	• Hourly	• Hourly

Notes: Best scenarios we currently have available. Further modelling will be undertaken in the other archetype countries.
Source: NESO (2022) *Future Energy Scenarios 2022*; TERI (2024) *India's Electricity Transition Pathways to 2050: Scenarios and Insights*

Demand curves for GB and India analysis reflect highly electrified view

	Archetype 1: Northern latitude Case study: GB	**Archetype 2:** Low latitude/tropical Case study: India
Source	**FES 2022, *'Consumer Transformation'*** – GB ESO	**India's transmission Pathways to 2050: Scenarios and Insights *'Low Carbon Scenario'*** – TERI
Key assumptions	Annual power requirement today/2050 = ~280 TWh / **518 TWh** Maximum power required today/2050 = ~100 GW / **165 GW** **Assumes:** highly electrified scenario with large rollout of electrified heating, vehicles, and industry **Excludes:** • Electricity load from storage and electrolysers as loads very specific to system design • Flexibility consumption uses **Compares to:** • ~600 TWh per annum in 2050 in CCC's balanced pathway	Annual power requirement today/2050 = 1,850 TWh / **5,550 TWh** Maximum power required today/2050 = 517 GW / **735 GW** **Assumes:** highly electrified scenario with large rollout of electrified cooking appliances and refrigerators, cooling equipment and electric vehicles, and electrified industry **Excludes:** • Comprehensive rollout of electrified cooking (i.e. ~50% of households) • Comprehensive shift to electrified transport (~20% conventional)

Notes: Best scenarios we currently have available. Further modelling will be undertaken in the other archetype countries.
Source: NESO (2022) *Future Energy Scenarios 2022*; TERI (2024) *India's Electricity Transition Pathways to 2050: Scenarios and Insights;* BNEF (2024) *Installed generation and capacity*

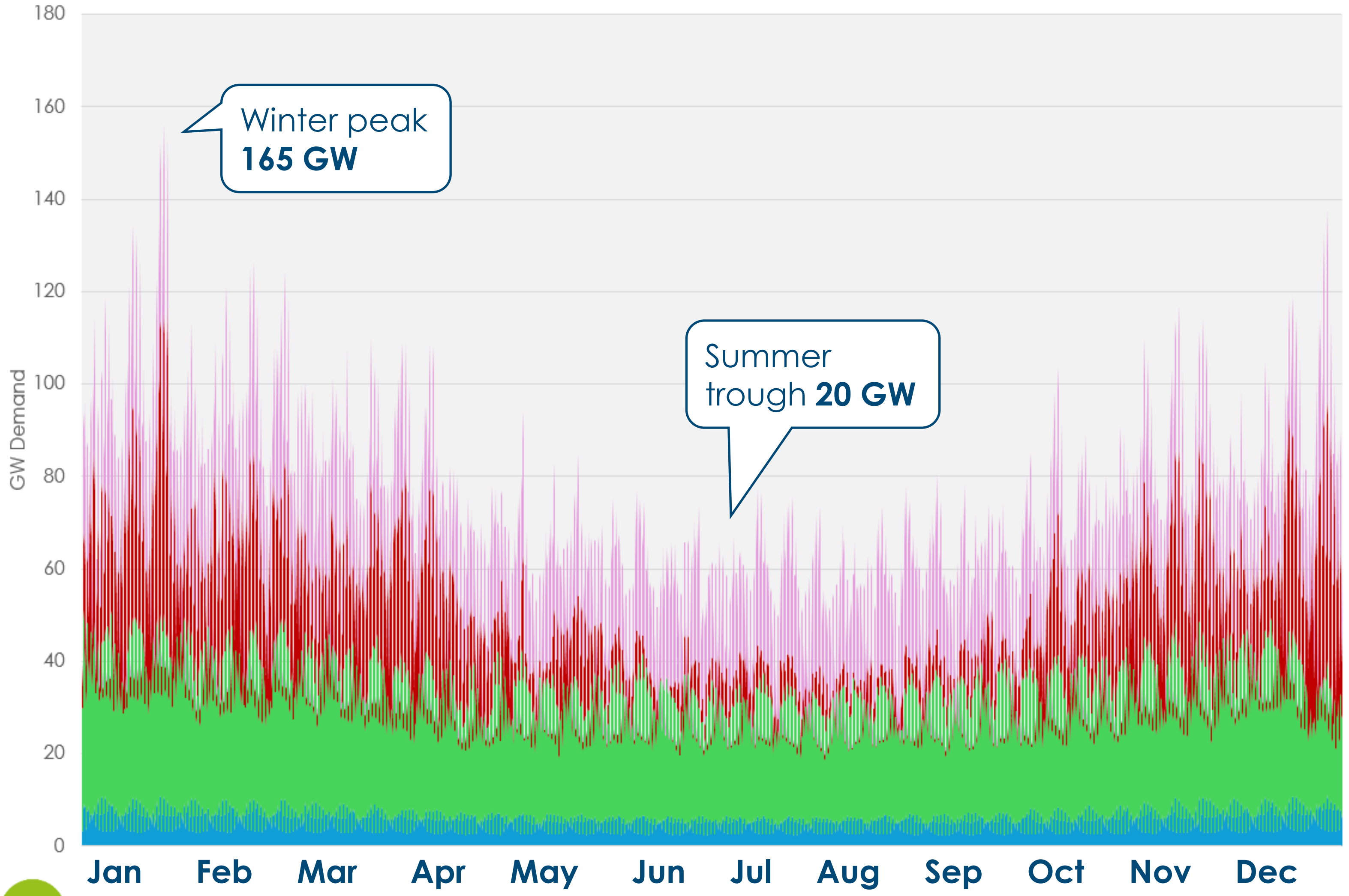
Snapshot of the Northern Latitude archetype (GB)

Annual view: seasonal demand fluctuation, driven by heating load

Archetype: Northern latitude (GB)

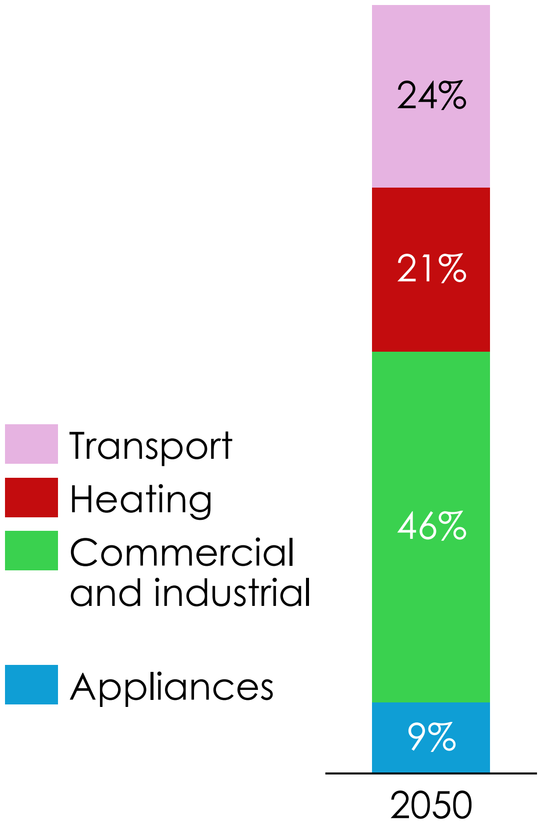
GB hourly demand load 2050, highly electrified scenario

GW demand for each hour of the year



Demand by use case

Proportion of total, %

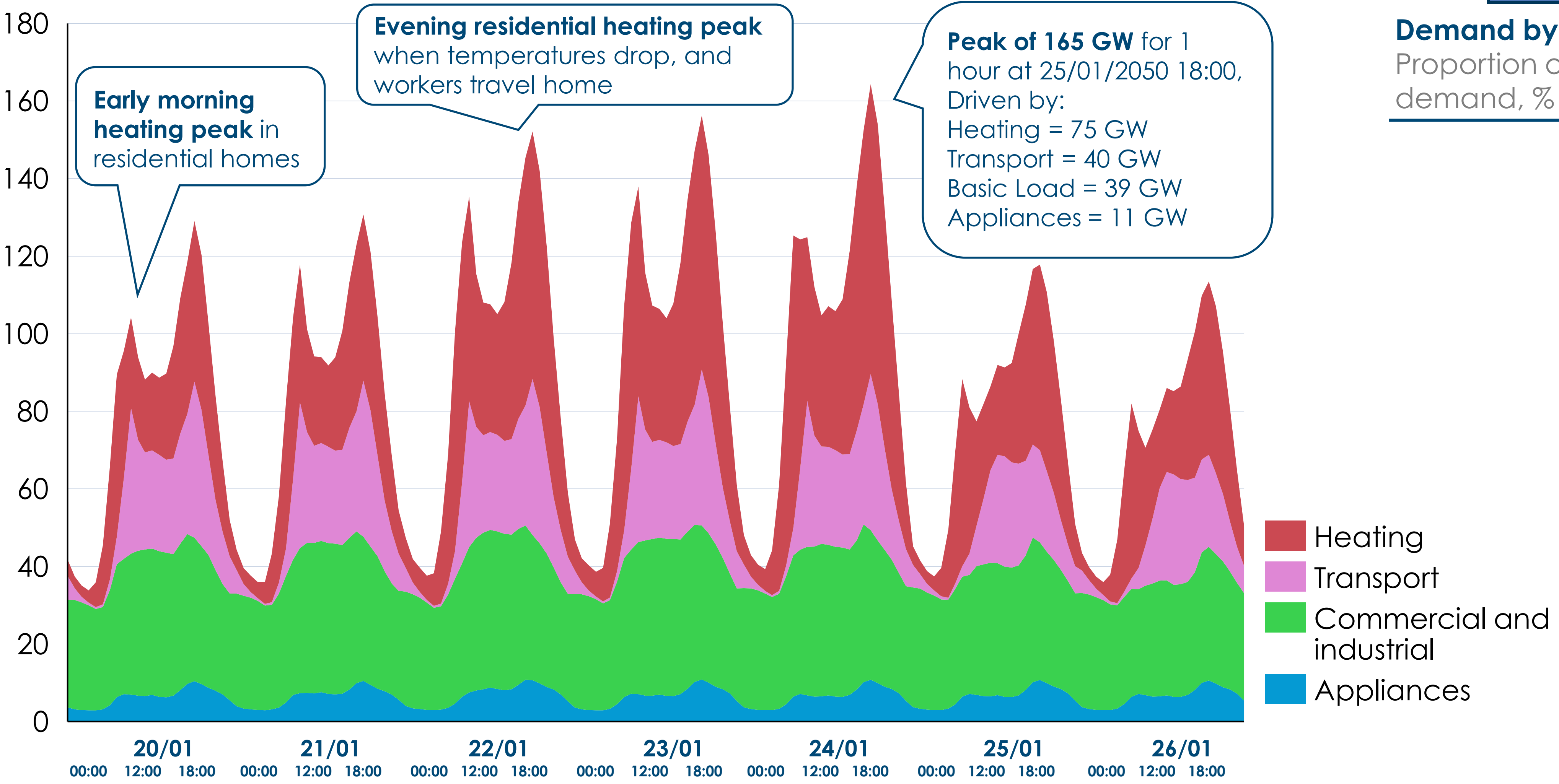


Source: Systemiq analysis for the ETC; NESO (2022) *Future Energy Scenarios 2022*

Weekly view: in cold months, daily fluctuations primarily driven by heating

Archetype: Northern latitude (GB)

GB hourly demand load January 20-26, 2050, highly electrified scenario
GW demand for each hour week

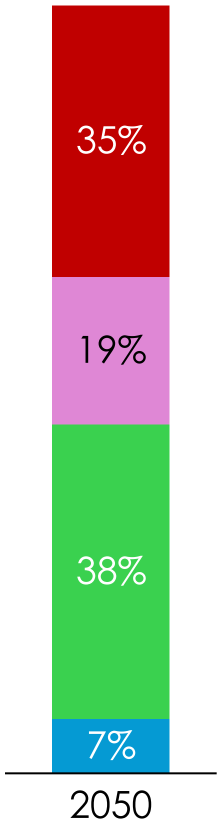


Early morning heating peak in residential homes

Evening residential heating peak when temperatures drop, and workers travel home

Peak of 165 GW for 1 hour at 25/01/2050 18:00,
Driven by:
Heating = 75 GW
Transport = 40 GW
Basic Load = 39 GW
Appliances = 11 GW

Demand by use case
Proportion of peak weekly demand, %



Notes: 20/01/2050 is the first day of the week.
Source: Systemiq analysis for the ETC; NESO (2022) *Future Energy Scenarios 2022*

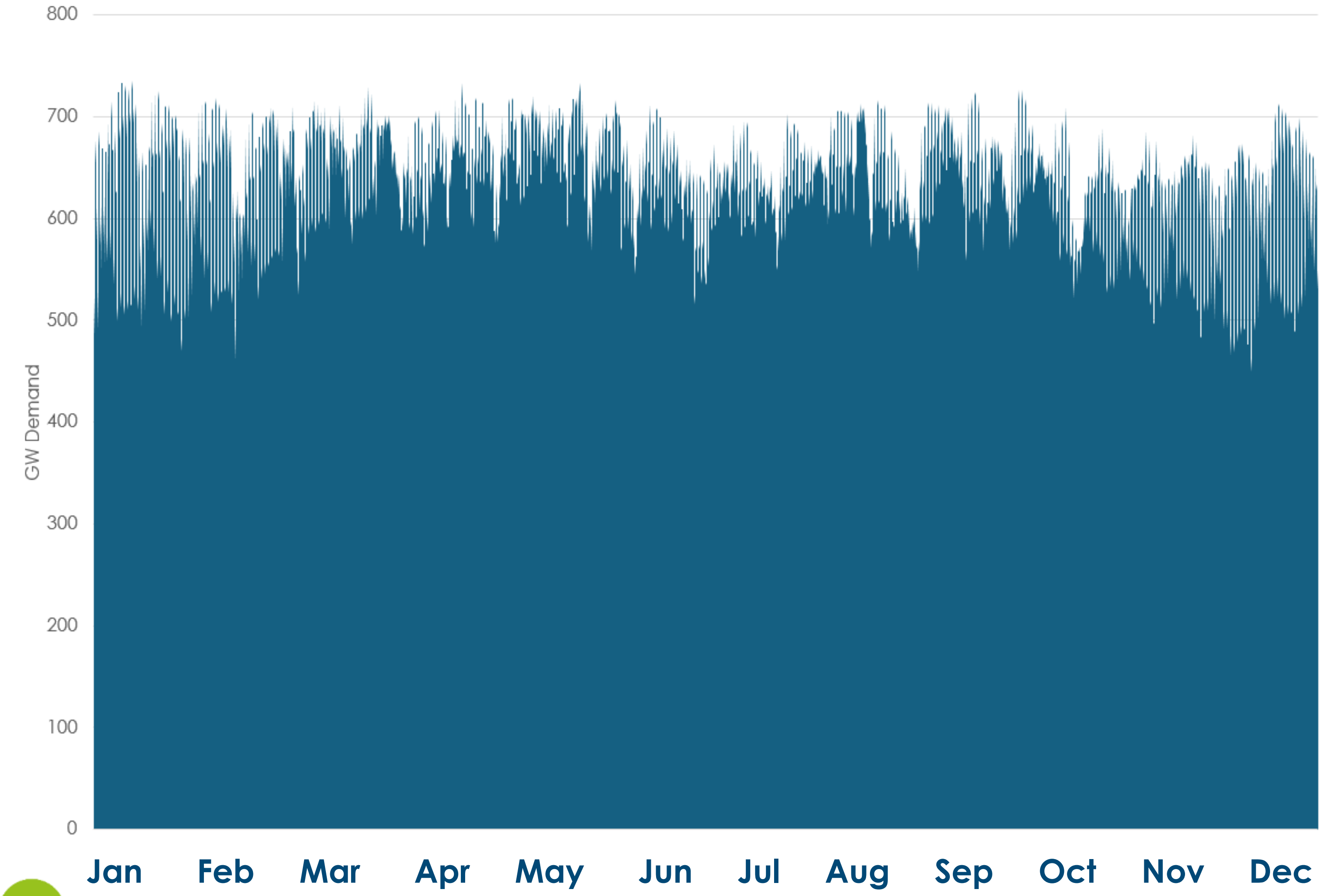
Snapshot of Tropical archetype (India)

Annual view: limited seasonal variation, driven by constant cooling need

Archetype: Low latitude/tropical (In)

Indian hourly demand load 2050, highly electrified scenario

GW demand for each hour of the year



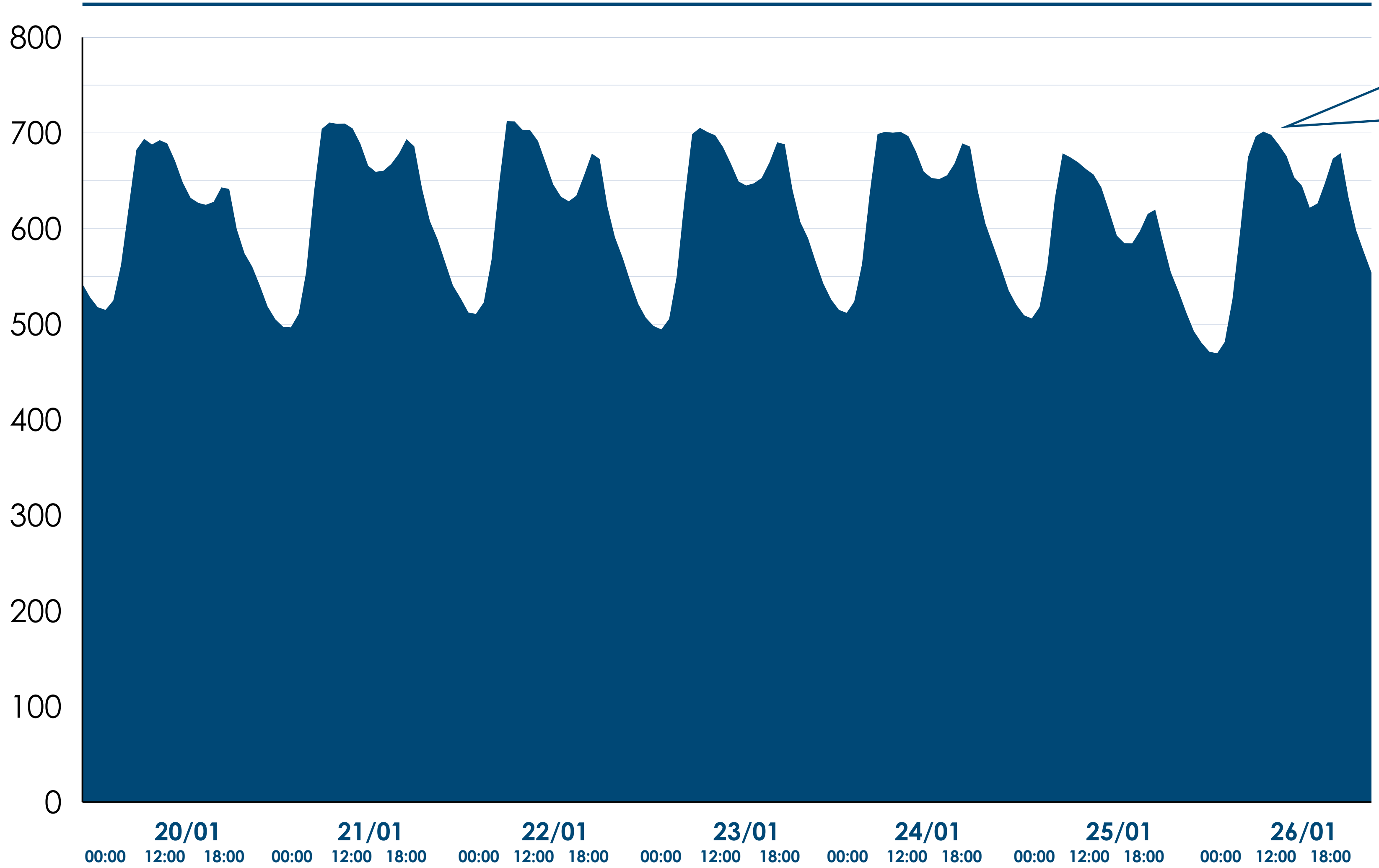
- **Constant cooling demand throughout the year**, which lessens in some areas in Winter months
- Given the sheer size of India (over 15* bigger than GB), **some geographical areas will experience both heating and cooling needs**

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

Weekly view: daily variation driven by midday and evening peaks

Archetype: Low latitude/tropical (In)

India hourly demand load February 20-26, 2050, highly electrified scenario
GW demand for each hour week



Midday peaks increase ~200GW from midnight troughs, as cooling requirement higher during the day

- Indian air conditioning units forecast to increase from **0.08 billion units in 2023** to **1.14 billion units in 2050**, a key driver of increased demand. (Cooling ~25% total 2050 demand)
- **Big uptake in EVs** which charge during the day to align with solar patterns

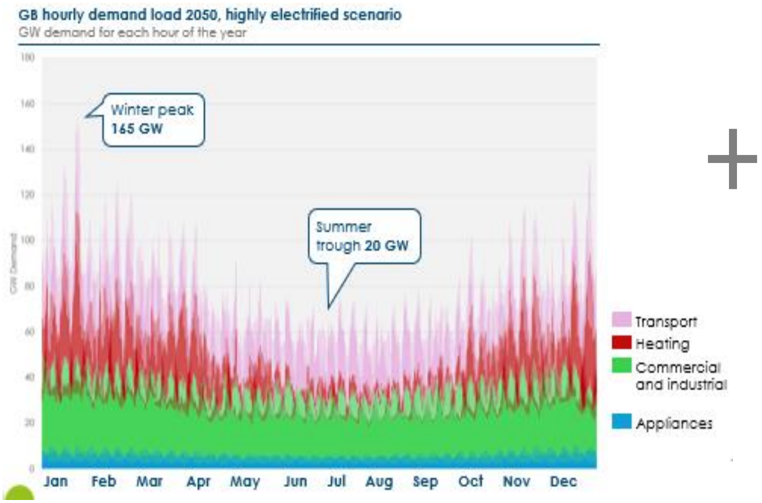
Notes: 20/02/2050 is the first day of the week. Source: Systemiq analysis for the ETC; TERI (2024) *India's Electricity Transition Pathways to 2050: Scenarios and Insights;* IEA (2024) *Growth in global air conditioner stock, 1990-2050*

Supply: bringing together 30 years of weather data for wind and solar

Approach to this analysis

For each archetype

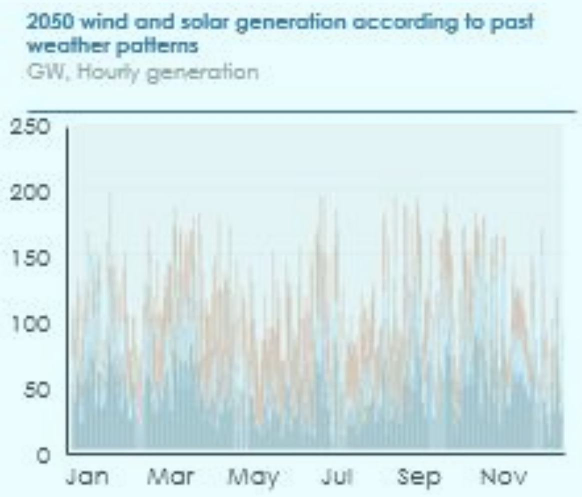
Demand


GB hourly demand load 2050, highly electrified scenario
GW demand for each hour of the year

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)

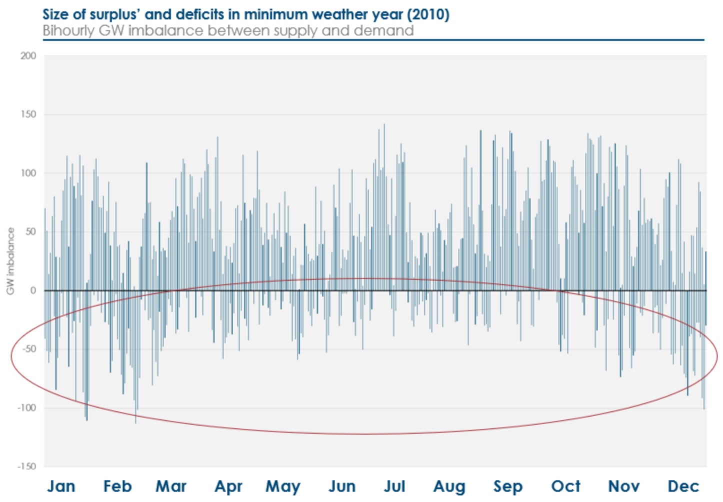
+

Supply (wind + solar)


2050 wind and solar generation according to past weather patterns
GW, Hourly generation

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


Size of surplus' and deficits in minimum weather year (2010)
Bihourly GW imbalance between supply and demand

Matching at bi-hourly level across demand and supply to assess periods of wind & solar generation excess/shortfall relative to demand

What would our supply curves ideally incorporate?

Key assumptions	Ideal inputs for modelling	Inputs for ETC modelling
Weather data		
Hourly weather data	• Global hourly weather data from the past 50 years	• Global bihourly weather data from the past 30 years (1994-2023)
Weather forward-looking modelling	• Weather modelling that considers impacts of climate change	• Not considered; variation captured only in historical data
2050 assumed renewable deployment levels		
Wind and solar installed capacities	• Committed national forecasts of 2050 renewable GW capacities for full power decarbonisation pathways	• Assumptions on 2050 renewable GW capacities mix based on current deployment rates and 2030/50 targets

Notes: Best scenarios we currently have available. Further modelling will be undertaken in the other archetype countries.
Source: ECMWH (2024) *ERA5 weather data;* UK Government (2023) 'Untapped potential' of commercial buildings could revolutionise UK solar power; TERI (2024) *India's Electricity Transition Pathways to 2050: Scenarios and Insights*

Weather data and supply side modelling: key steps

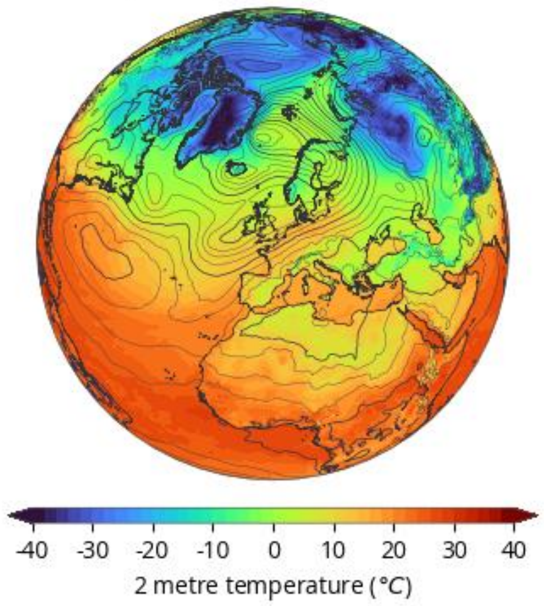
1. 2050 wind and solar deployment levels estimated taking best available forecasts and scaling up to 100% of generation consistent levels

2. Weather data downloaded ‘ERA 5’ wind speeds and solar irradiation for 1994-2023 for each country and bihourly timestep throughout the year (The data covers the Earth on a 31km grid)

3. Data processed using ‘Atlite’ open-source python model that converts weather data to energy systems data for renewable generation potential

4. TWh generation calculated via combining 2050 deployment levels with Atlite outputs to provide power levels that would have been generated in each bihourly timestep

5. Representative weather years selected which display the minimum, average, and maximum output across the 30-year period of realised weather data



ERA5 2 metre temperature and Mean sea level pressure
1 January 2023 at 00:00 UTC

Source: ECMWH (2024) *ERA5 weather data*

Renewable deployment assumptions build on government targets to install enough for a renewables dominated system in 2050

2050 installed capacities	**Archetype 1:** Northern latitude Case study: GB	**Archetype 2:** Low latitude/tropical Case study: India
Solar	**75 GW**	**2750 GW**
Onshore	**60 GW**	**650 GW**
Offshore	**100 GW**	**80 GW**
Why this deployment profile?	**Solar:** GB has a target of 70 GW by 2035 we take a conservative assumption of +5 GW by 2050. **Onshore**: GB target of 30 GW by 2030, optimistic assumption of +30 GW by 2050. **Offshore**: GB target of 60 GW by 2030, optimistic assumption of +40 GW by 2050.	**Solar:** TERI assume 1840 GW by 2050 as part of a combined generation mix. We add 910 GW to account for no nuclear, hydro and interconnection. **Onshore**: TERI assume 370 GW by 2050 (as above), we increased to 730 GW total and apportioned 650 GW to onshore. **Offshore**: (as above) we apportioned the remaining 80 GW to offshore wind.

Notes: Best scenarios we currently have available. Further modelling will be undertaken in the other archetype countries.
Source: UK Government (2023) ‘Untapped potential’ of commercial buildings could revolutionise UK solar power; TERI (2024) *India’s Electricity Transition Pathways to 2050: Scenarios and Insights – NFS no new coal or gas pathway*

Snapshot of the Northern Latitude archetype (GB)

Annual generation: If our 2050 capacity was installed over the past 30 years, relatively small variation in generation from each technology

Archetype: Northern latitude (GB)

	'Realised' capacity factor range		*Assumed GW, % land used*
Solar	**14% - 15%**	***X***	**75 GW, 0.3%**
Onshore	**39% - 52%**	***X***	**60 GW, 5.7%**
Offshore	**54% - 65%**	***X***	**100 GW, n/a**

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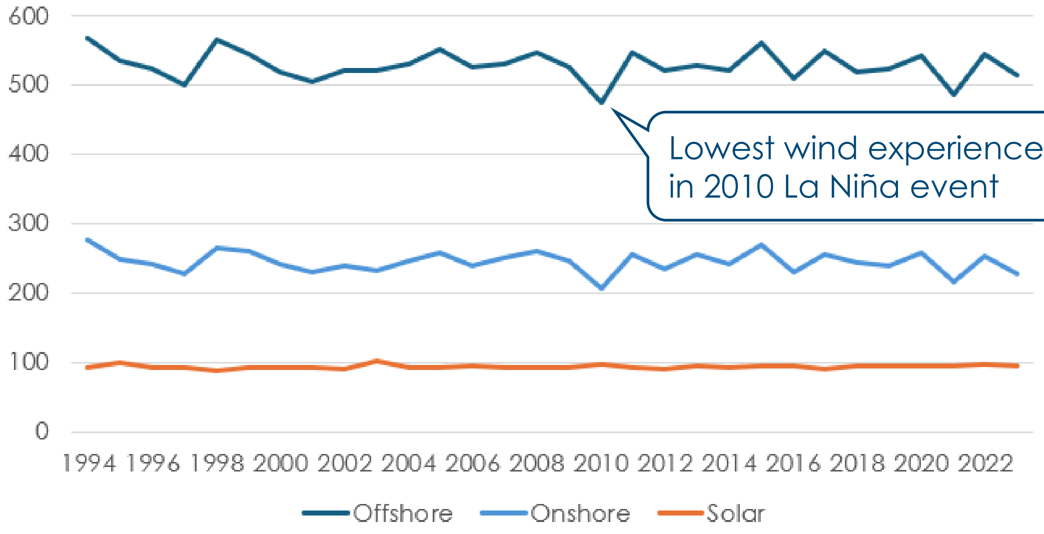
GB annual generation variation, 2050

TWh supplied by each technology



Lowest wind experienced in 2010 La Niña event

Little variation in solar

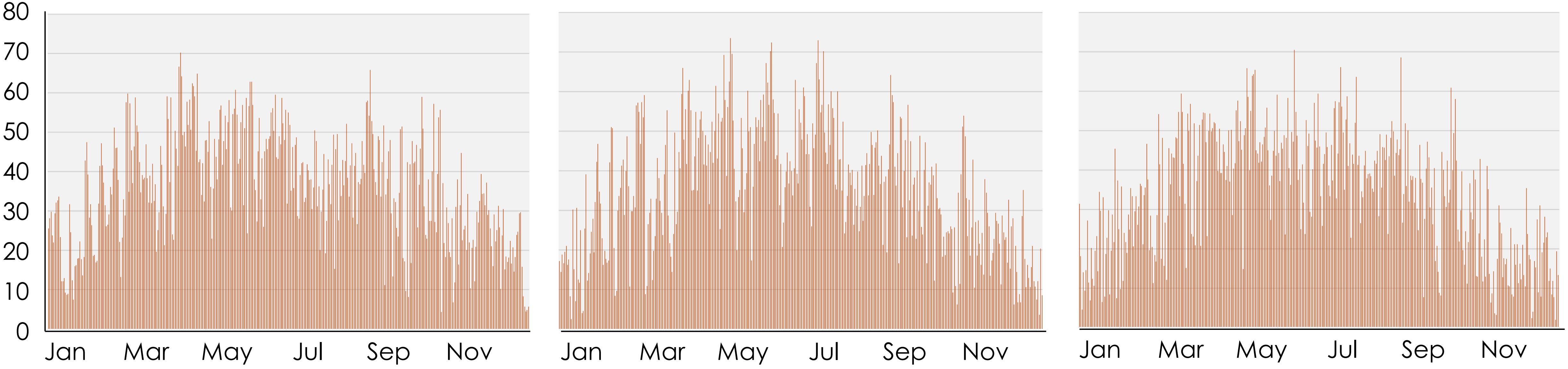
Annual TWh production	Lowest	Average	Highest
Solar	88	93	101
Onshore	207	245	276
Offshore	475	528	567

Notes: 'Realised' capacity factor is the percentage of energy generated in a given year compared to maximum possible generation given best weather conditions. Some floating turbines have realised theoretical capacity factors of 65% , with new onshore turbines ranging from 30-48%. Our values are for 2050 and could be seen to represent some efficiency improvements. Land use assumptions, solar = 142MW/km^2 wind = 5MW/km^2 (other uses are available for land with both wind and solar installed).

Solar output varies only a small extent across weather years

Archetype: Northern latitude (GB)

2050 solar generation according to past weather patterns
GW, Bihourly generation



Minimum – 1998

Average – 1996

Maximum – 2003

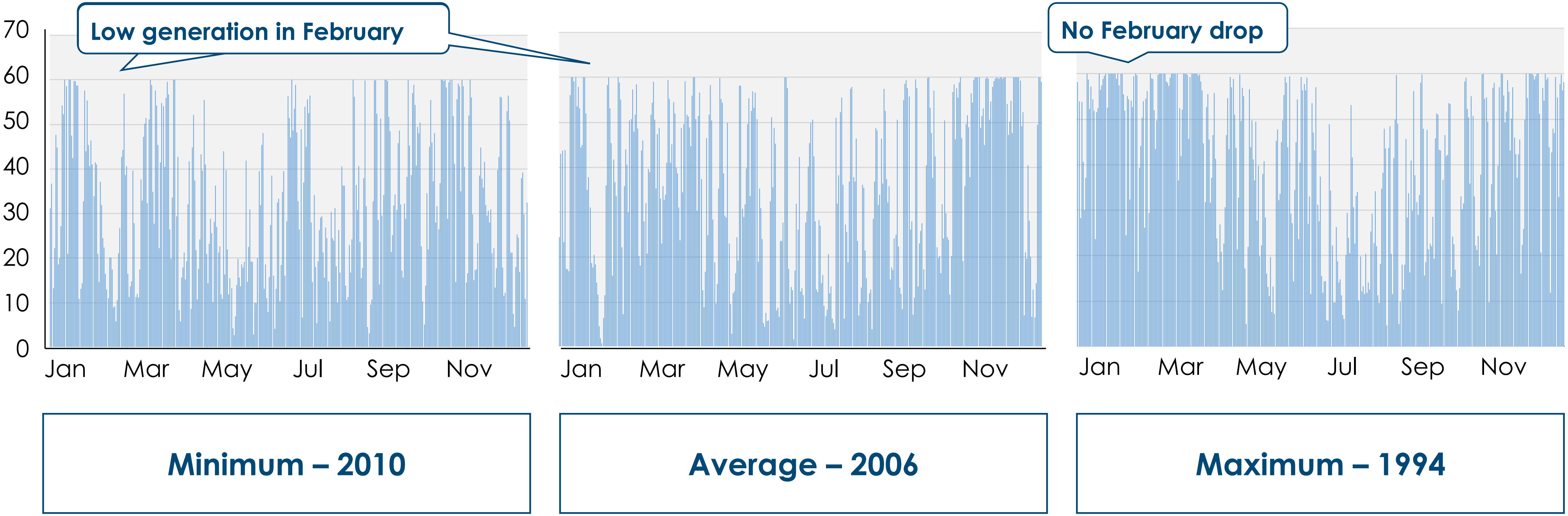
Key insight: Solar production in the UK does not vary much between years.

Notes: Weather data process using the 'Atlite' model. Different solar years are provided than the central scenarios as wind dominates overall GB supply.
Source: ECMWF (2024) ERA 5 modelling; Systemiq analysis for the ETC

Onshore wind output varies quite substantially across years

Archetype: Northern latitude (GB)

2050 onshore wind generation according to past weather patterns
GW, Bihourly generation



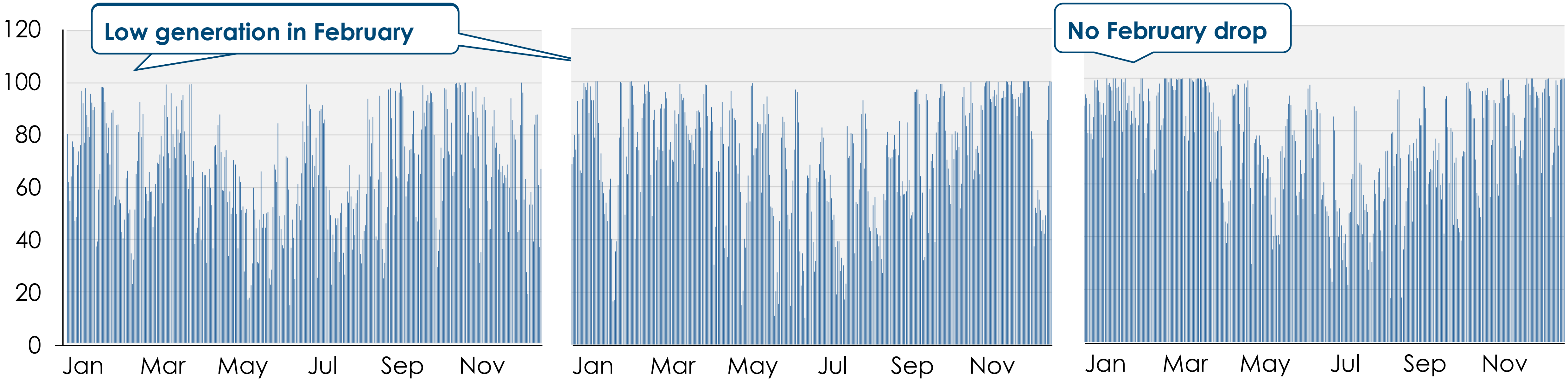
Key insight: Onshore wind production has a large drop in February in the minimum and average years; in the maximum year this February drop does not happen, but less output occurs over summer.

Notes: Weather data process using the 'Atlite' model, with weather generation years prioritised by the total amount of energy provided by both wind and solar in a given year.
Source: ECMWF (2024) ERA 5 modelling; Systemiq analysis for the ETC

Similar to onshore wind, offshore output varies quite substantially

Archetype: Northern latitude (GB)

2050 offshore wind generation according to past weather patterns
GW, Bihourly generation



Minimum – 2010

Average – 2006

Maximum – 1994

Key insight: Offshore wind production has a large drop in February in the minimum and average years; in the maximum year this February drop does not happen, but less output occurs over summer.

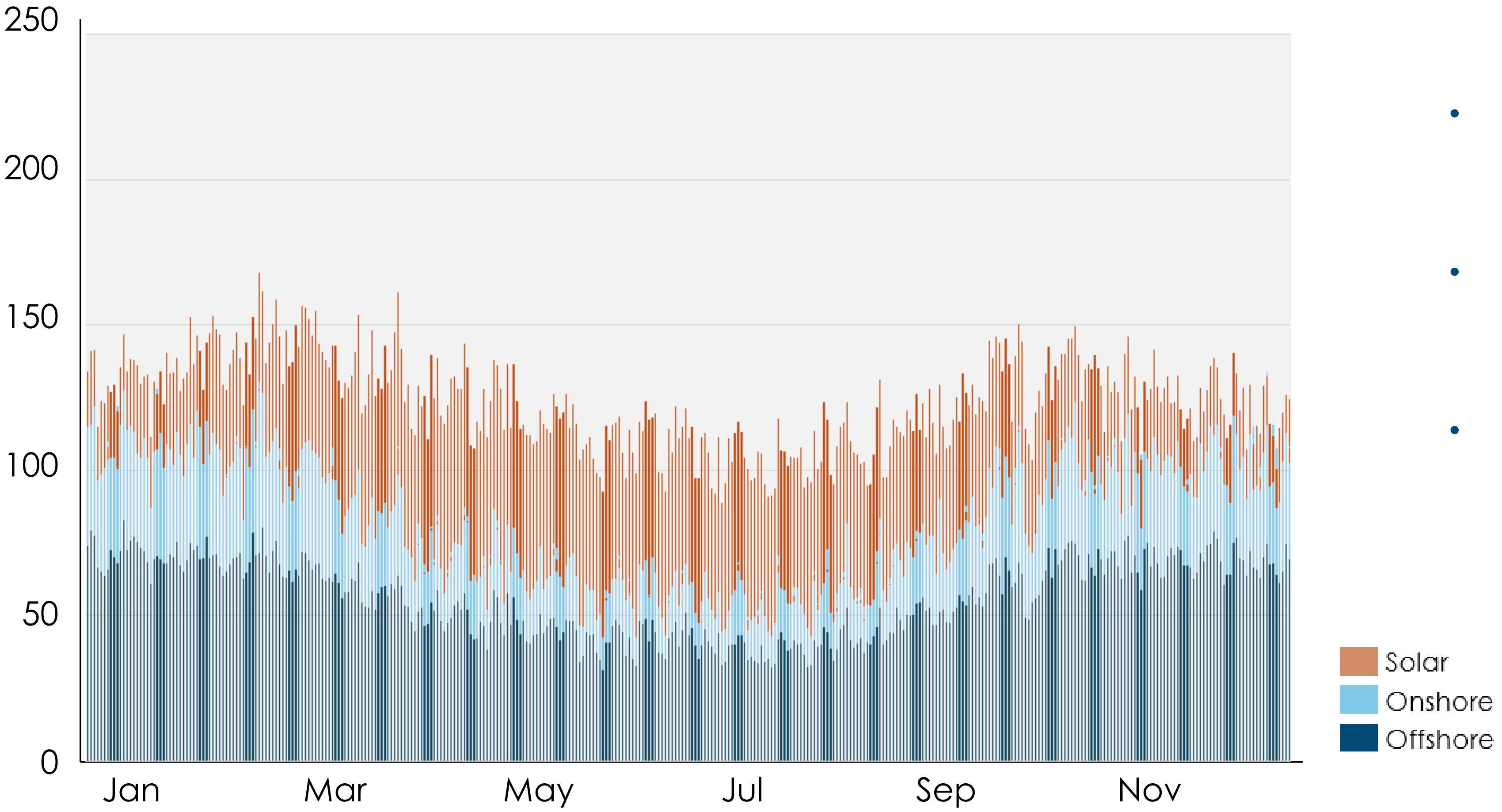
Notes: Weather data process using the ‘Atlite’ model, with weather generation years prioritised by the total amount of energy provided by both wind and solar in a given year.
Source: ECMWF (2024) ERA 5 modelling; Systemiq analysis for the ETC

Total generation median view removes ‘peakiness’, shows average patterns

Archetype: Northern latitude (GB)

GB 2050 median hourly generation across 1994-2023

GW, Bihourly generation



- **Offshore wind dominates UK supply,** which provides more energy outside of Summer
- **More solar available in Summer** which somewhat offsets lower wind production
- **‘Peakiness’ seen in-year weather data is removed**, so median analysis should not be used to assess balancing needs

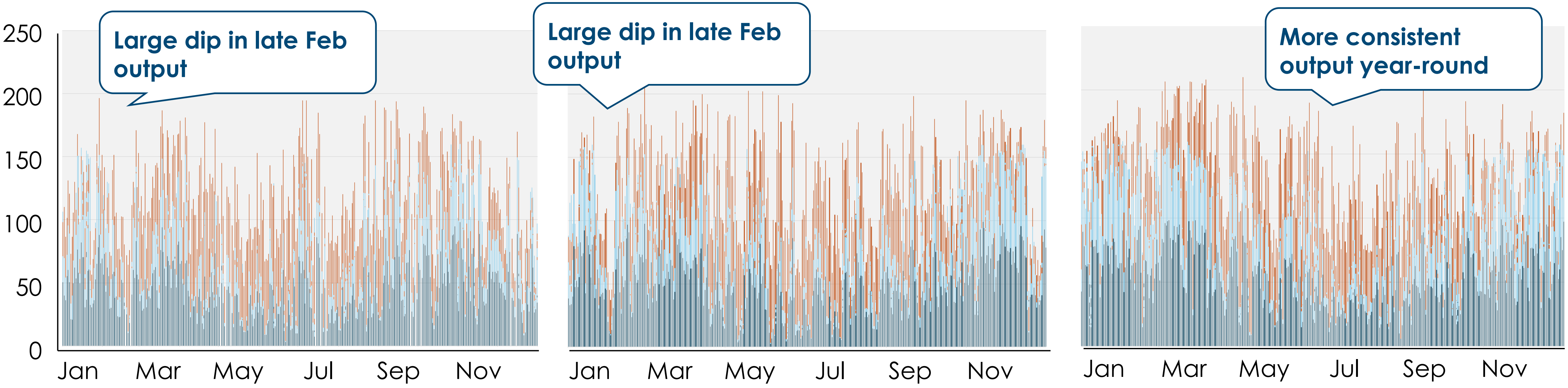
Source: ECMWF (2024) ERA 5 modelling; Systemiq analysis for the ETC

Total generation view shows large variation in the minimum year (2010) compared to the maximum (1994)

Archetype: Northern latitude (GB)

2050 wind and solar generation according to past weather patterns

GW, Bihourly generation



Large dip in late Feb output

Large dip in late Feb output

More consistent output year-round

Minimum – 2010

Average – 2006

Maximum – 1994

Key insight: Minimum scenario has the most gaps in generation, usually when wind speed have declined/stopped, balancing requirements should be calculated based on this scenario.

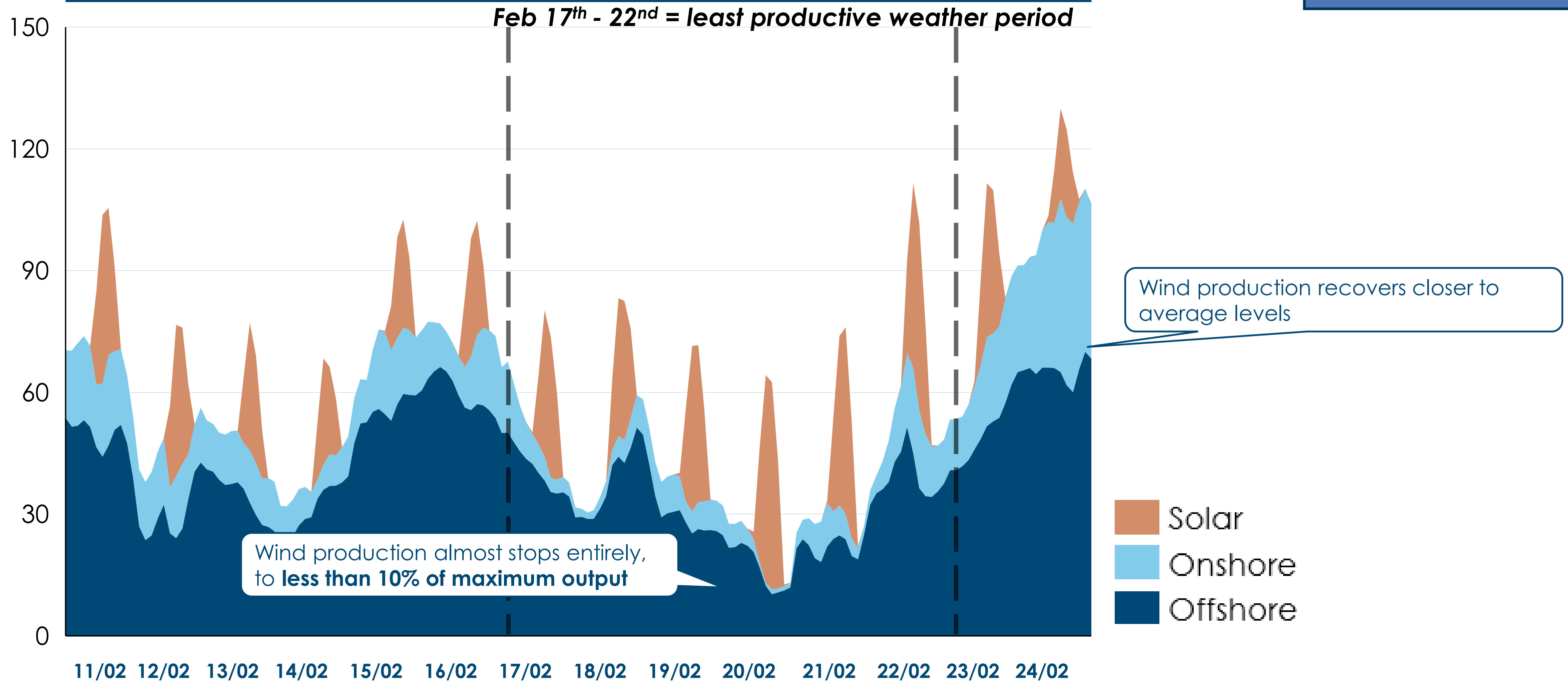
Notes: Weather data process using the ‘Atlite’ model. Different solar years are provided than the central scenarios as wind dominates overall GB supply.
Source: ECMWF (2024) ERA 5 modelling; Systemiq analysis for the ETC

There are some weeks in the minimum year where wind produces very little

Archetype: Northern latitude (GB)

GB 2050 generation in minimum weather year (2010), February 11-24

GW supply for every other hour over least productive period



Wind production almost stops entirely, to **less than 10% of maximum output**

Wind production recovers closer to average levels

Source: Systemiq analysis for the ETC;

Snapshot of Tropical archetype (India)

Annual generation: If our 2050 capacity was installed over the past 30 years, relatively small variation in generation from each technology

Archetype: Low latitude/tropical (In)

	'Realised' capacity factor range		*Assumed GW, % land used*
Solar	**24% - 25%**	***X***	**2750 GW, 0.6%**
Onshore	**23% - 29%**	***X***	**650 GW, 4.0%**
Offshore	**28% - 33%**	***X***	**80 GW, n/a**

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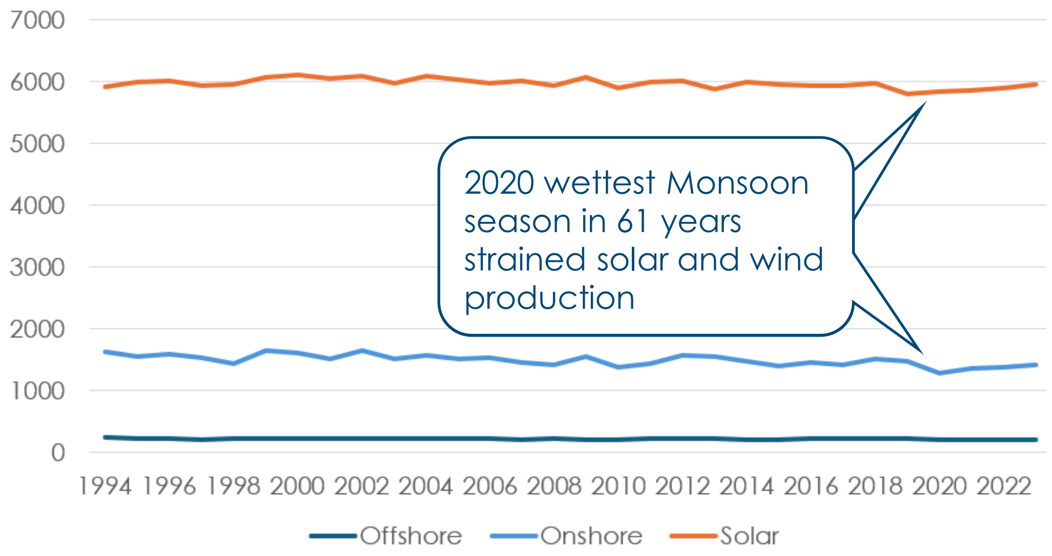
Much **higher solar capacity factors** and **lower wind capacity factors** than GB

India annual generation variation, 2050

TWh supplied by each technology



2020 wettest Monsoon season in 61 years strained solar and wind production

Annual TWh production	Lowest	Average	Highest
Solar	5800	5980	6100
Onshore	1280	1500	1650
Offshore	200	220	250

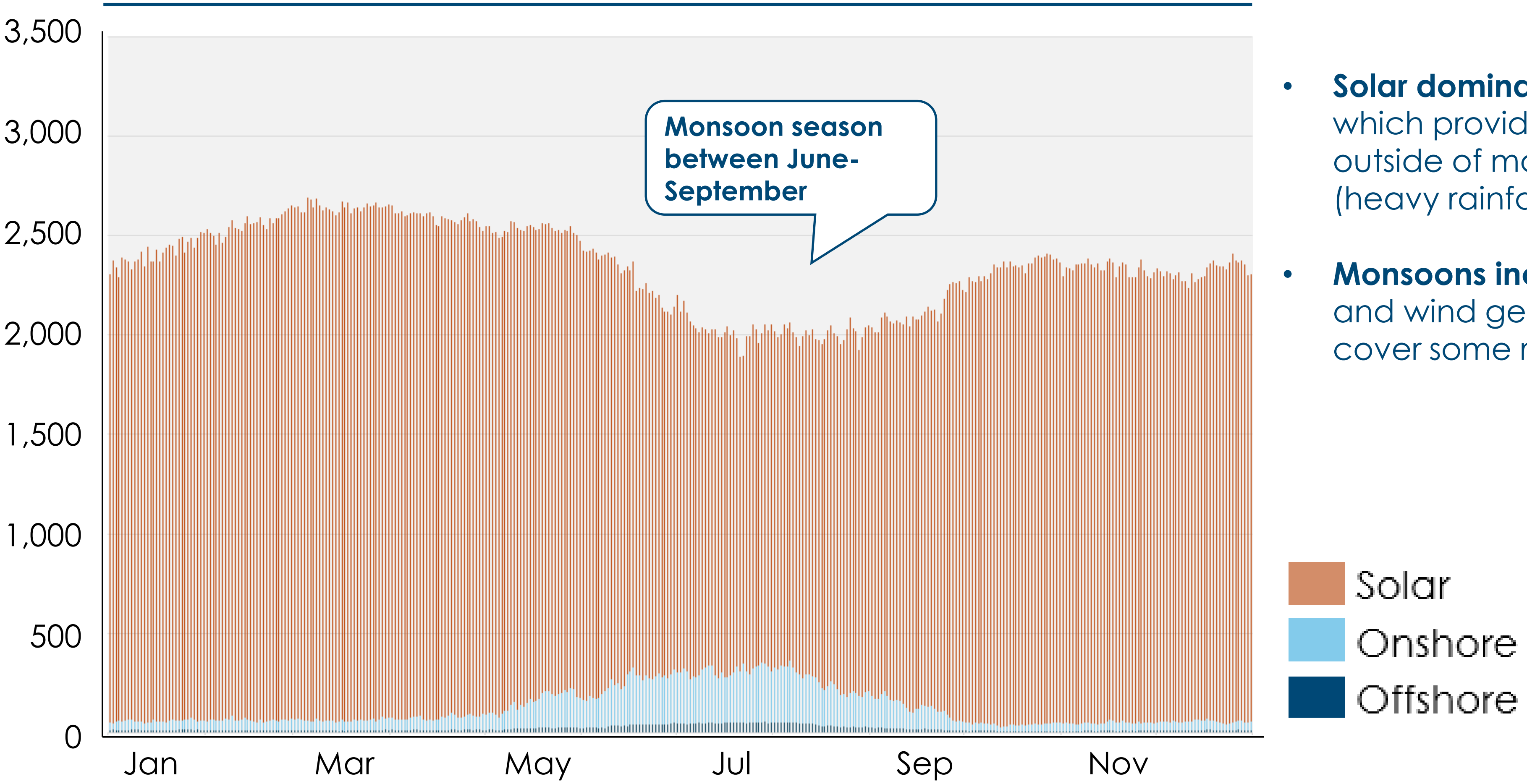
Notes: 'Realised' capacity factor is the percentage of energy generated in a given year compared to maximum possible generation given best weather conditions. Some floating turbines have realised theoretical capacity factors of 65% , with new onshore turbines ranging from 30-48%. Our values are for 2050 and could be seen to represent some efficiency improvements. Land use assumptions, solar = 142MW/km^2 wind = 5MW/km^2 (other uses are available for land with both wind and solar installed).

Indian median hourly generation shows consistent solar except for Monsoon season, when wind picks up

Archetype: Low latitude/tropical (In)

Indian 2050 median hourly generation across 1994-2023

GW, Hourly generation



Monsoon season between June-September

- **Solar dominates Indian supply,** which provides consistently outside of monsoon season (heavy rainfall and cloud cover)
- **Monsoons increase wind speed** and wind generation picks up to cover some reduction in solar

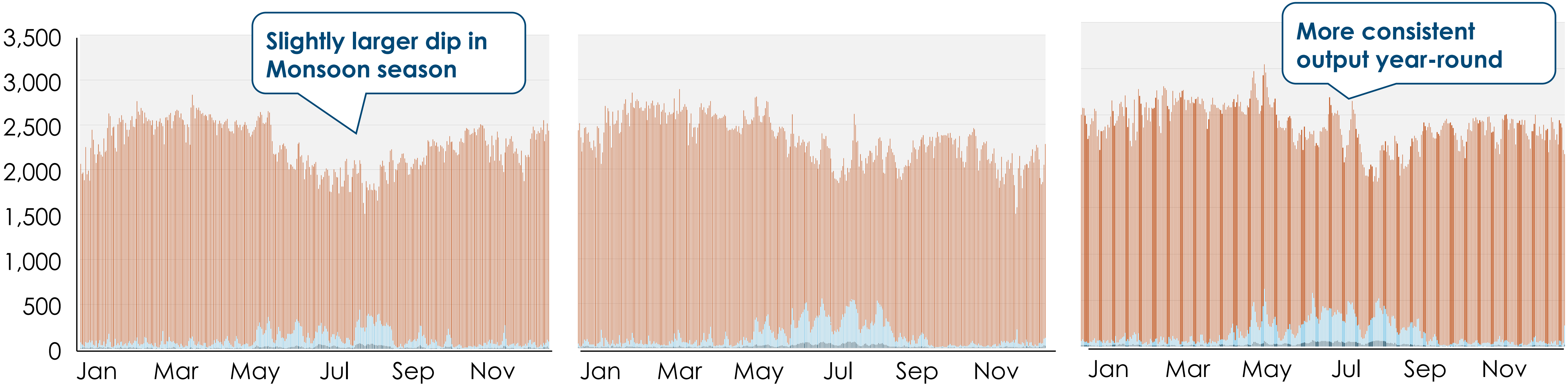
Source: ECMWF (2024) ERA 5 modelling; Systemiq analysis for the ETC

More consistent solar generation means smaller differential across years

Archetype: Low latitude/tropical (In)

2050 wind and solar generation according to past weather patterns

GW, Hourly generation



Slightly larger dip in Monsoon season

More consistent output year-round

Minimum – 2020

Average – 1997

Maximum – 2002

Key insight: Less variation between weather years than archetype 1 suggests less of an unpredictable balancing challenge.

Notes: Weather data process using the 'Atlite' model. Different solar years are provided than the central scenarios as wind dominates overall GB supply.
Source: ECMWF (2024) ERA 5 modelling; Systemiq analysis for the ETC

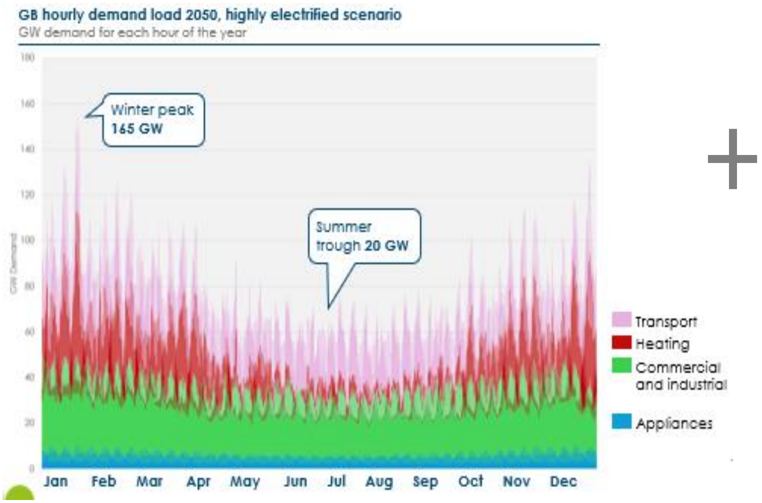
Pause for discussion ~5 minutes

Balancing challenge: bringing it all together

Approach to this analysis

For each archetype

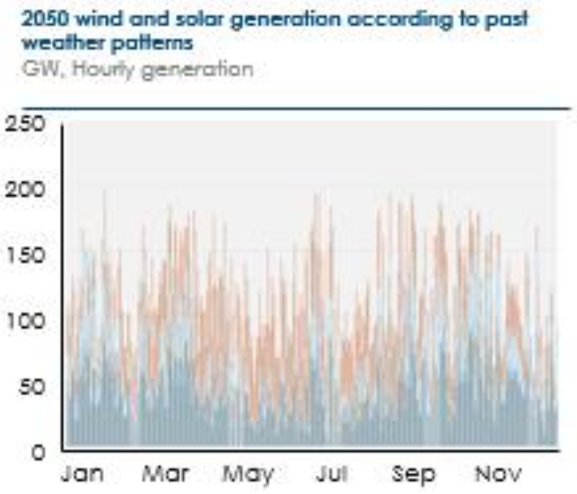
Demand



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)

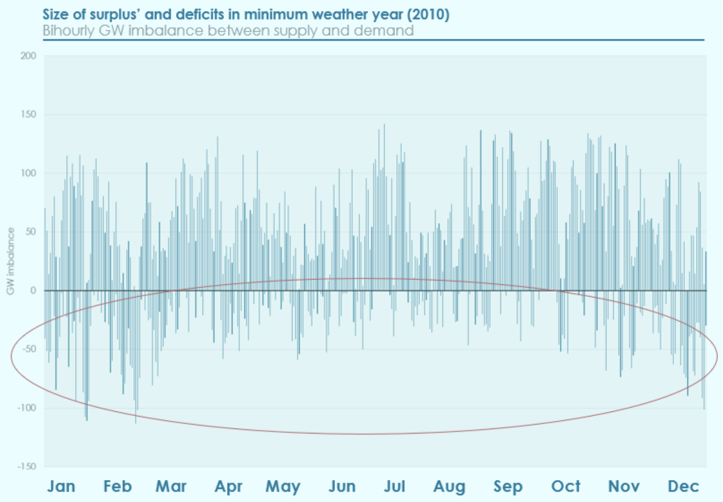
+

Supply (wind + solar)



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

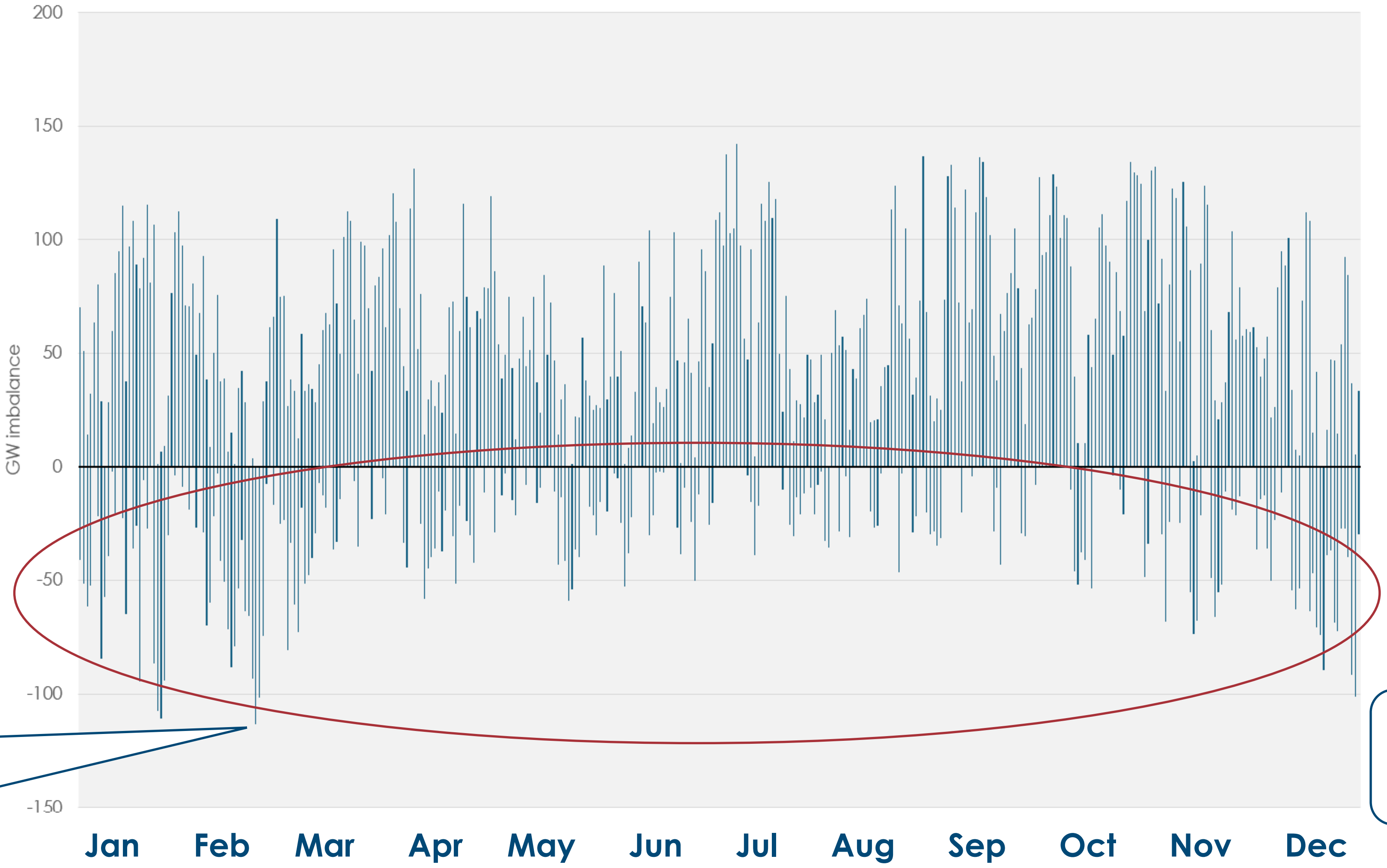
Snapshot of the Northern Latitude archetype (GB)

Minimum weather year: deficits indicate balancing needs

Archetype: Northern latitude (GB)

Minimum

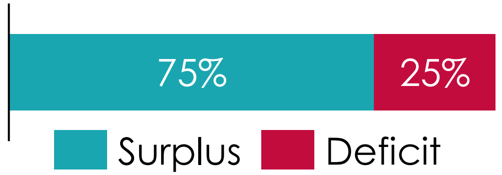
Size of surplus' and deficits in minimum weather year (2010)
Bihourly GW imbalance between supply and demand



At 0 Supply = Demand

Implies infrequent peaks of 113 GW

Percent of hours in surplus/deficit



Supply exceeds demand
Surplus = ***260 TWh***

Demand exceeds supply
Balancing required:
Max = ***113 GW***
Average = ***23 GW***

More frequent storage capacity required is closer to 23 GW

Source: Systemiq analysis for the ETC

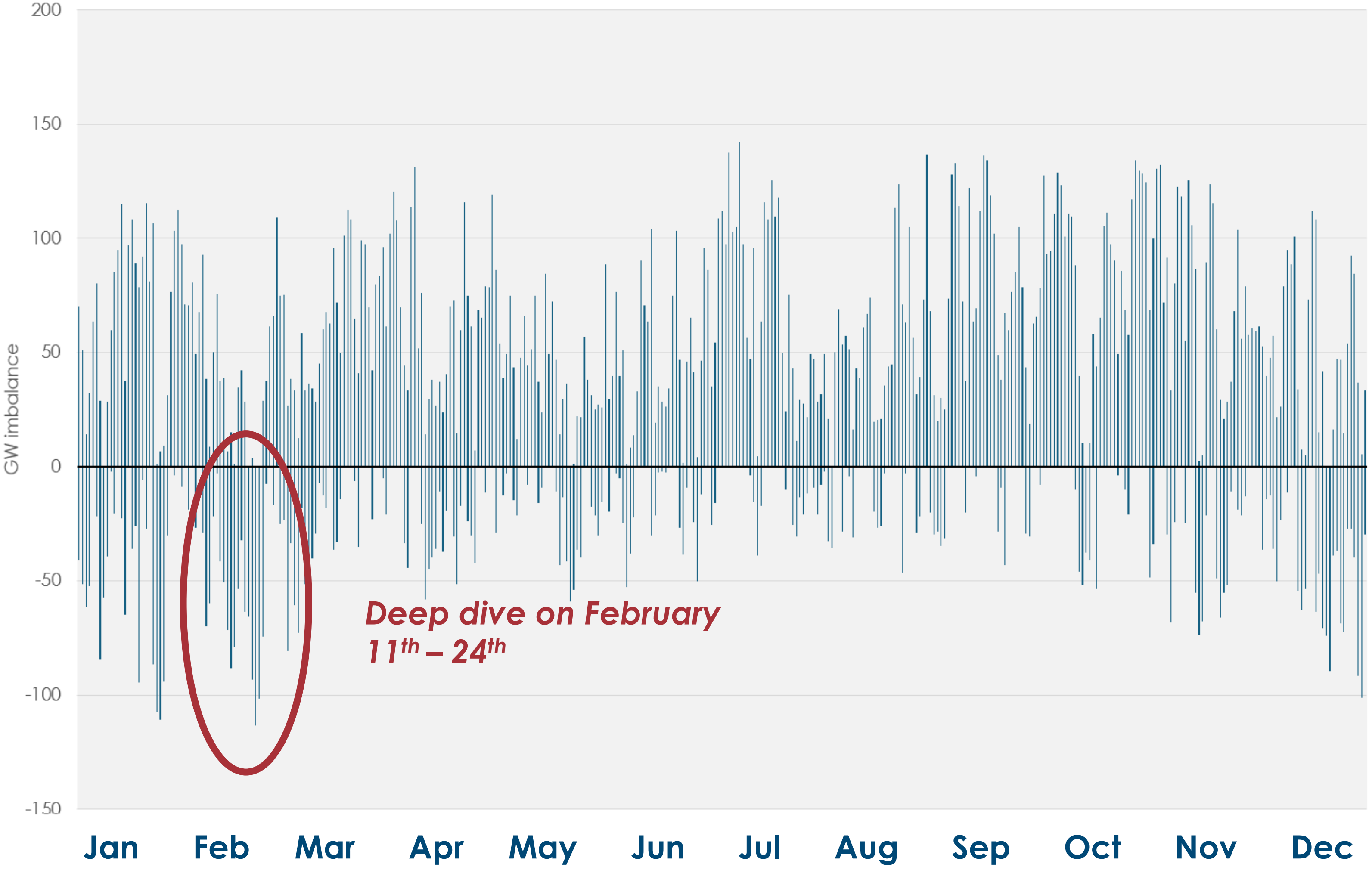
The longest period of deficit power is mid-February, which is worth exploring in more detail…

Archetype: Northern latitude (GB)

Minimum

Size of surplus' and deficits in minimum weather year (2010)

Bihourly GW imbalance between supply and demand



Deep dive on February 11th – 24th

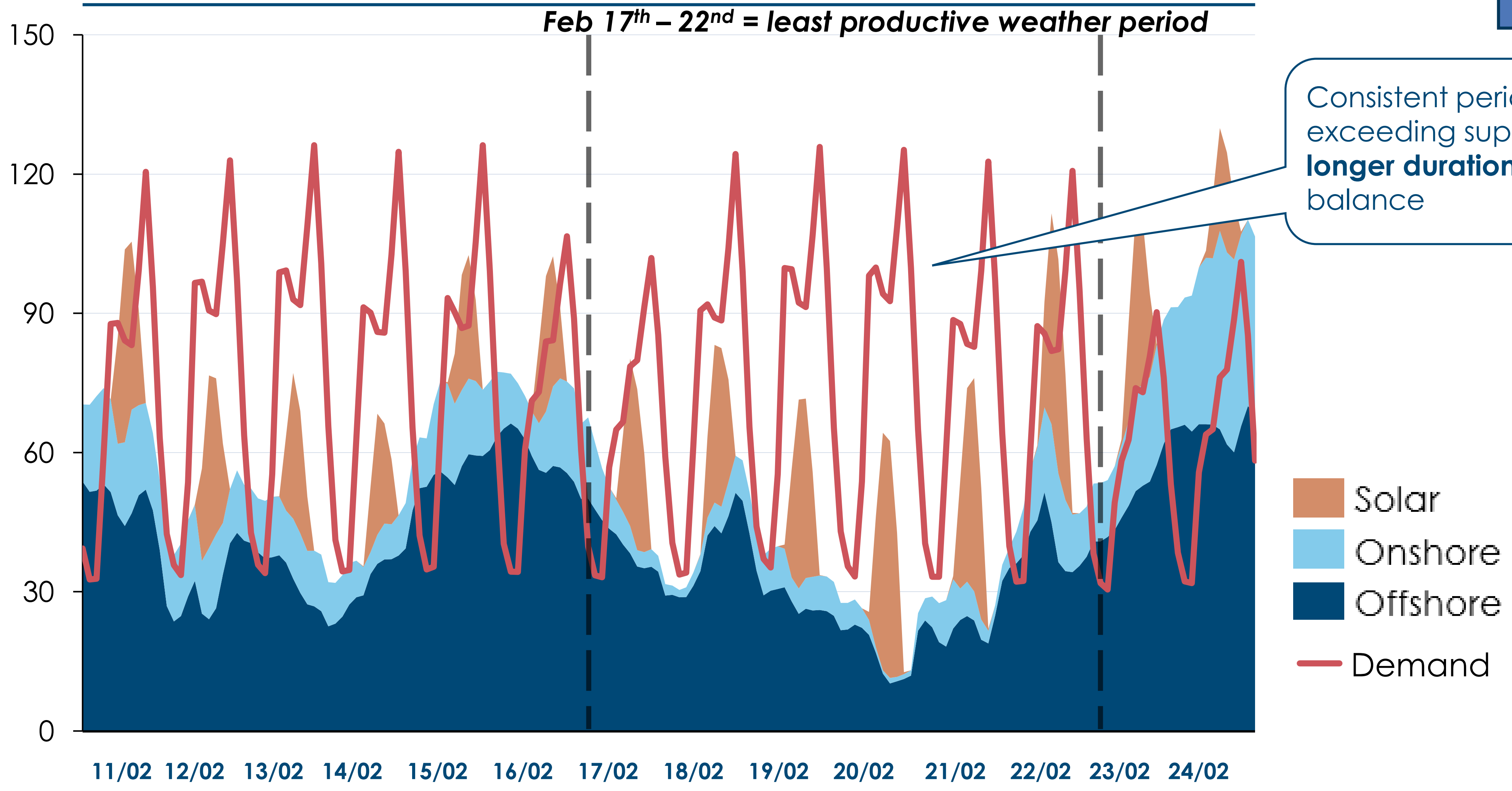
Source: Systemiq analysis for the ETC

… demand follows a broadly consistent daily pattern driven by evening heating, while sustained drops in wind require balancing

Archetype: Northern latitude (GB)

GB 2050 generation and demand in minimum weather year (2010), February 11-24

GW demand for each hour over least productive period



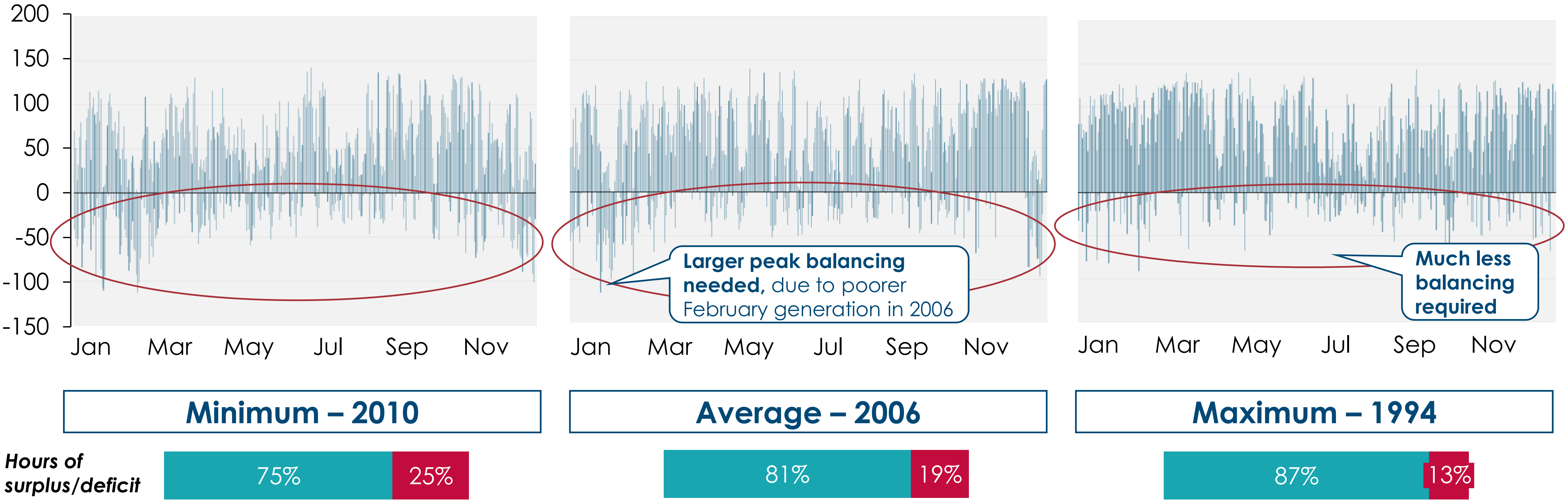
Consistent periods of demand exceeding supply will require **longer durations of storage** to balance

Source: Systemiq analysis for the ETC

Significant variation of balancing requirements across years

Archetype: Northern latitude (GB)

Size of surplus' and deficits in each key weather year
Bihourly GW imbalance between supply and demand



Larger peak balancing needed, due to poorer February generation in 2006

Much less balancing required

Minimum – 2010

Average – 2006

Maximum – 1994

Key insight: Many more TWh of balancing required in minimum year. System should be sized to accommodate this.

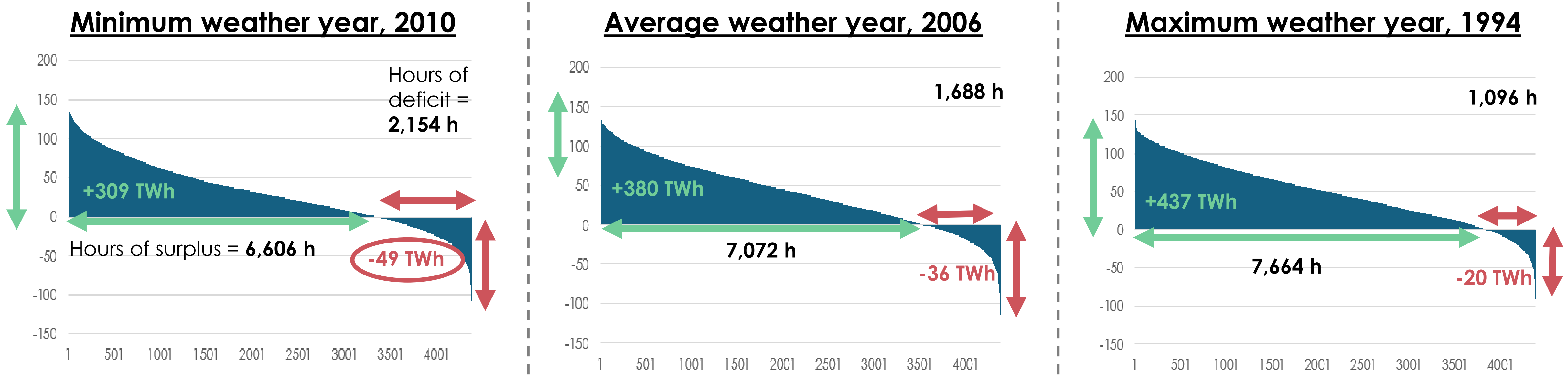
Notes: Weather data process using the 'Atlite' model, with weather generation years prioritised by the total amount of energy provided by both wind and solar in a given year.
Source: ECMWF (2024) ERA 5 modelling; Systemiq analysis for the ETC

Load duration curves show GB requires at least 115GW of peak storage, with a total of ~50 TWh of stored energy to be used throughout the year

Archetype: Northern latitude (GB)

Load duration curves, 100% wind and solar supply across weather years, 2050 demand

GW surplus and deficit, 2-hourly generation blocks



Minimum weather year, 2010

Average weather year, 2006

Maximum weather year, 1994

Max surplus = **142 GW**	Max deficit = **113 GW**	Max surplus = **141 GW**	Max deficit = **115 GW**	Max surplus = **144 GW**	Max deficit = **91 GW**

Notes: Average weather year has a higher maximum deficit/storage need due to having one 2-hour block where there was a larger difference between supply and demand than the minimum weather scenario. The minimum weather scenario has the highest cumulative amount of deficit.

Different methodologies that can help us understand the total storage needs by duration

Simplified method → Understanding the size of the balancing challenge by summing consecutive hours of deficit

Preferred method → Understanding the size of the balancing challenge by accounting for storage charging and discharging

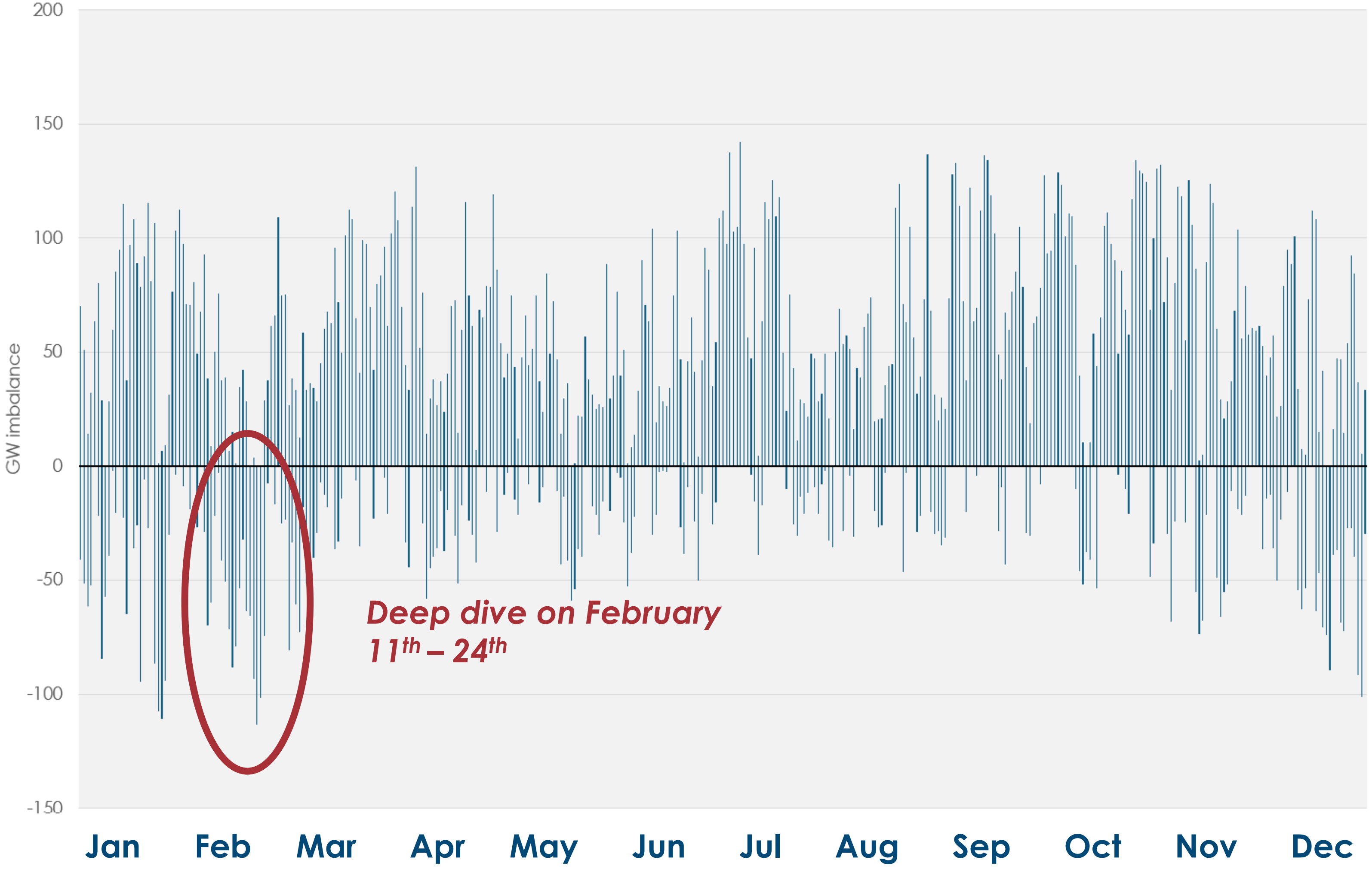
Reminder: longest period of deficit is February (high demand, low supply)

Archetype: Northern latitude (GB)

Minimum

Size of surplus' and deficits in minimum weather year (2010)

Bihourly GW imbalance between supply and demand



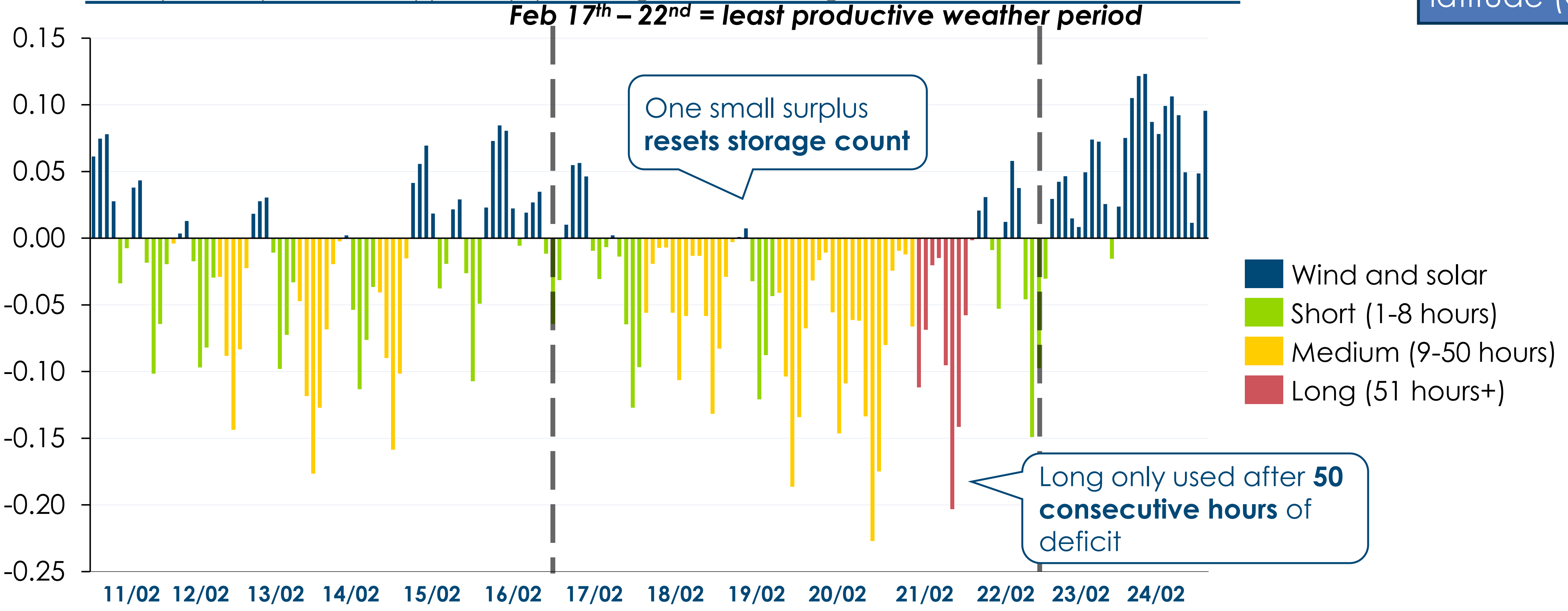
Deep dive on February 11th – 24th

Simplified method: looking at the period of largest continuous deficit, implies that short and medium storage can be utilised without recharging

Archetype: Northern latitude (GB)

Simplified method: Balancing requirement met by renewables and types of storage

Bihourly TWh surplus/deficit supplied by specified generation/storage



Feb 17th – 22nd = least productive weather period

One small surplus **resets storage count**

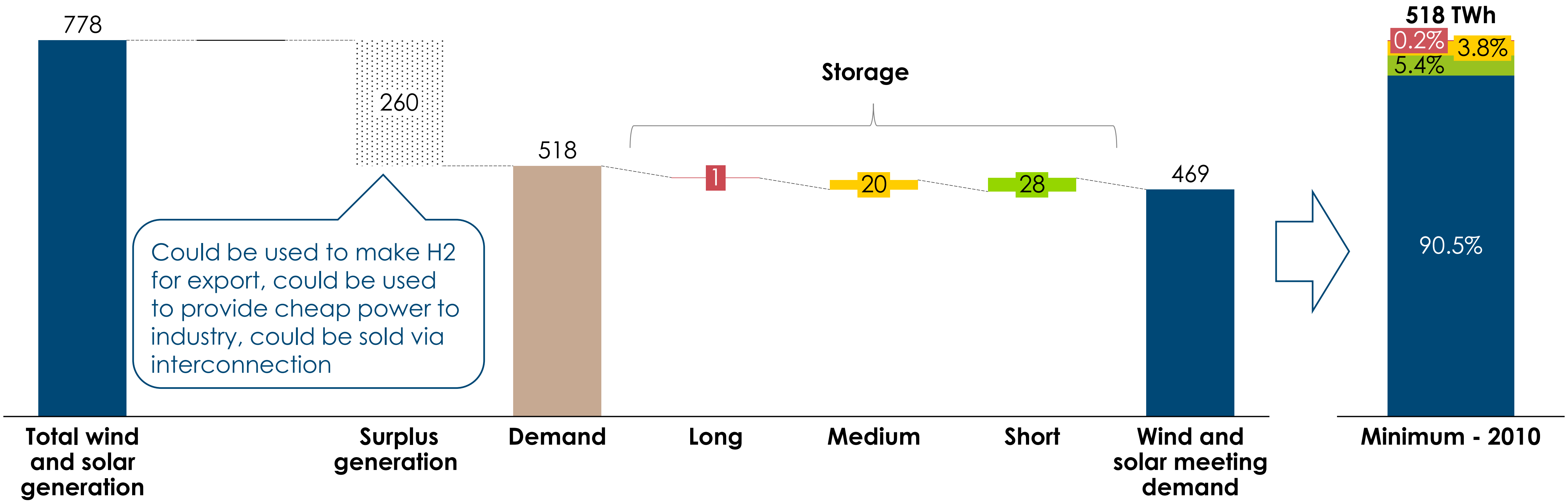
Long only used after **50 consecutive hours** of deficit

Therefore a new method is needed which takes account of durations of storage, and their efficiencies, draining in negative periods and “filling up” in positive periods, with long storage being used when short and medium storages are exhausted.

To size the balancing challenge, we break down how demand can be met

Archetype: Northern latitude (GB)

Preferred method: total demand supplied by each tech (Min)
TWh



Could be used to make H2 for export, could be used to provide cheap power to industry, could be sold via interconnection

Notes: each of the ‘storage’ categories captures the TWh value that contributes to the overall demand figure.

Simplified method: sizing balancing challenge by summing consecutive hours of deficit leads to overestimation of short and medium storage

Archetype: Northern latitude (GB)

Methodology

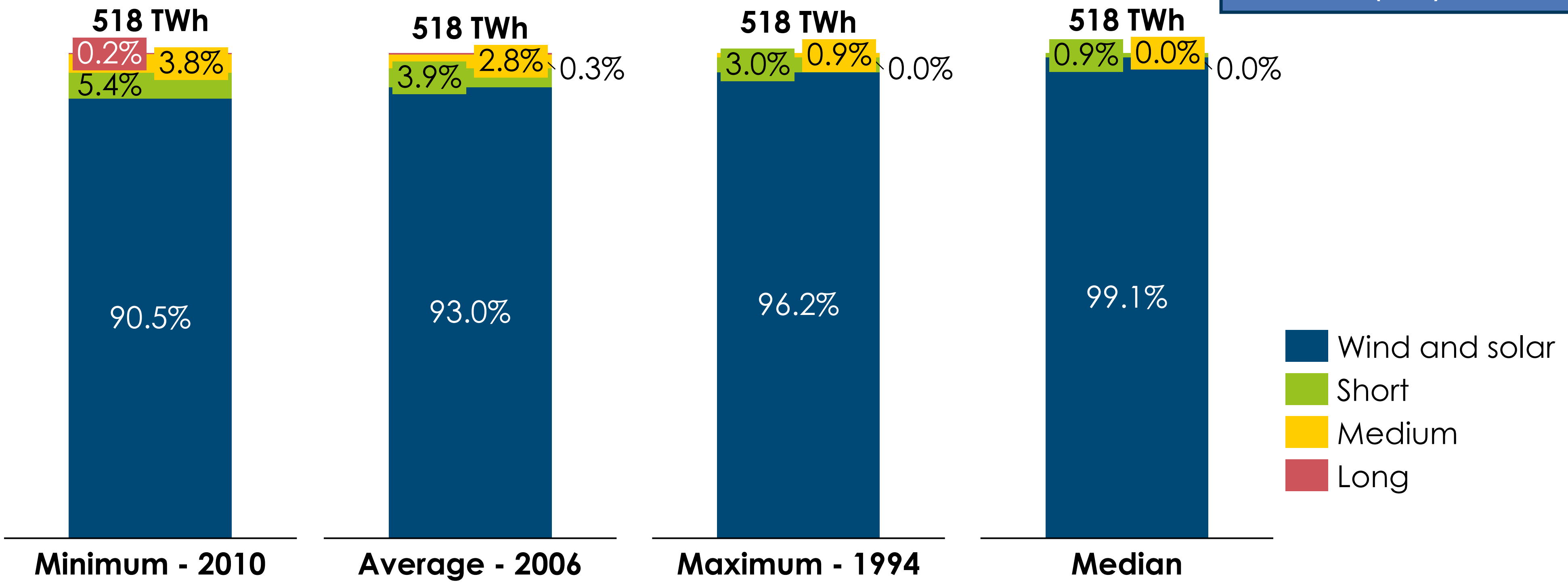
Durations of consecutive deficit used as proxy for type of storage active:

- **0 = no storage required, all power from wind and solar**
- **1-8 = Short**
- **9-50 = Medium**
- **51+ = Long**

Count starts in April to show full Winter effect

Balancing variability across UK weather scenarios in a 100% wind and solar system

TWh supplied by specified generation/storage (to meet demand only)



Simple TWh Surplus *[Supply – Demand]*	**260**	**343**	**417**	**341**

Current methodology does not account for:

- Storage charging and discharging
- Storage efficiencies
- Magnitude of storage types able to be installed

Preferred method needs to assign storage sizes and efficiencies

A more accurate model should build in:

- **Storage capacities –** to assign short, medium and long duration storage capacities
- **Storage efficiencies –** to assign efficiencies to each type of storage
- **Accounting for storage charge –** When there are periods of surplus, short and medium storage should use the excess electricity to fill up their storage capacities accounting for the efficiency penalty
- **Storage prioritisation – "cascading"** – the most efficient forms of storage should be used and fill up first, i.e. if short storage has 90% efficiency and medium storage has 60%, short storage should be cycled more

Note: In reality, medium and long storage may be utilised in some cases before short storage if they are close to full capacity, have other market arrangements, or are in a geographically more useful area. This model will assume short storage is used first, then medium storage, and long storage is the key variable to solve for.

Renewable deployment assumptions build on government targets to install enough for a renewables dominated system in 2050

2050 installed capacities	**Archetype 1:** Northern latitude Case study: GB	**Archetype 2:** Low latitude/tropical Case study: India
Short	**0.5 TWh**	**8.5 TWh**
Medium	**0.5 TWh**	**0 TWh**
Long	**100 TWh max [to solve for]**	**0 TWh**
Why this deployment profile?	**Short:** 25 GW battery storage @ 8-hour duration = **200 GWh**; + 30m EVs with 7 kW connection is 210 GW @ 10 kWh willing to provide to grid balancing = **300 GWh** = **0.5 TWh** **Medium:** X number of CAES, Iron-air, etc. **= 0.5 TWh** **Long:** Backup storage i.e. gas or H2 in caverns, **solve for this**	**Optimum amount of short storage to match India's prevalent deployment of solar whilst minimising surplus** **Short here may include any high efficiency options, i.e.:** Grid scale batteries, household batteries/V2G; pumped hydro; demand side flexibility, etc.

Notes: Best scenarios we currently have available. Further modelling will be undertaken in the other archetype countries.
Source: Systemiq analysis for the ETC

Preferred method: model accounts correctly for inability of short and medium to recharge when no surplus available in largest deficit period (Feb 11-24)

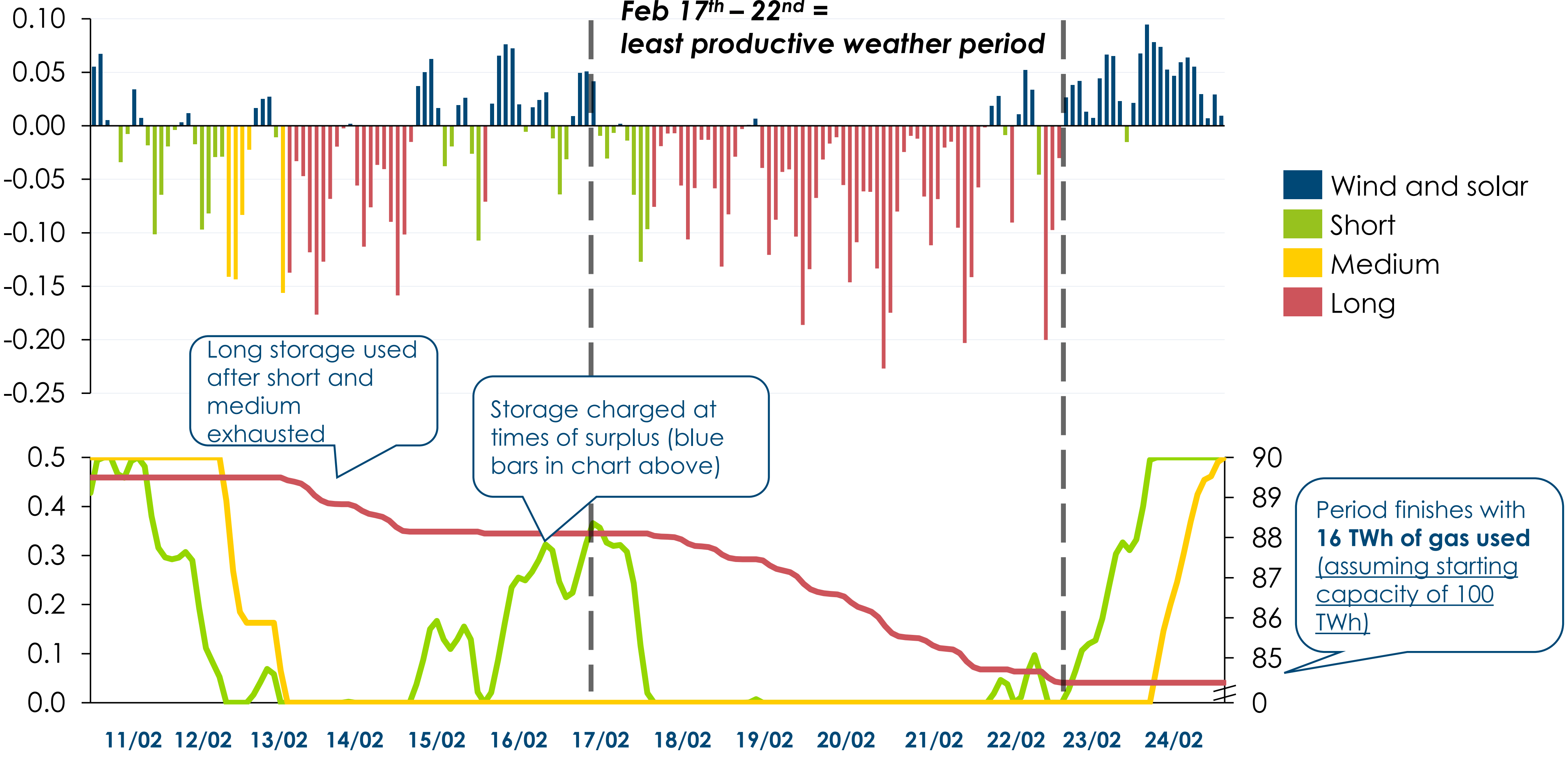
Archetype: Northern latitude (GB)

Balancing requirement met by renewables and types of storage

Bihourly TWh surplus/deficit supplied by specified generation/storage; levels of storage capacity

Drains on storage (TWh)

Storage capacity (TWh)



Feb 17th – 22nd = least productive weather period

Long storage used after short and medium exhausted

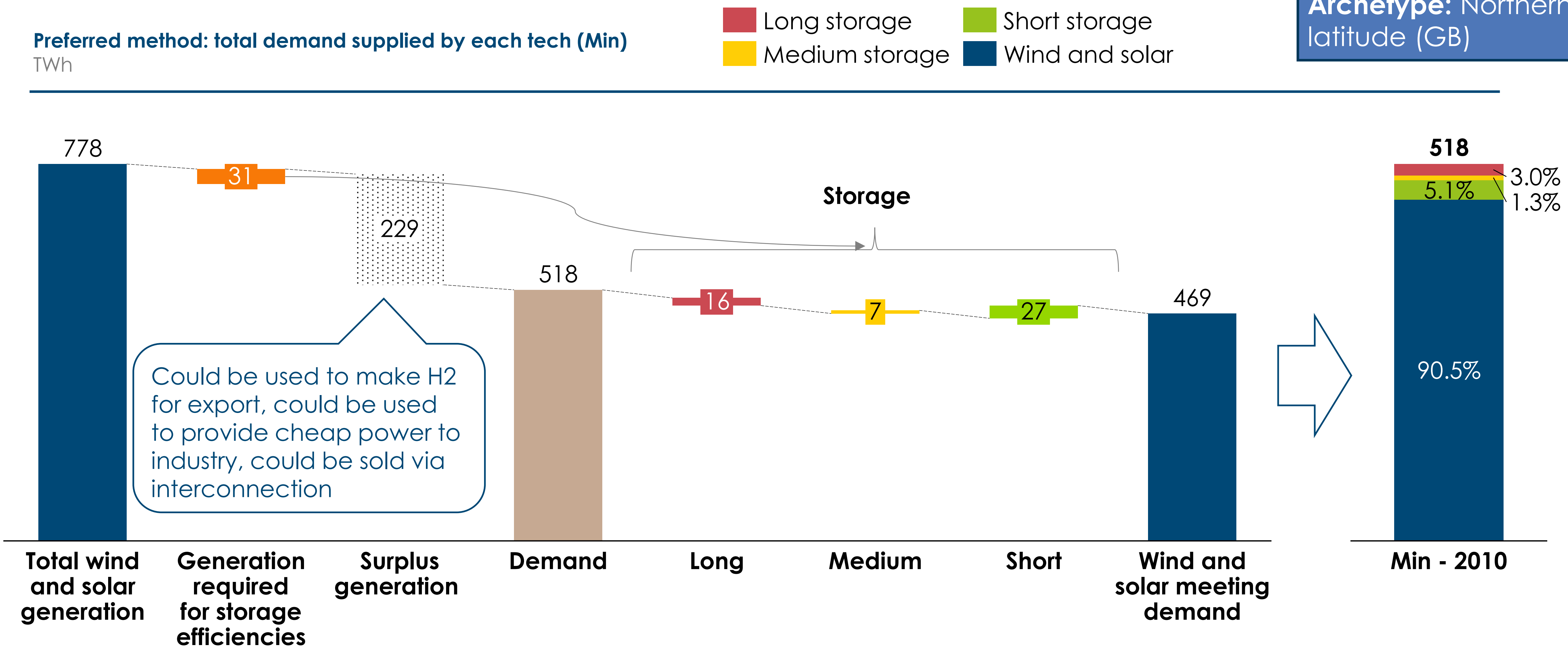
Storage charged at times of surplus (blue bars in chart above)

Period finishes with **16 TWh of gas used** (assuming starting capacity of 100 TWh)

To size the balancing challenge, we break down how demand can be met

Archetype: Northern latitude (GB)

Preferred method: total demand supplied by each tech (Min)
TWh



Could be used to make H2 for export, could be used to provide cheap power to industry, could be sold via interconnection

Notes: each of the 'storage' categories captures the TWh value that contributes to the overall demand figure. 'Generation required for storage efficiencies' relates to the extra power needed to charge the respective storage technology.

GB requires some long duration storage to assist with unpredictable seasonal balancing in poor weather years

Archetype: Northern latitude (GB)

Key assumptions

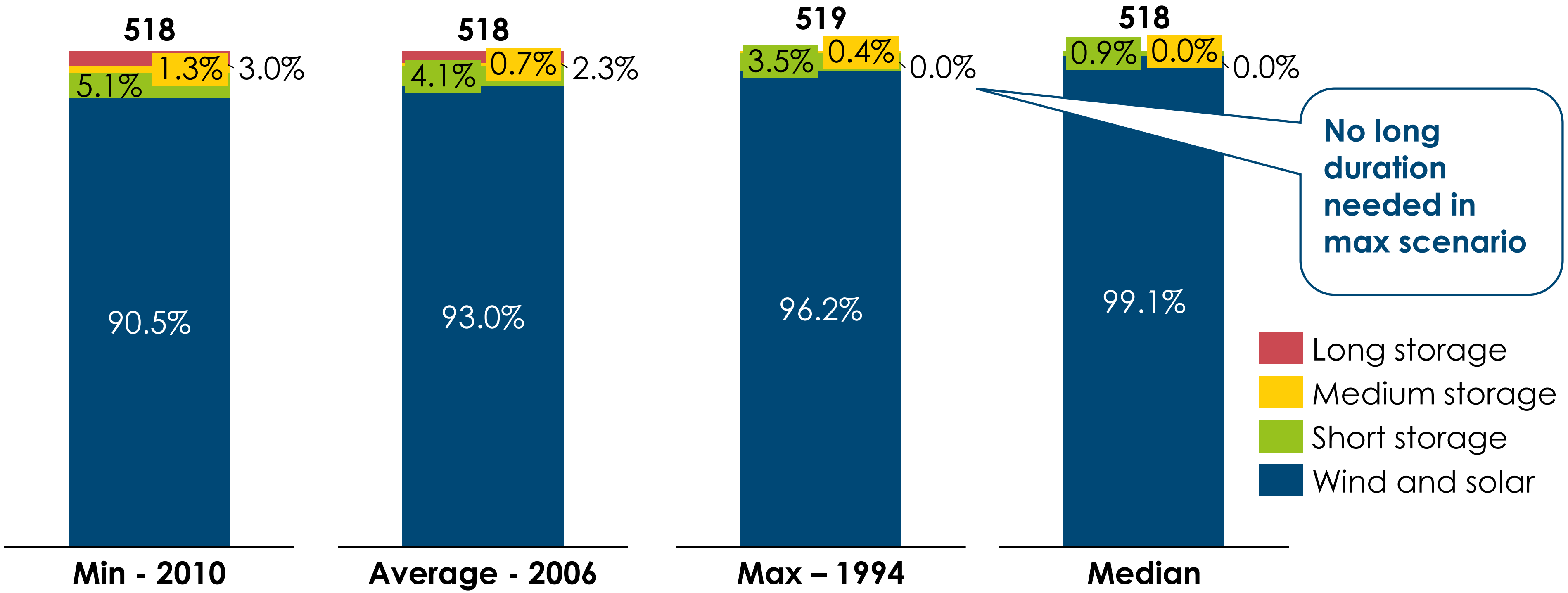
Storage

Type	Capacity	Efficiency
Short =	0.5 TWh	90%
Medium =	0.5 TWh	60%
Long =	100 TWh	40%

Generation capacity

Solar = **75 GW**
Onshore = **60 GW**
Offshore = **100 GW**

Balancing variability across GB weather scenarios in a 100% wind and solar system
% of TWh provided by specified generation/storage



No long duration needed in max scenario

Key TWh values for given scenarios

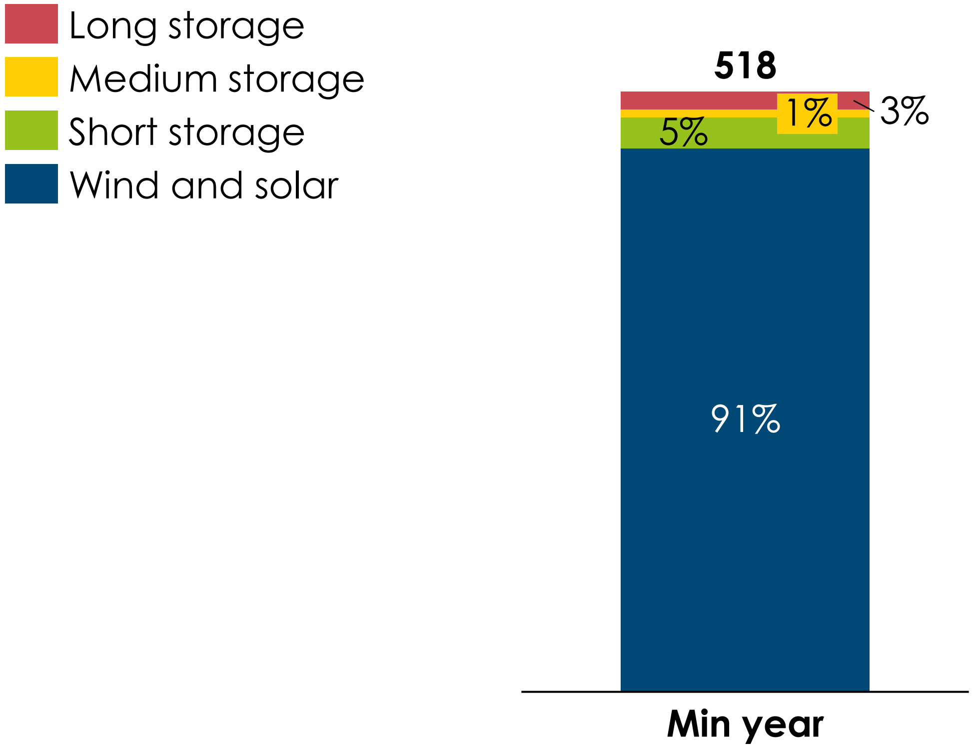
TWh used to charge storage	80	59	23	5
TWh Surplus *[(Supply*Efficiency)-Demand]*	229	321	413	340

Surplus remaining to be utilised or exported

Total system generation costs for UK will reflect higher cost of longer duration balancing, but could be competitive with fossil system

Balancing variability for GB in a 100% wind and solar system

% of TWh provided by specified generation/storage



16 TWh long duration
@ $400/MWh

7 TWh medium duration
@ $200/MWh

26.5 TWh short duration
@ $100/MWh

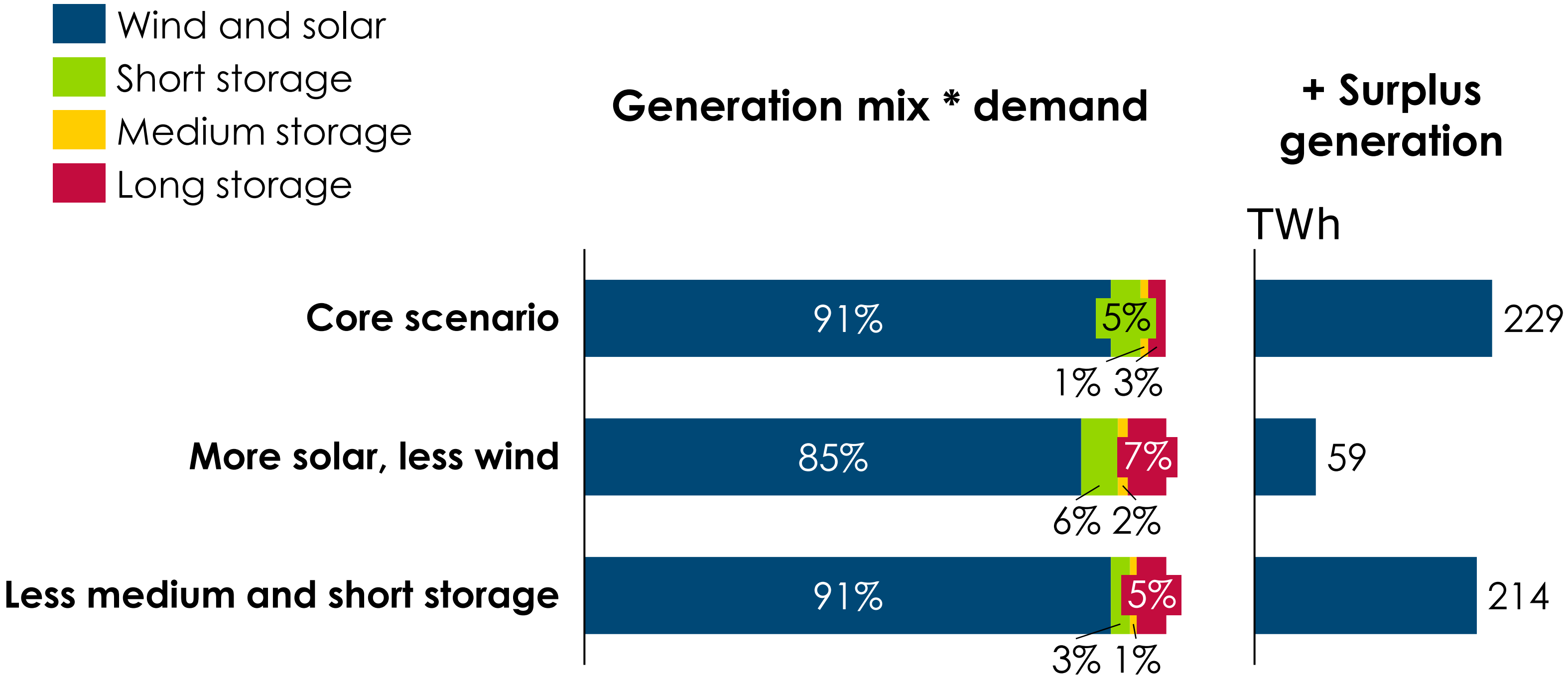
700 TWh wind and solar
@ $35/MWh
(includes surplus generation)

= $34.7 bn per year /
518 TWh demand

= $67/MWh
Total system generation cost

Sensitivity analysis suggests lowest cost systems have highest share of wind and solar; reducing need for long duration storage reduces costs

Archetype: Northern latitude (GB)



x LCOE

Wind/solar @ $35/MWh

Short storage @ $100/MWh

Medium storage @ $200/MWh

Long storage @ $400/MWh

= System gen cost ($bn/year) /demand

$67 /MWh

$70 /MWh

$72 /MWh

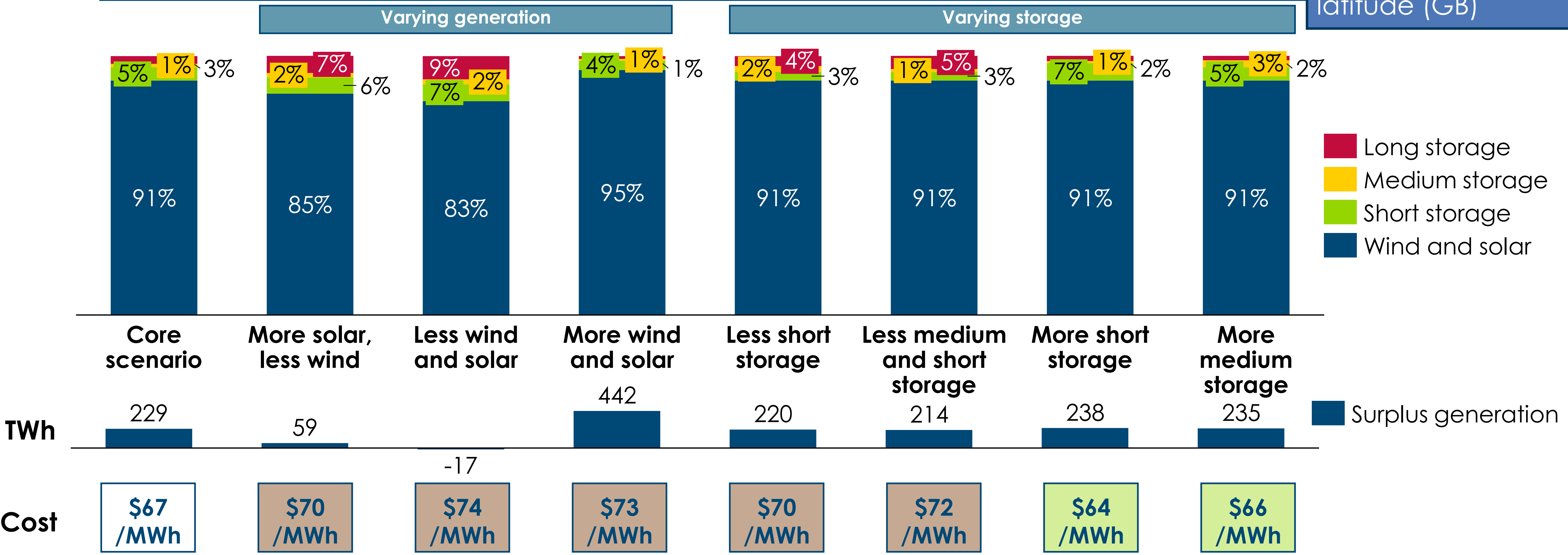
- **Reducing excess generation doesn't necessarily decrease costs: overbuild likely economic**
- **Reducing need for long duration storage reduces costs**

Sensitivity analysis suggest lowest cost systems have highest share of wind and solar; reducing need for long duration storage reduces costs

Archetype: Northern latitude (GB)

Varying generation and storage mix in the minimum weather scenario

% of TWh provided by specified generation/storage



- **Reducing excess generation doesn't necessarily decrease costs: overbuild likely economic**
- **Reducing need for long duration storage reduces costs, short and medium more economic**

Key insights

Archetype: Northern latitude (GB)

- Total system costs of our central scenario for Northern latitude archetype like UK, likely similar to fossil fuels

- Large levels of surplus electricity, through overbuilding renewables, may be cost-effective: reducing excess generation doesn't necessarily decrease costs. Question about what to do with 'excess' renewables:
  - **Potential use in additional flexibility or for other fuel production**, e.g. hydrogen, which doesn't require a continuous electricity supply (though does require a baseline offtake agreement)
  - **Export via interconnection** (although volumes could be well above export possibilities)
  - **Curtailment payments**

- Reducing need for long duration storage reduces costs, as it is the most expensive storage option. But some long duration necessary – raising need for market mechanisms to incentivise.

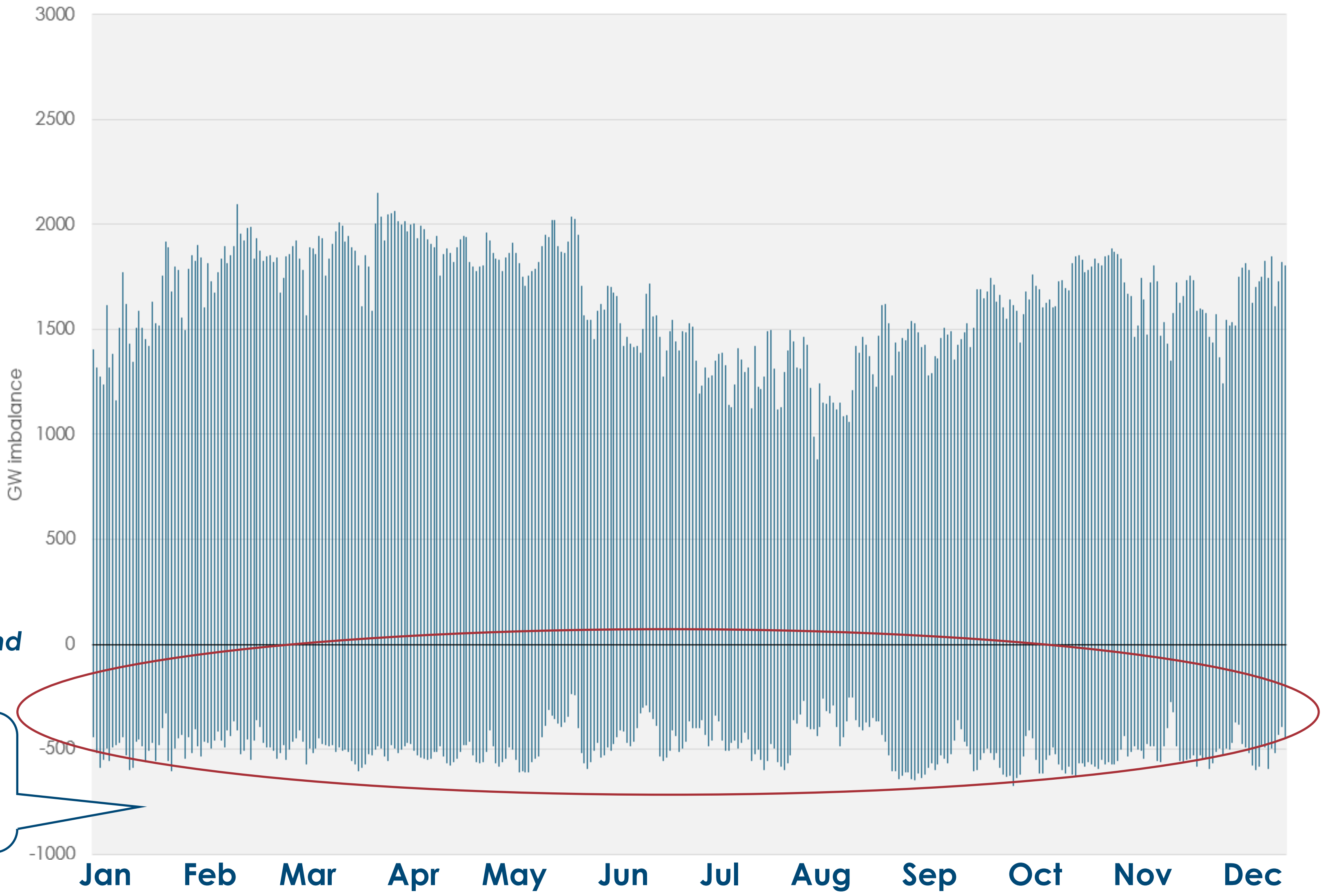
Snap shot of Tropical archetype (India)

India experiences many strong periods of surplus driven by overbuild of solar, but this drives high nightly imbalances when the sun does not shine

Archetype: Low latitude/tropical (In)

Size of surplus and deficits in minimum weather year (2020)

Bihourly GW imbalance between supply and demand

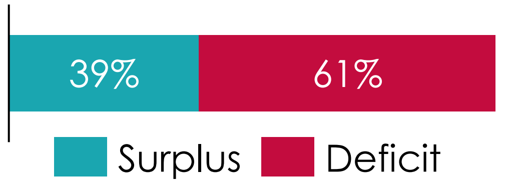


At 0 Supply = Demand

No unpredictable spike with much more power needed infrequently

Minimum

Percent of hours in surplus/deficit



Supply exceeds demand
*Surplus = **1790 TWh***

Demand exceeds supply
Balancing required:
*Max = **672 GW***
*Average = **393 GW***

Implies some very high utilisation storage/flexibility – i.e. 393 GW used frequently

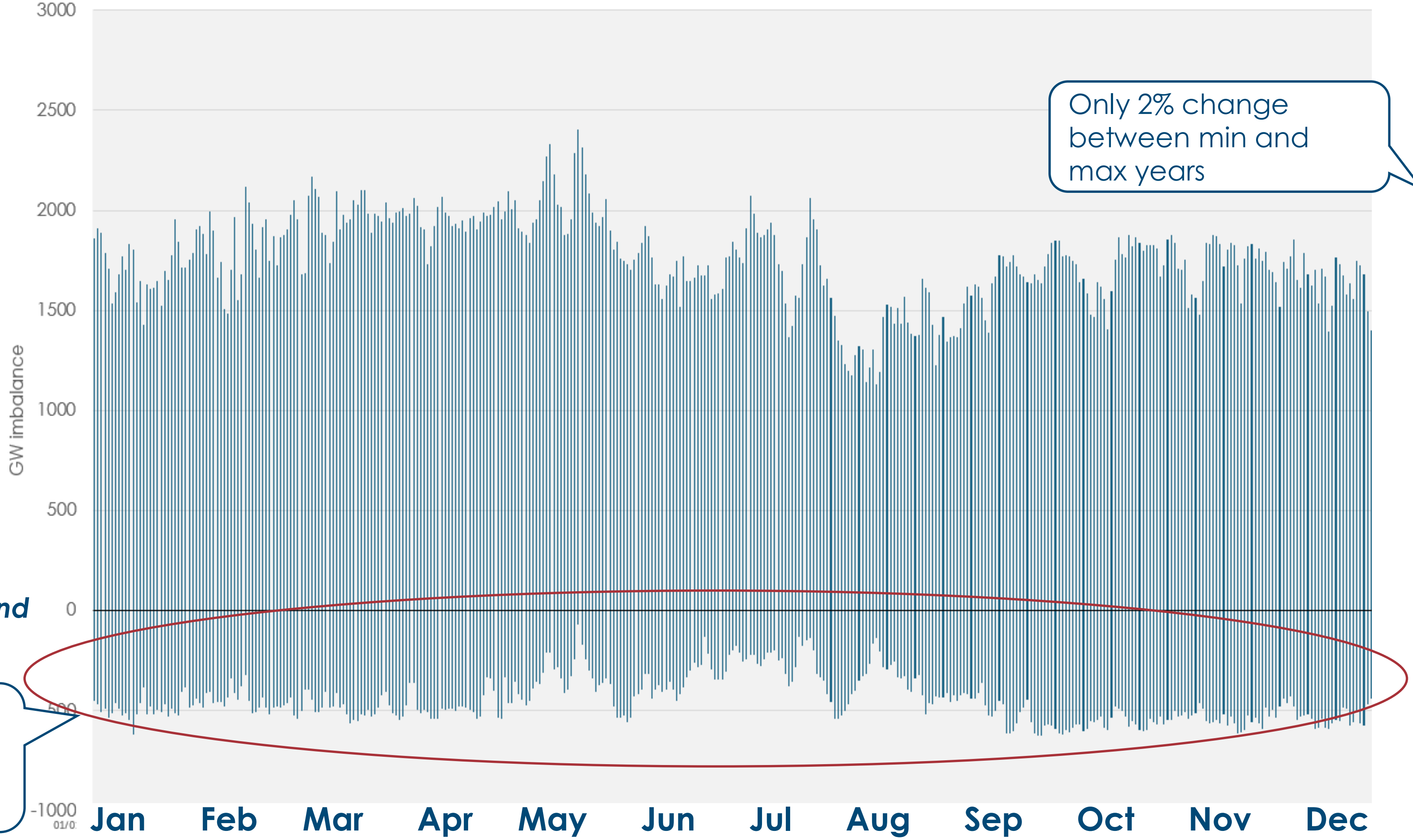
Size of balancing in max weather year is not so different, given more consistent solar generation across years

Archetype: Low latitude/tropical (In)

Maximum

Size of surplus' and deficits in maximum weather year (2002)

Bihourly GW imbalance between supply and demand

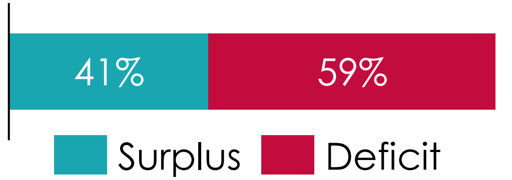


At 0 Supply = Demand

Only 2% change between min and max years

Same pattern as minimum means less unpredictable challenges

Percent of hours in surplus/deficit



Supply exceeds demand
*Surplus = **2440 TWh***

Demand exceeds supply
Balancing required:
*Max = **625 GW***
*Average = **360 GW***

Small reduction in average GW required– i.e. from 393 GW to 360

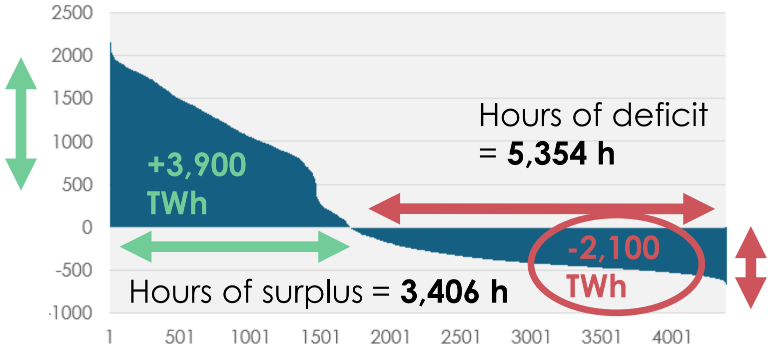
Load duration curves show India requires at least 672 GW of storage, with a total of ~2,100 TWh of stored energy to be used throughout the year

Archetype: Low latitude/tropical (In)

Load duration curves, 100% wind and solar supply across weather years, 2050 demand

GW surplus and deficit, 2-hourly generation blocks

Minimum weather year, 2020



+3,900 TWh

Hours of deficit = **5,354 h**

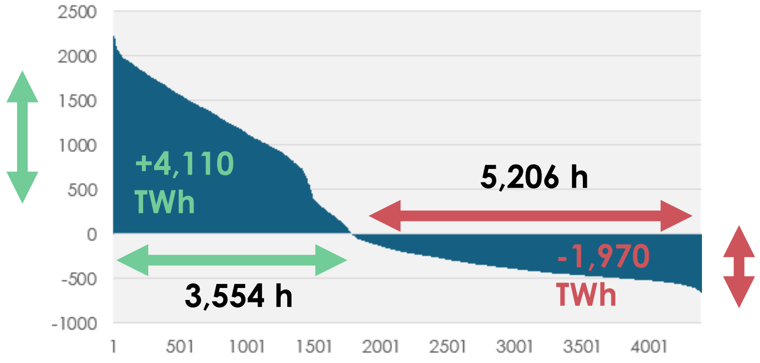
-2,100 TWh

Hours of surplus = **3,406 h**

Max surplus = **2,150 GW**

Max deficit = **672 GW**

Average weather year, 1997



+4,110 TWh

5,206 h

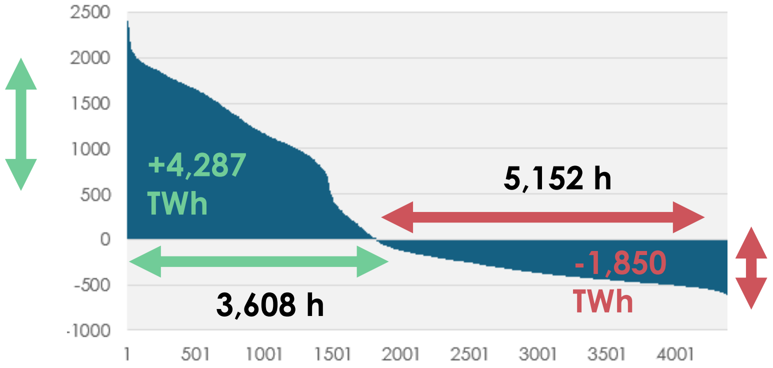
-1,970 TWh

3,554 h

Max surplus = **2,227 GW**

Max deficit = **666 GW**

Maximum weather year, 2002



+4,287 TWh

5,152 h

-1,850 TWh

3,608 h

Max surplus = **2,405 GW**

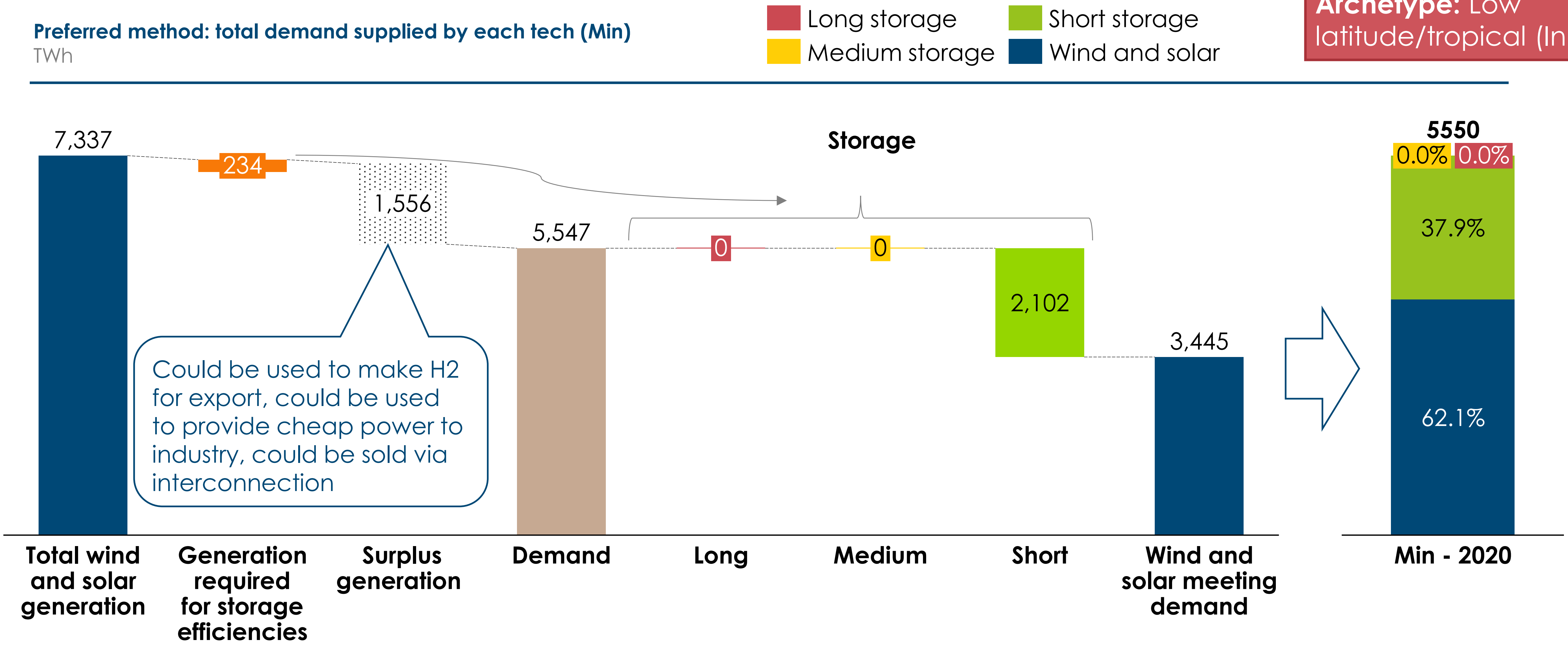
Max deficit = **625 GW**

Notes: Average weather year has a higher maximum deficit/storage need due to having one 2-hour block where there was a larger difference between supply and demand than the minimum weather scenario. The minimum weather scenario has the highest cumulative amount of deficit.

To size the balancing challenge, we break down how demand can be met

Preferred method: total demand supplied by each tech (Min)
TWh

Archetype: Low latitude/tropical (In)



Could be used to make H2 for export, could be used to provide cheap power to industry, could be sold via interconnection

Notes: each of the 'storage' categories captures the TWh value that contributes to the overall demand figure. 'Generation required for storage efficiencies' relates to the extra power needed to charge the respective storage technology.

India's balancing challenge is primarily around short duration

Archetype: Low latitude/tropical (In)

Key assumptions

Storage

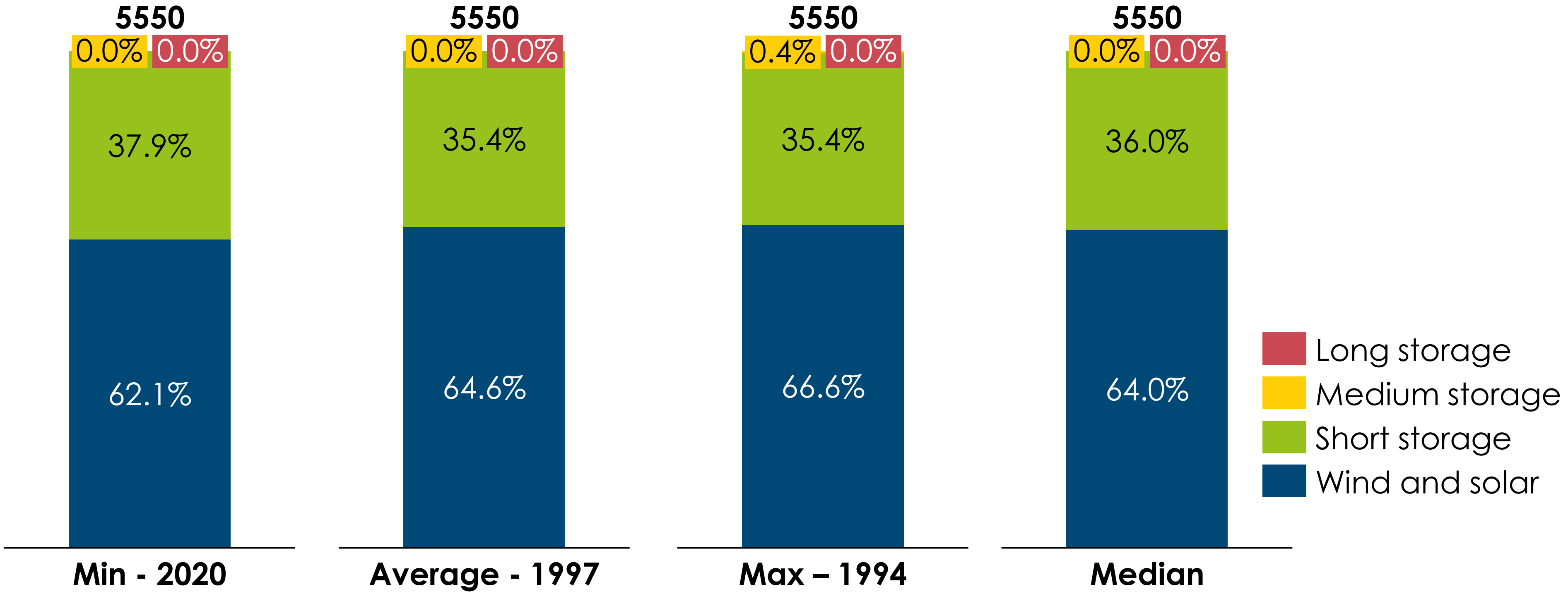
Type	Capacity	Efficiency
Short =	8.5 TWh	90%
Medium =	0.0 TWh	60%
Long =	0 TWh	40%

Generation capacity

Solar = **2750 GW**
Onshore = **650 GW**
Offshore = **80 GW**

Balancing variability across India weather scenarios in a 100% wind and solar system

% of TWh provided by specified generation/storage



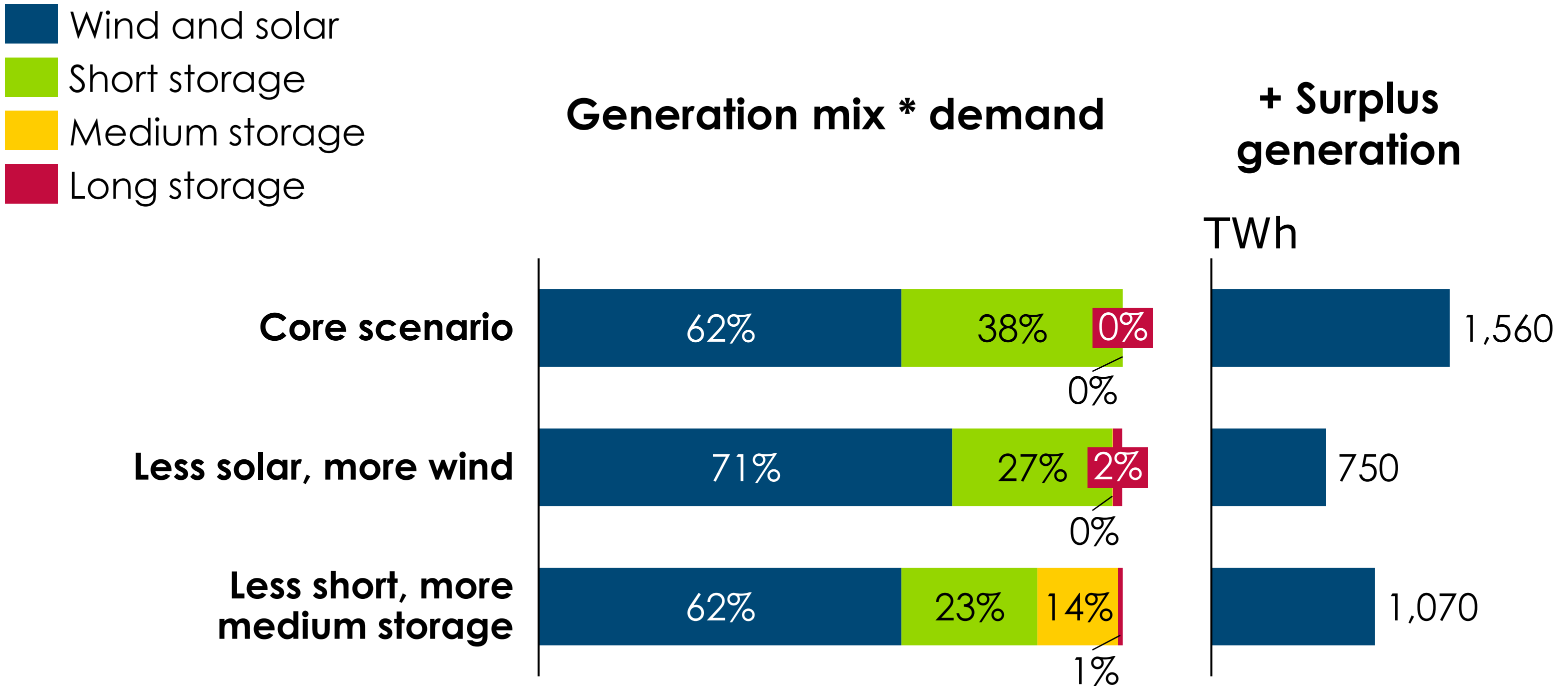
Key TWh values for given scenarios

	Min - 2020	Average - 1997	Max – 1994	Median
TWh used to charge storage	2340	2190	2060	2200
TWh Surplus *[(Supply*Efficiency)-Demand]*	1560	1910	2230	1900

Surplus remaining to be utilised or exported

Sensitivity analysis suggest lowest cost systems have proportionally higher share of solar than wind; with large short storage cost effective

Archetype: Low latitude/tropical (In)



x LCOE

Wind/solar @ $15/MWh

Short storage @ $100/MWh

Medium storage @ $200/MWh

Long storage @ $400/MWh

= System gen cost ($bn/year) /demand

Scenario	System gen cost
Core scenario	$51 /MWh
Less solar, more wind	$55 /MWh
Less short, more medium storage	$66 /MWh

- **Reducing excess generation doesn't necessarily decrease costs: overbuild likely economic**
- **Reducing need for long duration storage reduces costs**

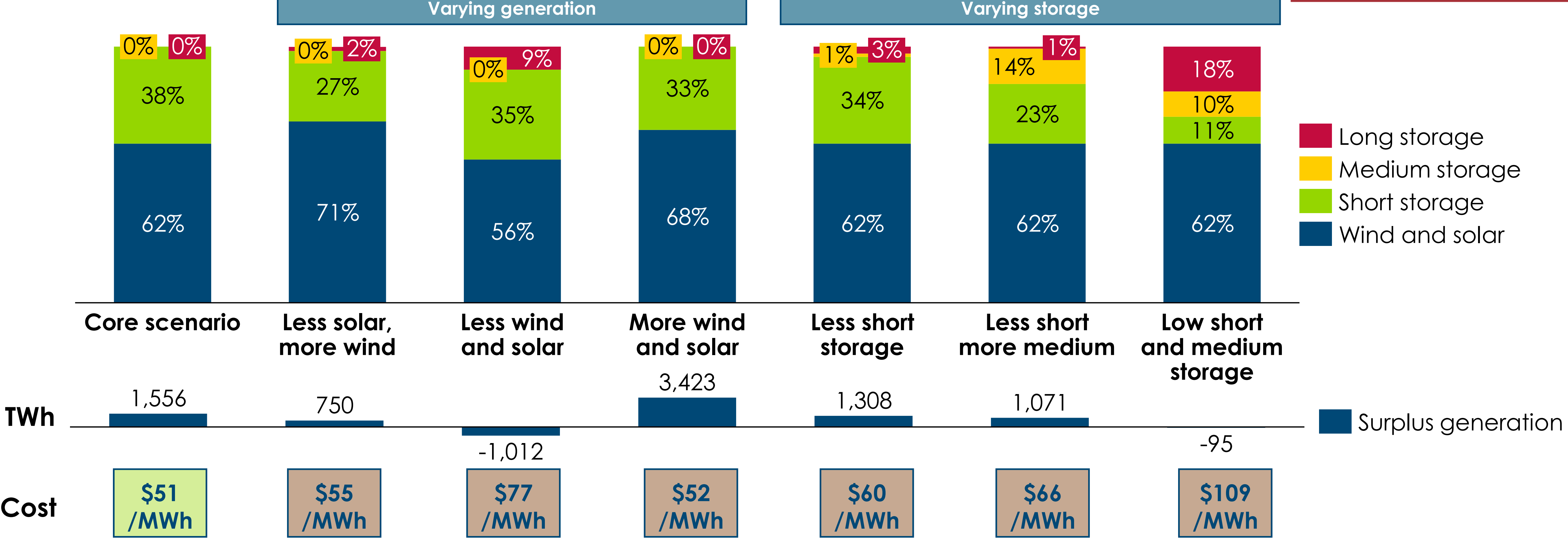
Notes: Solar/onshore/offshore & short/medium/long splits: Core scenario = 2750/650/80 - 8.5/1/500; Less solar more wind = 2000/1000/150 - 8.5/1/500; Less short, more medium storage = 2750/680/150 - 4/4/500. The 'Less solar, more wind' scenario uses a higher wind and solar LCOE of $25/MWh to reflect the increased cost of wind over solar in 2050. Long storage may obtain more economies of scale at higher deployment levels, assumed flat for this analysis.

Sensitivity analysis suggest lowest cost systems have proportionally higher share of solar than wind; with large short storage cost effective

Archetype: Low latitude/tropical (ln)

Varying generation and storage mix in the minimum weather scenario

% of TWh provided by specified generation/storage



- Reducing excess generation doesn't necessarily decrease costs: overbuild likely economic
- Reducing need for long duration storage reduces costs

Key insights

- **Total system costs** of solar + batteries in Tropical archetypes such as India appear competitive with fossil fuels
- As a Tropical archetype, **India can rely nearly solely on short duration storage** – even with seasonal Monsoon periods
- **What to do with the surplus?** Overbuild of renewables appears cheap but is it realistic? Reinforces role for interconnectors, potential cheap H2.
- **Just for India, if all met via batteries**, would be 2700% higher than total global battery capacity installed today. Adding in other Tropical archetypes would reinforce this message.

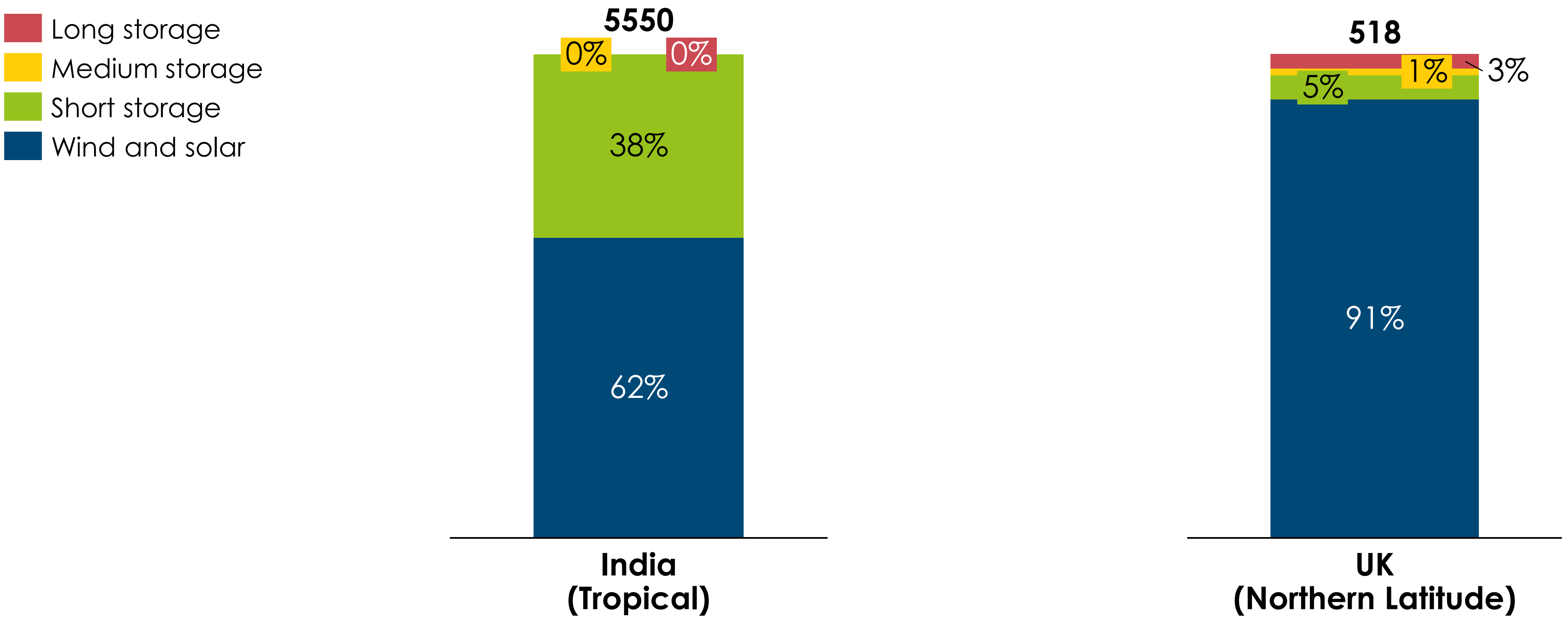
Pause for discussion

Implications on meeting the system balancing challenge

Balancing challenge varies for Tropical and Northern Latitude archetypes

Balancing variability for India and UK in a 100% wind and solar system

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



Primarily a diurnal challenge

Balancing required across short, medium and long durations

Source: Systemiq analysis for the ETC (2024)

Previously this year, we outlined an updated suite of different routes to meet balancing challenge

			System operation	Predictable Daily	Unpredictable Daily	Medium duration	Long duration
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*

Preliminary

We assessed a range of technologies to meet balancing needs

Very long-Duration

Seasonal balancing

Narrower range of technologies

Complex, with costs varying widely according to local conditions

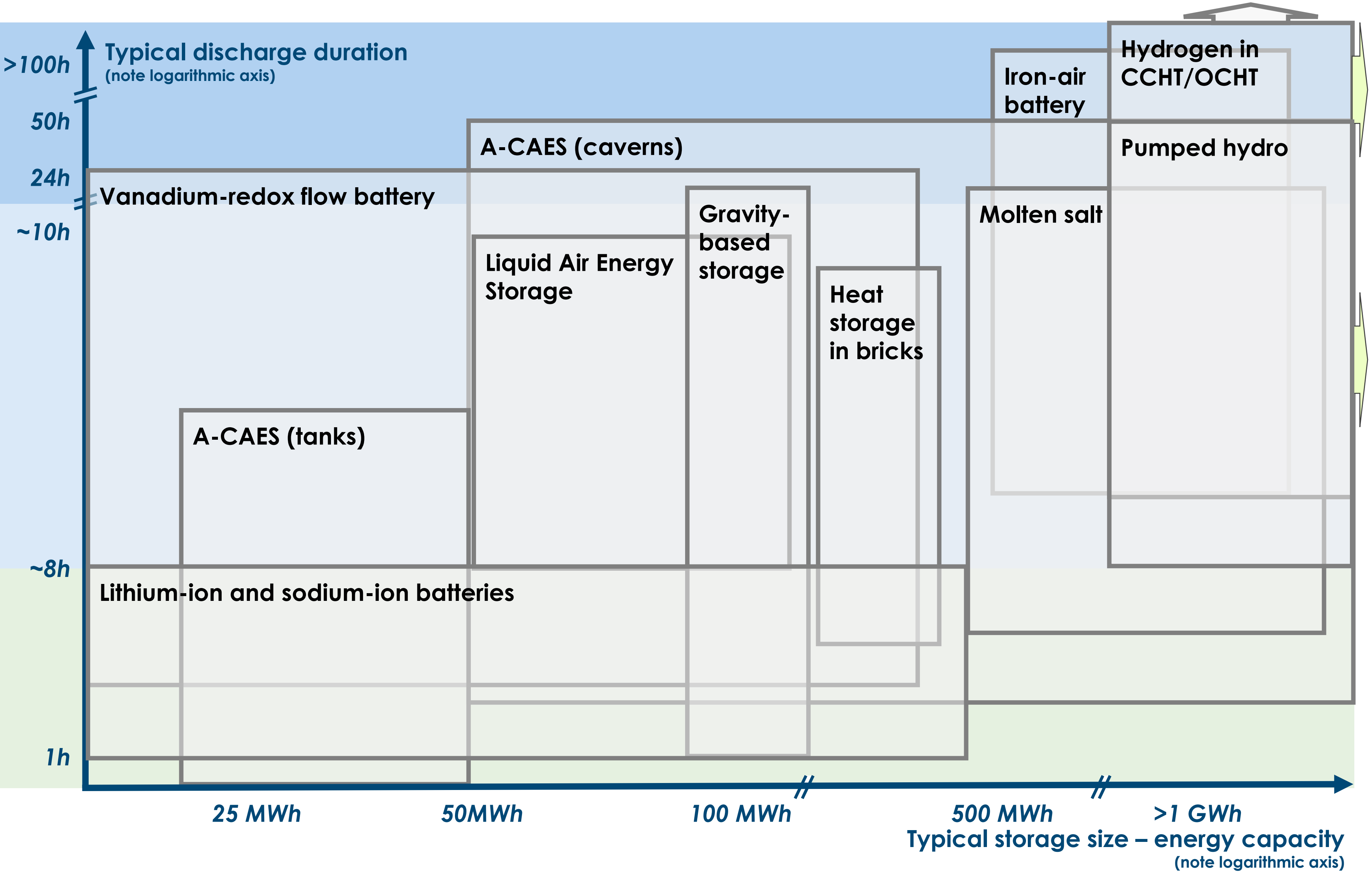
Long-Duration

Daily balancing

Wide range of technologies

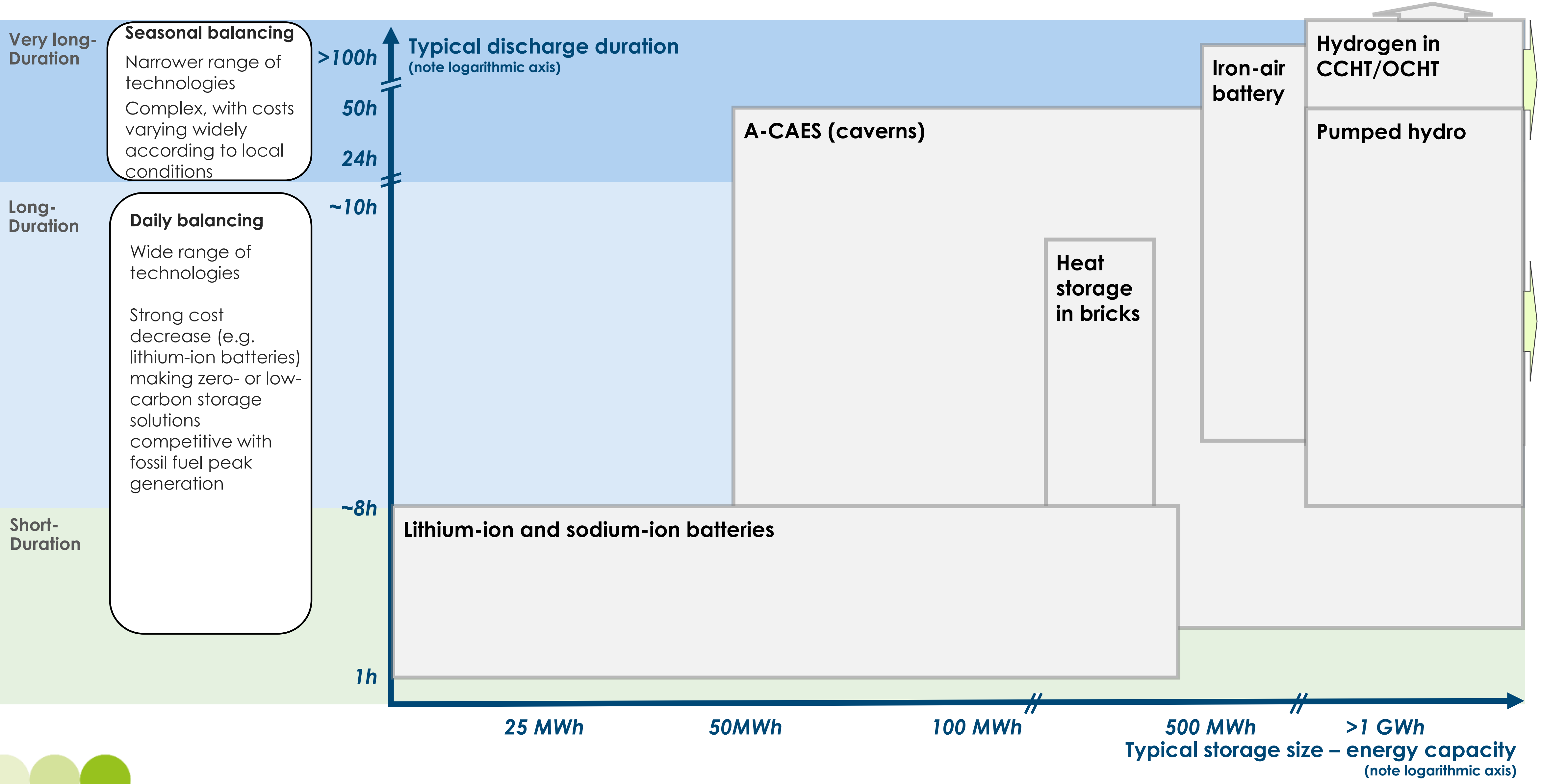
Strong cost decrease (e.g. lithium-ion batteries) making zero- or low-carbon storage solutions competitive with fossil fuel peak generation

Short-Duration



Preliminary

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



Very long-Duration

Seasonal balancing

Narrower range of technologies

Complex, with costs varying widely according to local conditions

Long-Duration

Daily balancing

Wide range of technologies

Strong cost decrease (e.g. lithium-ion batteries) making zero- or low-carbon storage solutions competitive with fossil fuel peak generation

Short-Duration

Typical discharge duration
(note logarithmic axis)

>100h
50h
24h
~10h
~8h
1h

Hydrogen in CCHT/OCHT

Iron-air battery

Pumped hydro

A-CAES (caverns)

Heat storage in bricks

Lithium-ion and sodium-ion batteries

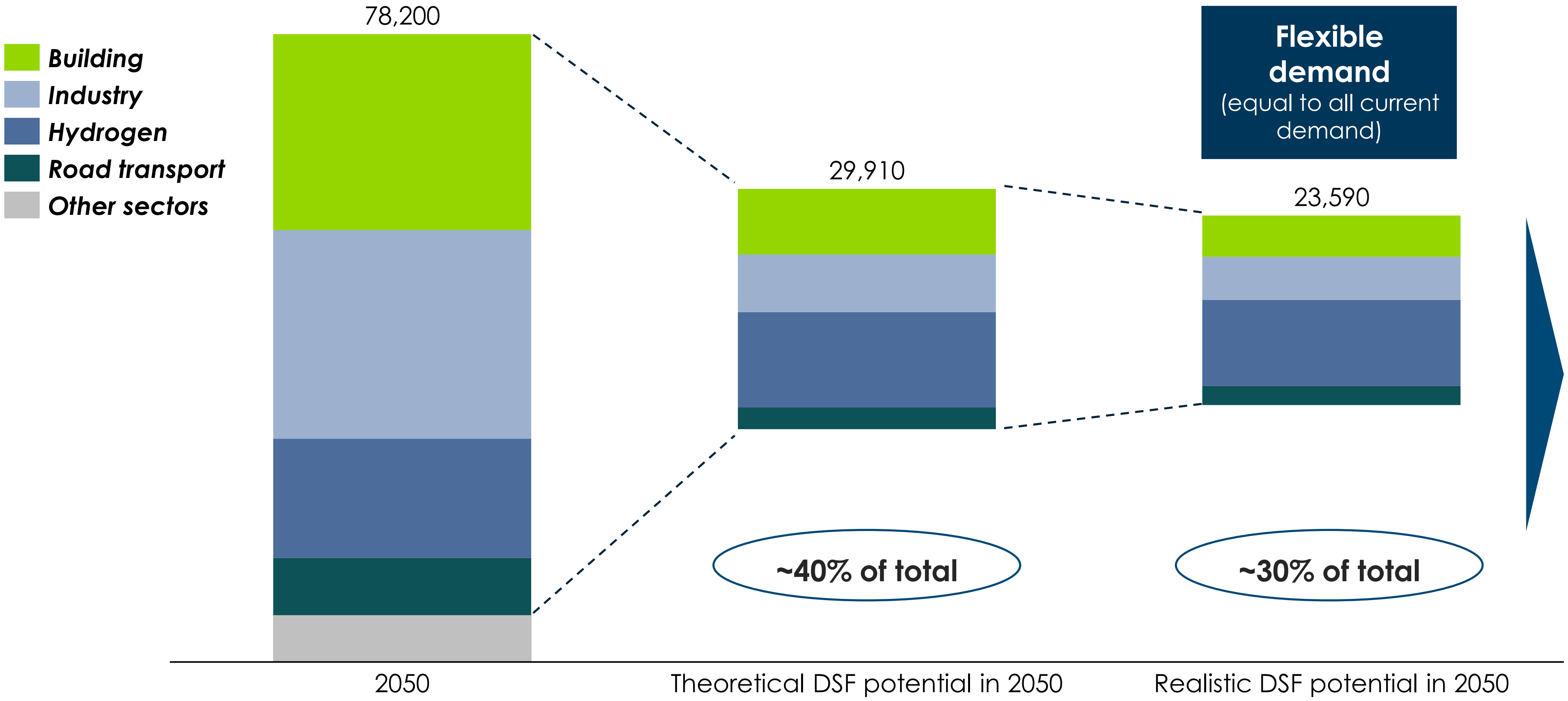
25 MWh
50MWh
100 MWh
500 MWh
>1 GWh

Typical storage size – energy capacity
(note logarithmic axis)

We also assessed role of demand side flexibility; a third of total electricity demand in 2050 has opportunity to be flexible

Global electricity demand and DSF potential, 2050

TWh



Flexible demand
(equal to all current demand)

~40% of total

~30% of total

Demand side flexibility ***has potential to meet important share of daily balancing challenge in a highly electrified system****; however, relies on significant barriers being overcome*

Key implications for Tropical archetype (India)

Focus on short duration: there is a large set of options to meet this need

			Predictable Daily	Unpredictable Daily
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]	✓	✓

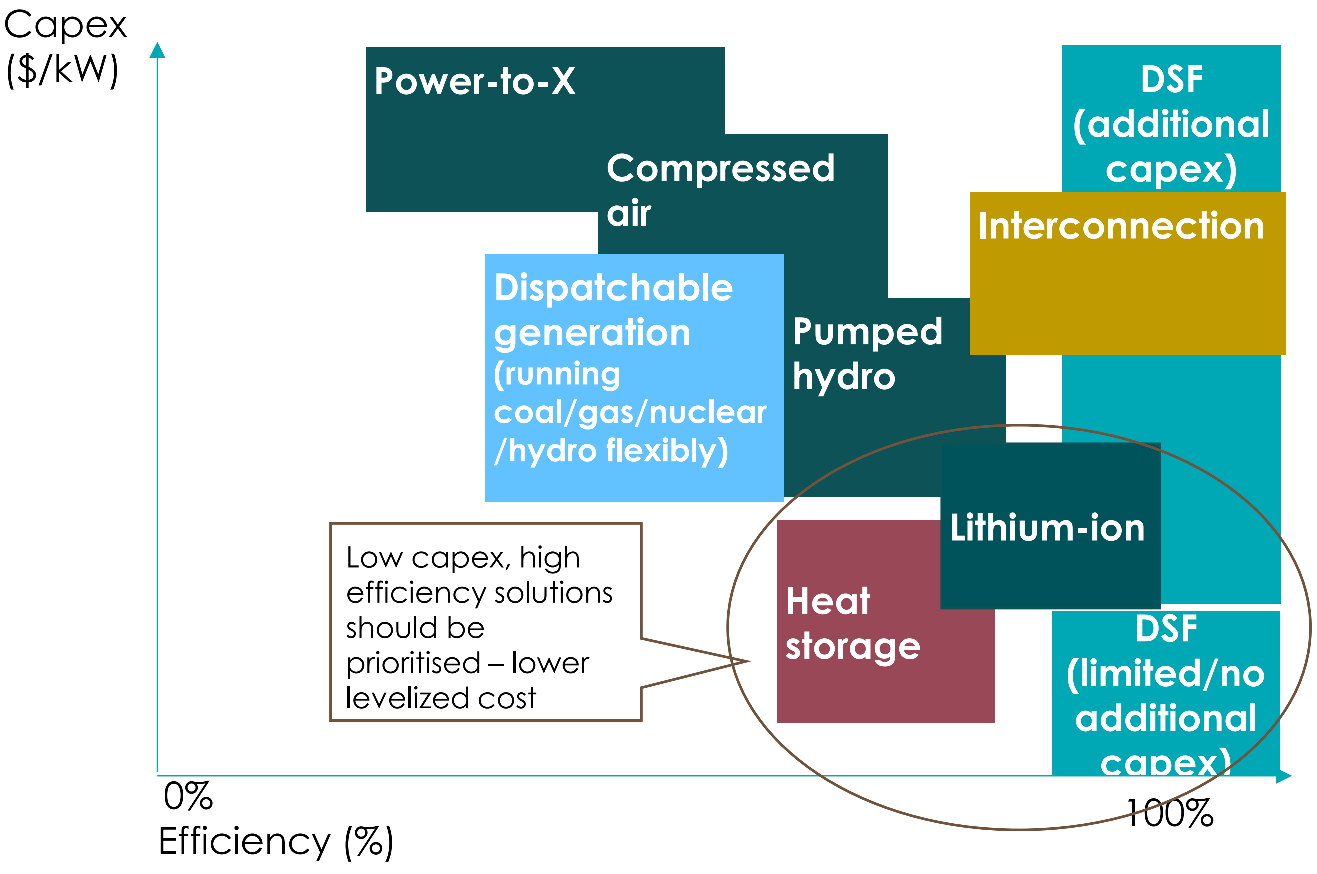
Lithium-ion will play a critical role

Key opportunities in heat storage & demand side flex

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*

Daily balancing: given option set available, low capex, high efficiency solutions should be prioritised

Illustrative view of selected flexibility technologies



Capex & efficiency key determinants for 'levelised cost'

- **Storage and demand-side flexibility** should both play a role in meeting daily balancing
- While some demand-side flex is lowest cost, **some required level of behaviour change could pose a barrier** to maximise deployment

Definitions

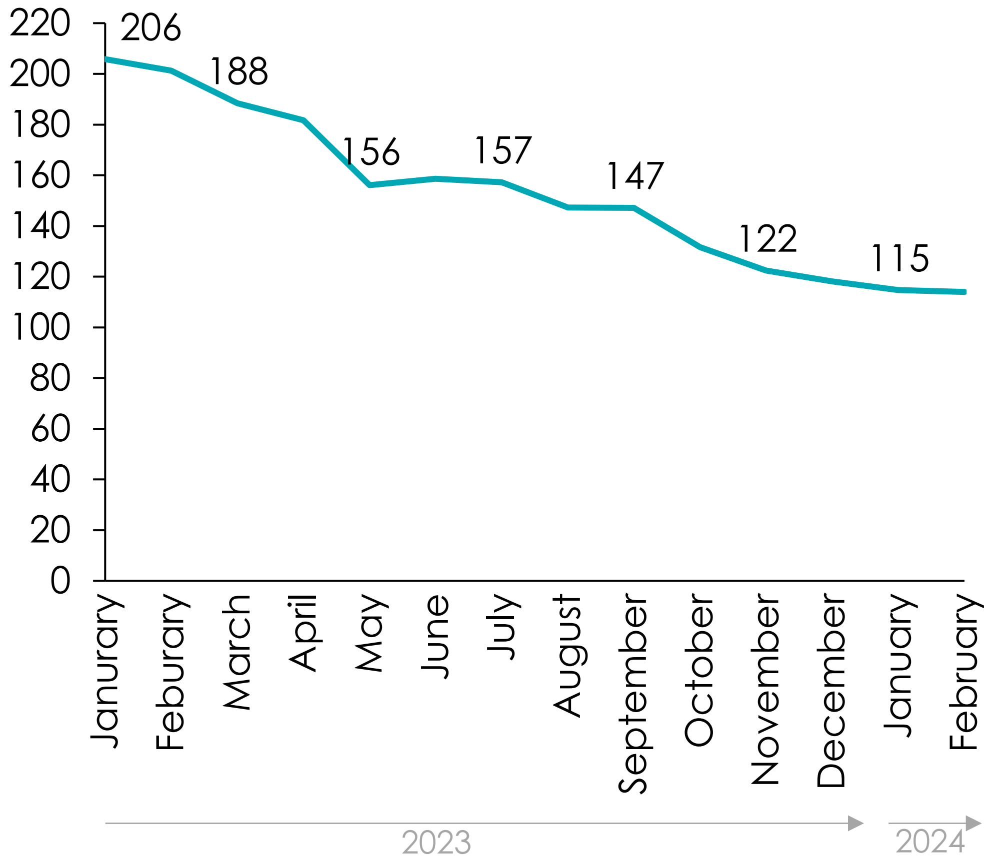
Demand side flexibility (limited/no additional capex)	• EV smart charging • Pre-heating • Smart appliances • Shifting data centre demand geographically
Demand side flexibility (additional capex)	• Water tanks in homes • Industrial load management (e.g. for alu electrolysis)

Source: Systemiq analysis for the ETC (2024).

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

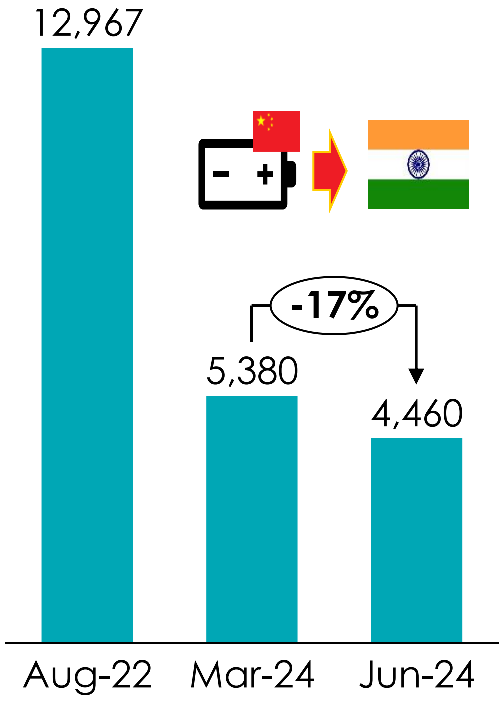
Price decline of battery systems from China…

$/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.*

For all energy storage, market and 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?

Renewable Energy Round-the-Clock (RTC) contracts could enable faster deployment

Round-the-Clock (RTC)

Power generators to supply a specified quantity of electricity at specified times throughout the year

Renewable Energy RTCs

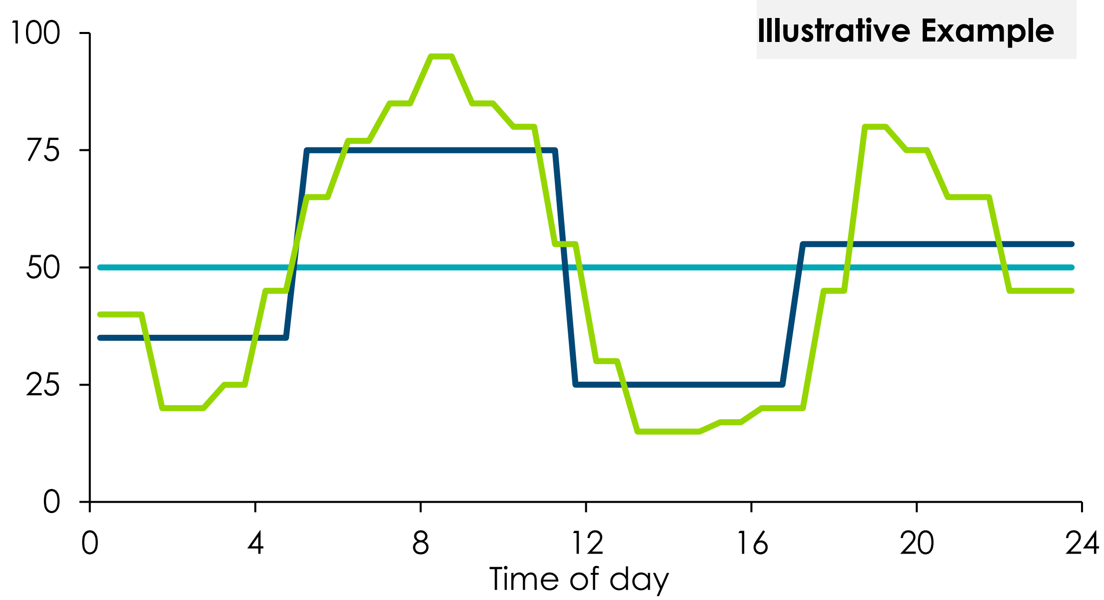
Renewable RTCs must include storage to ensure power still supplied when natural resources aren't producing

↳ **Easier to integrate variable renewables into grid:** a firm power supply removes balancing issues for grid operators

In addition to specifying times and quantity of power supplied, renewable RTCs include Capacity Use Factors (CUFs) which refer to the share of power that needs to come from renewables over specified time periods

↳ **Actual installed capacity grows even faster:** renewable RTC projects must be oversized by 3-4x to comply with CUF specifications

RTC Power Supply to Grid, GW



RTCs vary in their **time blocks**

- **Fixed supply** is constant regardless of demand, with time blocks on an annual basis
- **Slot-wise supply** steps up/down with peak demand hours, time slots can range from weeks to hours
- **Real-time supply** adjusts to demand, with blocks as short as 15-minutes

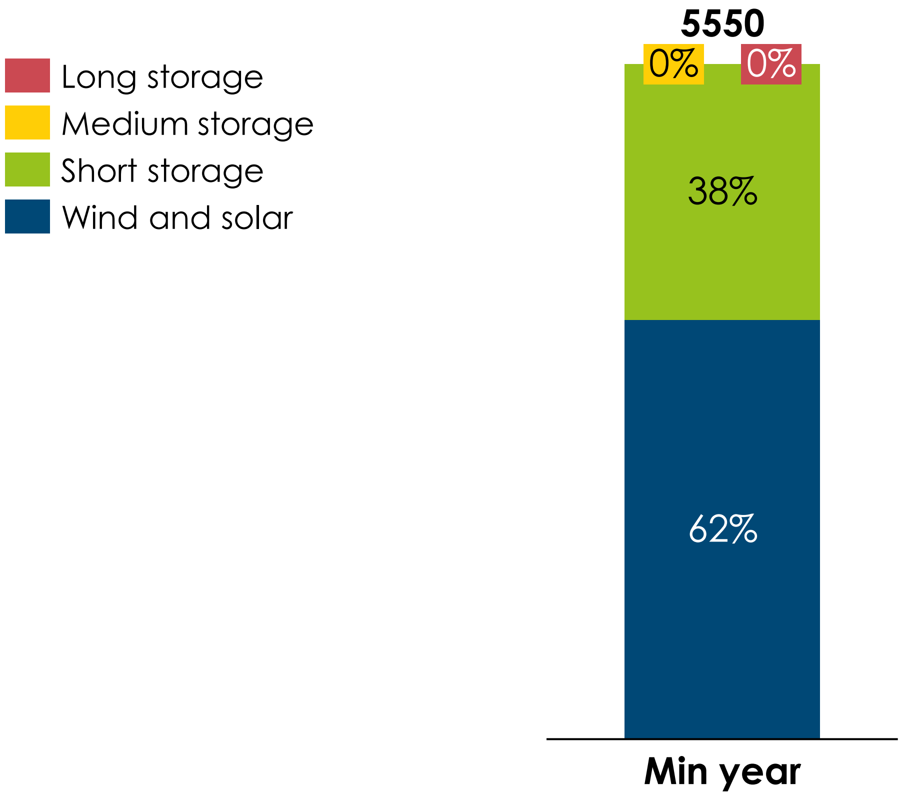
Key enablers for driving adoption of demand side flexibility

Hardware	Accelerate adoption of **smart meters** and **asset metering devices** through regulation and financing	• EU smart meters roll out
Data exchange	Establish clear rules on **data exchange** and **interoperability standards**	• EU Smart Grids Task Force on data protection and privacy
Pricing structures	Implement **time-of-use tariffs**, **real-time pricing** Wholesale **price signals** for supplier half hourly settlement	• California Public Utilities Commission (CPUC) • EU Clean Energy for All Europeans
Cost	**Reduce barriers to entry** via financing through **financial institutions and government-backed grants**	• Energy Service Companies (ESCOs)
Market reform	Enable DSOs to expand their **flexibility procurement capabilities** and **streamline the export licensing process** for V2G tech	
Behaviour change	**Reveal the value of DSF** to consumers through transparent billing, mobile apps, and personalized reports	
Other	Leverage other policy as incentives, such as **building codes, EPCs**	• Hong Kong reward point program

Total system generation costs for India could be competitive with fossil systems

Balancing variability for India in a 100% wind and solar system

% of TWh provided by specified generation/storage



*2,100 TWh * $100/MWh*

5,000 TWh @ $15/MWh
(includes surplus generation)

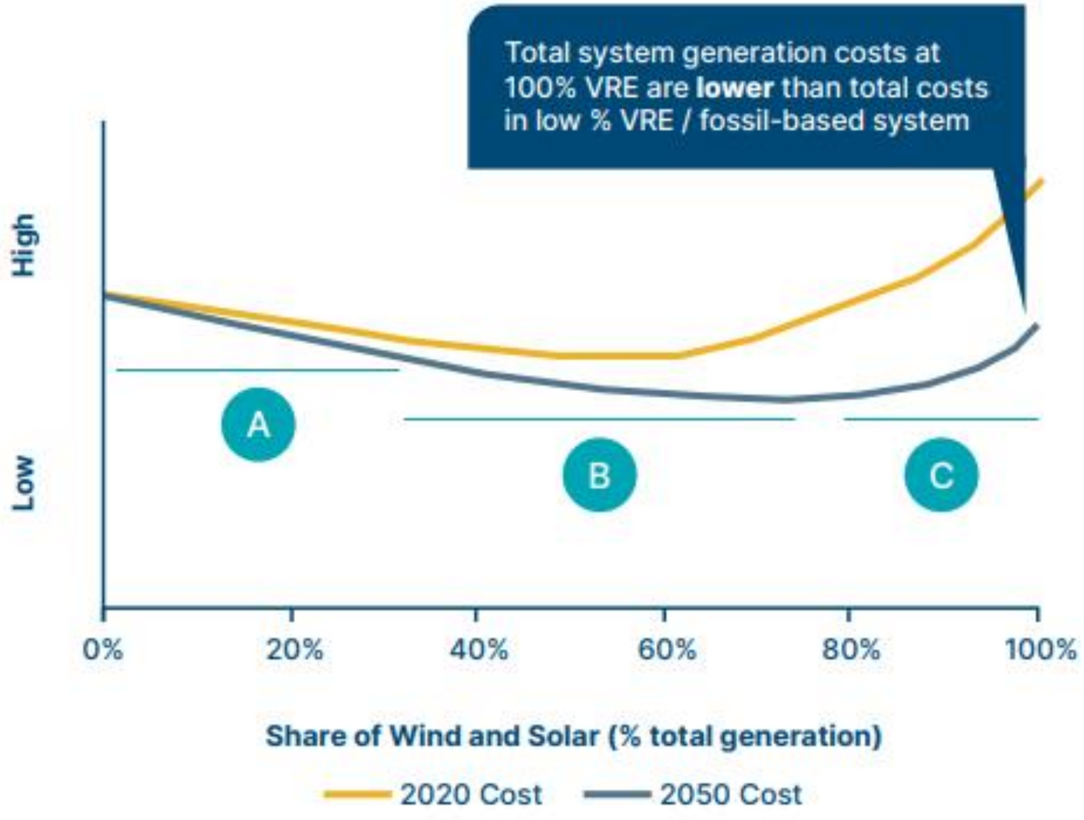
= $285bn per year /
5550 TWh demand

= $51/MWh
Total system generation cost

Source: Systemiq analysis for the ETC (2024).

TERI analysis (2020) concluded that total system costs in zero-carbon power systems could be below those of fossil-based systems

Total system generation costs as function of VRE penetration,
$/MWh, 2020 and 2050 cost scenarios



Total system generation costs at 100% VRE are **lower** than total costs in low % VRE / fossil-based system

SOURCE: Adapted from TERI/ETC India (2020) *The Potential Role of Hydrogen in India*

A

0-30% VRE penetration

Declining system generation costs as cheaper renewables replace fossil in baseload generation; no balancing needs

B

30-80% VRE penetration

Further cost declines as renewables + storage increasingly cheaper than fossil for dispatchable generation

C

80-100% VRE penetration

Increase in total system generation costs as significant costs required to provide zero carbon answers to the "last 10%-20%" of generation

Source: Adapted from TERI/ETC India (2020), *The Potential Role of Hydrogen in India*

Key implications for Northern Latitude archetype (GB)

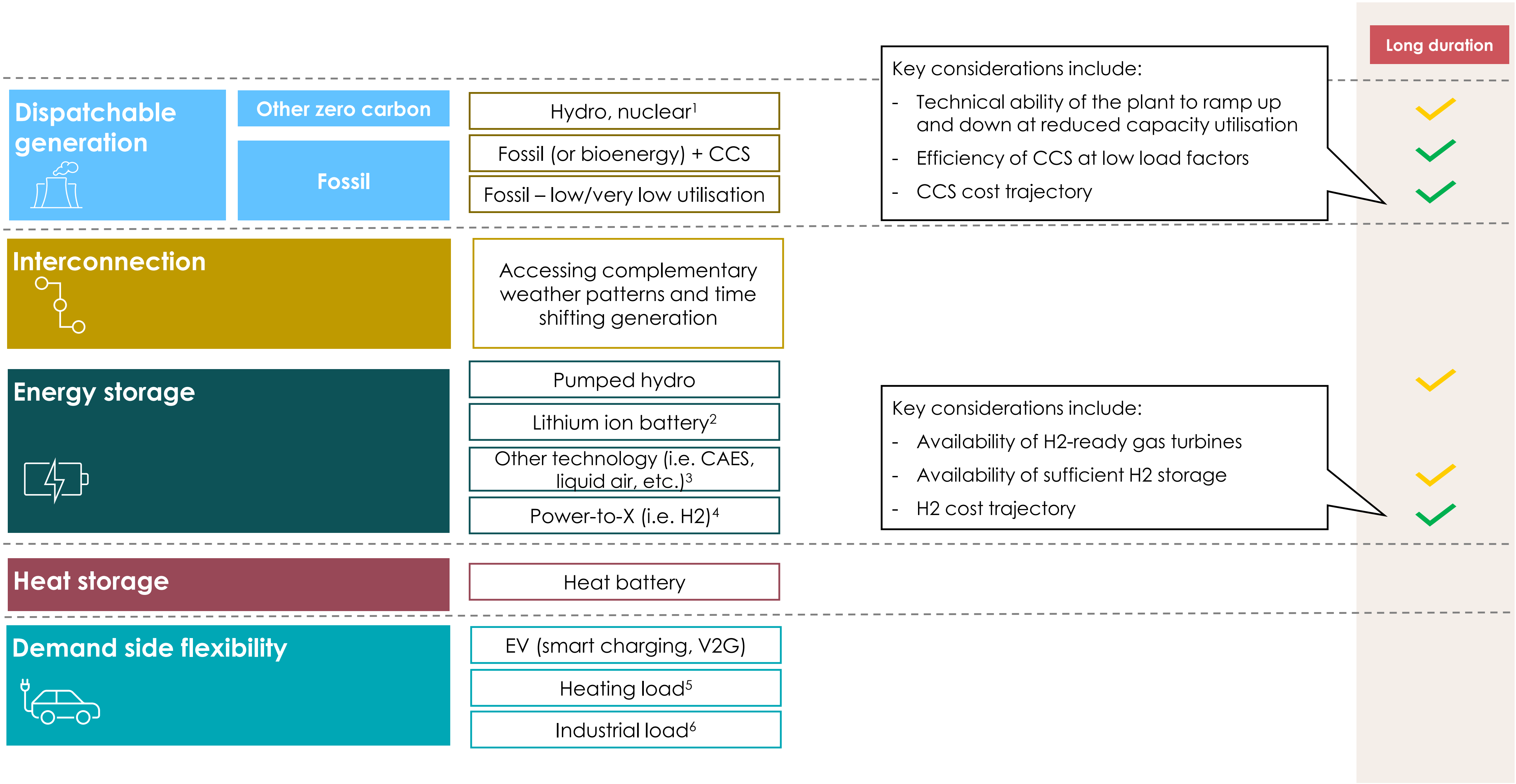
For medium duration storage, diverse options available

			Medium duration
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]	✓

Significant technology development and innovation around medium-duration storage

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*

For long duration storage, fewer options, and higher uncertainty over route



Long duration

Dispatchable generation

Other zero carbon
- Hydro, nuclear[1] ✓

Fossil
- Fossil (or bioenergy) + CCS ✓
- Fossil – low/very low utilisation ✓

Key considerations include:
- Technical ability of the plant to ramp up and down at reduced capacity utilisation
- Efficiency of CCS at low load factors
- CCS cost trajectory

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] ✓

Key considerations include:
- Availability of H2-ready gas turbines
- Availability of sufficient H2 storage
- H2 cost trajectory

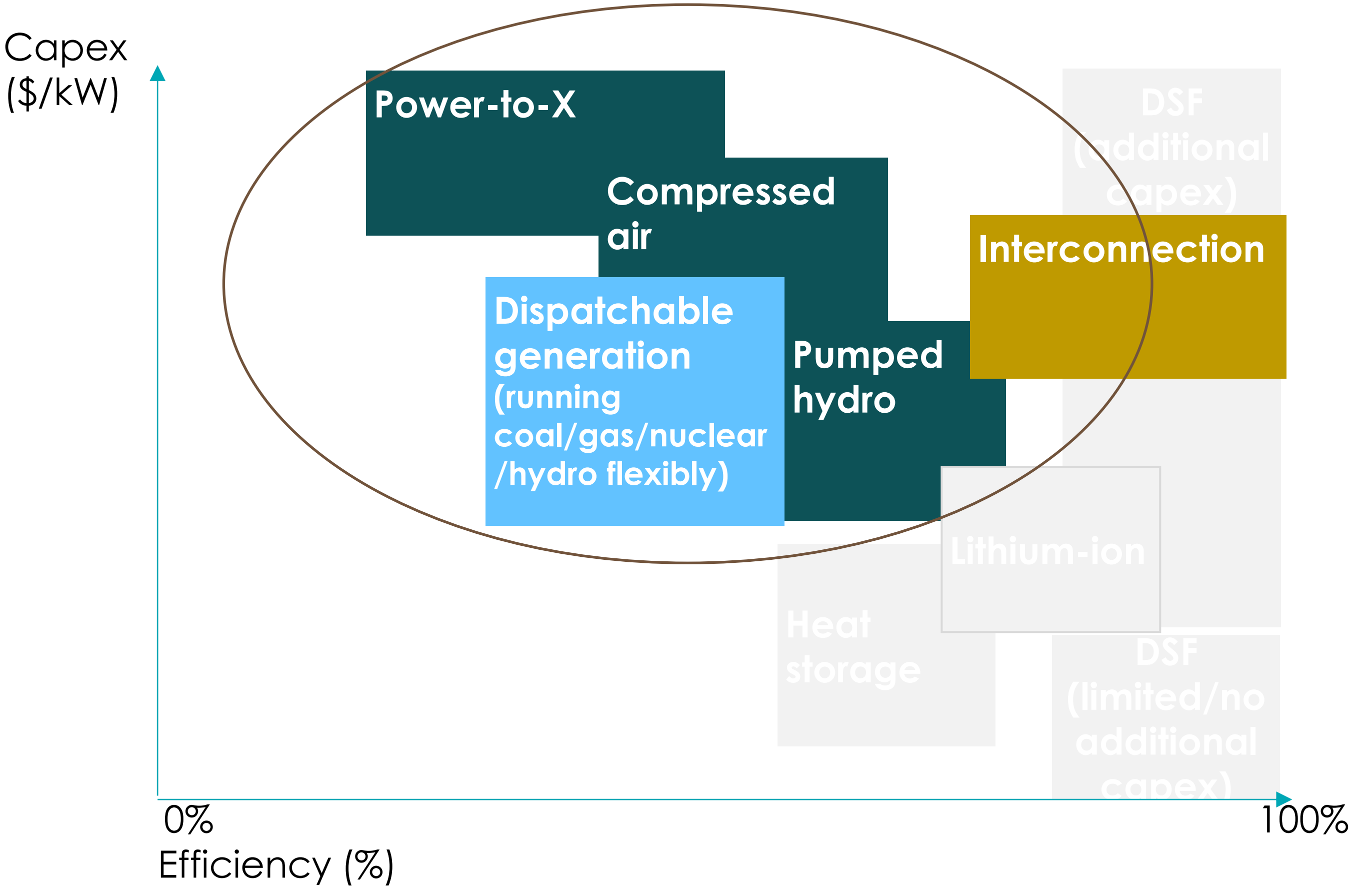
Heat storage
- Heat battery

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*

Medium, long duration balancing: reduced option set to meet these needs

Illustrative view of selected flexibility technologies



Capex & efficiency key determinants for 'levelised cost'

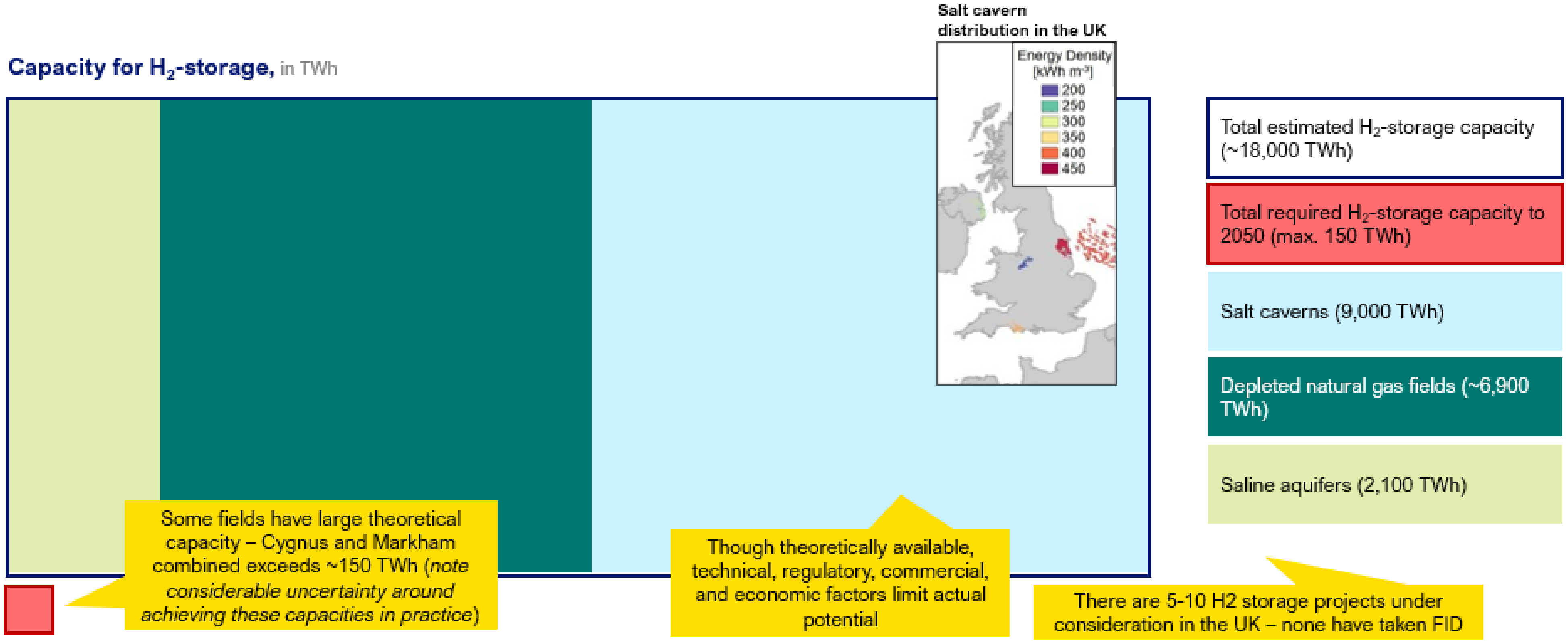
- **Significant technology development and innovation around medium-duration storage** which will determine cost pathways
- **For long-duration storage** (e.g. to meet security of supply needs), **only Power-to-X with storage** (e.g. H2 stored and then burned in CCGTs**) or dispatchable generation** will be able to meet duration needs

Source: Systemiq analysis for the ETC (2024).

Hypothetical: assuming all long duration was met via H2 route, annual volumes of H2 required could be easily stored within UK salt cavern potential

In minimum weather year, H2 requirements to meet all long duration storage would be ~40 TWh (~1.2 Mt)

Capacity for H_2-storage, in TWh



Total estimated H_2-storage capacity (~18,000 TWh)

Total required H_2-storage capacity to 2050 (max. 150 TWh)

Salt caverns (9,000 TWh)

Depleted natural gas fields (~6,900 TWh)

Saline aquifers (2,100 TWh)

Some fields have large theoretical capacity – Cygnus and Markham combined exceeds ~150 TWh (*note considerable uncertainty around achieving these capacities in practice*)

Though theoretically available, technical, regulatory, commercial, and economic factors limit actual potential

There are 5-10 H2 storage projects under consideration in the UK – none have taken FID

Note: assumes 26TWh of power generation needed in min weather year for the UK, with 50% CCGT efficiency of conversion from hydrogen into power. **Estimates for storage capacity and requirements are for the UK only, box sizes are proportional to total estimated storage capacity and not to volumes.**

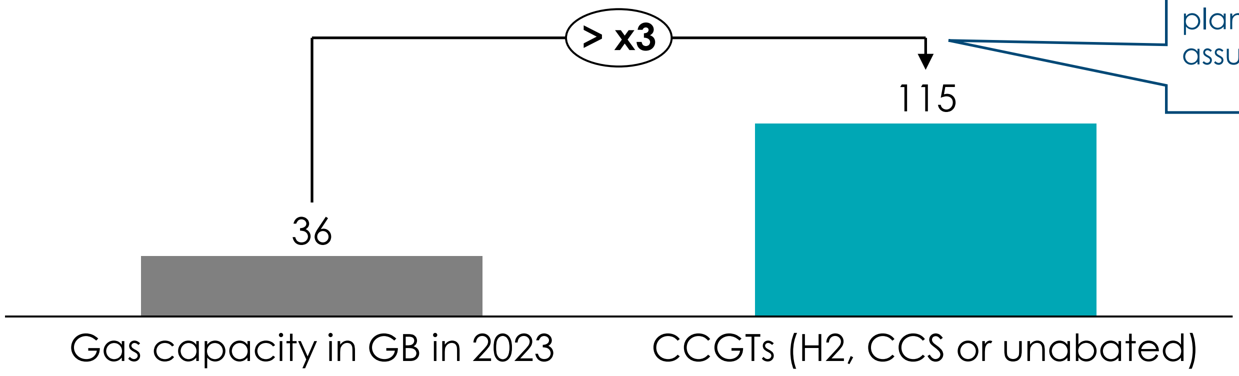
Source: Hydrogen UK (2022) Hydrogen Storage: Delivering on the UK's energy needs; Scafidi et al. (2021) A qualitative assessment of the hydrogen storage capacity of the UK continental shelf; Caglayan et al. (2020) Technical potential of salt caverns for hydrogen storage in Europe.
Systemiq analysis for the ETC (2024)

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

Archetype: Northern latitude (GB)

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

GW



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

	Gas capacity in GB in 2023	CCGTs (H2, CCS or unabated)
TWh of generation	**101**	**15***
Annual potential of TWh from fleet	315	1000
Annual capacity factor of fleet	32%	1.6%
Annual TWh of total demand	317	518
% of total demand met	32%	3%

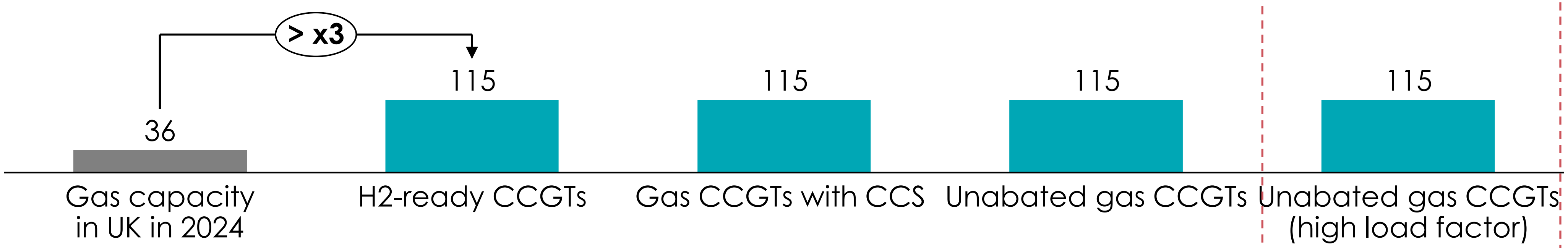
Sizing gas fleet to meet peak deficit periods for balancing **would require massive built of new low-carbon assets** – a fully renewable system could therefore actually require more (though much lower utilization, low carbon) turbine capacity

Note: based on max long duration balancing need. Note: Systemiq analysis for the ETC (2024).

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

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

GW



Cost vs emissions trade off for "last mile" decarbonization

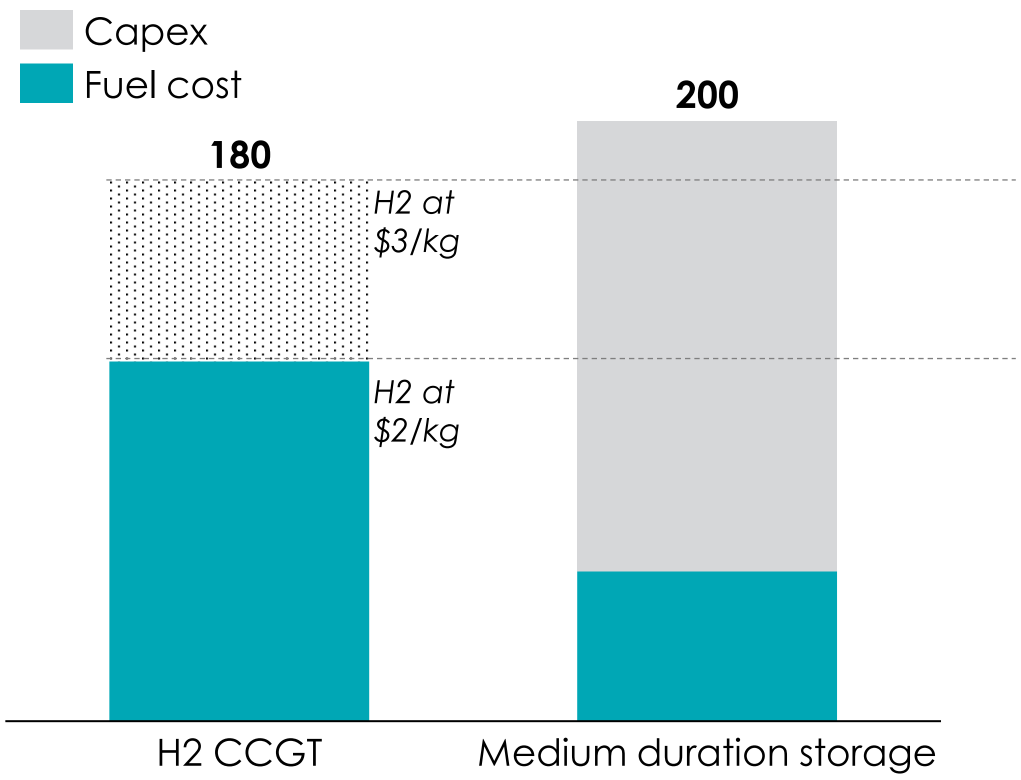
	Gas capacity in UK in 2024	H2-ready CCGTs	Gas CCGTs with CCS	Unabated gas CCGTs	Unabated gas CCGTs (high load factor)
Annual TWH of generation	101	15	15	15	50
Levelised cost ($/MWh)	n/a (existing)	370 $/MWh	460 $/MWh	204 $/MWh for new, but some existing	90 $/MWh for new, but some existing*
Additional annual cost for UK households (on typical household bill of $2000/year)	n/a	~ $ 95	~ $ 120	~ $ 40	~ $ 20
Annual emissions (MtCO2e)	~19 MtCO2e	~ 0 MtCO2e	~ 0 MtCO2e	3 MtCO2e	9 MtCO2e

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

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

If long duration storage already established on system, it may run at higher load factors, displacing medium duration storage

Short run marginal cost of long duration storage vs. levelized cost of medium duration storage
$/MWh



Key considerations:

- Medium duration storage may not meet sufficient balancing needs, requiring long duration storage instead
- If long duration storage already established on system then low marginal cost (mostly fuel cost) may displace role for medium duration
  - *Will depend on H2 cost pathways vs declining capex of medium duration storage*

Implications:

- May lower overall system costs by running 1x storage asset class more frequently
- Increases risk of higher emissions if unabated gas used for long duration

Source: Systemiq analysis for the ETC.
Notes: CCGT efficiency for H2 = 50%. Input elec price to medium duration storage = $30/MWh, with round trip efficiency of 60% assuming up to 20h duration with capex of $150/kWh..

Key considerations for delivering zero-carbon long duration storage

Need to maintain a portfolio of options, while de-risking early investment

To deliver zero-carbon long duration storage, will need to build some new gas capacity that is CCS/H2 ready; given **significant uncertainty over cost trajectories of CCS and H2, de-risking mechanism should ideally be technology-agnostic**

Any role of very low utilization gas should be properly ring-fenced

Role of **unabated gas should be limited to very low utilization for security of supply**, and properly ringfenced to ensure limited emissions; unabated gas emissions should be offset via carbon removals

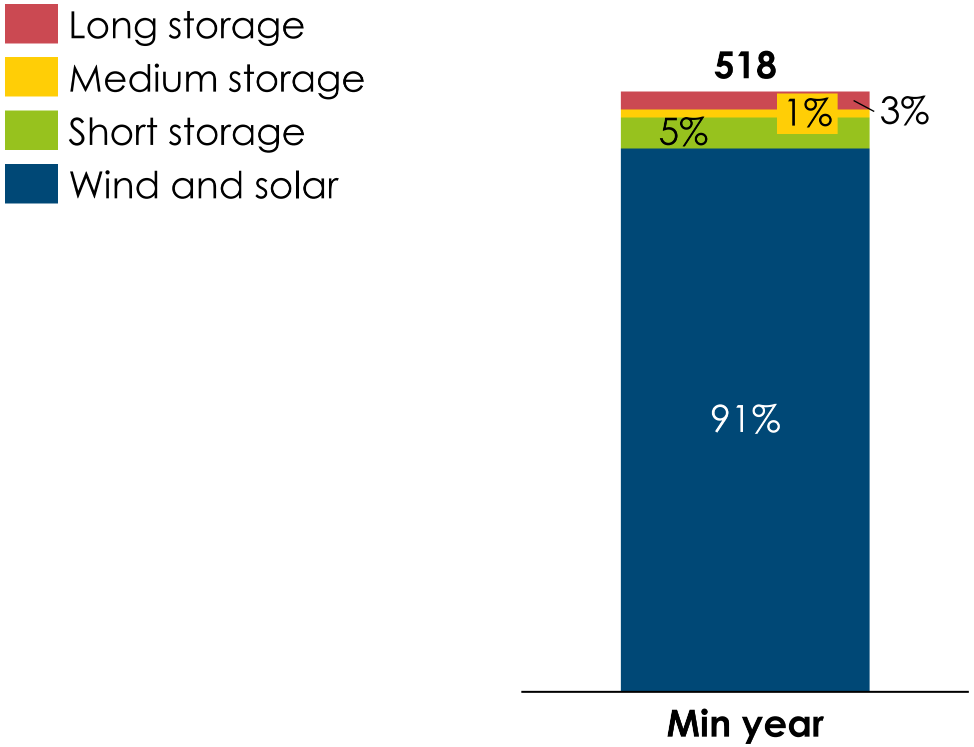
Cost of bringing on very low-utilization assets for security of supply

Low utilization capacity would likely need to be paid for by **additional capacity market revenue stream and/or strategic reserve model**

Total system generation costs for UK will reflect higher cost of longer duration balancing, but could be competitive with fossil system

Balancing variability for GB in a 100% wind and solar system

% of TWh provided by specified generation/storage



16 TWh long duration @ $400/MWh

7 TWh medium duration @ $200/MWh

26.5 TWh short duration @ $100/MWh

700 TWh wind and solar @ $35/MWh (includes surplus generation)

= $34.7 bn per year / 518 TWh demand

= $67/MWh Total system generation cost

Step back: macro considerations from this analytical approach

Key conclusions

1. **Assessing historical weather years is critical** - variation shows need to size the system for the “min” year

2. **Sizing a system with some level of overbuild of wind and solar *may* be cost-optimal, if it minimises the need for more expensive medium and long-duration storage.** In terms of excess renewable generation from overbuild:
   - A small share will be needed to charge storage during deficit periods;
   - A relatively significant share may be used for low-cost green hydrogen production;
   - A potentially large share could be used for export – but not for every country;
   - Some share will likely need to be curtailed; the cost to the system will depend on the renewable LCOE.

3. **For the Tropical archetype, meeting the short duration challenge would require a vast amount of short duration storage** – just for India, if all met via batteries, would be 2700% higher than total global battery capacity installed today. **Batteries also critically important in lowering system costs in other archetypes.**

4. **For the Northern latitude archetype, meeting the long duration balancing challenge could require building more new gas turbine capacity than exists today, though at much lower utilisation.** Meeting this challenge requires a portfolio of options (e.g. CCS, H2, likely marginal role for unabated gas – if properly ringfenced to ultra-low utilisation). **Once built, long duration storage may erode some need for medium duration.**

5. **Total system generation costs of zero-carbon power systems** will be lower for Tropical archetypes vs Northern latitude archetypes, could be competitive vs fossil in both cases

Workshops

Grid build challenge

Briefing note published in September 2024

March 26th

Key technologies to balance the system: *dispatchable generation, energy storage, heat storage*

June 18th

Key technologies to balance the system: *demand side flexibility*

Oct 9th

Sizing balancing needs across key regions

Oct 24th

Role of interconnectors
Key enablers

End 2024 / early 2025