Long duration electricity storage in GB

February 2022

About the study

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This study was conducted for a group of clients in the public and private sectors interested in the role of long duration electricity storage in the GB energy system. Some of the clients are shown below.

Our findings and policy conclusions are based on our own independent analysis and do not necessarily reflect the views of the participating clients. This document presents a summary of the key analysis and findings from the full report that was developed for participants.

About Aurora Energy Research

Aurora was founded in 2013 by University of Oxford professors and economists who saw the need for a deeper focus on quality analysis. With decades of experience at the highest levels of academia and energy policy, Aurora combines unmatched experience across energy, environmental and financial markets with cutting-edge technical skills like no other energy analytics provider.

Aurora's data-driven analytics on European and global energy markets provide valuable intelligence on the global energy transformation through forecasts, reports, forums and bespoke consultancy services.

By focusing on delivering the best quality analysis available, we have built a reputation for service that is:

- **Independent –** we are not afraid to challenge the 'norm' by looking at the energy markets objectively.
- **Transparent –** all our analyses undergo further refining through a detailed consultation process across our private and public sector clients.
- **Accurate –** we drill right down to the requisite level of detail and ensure results are internally consistent. In power market analysis, this means half hour granularity with complete internal consistency across energy, capacity, balancing and other markets.
- **Credible –** trusted by our clients, our results have proven bankability.

Main contacts

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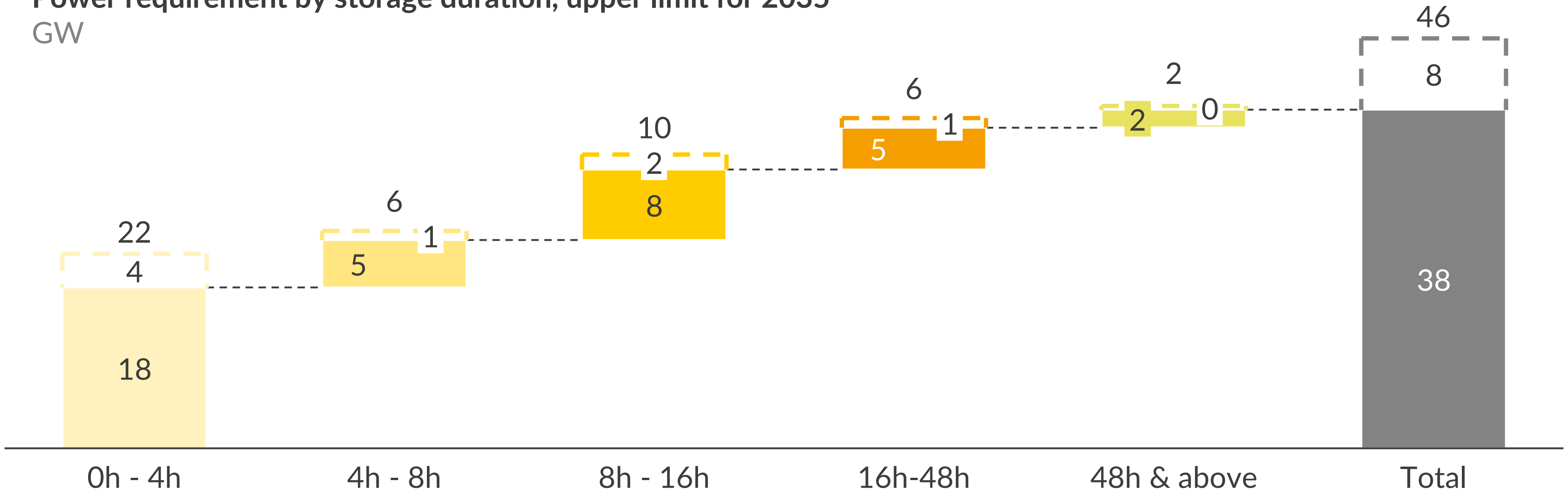
Executive Summary

- In a Net Zero world, up to 46 GW of electricity storage is needed by 2035, with up to 24 GW of Long Duration Electricity Storage (LDES) required to effectively manage the intermittency of renewable generation[1]
- LDES can be defined as technologies that are able to respond to supply and demand variations caused by daily peaks, weather events and seasonal patterns; providing energy for over 4 hours at their full capacity
- LDES has the potential to manage system constraints by reducing strain on the transmission network through locational balancing and to provide other system services, including voltage and stability control, required to meet security of supply objectives

Power requirement by storage duration, upper limit for 2035
GW



1) Excluding storage addressing the 0h-4h bracket yields 24 GW / 48 TWh of LDES. 2) The emissions reduction achieved by introducing LDES for system management at and above the B6 boundary.

Source: Aurora Energy Research

Executive Summary

- Introducing LDES will result in up to a 10MtCO_2/a fall in power sector emissions in 2035
- Total annual system costs could be reduced by £1.13 bn (2.5%) in 2035 if LDES is introduced, cutting average annual household bills by £26
- LDES deployment could reduce GB's reliance on gas in the power sector by up to 50 TWhth in 2035
- LDES can achieve revenues via energy trading in the wholesale market and through the balancing mechanism, which can be supplemented through capacity market and ancillary service revenues
- The need for LDES has been recognised by policymakers but at present, high upfront costs and long lead times, combined with a lack of revenue certainty and missing market signals, leads to under investment, resulting in higher power sector costs and emissions
- Policy support could be provided through direct support mechanisms, or via other market reforms to strengthen market signals
- A Cap & Floor mechanism is best positioned to support the deployment of LDES, however may not incentivise effective dispatch, and additional reforms could be required to incentivise investment

Source: Aurora Energy Research

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The UK Net Zero strategy targets net zero emissions in the power sector by 2035

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In the power sector, emissions have fallen by 72% between 1990 and 2019 to 59 $MtCO_2e$. Further emission reductions will be challenging as the most carbon-intensive abatements, such as coal emissions, have already been achieved by existing policy. The strategy highlights that the new 2035 target for all electricity to be sourced in a low carbon manner will not be easy, and provides a pathway to achieve the goal by reiterating previous policy as well as outlining new mechanisms and technologies.

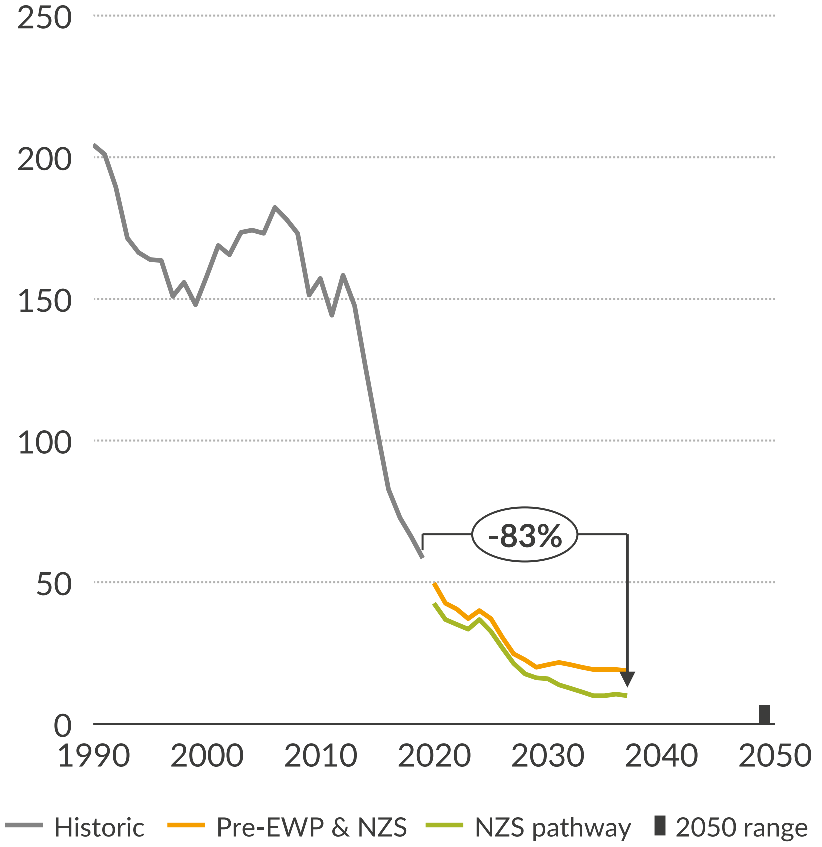
Key commitments in the Net Zero Strategy for power

2035	▪ Take action to ensure a low carbon energy system by 2035, subject to security of supply, which is expected to include some negative emissions BECCS to cover certain sectors[1]
	▪ Review the CfD auction frequency with the aim of **accelerating** deployment of renewables in GB, and ensure the volumes can scale, starting with the largest AR so far last December
	▪ Reach 40 GW of offshore wind by 2030, including at least 1 GW of floating offshore turbines. To reach this target a deployment rate of over 3 GW/yr will be required.[2]
	▪ Reach a final investment decision on a large, new build nuclear reactor before the end of the current Parliament (e.g. 2024). The recently announced Regulated Asset Base business model will help reduce financing costs and provide more revenue certainty for developers
	▪ Drive market-wide roll-out of smart meters, and deliver the 'Smart Systems and Flexibility Plan and Energy Digitalisation Strategy' to improve system flexibility significantly
	▪ Adopt a 'new approach' to onshore and offshore networks, improving efficiency and minimising environmental impact. Regulatory changes to allow anticipatory investment
	▪ Define the role of BECCS and CCS. The 2022 Biomass Strategy will assess the potential for BECCS, while CCUS has a target to remove up to 6 $MtCO_2e$/a by 2030.[3]

Whilst the government has made a number of key commitments to achieve Net Zero Power by 2035, new policies, further support for a wide range of low carbon technologies, and further consideration to network operability will be required if this target is to be reached.

Emissions outlook for the power sector

$MtCO_2e$ per annum



1) Such as residual emissions in agriculture, aviation and industry. 2) The deployment rate to date has been 0.9 GW/yr. 3) One of the polices discussed is to establish a liquid market for carbon removals through the UK ETS scheme which would provide a market-based solution for stimulating investments in carbon removals.

Source: Aurora Energy Research, BEIS

The policies and roadmaps within the strategy pose key questions about the buildout of low carbon generation and security of supply

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To achieve net zero by 2035 in the power sector, significant increases to annual deployment rates will be required for all renewable technologies, on top of new innovative capacity such as hydrogen, CCUS and BECCS. The Aurora Net Zero scenario requires the buildout of 40 GW of wind, 23 GW of solar PV, 11 GW of storage, 6 GW of peakers and 11 GW of gas CCS and H_2 CCGTs between 2021 and 2035.

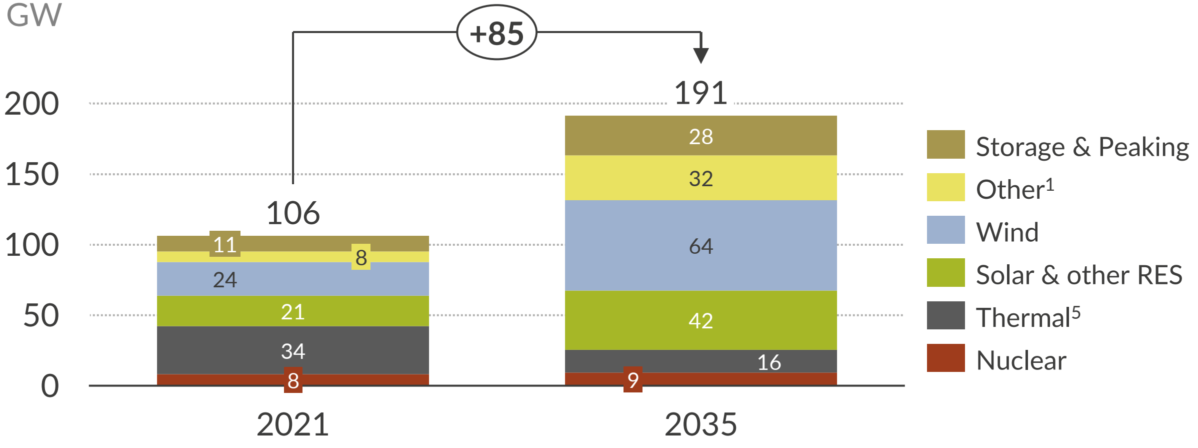
Low carbon capacity

- In order to meet demand but also reach net zero, total GB generating capacity must increase by at least 85 GW from today's levels by 2035, due in part to the lower load factors of intermittent renewables, which are expected to drive the net zero agenda
- This increase also includes significant peaking, interconnection and storage capacity that the Net Zero Strategy states is required to support the renewable fleet in a net zero power system

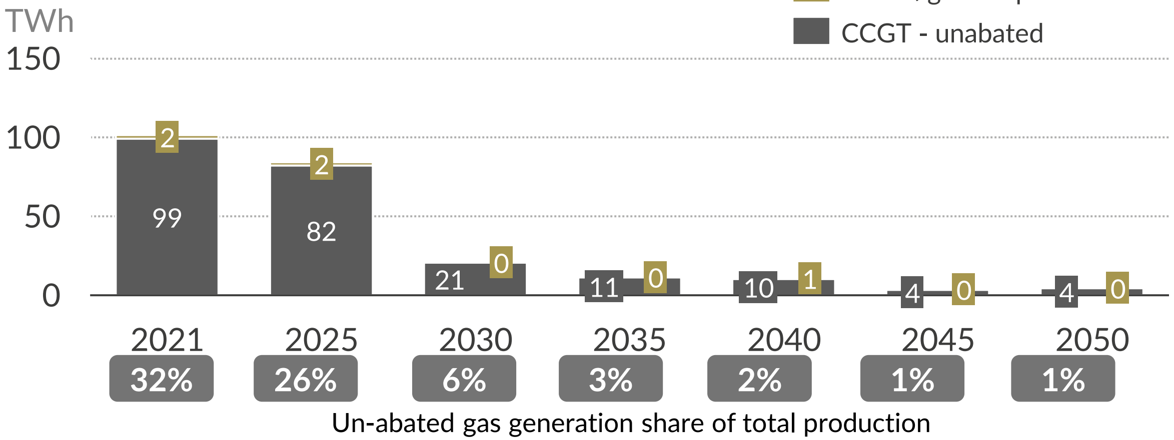
Security of Supply

- The Net Zero Strategy's 2035 target for the power sector is subject to security of supply being maintained
- Gas–fired technologies currently remain the only source of reliable capacity to keep the lights on during extended periods of low wind after shorter-duration storage technologies become depleted
- Long duration electricity storage is a viable alternative to gas-fired plants to provide reliable capacity during periods of low RES generation

Total installed capacity in Aurora Net Zero[6] scenario



Un-abated gas generation in Aurora Net Zero



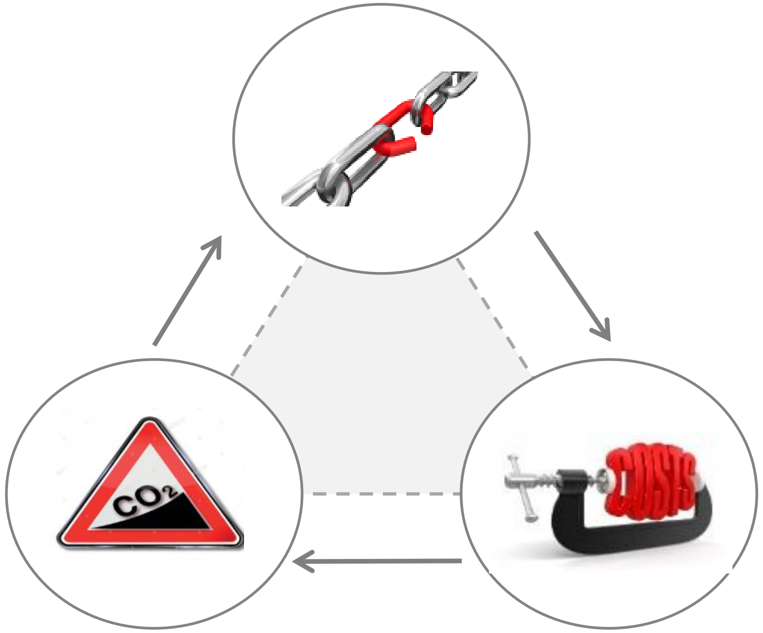
1) Other includes interconnection, DSR, Gas CCS and BECCS. 2) Storage includes battery storage and pumped hydro storage. 3) Peaking includes gas recips, OCGTs and hydrogen peakers. 4) Other RES includes biomass, hydro, EfW and marine. 5) Thermal includes coal, gas CCGT and oil-fired. 6) Note that when accounting for thermal constraints (thermal turn up caused by transmission capacities being exceeded), Aurora's Net Zero falls shy of 0 emissions by 2035, as explained in slide 23.

Source: Aurora Energy Research

To maintain security of supply, multiple system operability requirements need to be satisfied

UK energy policy aims to meet three overarching objectives, often referred to as the 'energy trilemma'. Of the three, ensuring energy security is expected to be most challenging in a Net Zero world and will have several key requirements.

Security of Supply



Decarbonisation

Minimising cost

X Deep-dives for each in next slides

1 Firm Capacity

- Energy security is guaranteed by ensuring adequate capacity is available during peak times

2 Flexible Capacity

- Capacities that are able to ramp up rapidly will be required to guarantee energy security as more intermittent renewable capacity comes online. This could see output vary significantly between settlement periods necessitating fast ramping capacities and increasing the need for balancing actions

3 Thermal constraints

- Thermal constraints must be managed to ensure transmission capacity is not exceeded. With higher renewable generation far from demand, the need for constraint management will rise

4 Frequency Response and Inertia

- Changes in system frequency can be harmful to the grid resulting in blackouts. Inertia is critical to prevent sharp movements in frequency, increasing resilience to energy imbalances
- Frequency response is also essential to counteract deviations if they occur. This is mitigated by generators that react instantaneously to changes in frequency by ramping up or down

5 Voltage

- Voltage on the grid must be kept stable to prevent damage to infrastructure and blackouts. Maintaining voltage is dependent on reactive power and Short Circuit Levels

6 Black Start

- Black Start services are vital in the event of total or partial system shutdown. As thermal assets are no longer reliably warm, alternative Black Start arrangements are needed

Source: Aurora Energy Research

Storage assets are an effective low carbon technology to maintain security of supply

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	Nuclear		Storage		Interconnectors	Synchronous condensers	Unabated thermal gas	
	Conventional	*SMR*	*Short-duration (0.5-4hr)*	*Longer-duration (>4hr)*	*EU-wide*	*Rotating stabilisers*	*Large-scale CCGTs/CHP*	*Peakers*
Commercial readiness	Mature	Nascent	Mature	Intermediate[3]	Mature	Nascent	Mature	Mature
Asset availability[1]	81%	Unknown	12 – 74%	95%	49 – 90%	No active power	90%	95%
Start-up time	12hr >	30 – 60 min	<0.1 min	0.1 – 10 min	<30 min	N/A	30 – 60 min	0.5 – 15 min
Synchronous generation and inertia contribution[2]	✓	✓	✗	✓	✗	✓	✓	✓
CAPEX	£4,000-5,000/kW	£3,600-4,500/kW	£250-950/kW	£600-5,500/kW	£600-700/kW	N/A	£500-600/kW	£300-450/kW
Carbon intensity	Zero	Zero	Zero	Zero	Low	Zero	High	High
Other comments	Only 20 GW of suitable sites available	Potentially large pipeline as land is not a limiting factor	Short duration assets have low de-rating factor owing to lower contribution to firm capacity provision	Variety of technologies at differing states of commercial readiness	19 GW potential capacity but limited reliability due to RES correlation in EU	Do not produce energy and will be powered by the grid	Thermal gas assets could be abated through conversion to hydrogen or CCS	

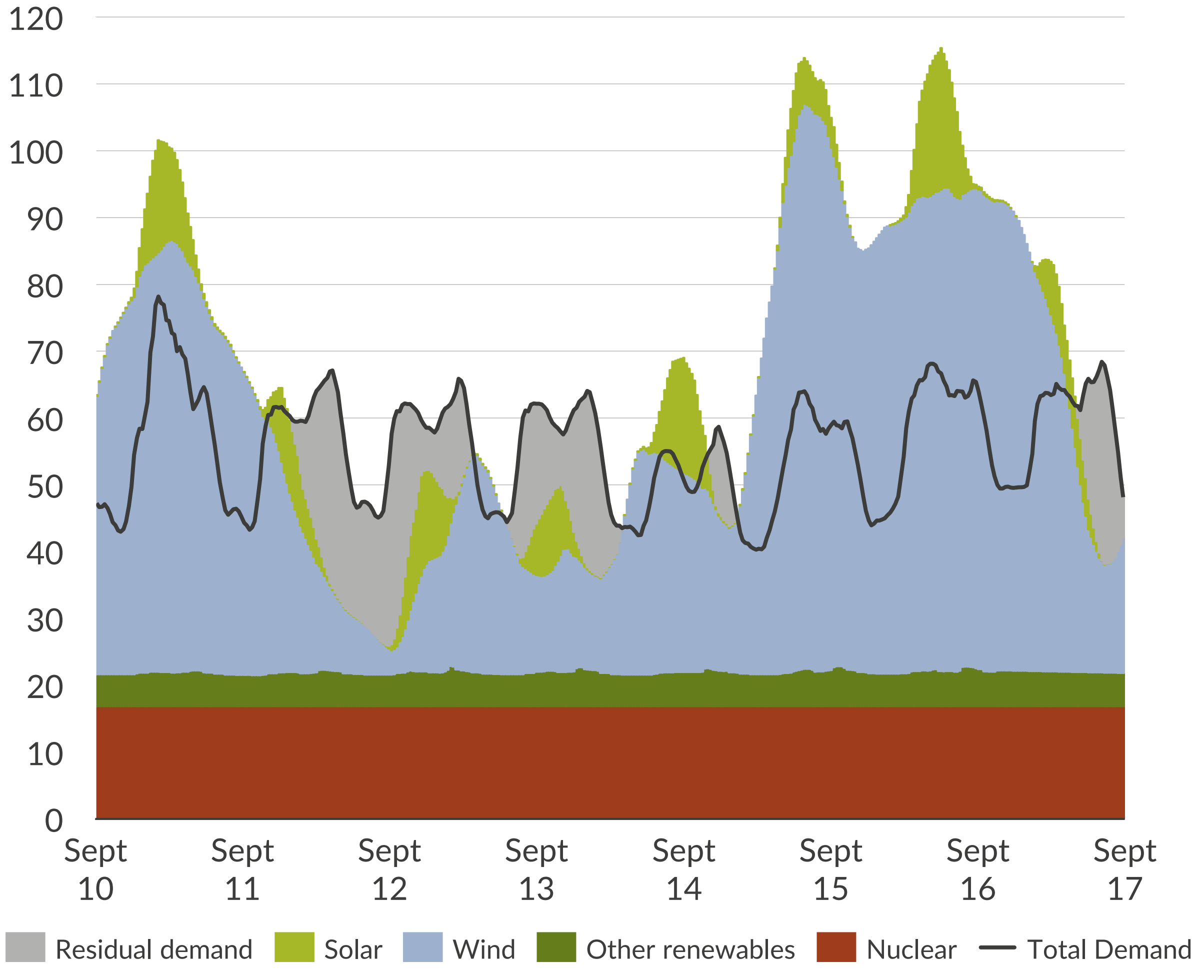
Focus of report

1) Quantified by the de-rating factors set in the Capacity Market auctions. 2) Synchronous generation also provides reactive power and short-circuit alongside with inertia. 3) Pumped Storage is a mature technology unlike other longer duration technologies. However, pumped storage is limited by suitable sites and costs can be very site specific. Overall, GB has the potential for roughly 10 GW of pumped storage.

Sources: Aurora Energy Research, EMR, BEIS

Daily and weekly energy shifting will be required to balance supply and demand across high and low wind weeks

Illustrative power demand in typical weeks
GW



1 Deep dive: Firm Capacity

Storage can provide firm, flexible capacity to help shift residual demand on a daily and weekly basis as the proportion of intermittent renewables in the power system increases

- A typical daily demand profile sees evening peaks in electricity demand and therefore in wholesale prices.
- Energy storage technologies allows these peaks to be met through the shifting of intermittent low carbon generation, rather than by peaking technologies, which may have higher carbon emissions
- As the electrification of heating takes place, peak demand in cold periods is expected to be amplified, although this effect may be offset by smart EV charging, DSR & H2 production
- Typically, peak demand periods are under 4hours in duration, meaning existing storage technologies can contribute to resolving this issue
- Shifting demand to mitigate the effects of longer term weather fluctuations, which last from days to weeks, can only be addressed by longer duration storage technologies

Source: Aurora Energy Research

Weather and demand patterns lead to a shortfall of low carbon generation in winter, which could be met via interseasonal storage

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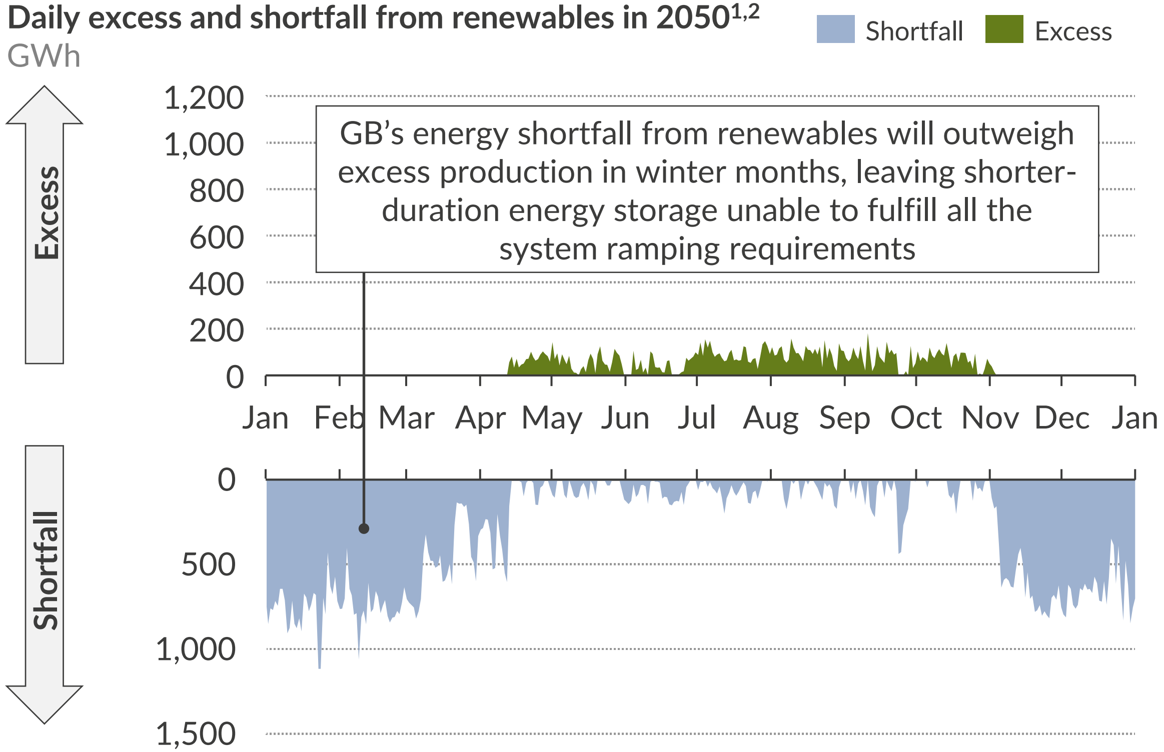
1 Deep dive: Firm Capacity

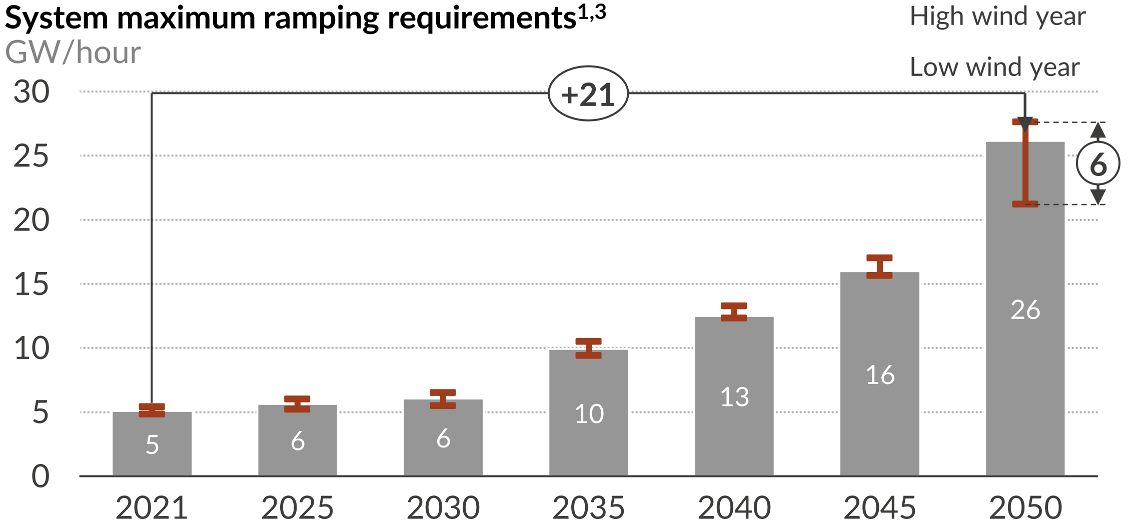
Daily excess and shortfall from renewables in 2050[1,2]
GWh



- Seasonal weather and demand patterns lead to a shortfall of low carbon generation in winter months, amplified by the electrification of heating, requiring firm capacity that can dispatch flexibly over weeks to months
- In a net zero world, this residual demand could be met by inter-seasonal storage such as hydrogen to power, or through abated gas

2 Deep dive: Flexible Capacity

System maximum ramping requirements[1,3]
GW/hour



- The growth of renewables will necessitate a higher buildout of faster-ramping generation as intermittent renewables can experience sudden shifts in output between consecutive hours
- By 2050, renewable output between two consecutive hours can fluctuate by up to 26 GW (up from 5 GW in 2021). However, this can also depend on weather outturns, where deviations in wind profiles could result in differences in requirements of ~6 GW
- The need for fast-ramping generation rises by over 20 GW from now to 2050

1) Shown for Aurora Net Zero. 2) Excess and shortfall are calculated as the difference between demand and production from low carbon sources including solar, offshore- & onshore wind, and nuclear. 3) Difference in residual demand from one half-hour to the next. Residual demand is calculated as the difference between demand and generation from intermittent renewables.
Source: Aurora Energy Research

Increasing renewable penetration will increase thermal constraints which must be managed to prevent transmission capacity being exceeded

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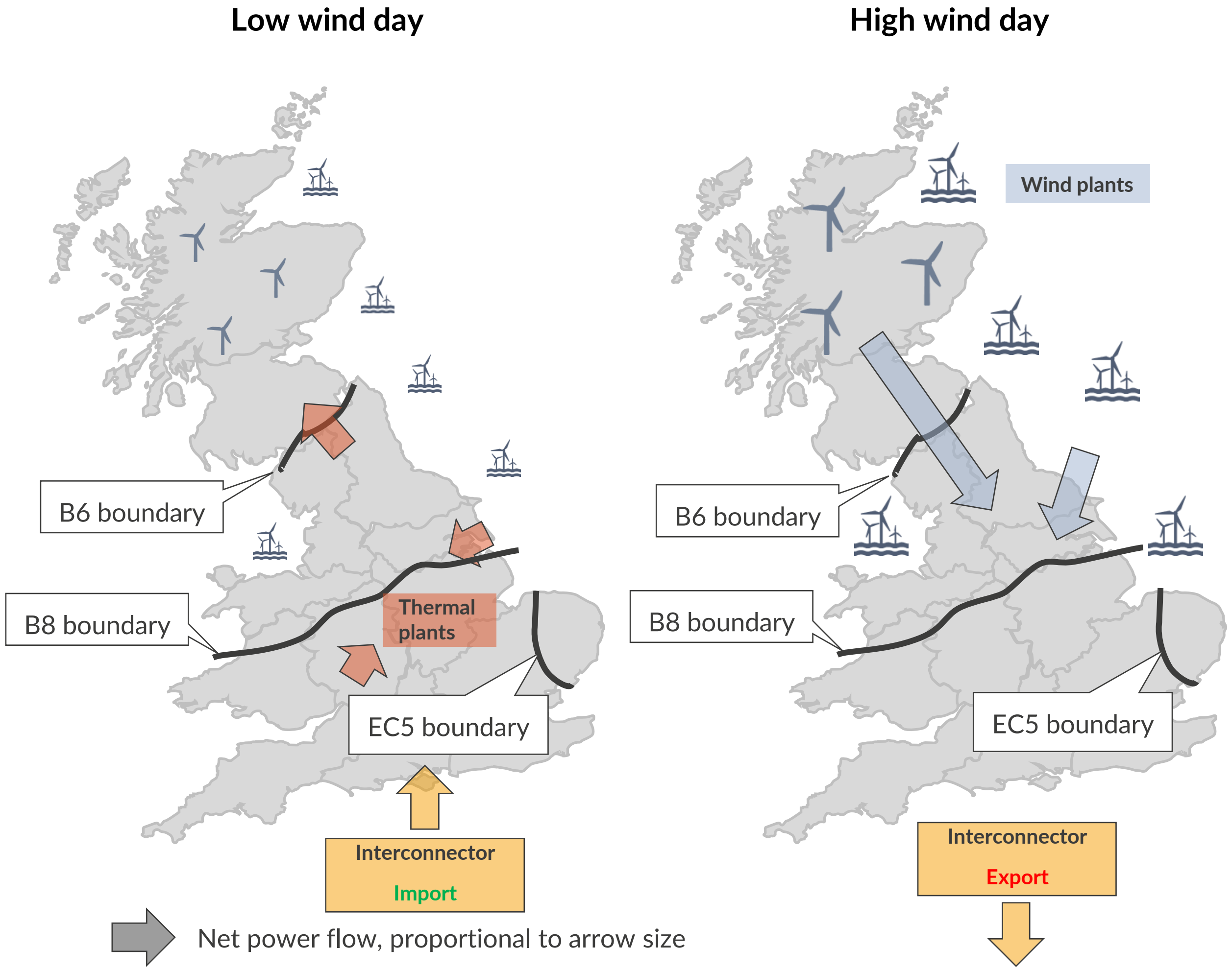
3 Deep dive: Thermal constraints

Higher renewable penetration has lead to increased thermal constraints, putting pressure on transmission infrastructure

- Changes in the generation capacity mix are seen as a key enabler in reaching Net Zero in the UK and are often discussed at length, however the impact on power flows and networks are often less referred to
- With demand focused in the South and large volumes of intermittent wind generation expected to be located in the North, this has increasingly lead to highly variable North-South power flows
- Interconnectors also add a bi-directional valve to the system, predominantly in the South of the country
- The B6 boundary, the main bottle neck between the low carbon generation of the North and the demand centre of the South is constrained for the majority of the time and c.10% of total system constraints occur here. Other key constraints include the B8 and EC5 boundaries
    - Distribution constraints, particularly in the southwest which has high levels of embedded solar, are also becoming more significant
- The transmission network will have to adapt to accommodate growth in demand and the changing configuration of power flows which will require continued investment to keep the power flowing
- Other system considerations, such as voltage and reactive power, must also be considered on a locational basis

Power flows across GB on a windy or non-windy day in the North GB



Sources: Aurora Energy Research, National Grid ESO

Storage can help manage thermal constraints, reducing the curtailment of wind output and reducing power sector emissions

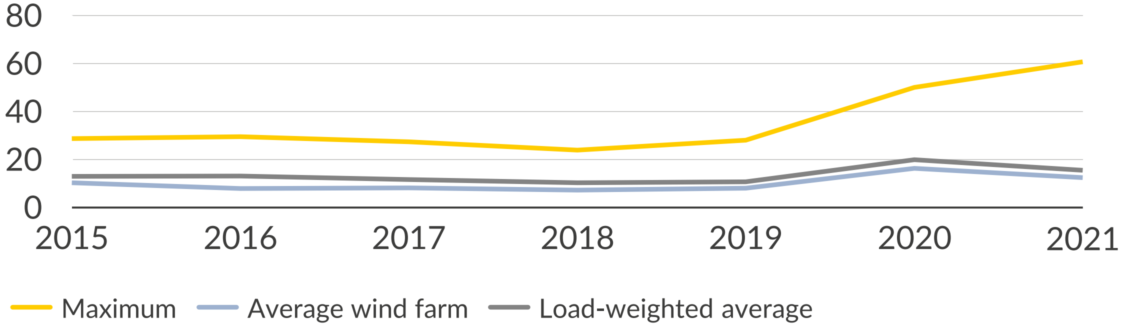
3 **Deep dive: Thermal constraints**

- There has been an increased need for system balancing actions to manage constraints created by locational imbalances in supply and demand
- This increases total system costs and results in higher emissions overall as thermal plants are also required to turn up
- COVID-19 lockdowns provided an insight into how a future power system might look, with high renewable generation in relation to total system demand. This resulted in high volumes of curtailed wind generation, high BM costs and high BM emissions as a proportion of total sector emissions

Long duration storage presents an alternative to transmission infrastructure reinforcement as curtailed energy could be stored and dispatched in low wind periods, reducing constraint-induced system costs and emissions

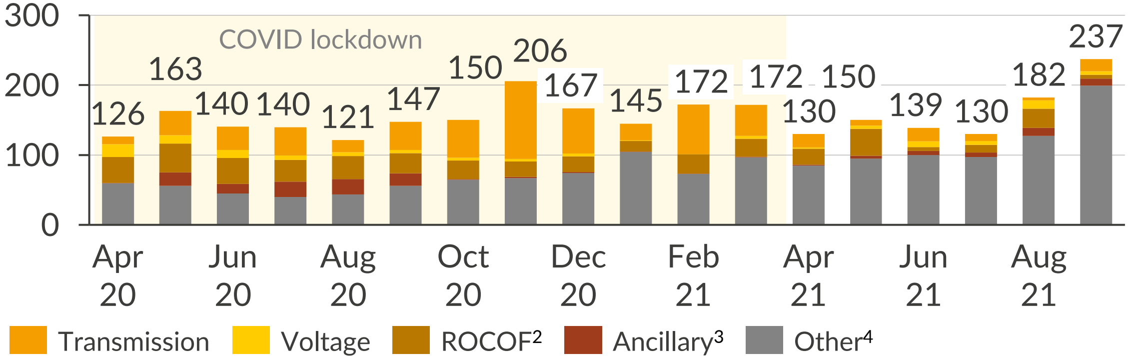
Curtailment of a load-weighted average onshore wind farm reached c.20% of FPN volumes in 2020, driven by system balancing requirements

Curtailment rates for BM registered onshore wind[1]
% of FPN



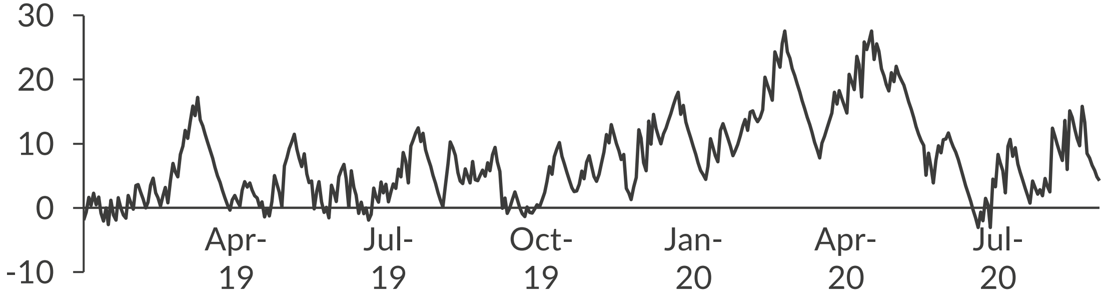
The costs of managing transmission constraints comprises a significant proportion of total system balancing costs

Balancing costs in 2020/21, £m, monthly



Up to 25% of power sector emissions have resulted from balancing actions as thermal plants in the south turn up to counteract system curtailment

Proportion of power sector emissions from BM
% of power sector emissions



1) Curtailment defined as Tagged actions in the BM. 2) Rate of Change of Frequency. 3) Includes payments to EDF to turn down Sizewell nuclear station. 4) Includes Energy Imbalance, Frequency Response, Reserve, Reactive, Black Start, and Minor Components.
Sources: BEIS, National Grid, Aurora Energy Research

A high RES system will have lower interia and higher requirements for voltage control and reactive power, which could be met by LDES

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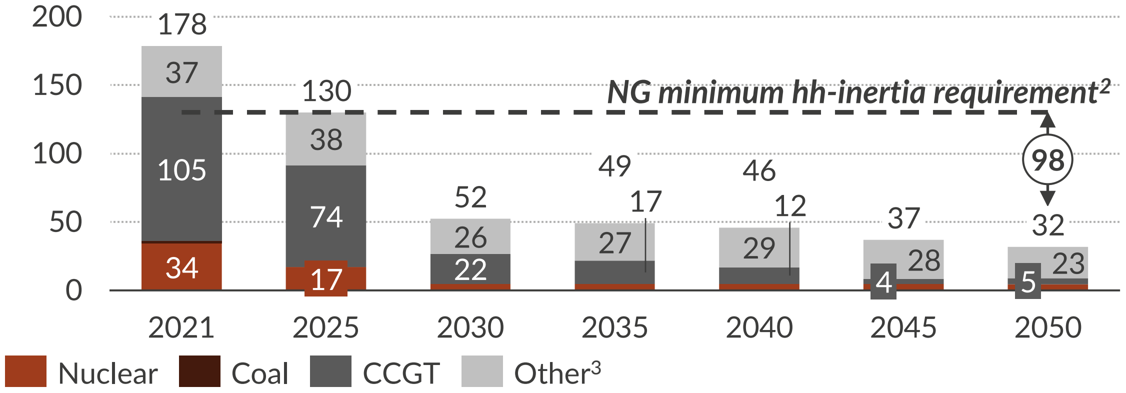
Deep dive: Frequency Response and Inertia, Voltage and Black Start

- A shift away from un-abated thermal generation towards non-synchronous renewables lowers system inertia which must be replaced
- As renewables erode the load factors of thermal capacities, new sources of voltage control are needed, which could be provided by storage assets
- A system where these requirements are not met will suffer a lack of operability and threaten energy security. This could result in frequent power outages and blackouts. The system will therefore require sufficient low carbon firm capacity that is capable of meeting these requirements

Long duration electricity storage will be able to contribute to these system requirements, reducing costs of procuring these services from elsewhere

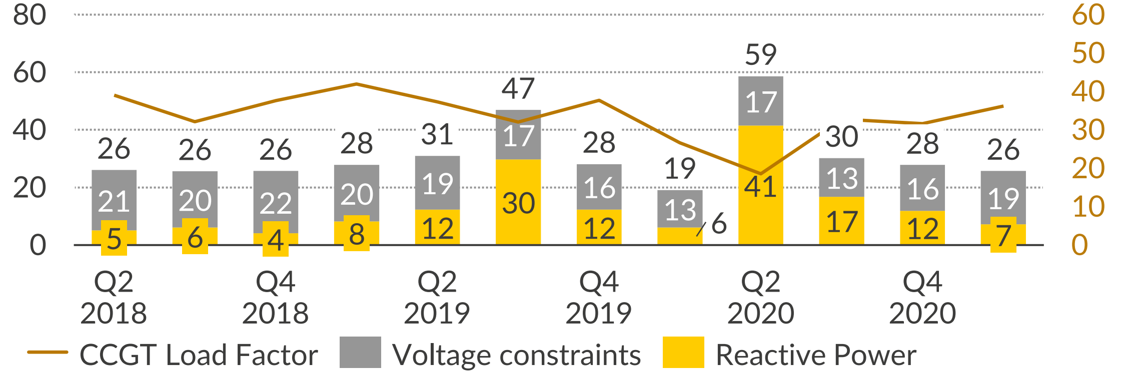
4 Inertia contribution from conventional assets is set to fall by more than 80% to 32 GVA.s by 2050, well below National Grid requirements

Yearly average inertia contribution from existing capacity, GVA.s[1]



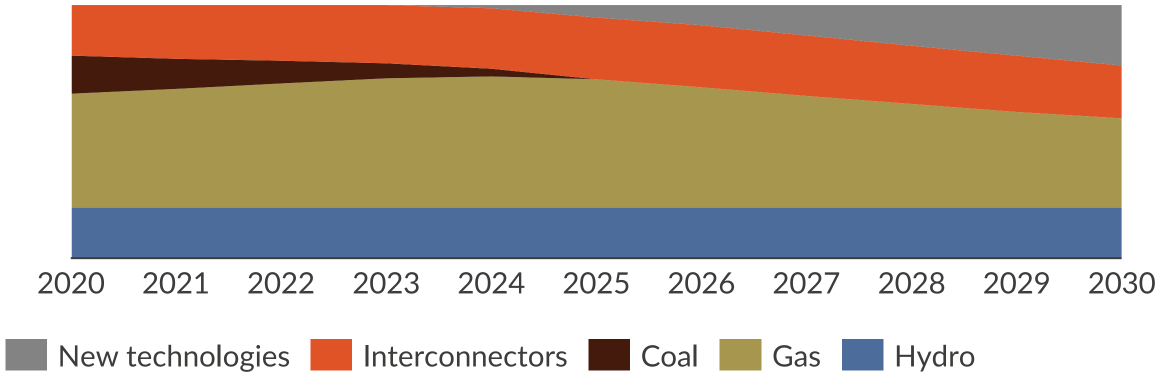
5 In a high renewables power system, CCGT load factors will be lower than today, leading to greater requirement for alternate sources of voltage

Reactive and voltage costs, £m, (real 2020) **CCGT load factors,** %



6 Black Start services will require reform as thermal technologies are no longer reliably warm and able to act when required

Indicative Black Start provision technology breakdown



1) Giga volt amp seconds. 2) National Grid has previously published that the lowest amount of inertia the system can manage at any given half-hour is 130 GVA.s. However, the system has on a few occasions already seen system inertia fall below this level.
3) Includes biomass, pumped storage, run-of-river and OCGTs.
Sources: Aurora Energy Research, National Grid

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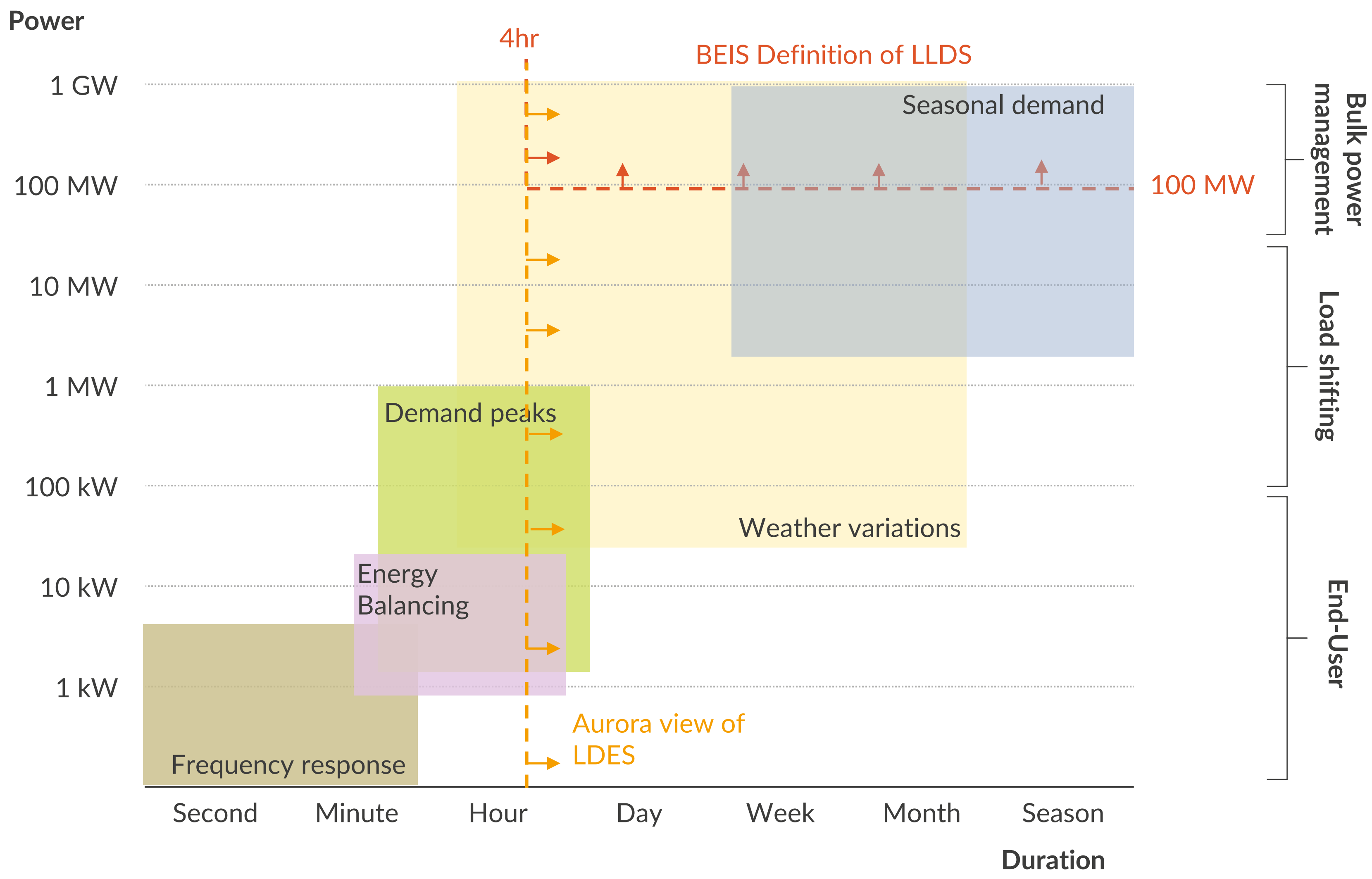
Long-duration storage can be defined by its ability to mitigate the intermittency of renewable generation



BEIS Proposed Definition

Large-scale and Long-duration electricity storage is expected to be able to store and discharge energy for over **4 hours**, up to days, weeks and months and deliver power of at least **100MW** when required

Aurora view

Long-duration storage technologies are able to respond to supply and demand variations caused by daily peaks, weather events and seasonal patterns

For GB, this primarily means intraday, interday, weekly and seasonal shifting. Therefore LDES technologies are able to provide energy for over **4 hours**, with no **power limit**

Durations above four hours, or higher capacities, could therefore be reached through different combinations of asset durations and capacities[2]

1) Note the definition proposed by BEIS in the LDES consultation referred to large scale and long duration storage, whereas Aurora has chosen to focus on all long duration storage regardless of size. 2) I.e. several shorter duration plants could act in tandem to achieve longer durations and several smaller capacity plants could act in tandem to achieve higher capacities, depending on the needs of the system

Source: Aurora Energy Research

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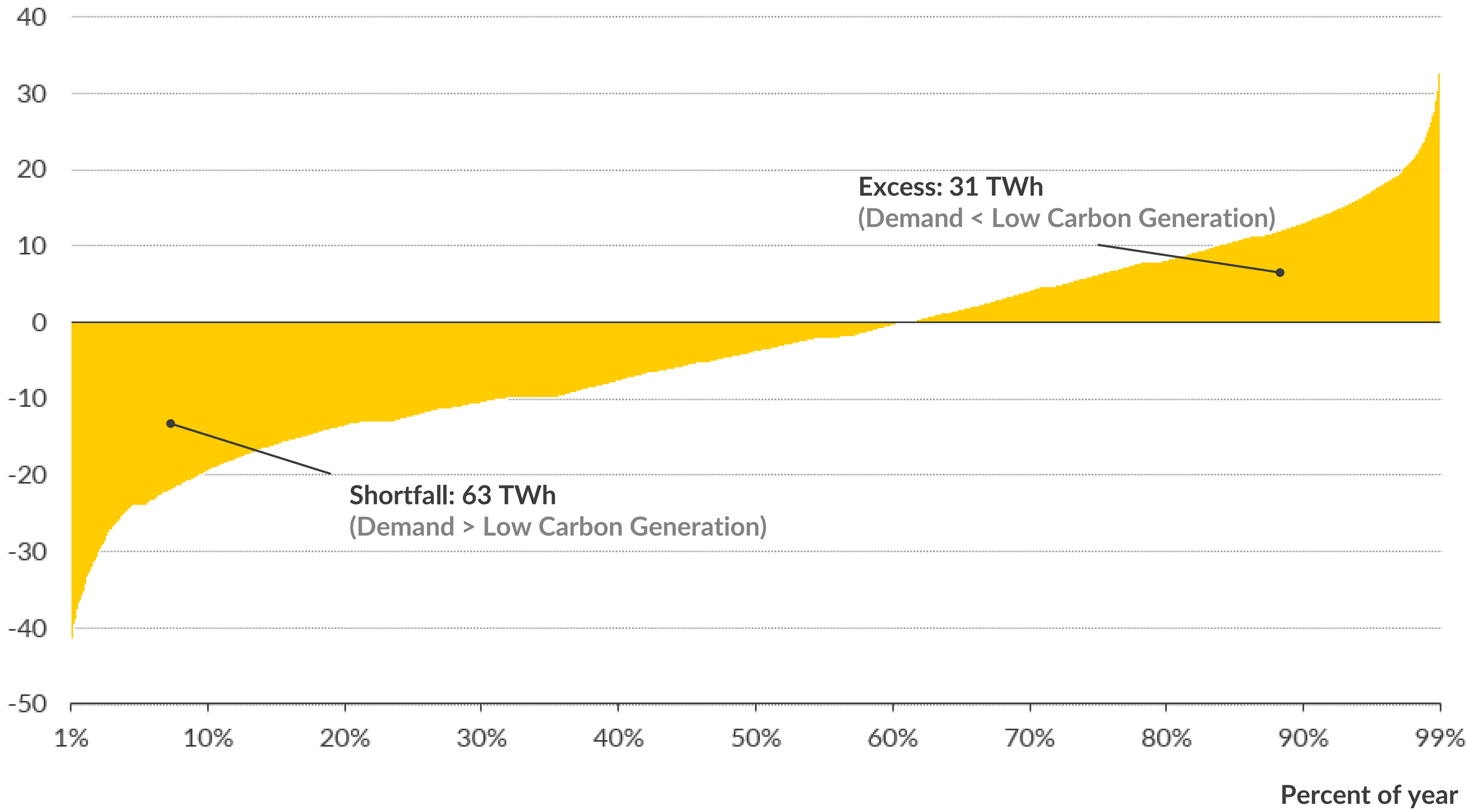
Long-duration storage could be vital in managing periods with an excess or deficit of renewable generation in a net zero world

Residual demand[1] (2035 in Net Zero)
GW



1) Includes generation from wind, solar, nuclear, biomass and interconnector flows

Source: Aurora Energy Research

- Net Zero in 2035 will see larger and more frequent periods where there is excess generation from low carbon sources[1]
- Nuclear and renewables alone cannot securely supply all electricity throughout the year, around 61% of the year (63 TWh) will need to be supplied by dispatchable generation, such as CCGT's with CCS, at peak powers of up to 50 GW
- The remaining 39% of the year will see generation from low carbon sources exceed demand with a peak power reaching 38 GW
- Without some form of long-duration storage or generation sink, this 31 TWh of excess generation may end up being curtailed
- Additional curtailment may also be required for transmission constraint purposes

Additional LDES may help to reduce the curtailment of Scottish wind generation in a net zero world

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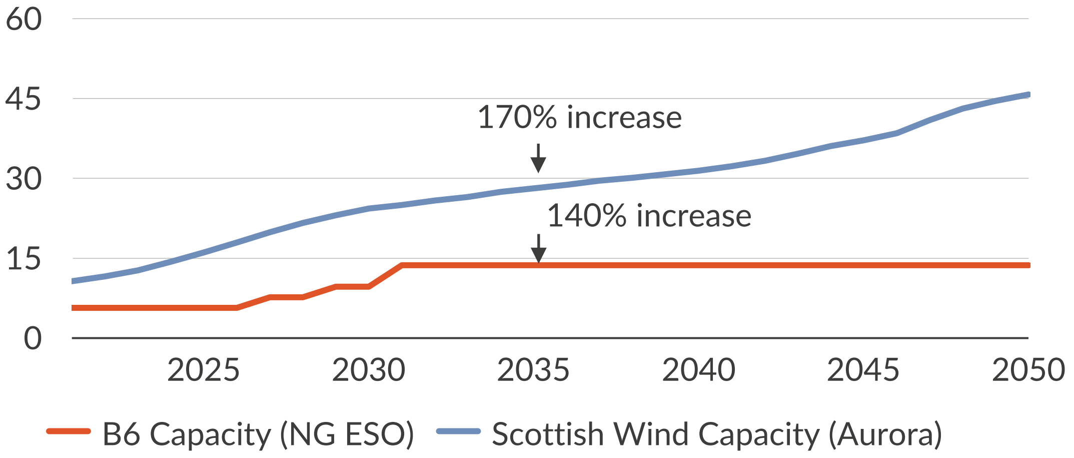
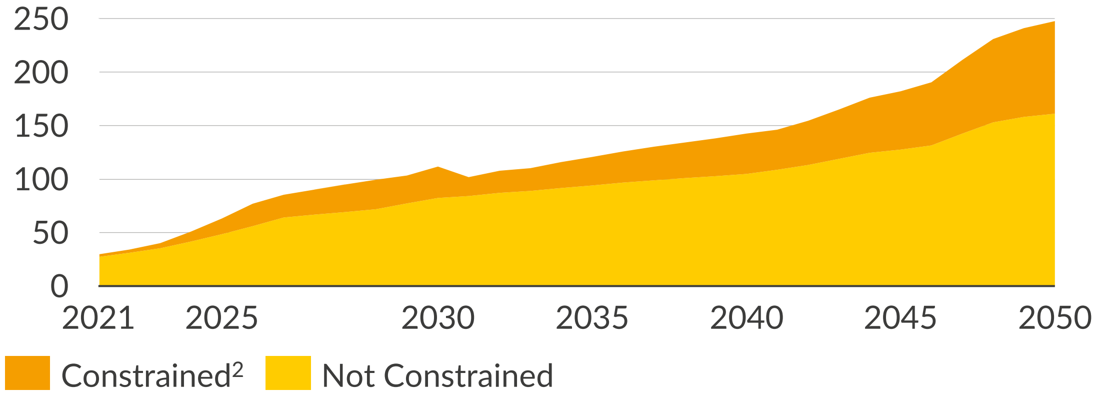
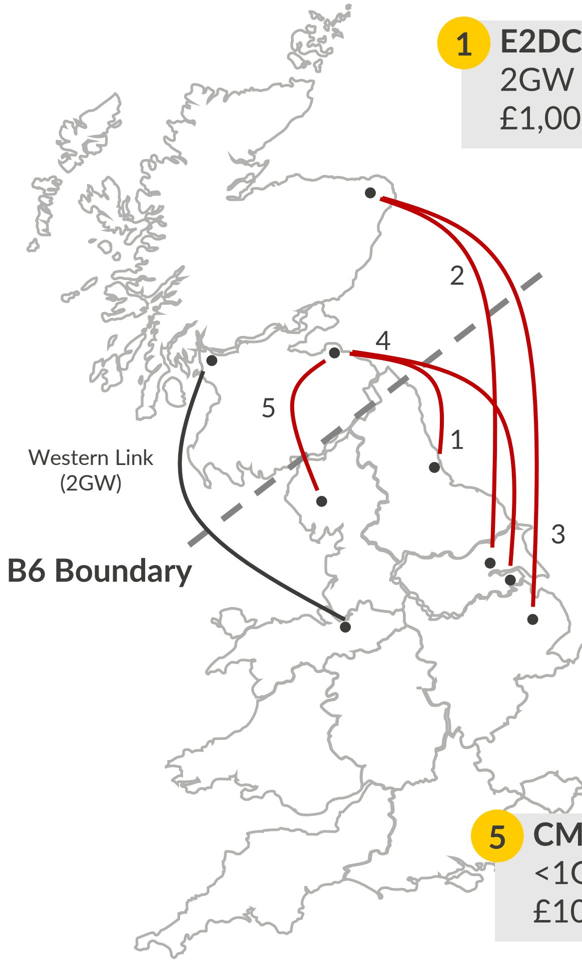
Changes in Scottish wind capacity compared to B6 transmission capacity[1]



Scottish wind generation





1 E2DC – Torness to Hawthron
2GW by 2027
£1,000 - £1,500 million

2 E4D3 – Peterhead to Drax
2GW by 2029
£2,000 - £2,500 million

3 E4L5 – SE Scotland to NE England
1GW by 2031
£2,000 - £2,500 million

4 TGDC – Torness to South Humber
2GW by 2031
£1,500 - £2,000 million

5 CMNC – SE Scotland to NW England
<1GW by 2033
£100 - £500 million

NG is planning 7 GW build out of transmission capacity across the B6 boundary by 2035, however this will not keep pace with the expected build-out of Scottish wind capacity in a net zero world, which could result in further curtailment of RES resources

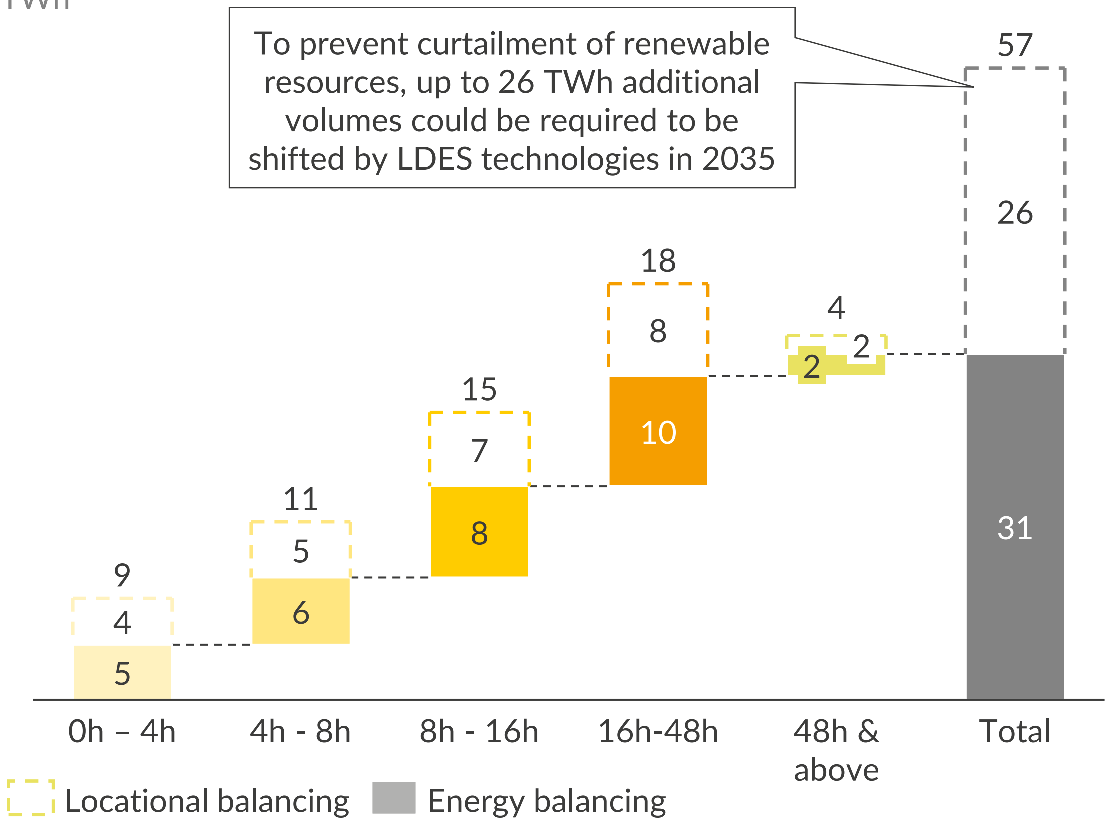
1) Assumes build out of transmission capacity in line with NOA6 targets, and build out of Scottish wind capacity in line with net zero targets laid out by UK & Scottish governments. 2) Constrained generation is equal to 8% in 2021 and rises to 35% in 2050.

Source: Aurora Energy Research, National Grid ESO

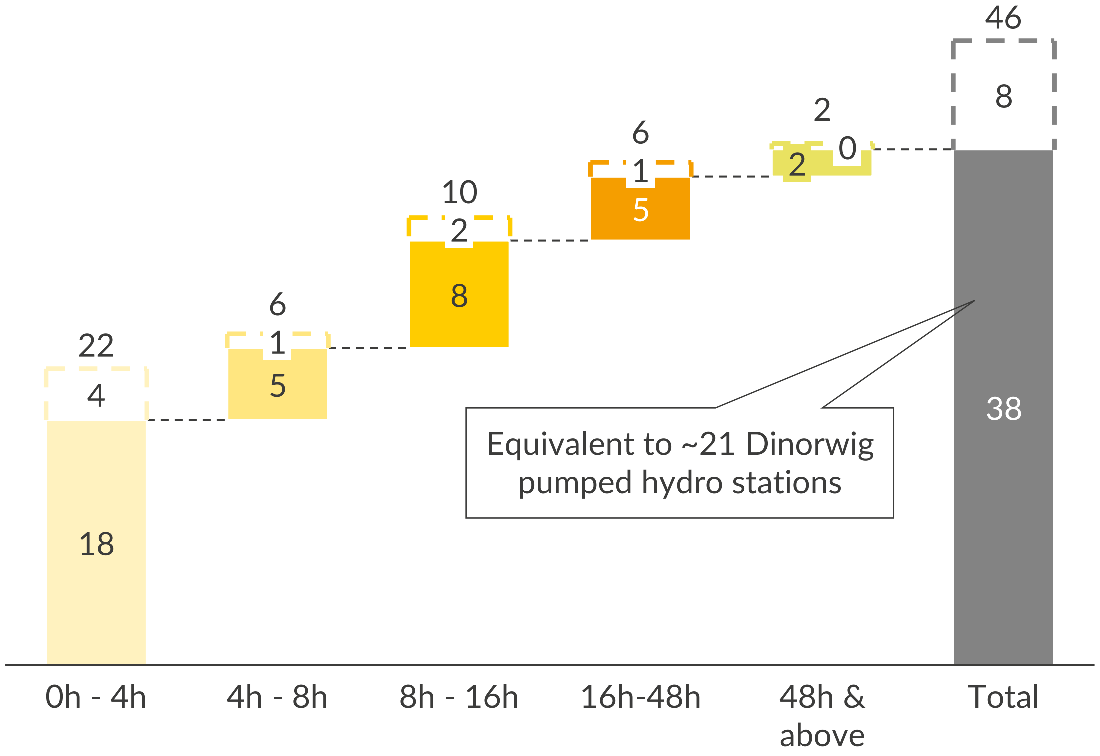
In our Net Zero scenario, as much as 38GW storage is required in 2035 to redistribute excess RES generation

It is estimated that a maximum of 31 TWh is available to be shifted from periods of excess renewable generation in 2035, this corresponds to a maximum power requirement of 38 GW. In addition to this, it is estimated that up to an additional 26 TWh of energy will be constrained due to network capacity limits. Detailed network modelling would be required to understand how much of this could be addressed by storage but, if it could all be addressed, that would lead to a potential further power requirement of 8 GW. The requirements for different durations for energy shifting shown was determined using the number of forecast consecutive half hourly periods with an energy shortfall or excess. The remaining shortfall will be met using gas (abated or unabated).

Energy available to be shifted by storage duration, upper limit for 2035
TWh



Power requirement by storage duration, upper limit for 2035
GW



Source: Aurora Energy Research

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Introducing LDES reduces total power sector emissions by up to 10 $MtCO_2e$ by 2035 compared to our standard Net Zero scenario

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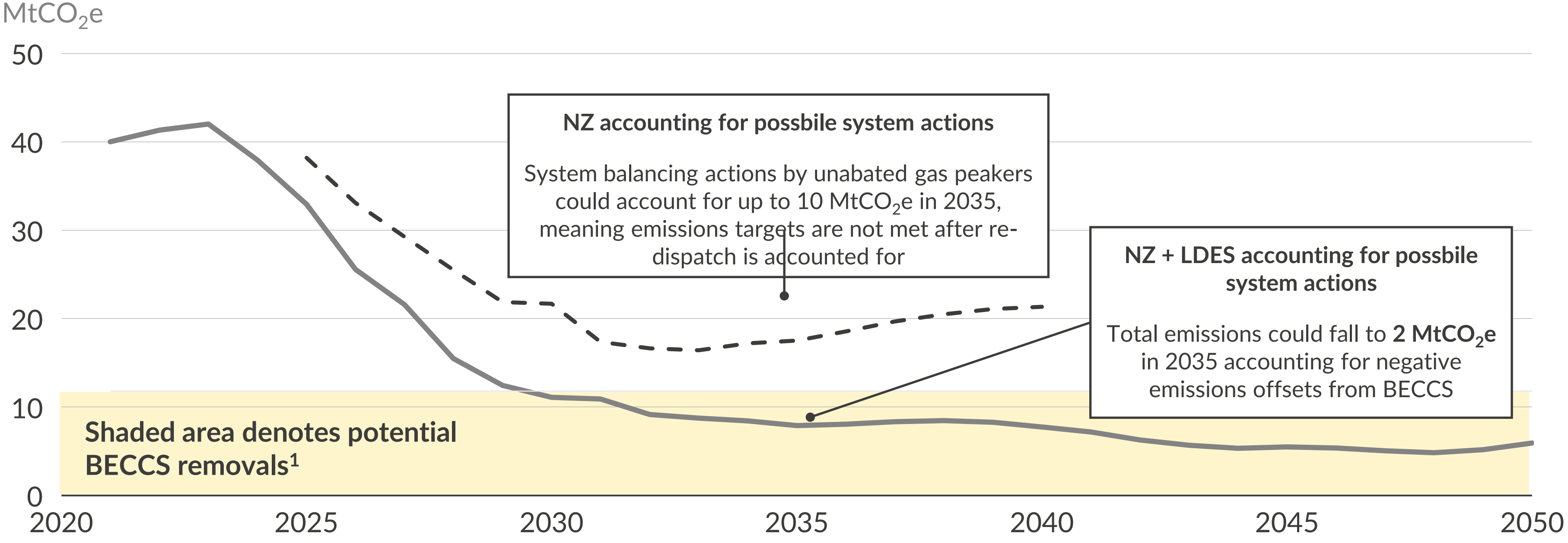
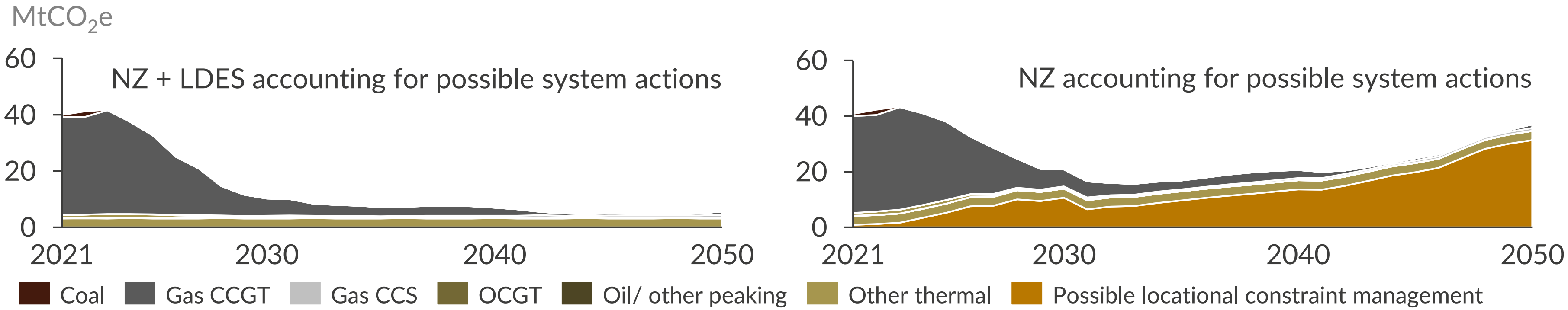
Total power sector carbon emissions (before BECCS)



Total power sector carbon emissions by technology (before BECCS)



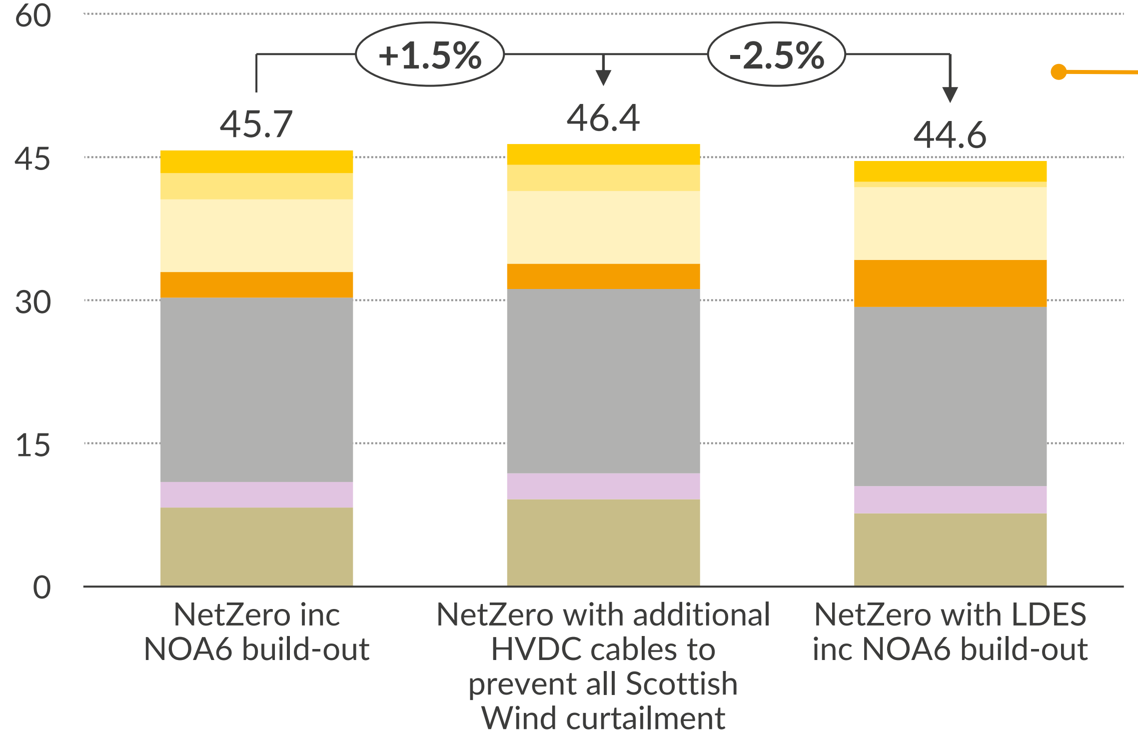
1) Removals calculated using an assumption of 3 GW of BECCS capacity running at 47% load factor, using a carbon intensity of -941 gCO2/kWh.

Source: Aurora Energy Research

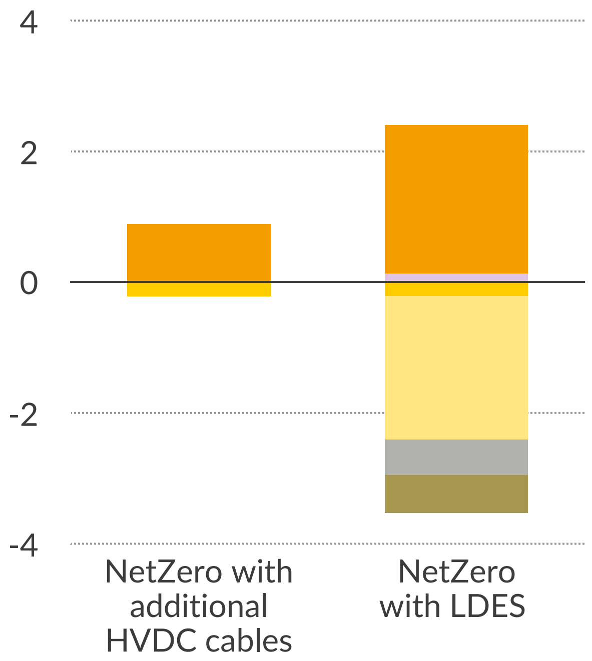
- Power sector emissions from the wholesale market are around net zero by 2035, after accounting for negative emissions from BECCS
- However, without LDES technologies, the requirements for upwards actions from thermal plants for constraint management purposes could result in up to 10 $MtCO_2e$ additional emissions, meaning emissions targets are missed
- With the introduction of LDES, these emissions can be reduced as any upwards balancing requirements are offset by the discharge of LDES in low wind periods, replacing thermal dispatch in these periods

The introduction of LDES could result in up to 2.5% lower total system costs by 2035

Power system costs (2035)
£bn (real 2020)



Potential cost reductions achieved by using LDES to achieve Net Zero, compared to Aurora standard NZ
£bn (real 2020)



Average annual household bill in 2035 (electricity only, no supplier admin costs)
£ (real 2020)

£1,042	£1,057	£1,016

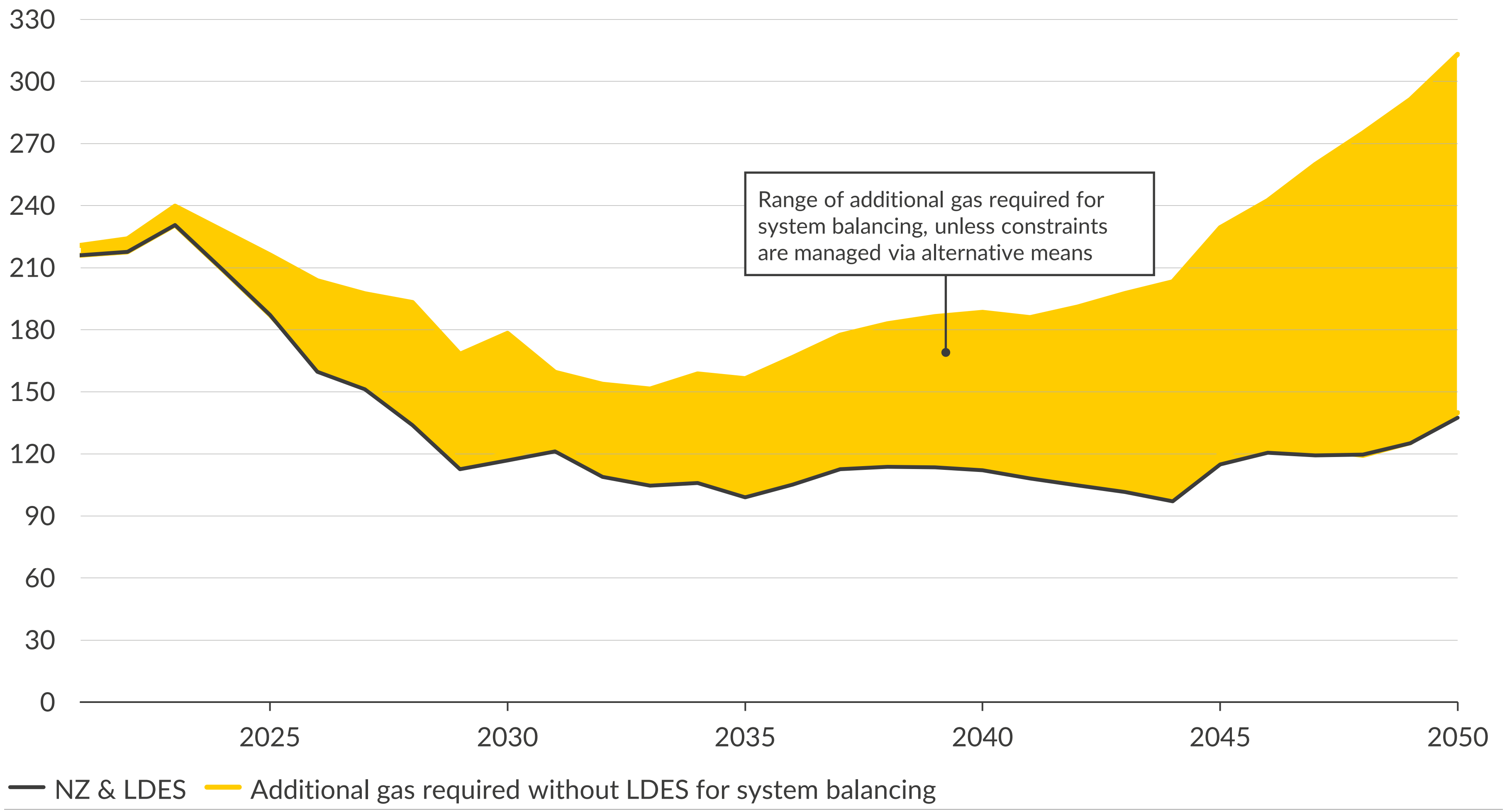
Balancing | Capacity Market | Existing Subsidies[1] | Subsidy topup[3] | Wholesale | Hydrogen | Other

- Total system costs, and therefore costs to consumers, could be reduced by c.2.5% if LDES was introduced
- Build-out of transmission capacity laid out in NOA6 is assumed in both scenarios
- In an alternative scenario, where sufficient network capacity was constructed to prevent all curtailment of Scottish wind generation for system balancing reasons[2], total system costs, and therefore costs to consumers, are expected to be 1.5% higher then our standard Aurora net zero scenario
- The cost of supporting low carbon generation is shown in the existing subsidy topup, with LDES support shown in the subsidy topup

1) Includes forecast cost of FiT, ROC and CfD payments. 2) 28GW Scottish wind assumed in 2035. 3) Represents subsidy schemes that have not yet been developed and covers any additional subsidies required to ensure positive IRRs of added technologies
Source: Aurora Energy Research

Introducing LDES results in a reduction of 50 TWHth gas used in the power sector in 2035, reducing GB's reliance on imported supply

Average annual gas usage
TWhth



- Gas usage in Net Zero declines rapidly out to 2035 as unabated Gas CCGTs are displaced with RES. Post 2035, gas usage remains flat and then increases slightly post 2045 as more Gas CCS enters the system and from system balancing needs
- Fluctuations in gas prices create market vulnerability, as seen in Sept 2021 when gas prices reached new highs, causing higher bills for consumers
- Introducing LDES will reduce the UK's dependence on gas imports for the power sector by up to 50 TWhth in 2035 by reducing the need for unabated gas turn-up from system balancing
- However, as LDES competes with electrolysers during low price periods, the introduction of LDES could results in higher demand for blue H2 (therefore gas) for use in other sectors

Source: Aurora Energy Research

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Several LDES technologies are in the spotlight to be commercially deployable in the near-term, each fulfilling niche system needs

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Descriptions of long duration storage technologies

	Description	Development	Advantages	Disadvantages
Pumped Hydro Storage	Surplus electricity used to pump water from low to high reservoir. Flow reversed to produce electricity	▪ Largest global project: China, Fengning PSH station, 3.6 GW / 3.42 TWh	▪ Long lifespan and low costs of storage ▪ Established technology with high technical maturity	▪ Deployment restricted geographically ▪ Large projects with long lead times require secure revenue streams
Li-Ion Batteries	The movement of lithium ions between the anode and cathode in an electrochemical reaction results in battery charge and discharge	▪ Largest global project: Hornsdale, Australia 100 MW/ 129MWh	▪ EV deployment will drive cell costs down ▪ Multiple chemistries available offer different. operating characteristics ▪ Throughput warranties now readily offered	▪ Storage life limited by high degradation costs ▪ Depth of discharge limited by degradation ▪ Poor voltage and stability support ▪ Resource and end of life environmental and social issues
Liquid Air (LAES)	Surplus power used to compresses and cool air to liquid form. Air is evaporated and run through a turbine to produce electricity	▪ Largest global project: Bury, England 5MW / 15 MWh	▪ Long project lifetime and discharge duration ▪ Locational flexibility ▪ Can simultaneously charge and provide stability services ▪ Long life and scalable	▪ Significantly slower response times than Li-ion ▪ Low efficiency (50-60%): requires waste heat to reach 70% efficiency
Flow Batteries	Electrolytes are stored in separate tanks; where they meet, ion exchange occurs causing charge/discharge	▪ Largest global project: Dalian, China 200 MW/ 800 MWh	▪ Lack of degradation; 0-100% depth of discharge operation ▪ Long lifespan (20,000 cycles) ▪ Scalable and recyclable	▪ Lower efficiency and power density than Li-ion ▪ High relative £/kW capex due to relatively higher BoS costs

Sources: Aurora Energy Research, RedT, Invinity, Highview Power, Lazard, REEM, Hydrowires

Several LDES technologies are in the spotlight to be commercially deployable in the near-term, each fulfilling niche system needs

AURORA

Descriptions of long duration storage technologies

	Description	Development	Advantages	Disadvantages
Compressed Air Energy Storage (CAES)	Air is compressed and stored underground. Expanding air is released through turbine to produce electricity	▪ Northern Ireland – 268 MW (Estimated 2020)	▪ Longer asset life than batteries ▪ Components are well developed technologies	▪ Diabatic CAES still requires gas for heating ▪ Location requires specific geological features e.g. salt caverns
Gravitational Storage	Similar to PHS: mass is lifted using surplus power, The lowering of mass is used to turn generators to produce electricity	▪ Gravitricity – 250 kW pilot (Currently under construction) ▪ Energy Vault – 8 MW demonstrator (under testing)	▪ Easy to construct near established networks ▪ Levelised cost below that of lithium ion batteries	▪ Requires suitable geological conditions ▪ Technology under development
Thermal (i.e. molten salt)	Using solar heat to increase the temperature of molten salt, which can be used to heat water to steam to run turbines	▪ Dunhuang, China – 100 MW	▪ Established technology ▪ Scalable ▪ Capable of interseasonal storage	▪ Relatively low energy density ▪ Requires insulation to prevent large heat losses
Hydrogen to Power	Hydrogen can be produced via electrolysis. The stored chemical energy can be released by combustion or in a fuel cell to generate electricity	▪ ITM Power – 24MW[1] (attained Government funding)	▪ Can be transported ▪ Can power vehicles, heating devices and industrial processes. ▪ Can be stored at large volumes for long periods	▪ High cost of pressure tanks for storage that cannot store much H2 ▪ Need construction of hydrogen infrastructure

1) Power-to-gas

Sources: Aurora Energy Research, Gravitricity, Lazard, REEM, Hydrowires, IRENA, Energy Vault

Eight LDES technologies are in the spotlight to be commercial deployable in the near-term, fulfilling niche system requirements

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Parameters of long duration storage technologies[5]

Key value areas ● More applicable ○ Less applicable

	Construction time, yrs	Market readiness	Location flexibility	Congestion relief	Energy Arbitrage	Ancillary Services	Operating cost[6]
Pumped Hydro Storage	3-8	●	○	◕	◕	Inertia, reactive power, SCL, Black Start	◕
Li-ion Batteries	1-2	◔ [1]	●	◔	◕	Frequency	◑
Liquid Air (LAES)	2	◑	●	◕	◑	Inertia, reactive power, SCL, Black Start	◑
Flow batteries	0.5-2	◑	●	◑	◕	Frequency, reserve, inertia[2], reactive power[2]	◕
Compressed air (CAES)	3-5	◑	◑	◕	◔	Inertia, reactive power, SCL, Black Start	◑
Gravitational	2	◔	◑	◕	◕	Frequency, reserve, Black Start	◑
Thermal (i.e. molten salt)	2[3]	◕	◑	◕	◔	Inertia, reactive power, SCL, Black Start	◕
Hydrogen to power	3-4[4]	◑	◔	◕	◑	Inertia, reactive power, SCL, Black Start	◔

1) Short duration Li batteries are market ready, long duration is not yet seen to be established in the market; 2) Suitable power conditioning system required; 3) Concentrated solar power with storage; 4) CCGT only 5) Under consideration are versions of technologies that fall within the Aurora definition of LDES (durations of 4+ hours) 6) A full Harvey ball implies favorable operating costs, i.e.: low.

Sources: Aurora Energy Research, Invinity, Hydrowires, RedT, Invinity, Highview Power, Gravitricity, Lazard, Riverswan, Energy Vault, Hydrostor, Element Energy

The costs of deploying LDES assets is anticipated to fall over time, with decline rates dependent on volumes deployed

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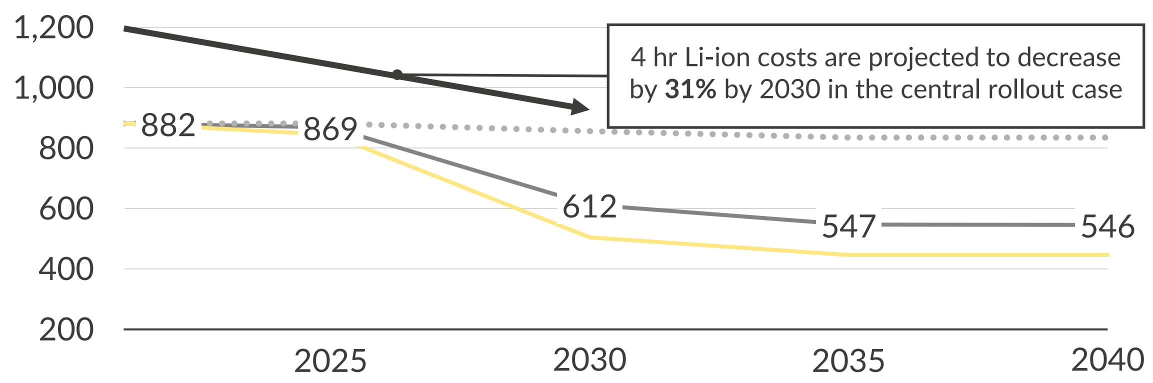
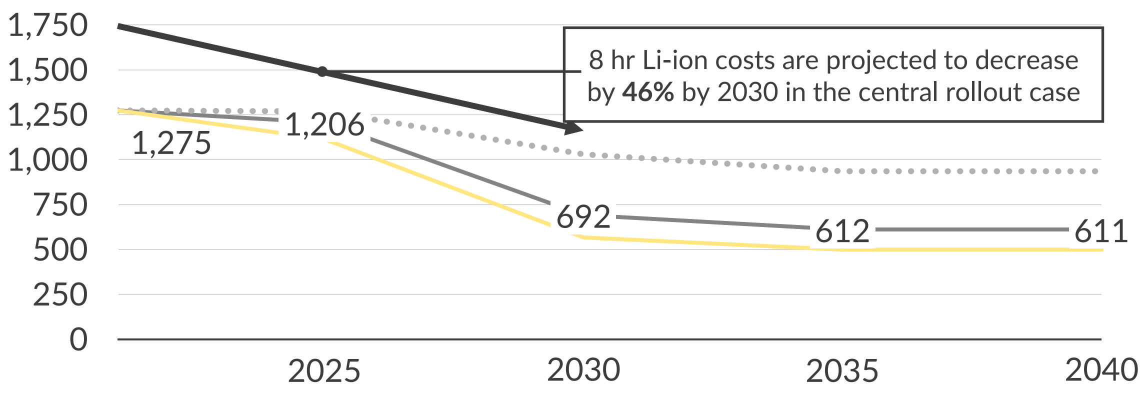
Cost declines are shown for 3 different technologies based on rollouts anticipated globally by 2050. PHS and CAES are considered mature technologies & costs are not expected to decline significantly with rollout. Cost declines for Li-ion and VFB depend heavily on assumed commodity costs

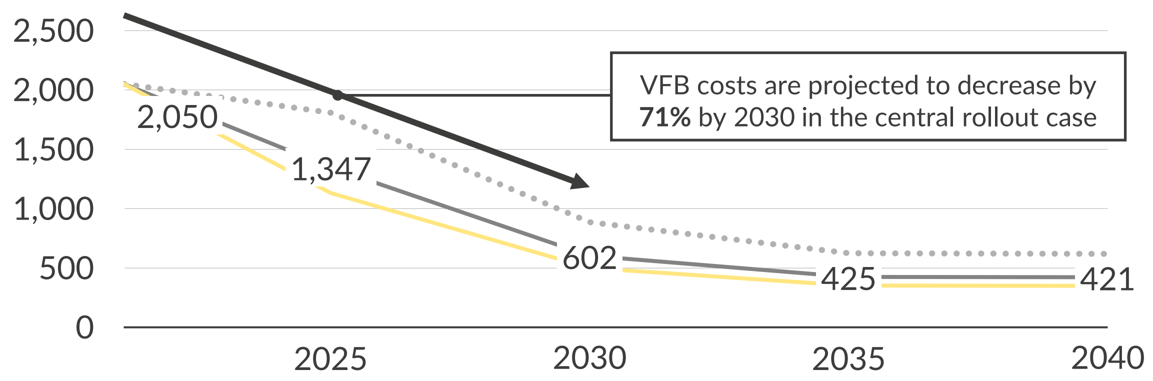
CAPEX Li-ion (4 hours)[1]
£/kW, real 2020



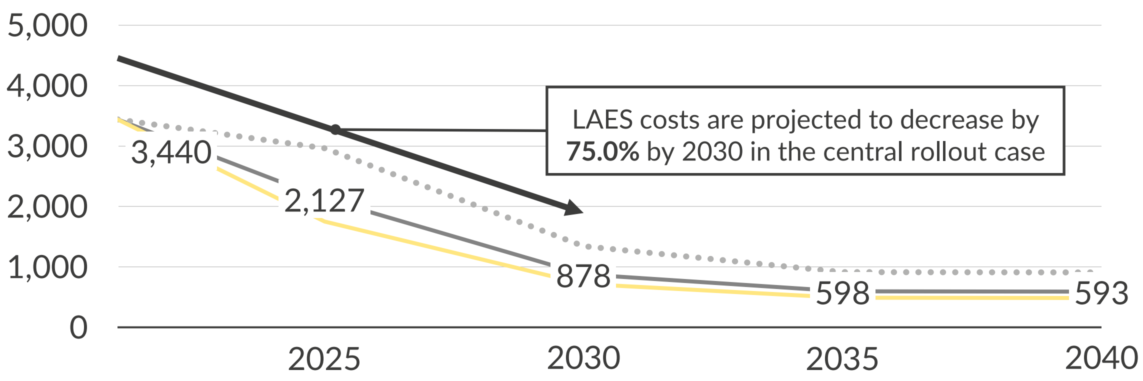
CAPEX Li-ion (8 hours)[1]
£/kW, real 2020



CAPEX Vanadium Flow (4 hours)
£/kW, real 2020



CAPEX LAES (8 hours)
£/kW, real 2020



Central (100 GW)[2] Low (10 GW)[2] High (300 GW)[2]

1) Inverter and rack costs included. 2) Capacity rollouts

Sources: Aurora Energy Research, Invinity

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LDES assets are expected to derive a significant proportion of their value via the provision of multiple balancing and ancillary services

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Whilst revenues from energy trading in the wholesale market and balancing mechanism energy actions will make up some of the value for LDES assets, a significant proportion of their value is anticipated to result from the provision of ancillary services through balancing mechanism system actions

Revenue streams		Opportunities	Risks
Capacity Market		▪ Prices expected to increase due to the retirements of CCGTs and nuclear capacities and coal closure, necessitating the entry of new build firm-capacities ▪ As providing power for long durations supports security of supply, LDES assets can receive relatively high CM de-rating factors ▪ The initial 15-year contract can provide a significant amount of secure revenue stream for new build assets that can act as an annual revenue floor for this period	▪ While new-build asset can auction for a 15-year contract, year-on-year volatility of auction outcomes could cause the contract to be locked-in based on a relatively low clearing price ▪ Long lead times for some LDES projects can be problematic as capacity delivery dates are required within 4 years of contract award ▪ Changes to Capacity Market structure creates uncertainty over future revenue available
Wholesale Market		▪ Price spreads are expected to grow, driven by the growing capacity of intermittent renewables and rising commodity prices, leading to an increase in gross margins over time ▪ Route-to-market providers could provide revenue floors, which can provide some protection from merchant price risk	▪ High exposure to merchant risks and movement of market fundamentals such as commodity prices and economics of renewables ▪ Bottom prices may increase in a net zero world, driven by smart EV charging and hydrogen electrolysers. Top prices may fall if lower gas demand prices commodity costs, reducing captured spreads
Balancing Mechanism	Energy actions	▪ Energy (supply/demand) balancing needs are expected to grow over time with the growing capacity of intermittent renewables, leading to higher price spreads	▪ High exposure to merchant risks and movement of market fundamentals such as commodity prices and economics of renewables

Source: Aurora Energy Research,

LDES assets are expected to derive a significant proportion of their value via the provision of multiple balancing and ancillary services

AURORA

Whilst revenues from energy trading in the wholesale market and balancing mechanism energy actions will make up some of the value for LDES assets, a significant proportion of their value is anticipated to result from the provision of ancillary services through balancing mechanism system actions

Revenue Streams		Opportunities	Risks
Balancing Mechanism System actions	Thermal Constraints	▪ Constraint management issues are expected to grow as more renewables capacity is built in – LDES could potentially defer the cost of network reinforcements	▪ The build-out of other flexible technologies such as short-duration assets could erode margins ▪ Slower wind build-out could slow down the increase in constrained volumes
Ancillary services *(contracted through BM or via separate services)*	Inertia	▪ Requirement for inertia service will increase over time due to the declining of thermal generation, which traditionally provides system inertia, and the growth of renewables generation ▪ Multi-year contracts are usually agreed	▪ Procurement is currently based on competitive auctions
	Reactive Power	▪ Requirement for reactive power is likely to increase as network loading becomes more volatile with baseload generators running less predictably, opening up new revenue stream such as the Reactive Power Voltage Pathfinder[1]	▪ Has low-risk level but provides only a small amount of revenue to the asset
	Black Start	▪ Provides security as revenues are locked-in based on a long-term contract	▪ National Grid is opening this service to more market players through auctions which could increase competition
	Reserve	▪ Potential revenue stream for LDES assets through services similar to Spin Gen in a high renewables, low thermal energy system	▪ Not stackable with energy trading revenues
	Frequency Response	▪ Reduced system inertia will lead to higher requirements for frequency response services ▪ Pre-fault services with high throughput requirements, such as dynamic regulation, suited to technologies with low degradation	▪ LDES technologies may not meet all technical parameters for some services

1) This is currently on trials in specific regions such as the Mersey, North of England, and Pennies regions.

Source: Aurora Energy Research,

Contents

Despite the benefits LDES could provide to the system, there are a number of challenges to its deployment that need to be addressed

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All pathways for the UK to meet Net Zero 2035 will require large amounts of flexibility to support high levels of variable renewable generation coupled with challenges around system stability, network constraints and changing consumer behaviour.

The introduction of LDES would contribute to security of supply in GB

LDES has the capability help keep lights on Net Zero scenario, keeping energy bills as low as possible and power sector emissions down. The primary benefits of LDES include:

1. **Utilizes increased renewable output** by reducing the need for curtailment due to network constraints, estimated at 2.3 TWh in 2021[1] and 27 TWh in 2035 (emitting up to 0.8 and 9.6 $MtCO_2e$ from gas turn-up)
2. **Provides increased system stability and resilience** by providing power, frequency, inertia, voltage, SCL and restoration
3. **Provides lower consumer bills** by reducing the need for additional network & capacity

Recent power crises have brought into focus the need to plan for weather events. **March saw the UK's longest low wind generation cold-spell** in over a decade with unabated gas filling the supply gap and **September saw record high power prices** from gas supply constraints.

LDES assets face numerous challenges to deployment

Near-term investment in LDES can reduce both the cost and long-term risk to security of electricity system decarbonisation. Despite the evident benefits LDES is able to provide, these projects are not currently able to attract investment due to 3 primary factors:

1. **Uncertainty about future project revenues;** current market design and existing support mechanisms do not reward LDES for the full value of services they can provide
2. **Uncertainty about the future market landscape;** future market reforms could impact LDES revenue streams
3. **High capital costs and long lead times for certain technologies**

These combined factors make it difficult to gain the confidence necessary to raise and allocate large sums capital sums; with similar challenges faced by CCUS and hydrogen.

BEIS has recognized need for support for LDES but there are still outstanding questions

Due to high upfront capital investment requirements and long development timescales, LDES cannot rely on near-term price signals for investment.

The primary issues that investors will want to be addressed by policy makers are:

1. **Address missing markets;** LDES is able to provide beneficial grid services that are not currently procured individually, with the value recognition of these services missing
2. **Policy confidence;** policy support for LDES which recognises the value and long-term need for this resource
3. **Contracted revenue confidence;** for a percentage of long-term revenue to be contracted or have revenue guarantees to ensure debt payments

1) From BM registered wind farms only.

Source: Aurora Energy Research

High upfront costs, a lack of revenue certainty and weak market signals result in limitations to financing for LDES in GB

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Despite the benefit LDES can bring to the system, there is currently only 2.8 GW Pumped Storage Hydro on the system, with no significant new capacity having been deployed since 1984. New LDES faces numerous barriers to deployment owing to high upfront costs, limited track record or long lead times for some technologies, as well as uncertain revenues and poor market signals.

Key focus area	Description
Upfront costs & lead times	▪ Longer duration storage often have high upfront costs which can vary significantly between technologies, increasing financing challenges, particularly for early projects ▪ Some, such as pumped hydro storage, require long construction times which increases investment risk as market uncertainty increases with time ▪ With long lead times and upfront costs, LDES investors could be put off by the uncertain nature and duration of the revenue streams
LDES technology track record	▪ A lack of a long track record can introduce additional investment challenges compared to mature technologies ▪ Many LDES technologies have not yet been demonstrated at scale anywhere
Revenue/cost uncertainty	▪ Revenues for storage are typically contracted on a short-term basis in day-ahead and intra-day markets, with the capacity market as the only exception ▪ Ancillary markets are undergoing reform, presenting uncertainty to future streams and prices, and well as to service requirements ▪ Long project lifespans means revenue stream values are hard to evaluate for the full project lifespan as future market changes could impact expected trading strategies and system needs ▪ Some technologies, such as PSH, face additional challenges related to uncertain/volatile pumping costs, presenting an additional challenge when considering the variability of cashflows
Market signals	▪ Current market structures are unlikely to capture the full value of LDES projects to the system ▪ Shorter duration flexibility is favoured, with multiple daily cycles attractive to storage assets of all sizes as intra-day signals are more attractive than inter-day or inter-week ▪ Locational price signals are currently limited
Grid connection timelines	▪ Difficulties in securing new grid connections present a major obstacle to the timely deployment of LDES ▪ Storage is currently treated as generation and as such, joins the back of the grid connection queue, resulting in long delays

Sources: Aurora Energy Research, BEIS

Policymakers have recognised the need for support if the deployment of LDES is to be accelerated

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BEIS had held a number of consultations relating to LDES and flexibility on the system

The need for LDES to provide system and grid flexibility and the positive externalities associated with the technology is starting to be recognised

- BEIS is beginning to show to support in their recent call for evidence which considers the role of large scale LDES in facilitating a Net Zero energy system, and recognises the challenges it faces in deployment
- Broader support for electricity storage has also been recognised through other consultations taking place, such as the network charging and CM consultations
- The support for storage is becoming increasingly important as it facilitates increasing commitments to power sector decarbonisation, shown in the 10 point plan, energy white paper and new target of Net Zero by 2035

Policies introduced to directly incentivise the deployment of LDES assets should considered against key criteria

1. **Accelerate LDES deployment –** *policy should assist the deployment of assets in time for them to support the grid. There is a greater risk of acting late, and waiting for perfect market design, than acting early as deployment costs will need time to come down*
2. **Incentivise effective dispatch of LDES assets** – *policy should be designed to send price signals to incentivise effective dispatch of storage assets to best support the needs of the system*
3. **Prevent market distortions**– *policy should be able to support assets without creating market distortions or competing effects with other policies*
4. **Provide investor confidence –** *policy should alleviate merchant risk and provide revenue certainty, this will likely require more than price signal creation*

Two different support options are available to policymakers to support the development and deployment of LDES

Option 1: Direct support

Deep dive in next slides

- Direct subsidies or support mechanisms can be used to improve financeability of LDES by ensuring required cashflows for debt payments
- Direct support schemes have proven track records of being able to support projects requiring large capital investments, such as Cap and Floor models for Interconnectors and RAB models for Nuclear. Direct subsidy schemes like CfDs have brought forward investment in RES

Option 2: Other electricity market reform

Deep dive in next slides

- The alternative scenario to direct subsidies is to indirectly support the finance case of LDES through market reforms
- This would require significant change to improve price signals to LDES and would likely need to be combined with direct support schemes to ensure the timely roll-out of LDES assets

Sources: Aurora Energy Research, BEIS

A suite of options to provide direct support to LDES are available to policymakers

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	Policy option	Description	Assessment criteria: Accelerate LDES deployment	Incentivise effective dispatch of LDES[5]	Prevent market distortions	Provide investor confidence
	Merchant (no support or reform)	▪ Relies on existing market arrangements and would rely on investors gaining confidence over different elements of a forecasted merchant revenue stack.	○	○	●	○
	Reformed CM[1]	▪ Entails a reform of the existing capacity market to directly incentivise low-carbon generators and plants able to contribute towards system security.	◔	◑	●	◕
	CfD[2] for storage	▪ This model has been successful in providing long-term revenue stability for renewable generators, where a generator is guaranteed a pre-agreed price level (the Strike price) in £/MWh for the duration of the contract. Wholesale revenues for generation above the strike price are returned by the generator.	◔	◔	◔	◕
	DPA[3]	▪ Similar to the CfD, with the key difference being that payment terms comprise of a capacity based availability payment and an variable payment designed to incentivise dispatch. This is being proposed to support power CCUS.	◕	◑	◑	●
	RAB[4]	▪ Companies receive a licence from an economic regulator to charge a regulated price to consumers in exchange for providing the proposed infrastructure with customers face risks of overruns. This is proposed for future nuclear projects	●	◑	◑	●
Deep-dive	Cap & Floor	▪ This model provides a guarantee underwritten by energy consumers of a revenue floor so that investors would be guaranteed a minimum revenue for an efficient project construction cost and cost of debt. Equity investors would have all their profits at risk which would also be capped at a reasonable rate of return. This model was able to attract investment for the development of interconnectors[6]	●	◑	◕	◕

● More applicable ○ Less applicable

Individual policies may be insufficient to incentivise LDES capacity and effective dispatch in isolation. Policy support could be combined with other market reforms to incentivise dispatch behaviour to maximise the benefit to the system

1) Capacity Market; 2) Contracts for Difference; 3) Dispatchable Power Agreement; 4) Regulated Asset Base. 5) With respect to the system. 6)Note that LDES can provide a range of grid services, like interconnectors, but without the firm OPEX costs.

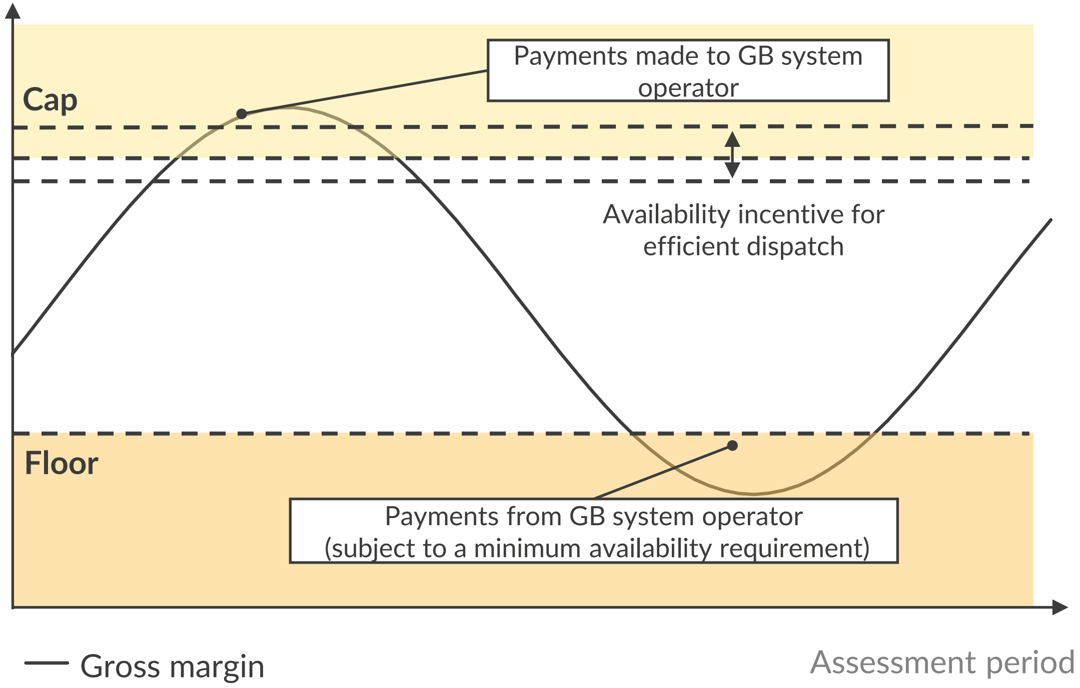
Source: Aurora Energy Research, BEIS

A Cap & Floor mechanism is best positioned to support the deployment of LDES, however additional signals may be needed

The Cap and Floor mechanism is currently the best positioned to support investment in LDES, however there are several limitations and potential modifications that should be considered.

Cap and Floor mechanism

Gross Margin £/kW/yr



1 Cap and Floor policy limitations

- **Does not fully incentivise optimal dispatch to benefit the grid**
- **May not support equity investment into LDES projects**

2 Potential considerations and modifications

- **Forecasted returns from energy and system actions –** LDES provides services that are not currently contracted in separated markets; a cap & floor scheme should consider recognising value from all services contributing to grid operation (such as inertia, SCL, constraint relief)
- **Length of contracts and timing of revenues assessment –** contract length should be considered to reflect LDES lifespans and could be combined with revenue assessments to ensure fairness for developers and consumers
- **Contract awarding –** contracts will likely need to be decided on a case by case basis initially but a move towards a competitive auction should be considered
- **Cap and floor prices -** Policymakers should consider whether the cap & floor is set: a) to be technology agnostic, such as only based on market signals and revenues (assuming reforms can provide these), or; b) set for individual assets based more granularly on their locational benefit and grid services provided
- **Hard floor and flexible cap –** projects should have to maintain a minimum level of performance to receive the floor price. A flexible cap would incentivise further output when needed by the grid if the cap is reached, this should be set to ensure services continue to be provided
- **Support to debt & equity –** price floors will need to be high enough to reduce merchant risk, to secure debt and operational costs. Better market signals may be needed to avoid revenues staying at the floor, to attract equity investors
- **Other reforms –** A cap & floor mechanism could be implemented in conjunction with further market reforms to improve market signals

Source: Aurora Energy Research

Broader reforms of the electricity sector provide additional levers to contribute to the overall financeability of LDES projects

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The introduction of a support mechanism such as cap & floor may not be sufficient by itself to ensure the bankability of LDES projects. However, it could be combined with other electricity sector reforms to improve the overall bankability of assets and to incentivise operating profiles that would best support the system

1 Ancillary Services are currently contracted as separate services on a short-term basis

- The segregated nature of grid service contracting means assets may not provide all the services they could, if contracts are not procured. Asset owners have to consider risk of separate revenue streams
- An alternate system, where services are bundled, could alleviate these risks and incentivise assets to act in a way to maximise the benefits they could provide, although investor confidence in other revenue streams with also need to be assured

2 Networking charging signals do not incentivise storage or network buildout

- Locational signals (such as TNUoS and EET[1]) do not incentivise storage to build in the right places, as the methodology incentivises plants to connect close to demand. For storage to help alleviate grid constraints this is not appropriate as it results in high TNUoS costs, without recognising the benefit of negative generation during constrained periods.
- Network charging reforms, recognising storage is separate to generation, could alleviate these issues

3 Zonal/nodal pricing could be introduced to alleviate locational constraints

- Nodal pricing, where individual regions have separate market prices, could incentivise capacity buildout closer to demand, such as in Scotland, where high wind buildout would result in long periods of cheap prices to charge at for storage assets
- These price signals could lead to buildout that alleviates constraints

4 Reforms to the Capacity Market should be considered

- The CM will have legacy issues toward 2035 as it provides subsidies to thermal assets which have gained 15-year contracts in recent auctions beyond the net zero target
- The 2021 CM consultation could potentially result in a two phase auction for low and high carbon assets, that could provide a valuable revenue stream that could be considered within the cap & floor mechanism

5 Is a wider market reform is needed?

- If action is not taken to align market prices (set by SRMC[2]) with total system benefit provided, then bilateral dispatch may cease to be efficient and could be increasingly overruled by SO redispatch, resulting in pseudo centralised dispatch. This would be a key change to market design and policy
- As an alternative to subsidising individual technologies, price signals for low carbon assets could also be improved by increasing carbon prices

6 Both wider market reforms and direct subsidies will push out other technolgoies

- Whether direct support or indirect market reform, or a combination of both, is determined to be the best support method, there will be an 'overspill' that affects other technologies
- These effects should be considered with respect to grid operability and total system cost to consumers in mind

1) Embedded export tariffs. 2) Short Run Marginal Cost

Source: Aurora Energy Research

Details and disclaimer

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