Written evidence submitted to the House of Lords Environment and Climate Change Committee inquiry into risks of renewable energy intermittency

12 October 2026

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We welcome the opportunity to submit evidence to this inquiry.

Key messages

1. **Dunkelflaute is an emerging resilience challenge.** Prolonged periods of low wind and solar output are infrequent but probable risks that must be planned for as the UK electricity system becomes more reliant on weather-dependent generation and electrified demand.

2. **Residual demand is important in understanding the potential impact of dunkelflaute on electricity system resilience, not renewable output alone.** System stress arises from the interaction between low renewable generation, electricity demand, available flexibility and weather conditions.

3. **Electrification increases the importance of resilience.** As electricity's share of final energy demand grows substantially in the coming decades, maintaining security of supply during extended low-renewable periods becomes increasingly important for the wider economy. However, many new sources of demand bring potential flexibility, of varied durations.

4. **Extended VRE-deficit events** (VRE alone unable to meet projected demand without demand-side flex) **are likely to occur and should be prepared for.** Modelling suggests events lasting several days (48-300h) will occur around ten times per year, while very long-duration events (>300h) will occur roughly once a decade.

5. **Dunkelflaute risk is best handled with a diversity of approaches.** Resilience will require a portfolio approach combining long-duration energy storage (LDES), low-carbon dispatchable generation, demand-side flexibility, interconnection and geographically diverse renewable deployment.

6. **GB needs a range of storage durations, not just batteries.** Batteries are valuable for daily balancing, but longer durations are likely to require other technologies such as pumped hydro, compressed and/or liquid air storage, and hydrogen in salt caverns which could maintain security during prolonged low-renewable periods.

7. **Current investment frameworks are not sufficient to secure adequate flexibility.** Existing market arrangements support short-duration batteries more effectively than longer-duration storage (or other options needed for rare but severe stress events). Innovation support and procurement signals for storage beyond more than a couple days are currently inadequate.

8. **Infrastructure decisions this decade will determine resilience in the 2030s and beyond.** Long development timelines for storage, transmission networks and interconnectors mean that delays today could create security and affordability risks later.

9. **International cooperation strengthens resilience.** Greater interconnection, electricity market cooperation and coordinated offshore energy infrastructure can help reduce system costs and improve reliability during adverse weather conditions.

10. **Demand flexibility should be treated as a strategic resource and integrated more prominently in analysis and policy.** Well-designed demand-side measures can reduce pressure on the system during stress events and work alongside storage to reduce overall costs; some forms offer natural economic complements for managing *Dunkelflaute* events.

11. **A strategic reserve for electricity security should be considered.** Seasonal storage and other low-carbon flexibility assets provide insurance against rare but high-impact events and may require strategic planning and procurement to ensure enough capacity is built and operated in line with system resilience needs.

Dunkelflaute likelihood and impact

1. How are Dunkelflaute events defined and how far in advance can they be predicted? How likely is it that the UK will be impacted by Dunkelflaute events lasting days to weeks and is that likelihood expected to change in the future?

12. Dunkelflaute ("dark lull" or "dark doldrums") lacks a precise qualitative or quantitative definition. Meteorologically, it describes sustained, near stationary pressure, combined with low clouds (typically stratus or stratocumulus), producing low wind and solar output (Li *et al.*, 2021). These events can be prolonged, lasting several days to weeks, rather than hours (Beck-Bang, Overgaard and Keles, 2026). The longest events are driven by atmospheric blocking, where high pressure systems block westerly winds across Europe for unusually long periods; they are, by nature, difficult to forecast more than a few days in advance (Ho-Tran and Fiedler, 2024).

13. The future likelihood of Dunkelflaute in the UK is uncertain. Climate models suggest European blocking may become less persistent (Dorrington *et al.*, 2022), but that rare, high-impact events remain possible (Woollings *et al.*, 2018). Dunkelflaute is therefore best understood as a long-tail risk in that these events are infrequent, difficult to predict, but whose presence must be prepared for. This risk becomes magnified as electricity supply is increasingly derived from weather resources and as demand, particularly for heating, becomes electrified.

14. Dunkelflaute events have been popularised as a concept with the integration of weather-based energy generation across European economies. The impact of a Dunkelflaute on the UK economy is therefore a question of the technology mix and operational procedures that enable the energy system to be resilient to low-generation potential weather events.

15. Kittel and Schill (2024) have proposed a more precise set of definitions including 'VRE droughts' in relation to low resource availability, 'VRE anomalies' in relation to the mean reference load factor of a given set of technologies, 'positive residual load events' in which VRE supply is below demand, and 'electricity system stress events' in which electricity markets exhibit high prices, signalling scarcity of supply. For the purposes of interrogating resource adequacy preparedness, we propose delineating events by 'residual demand' (Chambers *et al.,* 2026) (similar to Kittel and Schill's (2024) 'positive residual load'), therefore connecting the relationship between fluctuating supply and demand levels associated with variable generation, electrified demand (particularly of heating), flexibility resources, and meteorological events.

16. The UK currently faces a risk of exposure to 'VRE deficit' periods as an increasing proportion of energy generation uses variable weather resources, particularly wind. As VRE penetration increases, so does the need for longer-duration flexibility resources and demand management strategies that create a sufficient and appropriate menu of options for balancing the fluctuating volumes of supply and demand. In short, risk management regarding Dunkelflaute events is a product of synchronised integration of variable generation assets and the various technologies and services that balance them.

17. This is particularly important as the economy becomes more reliant on electricity, with the electrification of transport, heating and industry. Where demand for electricity follows weather patterns, for example heating demand tracking temperature events associated with Dunkelflaute, the economic consequence is more pronounced. Electricity is forecast to rise from around 20% of final energy demand today to between 40-70% by 2050 (*NESO FES*, 2025). Security of electricity supply therefore becomes increasingly critical to economic functioning.

2. How significant could the future demand-supply gap be during a Dunkelflaute in 2030 and 2050, under current plans and targets? Is the UK on track to deliver the infrastructure required to address these gaps?

18. A demand-supply gap is potentially significant in two ways: as a gap that is expensive to fill, potentially resulting in economic curtailment of demand, and as a gap that cannot be physically filled, resulting in (partial) physical curtailment of demand. Under current plans and targets, electricity generation and demand become more structurally interdependent with weather events with the integration of VRE technologies and the electrification of heat. Mitigating the demand-supply gap becomes a function of integrating both complementary infrastructure and operational measures that can close this gap. This comes in the form of dispatchable generation, long-duration storage, interconnection, and demand-side management. Plans and targets for 2030 are at risk of significant demand-supply gaps that could become expensive. Plans and targets for infrastructure delivery by 2050 are less certain

as specific technology targets remain vague, for example in the category of flexible technologies, and procurement processes are not currently underway.

19. Our modelling, as outlined in Chambers *et al.* (2026) and developed in Yang *et al.* (forthcoming), uses the technology mix and demand scenarios of the four NESO Future Energy Scenario pathways (2025) and four decades of weather data (the full ERA5 weather record, 1985-2025) to model the hourly balance between Great Britain's electricity demand and its low-carbon generation in 2030, 2035, and 2040. We identify periods of 'VRE deficit', i.e. when projected demand (without flexibility) exceeds available generation from VRE plus firm generation (including nuclear, biomass, waste-to-energy, biogas, large hydro, landfill gas, advanced biofuel, sewage gas and geothermal).

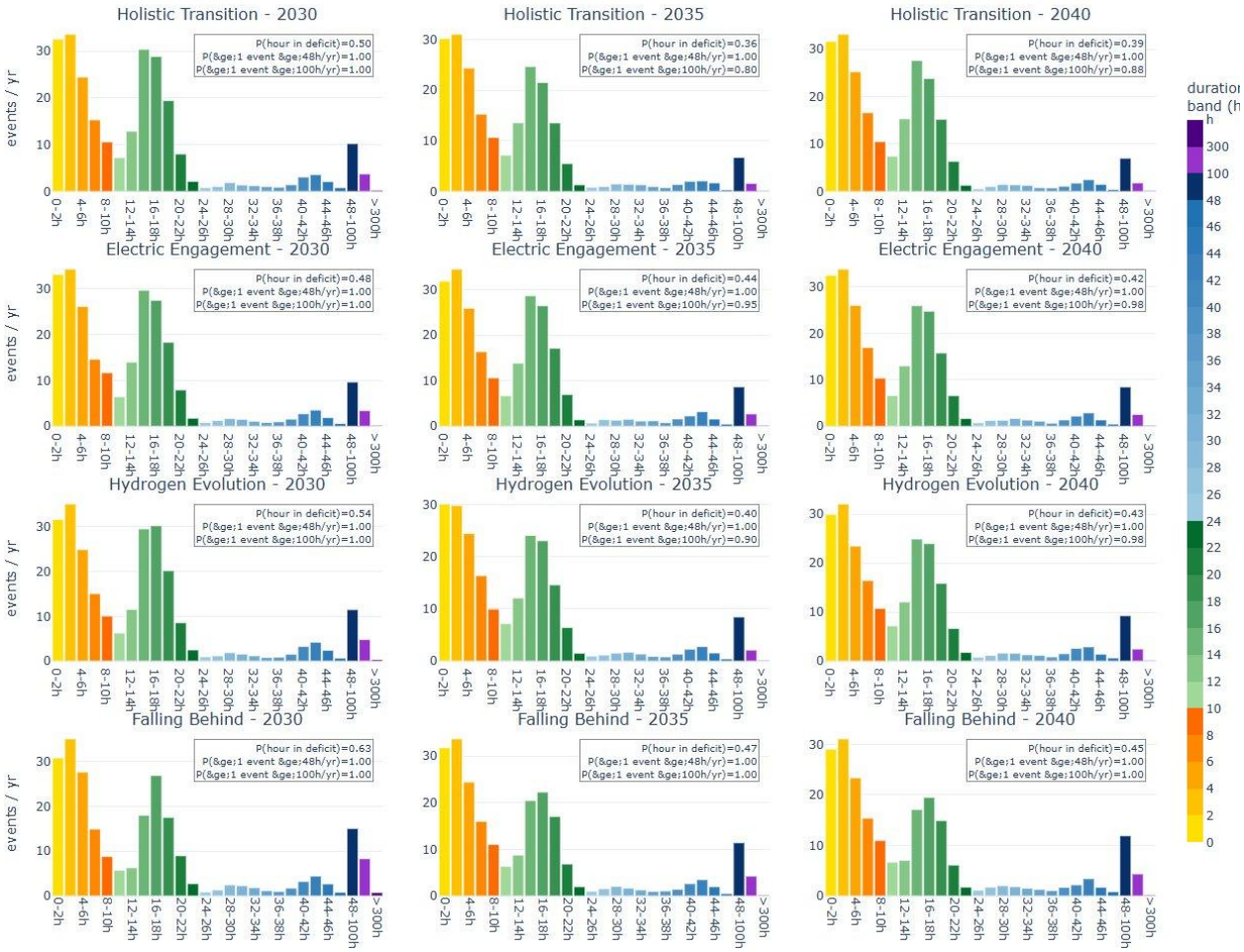


Figure 1. Distribution of VRE deficit events of different durations (2 hours bands up to 48hr, with colour coding for 0-10h, 10-48h, 48-300h, >300h) (Yang *et al.*, forthcoming).

20. Figure 1 shows the distribution of VRE deficit events of 2-hour duration bands up to events of 48 hours, then of larger time intervals for longer-duration events which are less frequent. Figure 2 is a violin plot showing the frequency of events of four different duration bands: 0-10h, 10-48h, 48-300h, >300h). The analysis (based on the four decades of ERA5 weather data) indicates that:

- VRE deficit events lasting 48-300 hours will occur on average roughly ten times per year (with significant variation across years), with events in range 100-300 hours averaging about 5 times a year)

- Events lasting more than 300 hours will occur roughly once a decade under current plans and targets. In a low-wind year, peak residual projected demand could rise from 31 GW in 2030 to 54 GW in 2040, so the flexibility of new demand growth will be an important factor (section 5).

21. We caveat that analysis based on future weather projections, for example Pan-European Climate Database (PECD) data could influence this analysis.

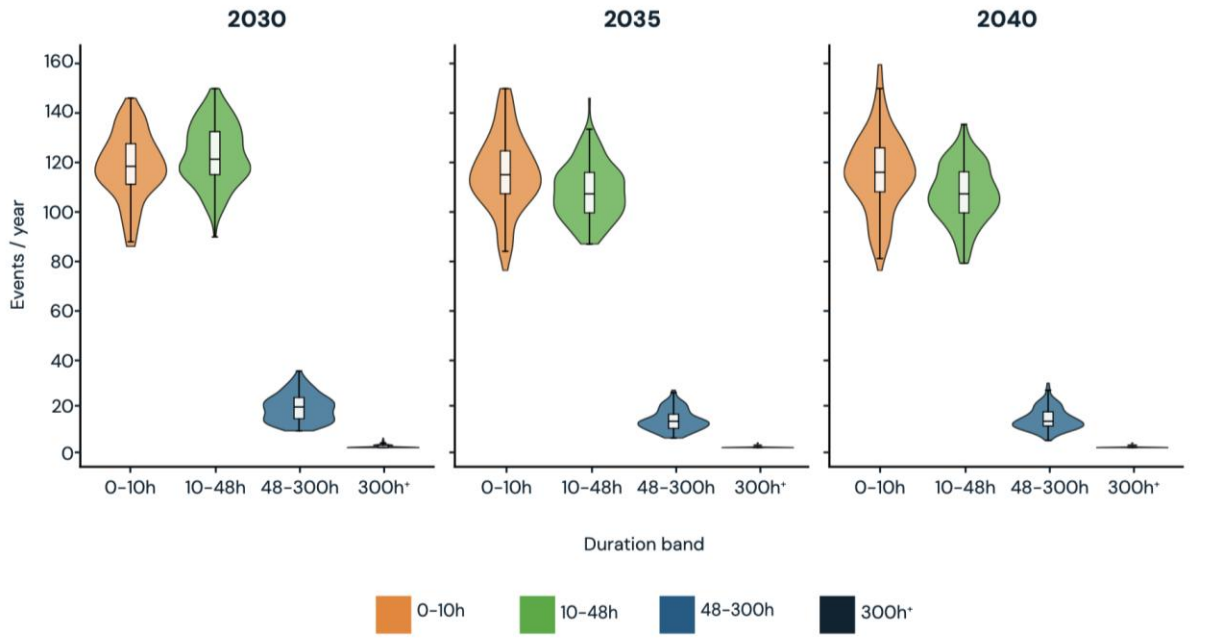


Figure 2. Frequency of VRE deficit events of different durations in GB (0-10h, 10-48h, 48-300h, >300h) (Chambers *et al.*, 2026)

22. For the long term (2050), estimates of the UK's long-duration storage need range from around 3 TWh (NESO FES, 2025) to up to 100 TWh (Royal Society, 2023) with a general consensus amongst experts that tens of terawatt hours will be needed (House of Lords Science and Technology Committee, 2024). Modelling by Price, Keppo and Dodds, (2023) describes a need for ~50-140 TWh of H2 salt cavern storage. All scenarios point toward substantially more need for strategies to integrate long-duration energy storage to provide system balance.

23. There are several options to fill the gap left by a VRE deficit period: long-duration energy storage, dispatchable technologies including such as hydrogen to power (a form of LDES) or gas/bioenergy with CCUS (which is discussed below in response to Q4), demand-side flexibility (response to Q5), and interconnectors. Continued use of a small amount of unabated thermal power generation (gas) could provide full supply back-up, however this is unlikely to be compatible with net zero emissions targets. Spatial diversification of VRE deployment is an

additional strategy to balance supply volumes across wider geographies with varied weather events.

24. Given the uncertainties surrounding future demand, technology deployment, fuel prices and weather patterns, maintaining multiple pathways to meeting long-duration VRE deficits will be more valuable than optimising around a single forecast of future system needs. It is therefore important to consider whether the processes are in place to enable investment in a range of options at various stages of technology readiness within realistic implementation timelines. NESO's Ten Year Outlook (2026) forecasts that batteries are the only Clean Power 2030 target to be met (Jennings, 2026). No new LDES is added before 2031, against a target of 4-6GW with ~3 GW of existing LDES capacity (at 8+ hour duration) today. The LDES Revenue Cap and Floor Mechanism's Window 1 would add 7.6 GW of storage if all projects from Ofgem's 'minded to' list are fully delivered, but projects are only in the range of 8-32 hours' duration. Currently nothing is being procured at inter-week and seasonal durations.

25. As Dunkelflaute events feature low renewables output over multiple days, the LDES capacity being procured by the Cap and Floor Mechanism would need to be complemented by other technologies, e.g. demand side flexibility (DSF) and interconnectors, to meet residual demand during extended periods of low VRE output.

26. Delivery timing for LDES is a challenge. Planning, permitting, construction and grid connection processes can mean LDES deployment is estimated to take ~5-15 years (Chambers *et al.*, 2026). Certain LDES technologies, including H2 LDES, will require further innovation investment to raise its TRL and become implementable. LDES capacity available in the mid-2030s will be largely determined by decisions taken now. Build times for LDES technologies range from ~2 years for BESS (flow batteries) to 5-10 years or more for pumped storage hydro, with most scalable technologies such as CAES and LAES (compressed- and liquid-air energy storage) systems falling in the 3–6-year range. On top of construction, planning, permitting, and grid connection delays can add 2-5 years to delivery timelines.

27. The government's Clean Power 2030 plans include LDES within a broader 40-50 GW portfolio of 'dispatchable long-duration flexible capacity', suggesting substantial reliance on complementary resources such as CCS-equipped gas and hydrogen to power plants that are at an early stage of full-scale deployment.

28. In terms of other infrastructure, building the transmission grid takes 5-15 years (IEA, 2023a) and building interconnectors take on average 9 years to build in Europe (IEA, 2022). NESO FES (2025) estimates ~26 GW interconnector capacity in GB in 2050, whereas Price, Keppo and Dodds (2023) describe much higher upper levels ~60 GW (albeit additionally accounting for transmission between Ireland and Northern Ireland).

Technologies and solutions

3. Which low-carbon technologies are most effective at addressing long-term dunkelflaute events, lasting days to weeks? At what point could these technologies be deployed at a system-wide level and what are the main barriers to their deployment?

29. There are a range of technologies and operational strategies that can complement VRE deficits, depending on the characteristics and duration of a given weather event. These can broadly be demarcated into the categories of demand-side flexibility, interconnectors, low-carbon dispatchable generation and long-duration energy storage. Spatial diversification of VRE assets is another strategy for mitigating Dunkelflaute risk across the electricity system. We propose the functional use of coordinating different categories of VRE-deficit events with applicable technologies within that 'days to weeks' period, focused on long-duration energy storage technologies.

30. Inter-day LDES (10-48 hours): pumped hydro, liquid air energy storage, compressed air energy storage, flow batteries and thermal storage are well suited for managing multi-day imbalances and could be deployed at scale within the next decade if investment conditions improve with the help of targeted policy support (e.g. reformed LDES Cap and Floor Mechanism). Inter-week LDES (48-300 hours): pumped hydro, compressed air storage and emerging iron-air/metal-air batteries appear particularly relevant for several-day to two-week Dunkelflaute events. Seasonal storage (>300 hours): hydrogen stored in salt caverns appears to be the leading candidate for extreme multi-week or seasonal shortages.

31. These technologies can be deployed from a technology readiness perspective, but face barriers pertaining to commercial viability. Commercial viability is partially a product of market arrangements that obfuscate demand signals on which two-way storage assets remunerate, and partially a product of limited opportunities to achieve economies of scale. Key barriers to deployment of LDES include uncertain and (under current market arrangements) insufficient long-term revenue streams for LDES; long planning and development timelines; grid connection delays; technology maturity challenges for some longer-duration technologies; a lack of market arrangements specifically designed for inter-week and seasonal storage services.

32. The costs of storage, especially when the technologies can be mass-produced (batteries), are coming down rapidly and deployment is exceeding forecasts whereas cost decrease and deployment of low-carbon molecules is slower than forecasts. Average battery costs have fallen by around 90% since 2010 and battery storage is now the fastest-growing clean-energy technology globally, with annual additions doubling in 2023 alone (IEA, 2024a). In contrast, low-emissions hydrogen and CCUS deployment remain significantly dependent on policy support and bespoke infrastructure (IEA, 2023b, 2024b). This is discussed in more detail under question 4.

33. Ongoing work at UCL has combined whole energy systems modelling using UK TIMES, with high temporal and spatial resolution power sector modelling using highRES to understand the

implications for future Net Zero energy pathways for the need of different durations of energy storage (for highRES model description see Price and Zeyringer (2022); Price, Keppo and Dodds, (2023)). This included considering the impact of adverse weather years based on 2010 weather data (covering the UK and Europe). While not specifically focused on assessing Dunkelflaute events, the work suggests that integrating multiple systems that provide incremental storage durations with high levels of interconnection can replace the use of natural gas-based systems – supplying the energy required to close the VRE deficit while also providing required ancillary services. Importantly, this requires a significant build out of hydrogen-based storage systems able to store energy interseasonally for over 3 months, to levels that allow near continuous discharge for ~2000 hours.

34. Interconnectors will continue to serve as a source of dispatchable power in the UK's electricity mix. From a system adequacy perspective, it is important to interrogate the technology base on which interconnected countries are generating electricity to determine whether those resources are a reliable compliment to Dunkelflaute events. Gøtske *et al.*, (2024) show that capacity layouts modelled across Europe are less affected by challenging weather conditions with the integration of increased backup generation, energy storage, and distributed H2 network.

4. What role will gas with carbon capture or other dispatchable generation need to play during a severe Dunkelflaute? What are the challenges associated with installing carbon capture for retained gas plants?

35. In principle, gas with carbon capture and storage (CCS) can play an important role in balancing the UK electricity system, including during prolonged periods of low availability of wind and solar electricity. Whilst it is at an early stage of deployment, investment in gas CCS is already happening in the UK and Canada (Global CCS Institute, 2025). The 740 MW Net Zero Teesside plant is under construction in the UK, and due to be completed in 2028. If it captures and stores emissions as planned, it will be the largest gas CCS plant in the world. There are also plans for CCS retrofits to existing gas plants in the UK (e.g. at Keadby), but these are planned from 2030 onwards – and have not yet reached final investment decision.

36. The role that gas CCS could play depends heavily on what mix of other technologies are deployed in a future decarbonised power system. NESO's future energy scenarios illustrate the range of uncertainty about this role (NESO, 2025). Across their four scenarios, dispatchable generation in 2030 ranges from 7% to 23% of UK electricity. This includes gas CCS, gas without CCS and hydrogen generation (which could involve the use of CCS upstream if hydrogen is produced from natural gas). Not surprisingly, gas CCS generates only 1.5% of UK electricity at most in 2030. In 2050, the potential is larger. The share of dispatchable generation is in a similar range to 2050. But gas CCS generates up to 12% of electricity. The capacity of gas CCS in 2050 is up to 27GW, which is over 35 times the capacity of Net Zero Teesside.

37. To play a significant role in balancing the grid, gas CCS plants will need to operate flexibly. This is technically possible, but more challenging for plants like Net Zero Teesside that use 'post combustion' carbon capture technology. This is due to the integration between the gas-fired power plant and the post-combustion carbon capture plant. CCS power plants work best when they operate at high load factors (i.e. as 'baseload' plants). To operate flexibly whilst continuing

to capture CO_2 at a high rate, additional modifications and equipment are required to partially decouple the capture plant from the power plant. One option is to install extra storage tanks to store the solvent that is used to remove the CO_2 from the power plant exhaust (Schnellmann *et al.*, 2019).

38. Fitting CCS to existing gas plants is also possible, but there are technical and economic challenges associated with this. These plants were not designed with carbon capture in mind. They may not have the space required on site for post-combustion carbon capture, and the technical modifications required could be costly. They are also likely to be much less efficient than a new gas CCS plant. Retrofitting CCS will reduce their efficiency further and increase fuel costs. Net Zero Teesside incorporates the latest gas-fired power plant technology which is significantly more efficient than most existing plants in the UK.

5. What is the role of demand management in shifting or reducing the demand-supply gap during extended Dunkelflaute events (days to weeks)?

39. There is a natural economic complementarity between generation, storage and demand-side approaches to handling long-duration VRE shortfalls. Investing in any generation that might only be required once every few years (or decade) is obviously very expensive per unit of value. The opposite is true for demand: the cost of a possible supply disruption once every decade is naturally much lower than if it happens several times a year. Correspondingly, many users might be very happy to have slightly cheaper electricity in return for possibly being called upon, once every few years, to reduce their demand until the wind picks up.

40. The system can never guarantee 100% reliability in all respects. The UK government has for many years set a target 'loss of load expectation' at 3 hours per year on average; this is *not* the expected extent of blackouts but defines the target for how much NESO may call on emergency balancing tools outside normal market operations to prevent supply shortages. The government's Panel of Technical Experts has previously underlined the extent of such 'latent capacity' in the system to help tackle potential stress events and repeatedly called upon the System Operator planning to take greater account of these capabilities (see for example BEIS (2018, 2019), though naturally the duration of these options varies.

41. Most forms of electrification can come with flexible capability (e.g. batteries in EVs, heat stores with electrical heating, many forms of industrial electrification). Industrial electrification could bring potential for long-duration flexibility, since few factories need to operate at 100% output all the time. Chinese analysts, for example, have highlighted the potential for seasonal scheduling of output from factories (highlighting aluminium) where production capacity now significantly exceeds product demand (Lyu *et al.*, 2026).

42. In GB, NESO project potentially around 10-12 GW of flexible demand already by 2030 in their CP2030 scenarios (NESO, 2026). Currently, this is speculative but can build upon existing experience and measures regarding industrial flexibility. Trials show that nationwide demand response trial programmes can incentivise demand reduction during scarce supply periods in the UK (Bernard, Metcalfe and Schein, 2026). This is an example of a lower volume shift over a short timescale; however, it shows the potential for response to events with shorter lead times, therefore trialling an operational strategy to respond to uncertain supply conditions.

43. Demand management is actively being explored in the UK to support system balancing in the context of multi-hour system stress events. As noted in NESO's Resource Adequacy report, demand management strategies play an important role in maintaining adequate system balance (NESO, 2025b). However, more sophisticated modelling approaches need to be developed to plan for this, and operational frameworks are needed to implement demand management measures for multi-day periods.

44. NESO has been developing the Demand Flexibility Service (DFS), which serves as the institutional structure to make operational use of flexible technologies. Tests are in place to trial demand turn down events. Responses to this DFS pilot have approached 4000 MWh (for winter 2024/25), equivalent to 400 MW saving over 10 hours, and the potential is much bigger. These volumes are however aggregated across 40+ events and therefore are not reflective of a prolonged demand turn down event that could be required of a Dunkelflaute period.

45. Demand management strategies can be considered on a spectrum of volumes and temporal scales. The metric of consideration is the volume of demand that can be manipulated upwards or downwards, on what time scale, and with what required lead-time, depending on supply conditions. Demand management and LDES can work together to bridge an extended Dunkelflaute event, e.g. LDES can enable shorter and less frequent demand reductions required, while DSF can make the LDES last longer by not requiring continuous discharge – useful when it's not clear how long the Dunkelflaute might last, and might be more cost effective than building and maintaining large seasonal LDES capacity.

46. Traditional demand management framings focus narrowly on technology-based flexibility and supply side efficiency improvements Barrett *et al.* (2022) took a more holistic demand-side approach to modelling future net-zero pathways for the UK. They estimated that, by shifting demand-side paradigms across energy service sectors (alongside traditional technology focused measures), it was possible to halve energy consumption in 2050 compared to 2020 without affecting quality of life. This finding echoes Grubler *et al.* (2018) applying a similar "avoid", "shift", "improve" lens to energy use at a global level. Preparing for Dunkelflaute events can therefore include shifting long-term planning and policy approaches, recognising the deeper opportunities that exist to shape future energy (and electricity) demand.

6. How important is international cooperation on electricity supply for resilience to Dunkelflaute events? What are the barriers to further cooperation?

47. International cooperation is important for resilience to Dunkelflaute given the variability in supply profiles of generation assets (inclusive of weather-based assets) across landmasses. Our estimates of projected 'VRE deficit' periods are for GB only weather. Naturally the frequency would be reduced if the analysis considered a broader geography, and the options for addressing such periods would be enhanced (with enhanced access to Norwegian hydro being one obvious example). From a purely physical perspective, regional aggregation therefore has high potential to contribute to reliability gains across high-VRE systems due to the balance of supply profiles across space (Tong *et al.*, 2021).

48. International cooperation on electricity involves a continued and likely growing role for interconnection and electricity market integration, especially across the North Sea. This also

involves opportunities to make use of shared offshore wind resources in the North Sea through the potential development of radial connections and/or a 'meshed offshore grid', often collectively referred to as 'hybrid assets' or 'multi-purpose interconnectors', that enable shared ownership of offshore wind assets across interconnected North Sea nations (Konstantelos *et al.*, 2017).

49. One barrier to international cooperation on electricity is the fact that the GB electricity market and European Internal Energy Market (IEM) are currently distinct markets. Recoupling those markets requires alignment of GB trading arrangements with the IEM, and legal agreements between involved nations, which requires political will. Additional barriers to cooperation involve physical and cost barriers associated with building sub-sea transmission cabling. Multi-purpose interconnectors are a novel technology with no precedent in UK waters, therefore support schemes associated with innovative technologies, e.g. pilot schemes and government funding, are needed to reach maturity (National Grid and Renewable UK, 2026). Legislative frameworks need to be developed to enable deployment of multi-purpose interconnectors (Marsh and Miletic, 2024).

50. UCL analysis suggests that interconnection expansion beyond planned targets at the time of analysis (~16.5GW) lowered total system costs, therefore has a substantial role to play in manage weather dependent electricity supply and demand (Price, Keppo and Dodds, 2023). Levels increased to ~60 GW between UK and Europe, including links between Northern Ireland and Ireland where they were allowed to expand to the cost optimal level.

Policy, market and governance frameworks

7. What analysis has been done to identify the most cost-effective approach to maintaining security of supply and meeting electricity demand under long-term Dunkelflaute conditions?

51. A European study of worst-case regional Dunkelflaute events uses a long-term capacity expansion model with an adaptive robust optimisation framework to represent a fully decarbonised, interconnected European electricity system under extreme weather conditions (Bernecker *et al.*, 2026). They found that for small, localised scarcity events, expanding renewables, transmission capacity, and batteries is sufficient and cost-effective. However, as scarcity events become more widespread, load shedding and long-term hydrogen storage become essential to maintain system resilience.

52. While not focused specifically on Dunkelflaute, a 2020 study for the United States has demonstrated the role of long-duration energy storage in supporting VRE based electricity systems (Dowling *et al.*, 2020).The study relies on 39 years of hourly U.S. weather data and applies a simplified modelling framework to describe the structure of a 100% renewable system that is fully reliant on wind and solar power. Importantly, they highlight that the introduction of LDES lowers the overall system cost relative to systems that rely only on shorter duration storage systems – and – that reductions in LDES costs have twice the impact on overall system cost as a similar relative reduction in battery cost. Their research highlights

dynamic interactions between storage types, transferring stored energy from longer to shorter terms storage options and back; and uses multi-year simulations to demonstrate the ability of LDES systems to "ensure system reliability during infrequent low-resource periods". This ability relies on energy storage capacity that is up to 85% larger than it would be if assessed over a single year and relies on the system's ability to store energy over multiple years ahead of periods of VRE deficit.

53. While also not focused specifically on Dunkelflaute conditions. Price, Keppo and Dodds (2023) looked at least cost net-zero electricity systems for the UK in 2050 that are adequate and secure, i.e. accounting for inertia and frequency/operating reserve requirements. They selected 3 weather years from the period 1993–2017 to span "best" to "worst" to capture weather uncertainty in system design and operation. The worst selected year was 2010, corroborated by an analysis looking at 60 years' worth of weather data for Europe as a whole (Gøtske *et al.*, 2024), due to its comparatively low annual wind generation and high heat demand.

54. Price, Keppo and Dodds (2023) modelled scenarios which explored futures with varying interconnection expansion and low carbon generator availability. Ultimately, they concluded that even in the worst weather case the lowest cost, reliable system was underpinned by long duration (1000+ hours) of hydrogen storage in salt caverns coupled with short duration (8 hour) batteries and interconnection to Europe. Synchronous condensers were found to be a cost-effective option to provide low-carbon inertia, i.e. not relying on fossil fueled thermal generators, to limit the rate of change of frequency to within tolerable limits and so meet system security needs.

55. Ongoing work at UCL has applied more complex modelling approaches that combines whole energy system modelling using UK TIMES, with high temporal and spatial resolution power sector modelling for the UK and Europe using highRES (Price, Keppo and Dodds, 2023). Net-Zero system pathway analyses from UK TIMES describe the impacts of end-use sector electrification for electricity supply – including competing and connected uses to e.g. hydrogen production or electro-fuels. These supply requirements are combined with sectoral load-curves and analysed using hourly over two snapshot years for 2035 and 2050 using highRES. Different past weather years are used to assess system change under varying conditions, including "worst case" years such as 2010.

56. Overall, this combined analysis shows that a cost-effective resilient approach includes interconnection and trade with other European countries, and investments in storage technologies that can provide a range of storage durations and ancillary services, such as frequency response, inertia, and reserves. Batteries are cost-effective for daily balancing and for frequency response. Hydrogen storage in salt caverns is essential to ensure security of supply cost-effectively over winter, especially in bad weather years. with the ability to provide ~3 months of energy discharge in a cost-effective way. When hydrogen stored in salt caverns is made unavailable, the total annualised system cost is found to be 20% higher by 2050.

8. Do current market arrangements provide sufficient incentives for investment in the range of solutions needed to maintain security of supply during Dunkelflaute conditions? Do market arrangements support the establishment of a 'strategic reserve'?

57. Current arrangements do not yet provide sufficient incentives across the full portfolio of technologies needed for long-duration security of supply. Looking at storage specifically, current market arrangements work relatively well for short-duration batteries because operators can stack revenues from wholesale, balancing, ancillary service and capacity markets – but not for LDES, one of the leading solutions to mitigate Dunkelflaute risk, which faces a lack of market signals and revenue streams.

58. Our recent report (Chambers *et al.*, 2026) concludes that the new LDES Revenue Cap and Floor Mechanism represents an important first step but is unlikely to be sufficient in its current form to deliver the full range of storage durations required (i.e. beyond two days and toward 300+ hours). Modifying the LDES Revenue Cap-and-Floor Mechanism to include separate auction 'pots' for storage of different minimum durations; a lower minimum TRL requirement (TRL 7, to create a route to market for piloted technologies like LAES or flow batteries); and a smaller minimum project size – for example, a limited number of contracts available for projects below 50 MW, to help emerging technologies access revenue support to operate, scale up and build supply chains in the UK - could support investment in a greater range of LDES assets of different durations, in line with system needs. However, even with these changes, inter-week or seasonal LDES, capable of discharging over extended periods, may require additional regulation to ensure the assets are operated in line with system needs rather than individual profit maximisation, so that they are charged and available to contribute to security of supply going into Dunkelflaute events.

59. A strategic reserve model merits serious consideration, particularly for seasonal storage assets like hydrogen storage whose principal value lies in insurance against rare but severe events. The significant revenue uncertainty faced by seasonal LDES assets suggests that even with policy support, such as a dedicated >300h duration 'pot' within the LDES Revenue Cap-and-Floor mechanism, it may not be an attractive enough proposition to private investors to incentivise enough to be built in time for when it is needed. Given the potentially critical role of seasonal LDES in ensuring security in the UK's highly electrified future economy, uncertainty about investment could translate into significant economic risk. Direct state investment in seasonal LDES in strategic reserve (which could also include other low-carbon flexibility) would ensure that the capacity needed to ensure security of supply is procured and maintained. Operation of the assets by NESO, outside of the electricity market, would be entirely for the purpose of ensuring system resilience.

60. As the UK moves to an electrified, renewable-powered economy and its reliance on fossil fuels decreases, there is a need for an equivalent strategic reserve to support electricity security. For this reason, the UK's National Infrastructure Commission has recommended the development of a strategic reserve that can be used to generate 25 TWh of electricity in 2040 (equivalent to about two months' worth of the non-renewable part of the UK's energy system in 2040), controlled by the government, to support both energy and economic security (House of Lords, 2024).

9. What, if any, are the key decisions that Government needs to take before 2030 in relation to long-duration energy storage and low-carbon dispatchable power solutions to support a resilient decarbonised electricity system?

61. Reform the LDES Cap and Floor mechanism to support a broader range of storage technologies and durations (i.e. toward 300+ hours).

62. Establish a clear government strategy for seasonal energy storage, including the role of hydrogen salt-cavern storage, and potential longer-duration demand-side flexibility.

63. Accelerate planning, consenting and grid connection processes for strategic flexibility infrastructure.

64. Undertake detailed system-planning analysis to determine the optimal mix of storage of different durations, low-carbon dispatchable generation, interconnection and demand flexibility under severe Dunkelflaute scenarios.

65. Recognise strategic electricity storage as the future equivalent of today's oil and gas stocks and plan accordingly.

66. Integrate a deeper focus on energy demand reduction options and demand-side strategies. See Barrett *et al.* (2022)

10. What best practice can be learned from other countries about the innovative use of technologies for managing the risk of intermittency from renewables?

67. Arguably the challenge of managing the risk of renewables variability is greater in wind-dominated electricity systems compared to solar power-dominated systems, where fluctuations in electricity supply are easier to predict and smooth with diurnal storage. Amongst wind power-dominated systems, GB is at the forefront in developing LDES, Demand-side flexibility, and interconnections.

68. Following its National Electricity Market Review, Australia is setting up a new Electricity Services Entry Mechanism (ESEM) which will replace existing schemes from 2027. The ESEM will auction long-term contracts, based on targets determined by reliability requirements and emissions goals, for key services: (1) bulk zero emissions energy; (2) shaping, i.e. moving electricity to the time of day it is needed (demand-side flexibility, batteries); and (3) firming, i.e. long-duration dispatchable capacity. A fourth category of essential system services (e.g. frequency and voltage regulation, inertia, system strength) is crosscutting, where projects providing the other services are expected to also be able to provide this. The government is currently consulting industry on the design of these contracts. The contracts for firming services could be an interesting comparator for the UK. See Department of Climate Change, Energy, the Environment and Water (2025), National Electricity Market wholesale market settings review.

69. Italy has an investment scheme for energy storage which includes obligations for the storage to operate in a system-oriented way. MACSE (Mechanism for the Acquisition of Storage Capacity) is Italy's long-term capacity procurement scheme for standalone energy storage through competitive auctions, run by Terna, the transmission system operator. Successful projects have system-oriented dispatch obligations, including mandatory participation in the dispatching services market which Terna uses to maintain system security. The first auction

round in 2025 procured 10 GW of BESS, awarding 15-year contracts for fixed annual payments to projects of 7 hours' duration on average. See Modo Energy MACSE Results (Baltay, 2025).

70. California's Long Duration Energy Storage Program awards grants using carbon tax revenues to grid-scale demonstration projects for non-lithium-ion battery LDES projects (California Energy Commission, 2026).

71. International evidence suggests that predictable revenue support mechanisms are important for storage deployment. Markets like GB that have revenue stabilisation policies for storage (such as a capacity market open to storage or a dedicated storage deployment policy), in addition to allowing storage to participate in arbitrage and ancillary services markets, tend to secure higher deployment levels in proportion to their level of VRE penetration than countries without such policy support for storage.

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Note: Figure 1 and references to Yang *et al*. (forthcoming) represent unpublished analysis in development at UCL's Institute for Sustainable Resources, led by Dr. Pu Yang. For further information on conceptualisation and modelling analysis of this work, please contact pu.yang@ucl.ac.uk.