



Dunkelflaute and the Risks of Electricity Intermittency

The House of Lords Environment and Climate Change Committee

UKERC Consultation Response

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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?**
- 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?**

Work presented in [1] assessed the adequacy challenges facing a highly decarbonised GB power system and is relevant to Q1 & Q2 together. Using a generation and demand background compliant with the Further Flex and Renewables scenario (FFR) set out in NESOs Clean Power 2030 (CP30) reporting, 34 historic weather years were processed to determine the resulting residual demand impacts for the GB electricity system. The analysis showed that total annual variable renewable output (VRE) could swing by up to 80TWh's across different weather years representing $\pm 10\%$ deviations from the Mean.

Maximum energy deficits were assessed over rolling daily, weekly, fortnightly and monthly windows for each year analysed. The peak 28-day energy deficit was 14.5 TWh with 1 in 5 years seeing a peak 28-day deficit in excess of 10 TWh. The average peak deficit across 34 years was 8 TWh with 1 in 8 years falling below a 5 TWh requirement.

The analysis implies the need for 40-50 GW of dispatchable capacity with an ability to largely sustain output for periods extending to multiple weeks. The FFR scenario, in contrast, assumes an installed energy storage capacity (Battery + LDES) connected to the electricity system of just 35 GW and 0.15 TWh.

In a 2030 to 2035 timeframe, assuming the system background approaches something akin to that implied in the CP30 scenarios (albeit likely later than 2030), the main realistic option for ensuring these adequacy challenges are met is to ensure that the existing gas CCGT fleet is maintained and sustained. To decarbonise the meeting of these requirements, low carbon dispatchable generation such as carbon capture technologies or hydrogen to power facilities or very long duration energy storage (VLDES) technologies, as discussed later, would need to become economically viable.

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?

A deeply decarbonised electricity system will rely on four complementary defences against Dunkelflaute events: (i) a diverse renewable generation portfolio; (ii) international interconnection; (iii) dispatchable, firm, low-carbon generation; and (iv) very long-duration energy storage (VLDES). VLDES is not simply one option among many. It is the only defence that shifts energy across weeks, using renewable output that has already been generated. Firm generation adds new supply, interconnection moves energy between regions, and a diverse generation portfolio reduces weather-dependent variability. None of these substitutes for the others, and a resilient net-zero system will need all four.

Recent studies show that Dunkelflaute events can extend over several weeks and may require storage capacities measured in tens to hundreds of TWh at continental scale. Wind droughts of 14 days occur about every five years in Great Britain, and the longest on record, 26 days, is expected once a century [2]. As set out in answer to Q1 and Q2, over a comparable 28-day window, a CP30-compliant GB system would face a peak shortfall of 14.5 TWh between demand and renewable output across 34 historic weather years, with one year in five exceeding 10 TWh [1]. At European scale, the most extreme wind and solar drought on record occurred in winter 1996/97. Even with wind and solar combined across the continent, and perfect interconnection between countries, a fully renewable system would have drawn on long-duration storage for 55 days [3, 4]. Coping with such an event requires 351 TWh of long-duration storage, equivalent to 7% of annual European demand [5]. Dispatchable low-carbon generation reduces that requirement without removing it. Adding a nuclear capacity of 24 GW across Europe, including the UK, lowers least-cost storage needs by 4 to 8%. A much larger 102-GW fleet lowers them by 26 to 37% [5]. More specifically to the UK, the Climate Change Committee [6] finds that when Britain is most stressed, its interconnector partners are commonly short at the same time. In other words, dispatchable low carbon generation, a diverse generation portfolio and interconnection narrow the problem but do not close it. What remains must be covered by a strategic energy reserve that is built up over months or years and held for rare, severe events, a role that only VLDES can play. The remainder of this answer therefore focuses on VLDES.

The choice of VLDES technology depends strongly on the assessment framework employed. Screening technologies solely on capital cost tends to favour low-cost approaches such as compressed air energy storage, bidirectional hydrogen energy storage, and, potentially, iron-air batteries. It also overlooks self-discharge. Losses that are negligible over a ten-hour cycle become decisive for interannual storage, where energy may be held for months or even years. However, when storage assets are evaluated as commercial projects rather than purely as system assets, the ability to stack revenues from multiple

markets becomes key. This changes the competitive landscape between candidate technologies.

Future storage assets are unlikely to be financed solely to provide energy during rare multi-week droughts. Their commercial viability should account for their ability to generate value throughout the year via participation in multiple electricity and flexibility markets. The fundamental question is therefore not simply “how to store terawatt-hours of energy cheaply?” but rather “how to provide seasonal and interannual security of supply while maximising year-round revenue?”

Rather than building a strategic reserve that sits idle most of the time, a single power block can be shared between two stores operating at different timescales: a small, frequently cycled store serving short-term markets (e.g., arbitrage) and a larger store reserved for long-term resilience.

Hence, policy should not simply focus on the cheapest store. It should also reward technologies that pair well, earning short-term revenue while holding strategic reserves. The most attractive solutions may combine stores holding hundreds of GWh, or even TWh, over months with smaller stores cycling daily in electricity markets. The conversion machinery then runs all year, which spreads its cost and lowers system costs. Most importantly, the way technologies are screened can reverse the ranking. Choices of this scale need tools that capture the full picture.

The principal barriers to deployment are not solely technological. Geological storage availability, planning and permitting, long lead times and uncertainty over future markets are many barriers to consider. Current market frameworks reward short-term flexibility more effectively than strategic reserves used infrequently. In the vein of the cap-and-floor scheme, long-duration storage therefore requires market designs that value system resilience.

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?

Dispatchable low carbon generation remains one of the four defences. It provides firm capacity irrespective of how long an event lasts, without the need for a large energy store behind it. Central-planner power system optimisation studies, which optimise storage and firm generation over full years of operation, find that the two complement rather than substitute for each other. Sepulveda et al. [7] conclude that wind and solar must be complemented by a combination of storage and firm capacity, and that displacing firm generation entirely would require storage energy costs below about 10 \$/kWh for nuclear and approaching 1 \$/kWh for gas with carbon capture and storage (CCS) and hydrogen. Kittel et al. [5] find that firm generation does not displace storage either: nuclear capacity only partly reduces European storage requirements, and fossil backup combined with carbon removal reduces them less still. Neither technology displaces the other. The revenue-stacking argument made in answer to Q3 concerns how candidate VLDES technologies

compare with one another and how they are financed. It may shift the balance towards storage but is unlikely to remove the need for firm generation.

Gas with CCS faces its own deployment constraints, as does long-duration storage. Capture equipment is associated with large investment costs. Retrofitting existing plants is site-specific and may be limited by integration with the existing plant and access to CO₂ transport and storage. A further constraint is fuel dependence. Dunkelflaute events are continent-scale events that coincide with high demand across neighbouring countries. In a renewable-dominated power system, reliance on gas at these moments exposes the UK to price spikes and supply risk [8]. Gas with CCS is thus a complement to long-duration storage rather than a substitute for it.

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

Demand-side flexibility is valuable over minutes to hours, and increasingly over several days. Flexible electric vehicle charging, industrial demand response, thermal storage in buildings and smart heat pumps all reduce peak demand and lower system costs.

It is not, however, a solution to multi-week events. Consumers may defer consumption for hours or days, but sustaining substantial reductions across weeks would be de facto rationing. Demand management is therefore a solution to reduce the size of the problem rather than a defence against it. By lowering peak residual demand, it makes portfolio diversity, interconnection, dispatchable generation and storage go further, and allows a strategic reserve to last longer.

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

International cooperation is among the most effective and lowest-cost responses to renewable intermittency. Rodríguez et al. [9] find that for a fully renewable European system, balancing energy falls from 24% of annual demand in isolated national systems to 15% with unconstrained interconnection. Cooperation cannot remove the risk, however. Kittel and Schill [3, 4] identify a European event lasting 55 days even in a system assumed to be perfectly interconnected, and the Climate Change Committee [6] finds that when Britain is most stressed, its interconnector partners are short at the same time.

The barriers are not primarily technical. The scale of build-out is itself a constraint. In a modelled fully renewable (wind and solar) European system, capturing nearly all (97%) of the benefit of interconnection in reducing backup needs would require total cross-border capacity about six times that of 2010-11 [9]. A further concern is energy sovereignty during system stress. In a severe Europe-wide Dunkelflaute, every country may prioritise domestic supply, which makes imports unreliable. Interconnection and domestic capacity therefore complement

each other. Interconnection reduces how much backup is needed during extreme weather events, but domestic VLDES and dispatchable generation are needed to cover what remains.

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