What Could Keep the Lights on When the Wind Stops Blowing in a Zero Carbon UK Electricity System?

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The UK's Clean Power 2030 mission is accelerating the shift to a power system in which renewables provide nearly all electricity. Whilst progress is being made towards the goal of 95% renewable electricity within the next four years, this sharpens the challenge of finding low carbon solutions for when wind and solar output fall short of demand.

The leading methods to enable a clean, resilient electricity transition are electricity storage and low carbon dispatchable power. NESO analysis suggests that if 2030 Clean Power goals are met, the UK will need between 4 - 6 GW of long-duration electricity storage (current installed capacity is at 2.8 GW mostly from pumped hydro projects) and 2 - 7 GW of low carbon flexible generation. Since many of the most promising technologies are not yet ready for deployment, UK policy must accelerate the development of new flexibility technologies through research and innovation and bring forward the commercialisation of the most promising options.

A number of relatively mature options have been developed in recent years that could be scaled up in the UK. The UK Energy Research Centre (UKERC) and the Energy Systems Catapult were commissioned by UK Research and Innovation (UKRI) to review evidence on ultra-long duration electricity storage and low carbon dispatchable power that can be delivered by 2030/2035. Our research shortlists ten technologies that appear most promising for accelerated deployment by 2030-2035, with several options close to achieving scalability. Five of the shortlisted technologies relate to ultra-long energy storage (ultra-LDES) and five to flexible power (LCDP).

Long Duration Electricity Storage (LDES)

LDES technologies store energy with a discharge duration (continuous at maximum power) of at least eight hours and can be combined with charge and discharge from and to the electricity grid providing two-way flexibility to the system. Ultra-LDES allows greater system flexibility, with storage of at least 100 hours.

Low Carbon Dispatchable Power (LCDP)

LCDP technologies provide energy generation which is low carbon (less than 50gCO2/kWh), and is dispatchable. They can combine 'schedulability', 'flexibility' and 'reliability' on request by the grid operator to balance electricity supply with demand.

Our analysis, derived from a rapid evidence assessment of more than 1,500 documents, whole-system modelling, and an expert consultation through 25 workshops involving over 100 participants, suggests these two types of technology can make complementary contributions to a resilient net zero system. LDES provides flexibility by storing electricity and returning it to the grid over longer periods, while LCDP allows low carbon power generation that can be scheduled, ramped up and relied on during periods of limited wind and solar output.

Promising Options for Accelerated Development

Our shortlist of technologies, presented in the tables below, identifies the most promising technologies for development and deployment, rather than a preferred solution. Other technologies are presented in longlists in the report. Our research suggests that no single option offers a perfect fit of long duration/dispatchability, low cost, scalability, geographical independence and readiness for deployment within the next ten years. The tables below demonstrate that some options stand out because they are highly mature and deliverable, while others are attractive because of their scalability, low costs, or strong UK competitive advantage.

LDES technology		Rationale
Hydrogen (H_2)	Salt cavern storage (Low cycle)	High Technological Readiness Level (TRL) (9), ultra-long storage/discharge durations, strong UK competitiveness
Electrochemical	Metal air	Low cost, strong scalability potential, strong UK competitiveness
	Flow batteries (Vanadium/ Zinc bromine)	Strong scalability potential, relatively high TRL (7-8), relatively low cost
Mechanical	Adiabatic compressed air energy storage (A-CAES)	High TRL (8), intermediate duration, relatively low cost, strong UK competitiveness
	Pumped hydro energy storage (PHS)	High TRL (9), intermediate duration, relatively low cost, strong UK competitiveness

Table 1: Shortlisted Ultra-LDES technologies and rationale for inclusion

For long duration storage, we identify technologies with potential to provide 'ultra-LDES' or discharge duration of, at least 100 hours, up to multi-week storage capacity. Hydrogen and to a lesser degree metal-air batteries (at much lower storage capacity), can achieve a discharge duration of 100 hours or greater. Pumped hydro storage (PHS), adiabatic compressed air energy storage (A-CAES) and flow batteries are currently in the intermediate discharge duration range of 12 to 24 hours but, in the future, all of these technologies have the potential to reach 100 hours storage duration. Ultra-long storage matters for the rare occasions when renewables have low output for days at a time.

Figure 1, looking at Ultra-LDES specifically, shows why no single technology will be sufficient. Some options such as metal air and flow batteries are easier to scale because they are more modular and less geographically constrained, but tend to offer shorter discharge durations and/or lower storage capacity. Others, including pumped hydro storage, offer high-capacity, longer duration storage at lower cost, but their dependence on specific sites makes rapid scale-up harder. In this sense, whilst hydrogen salt caverns with a low cycling frequency stand out for their very large storage capacity and relatively low storage cost, they have low efficiency (only 18-46% of energy is retained), require underground storage, and are geographically constrained. Adiabatic compressed air energy storage sits between these extremes, combining intermediate storage capacity and durations with its own siting constraints. This means investment decisions need to strike a balance between duration, efficiency, location, scalability, utilisation and role in the energy system.

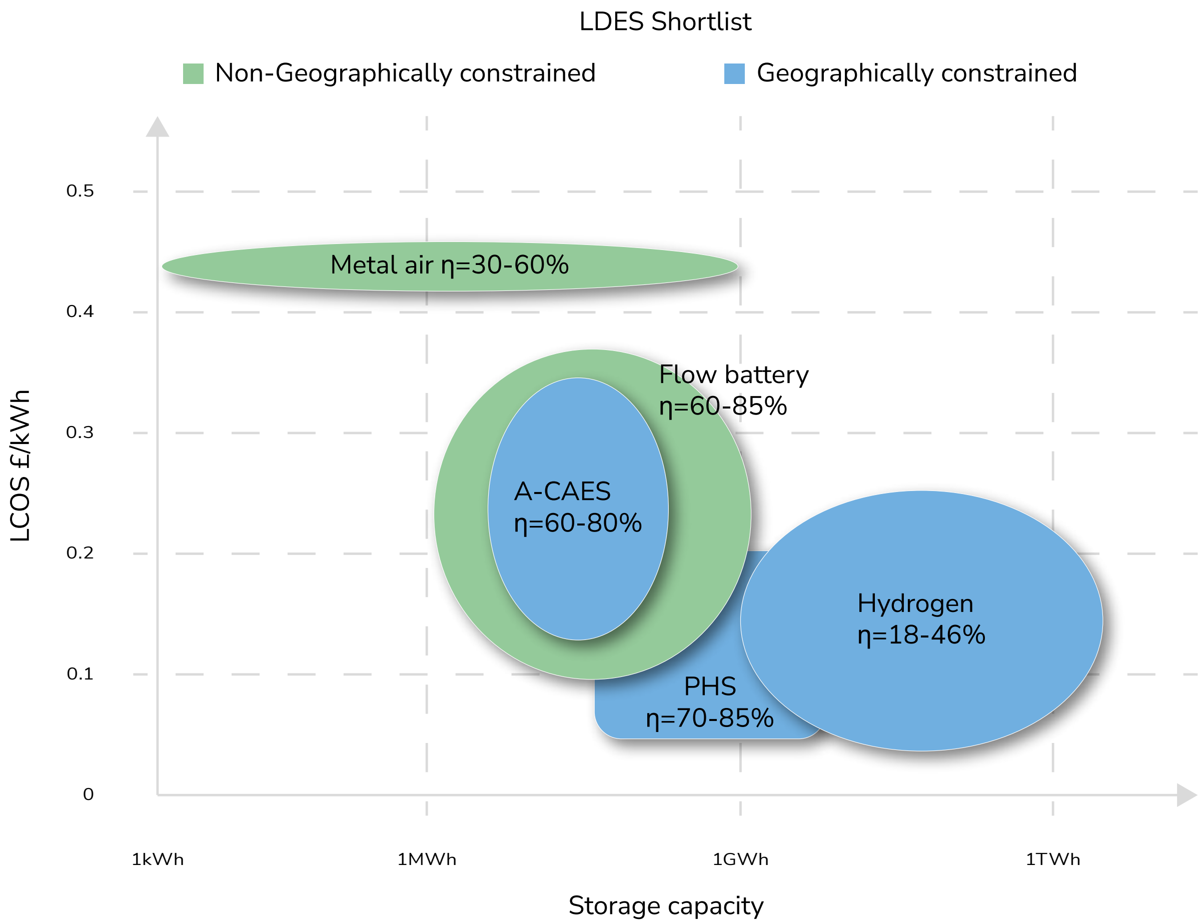


Figure 1: How shortlisted Ultra-LDES technologies differ in levelised cost of storage, capacity and constraints

LCDP technology		Rationale
Hydrogen (H_2)	Reciprocating engines	High TRL (9), high dispatchability
	Gas turbines	Relatively high TRL (7-9) (depending on natural gas/hydrogen blend ratio), high scalability
Carbon Capture and Storage (CCS)	Combined Cycle Gas Turbine (CCGT)	High TRL (8), high scalability for core CCGT technology but dependant on available CO_2 storage market, strong UK competitiveness especially with vast carbon storage in North Sea
	Bioenergy and Carbon Capture (BECCS)	High TRL (8-9), strong UK competitiveness especially with vast carbon storage in North Sea
Nuclear	Small Modular Nuclear Reactor – Gen III (SMR)	Relatively high TRL (7-8), scalability, strong UK competitiveness (Rolls Royce – UK led design)

Table 2: Shortlisted LCDP technologies and rationale for inclusion

For LCDP, our research suggests that hydrogen-based technologies are potentially an important source of system flexibility for the UK energy system, best suited to fast balancing and system support. Carbon capture and storage (CCS) technologies are less dispatchable but could potentially contribute large volumes of low carbon power and bring strong UK advantages (especially due to carbon storage potential in North Sea); SMRs sit apart as a longer-term strategic option. While there is a clear UK competitiveness, they cannot be delivered in the immediate future.

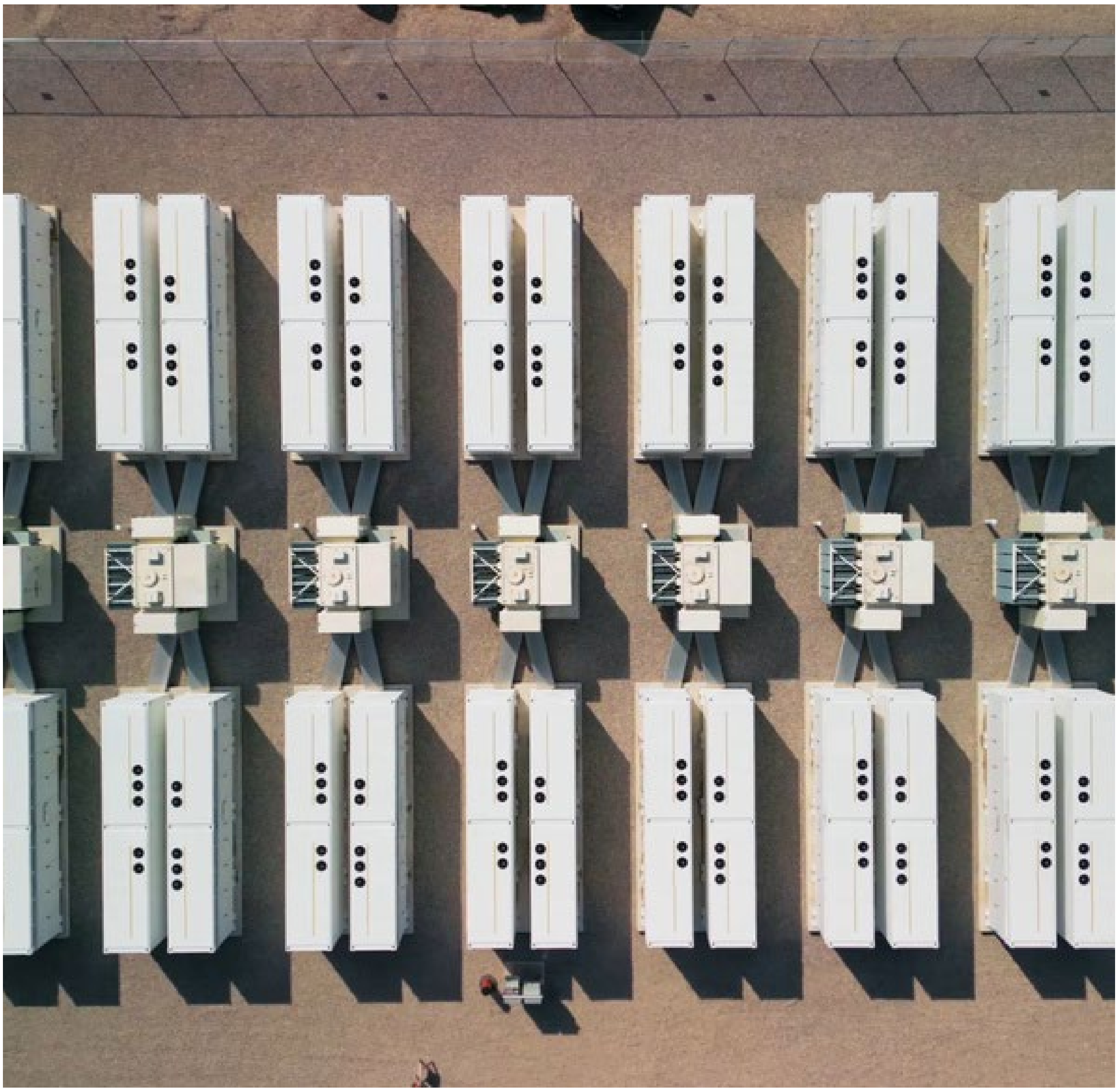
Our analysis also included whole-system modelling to understand how each technology would behave in the future power system. The modelling suggests that least-cost net zero pathways require a mix of technologies working together: batteries can help smooth intra-day fluctuations during extended supply deficits, while fast dispatchable generation can supplement storage during particularly large inter-day or intra-day shortfalls.

The expert consultation and evidence review also highlighted that different technologies face a range of barriers to deployment at scale, including supply chains and investment risk, siting constraints, market access and system integration challenges. This means that the most promising options are not always those that are the easiest to commercialise under current arrangements. A consistent message from both the expert workshops and system modelling is that shorter-duration and more modular technologies may be easier to bring forward because they can access a wider range of revenue streams, whereas longer-duration storage and some forms of dispatchable low carbon generation may deliver high system value but are harder to finance and deploy without changes to market design, business models and supporting infrastructure.

Policy Recommendations

For clean power in the electricity system to be achieved by 2030, the UK energy system would require LDES and LCDP technologies delivered at scale. LDES provides important system benefits by shifting electricity across hours, days or longer periods, helping to absorb surplus renewable generation and release it when wind and solar output are low, thereby strengthening flexibility and resilience in a high-renewables system. The technical benefits of LCDP are often underappreciated but have similar system value to LDES. LCDP technologies provide low carbon generation that can support system balancing and supplement LDES technologies, especially during large inter-day or intra-day supply deficits.

There are still significant challenges in bringing LDES and LCDP to scale at pace. Solving these challenges will require a mix of policy instruments: innovation funding to improve technical performance and lower costs; market reform to better reward flexibility and strengthen business models; and improved understanding of challenges for technological deployment including location, system optimisation and social opposition.



Innovation funding to lower costs and improve performance

All shortlisted LDES and LCDP technologies will benefit from innovation funding to reduce costs, improve efficiency and performance. These activities will need close collaboration between developers, innovators, government and local authorities. Moreover, additional funding for demonstrators can help bring these technologies closer to commercialisation stage and provide evidence for the development of safety and regulatory policies.

Reform market mechanisms and strengthen business models

Beyond innovation funding, our report suggests that delivering these technologies at scale will require government to bridge gaps in how markets value ultra-LDES, for example by developing new market mechanisms or revenue frameworks that better reward long-duration flexibility and firm capacity. It will also require a greater level of business model innovation, including financial risk products and other structures that help projects get to final investment decision faster and reduce exposure to investment risk. Finally, it will need system-level testing and demonstration, such as testbeds and collaboration platforms that can build confidence in electricity system integration, subsurface knowledge development and supply-chain cooperation.

Improve understanding of deployment challenges

To support the success in innovation funding for LDES and LCDP, the key policy challenge for government is to reduce uncertainty and create the conditions for rapid deployment. That means testing practical questions such as where assets should be located, how salt caverns or batteries should be optimised, and how technologies like SMRs might fit into the wider system. It also means taking social acceptance seriously, since some technologies may face greater public opposition than others.

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