Energy Storage

Gaps and Opportunities Analysis

Contents

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Terminology

When people refer to energy storage, what they really mean – almost always – is exergy storage.

Exergy is a formal concept in thermodynamics that refers to the minimum amount of electrical energy or mechanical work that was needed to achieve a certain effect, or to the maximum amount of electrical energy or mechanical work that can be recovered by allowing a system to come back into equilibrium with ambient conditions. Electrical energy and mechanical energy are pure exergy forms but heat and coldness are not. Heat pumps provide one illustration of the essential difference. A heat pump can often deliver 4 units of heat into a space using only 1 unit of electrical energy and drawing 3 units of heat from outside that space. Storing the heat is perfectly possible and doing such thermal storage could potentially contribute useful flexibility to the electricity grid. In the present case, storing 4 units of heat could be an alternative to storing 1 unit of electrical energy. Liquid air energy storage (LAES) is another example where the distinction between exergy and energy is essential. With LAES, exergy is stored as coldness – in effect, negative energy. Although the modern LAES systems do not simply draw heat out of ambient pressure air to make liquid air (because that would be very expensive), that is a possible approach. The negative energy held in liquid air contains positive exergy that can be used to develop real mechanical work again by allowing the liquid air to return to ambient temperature and pressure.

For the sake of brevity and readability, throughout this report we use the term "energy" as shorthand for both energy and exergy and make the distinction only when strictly necessary.

We have tried to avoid jargon that would be meaningful only to energy storage experts. This subject contains some acronyms and initialisms that would be unnatural to avoid. Some of the key abbreviations are defined here.

Glossary

CAES	Compressed air energy storage
ES	Energy storage
EV	Electric vehicle
HP	Heat pump
HVDC	High-voltage direct current
LAES	Liquid air energy storage
LDES	Long-duration energy storage
MDES	Medium-duration energy storage
PCM	Phase-change material
PHES	Pumped hydro energy storage
PTES	Pumped thermal energy storage
R&D	Research & development
RTE	Round-trip efficiency
SDES	Short-duration energy storage
TCS	Thermochemical storage
TES	Thermal energy storage
TRL	Technology readiness revel
UTES	Underground thermal energy storage
V2G	Vehicle-to-grid
VSDES	Very short-duration energy storage

1. Introduction

By now everybody understands that a largely renewable energy system will require huge amounts of energy storage. At its simplest, this means absorbing surplus energy when renewable generation is high and demand is low and discharging in the opposite conditions. Investing in storage therefore reduces the amount of generating capacity needed to satisfy our energy needs. Storage can also provide essential services to keep the grid stable such as frequency response and voltage control.

It is wrong to assume, however, that the need for storage started with renewables. Even in a largely fossil-fueled energy system, we benefitted from the energy storage provided by piles of coal next to the power station; 'line pack' in the gas transmission system; strategic oil reserves; and the momentum of spinning thermal generators. It is just that these forms of storage, and their costs, were largely invisible.

The difference now, with the elimination of coal and reduction of gas generation, is that storage and services it provides must be performed explicitly by a whole spectrum of new technologies, which need to be researched, developed, rolled out and paid for. The catastrophic blackout in Spain and Portugal at the end of April 2025 provides a stark illustration of what is at stake. Although the exact cause of the power failure is still disputed, it might have been averted if appropriate energy storage had been in place.[1]

The purpose of this report is to provide a comprehensive list of the remaining gaps and opportunities in energy storage R&D.

In the public mind, 'energy storage' is often conflated with 'electricity storage' and each seen as synonymous with batteries. This is understandable but misleading.

Batteries are of course ubiquitous and certainly count among the most developed forms of energy storage. This is partly due to their inherent characteristics and partly because the emergence of mass markets for laptops and mobile phones paid for their development. This later provided a solid platform from which to develop EV batteries.

In static applications such as the electricity grid, however, the cost characteristics of batteries limit their role to applications with shorter durations. At longer durations, and at extremely short durations, a whole range of different technologies comes into play, each with its own technical and cost advantages in a particular role.

For very short-duration energy storage (VSDES), for example, where discharge durations range from sub-second periods to minutes, the most promising technologies are flywheels and supercapacitors. In short-duration energy storage (SDES), where discharge ranges from minutes up to four hours, batteries will indeed rule. Medium-duration (MDES), between four and 200 hours, will probably be dominated by electro-mechanical technologies such as pumped hydro, liquid air energy storage (LAES), compressed air energy storage (CAES) and pumped thermal energy storage (PTES). And in long-duration (LDES), where discharge could last weeks or months and where the energy could be held in storage for years or even decades, the economics will favour fuels: hydrogen, ammonia or even biomass. Flow batteries are likely to bridge SDES and MDES.

Some of these technologies, such as LAES and flow batteries, are still being developed; others like CAES and hydrogen in salt caverns are already established but need to develop plants many times larger than currently exist; all need continued R&D to improve efficiencies and reduce cost.

The boundaries between the various energy storage durations are only now becoming clear. At either end of the electricity system, however, the definition of energy storage becomes more blurred.

At an offshore wind farm, for example, the energy produced needs to be transported to shore and then some of it stored to help 'firm' the output. This would typically involve two separate technologies: an HVDC cable and a stand-alone storage technology. The two functions could however be combined in a single vector that provides both. The wind farm's power could be used to produce compressed air or hydrogen, which would be transported ashore by pipeline and stored until needed to generate electricity – with fewer energy conversions along the way. Early research suggests this kind of approach could reduce overall costs significantly.

At the consumer end, it is now becoming clear that distributed thermal storage could, be provided by heat pumps (HPs) operating with an optimiser. These devices combine a local weather forecast and time-of-use tariff to reduce energy consumption and cost. In effect they use the home as a thermal battery – while keeping the internal temperature constant – and so avoid the need to invest thousands of pounds in an actual thermal battery. This also benefits the grid by greatly reducing HP energy consumption during peak hours.

In between the extremes, it is also clear there are big opportunities for hybrid energy storage systems (HESS) which combine various technologies (such as batteries, hydrogen, thermal, supercapacitor) and use their complementary strengths to provide a more consistent energy supply and reduce the strain on power infrastructure.

This report – the final output of the EPSRC-funded Supergen Energy Storage Network Plus project – concentrates on grid energy storage. We largely exclude batteries and other electrochemical technologies such as fuels cells and electrolysers, since there is little point duplicating the work of the Faraday Institute. We also exclude Carbon Capture and Storage (CCS). The overall purpose is to gather in one place a concise set of observations indicating where significant additional benefits could attach to further research effort.

We concentrated largely on applications relevant to the UK, and the report draws mainly on British source material. This includes the academic literature along with information gleaned from conferences, technology developers and potential customers. The development of this report was led by two academics but the text was contributed to by many more, whom we thank and acknowledge at the end of the report. An early draft was circulated and discussed with colleagues at the UKES2025 conference (Sheffield, April 2025) and their feedback has been integrated into this final version.

This introduction and the subsequent two sections set out the main themes of our work and some underlying terminology and principles. Most of the subsequent sections are specific to a single set of technologies, to research areas where we recognise that significant value remains to be released, or to interactions between areas where there are strong prospects of deriving further advantage.

Key areas of interest include:

- Salt caverns, for hydrogen, compressed air or bio-gas
- Hard rock caverns, for hydrogen, compressed air or bio-gas
- Aquifers for storing heat, compressed air or hydrogen
- Aquifers transformed into caverns using a front of pumped grout
- High-grade heat storage and exchanging stored heat with pressurised fluids
- Heat exchangers for heat-transfer fluids
- Air compressors, especially at the high-pressure end (with variable ratio)
- Air expanders, especially at the high-pressure end (with variable ratio)
- Isobaric storage technologies for optimally exploiting containments
- Hydrogen compressors and expanders for storage and recovery of physical exergy from hydrogen
- Thermodynamic cycles involving:
  - supercritical CO_2
  - ammonia-water mixtures
  - other mixtures (not NH_3-H_2O) exhibiting 'glide'
  - Thermodynamic cycles in which heat is stored thermochemically

If there is a single overarching conclusion from our work, it is perhaps that integration pays: if we can develop a machine to perform two roles rather than one, society wins. As the rest of this report shows, the opportunities in energy storage for this – and many other advances in efficiency and cost – are legion.

References

1 *Spain Blackout Accounts Pin Blame But Do Little for Grid: React. BloombergNEF Research Note, 20 June 2025.*

2. Taxonomy of energy storage technologies

At the highest level, energy storage can discharge two different functions:

- Energy storage provides temporal flexibility – allowing energy to be withdrawn from a system (or subsystem) at times different from when it is supplied.
- Energy storage makes energy mobile – supporting the movement of energy from one location to another. Often but not always, this energy is used within the same subsystem that carries it.

Both functions are important, and both are addressed in this document. In some areas of discussion, especially around electro-chemistry (that is, batteries and fuel cells), other sources already provide a comprehensive account and we deliberately avoid duplication. As it happens, this affects our coverage of energy mobility (transport) much more than temporal flexibility (grid).

In electricity grids, energy storage competes with other potential sources of temporal flexibility such as transmission of energy to other locations using electrical transmission lines, and the flexible consumption of electrical energy to deliver energy services that can be stored. In this last category, some of the energy services are themselves other forms of energy such as heat.

In studies of grid energy storage, it is common to try to form a hierarchical framework in which each technology has a unique place, but such an approach is unnecessary here. We discuss several ways to categorise energy storage technologies below, which will help map them against the research gaps we identify. To note, we attach no significance to the order in which the categories are presented.

Storage duration

Several different meanings can be attached to the term 'duration of energy storage'. It could refer to the time taken to charge the store completely at maximum input power; or to discharge completely at maximum output power; or it could describe the average duration the energy resides in the store.

Clearly, the first two definitions above are physical attributes of the energy storage system itself while the third definition reflects how that system is used.

Throughout this document, what we mean by 'storage duration' is the period of discharge from completely full to completely empty at maximum output power.

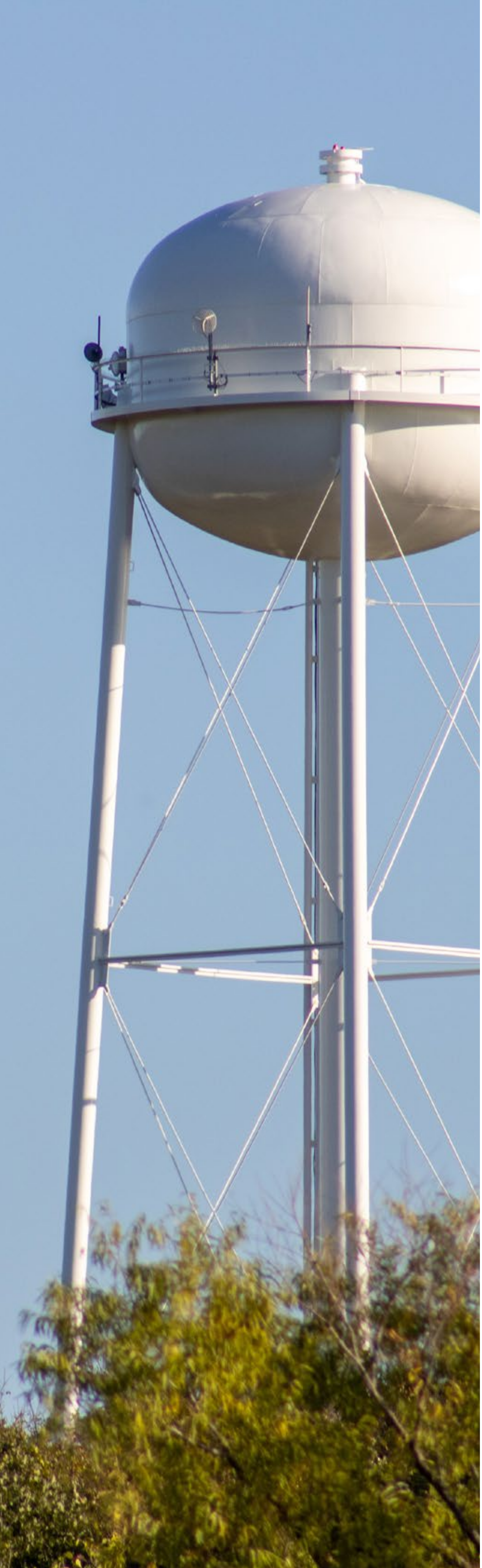
Storage durations

- VSDES: very short-duration energy storage, meaning that discharge times range between sub-seconds to minutes
- SDES: short-duration energy storage has discharge times from minutes to ~4 hours
- MDES: medium-duration energy storage typically has discharge durations of ~4-200 hours
- LDES: long-duration energy storage has discharge durations exceeding 200 hours

The boundaries dividing these different categories are not fixed and they depend on the cost of competing energy storage technologies for providing various derivatives of energy. Moreover, it should be recognised that technologies suited to discharging mainly in one of the above bands of discharge durations can provide services in timescales that are shorter.

There are four main measures of cost: cost per unit of energy ($/kWh); cost per unit of power ($/kW); cost per unit of power slew-rate, or speed of change ($/(kW/s); and cost of losses due to round-trip efficiency (RTE). It is the price of each technology against each of these measures that determines what duration of storage it can best provide. A flywheel, for example, currently has one of the lowest costs of power slew rate and therefore excels in VSDES. Batteries have the lowest cost of power and therefore dominate SDES. In contrast, MDES is less affected by the price of power and more by the price of energy and so favours electro-mechanical technologies such as CAES and LAES. LDES is predominantly about the bulk storage of energy, and so fuels such as hydrogen or ammonia, which are relatively cheap to store, dominate here.

While the boundaries between the duration categories are not fixed, they may well move as a result of changes in relative cost driven by R&D.



Power

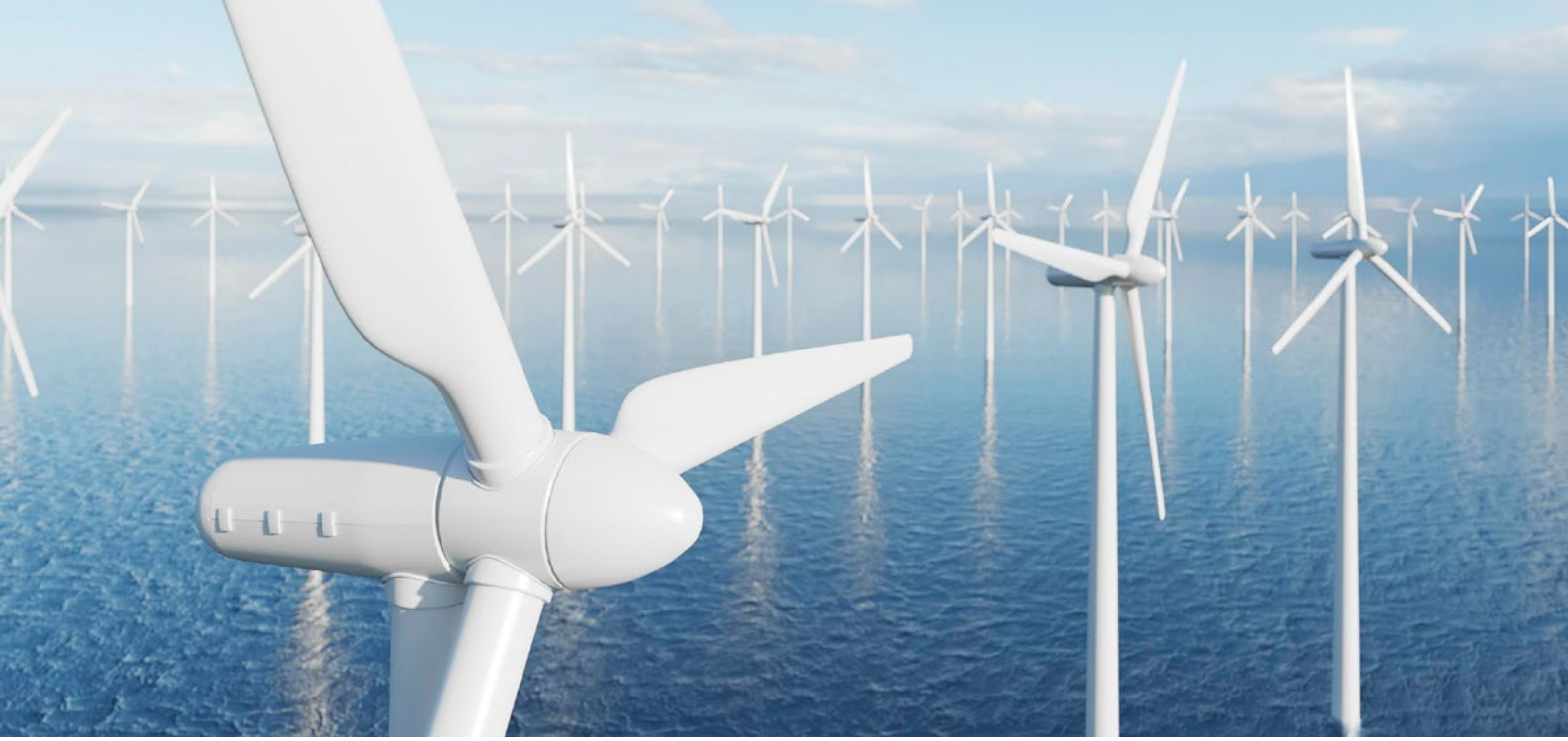
Energy storage can be categorised by scales of power – or the size of an individual plant – and this has a strong influence on the type of technology deployed. We distinguish between small-, medium- and large-scale energy storage applications, abbreviated as SPo, MPo and LPo. A suitable division between small- and medium- scale is ~20kW; powers below this are domestic scale. A suitable division between medium- and large- scale is ~10MW. Powers below this level are at the scale of individual company sites or institutions such as hospitals, university campuses and large office buildings.

The form in which energy is stored

Energy or exergy can be stored in several forms. These include chemical energy (CE), kinetic (KE), gravitational potential (GPE), strain or pressure (SE, PE) and thermal (ThE). Sometimes these forms are combined and it is not possible to distinguish what proportions of the stored exergy are attributable to the elemental forms. For example, thermal exergy and pressure exergy combine to form what we might reasonably refer to as thermodynamic exergy.

Mobile or stationary storage

Some energy storage is required for mobile computing or transport applications – usually in the form of batteries. In these cases, the mass of the system components is an important consideration. In other cases, energy storage does not need to move, and often the technologies suited to mobile applications are too expensive for deployment in stationary (grid-supporting) roles.



3. Roles of energy storage in electricity systems: gaps and opportunities in modelling

Energy storage technologies have emerged as a cornerstone of modern energy systems, providing diverse services that improve the reliability, efficiency and sustainability of the grid. They play crucial roles across various timescales, from instantaneous frequency response and voltage control to daily energy arbitrage and seasonal storage. They support the integration of variable renewable energy sources – thus reducing carbon emissions – and provide capacity to meet peak demand. The benefits also extend to network management, where storage can avoid or defer costly grid infrastructure investments by providing local peak shaving and congestion management.

Beyond these operational benefits, energy storage serves as a critical resilience tool, providing backup power during outages and helping power systems adapt to the increasingly uncertain and extreme conditions driven by climate change.

Since energy storage capacity must now rise to unprecedented levels, understanding the ramifications of future scenarios becomes ever more important. Here we discuss recent developments in energy storage modelling for system integration and identify gaps and opportunities for further development.

3.1 Security of supply

An essential contribution of energy storage is the security of supply. Giannelos et al.[2] introduce a methodology (based on the F-factor) for quantifying how energy storage systems contribute to electricity grid security of supply by reducing peak demand. The methodology calculates the ratio between peak demand (after the maximum possible demand reduction) and the power capability of the energy storage system. The research demonstrates that the contribution of energy storage to security of supply increases with higher storage efficiency, longer charge/discharge duration and 'peakier' load profiles, but does not necessarily increase with greater storage power capability.

The research also finds that while adding multiple storage units at a single bus (grid) location could provide peak reduction benefits, the marginal security contribution tends to decrease with each additional unit. This work provides valuable insights for grid operators, regulators and energy storage investors to quantify and evaluate the security benefits of energy storage deployments in power systems.

In general terms, there is strong scope for further research on the positive impacts of energy storage on increasing security of supply. Specifically, it is of interest to model and understand how energy storage can avert power-outs, respond to actions by mischievous actors and improve resilience in the increasingly common weather extremes.

3.2 Managing and deferring grid investment

As well as improving security of supply, energy storage can defer or permanently displace expensive conventional grid reinforcements. This capability gives rise to the concept of option value, which is the net economic benefit accrued from deploying energy storage to the system.

Giannelos et al.[3] refer to the option value of a portfolio of energy storage with 'soft open points' – electronic devices that enable better voltage and power control. It presents an investment model for optimally integrating solar photovoltaic (PV) capacity and energy storage systems in electricity distribution networks. The research shows that the flexibility provided by a portfolio of energy storage and soft open points represents significant option value that can help defer or avoid conventional network reinforcement while maintaining the security of supply and reducing the risk of stranded assets.

Similarly, Giannelos et al.[4] develop a mathematical framework for calculating the option value of Dynamic Line Rating (DLR) and energy storage in electricity distribution networks. Case studies demonstrate that a combined portfolio of DLR and storage can generate significant option value by allowing strategic 'wait-and-see' investment decisions rather than committing to expensive conventional upgrades upfront.

The research also shows, however, that while both DLR and storage provide individual option values, their combined value is less than the sum of individual values since they can substitute for each other in accommodating power flows and managing uncertainty.

While most studies use exogenous modelling of uncertainty when evaluating the option value of storage, the research highlights the importance of also considering decision-dependent uncertainty, because the former approach may undervalue the benefits of early adoption.

Further work by Giannelos et al.[5] describes a stochastic optimisation model that considers how early investments in storage can provide information about future cost reductions and technological improvements, creating a 'learning effect' that influences subsequent investment decisions. Through case studies on a distribution network, the work demonstrates that early storage deployment, despite higher initial costs, can be valuable as it allows planners to discover whether further cost reductions are possible and adjust their strategy accordingly.

Substantial scope exists for further research on how energy storage can introduce value in terms of providing flexibility in the timing of investments in energy infrastructure. There is a tendency to assume that infrastructure upgrades are inevitably needed, and to ignore the strong value that can be attached to deferring those upgrades whilst other uncertainties resolve themselves.

3.3 Business models for energy storage beyond arbitrage

At the simplest level of analysis, the economic value of energy storage comes from energy arbitrage. This is the practice of storing energy when electricity prices are low, typically during off-peak periods, and selling or using that stored energy at peak times when prices are high. This creates economic value by taking advantage of price differentials in electricity markets while helping to balance supply and demand across different periods. In most cases, however, arbitrage alone has not provided sufficient commercial justification to implement energy storage.

In more advanced applications, the storage can do arbitrage while also providing ancillary services. For example, Tamrakar et al.[6] present a Model Predictive Control (MPC) framework that allows energy storage to simultaneously perform energy arbitrage and provide power quality services like voltage regulation and power factor correction. The researchers demonstrate that their framework enables storage systems to maintain grid voltage and power factor requirements without significantly impacting the arbitrage revenue potential. The results show that in some cases, combining voltage regulation with arbitrage can increase revenue by allowing more charging and discharging opportunities while keeping voltages within limits.

Incorporating energy storage in the market clearing problem is challenging and methods should be developed to solve the problem more efficiently. For example, Wu et al.[7] present an efficient decomposition method to solve the two-level energy storage arbitrage problem, where an energy storage system aims to maximise its profits by buying electricity when prices are low and selling when prices are high. The authors prove that the locational marginal price (LMP) at the storage connection node is a piecewise constant function of the storage bidding strategy, allowing them to eliminate the complex market clearing problem and reduce it to a simpler mixed-integer linear programming (MILP) problem. The proposed method achieves the same optimal solution as conventional approaches but solves the problem over 200 times faster, as demonstrated through case studies on an IEEE 118-bus system.

In a similar vein, Yu et al.[8] propose a Double-Q learning approach for optimising energy storage arbitrage in grid-connected microgrids under real-time market price uncertainty. The authors demonstrate that their learning algorithm performs better than traditional Q-learning by avoiding overestimation issues, resulting in approximately 43% higher arbitrage profits when trading in electricity markets. They then extend their approach to consider joint arbitrage across both electricity and carbon prices, showing that including carbon price information in the arbitrage strategy can increase profits by over 110% compared to electricity-only arbitrage. The research demonstrates that energy storage systems can effectively participate in both electricity and carbon markets to maximise revenue while helping to stabilise the grid and support renewable energy integration.

Summarising this subsection, the area of discovering optimal commercial operating strategies for energy storage systems within markets offering a complex array of services remains a rich area for further work where there is significant potential for useful new developments.

3.4 Integrating high penetrations of renewable energy in energy systems

In recent years, the problem of integrating high penetrations of renewable energy sources into the energy system has been a critical focus in the transition to sustainable energy. Some novel solutions have been proposed, from hybrid systems and AI-driven innovations to shared storage strategies.

A significant challenge in renewable integration is managing the intermittency and variability of renewables. Hybrid energy storage systems (HESS) have emerged as a promising solution. In this context, Adeyinka et al.[9] discuss advancements in HESS, which combine various storage technologies such as batteries, hydrogen storage, thermal storage and supercapacitors, to make use of their complementary strengths. This approach enhances the reliability and stability of renewable energy integration into the grid, providing a more consistent energy supply and reducing the strain on power infrastructure. Similarly, Suberu et al.[10] highlight the role of energy storage in mitigating renewable energy intermittency.

Modelling the role of energy storage in systems comprising high penetrations of renewable energy generation requires significant further research. Potential future value can be added by modelling the operation of hybrid energy storage systems, which may include one or more stores located locally with the renewable energy generators and other energy stores elsewhere.

In addition to the points raised in the subsections above, there is also justification for:

Modelling endogenous uncertainty

While Giannelos et al.[11] introduce endogenous uncertainty in storage modelling, this appears to be an emerging area with significant room for expansion. Further work by Giannelos et al.[12] shows that most research focuses on exogenous uncertainty. There is a clear gap in modelling how storage investment decisions themselves affect future uncertainties across various aspects: not just cost reductions, as explored in Giannelos et al.,[13] but also how storage deployment might influence renewable integration patterns, market prices and grid operation strategies.

Comprehensive value stacking and market frameworks

The literature discusses separate value streams – arbitrage, security of supply, option value – but there is limited research on comprehensive models that can capture these value streams simultaneously while accounting for their interactions and potential conflicts. This gap is particularly relevant for real-world applications where storage systems must provide multiple services to maximise their overall value to the grid. Another barrier to storage is that the current energy and ancillary service market frameworks cannot capture and remunerate the whole system value of storage. This reduces the incentives to build energy storage. If the models could be developed, the market frameworks might follow.

Understanding the effects of uncertainty in distributed energy storage operation

The emergence of uncontrolled distributed energy storage, such as domestic batteries and thermal storage, and HPs controlled by optimisers, which in effect treat the home as a thermal battery, may pose a challenge in the planning and operation of active networks. The uncertainty of their operation is often managed by assuming worst-case operation scenarios, leading to a higher network reinforcement cost. Better integration of such technologies should be developed to minimise the system costs and maximise the value of energy storage.

3.5 Optimal scheduling of energy storage operation in multi-store energy systems

Modelling serves to highlight the potential value of energy storage within energy systems in two quite distinct ways. In one context, modelling may be used to determine how much revenue may be captured by an energy storage plant offering various services within a market structure and a set of likely scenarios. In this first context, the energy storage plant is usually considered to be a 'price taker' in the sense that its presence and operation is likely to have negligible effect on changing the value of the services that it may provide.

A second and entirely different usage for modelling is to determine how energy stores might best be operated within a given energy system to minimise system costs. In this second situation, energy storage can profoundly affect the instantaneous value of energy and grid services, and smart scheduling can make a very significant difference to overall system cost – but only if multiple different energy storage plants of differing characteristics are present.

Technologies that have high roundtrip efficiency and relatively low costs per unit of input and output power rating will tend to be used very often to handle the relatively high-frequency components of storage duty. Conversely, technologies that have much lower roundtrip efficiencies but very low cost per unit of energy storage capacity are well-suited to infrequent operation where the energy exchanged per cycle may be extremely large.

There is a continuous spectrum of storage operation frequency between the high-frequency and the very low-frequency ends, with different storage technologies optimal for different parts of this spectrum. In a cost-optimal real system, multiple storage technologies would be present with each one of those providing service within the part of the spectrum to which it is best suited, as well as in other parts.

To simulate how a multiple-store system could best operate, it is essential to know how the operation of those stores would be scheduled. In simple terms, if there is an excess of supply at any one time, which stores should be charged by preference? Conversely, if there is a shortfall in supply relative to demand, which stores should be discharged? The principles of this problem are understood and discussed in Cosgrove et al.,[14] Cardenas et al.,[15] Garvey[16] and Zachary,[17] but there is clearly much more to do in terms of utilizing foresight and embedding probabilistic information for time-series data comprising hundreds of thousands of one-hour or half-hour periods.

3.6 Virtual Energy Systems

An additional point raised during the discussion session about this report at the UKES2025 conference was that more work is required on Virtual Energy Systems – digital twin models of the complete energy systems that can mimic and simulate the behaviours of an interconnected energy system.

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4. How energy storage technologies may develop in the future

Batteries are without doubt the world's most successful form of energy storage so far. Their rapid technological advance means that in 2025 one in four cars sold worldwide will be an EV, and they already dominate short-duration grid storage.[18]

The early development of batteries has been funded by the emergence of mass markets for laptops and mobile phones, which then provided a platform from which to develop batteries for EVs and grid storage. Many other energy storage technologies are less fortunate, having only the market for grid balancing to support their development. Examples include large compressors and expanders for air and hydrogen, flywheels and heat exchangers. These face a 'Catch-22' situation in which the lack of a vibrant market discourages investment, and the lack of development then subdues the possible development of any market.

This issue was highlighted during the development of the 2023 Royal Society report on Large-Scale Electricity Storage.[19] While investigating the potential role of adiabatic compressed air energy storage (ACAES), the authors attempted to establish the future capital costs of large-scale compressors and expanders. The range of costs at ~95% confidence remained stubbornly wide, stretching from £60/kW to £600/kW. The future performance of these machines was also uncertain but less so than the costs.

It was striking to find that if the capital costs were towards the lower end of the range, the role for ACAES would be significant and the savings could amount to 10% of total energy costs. If, however, the costs were at the upper end of the range, then in a cost-optimised system there would be no ACAES whatsoever.

These problems are especially acute for mechanical power-conversion equipment for four main reasons:

- Mechanical machines tend to particularly benefit from being implemented at high-power capacities. For example, a single 100MW compressor would probably perform much better and cost much less than 20x5MW compressors if the required duty comprised mainly full load or off. This is much less marked for other equipment where the benefits of mass production outweigh the benefits attached to larger scale.
- High-power equipment is manufactured much less often than equipment at smaller power levels and tends to be custom-designed for specific locations and application features. Developing standardized machine types at large power scales is possible where a market is established. It is much more difficult to justify it where a market is still uncertain.
- Evoking established scaling principles in engineering such as Baniamerian et al.[20,21] that make clear how component costs vary with operating conditions such as input and output pressures and the relevant physical properties of the fluids being worked.
- Most pieces of large mechanical equipment have very long natural lifetimes – closer to 50 years than five years. This means that such projects are very sensitive to the discount rates applied, which determine the cost of borrowing.

Just days after the Royal Society's landmark report was released, Staffell and Schmidt published an open-access book[22] addressing a part of this problem. The book charts how 'learning by doing' has driven down the costs of different technologies. Similarly, books supporting engineering design such as by Branan[23] provide general suggestions about the non-proportional relationship between cost and power for large power-conversion machines, as well as between cost and number of units produced.

Some work has been done on establishing the connection between operating pressures and cost per kW, but these do not answer all the relevant questions.

It is vital for the UK and the future net zero world to achieve much more reliable ways to assess future development, commissioning, maintenance and unit costs, and dependencies on critical materials and energy, for a number of classes of components that will almost certainly serve major energy storage roles in the UK and worldwide.

Key components for future energy systems

- Large (mainly axial-flow) compressors drawing in ambient air
- Large (mainly axial-flow) expanders exhausting air to ambient
- Water pumps and water turbines
- Hydrogen compressors (from ~20-30 bar) up to cavern/transmission pressures
- Hydrogen let-down expanders from cavern/transmission pressures
- Heat exchangers transferring heat into/from pressurised liquid
- Heat exchangers transferring heat into/from pressurised gases
- Adiabatic compressors operating in reversible heat-pump/heat-engine cycles
- Adiabatic expanders operating in reversible heat-pump/heat-engine cycles
- Dehumidifiers of ambient air
- Units for recovering oil from compressed/expanded gases

The information and the data processing capability now exist to create models – probably based on AI – to answer the key questions for the equipment listed above. In all cases, the answers will depend strongly on the length of the forecast, how much money has already been invested in developing 'similar units', and how many 'similar units' have by then been brought into service.

The required capability could be described as a tool or set of tools that can produce confident predictions of total costs and marginal future unit costs for different classes of power-conversion components relevant to energy storage.

Such a tool(set) would be based on several types of information, including:

- as much historical cost information as can be gained
- application of learning-by-doing principles to historical costs as done in Staffel & Schmidt[24]
- drawing upon the principles of economies of scale from multiple related manufacturing contexts
- capturing the knowledge and know-how from experienced designers and producers of the respective equipment types
- using a bottom-up 'bill-of-materials' approach to determine absolute lower-bounds for the costs.

The toolset should be able to produce and justify an estimate of confidence in the costs prepared. It should also identify what externalities could most strongly affect the viability of any particular piece of equipment. Without this vital capability, a great deal of uncertainty will remain over how both the UK and other countries should progress most affordably and most quickly towards net zero.

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5. System integration opportunities

As outlined in previous sections of this report, energy storage can provide significant functions to power networks, ranging from control of voltage and frequency, to managing power flow constraints, to providing additional capacity. The resulting benefits include increased energy security, the integration of renewable energy and avoiding costly network reinforcement. These benefits can be delivered by a variety of energy storage technologies across both transmission and distribution networks, from large-scale projects to smaller distributed systems, some even co-located with renewables.

Energy storage has seen a tremendous uptake in power networks. In June 2022, storage exported more than twice as much energy to the grid as coal.[25] According to National Grid's Future Energy Scenarios, UK energy storage will reach ~38GW by 2050.[26]

In distribution networks, energy storage is especially important in integrating not only smaller scale generation, but also the electrified load from heat and transport networks, where it can time-shift demand and reduce new peaks.

Despite the benefits and fast adoption of energy storage, however, there are significant gaps in coordination across voltage levels between distribution to transmission in both system design and operation.

At present, energy storage is deployed and operated in response to markets that have been created by regulation to achieve a single purpose, without considering the impacts across wider network areas and voltage levels. This can leave storage assets under-exploited or even lead to operational conflicts.[27] One example is the emergence of new peaks in distribution networks when locally connected storage offers services to the transmission network.[28] It is imperative that we develop a new 'system-thinking' approach to the sizing, siting, and technology choice of energy storage systems. This will without doubt reduce costs and shorten the current long queues for grid connection.

Another related problem is that current regulatory and market frameworks are often blind to the characteristics of an individual storage technology; they cannot see its true potential or limitations, nor even its lifecycle contribution to net zero.[29]

This can mean that less suitable technologies are deployed over more suitable ones, driven by commercial availability and economies of scale, and the coordination of diverse technologies across the system is hindered. It is therefore critical that we develop top-down approaches that start from the service required, to determine the most appropriate energy storage technology to deliver it.

Finally, the electrification of heat and transport and the emergence of new loads such as data centres will inevitably challenge transmission and distribution grids in terms of adequate supply, stability and network capacity. This means we must coordinate the planning and operation of energy storage systems not only between electricity grids but also with other sectors, particularly as most of the electrified transport and heating systems have inherent energy storage characteristics themselves.[30] We need urgently to develop methods to plan, build and operate energy storage systems in power networks in tandem with electrified transport, heat and other new loads in the system. This will help accelerate the rate of electrification while deferring costly network reinforcements or rendering them unnecessary.

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6. Hydrogen, ammonia and other E-fuels in energy storage

Our general understanding of the energy storage roles for which hydrogen is or is not suitable has advanced significantly in the last several years. We therefore have no need to replicate the work of two major EPSRC hub programmes - UK-HyRES led by the University of Bath,[29] and HI-ACT led by Newcastle University[30] – nor that of the 2023 Royal Society report on Large-scale Electricity Storage.[31] Here we simply record some further significant observations of the energy storage and energy system communities.

Hydrogen compression: the energy density of hydrogen is high relative to its mass but low by volume. Its production, storage, transmission and use therefore involves compression. As a result, hydrogen exhibits non-ideal behaviour in most cases, particularly during storage. It is very challenging to achieve efficient hydrogen compression and an isentropic efficiency of ~50% is quite typical at present depending on the scale and method, leading to the generation of a large amount of heat.[32] This is especially important for hydrogen since the quantities of work required to compress hydrogen from electrolyser pressures up to storage/transmission pressures can be a significant fraction of its total exergy value as a fuel. The first set of challenges and hence research gaps are related to cost-effective methods for efficiency enhancement of hydrogen compressors and compression processes, and the use of compression heat.

Hydrogen expansion: because of its low volumetric energy density, hydrogen is often stored at a high pressure or in cryogenic form. To be used as a fuel, hydrogen must expand. Due to its negative Joule-Thomson coefficient, hydrogen expansion causes a temperature rise if the gas is simply throttled (that is, passed through a small hole to reduce its pressure). As a result, another set of challenges and hence research gaps include cost-effective and scalable methods for efficient recovery of pressure exergy from hydrogen gas as it is released from storage or transmission infrastructure, or alternative methods for exploiting expansion heat.

The Royal Society report suggests that hydrogen is the most cost-effective method for large scale electrical storage under a renewable dominated net zero scenario. However, the report says nothing about business models, which remain a challenge and hence a research gap.

Hydrogen and hydrogen-based energy vectors such as ammonia and e-fuels have an important role to play in a renewables-dominated net zero scenario. At the same time, the low efficiency of hydrogen production, storage, transport and applications presents many challenges. As outlined above, cost-effective and efficient use of the waste energy from hydrogen production and management, mostly heat, presents a challenge. It is possible that sector coupling (exploiting the interactions between different sectors within the energy system) could provide useful opportunities if hydrogen processes were combined with, for example, ammonia production, minerals processing, air separation, and the direct reduced iron (DRI) technology of steel production, which also relies on large amounts of heat.[33]

The connection between hydrogen and ammonia and the use of ammonia both in the formation of fertilizers for agriculture and as a dense energy carrier is also an area in which further research will bring dividends. A further point from the UKES2025 discussion was the desirability of lower-cost high-pressure tanks for hydrogen, and potential integration of over-wrapping and integral condition-monitoring of those tanks for safety.

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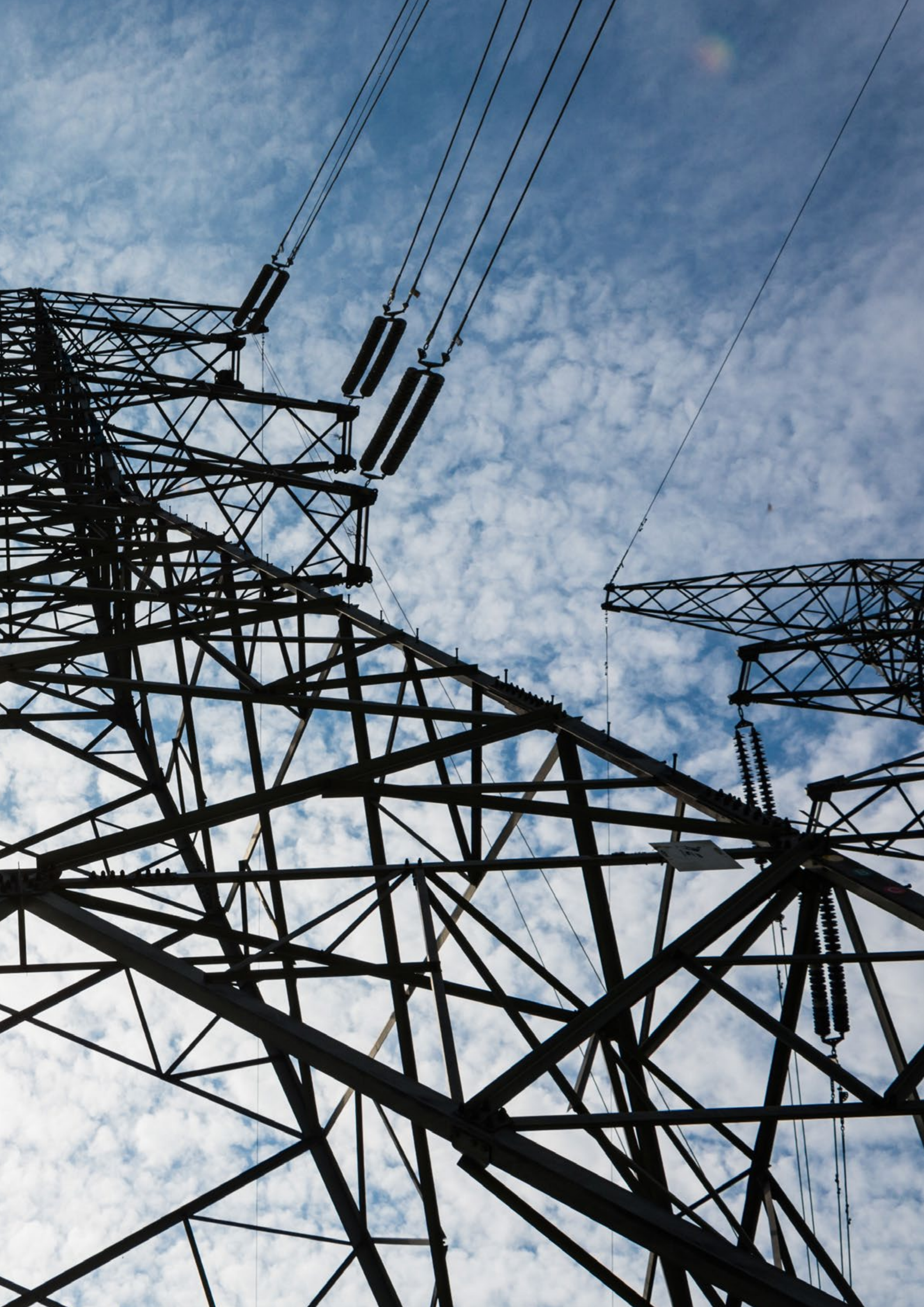


7. The renewable-generation ↔ energy-storage nexus

Before we recognised the threat posed by burning fossil fuels, there was almost no discussion in the electricity industry of energy storage or demand side response, and very little around interconnectors. It was unnecessary because supply and demand could always be matched through flexibility on the supply side.

Just because energy storage went unremarked, it does not mean it wasn't there. Quite the contrary: two decades ago Britain had more energy storage than it does now and may ever have in future. It came in the form of piles of coal, tanks of oil, gasometers, salt caverns and aquifers. Altogether this energy storage typically ran to several hundred TWh of electricity-equivalent – three times more than our current pumped hydro capacity.

In those days, the important metric was the cost of generation, described as the Levelised Cost of Electricity (LCoE) and measured in £/MWh. No separate value was ever placed on the ability to store energy because it came effectively for free. In the new paradigm, intermittent renewables now undercut fossil fuel generators on LCoE, often steeply, but storage no longer comes as an inherent benefit.

In the early days of the transition, renewable penetration was low enough that none of this was a problem. Nowadays, in some countries renewables regularly generate well over half the electricity, and occasionally as high as 100%.

The catastrophic blackout in Spain and Portugal in late April 2025 may be an indication of the potential hazards. Although the exact cause of the disaster is not yet known, immediately beforehand more than half of Spain's electricity was being generated by solar, which unlike the spinning machinery of fossil fuel generators, provides no momentum to support frequency and voltage in case of a grid fault.

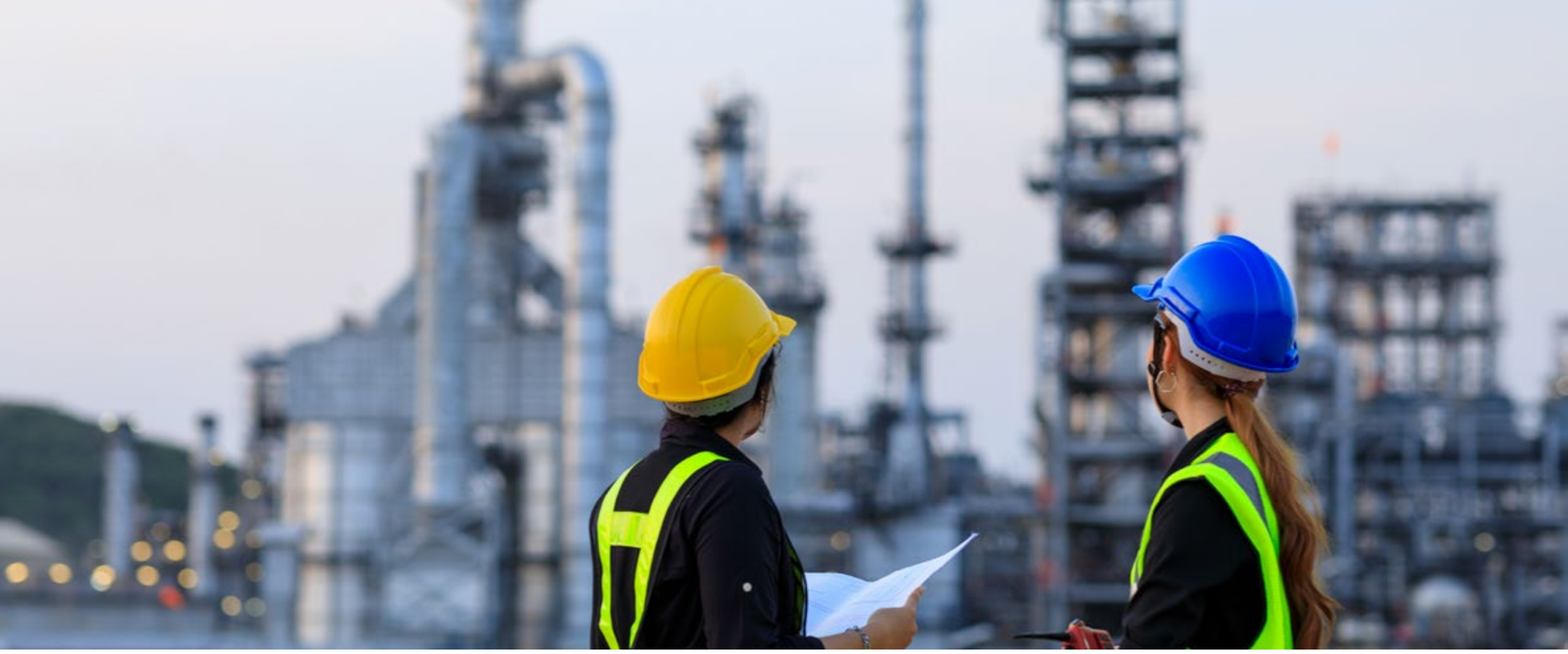
A blackout is only the most extreme and economically damaging form of mismatch between supply and demand, but reconciling the two always has associated costs. It is now clear that substantial thought must be given to minimising those costs.

Of course, some of that thought is devoted to developing energy storage solutions that can take in electricity at times when demand and prices are low and return it in when they are high, and to demand side management (DSM), which is discussed in Section 22. These measures can provide help in reshaping the value profile of electricity but cannot fully reconcile the supply-demand mismatch. The answer must involve not just more research into energy storage and DSM, but also more research into renewables.

There are two main areas where considerations about energy storage should drive substantial further research into renewables. The first is about the optimal blend of renewables to minimise the mismatch between supply and demand as much as possible. Several authors such as Cardenas et al.,[34] Cosgrove et al.[35] as well as the 2023 Royal Society report[36] already commented on the desirability of balancing wind and solar power for the UK such that the average level of excess in winter is approximately the same as the average level of excess in summer.

The Royal Society report also notes that as the proportion of energy provided by nuclear power rises, the optimum ratio between how much of the remaining energy should be provided by wind and how much by solar power also changes. The report finds that with no nuclear power, the wind-solar ratio should be around 80:20, whereas with 10TW nuclear, it should be 100:0 – in other words, all wind and no solar.

The optimisation problem is harder than it might seem because wind power in particular varies widely not just between the seasons but also from year to year. Further research is needed to determine the optimal mix of low-carbon generation, including not just wind and solar, but also wave, tidal and power from salinity gradients. We specifically need to understand how best to blend the low-carbon generation forms in light of their different variability characteristics, and what requirements the blend would impose on supply-demand reconciliation.



The second main area where renewables should interact directly with energy storage is related to generation-integrated energy storage (GIES) as defined in Garvey et al.[37] GIES was what existed in the fossil fuel era, as noted above, and has great potential in a renewables-dominated grid. Some work is already well-established in developing wind turbines with integrated storage, as described in Garvey at al.,[38] Garvey et al.,[39] Okazaki et al.,[40] Chen et al.[41] and Swinfen-Styles et al.[42] Nevertheless, additional work is needed to quantify the economic case for integrating storage with wind turbines for the UK.

The concept of GIES is even more relevant for solar power capture. Several methods already exist for photo-catalytic creation of useful products, such as direct ammonia production[43] and hydrogen from water.[44] There is scope for research on combining photo-catalytically assisted mechanisms with electrochemical ones to produce high-energy fuels in processes that intrinsically consume electricity when sunshine is strong.

Biomass is potentially the basis for one of the ultimate forms of GIES. Biomass grows naturally when the sun shines and can then be prepared for combustion and stored for very long periods. The preparation processes can also be flexible. There is a tendency, manifested also in the Royal Society report, to regard that generation powered by biomass should be 'baseload': that electrical power should be produced at a constant rate from the power-plant. This view misses a significant opportunity and there is a clear case for research to develop a biomass-powered generation plant that could be flexed significantly.

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8. Electrochemistry for large scale energy storage

We discussed the role and limitations of batteries for the purposes of grid storage in the Introduction and Section 3. In some configurations, however, lithium-ion batteries can contribute to large-scale energy storage, as can other battery chemistries. Limiting our observations to those beyond the scope of the Faraday Institute, research gaps and opportunities in this area include:

Lithium-ion batteries in vehicle-to-grid (V2G) & grid-to-vehicle (G2V)

There are currently 40 million vehicles in the UK. If all were electric, and assuming 50kWh energy storage per vehicle, the maximum available to the grid would be roughly 2TWh, at least in theory. Of course, in reality a tiny fraction of this might be accessible at most, yet even this could offer a substantial short-term flexibility lever. The challenges and hence the research gaps are about how consumers can be incentivised to take part, how the resulting capacity could be used, and what policy support would be needed.

Deploying Lithium-ion batteries in battery energy storage systems (BESS)

There is scope to understand whether BESS could contribute to MDES and LDES and if so, to what extent. It is useful to consider lithium-iron-phosphate (LFP) batteries as an example. Currently, LFP cell costs are ~$50/kWh. Allowing a systems factor of 2, this puts a GWh system at $100M USD of capital expenditure ($100/kWh). Some of the currently considered thermo-mechanical energy storage systems seem likely to be deliverable at costs below $100/kWh for discharge times longer than 4-8 hours. However, it is obvious that since the presence of BESS within energy systems will be justified by their service at the shorter timescales, it may be optimal to use these for at least some service in the medium-duration timescales. The challenges and hence the research gaps are around the upper bounds for the BESS to be used for MDES and their integration with other energy storage technologies.

Further developments in redox flow batteries (RFBs)

RFBs are attractive for MDES and LDES because they decouple the energy capacity of a storage system from its power rating, and offer high RTE.

They are still expensive, however. The most advanced vanadium-based RFBs cost 300-500 $/kWh, with a possible pathway down to $100-150/kWh. A challenge and hence a research gap is associated with the amount of capital tied up in inventory of electrolytes. Another is to develop cost-effective redox couples such as non-aqueous solvents to improve cost and increase voltage window for enhanced energy density.

Redox batteries (RBs)

A number of RBs in development worldwide, including rust batteries and chemical looping. In RBs, one oxidizable material forms the basis of the overall energy store. Energy is released as the material is oxidized and energy is invested again when the material is reduced again (i.e. stripped of oxygen). One developer, *Form Energy,*[45] claims a pathway to $20/kWh with readily available materials. UK-based research on RBs is limited, and an assessment is needed if the UK should invest in the area.

Zinc-based batteries

These are attractive due to low cost of zinc, the use of aqueous solvents and safety benefits. Chinese teams have made some significant progress recently.[46,47] The UK should assess whether it also needs to invest in this area.

Sodium-ion batteries

China and India are going strong in the area, mostly for low-cost passenger vehicles. Sodium is more abundant and costs less than lithium, and the market leader, *CATL*,[48] has invested and claims a pathway to ~$40/kWh. Again, the UK should assess whether it also needs to invest in this area.

Molten metal batteries

These may offer some advantages in grid storage, but research challenges for molten sodium batteries include long term corrosion. Another example is sodium-sulfur (NaS) battery, which may come back after safety problems are resolved. Yet again, the UK should assess whether it also needs to invest in this area.

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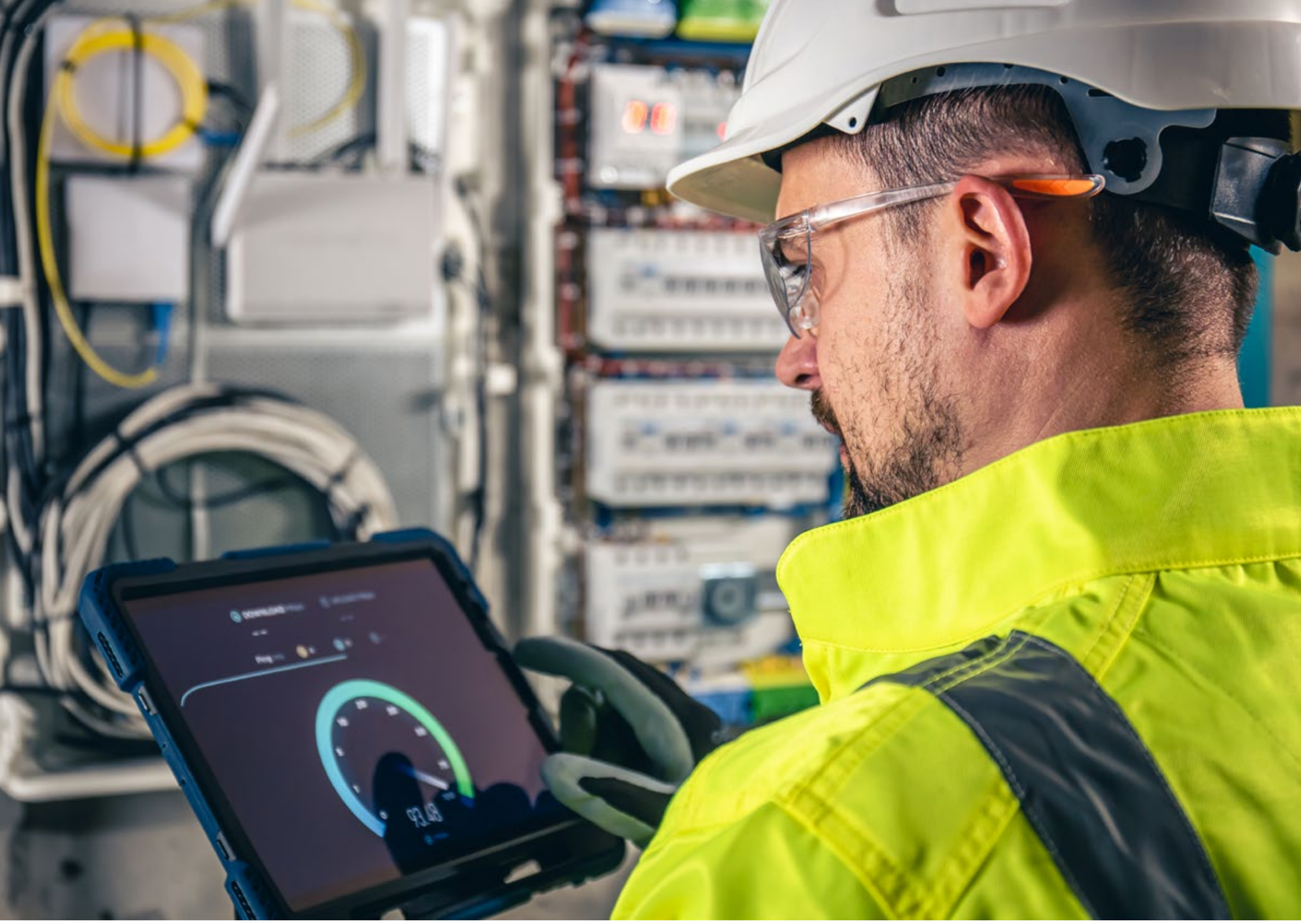

9. Compressed air energy storage

Compressed air energy storage (CAES) comprises a wide family of technologies, which are differentiated in several ways:

- Where and how the air is stored: primarily tanks, caverns and underwater containments
- The pressure-vs-fill characteristic of the air stores, which are either isochoric (constant volume) or isobaric (constant pressure)
- The way temperature is managed during air compression and expansion
- The way the heat of compression is stored and recovered
- The power scale of a single unit

Most physical energy storage technologies involve shifting storage material between two states. For example, pumped thermal involves changing the temperature of one or more bodies markedly, whereas the CO_2 battery stores CO_2 in liquid and gaseous forms. CAES is unusual in this respect because the material used to store energy is air itself, and the air is both drawn from and returned to the atmosphere. In other words, the environment comprises one of the two material stores.

The basic principles of CAES are well understood and described in several publications, including Budt et al.,[49] Olabi et al.,[50] Wang et al.,[51] Barbour and Pottie,[52] Chen et al.[53] and Rabi et al.[54] A number of CAES plants have been built in recent years, especially in China. The points made in Section 4 about the need to predict future costs for machinery, and in Section 19 about access to underground resources, are especially important for CAES.

CAES would benefit from any general advances in turbomachinery design, but there are areas where further research could be highly advantageous for CAES in particular:

Variable pressure-ratio machinery for the high-pressure end of the compression-expansion train that is efficient, reversible and cost-effective

This would mean constant-volume air stores such as in underground caverns that can be managed without throttling. These are expected to be positive-displacement, and probably reciprocating, machines. Some of the key challenges here relate to piston sealing and valve actuation.

Heat exchangers designed specifically for CAES taking advantage of modern manufacturing methods, especially additive manufacturing

These units would exchange heat reversibly between pressurised air, potentially at several different pressure levels, and a heat-transfer fluid that might itself be air.

Integrated heat-transfer and thermal storage units for CAES

These would provide the potential to avoid a two-stage heat transfer between pressurised air and the main thermal storage medium.

Cheaper air storage tanks ('receivers') for smaller scale CAES

Fundamental calculations indicate that tanks should be capable of achieving storage costs below \$70/kWh for air at ~300bar. Existing tanks are typically 2-3 times more expensive, however. Applying over-wrapping techniques to exploit the difference between hoop stress and axial stress in long cylindrical air tanks is one way to capture more value from the same metal tank. As emphasized during the discussion session at UKES2025, there are interesting possibilities to combine tank health modelling with tank reinforcement.

Reversible turbo machines that can be used both as a compressor and an expander

CAES never needs to compress and expand simultaneously, so dispensing with one of the two turbo machines currently required is an obvious and potentially major cost saving.

Techniques to produce low-cost thermal storage media from multiple components

Enthalpy-vs-temperature profiles that closely resemble those of air would minimise the exergy losses in the compressed air cycle.

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10. Liquid air energy storage

Liquid air energy storage (LAES) is a developing technology that could provide large-scale energy storage of 100s MW to 100s GWh, for durations ranging from several hours to weeks. A standalone LAES system can achieve 50-60% RTE to support grid services such as peak-shaving, fast reserve, transmission constraint relief, renewable firming and black start.

Recent studies have shown the adaptability of LAES technology for various applications through sector coupling. Examples include LAES-based combined heat, cooling, and power supply;[55] efficient and cost-effective industrial waste heat or cold recovery, for instance with liquid natural gas (LNG) regasification;[56] resource-efficient ammonia synthesis;[57] cost-saving integration with air separation plants;[58] combined cold and power for cold-chain transport.[59]

LAES was invented in the UK, which remains the world leader in lab, pilot and pre-commercial scale work. *Highview Power Ltd.* announced the construction of the world's first commercial plant (50MW, 300MWh) several years ago, and further plans to build 10GWh plants in 2024.[60] Progress has been slow, however. The UK has established a commanding position but is in danger of losing out in the commercial race, evidenced by the following developments:

- In Japan, *Sumitomo Heavy Industries* will build demonstration plant, next to the Hatsukaichi LNG Terminal.[61]
- In China, the State Grid Global Energy Research Institute built a 500kW, 500kWh demonstration project in 2018.[62]
- China Green Development Investment Group is supporting construction of a 60MW, 600MWh LAES system in Golmud, designed to integrate renewables into the grid.[63]
- A 1MW, 2MWh LAES plant was built in Shijiazhuang in 2024 and is now operational. The partners are Hebei Construction&Investment Group Co. Ltd. and Shijiazhuang Tiedao University.[64]

As a result, research gaps still exist in the space between lab research and pilot project, and from there to commercial scale:

Materials

Robust and cost-effective thermal energy storage materials for storing high-grade cold at ~-160oC and medium temperature compression heat at ~250-350oC is vital to a highly-efficient LAES system. Currently, gravels are used for cold storage, whereas pressurised water tanks are used for heat storage (~150oC) for cost effectiveness. This calls for the development of cost-effective thermal energy storage materials for the necessary temperature ranges with the right thermophysical properties.

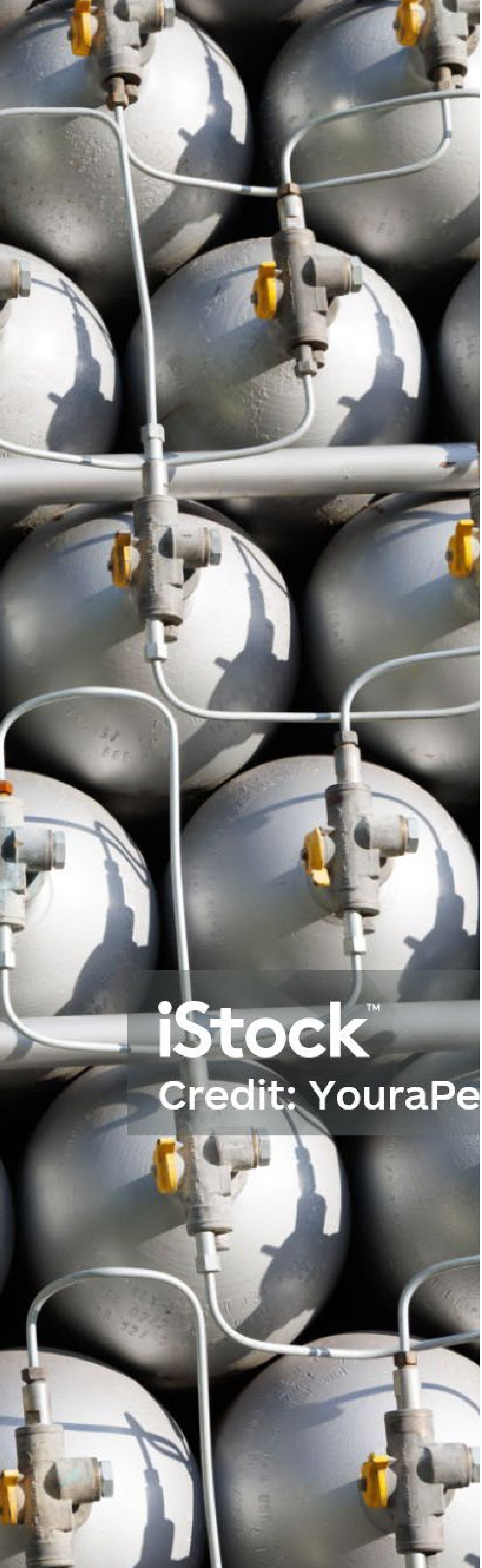
Components

Air compressors and turbines, which convert electrical energy into stored thermal energy and back, are central to LAES systems. The current generation of these components lacks the efficiency and operational flexibility needed for optimal performance across diverse LAES applications. Enhancements in compressor and turbine technology that allow for variable operational modes and improved efficiency curves are critical. This includes the development of components that can operate effectively under varying load conditions and integrate seamlessly with renewable energy sources. Additionally, research into high-pressure heat exchangers for cryogenic temperatures and cryogenic turbines to replace Joule-Thomson valves demands significant attention.

Systems

While static models have provided foundational insights into LAES operations, advanced dynamic modelling techniques are necessary to simulate real-time system responses to fluctuating supply and demand. These models should facilitate more accurate predictions of system performance and more effective integration into the energy grid. LAES for sector coupling requires additional research into system integration, economic performance and experimental perspectives to assess its true value in various sectors.

A further point raised at the UKES2025 session contributing to this report was that there is high advantage, specifically in the context of LAES, to the further development of thermal energy storage approaches that can retain heat at temperatures up to ~500°C.



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11. Pumped thermal energy storage

Pumped thermal energy storage (PTES) is an umbrella term that refers to a collection of technologies, each based on one of three thermodynamic cycles: Joule-Brayton, Rankine and transcritical.

PTES currently stands at TRL 5-7, with an increasing number of commercial pilot plants being developed. A 2022 review identified around 30 different projects at various stages of development, including LAES (see previous section), compressed heat energy storage (CHEST) and other related concepts.[65] A 2023 International Energy Agency report lists 19 existing PTES projects – again, including LAES and CHEST – of which 13 consider the whole electricity storage cycle rather than individual components.[66]

In earlier work, starting in 2004 *Isentropic Ltd.* in the UK built several prototypes and improved their performance through work on both the compressors/expanders and the thermal stores. The company later built a 150kW PTES demonstrator based on the Joule-Brayton cycle, reciprocating compressors/expanders and packed-bed thermal energy store.[67] In parallel, the University of Cambridge[68] and Imperial College London[69] were awarded Research Council funds to further work on technical aspects of the *Isentropic* system. The *Isentropic* pilot plant was later purchased by a team from Newcastle University (now at Durham) who performed tests on the system.[70] *Isentropic Ltd.* went into administration in 2016, primarily because the market was not sufficiently strong at the time to justify the needed investment.

More recently:

- Researchers at Friedrich-Alexander-Universität (FAU) Erlangen-Nürnberg developed a 9-kWel / 270-kWhth PTES system based on a reversible Organic Rankine Cycle (ORC) and presented preliminary results in 2021.[71]
- *Echogen Power Systems* based in the US recently presented results from a 100kW transcritical CO_2-based PTES pilot plant. The company is planning to construct a 100MW, 1200MWh system by 2028.[72]
- *MAN* has developed a CO_2-based PTES system that also delivers hot and cold energy,[73] although it appears that so far only the HP has been commercially deployed for heating applications.[74]
- *Storasol*, a German company, has developed and demonstrated a high-temperature thermal store coupled with an ORC[75] and an open Brayton cycle.[76]
- *Siemens Gamesa* has been operating a 130MWh pilot plant based on resistive heating, high-temperature storage, and a steam cycle for discharging since 2019.[77]
- *Malta Inc.* of the US is a leading developer of PTES technology and has raised investment of more than $100 million, along with grants from both the US Department of Energy and the EU. It aims to build systems greater than 100MW and up to 19,200MWh.[78]
- *SynchroStor Ltd.*, based near Edinburgh, developed a PTES system based on modular, reversible piston compressor-expanders with a power rating of 520-670kW. The company has been awarded £9.4 million under the DESNZ-funded Longer Duration Energy Storage programme to build a 1MW pilot plant.[79]
- The German Research Foundation (DFG), an academic body, recently funded a large priority programme on the development of PTES systems including 17 individual projects.[80]

Progress and key remaining challenges for the development of PTES, as well as other thermo-mechanical energy storage technologies, are summarised in a review paper by Olympios et al.[81] The most important remaining gaps include:

- Cost-effective design and manufacturing of bi-directional compressor/expander machines. Conventional PTES concepts require four machines: a hot compressor and a cold expander for charging, and a cold compressor and a hot expander for discharging. The development of reversible machines would halve that number (a single cold machine and a single hot machine) and thus potentially significantly reduce the capital cost of PTES systems.
- Thermal stores operated at specific range of conditions, which would reduce costs, pressure losses and thermal losses while storing thermal energy at appropriate temperatures.
- Flexible operation of PTES systems to maximise profits from volatile electricity markets.
- Exploring the integration of PTES systems with sources of low-cost heat or coldness or with customers for output heat and coldness can lead to much-improved business cases for PTES in certain contexts – a point that emerged from the UKES2025 discussion session.

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12. Pumped hydro and other gravitational methods

Pumped hydro energy storage (PHES) is one of the most mature forms of energy storage and, apart from the storage of energy in the form of fuels, accounts for by far the greatest energy storage capacity across the globe, as evidenced in Blakers et al.[82] and Barbour et al.[83]

Typical features of pumped hydro installations include high RTE, very long lifetime, natural provision of real inertia properties, moderate cost per unit of energy storage capacity, and low self-discharge rates (sometimes negative, when it rains).

The scope for further research into PHES is constrained by its maturity but there have been developments. As well as the natural inertia provided by the spinning metal of the turbine (or pump) while in operation, and by the water contained within each machine, there are now 'ternary pumped hydro units' that can operate in a mode where water is circulated in a loop between turbine and pump. The main effect is a smoother transition to full charging or discharging power from a zero import/export power mode and back again as required.[84]

The UK company *RheEnergise* is developing a PHES solution in which a heavy mineral is suspended within the water with the effect that pressure head is increased substantially for the same height difference between reservoirs.[85]

Other forms of gravitational potential energy storage (GPES) are also possible. The company *Energy Vault* is one example that has attracted attention in recent years due to having secured investment exceeding $100M.[86] The system stores energy by supporting huge weights high above ground. There is widespread doubt among energy storage experts that this can ever become economic due to the intrinsically high costs of the support structure.

The UK company *Gravitricity* operates on a better premise where the structure that can hold the mass at its "elevated position" is simply the ground and the mass itself is lowered down into disused mine shafts.[87]

The domain of storing gravitational potential has fewer opportunities for value-added research than others but there are still some noteworthy possibilities:

- Devising ways to prevent or to capture methane releases from large areas of land flooded to form pumped-hydro reservoirs.
- Applying optimal control methods to ensure that the rate of release of gravitational potential energy and kinetic energy combined matches most closely to the intended power output from the storage.
- A point raised at the UKES2025 discussion session was that there may be significant further scope for developing higher-density fluids than water that may increase the viability of PHES installations at sites with lower natural heads than would be attractive for simple water-based systems. *RheEnergise Ltd.* is already progressing one such solution.[88]

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13. Carbon dioxide-based energy storage systems

Carbon dioxide-based energy storage (CES) uses CO_2 both as a working fluid and an energy storage medium using one or more of the Brayton, Rankine and transcritical cycles.[89]

Due to the hazardous nature of carbon dioxide, the systems must be closed cycle, meaning the storage medium is stored in both its charged and discharged states. This gives CES a low energy density overall compared to CAES and LAES.

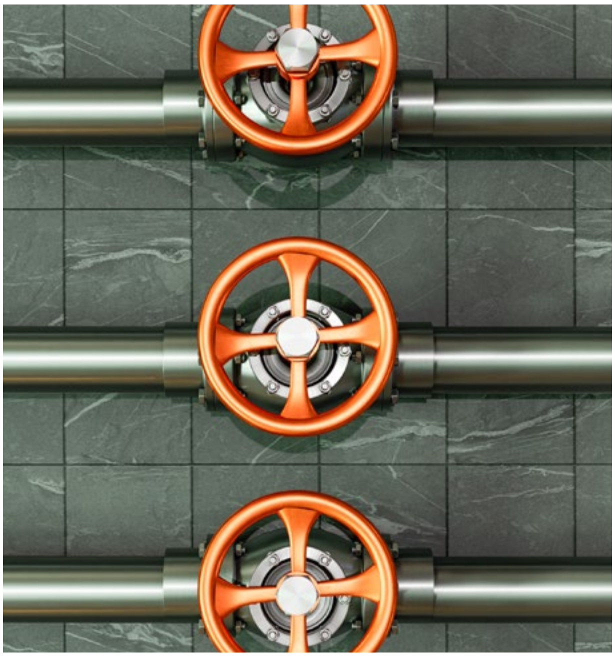
Various studies have been conducted in the area including Mercangoz et al.,[90] Wang et al.,[91],[92] Liu et al.,[93] Zhang et al.,[94] Liu et al.[95] and Xu et al.[96] These suggest a RTE ranging from 30% to over 70% depending on system configurations, the states of the storage medium at the charge and discharge states (liquid-liquid, gas-liquid, gas-gas), operating conditions, and the use of thermal energy storage. The work by Liu et al.,[97] Zhao et al.,[98] Liu et al.,[99] Tang et al.,[100] Xu et al.[101] and Sun et al.[102] indicated that the LCOE of CES ranges between $73/MWh and $148/MWh. The work by Ipakchi et al.[103] suggested a payback time of 4-6 years.

The application of CES through sector coupling has also been investigated, mostly by desktop analyses. Examples include:

- Qi et al.[104] on the integration of CES with power-to-methane
- CES for combined heating, cooling and power proposed by Liu et al.[105]
- An integrated steam thermal power cycle with CES by Hou et al.[106]
- The integration of CES with LNG gasification and ORC power cycle by Bao et al.[107]

There have also been a small number of experimental studies – see for example Alami et al.,[108] Zhang et al.[109] and Peng et al.[110]

Despite the extensive research efforts, CES is at TRL 4-7. Recently, a demonstration plant at 2.5MW, 4MWh was reported by *Energy Dome*,[111] which stores the discharged CO_2 at close to ambient temperature, occupying a large space. More recently, *Energy Dome* announced a 20MW, 200MWh CO_2 battery to be completed by the first quarter of 2025, with a target RTE of 75%-80% and a cost of $50-$60/MWh.[112]



In China, parallel development efforts have been reported, including a 100kW, 200kWh CES demonstration project by *Boruiding Energy;* a planned 100MW, 400MWh CES commercial power station;[113] and a 10MW, 80MWh CES demonstration project under construction by *Bairang New Energy,* with a projected cost of electricity as low as $20/MWh.[114]

Despite various efforts, significant challenges and research gaps remain:

- At the CES system level, there is a lack of off-design and dynamic studies.
- At the component level, robust and cost-effective CO_2 expanders remain a challenge, particularly for applications near the critical point. Research efforts are also needed on heat exchangers.
- At both component and system levels, most studies are desktop-based, and a significant gap exists in experimental data and validation of the theoretical analyses and modelling studies.
- It was noted at the UKES2025 discussion session that there may be other fluids than CO_2 that can also be operated in reversible liquefaction processes and that as an alternative to storing the low-pressure gas directly in gaseous form, some adsorption processes may be advantageous.

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14. The electricity-transmission ↔ energy-storage nexus

Renewable generation needs storage – that much is already clear. The energy from remote generators also needs to be transported to the grid. Current thinking suggests that these two functions should necessarily be performed by two separate technologies. Electricity is carried from the offshore windfarm to the onshore grid by HVDC or alternating current (AC) cables, and any matching storage is provided by a battery or other technology at the connection point.

Recent work suggests it may be cheaper to combine transport and storage in a single vector that performs both functions. The wind farm's power could, for example, be used to produce compressed air or hydrogen, which would be transported ashore by pipeline and stored until needed to generate electricity – with fewer energy conversions along the way. Early research suggests that this kind of approach could reduce overall costs significantly. It may also be possible to repurpose legacy oil and gas pipelines to transport and store the new vectors.

Transporting electricity by cable is generally seen as economic because costs are typically based on overhead transmission. For offshore generation, however, overhead lines are replaced by subsea cables, which raises the cost of environmental mitigation, maintenance and repair. According to the Institution of Engineering and Technology[115] and National Grid,[116] overhead lines cost between £2 million/km and £4 million/km, while direct buried underground cables range from £10 million/km to £24 million/km, with deep tunnels costing even more.

Much of this difference stems from specialised cables, underground construction and the additional insulation needed to protect marine ecosystems from electromagnetic fields.[117] In some cases, cables must be protected in underground tunnels known as power tunnels, rather than simply buried in trenches.[118]

The insulation increases not only the capital cost but also the energy losses from cable resistance.[119] In 2022, the UK saw transmission losses of ~25TWh, about 8% of supplied electricity, compared to over 30TWh in the early 2000s. The recommended loss rate is ~2%.[120]

14.1 Opportunities in storage-integrated transmission

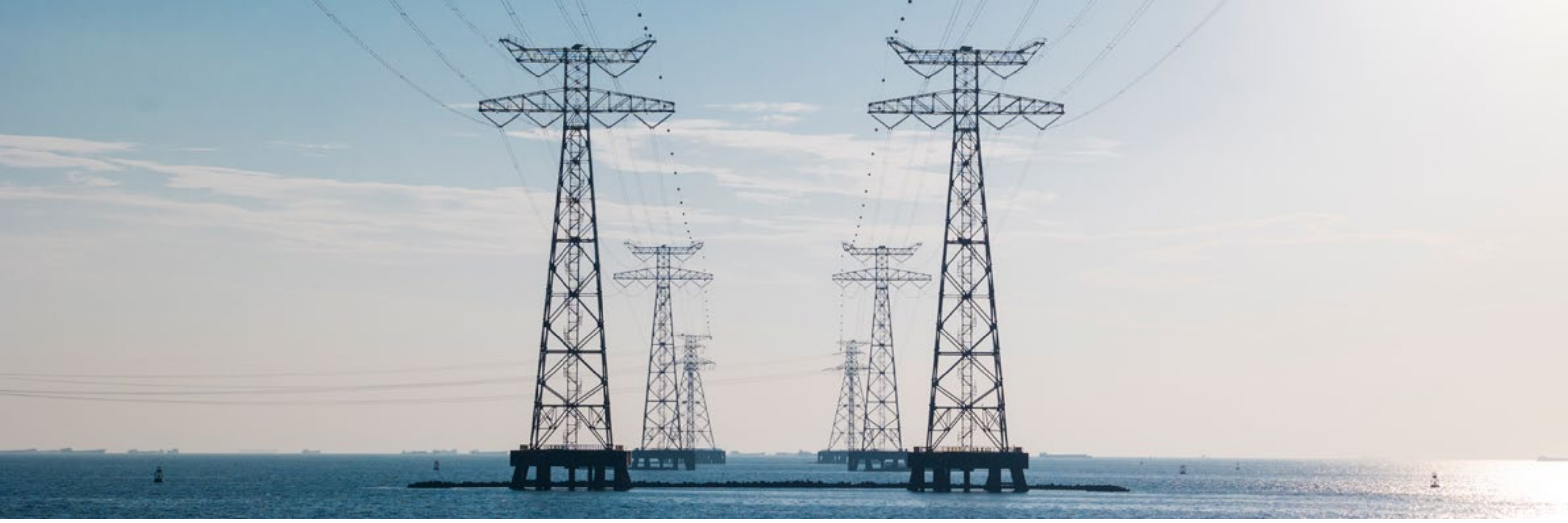
One of the main opportunities for storage-integrated transmission could be provided by offshore power tunnels. These currently protect HVDC cables but could be used to transport other energy vectors as well as or instead of electricity.

These vectors could be compressed air, compressed hydrogen or liquid ammonia. These would be produced offshore and transported through the power tunnel, which would also provide some storage, and be used to generate electricity onshore when needed. These scenarios are extensively discussed in Baniamerian et al.[121] demonstrating how they could simplify offshore operations by integrating storage within the transmission system, removing the need for cables and siting caverns onshore.

The efficiency of storage-integrated systems varies by vector and distance. Hydrogen compression demands high energy for electrolysis and compression, while producing ammonia adds complexity with air separation and synthesis. Efficient operation is key to viability. Designing pipelines for high-pressure hydrogen also presents safety and material challenges, making advanced materials and sealing techniques essential for scaling.

Nevertheless, Baniamerian at al.[122] find that the new approach could also reduce costs against a number of benchmarks:

- *Compressed air:* by setting the allowable transmission losses at 2% – the target level for electricity transmission by HVDC over distances over 300km – compressed air at 500bar emerges as a more cost-effective option for transmitting up to 450MW compared to HVDC cables. Additionally, it offers an energy storage capacity equivalent to 62 hours of wind farm output at a cost of $25/kWh.
- *Hydrogen:* at distances of more than 310km, hydrogen in pipelines can transmit 230MW more cost-effectively than HVDC with storage equivalent to 58 hours of wind farm output, albeit at a higher cost of $128/kWh.



- *Ammonia:* this vector stands out for its superior volumetric energy density and cost-effectiveness over long distances. At any distance over 140km, ammonia could transmit up to 2000MW more cost-effectively than HVDC and offer a storage capacity equivalent to 152 hours of wind farm output at $9/kWh.
- *Redeployment of gas pipelines:* DeOliveira and Barbour[123] investigate whether existing North Sea gas pipelines could usefully be re-deployed in the post-methane era for storage-integrated transmission using compressed air.

14.2 Opportunities for research

A major gap in storage-integrated power transmission is the lack of accurate tunnel cost estimates, as existing models focus on unsuitable utility tunnels and show inconsistencies. While a universal model is challenging due to many variables, further research is essential for better feasibility and economic assessments.

Another open question is the optimal tunnelling, trenching or piping method for this application. Refining tunnelling techniques could greatly improve efficiency and cost-effectiveness.

A further promising research avenue is repurposing offshore pipelines for dual use as transmission lines and storage systems. This requires comprehensive studies on technical feasibility, safety, material integrity, compatibility with alternative energy carriers, and regulatory frameworks.

Comments made at the UKES2025 discussion session noted that increased coordination between the planning of transmission upgrades and the planning of energy storage infrastructure can add significant value. It was also noted that there may be significant new possibilities related to the transmission-storage nexus as a result of plasma-enabled drilling. Potentially this technology can bring about transformative reductions in the costs of forming accurately steered ducts and tunnels over long distances.

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15. The nexus between heating, cooling, the electricity grid and thermal energy storage

15.1 Space heating

The starting point of any discussion about making space heating more sustainable should be the reduction of heating demand through improvements in thermal insulation and reduction in uncontrolled air leakage in homes. Whilst acknowledging this clearly, it remains true that most homes in the UK will still have some requirement for significant amounts of heating energy during the year and the way in which we do heating in the future can contribute dramatically to flexibility within the electricity system, as well as reduce the need for energy storage.

After years of debate, pilot schemes and early commercial roll-out, heat pumps (HPs) are now firmly established as the default technology for domestic space heating. They are central to the UK government's Heat and Buildings Strategy[124] and the overwhelming majority of Britain's 28 million homes will eventually have one.

This means that designing the future electricity system requires a comprehensive understanding of how those heat pumps will be managed – along with other new electricity loads such as EVs. Without this critical insight, we may struggle to meet evolving energy needs, integrate renewable generation and ensure a stable grid.

15.1.1 The heat pump challenge

Despite HPs' obvious environmental advantages, their widespread take-up will present important system-level challenges. They will clearly increase electricity demand overall but may also significantly increase demand during peak hours. That would require not only more generation but also more capacity in transmission and distribution grids. The scale of grid investment needed will depend critically on how the heat pumps are managed.

In the UK, domestic heat demand, like that for electricity, has two marked peaks during the day: in the morning before people go to work, and in the evening as they come home. Most households turn their heating down during the working day and overnight.[125] This is possible because gas boilers are typically set to operate at high flow temperatures, meaning a home can be brought back up to a comfortable temperature quickly. If HPs were operated in the same way, it could massively raise the size of electricity demand peaks.

A 2018 report by the UK Energy Research Centre[126] notes that during wintertime, daily gas demand is about four times higher than daily electricity demand. More importantly, the morning peak in gas demand, between 5am and 8am, is almost ten times as high as the electricity demand peak. The gas network meets this large and rapid ramp-up in demand by increasing gas pressure within pipelines overnight ('line pack'), which allows the network to store more gas. The electricity grid on the other hand has no inherent means of storing electricity within the delivery infrastructure itself.

Several recent studies have tried to calculate the impact of HPs on overall and peak demand for electricity. Cardenas et al.[127] considered the heat demand profile of an average UK property. Using mean ambient temperature data and an empirical model for the coefficient of performance (CoP) of an air source HP, the authors estimated that annual electricity demand may increase by ~26% over current levels. This aligns with estimates published by other researchers who also concluded that the UK's peak electricity demand of ~63GW could rise by more than 70%.

Watson et al.[128] reported that the peak load in the grid could rise to between 113GW and 132GW if space heating were electrified. Zhang et al.[129] reported that the UK grid could see an increase of ~39-50GW in peak demand when heat demand is fully supplied by electricity, assuming HPs have an average CoP of 2.9. Whalen[130] estimated that having a 100% HP penetration in homes will add ~65-70GW of peak load.

Although these figures are pessimistic, they remain in a realistic ballpark. As a result of these kinds of analysis, many doubt whether the current electricity grid could meet the additional demand from fully electrified space heating. According to the 2023 report on Building a GB Electricity Network Ready for Net Zero,[131] energy analysts at Regen emphasize that achieving the UK's net zero goals will mean transforming the electricity grid on a scale not seen since the 1960s. The extensive upgrades required would be feasible provided sufficient investment is available, as explored by Cardenas et al.[132] and Zhang et al.[133]

The more pessimistic of these studies assume that people will use and schedule HPs in the same way they currently do boilers: running at full blast for short periods twice a day. This would be inefficient and expensive and would indeed raise peak demand dramatically.

A key variable in the future will be the use of HP optimisation either at the level of an individual home or by energy suppliers and grid operators. Optimisation seems likely to be widely adopted because it cuts customers' bills and benefits big energy companies. If so, it should also greatly mitigate electricity demand peaks.[134]

HPs are fundamentally different from traditional natural gas boilers and massively more efficient because they operate at lower flow temperatures. This means they operate most efficiently when running virtually full time (24/7) rather than in short bursts. This alone would tend to mitigate peak demand by spreading out the HP's electricity consumption evenly across the day, rather than concentrating it during the peaks.

Optimisers, which are small electronic devices or mobile phone apps, go a step further by integrating a local weather forecast and time-of-use tariff to reduce the HP's energy consumption and cost. They run the HP harder when electricity is cheaper and much less during peak periods. The collective effect of millions of optimisers on grid demand profiles could therefore be enormous. *Octopus Energy's* own-brand HPs come with optimisation built in, and the company sells this peak demand reduction to grid operators.

Recent research by Terry and Galvin[135] suggests that while many homes can be adequately heated by HPs producing water at or below 55°C, this may require alterations in heating schedules and increased annual energy demand, highlighting the need for further study in this area. Again, with an optimiser, scheduling is entirely automated. All the users need do is select the temperature they desire and for what periods; when the HP actually runs to provide the necessary heat is decided by the optimiser.

15.1.2 Distributed thermal storage

Shifting the demand for heat from the gas network to the electricity system will demand far more of the electric grid.

Shaving the peak demand created by electrified heat could, in principle, be achieved through grid scale electricity storage. But this would require electricity to be converted to some other form of energy such as compressed or liquid air, then back into electricity, and finally to heat in the home. It might make more sense to store the energy as heat close to where it is needed, with fewer energy conversions along the way.

In-property heat storage technologies could play an important role in managing peak electricity demand in a scenario where domestic heating has been fully electrified. These systems store heat generated during off-peak periods and release it when needed, reducing the load on the electricity grid during high-demand periods.

The amount of distributed thermal storage required will, however, depend significantly on the extent to which HP electricity consumption can be managed with optimisers, as above. One advantage of optimisers is that in effect, they treat the home as a thermal battery while keeping the internal temperature close to target. This helps the user avoid peak electricity prices without the need to invest thousands of pounds in an actual thermal battery. In short, in-property thermal storage coupled with the operation of local controllers (optimisers) can provide services that are equivalent to storing electricity at a cost level that falls far below the cost of electricity storage.

15.1.3 Research opportunities

The nexus between space heating, the electricity systems and energy storage offers vast opportunities and many time-sensitive challenges to solve. For example:

In-property thermal storage needs

- New materials for storing heat, including phase-change materials and thermochemical materials
- Methods for optimising the use of new in-home heat storage technologies, including new builds and retrofitting
- Optimising the integration of existing technologies such as hot water tanks into future heating systems

More detailed system-level modelling is needed to understand several key aspects

- What are the precise impacts of widespread HP adoption on local and national electricity grids?
- What impact will HP optimisers have on predicted daily demand peaks? What policies are needed to ensure an adequate penetration of optimisers in the HP market?
- What is the potential impact of thermal storage on the electricity grid? To what extent can we reduce the peak loads and defer, minimise or avoid expensive grid upgrades and reinforcements (including grid-scale energy storage capacity)?
- By how much can peak demand be reduced by upgrading home insulation?

Further points raised at the UKES2025 discussion

- Further research is needed on the social-science aspects of bringing the homeowners along on the journey of re-configuring their heating system.
- More attention needs to be paid to the importance of district heating solutions in future newbuild sites.

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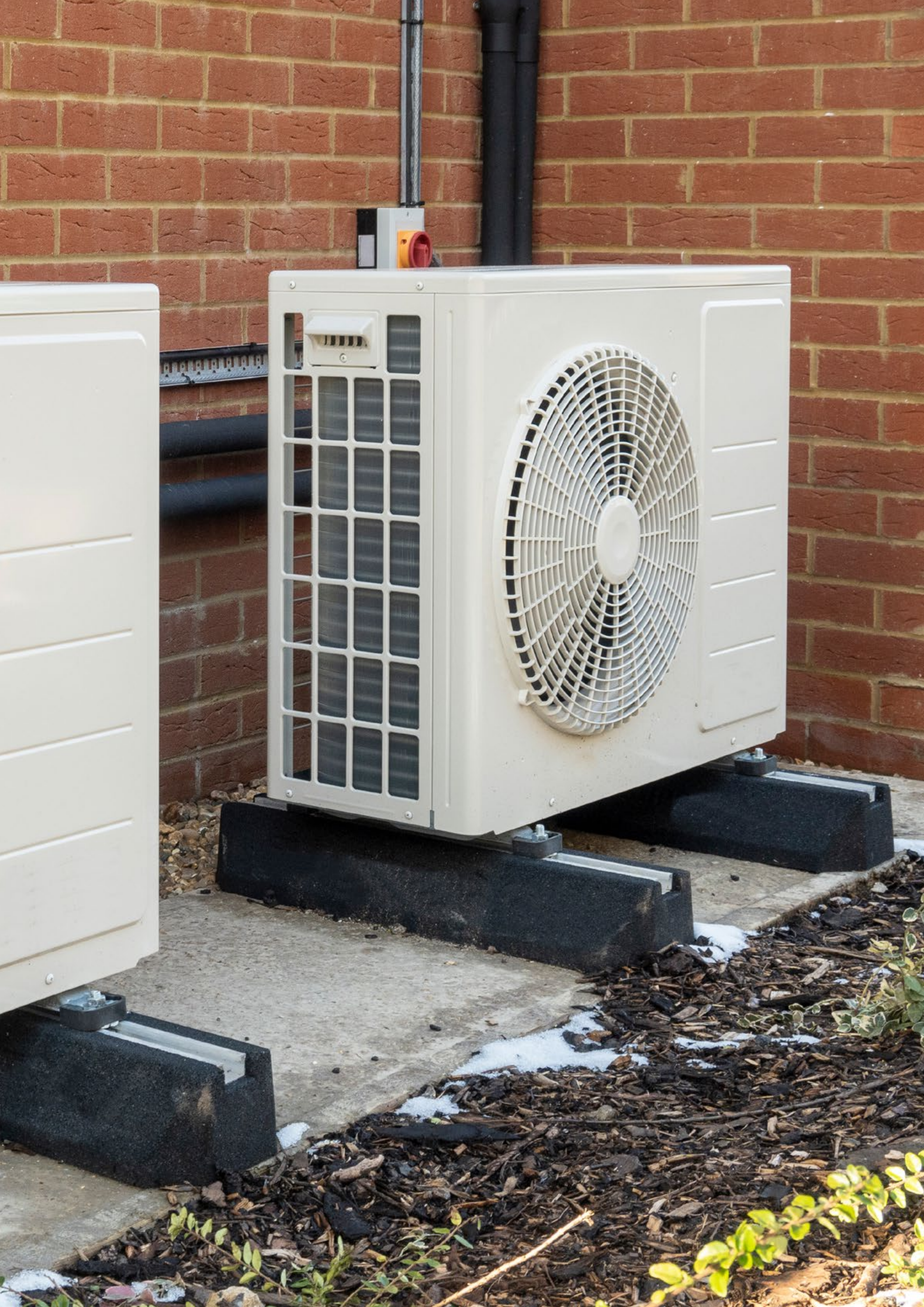

15.2 Cooling

The rising demand for cooling, driven by urbanisation, industrial growth and climate change, underscores the need for technologies that store exergy as cold to improve efficiency and sustainability. Worldwide cooling demand is expected to more than triple by 2050 as the planet continues to warm and more countries gain access to air conditioning.[136] Air conditioning already accounts for ~7% of global electricity consumption and causes ~3% of CO_2 emissions.[137]

The International Energy Agency (IEA) reported that in 2022, space cooling consumed about 2,100TWh of electricity, reflecting a significant increase from previous years.[138] Thermal energy storage (TES) emerges as a pivotal technology to mitigate peak energy demand, optimise energy distribution and help integrate renewable energy into cooling applications.

15.2.1 State of the art and major players

Advances in cooling storage are being driven by collaboration between researchers, industry leaders and policymakers. Phase-change materials (PCMs) offer a highly efficient way to store energy through latent heat, making them a compact and effective means of thermal management. Meanwhile, sorption-based storage systems, which rely on adsorption and absorption processes, are being explored for their potential to enhance cooling efficiency, with materials like zeolites and silica gels showing promise.

These technologies can be classified according to TRLs:

- PCMs (TRL 2-8) are already being used commercially in district cooling, data centres and HVAC systems. Researchers continue to improve their stability and cost-effectiveness.
- Sorption-based systems (TRL 2-5), while showing strong potential in laboratories and pilot studies, have not yet been widely adopted due to high costs and operational challenges.

Several companies are working to bring TES technologies to market. *Nostromo Energy* has developed IceBrick,[139] which allows buildings to store and use cooling more efficiently by taking advantage of off-peak electricity. This system boasts a RTE of over 85% and has already been installed in commercial buildings in Israel and the US, helping to cut energy use and reduce peak demand.

Liquid air energy storage (LAES) is being developed to store excess energy and optimise cooling loads in large-scale commercial and industrial applications.[140]

Engie, meanwhile, has been integrating TES into district cooling networks,[141] demonstrating how scalable these solutions can be in urban environments. Engie's Paris cooling network – one of the world's largest – has improved energy efficiency by 50% while significantly reducing CO_2 emissions.

Other companies incorporating TES into district cooling systems include *Tabreed*[142] across the Middle East, which uses chilled water storage tanks to optimise cooling loads, and Canada's *Enwave*,[143] which taps cold water at the bottom of deep lakes to manage peak demand more efficiently.

In academia, the University of Birmingham's Centre for Energy Storage is researching thermal and thermochemical energy storage to raise efficiency and cut carbon emissions. Together with *CRRC Shijiazhuang*, the Centre developed a passively cooled container for road and rail transport that keeps fresh produce cool for over 94 hours while using 85% less energy than conventional refrigeration.[144]

Separately, Imperial College London is studying thermal energy storage in aquifers as a low-carbon solution for seasonal heating and cooling.[145]

Beyond the UK, Fraunhofer Institute for Soler Energy Systems in Germany is making advances in cold storage and thermochemical TES for buildings,[146] and in the US, the National Renewable Energy Laboratory is researching how TES can be integrated into district cooling systems.[147]

This global research is helping to make TES more efficient, scalable and compatible with renewable energy. With demand for cooling growing worldwide, the TES market is expected to expand at a compound annual growth rate (CAGR) of 11.7% from 2023 to 2030, driven by the rise of district cooling networks, data centres and improvements in HVAC systems.[148] According to the IEA, integrating TES can significantly reduce peak cooling loads, leading to major energy savings and lower costs.[149]

15.2.2 Challenges and research gaps

Despite advances in TES for cooling, several technical, economic and regulatory challenges limit widespread adoption of the technology. Addressing these challenges demands targeted research, policy interventions and further technological advances.

One of the main technical challenges is the low thermal conductivity of many PCMs, which constrains the rate of heat transfer. This can be improved by adding nanoparticles, carbon or metal to the formula.

PCM stability and long-term durability are also challenging and require further research into composite and encapsulated PCMs. Sorption-based TES materials such as zeolites and silica gels degrade over repeated cycles, which worsens efficiency over time. Research should therefore prioritise developing durable and high-performance materials.

TES also needs to work efficiently with HVAC systems, district cooling networks and renewable energy sources, but integration remains limited. Many current projects lack adaptive controls that can adjust charging and discharging cycles dynamically to match fluctuating energy demand and pricing. AI-driven predictive models could help here.

TES take-up is also hampered by high initial investment costs and an absence of modular technologies. Chilled water storage is widely used but latent and thermochemical energy storage not yet, because of high capital costs and operational uncertainties. To bridge this gap, demonstration projects and modular TES approaches could help validate feasibility in real-world applications. More research is needed to quantify the return on investment (RoI) and long-term cost savings of TES compared to traditional cooling methods.

Another critical barrier is underdeveloped market incentives and regulatory frameworks. Unlike battery storage, TES lacks strong financial support, which reduces its attractiveness to investors. Policies that provide subsidies, carbon credits or tax incentives for TES could stimulate the market.

TES could ultimately reduce cooling-related energy consumption and carbon emissions significantly. Making it happen will require coordinated efforts from researchers, industry leaders and policymakers.

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15.3 Medium-high grade thermal storage for industrial processes

15.3.1 State of the art

Medium- to high-temperature thermal energy storage (TES) systems typically operate in the range between 100°C to over 1000°C and play a crucial role in raising efficiency and enabling industrial decarbonisation.[150]

There are three broad categories of TES technologies:

- sensible heat storage uses materials such as molten salts, ceramic bricks and rocks, and is still widely used because it is simple and scalable
- latent heat storage uses phase change materials (PCMs)
- thermochemical storage (TCS) stores energy through thermochemical processes

The last two have gained significant attention because of their high energy density and ability to store and release heat at specific temperature ranges.[151]

Medium-high TES is especially important for the electrification of process heat in industry, because many industrial processes rely on high temperatures and there are typically waste heat resources on-site that could be recycled.

Although the chemical, cement and steel industries are the most challenging to electrify, recently there have been some major advances led by academia, research institutions and industry. Noteworthy commercial projects that illustrate the rapid development in this field include:

- *EnergyNest's* modular sensible TES system, commissioned at *YARA International*, showcasing the ability of sensible TES to recycle industrial waste steam and provide on-demand energy.[152]
- *Brenmiller's* sensible TES system using crushed rocks, has been integrated with biomass plants in Brazil and combined heat and power plants in Italy, highlighting its flexibility and scalability.[153]
- *Polar Night Energy's* sand-based TES system in Finland can operate up to 1000°C to provide efficient energy storage, emphasising the potential of simple and sustainable designs for industrial decarbonisation.[154]
- At lower TRL and using composite PCMs, projects like SandTherm have demonstrated the viability of waste foundry sand for high-temperature TES in the steel industry.[155]
- The SOCRATCES project, funded by the European Union, explored the use of calcium carbonate for thermochemical storage and its integration with concentrated solar power (CSP) systems.[156]

15.3.2 Key challenges and research gaps

Despite recent advances, medium-high temperature TES still faces technical, economic, and regulatory challenges that limit its take-up. These challenges can be categorised into material performance, system design and integration, and commissioning and operation.

In terms of material development, while PCMs offer high energy densities compared to sensible TES, they face limitations such as low thermal conductivity, degradation over charge-discharge cycles and limited thermal stability.[157] For instance, thermochemical materials such as calcium oxide face issues with sintering, and performance decreases with repeated cycles. Further development is needed to create cost-effective, scalable materials with improved heat transfer properties and cycle stability. Innovations in composite materials with additives of nanoparticles or graphene have shown promise in improving thermal conductivity and stability.

Efficient heat exchangers and insulation systems are critical to reduce heat losses and improve thermal efficiency. Designing compact and cost-effective heat exchangers capable of handling high-temperature gradients remains a challenge, however. Emerging concepts such as 3D-printed heat exchangers and advanced computational fluid dynamics modelling offer the potential to optimise heat transfer efficiency.[158] Another challenge is retrofitting TES into existing industrial processes, which often involves overcoming spatial constraints and ensuring compatibility with existing systems, which increases complexity and costs. Operational control strategies for medium-high temperature TES systems need further research, including the integration of advanced monitoring and predictive maintenance tools.

New tools such as AI-driven predictive maintenance and real-time thermal monitoring have shown significant potential to improve system reliability and operating life. These technologies can support dynamic performance optimisation by identifying inefficiencies during operation, enabling more adaptive and resilient TES systems that align with industrial demands and renewable energy applications. Together, these advances offer great promise for improving reliability and reducing lifecycle costs.

Sustainability and life cycle considerations are now embedded in the design and implementation of new technologies. Materials with low environmental impact like sand, or derived from industrial waste like foundry sand or slags, hold promise but require further research to ensure their safety and sustainability. Comprehensive lifecycle assessments are needed to quantify environmental impacts and identify areas for improvement.

Bridging the gap between laboratory-scale research and commercial deployment remains a significant challenge. Demonstrators at both pilot and industrial scales are essential to validate technologies in real-world conditions. Take-up is also hindered by high initial costs for advanced TES systems tailored to a specific industrial site, especially those involving PCMs or TCS. It is vital, therefore, to introduce incentives, regulations and standards that support the take-up of TES, particularly for renewable integration, energy efficiency and industrial electrification.

15.3.3 Research opportunities

Addressing these challenges provides a clear roadmap for future research, which includes the development of hybrid storage systems and advanced materials.

Systems that combine different ES technologies offer an opportunity to make the most of each technology's strengths to develop diverse applications. Advanced materials research could significantly enhance thermal conductivity and stability to address key limitations in existing TES materials.

Collaboration with industry is essential to design modular, scalable TES systems tailored to specific needs, such as industrial waste heat recovery and renewable energy storage.

A broader exploration of circular economy approaches could improve the sustainability and economic viability of TES solutions and align with global decarbonisation goals.

Little research has been on the manufacturing of TES materials, which is clearly a research gap, both for medium-high temperature TES materials and other applications.

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16. The transport ↔ energy-storage nexus

In this field, by far the most debate has been around the vehicle-to-grid (V2G) technology, whereby EV batteries are used not only to power a car or a truck but also to support the grid. There is far less discussion of energy storage for trains and aircraft. Another issue is the 'second life' use of EV batteries for static storage once their capacity has degraded.

16.1 Vehicle-to-grid technology

V2G is far more written-about than put into practice. There are very few commercial examples so far, and the projected take-up is also low. Unsurprisingly, much of the extensive debate is about the barriers.

Here we review the issues raised in papers which have focused wholly or significantly on those barriers. By far the most comprehensive recently is Micari et al.,[159]; another relatively recent review by Bibak & Tekiner-Moğulkoç[160] covers fewer sources and suggests areas for future research.

Despite its apparent advantages, V2G faces several technical challenges:

Battery degradation

Micari et al.[161] describe the mechanisms of battery degradation and contrasts calendar ageing with cyclic ageing, which will clearly be accelerated by the additional and regular cycles involved V2G. Degradation is made worse when discharge is deep, so deterioration can be mitigated by 'smart charging', a term which does not appear to be fully defined in this context.

Bespoke infrastructure

V2G requires additional infrastructure including bidirectional chargers, which can feed energy back to the grid as well as from grid to the vehicle battery. These are expensive and raise the costs involved. There also seems to be a proliferation of incompatible standards for bidirectional chargers, making a common approach problematic.[162]

Incompatible vehicles

While Micari et al.[163] list nine V2G-compatible vehicles, many EVs are not compatible with V2G, and those that are do not all use the same charging standard (CHAdeMO, CCS).

Control algorithms

Sophisticated control algorithms will be needed to manage energy storage within a V2G system so as to balance between competing requirements of grid demands, minimising battery degradation and ensuring that the vehicle is suitably charged when it is likely to be required.

As well as the technical challenges, there are also human and individual factors that hinder the rollout of V2G. EV owners are likely be put off by:

- The expense of installing a bi-directional charger at home, as described in Micari et al.,[164] Bibak and Tekiner-Moğulkoç,[165] and Vishnu et al.[166]
- Justified fears of battery degradation described in Liu et al.[167]
- Range anxiety due to partial discharge after the vehicle has supplied the grid, as described in Liu et al.[168] and Shariff et al.[169]
- Data security: because V2G requires access to large amounts of data, it could be vulnerable to hacking, denial of service attacks, malware and physical tampering. Secure communication protocols needed for V2G are reviewed by Vishnu et al.[170] and were previously explored by Han & Xiao in 2016.[171]

Human factors are explored further in Section 21 of the present report.

In terms of business considerations, new business models and markets will be needed to exploit EVs as a means of energy storage.[172] According to Gissey et al.[173], this comes on top of broader barriers for energy storage such as its treatment under grid regulations as a generating asset, which imposes higher charges making energy storage less commercially attractive.

A 2017 paper by Lauinger et al.[174] contains a meta-review of 17 articles on V2G and explores why the technology had not generally been implemented by that point.

An important concept in V2G technology is the aggregation of EVs into larger controllable amounts of energy, whether in relation to a fleet or a large car park with chargers. Giordano et al.[175] focus on optimal aggregation strategies for EV participation in the grid for both reserve purposes and for energy arbitrage (trading).

Similarly, Jin et al.[176] propose a method for aggregation to enable V2G to operate in the energy market. Lauinger et al.[177] suggest the use of EVs on military bases both as a pilot for rollout of V2G and as an emergency energy reserve. This is an interesting idea because these vehicles are controlled by a common entity, and so easier to aggregate, and are not bound by commercial targets.

16.2 Local energy storage at EV charging stations

One barrier to the widespread adoption of EVs is that grid infrastructure cannot support the high demand imposed by large numbers of vehicles charging simultaneously. This is a particular issue at fast charging stations where demand at peak times is likely to exceed the capacity of the local grid, regardless of overall grid capacity. Demand is likely to be highest during the day and lower at night, when fewer vehicles are likely to stop en route.

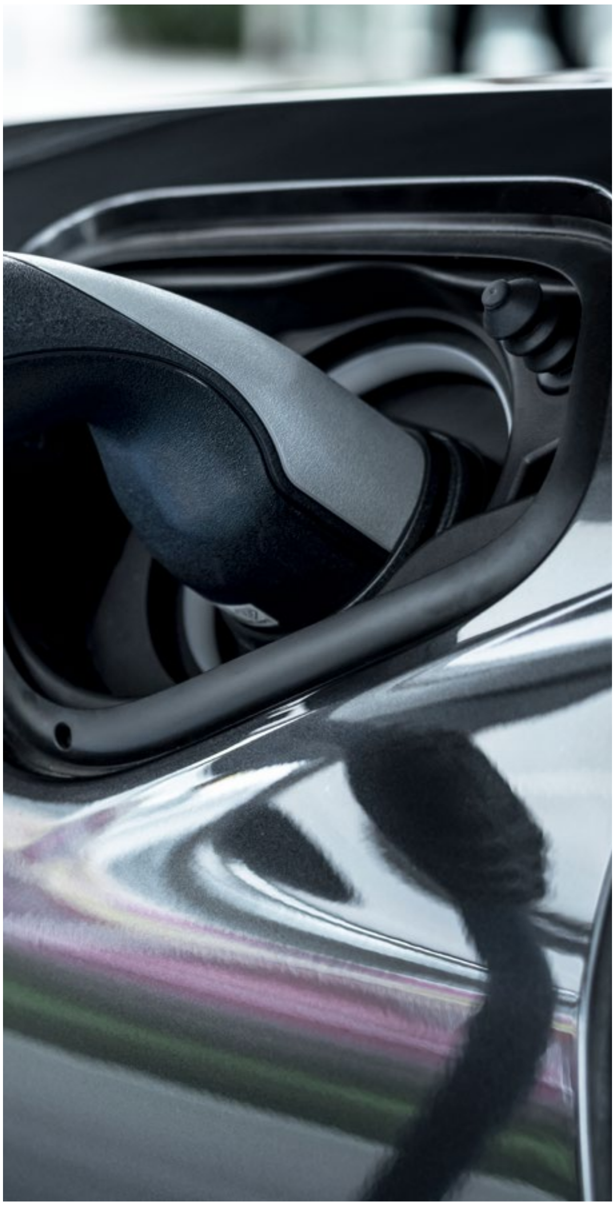
This problem could be mitigated by local storage at the charging station according to Bokopane et al.[178] who investigate the issue within a wider optimisation strategy. Their paper refers to several other studies including by Abronzini et al.,[179] Chacko and Sachidanandam[180] and Kouka et al.,[181] that consider local storage at charging stations along with other energy sources such as photovoltaic (PV).

Bartolucci et al.[182] and Dong et al.[183] conducted similar studies. Such storage could, of course, be based on second-life batteries as discussed in Section 16.5 below, and indeed this was implemented by 2017.[184] Given the increasing requirements for rapid charging at motorway service stations, which are often in remote locations and may suffer especially from grid bottlenecks, there would appear to be scope for local storage at such places.

The issues of demand, supply and local storage on highways are explored to some extent by Funke et al.[185] but we believe there is more work to be done in relation to motorway service stations.

16.3 Railways and train-to-grid technology

Although the above discussion so far relates mainly to electric road vehicles, similar arguments can potentially be applied to battery-electric rail vehicles. These are far less common than road EVs but they are used in Japan and being introduced in other countries.[186] Go et al.[187] explore the scope for train-to-grid (T2G). We have seen no evidence, however, that any such systems are actually in use. In any event, the amount of energy which could be stored in them would be small compared to that in road EVs.



16.4 Aviation

Although hydrogen is seen primarily as a fuel, it is manufactured by electrolysis using energy that may be surplus or from low-carbon sources such as wind and solar. Hydrogen may therefore also be regarded as a form of storage for electrical energy or for energy more generally.

Although there seems to be little interest in using hydrogen to power road vehicles, either using fuel cells or combustion engines, there is some interest in its use in aviation, where it might be feasible to store liquid hydrogen at low temperature for the necessary few hours of flight.

An early (2002) report by Colozza[188] outlines options for hydrogen storage technologies for aircraft. A recent (2023) review by Degirmenci et al.[189] explores challenges for the hydrogen supply network at airports and quotes evidence that the hydrogen supply network constitutes a major barrier to hydrogen aviation.

Gu et al.[190] explore the airport infrastructure needed to make the transition to hydrogen-powered aviation. These include the need for extensive space for a hydrogen plant as well as the existing kerosene infrastructure, since the two would need to coexist for many years. The authors conclude there is little incentive to invest in this infrastructure, which in any case would take many years to plan, obtain approval for and construct.

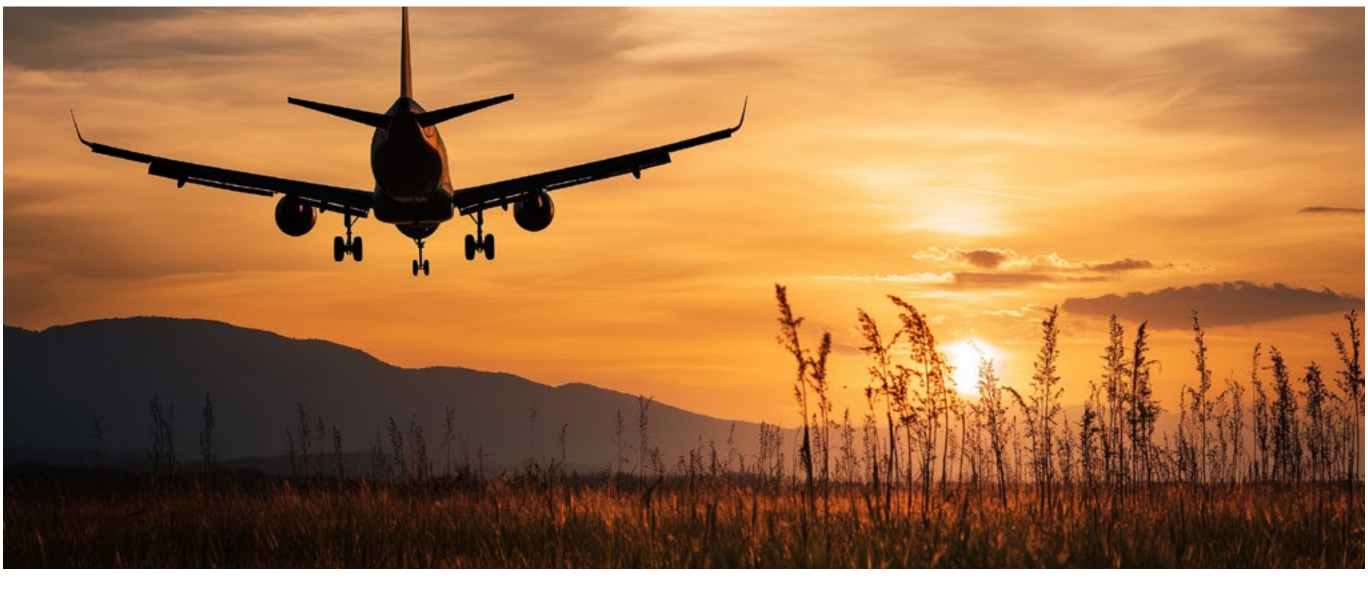
An Australian perspective on sustainable aviation fuels, partially informed by *Boeing*, is given in a CSIRO report by Bruce et al.,[191] with particular emphasis on hydrogen and hydrogen-derived synthetic fuels.

Given the difficulty of transporting and storing liquid hydrogen at cryogenic temperatures, for hydrogen to be remotely realistic in aviation, it would seem necessary to produce and liquefy it on site, either immediately before aircraft refuelling or during off-peak periods.

We could find no literature that tackles this issue, and the considerable demands for cooling which would need to be met, which could be partially mitigated by stores of coldness at airports. These could be charged off-peak and then used for hydrogen liquefaction when needed. The stores could be either simple low-temperature reservoirs or could exploit latent heat.

Michael Liebreich, an independent energy analyst, has calculated that on-site hydrogen production to replace all the jet fuel consumed at Heathrow airport would need an electricity supply of 2.7GW, and that rejected heat from liquefaction could raise the temperature of the Thames significantly. He argues that bioenergy with carbon capture and storage (BECCS) would be more practical and cheaper as a means of decarbonising aviation.[192] The power supply that failed in March 2025 causing a blackout at the airport and widespread travel disruption was 70MW.[193]

A relatively recent development described in Yao et al.[194] is a process for conversion of carbon dioxide into aviation fuel using a combination of the hydrogenation of CO_2, the reverse water-gas shift reaction and Fischer-Tropsch synthesis. This could provide a route to sustainable air travel that avoids major transition to a new fuel required for hydrogen-based aviation. This approach is alluded to by Bruce et al.,[195] and other similar approaches are reviewed by Wei et al.[196]



16.5 Second-life use of EV batteries

Regardless of whether V2G ever becomes commercial, EV batteries could well provide grid storage as a 'second-life' function after their performance degrades and they are replaced. They will still have useful capacity for static applications even after their range is too small.

This question is explored in a large number of publications, including an early (2014) paper by Ahmadi et al.[197] as well as a recent (2024) and detailed review of the literature conducted by Salek et al.,[198] who observe that much of the research has focused on environmental and economic issues rather than technical challenges. Nonetheless they compare twelve modelling methods to calculate the ageing of second-life batteries, with ten modelling the battery cell and two modelling the battery pack.

The authors conclude that there is a shortage of studies on experimental analysis of second-life batteries. They also identify the need for battery management systems especially designed for second-life batteries to address concerns about thermal runaway under a regime different from the batteries' intended use.

Another fairly recent (2022) review is presented by Hu et al.[199] covering some of the same areas, but also battery management, optimal sizing and energy management strategies. A slightly older (2018) review is presented by Martinez-Laserna et al.,[200] and more recent still (2024) is a thesis by Fallah.[201]

One important issue explored by Wang et al.[202] relates to selecting the retirement points for batteries as their performance deteriorates, from first to second life, and then end of life.

A commercial website from a UK enterprise *Connected Energy*, though not an objective or academic work, provides some industry perspective on energy storage in second-life batteries and specifically on modular (container-based) storage units.[203]

A further issue which does not seem to be mentioned explicitly in any references in the context of battery re-use (though alluded to by Vishnu et al.[204]) is that the re-use of batteries for energy storage means that more raw materials must be mined and processed to make additional EV batteries, given that the second-life batteries will not be available for recycling in the short term. Conversely, this may buy time to install and commission the recycling centres which will be needed as increasing numbers of EV batteries reach the end of their first and ultimately second lives.

16.6 Research gaps

Research gaps in this field include:

- Challenges related to charging at motorway service stations where demand is intense during peak periods, and grid supply constraints may be severe due to location. There appears to be scope for development of systems specific to motorway charging stations, including use of local storage to mitigate supply constraints.
- Environmental impacts, both positive and negative, of taking potentially recyclable EV batteries out of the recycling chain for the duration of their second lives.
- How second-life batteries, and indeed other forms of electrical energy storage, can be used to confer environmental benefits rather than merely improved margins for the utility providers. This will require the development of battery management systems different from those used in vehicles, to provide optimal performance and address safety concerns regarding ageing batteries.
- Barriers to adoption of T2G systems, especially in countries where battery-electric trains are already in use.
- Potential for flexible use of electricity for generating coldness to support hydrogen liquefaction at airports, whether for use on-demand liquefaction or short-term storage.
- Costs and timescales for large-scale implementation of the CO_2-to-aviation fuel process.
- A point raised at the UKES2025 discussion session noted that energy storage at sea ports also deserved significant further attention – both in terms of safe bunkering of fuels (including hydrogen and ammonia), and the use of localised electricity storage systems to support the 'hotel load' of ships so that they do not need to run their engines whilst in port.

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17. The water ↔ energy-storage nexus

Water and energy are critical resources that have always been interconnected. The relationship between the two varies, however, according to regional climates and the effects of climate change.

As a general proposition, in arid countries water is the priority and this tends to raise energy consumption, with desalination in the Middle East as an example. By contrast, in historically wet regions such as northern Europe, water has generally served energy through hydro, pumped hydro and the cooling of thermal plants.

However, the apparently relentless rise in global temperatures is sharpening the water-energy dependency everywhere. Hotter summers increase demand for air conditioning and therefore electricity, which in turn requires more cooling water; droughts mean less water is available. In the heatwave of 2022, France was forced to shut down many nuclear power stations because its rivers were too low, and Norway restricted its hydro output.

Some storage technologies might at first glance appear relevant in this context – off-peak generation of coolth stored as chilled water, for example, explored in Sections 15.2 and 20 - but these do nothing to improve the water supply.

More relevant is the water industry's energy demand, which is high – even in countries that do not yet need desalination – and might be made flexible. If it were possible to time-shift the water industry's energy consumption it could help balance supply and demand on the electricity grid and therefore reduce the need to invest in energy storage.

17.1 Wastewater treatment

In Britain, the water industry consumes between 2% and 3% of the country's electricity, of which sewage treatment takes roughly half, and of that the aeration of treatment tanks takes up to 60%. In other words, aeration alone consumes almost 1% of Britain's electricity. Given public outrage over the frequency with which untreated sewage is discharged into rivers, and disciplinary actions by the regulator, treatment capacity and therefore aeration energy consumption is likely to rise.

Aeration consumes so much energy because it needs powerful compressors to supply oxygen to aerobic microorganisms in the treatment tanks. If these could be operated flexibly they might become a valuable asset to help manage load in the electricity system.

It is important to note that energy consumers in the water and electricity sectors behave very differently throughout the day and the year, and we need to understand these patterns better.

Energy consumption could be reduced by investing in modern technologies such as fine-bubble diffusers, higher efficiency pumps and smart-controlled aeration systems. Net energy consumption could be reduced by further investment in technologies such as anaerobic digestors to produce biogas.

Yet, the financial straits of the UK water industry are well known – it is massively in debt and has a significant infrastructure investment backlog. In these circumstances, intermittent operation of aeration pumps might be one of the lower-cost options and could be supported through funding from the electricity grid. This is why its potential to help grid balancing needs to be thoroughly assessed.

17.2 Energy recovery from water towers

Water towers have traditionally been a key component of water supply systems and pressure management. With advances in technology, the towers are being replaced by underground tanks and smart pumps, but many still exist. It is important to investigate whether they could provide flexibility not only for the water system but also for the electricity grid.

By storing water at height, we store not only water but also potential energy. That means a water tower could be turned into a small-scale pumped hydro system to provide energy at peak times as well as manage pressure in the water system. If peak demand for water and electricity coincide, it would greatly benefit the electricity grid. The same is true if the water tower can be refilled using renewable electricity during off-peak times, maximising the use of renewables and reducing their curtailment.

As with wastewater aeration, we need to better understand the current operation of water towers for water management, and the extent to which it complements the needs of the electricity grid.

17.3 Ice-source heat pumps

Another challenge lies in the use of water-source and ice-source HPs, which, despite their high performance, face issues related to ensuring adequate water supply.

The concept of an ice-source HP is based on the counterintuitive fact that turning cold water into ice releases a lot of latent heat.[205] Mehdipour at al.[206],[207] recently demonstrated how this could provide space heating for homes through a prototype device they liken to a slurpee maker. The researchers propose that redundant gas pipelines would be repurposed to supply non-potable cold water to an internal-source heat pump (ISHP) in the home, which would cool the water electrically to turn it into a slushy ice-water mix. The resulting heat would be captured to warm the home and the slushy mix would then be removed through another redundant gas pipeline.

The researchers calculate such a system could supply up to 40% of the energy required during peak hours. How to meet the water demand to support this remains unresolved.

17.4 AI in water usage

Data and artificial intelligence could play an increasingly important role in the water-energy nexus. AI-driven algorithms could optimise water and electricity consumption in systems such as pumping, cooling and wastewater treatment. By predicting energy demand based on historical and real-time data, AI could dynamically schedule water pumping during off-peak hours.

AI could also enhance cooling system performance by monitoring environmental conditions and adjusting operations to minimise energy consumption. Integrating renewable energy sources like solar and wind with AI optimization strategies can improve efficiency by balancing energy production and consumption in real-time.

17.5 Research gaps

To manage the water-energy nexus we need to better understand:

- Operating schedules of wastewater aeration equipment and the degree to which these could be made flexible to avoid electricity peaks and maximise consumption of the cheapest off-peak energy.
- Costs of any additional equipment needed to run aeration flexibly.
- Operating schedules of water towers and the degree to which these coincide with the peaks and troughs of electricity demand.
- Costs of additional equipment needed to generate electricity from the potential energy stored in water towers.
- The real potential of and barriers to repurposing existing gas networks to supply ISHPs and dispose of ice slurry.
- The extent to which AI could optimise any of the potential synergies listed above.
- A key point added from the UKES2025 discussion session uncovered that future electrolysis will require very large amounts of fresh water and even in the UK, that may have to be sourced from desalination for some parts of the year.

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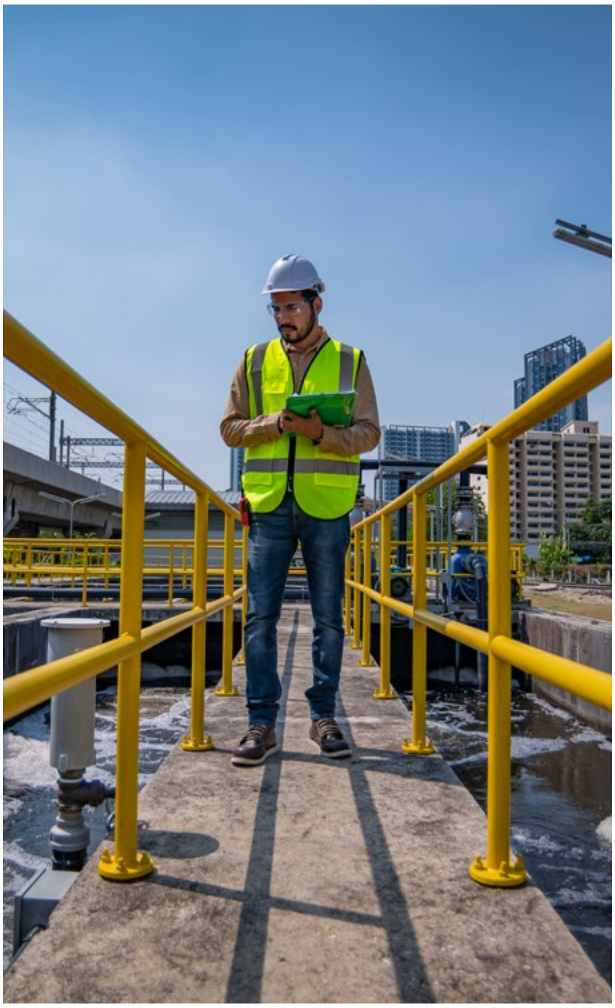

18. Inertia and grid-forming inverters

In the electricity system of two decades ago, power was generated almost exclusively from large spinning synchronous alternators whose natural inertia formed the first line of defense against disturbances on the grid. If the power being drawn from the grid exceeded the power being supplied into it by gas or coal fired steam-turbines, the frequency would begin to drop and some of the kinetic energy held in the spinning metal would be released automatically to make up the shortfall for a brief time until the power was balanced again.

Present forms of renewable energy generation do not inherently provide such grid support. Solar farms have no kinetic energy and most existing wind turbines, although spinning, do not naturally adjust the power input to the system according to whether grid frequency is increasing or decreasing. In both cases, some of the features of synchronous generators can potentially be restored to these generation forms using additional power electronics, but this is not often done at present.

As we install huge additional wind and solar capacity towards 2030, Great Britain's power grid faces the following challenges, as outlined by Ratnam et al.[208] and Ahmed et al.:[209]

- Declining capacity to supply fault currents, which can lead to control and protection problems.
- Reduced natural system inertia, leading to rapid changes in frequency in response to natural imbalances between generation power and demand, and a reduced capacity to control frequency which may lead to instability.
- Diminished natural smoothing effect of the synchronous generators, making the system more prone to harmonic distortion than it was previously.

There are essentially two ways to solve these problems. We could either:

- Provide power-electronic methods together with fast-responding energy stores to replicate what real inertia used to do, or
- Link significant synchronous machines (motors, generators or compensators) back into the grid.

If the main problem turned out to be rapid change of frequency, then a partial solution would be to relax the trip-settings in system relays so that they could simply tolerate higher rates of change. At present, we have the possibility for an anomalous situation in which a high rate of change of grid frequency can lead to the automatic disconnection of several large generators, including nuclear power stations which are actually very helpful in managing the rate of change of frequency problem.

The main power-electronic solution is known as 'grid forming control' and is implemented by so-called grid-forming inverters.[210] These systems try to mimic the dynamic characteristics of synchronous generators and are sometimes referred to as 'virtual synchronous machines'. The technology allows inverter-based power resources such as wind turbines, batteries and solar farms to act as a voltage source behind an impedance. With grid-forming control, energy storage can 'set' the system frequency as would a synchronous generator.

The alternative would be to incorporate real inertia again. This is highly compatible with many of the thermo-mechanical energy storage technologies because these usually connect to the grid via synchronous machines serving sometimes as generators and sometimes as motors.

Some of the challenges and solutions associated with real synchronous inertia are outlined in Mishra et al.,[211] Rouse et al.,[212] Hoskin et al.[213] and Rouse et al.[214] Both grid-forming inverters and real inertia provide energy storage solutions dealing with the VSDES part of the energy storage spectrum.

The key research opportunities in this field are:

- Re-examining the role of frequency within electricity grids as an indicator of system health. Alternative measures might be facilitated by the very fast computations and communications available in modern power systems.
- Exploring the advantages that might arise from using AI to control grid-forming inverters.
- Blending real-inertia and power electronic solutions so that the best features are drawn from both.
- Developing methods by which the kinetic energy available in wind turbine rotors can act as the energy store for a grid-forming inverter; and exploring how the long-distance alternating current (AC) transmission technologies of companies such as *EnerTechnos*[215] might allow the resulting 'inertia' of offshore wind turbines to be effective onshore.
- Developing long-life, low-loss mechanical clutching mechanisms that can connect synchronous machines to a thermo-mechanical energy storage system as needed, but which allow the machine to continue spinning even when the main energy storage system is neither charging nor discharging.
- The UKES2025 discussion session called for more detailed investigations to be conducted into the ability of batteries to provide the very fast response services that the future grid will need. It was highlighted that flow batteries are increasingly installed alongside Lithium-ion batteries to protect the Lithium-ion batteries from exposure to those rapid changes in power direction.

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19. Underground energy storage

Underground thermal energy storage (UTES) is an umbrella term that covers thermal energy storage in aquifers, boreholes and minewater.

Underground storage is well-suited to support longer-duration and larger-scale forms of energy storage. These include storing surplus renewable energy, inter-seasonal storage, support for peak-shaving during periods of extremely high energy demand, and sustained delivery of consistent energy to support industrial processes.

Many geological processes are influenced by the natural variability of the bedrock, and therefore may be poorly understood. As a result, there are several research gaps that may delay the development of geological energy storage.

Geological energy storage technologies rely on voids in the rock – either pore-spaces or natural or engineered caves – to accommodate fluids over different time periods. It is within these fluids that energy or exergy is stored, for example thermal energy in hot or cold water or in a phase-change material; mechanical or potential exergy as high-pressure air; or chemical energy as methane or hydrogen. Alternatively, mechanical or potential energy can be stored in gravity energy storage systems or pumped hydro schemes.

Geological energy storage can employ a diverse range of technologies, some well-established with TRL 9 while others are in development at a range of lower TRLs. These are described in Sections 19.1-19.4 below.

19.1 Underground thermal energy storage

Underground thermal energy storage (UTES) is an umbrella term that covers aquifer thermal energy storage, borehole thermal energy storage and minewater thermal energy storage.

There are knowledge gaps related to the amount of thermal energy that can be stored in different rock types, and how much of that energy is retrievable. Where several schemes are located locally, there is potential for interference between, for example, one storing heat and another storing cool. This is poorly understood in terms of zones and magnitudes of influence.

Some of these concerns could be addressed by novel system design approaches such as using different underground strata for different thermal storage purposes, or through the development of planning rules. For these thermal energy storage technologies, an understanding of hydrogeology – flow, yields and transmissivity – will affect thermal input and output. The scalability of schemes may also be influenced by thermal properties of the bedrock, and by the presence of natural discontinuities that may influence groundwater flow.

The main research gaps related to UTES are:

- Quantifying the amount of thermal energy that can be stored in different rock types, and how much of that energy is retrievable.
- Exploring the potential for interference between underground storage projects located near one another. This is poorly understood in terms of zones and magnitudes of influence.
- Better understanding of hydrogeology (flow, yields and transmissivity) affecting thermal input and output.

19.2 Underground gas storage

Many commercial schemes operate natural gas storage in engineered, solution-mined caverns in rock-salt, depleted reservoirs or saline aquifers. For storage in porous rocks, research is concerned with reducing the amount of cushion gas required to maintain a minimum pressure in the storage complex. This may help reduce both the capital investment needed to establish a facility and its operational costs. There are also questions related to the potential to store gas at higher pressures and with faster rates of injection and release.

These technologies are being applied to hydrogen storage, although questions remain about the behaviour of hydrogen underground compared to methane or other gases such as helium. IEA's Underground Hydrogen Storage report[216] identified several knowledge gaps related to storing hydrogen in geological formations. Of these, the potential of hydrogen to stimulate biological and geochemical reactions in the subsurface was seen as key, along with hydrogen flow, migration and thermodynamic behaviour underground.

Further research is required to understand the ability of porous rocks to store hydrogen, and that of low-permeability rocks to act as seals – because hydrogen molecules are so small. Addressing this research gap could expand the locations in which hydrogen storage could be available, thus increasing total storage capacity.

Key research challenges remaining with underground gas storage include:

- Reducing the amount of cushion gas required to maintain a minimum pressure for storage in porous rocks.
- Examining the potential to store gas at higher pressures and with faster rates of injection and release.
- Understanding the behaviour of hydrogen underground compared to methane or other gases such as helium.
- Exploring the potential of hydrogen to stimulate biological and geochemical reactions underground.
- Developing a better understanding of hydrogen flow, migration and thermodynamic behaviour underground.
- Probing the ability of porous rocks to store hydrogen, and that of low permeability rocks to act as seals.

19.3 Underground storage of pressurised air for CAES

An earlier section of this report discusses compressed air energy storage (CAES), with emphasis on the technologies used to convert electrical energy into pressurised air and heat, and vice versa. Here, we focus on relevant aspects of subsurface technology. Solution-mined caverns in salt deposits are the default choice for large and inexpensive air stores with near-zero leakage rates.

As an alternative to CAES in solution-mined caverns, the potential for storage in porous rocks remains poorly understood in terms of containment, frequency of cycling and response of the subsurface to the storage of large volumes of air. If storage in porous rocks proves feasible, then it would greatly increase the geographic regions where CAES could be deployed, including those remote from rock-salt geology.

Developing engineered, lined caverns to allow deployment in areas where porous or solution-mined caverns are not possible could also be extremely valuable.

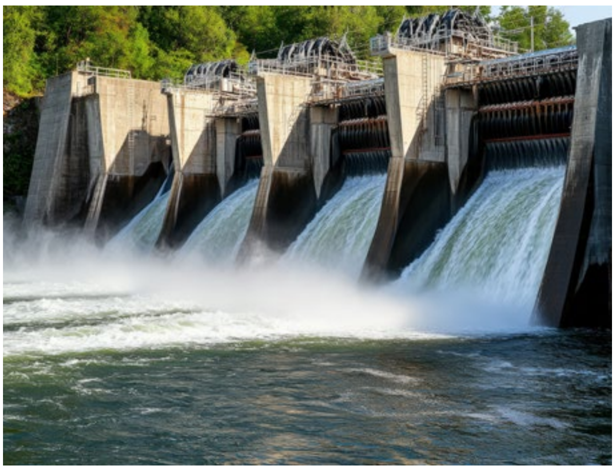
Thermal management is a key research area for CAES. Research so far has focussed on the storage and retrieval of low-enthalpy heat underground, but the enthalpy heat of compression (above ground) is a much bigger prize. If we could capture and recycle that, it would greatly reduce the need for a heat source during the decompression phase.

Key areas of subsurface engineering research relevant to large-scale CAES systems include:

- Moving towards higher pressure CAES for improved system performance and cost
- Probing the potential for storing pressurised air in porous rocks rather than caverns, taking into account containment, cycling frequency, and response of the rock to the storage of large volumes of air
- Advancing the practice of using engineered lined caverns in locations that lack salt deposits
- Exploiting the enthalpy heat of compression to reduce the need for a heat source during decompression

19.4 Underground pumped hydro and other gravitational potential energy storage

Underground gravity storage includes underground pumped hydro and the raising of weights in mineshafts, which are attractive options as they do not rely on topographic variations. Research gaps with these opportunities are related to understanding the RTE, lifespan and for schemes involving water, containment.



19.5 Research gaps relevant across technologies

In addition to the specific research gaps indicated above, some processes are relevant to a broad range of geological storage technologies:

- The response of the subsurface to changes in temperature or geochemistry, which could mobilise minerals or contaminants and/or stimulate microbial activity.
- The potential to activate geological faults through changes in pressure during gas injection or release, especially where this could damage subsurface infrastructure or cause earth tremors.
- Migration of fine particles through porous rocks during fluid flow, which could reduce storage efficiency.
- The pressure ranges and rates at which fluids can be stored. If these ranges can be expanded, then the amount of stored energy and the speed of its delivery can be increased.
- The development of appropriate monitoring strategies to understand leakage and regulatory compliance, to increase the confidence about safety of these technologies.
- The potential for the subsurface to support several uses in a limited area, including energy storage, geothermal and mineral extraction, along with permanent storage of waste (CO_2 and radioactive waste) is a useful area to consider, especially as demand for subsurface space and assets develops.
- The attitudes of local populations and stakeholders to accept these technologies is important to understand if schemes are to be successfully embedded in communities.
- Comments made at the UKES2025 discussion recommended to consider surface and subsurface simultaneously. The UKES2025 discussion also raised a major point about wellhead integrity. Many wellheads were installed originally to manage natural gas but in the future could manage hydrogen or other gases. The transition from natural gas to hydrogen needs to happen continuously but this is not a convenient approach for the people charged with implementing the change.

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20. Maximising lifetime energy returns of energy storage

Much of this report concerns detailed questions about individual technologies. There are also broader questions that need to be answered:

- What is the total amount of storage capacity required?
- How to assess and compare the lifecycle energy returns of storage types?
- How to improve those energy returns to reduce cost and speed the transition?

20.1 How much energy storage is needed for the clean energy transition

There is extensive research estimating the amount of energy storage required during the energy transition, but it is not always clear whether an estimate relates to some intermediate period or to the final destination, when the maximum possible share of generation is to be supplied by renewables.

Limpens[217] explores energy storage needs for the energy transition and concentrates on four scenarios relating to Belgium. It considers only Lithium-ion batteries and uses source data derived from Barnhart and Benson[218] and Barnhart et al.[219] Crownshaw[220] describes a method to model the economics of transition within the whole energy system. The paper mentions storage to mitigate intermittent generation and cites several relevant sources, but makes little reference to practical engineering issues and does not appear to model storage explicitly. Kalair et al.[221] review the role of energy storage in the energy transition in general and sometimes speculative terms, focusing mainly on overall figures rather than detailed technologies.

In a 2016 paper with 201 references, Gallo et al.[222] identify 28 energy storage methods in the context of the energy transition and list 10 application areas. The characteristics of energy storage methods are tabulated. They identify two key barriers to energy storage: economic feasibility of business models and regulation.

Child et al.[223] present a simulation-based study of energy storage technologies to reach 100% renewable energy in Europe. This is not primarily a study of different technologies but focuses on capacity and economics. The technologies include batteries, pumped hydro storage, synthetic natural gas storage and biomethane storage.

20.2 Lifecycle energy returns of energy storage technologies

A wide range of energy storage technologies is already available, as demonstrated throughout this report. Various sources have catalogued these technologies and listed their RTE and/or costs, including Bowen et al.[224] and Zablocki et al.[225] Far fewer have assessed the lifecycle energy returns for these technologies.

Most people are by now familiar with the idea of the energy payback time of renewable generators. As an example, it might take a year for a wind turbine, or four years for solar panels, to recoup the energy spent on their manufacture. This measure is known as energy returned on energy invested (EROI).

Similarly, storage technologies can be assessed and compared against energy stored on energy invested (ESOI). Here the total energy stored and discharged by an asset over its lifetime is divided by the energy consumed to make it.

ESOI is less well known than EROI and more problematic. As with EROI, we have found the data can be unreliable, out of date, biased or inconsistent.[226] Worse, different researchers get wildly varying ESOI results for the same technology, and these inconsistencies need to be resolved. Worse still, almost all ESOI assessments suffer from a methodological flaw that must be corrected if we are to fully understand where costs can be reduced in future.

The range of ESOI scores for each technology is enormous, as demonstrated in Table 20.1 below. For CAES the lowest score is 240 and the highest 1100; for pumped hydro the spread is 210 to 830; and for Lithium-ion batteries one researcher gives 35 and another no higher than 2.

Table 20.1: Summary of ESOI figures from a variety of sources, showing considerable variation depending on exact method of calculation

Energy storage technology	ESOI	Reference
Lithium-ion battery	35	Pellow [R19.15]
	8-28	Kurland and Benson [R19.17]
	32	Barnhardt and Benson [R19.3]
	10	Barnhardt [R19.19]
	<1-2	Capellan-Perez [R19.20]
Sodium-sulphur battery	26	Pellow [R19.15]
	20	Barnhardt and Benson [R19.3]
	6	Barnhardt [R19.19]
Vanadium redox battery	14	Pellow [R19.15]
	10	Barnhardt and Benson [R19.3]
	3	Barnhardt [R19.19]
Zinc bromine	15	Pellow [R19.15]
	9	Barnhardt and Benson [R19.3]
	3	Barnhardt [R19.19]
Lead acid battery	5.8	Pellow [R19.15]
	5	Barnhardt and Benson [R19.3]
	2	Barnhardt [R19.19]
	2	Yan and Crittenden [R19.18]
CAES	1100	Pellow [R19.15]
	797	Barnhardt and Benson [R19.3]
	240	Barnhardt [R19.19]
PHES	830	Pellow [R19.15]
	704	Barnhardt and Benson [R19.3]
	210	Barnhardt [R19.19]
Regenerative hydrogen fuel-cell (hydrogen tanks)	59	Pellow [R19.15]
Regenerative hydrogen fuel-cell (liquid organic hydrogen carrier)	18-53	Lee [R19.16]

In terms of individual analyses, Pellow et al.[227] compare the ESOI for a regenerative hydrogen fuel cell, where the hydrogen is stored in high-pressure tanks, with a Li-ion battery. They find that the fuel cell (ESOI=59) considerably outperforms the battery (35) but is greatly inferior to pumped hydro (830), or compressed air or natural gas storage (1100). Lee et al.[228] conducted an energy study on regenerative hydrogen fuel cells where the storage is provided by hydrogen stored in an organic liquid, and find an ESOI of 53 for weekly storage and 18 for monthly. Kurland and Benson[229] give lower ESOI figures of 8-28 for a Lithium-ion battery depending on how much the battery is used.

More recently, Yan and Crittenden[230] proposed what appears to be an alternative methodology and found that the ESOI for mechanical storage is far higher than those of chemical methods, with Lead-acid batteries scoring just 2.

Section 16 explored the barriers to adoption of V2G technology, but Capellan-Perez et al.[231] provide a different angle by investigating the ESOI values for different EV battery sub-technologies. Worryingly they find that the ESOI values for EV batteries are in the range of 1-2, and these drop to below 1 when ancillary equipment such as chargers and the grid itself are included. The researchers also find that extending the life of EV batteries by re-purposing the batteries for energy system backup would not significantly improve these figures, and conclude bluntly that "electric batteries do not seem a very useful technology to back-up the energy system".

Capellan-Perez et al.[232] go on to argue that the shift to electric vehicles faces risks relating to availably of the minerals needed. As the arguments and figures here disagree drastically from those of Barnhart and Benson,[233] further exploration of the assumptions will be needed.

It could be argued that some of the ESOI findings, particularly the low scores for EV batteries, make no practical difference since there is no alternative; you could hardly power a car using pumped hydro. And once the EV batteries exist, and their range has declined, it surely makes sense to extract some further service as grid storage before recycling the materials. Where two technologies compete to provide the same service, however, the ESOI is well worth knowing. If one technology has a higher ESOI than another it may make sense to promote it – although the ESOI advantage may already be reflected in relative costs.

Aside from the wide range scores for each technology, ESOI assessments are also undermined by the fact that almost all treat each unit of energy consumed to produce the storage asset as having the same value regardless of when it was consumed. For example, the energy used to drive the pumps used in creating a salt cavern for hydrogen storage can be switched on and off at will to exploit off-peak, surplus or cheap energy, the reducing the cost and the environmental impact. Yet this is not captured by current ESOI assessments, which deal only in MWh.

If ESOI could be developed to include cost and perhaps carbon, it might lead to smarter manufacturing approaches which could reduce costs. It is ironic that technologies designed to deal with variability do not yet acknowledge or value it in their own manufacture.

20.3 Research gaps

The research gaps identified here include:

- The ESOI values of each energy storage method vary widely. We clearly need to reconcile the differences to inform sound decision-making.
- Present definitions of ESOI do not take account of the flexibility of energy consumption during creation of an asset. Expanding the definition of ESOI to take account of cost and emissions is clearly a research gap.
- We have found no literature on the timescales involved in setting up the energy storage infrastructure required for a transition to clean energy, so this appears to be an area requiring further investigation.
- The UKES2025 discussion session identified that detailed lifecycle analysis should be an intrinsic part of the considerations described in this section and highlighted that the management of CO_2 emissions during the transition to net zero should be considered independently of the energy being consumed during that transition.
- The UKES2025 discussion also emphasized the need to remain mindful of the core ideas of "just transition" which should take account of what skillsets are being made redundant at the same time as new skillsets are coming into shortfall.

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21. Energy storage and social acceptance

The energy transition is not simply about solving technical and economic challenges. There are also human and social barriers to overcome, as illustrated by the recent cancellation of several pilot projects for hydrogen home heating and the decades-long search for a geological nuclear waste repository.

Steg et al.[234] propose a four-point framework for considering sustainable energy behaviours, and review psychological studies on four topics: understanding which behaviours need to change; understanding of the factors which underlie those behaviours, specifically knowledge, motivations and context; testing interventions to promote sustainable behaviours; and understanding which factors affect the acceptability of relevant policies and changes.

There has been less attention to public acceptance of energy storage specifically, however, with only a small number of studies by social scientists so far. These include Thomas et al.[235] who investigate public acceptance of energy storage technologies in the UK, and Devine-Wright et al.[236] who propose a theoretical approach to understand acceptance of energy storage technologies through the belief systems and/or social representations held by stakeholders.

Thomas et al.[237] conducted workshops with the general public and found it to be "largely ambivalent and [exhibiting] acceptance reliant on design, regulation and governance with regards to reducing technical/safety concerns, in addition to environmental impacts and reliability".

Much of the remaining research is focused on reactions at the household level, such as Ambrosio-Albala et al.[238] and Scott and Powells;[239] on specific forms of energy storage; and on broader scale energy transitions such as the hydrogen futures, including Gordon et al.[240] and Scott and Powells.[241]

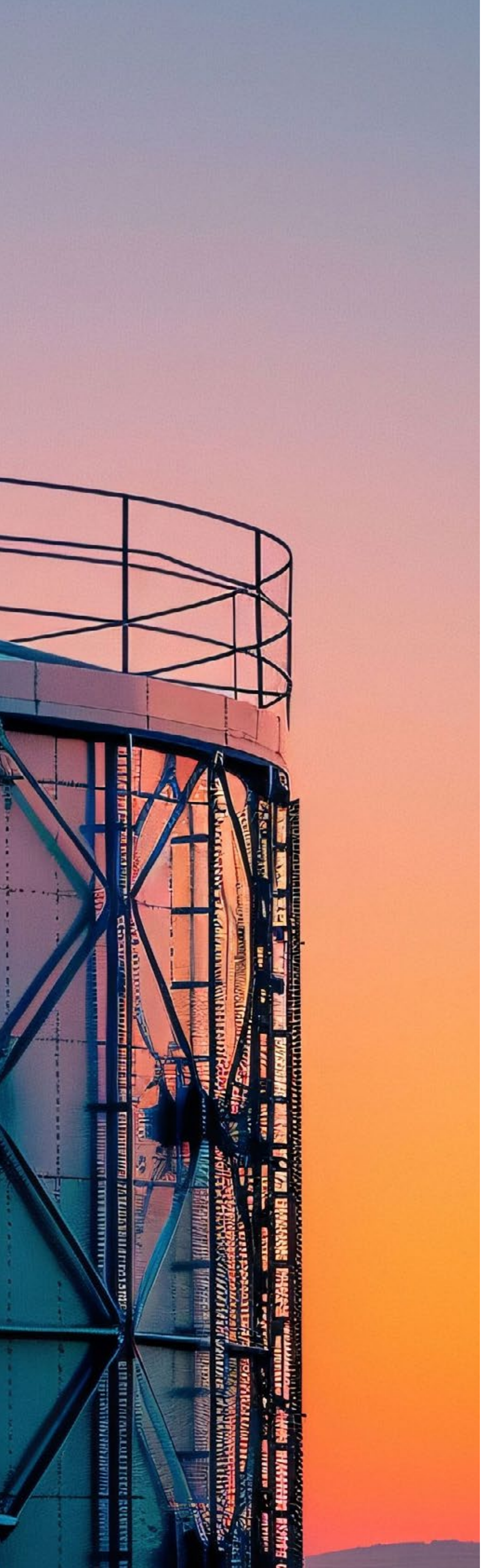
One common area highlighted for future attention has been governance and regulation, which influences public acceptance more broadly, as noted in Thomas et al.[242] Devine-Wright et al.[243] identify this as one of the key areas for future research, alongside markets and innovation, and socio-cultural and public acceptance.

Similar arguments are made in a review of barriers to underground hydrogen storage by Tarkowski and Uliasz-Misiak.[244] Gordon et al.[245] discuss potential conflicts of interest in accessing geological reserves for underground storage, and Hámor-Vidó et al.[246] discuss the need for governance solutions in the future use of underground space.

Another commonality is the need for more interdisciplinary and multidisciplinary research that moves beyond the technical and design aspects of energy storage and includes perspectives from social scientists. One way to encourage this is more funding calls fostering collaborations in this research space.[247]

The research gaps identified here include:

- Governance and regulation in relation to social acceptance of energy storage technologies
- A pressing need to encourage more inter- and multidisciplinary collaborations in the area of energy storage
- The UKES2025 discussion session also highlighted that to secure the willingness of the different publics to accept new technology implementations, it is necessary to consider those publics right at the concept stage and engage them from that point. There is important social science left to be done here.



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22. Final observations

Any report on research gaps would be incomplete if it did not mention artificial intelligence (AI). Of course, no amount of intelligence (artificial or otherwise) can create or destroy energy but AI can potentially provide very useful functions that enhance energy storage, or help to obviate the need for it. Specific areas where AI could help are:

- Optimisation of highly complex systems for cost
- Forecasting both demand and weather, and scheduling the operation of energy stores
- Devising a constantly-evolving price function to realise effective demand-side management

Another aspect of energy storage is the resilience it provides against unforeseen shocks. We live in an increasingly insecure world with many malign state and non-state actors for whom disrupting the energy system would be highly desirable. We should value the ability to recover from such attacks – and other shocks – and this points to removing 'single points of failure'. Energy storage is valuable in this context and should be appropriately rewarded. An open question remains: **how can appropriate value be attached to the resilience benefits provided by energy stores?**

While organising this report, we adopted the standard practice of breaking down a wide area of inquiry into many smaller spaces, with independent analysis of each. This approach has a big shortcoming: it omits to explore potential advantages to implementing solutions to two or more problems with the same system.

One example is to **hybridise renewable energy generation with energy storage**. Another is to develop hybrids of several energy storage technologies, and there is a clear case for examining specific hybrids including:

- LAES-CAES hybrids
- Synchronous flywheels hybridised with PTES
- Synchronous flywheels hybridised with CAES
- CAES hybrids with long-duration thermal storage
- CAES-LAES hybridisation with different generation plant or with loads

Market structures will be absolutely essential in determining how successfully energy storage is implemented within the future energy systems, both in the UK and elsewhere. This is the single biggest message from all industrialists, utilities and energy storage system developers.

For the most part, the work required to advance thinking on market structures is not research, but there is one key element that does fall into the research space. An agent-based modelling tool for testing possible market structures could be an extension of research conducted by Ringler et al.,[248] and could test various candidate market approaches and provide insight into what will work or not, based on representative characterisations of all market elements.

There is also a need for **formalising definitions** of the different durations of energy storage. As yet, there is not a common consensus on terminology – for example, the term 'LDES' for long-duration energy storage means different things to different people. A start on this has been made in a 2024 report by the IEA,[249] but potentially should be integrated into a future research project.

In terms of **energy storage durations**, the existing suite of technologies and research projects focuses very much on the shorter-durations end of the spectrum. This is entirely understandable because the nature of the duty performed by energy storage evolves significantly as the penetration of low-carbon generation rises. At low penetrations of renewables, there was no need for any energy storage at all, apart from what was provided naturally by the storage of fossil fuels. At present, the main actions required from storage still involve discharging over periods of a few hours at most. The 2023 Royal Society report on energy storage[250] revealed, however, that in a future net zero UK with a high proportion of wind generation, storage durations would extend dramatically. In this scenario, some energy could stay in storage for decades, due to the relatively high inter-annual variability of wind.

The 2025 EPSRC call for proposals addressing interseasonal energy storage (IES)[251] is timely, but we will need storage to go beyond inter-seasonal timescales and into the realm of multi-year or decadal storage. Potentially, some of the responses to the present call including IES-suited technologies will also address such multi-year storage.

One highly important possibility that clearly deserves further attention in research is the potential for demand-side management (DSM) over very long timescales. Most of the current thinking around DSM relates to timescales of a few hours, but there is scope for thinking about whether some loads might possibly have the ability to be ON or OFF for periods spanning years. Examples might include refining minerals, recycling materials, mineral extraction from seawater, geo-engineering measures, drying and pelletising biomass materials, processing of other storable low-value and non-perishable commodities.

The **supply chain** in the UK, and indeed worldwide, is not prepared for the likely growth in energy storage technology and capacity. The skills base needed in the coming decade does not yet exist and, on current trends and policy, nor does it look likely. There are major open questions around how these separate but related problems can be solved.

A general remark made at the UKES2025 discussion was that more sophisticated approaches should be developed into **managing multiple stakeholders** with different emphases and perspectives. This was felt to be an issue that potentially touched most of the energy storage and energy system technologies alluded to in this report.

Another note from the UKES2025 discussion recommended that a fresh approach is taken to the assessment and presentation of **safety of different storage types**, given that all large energy stores have the potential to do great damage if the energy was released quickly.

A final note from the UKES2025 discussion was that energy storage adds very positively to **system resilience** and that some work might possibly be done to value that additional resilience. That remark was somewhat prophetic in view of the Iberian peninsula largescale blackouts that occurred only 11 days after the discussion.

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