Potential Electricity Storage Routes to 2050

Every year National Grid Electricity System Operator (ESO) produces our *Future Energy Scenarios* (FES). These scenarios explore a range of credible pathways for the development of energy supply and demand and how the UK's 2050 net zero carbon emissions target can be met. Energy storage has an important role to play in meeting this target and supporting the smart energy system of the future. Kelly Loukatou, one of the ESO's energy insight leads, considers the role energy storage plays in the current energy landscape and how this is likely to develop.

Energy systems need to continuously match supply and demand to ensure that electricity is delivered securely to UK houses and businesses. This is called energy balancing and most actions related to electricity are performed by the ESO as the electricity system operator in Great Britain, with increasing contribution from distribution operators. Very often we see deviations between supply and demand. There are various reasons for these deviations, such as generation outages, variable demand / supply patterns and forecasting errors. Energy balancing needs can also be affected by network constraints, which can prevent energy flowing from sources of supply to locations of demand. Within-day energy system flexibility is needed to address these challenges and ensure supply matches demand on a second per second basis to keep the lights on.

In general, energy system flexibility can be provided by both supply and demand. Currently, most of the flexibility requirements are covered by the supply side, i.e. thermal generation that can react quickly to system disturbances by increasing or decreasing output as required. In the upcoming years, the role of flexibility will become more vital as the share of variable renewable generation in the electricity system increases and electrification occurs in the transport and heat sectors to meet the net-zero target. Changes in consumer behaviour will also enable future higher levels of flexibility from the demand side. Types of flexibility will vary according to how much energy they can deliver, the length of time they can deliver this for and how quickly they can respond. For more details on types of energy system flexibility, please see our thought piece here.

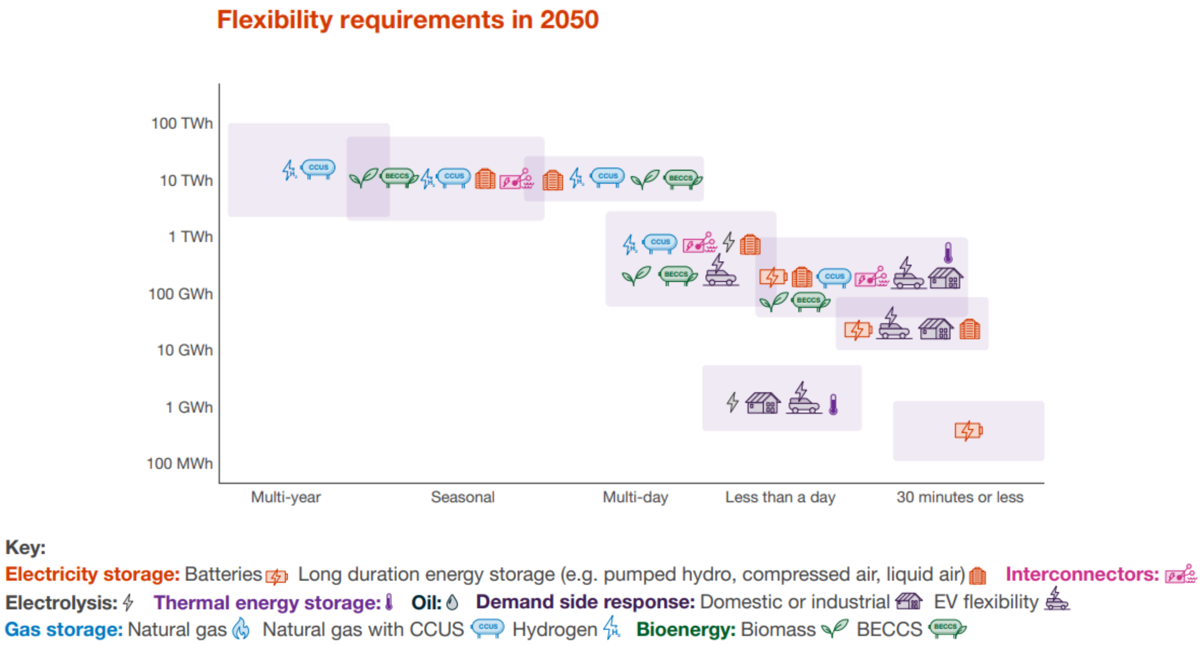

Figure 1: Different levels and types of energy system flexibility for the year of 2050[1].

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[1] Future Energy Scenarios-2022, p. 190.

Figure 1 shows the requirements of different types and levels of flexibility for the year of 2050 across gas, hydrogen, biomass, interconnectors, electricity storage, as well as demand side flexibility coming from the residential, industrial, transport sectors and thermal storage. The latter implies that demand will increasingly have to be adjusted to meet supply changes from a few seconds to seasonal timescales.

In this thought piece, the focus is on electricity storage, and specifically on the current and future landscape for its deployment. According to Figure 1, technologies that are examined here include pumped hydro storage (PHS), liquid air energy storage (LAES), compressed air energy storage (CAES) and battery storage (lithium-based and flow batteries). This is in accordance with how electricity storage is currently treated in FES to provide flexibility from the supply-side for different durations and applications. Other forms of storage that have stronger links to other non-electricity uses, including thermal and hydrogen storage, are not included here and will be further examined in future ESO articles.

Available electricity storage technologies and their characteristics

Storing electricity in another form so that it can be used during later periods, when and where it is most needed, is vital to accommodate higher renewable penetration in power systems and ensure security of supply[2]. Given optimal market signals, electricity should be stored at times of high renewable generation / low demand and delivered back when demand needs are higher and generation outputs are low. There are various electricity storage technologies which have different characteristics and play different roles in the system.

Table 1 presents a brief description of the above applications, as well as their commercial readiness. For the Technology Readiness Level (TRL) of the different phases various energy storage technologies lie in (development, research, deployment), its definition and categorisation, please see Table 53 here.

Table 1: Selected electricity storage technology characteristics and commercial readiness[3,4].

Technology	Brief description	Commercial readiness
Pumped Hydro Storage	Electricity is used to pump water from low to high reservoir and then release it back through turbines which generate electricity.	Mature technology, long history of deployment worldwide.
Lithium Batteries	Movement of lithium ions between the anode and the cathode in an electrochemical reaction results in battery charge and discharge.	Mature technology, widely deployed in the UK for short-term storage in both distributed and transmission levels.
Compressed Air Energy Storage	Electricity is used to compress air and store it in caverns or above-ground vessels. Expanding air is released through the turbines to produce electricity.	Deployed in two worldwide applications (Germany -290 MW, US – 110 MW) as diabatic CAES. Currently adiabatic technologies, which remove the need for natural gas, are under investigation.
Liquid Air Energy Storage	Excess electricity is used to compress and cool air in liquid form. Air is then evaporated and run through a turbine to produce electricity.	Advanced pre-commercial demonstrators in the UK but limited applications worldwide.
Flow Batteries	Energy storage in the electrolyte tanks is separated from power generation stacks. The	Deployed and increasingly commercialised, there is a growing

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[2] Energy storage European Commission (europa.eu)

[3] Aurora Energy Research, Long duration electricity storage in GB, 2022.

[4] Energy Storage Systems: A review, https://reader.elsevier.com/reader/sd/pii/S277268352200022X?token=860DDB1A730C9D424501DFBAE4E4F806E856B214872F3979AAEAEED88D78FFEA02C6755F5BBF3ACA1BCE2A5A77E9C68E&originRegion=eu-west-1&originCreation=20221124082413

	stacks consist of positive and negative electrode compartments divided by a separator or an ion exchange membrane through which ions pass to complete the electrochemical reactions.	number of companies worldwide offering VRFB to the market, many of which are located in Europe.
Gravitational Energy Storage	Electricity is used to raise large masses to a certain height over the charge cycle. Once raised, the masses have potential energy, which is recovered over the discharge cycle as the masses are lowered, driving electric generators.	Currently limited deployment, technology under further development.

Gravitational energy storage is an electricity storage technology that is not further examined in FES, as there is very limited information on future sites and its deployment. However, as the technology further deploys, it remains possible that it may displace some capacity and volume currently allocated to other electricity storage technologies.

Table 2 presents some of the technical characteristics of the selected electricity storage technologies for examination in FES, i.e. response time, discharge duration and their round-trip efficiencies, which helps map them onto their potential applications. For more information on additional electricity storage characteristics, please see this review of various electricity storage systems. The definition proposed by AFRY Consulting will be utilised here to define long duration energy storage. Specifically, this definition splits electricity storage into short-duration (1-4 hours) used for addressing short-duration balancing needs, medium-duration (4-12 hours) used for addressing within-day variations and long-duration (over 12 hours) storage used for multi-day and seasonal balancing needs[5].

Table 2: Technical characteristics of the selected electricity storage technologies[5,6].

Technology	Response time	Discharge duration	Round-trip efficiency
PHS	few seconds	medium, long	78-81%
Lithium Bat.	ms	short, medium up to 6-8 hours	90-95%
CAES	3-10 minutes	medium, long	42-56% (depending on if it is adiabatic or no)
LAES	~2 minutes	medium	55-65%
Flow Bat.	ms	medium	65-80%

For an electricity storage technology both the rated storage capacity (GW) and the rated volume (GWh) are important to define the storage ratio - the amount of time a technology can discharge for at full power. This, in turn, influences the application type each specific electricity storage technology can be used for. Currently, lithium-based batteries can discharge economically for 1 or 2 hours based on their market potential and revenue stacking, albeit that some have the potential to discharge for longer. Lithium-based batteries alongside PHS in the UK, help meet the intra-day variations in supply and demand, provide short-term ancillary services (frequency response and reserve) and manage the real-time operability of the network. PHS and the other electricity storage technologies examined here can also discharge for longer periods of time and help secure the system over more extended periods of high or low renewable output and/or high demand. It is worth mentioning that from these technologies, CAES and flow batteries are examined for commercialisation as part

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[5] Benefits of long-duration electricity storage (afry.com)

[6] Storage and flexibility – Net zero series, Non-battery Electrical Storage, Energy Systems Catapult, June 2020.

of the long-duration energy storage demonstration competition BEIS published in 2021[7]. In general, other use cases for electricity storage include peak demand reduction, time-shifting of energy to periods of lower demand, network reinforcement deferral at both transmission and distribution level, minimisation of imported grid energy, inter-seasonal storage (moving energy across seasons to accommodate intermittent renewable generation and seasonal demand profiles) and reduction of renewable energy curtailment[8].

Today’s GB electricity storage technology landscape

Currently in the UK, there is 1.6 GW of operational battery storage capacity mostly with 1-hour discharge duration, i.e. 1:1 ratio of energy to power, GWh to GW. The maximum installed volume of PHS is 25.8 GWh with 2.74 GW of capacity, a much higher ratio.

In recent years, there has been a surge in the pipeline of battery energy storage projects. Figure 2 shows the specific capacities under different phases of development for battery storage in the UK in 2022. The pipeline of pumped hydro storage is shown in Figure 2. Currently, there are 2.7 GW of operational PHS and the rest of the projects are under scoping (3.9 GW) or have their consents approved (Coire Glas - Stage 1, Glenmuckloch 132kV Substation), as shown below (0.8 GW).

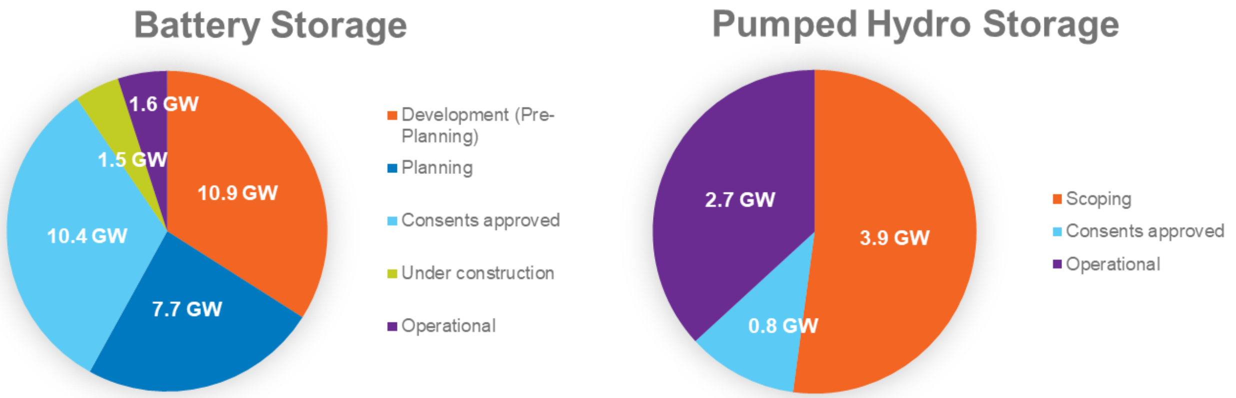

Figure 2: UK portfolio by status for battery storage (a., left) and pumped hydro storage (b., right) in 2022 (GW)[9,10].

The main drivers behind this significant battery storage pipeline growth are recent changes in legislation and reductions in costs. In December 2020, the law changed to allow local planning authorities to give consent to projects over 50MW of capacity in England and over 350MW in Wales. Previously, only central government could authorise this capacity deployment, making the process longer and more complex. Battery storage costs per kWh have fallen significantly as a result of massive electric-vehicle growth (and therefore lithium battery production) in power networks as an attempt to electrify the transport sector[9].

Not all of this pipeline will materialise as operational projects, in some areas there are challenges to secure planning permission or suitable grid connections, this is an area that the ESO is looking to address. Co-location of energy storage with renewable energy sources can play a key role in this deployment and we expect to see more projects under this category in the upcoming years. Co-locating battery storage with an existing renewable asset that has an established grid connection can save on planning restrictions and network charges. In addition, the batteries can help with potential curtailment at times when supply of electricity exceeds demand.

With respect to LAES, a few entries (of a couple of MWs) currently exist in the TEC register with consents approved or under construction. Regarding the CAES technology, no data are currently provided in the TEC register regarding their future pipeline so future projections are driven by our stakeholders and a relevant set of modelling assumptions.

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[7] https://www.gov.uk/government/publications/longer-duration-energy-storage-demonstration

[8] Energy_Storage_Use_Cases.pdf (publishing.service.gov.uk)

[9] https://www.renewableuk.com/news/601862/Pipeline-of-UK-energy-storage-projects-doubles-within-12-months.htm

[10] Transmission Entry Capacity Register (TEC): list of projects that hold contracts for TEC with the ESO, these include existing and future connection projects as well as projects that can be directly connected to National Electricity Transmission System or make use of it - https://data.nationalgrideso.com/connection-registers/transmission-entry-capacity-tec-register

The future of GB's electricity storage technology landscape

In our Future Energy Scenarios we explore a range of credible ways to decarbonise the energy system to deliver the UK's target to achieve net zero carbon emissions by 2050 and consider the potential impact of this on future energy supply and demand.

Supply and demand need to be matched on a second-by-second basis. To meet the net zero target by 2050 (and a carbon-free power system by 2035), many more renewable sources need to be connected to the future power network, which are clean and affordable. However, the nature of renewable sources is variable and weather dependent causing deviations in the supply and demand balance. Electricity storage can play a key role in balancing any potential variation.

Figure 3 shows the total electrical energy storage volume and capacity for each credible pathway out to 2050. Leading the Way (LW) has the highest installed capacity and volume across all scenarios; it is the scenario with the highest requirements for flexibility and the greatest incentives for development of new storage capacity and technologies. Consumer transformation (CT) follows afterwards with increased consumer appetite for low carbon technologies, high levels of variable clean generation and high flexibility requirements. These two scenarios see a relatively large share of storage connected to distribution networks and/or co-located with renewable generation. On the other hand, System Transformation (ST) and Falling Short (FS) see a greater share of storage deployment connected to the transmission network. In addition, the former scenario assumes presence of high volumes of hydrogen, which limit the use of short/medium/long duration electricity storage and introduces a higher requirement for hydrogen storage. Similarly, lower flexibility requirements in Falling Short means that energy storage does not come forward at volumes seen in the other three scenarios due to continued reliance on gas generation in the power sector, and so this scenario assumes mostly shorter-duration battery storage.

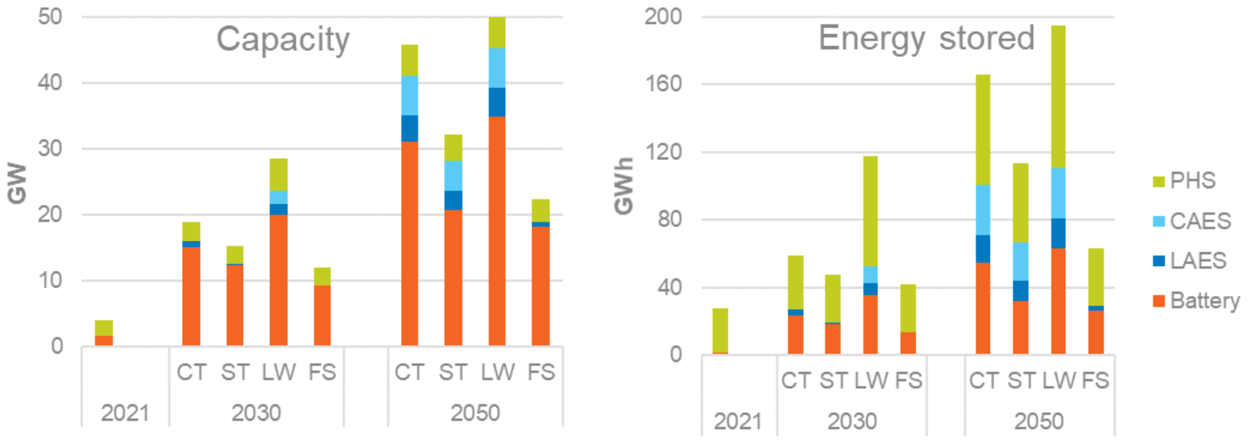

Figure 3: Total electrical energy storage volume (GWh) and capacity (GW) for all scenarios and examined technologies for the years of 2021, 2030 and 2050.

Next, each technology type is examined in detail starting with PHS and CAES in Figure 4, respectively. As can be seen, the trends across each scenario remain the same with the capacity for both technologies increasing significantly in Leading the Way, since this scenario assumes high flexibility requirements and higher levels of societal change. A significant evolution of this increase over the years, from today to 2050, is shown in the same sub-graphs for Leading the Way. The reason behind the significant PHS deployment in Leading the Way and Consumer Transformation scenarios is that we expect new plants to go live in the coming years according to the existing pipeline and the relevant longer lead times.

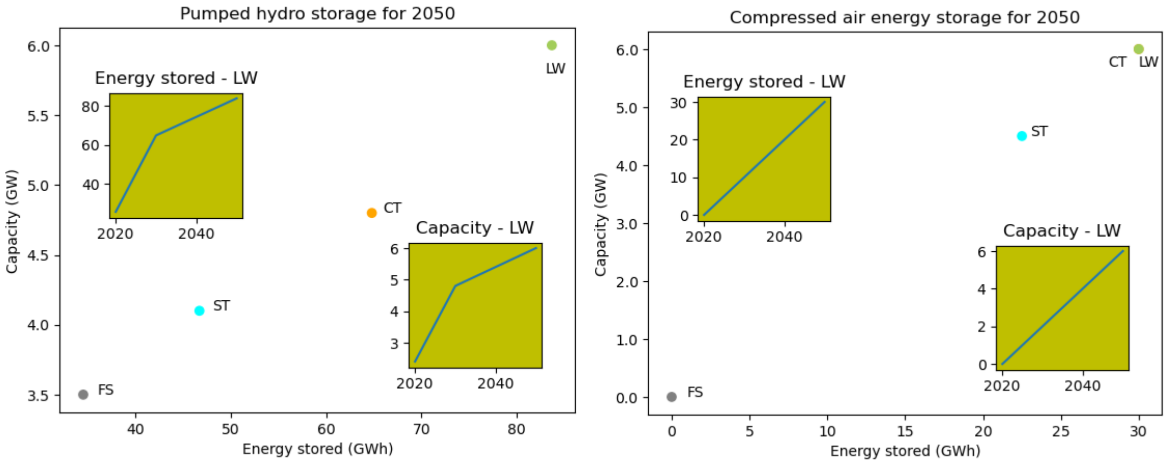

Figure 4: Volume (GWh) versus capacity (GW) for pumped hydro storage (a., left) and compressed air energy storage (b., right) for 2050. Sub-graphs show the evolution of energy stored and capacity from now till 2050 for Leading the Way.

With regards to CAES, similar reasoning exists for the pipeline according to stakeholders. Thus, another important consideration regarding the deployment of these technologies arises from stakeholder and developer engagement, which further informs our modelling assumptions. As PHS is a more mature technology, significant techno-economical improvements in energy/power capital costs and its round-trip efficiency are not expected. Analysis from Energy Systems Catapult[6] and Imperial College London[11] has indicated that the energy and power capital costs of PHS and diabatic-CAES will not decrease into the future and only adiabatic CAES presents an opportunity for a reduction in capital costs[12]. The reason behind this is that economies of scale, especially for PHS, will not be present due to geographical restrictions, whereas for adiabatic CAES, modular developments are in place for commercialisation, which will drive capital costs down. Significant improvements in round-trip efficiency of PHS are not expected because of the maturity of this technology. However, regarding CAES units, moving from a diabatic to an adiabatic technology, where heat is captured and the use of natural gas is minimised or is not needed at all, should result in higher efficiencies of 70% by 2030 and ~75% in the year of 2050[13,14].

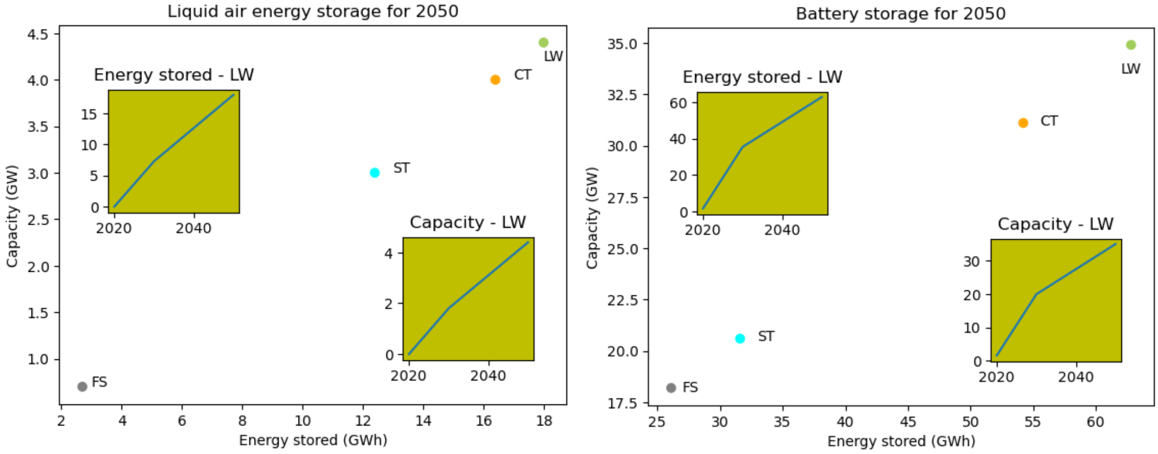

Figure 5: Volume (GWh) versus capacity (GW) for liquid air energy storage (a., left) and battery storage (b., right) for 2050. Sub-graphs show the evolution of energy stored and capacity from now till 2050 for Leading the Way.

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[11] Projecting the Future Levelized Cost of Electricity Storage Technologies - ScienceDirect
[12] www.restlessdb.co.uk
[13] Innovation readiness level Report: Energy Storage Technologies. REEEM. 2017. REEEM Project: Innovation readiness level Report, https://www.reeem.org/uploads/REEEM-D2.2a.pdf
[14] Joint EASE/EERA recommendations for a European Energy Storage Technology Development Roadmap: 2017 Update. EASE & EERA. 2017, https://ease-storage.eu/publication/ease-eera-energy-storage-technology-development-roadmap-2017/

LAES deployment is shown in Figure 5a. The deployment here is more restricted compared to PHS and CAES as there are fewer companies that can provide this technology. This is due to, as before, the lack of economies of scale which will restrict the potential for significant economic improvements[12]. However, the technology is not geographically constrained and that is a strong benefit compared to alternative energy storage options since it can be deployed widely in the UK depending on the relevant commercialisation rates. When it comes to efficiency of LAES, improvements are expected in the coming years which will enable further deployment. Efficiency is expected to increase by 2030 from the current range of ~50-55% to 60-70% for standalone systems (90%+ through harnessing of waste heat and waste cold from industrial processes). By 2050 round trip efficiency is likely to further improve to greater than 70% for standalone systems through improving the efficiency of the liquefaction process, and novel thermodynamic cycles[14].

Next, battery storage is examined in Figure 5b, which will present a significant deployment. Here, we do not differentiate between flow and lithium-based batteries since this distinction is not currently clear in the TEC and embedded registers we review when considering future deployment. However, we assume that the majority of future projects are lithium battery storage, as implied from the 1-hour or 2-hour duration batteries we currently see in the pipeline. Economies of scale will play a key role in driving the costs of lithium-based batteries down, primarily because of the continuing EV growth, which will also enable higher energy density improvements. In addition, their fast response enables revenue stacking from participation in wholesale, balancing, capacity and ancillary service markets, which will, in turn, improve the market performance of this technology. With respect to efficiency improvements, since these are already high for lithium-based batteries, no significant technical improvements are expected. However, improvements in efficiency are expected to be observed primarily for flow batteries, improving from the current range of 60-85% to 67-95% by 2030. This will be primarily because of improved electrodes, flow and membrane design[15]. Regarding the capital costs of flow batteries, again according to Energy Systems Catapult[6] and Imperial College London[11], these are expected to decline significantly over the next years, although they are still more expensive than PHS, CAES, LAES for large-scale applications due to less pronounced economies of scale. However, these technologies do not have geographical constraints and their construction time is also significantly quicker. Regarding future (possible) improvements of flow batteries, these are based around an improved understanding of flow and material behaviour, performance degradation, and the selection of corrosion-resistant materials[16].

For a more regional breakdown of electricity storage technologies across different scenarios and years per Grid Supply Point, please visit the associated FES map here.

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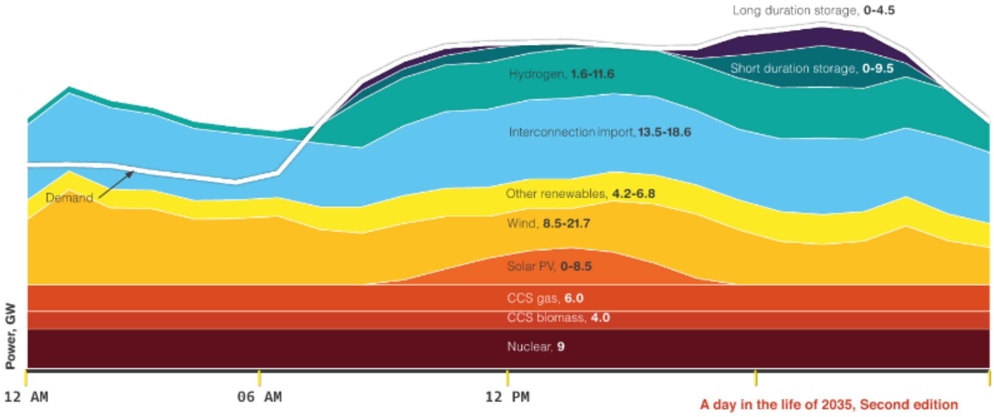
[15] Electricity storage and renewables: Costs and markets to 2030. International Renewable Energy Agency (IRENA) 2017. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017.pdf

[16] Briefing paper on electrical energy storage for mitigating climate change, S. Few et al, Grantham Institute, Imperial College London, 2016, https://www.imperial.ac.uk/grantham/publications/mitigation/electrical-energy-storage-for-mitigating-climate-change---grantham-briefing-paper-20.php

Market drivers and challenges for suggested electricity storage deployment

A recent publication by the ESO and Regen considering ‘A day in the life of 2035’ suggests deployment of both short- and long-term energy storage is needed for the summer and winter months. An example of a winter day in 2035 is given in Figure 6 below. Specifically, the study assumes 4-5 GW maximum installed capacity of pumped hydro storage as a long-term storage option and 19-21 GW maximum installed capacity of battery storage providing short-term response. Other technologies could constitute the remaining 1-2 GW of energy storage needed to balance the system. You can find more information about this study here. Over the next 10-20 years, we expect energy storage revenues to achieve an increasing share from longer duration services alongside shorter duration balancing/ancillary services, according to the relevant deployment levels. The focus next is on relevant services for energy storage via participation in ESO and non-ESO markets.



A day in the life of 2035, Second edition

Figure 6: A winter day in the life of 2035 alongside the essential dispatched capacities to cover national demand for that day. The role of short- and long-duration storage is highlighted during peak times.

The capacity market currently offers revenue streams for energy storage with 1-, 4-, or 15-year market contracts securing a significant revenue stream for new build assets. Long-duration storage assets can receive higher capacity market revenues, compared to shorter-duration storage, since they can discharge for a sufficient number of hours to support security of supply. However, project delivery is required within four years of contact award which can be challenging to meet if there are barriers to deployment, such as planning consents or network constraints. In addition to that, some new-build assets may be locked-in to lower clearing capacity market prices, which do not reflect market conditions at the time of delivery[3]. It is mentioned, though, that especially for long-duration energy storage projects that have lower utilisation rates across the year, capacity market revenues should constitute the main part of their revenue stack compared to merchant revenues which rely on higher utilisation rates and price arbitrage opportunities and are discussed below.

In addition to revenue streams from contractual agreements, such as the above, operating in both ESO and non-ESO markets offer alternative potential revenue streams for storage. The ESO procures a range of products via our suite of markets to ensure system stability, these include frequency response, reserve services and the balancing mechanism. For more information on the state of the ESO’s balancing and ancillary markets, please review the 2022 Markets Roadmap publication here.

A key consideration for storage investors is the extent to which incomes for a service can be stacked with revenues from providing other services. In some cases, storage providers have the option to stack services during the same period by providing multiple services simultaneously. In other cases, they will have to use revenue streams in different time periods to take advantage of opportunities at different times of the day. For example, Capacity Market rules allow revenue stacking for an asset without risk of penalty, but this is not the case for some of the balancing services such as Dynamic Containment (DC). Market conditions can affect how providers respond and the markets they participate in. In Autumn 2021, high prices in the wholesale market and balancing mechanism encouraged battery storage providers to switch their assets from DC to other markets. Providers also entered into monthly tenders for frequency products when they perceived a high risk of not securing sufficient agreements in day-ahead DC auctions.

Other considerations that may prevent revenue stacking include technical requirements. For example, a storage requirement for frequency response may include being at a certain state-of-charge level before providing this service and another requirement may expect storage to be full before discharging during high prices or periods of high demand. We note here that the ESO examines the revision of some of the considerations regarding stacking services, as well as regarding the co-optimisation of assets to provide multiple services, under the Enduring Auction Capability Programme. More details on the this programme will become available later in the year.

Some other wider considerations for energy storage that will need further clarifications in the future include the high upfront costs and long lead times of some energy storage technologies, the lack of existing technology track record causing additional investment challenges due to lack of economies of scale, supply chain considerations, cycling constraints with respect to warranties for battery units, provision of reactive power and short-circuit level services[3].

Looking forward, Aurora Energy Research[3] highlights that BEIS has held a number of consultations, especially related to longer duration energy storage and flexibility in the system, and policy should be on its way to further enable energy storage deployment. Specifically, direct support (in the form of subsidies) or other relevant market reform may be needed to enable further electricity storage deployment.

Conclusion

As we head towards a net zero system, electricity storage will play a vital role in helping manage supply and demand. There are various electricity storage technologies with different technical and commercial characteristics that can serve this purpose, with a wide range of outcomes for their future deployment. However, to deliver the levels of storage growth needed for net zero in 2050, barriers to electricity storage need to be overcome and appropriate market support put in place.

Current available revenue streams for electricity storage projects are insufficient to deliver the level of growth in capacity required to meet the 2050 net zero target. Different financial support mechanisms, policy interventions and direct investment will be vital to meet this target and its associated flexibility/storage requirements. The value of flexibility, and therefore of electricity storage, needs to be reflected in energy markets, such as the wholesale market with appropriate locational signals, capacity and balancing markets and most importantly, into other revenue support schemes, if we want to achieve further electricity storage deployment and be able to operate a zero-carbon electricity system.

Can we have your feedback?

We are keen to understand your thoughts on our electricity storage modelling and the assumptions discussed in this thought piece and have put together some questions below.

1. How do you currently use FES in a work or personal capacity?
2. Do you agree with the range of electricity storage technologies we assume?
3. Do you have any comments on the durations, capacities and volumes of energy storage we assume for each scenario and year in our FES 2022 projections?
4. What are your views on the future of domestic battery storage capacity?
5. What are the main barriers to electricity storage deployment today?
6. What sort of timeframes are reasonable for the deployment of long duration energy storage?
7. Which technologies would contribute mainly as part of the long-duration energy storage deployment?
8. Do you have any other comments regarding our assumptions and modelling of electricity storage?

We have created a **feedback form here** so that you can provide your feedback directly to us, otherwise please drop us an email. For more information and/or questions regarding our electricity storage modelling, please get in touch with us directly at FES@nationalgrideso.com.