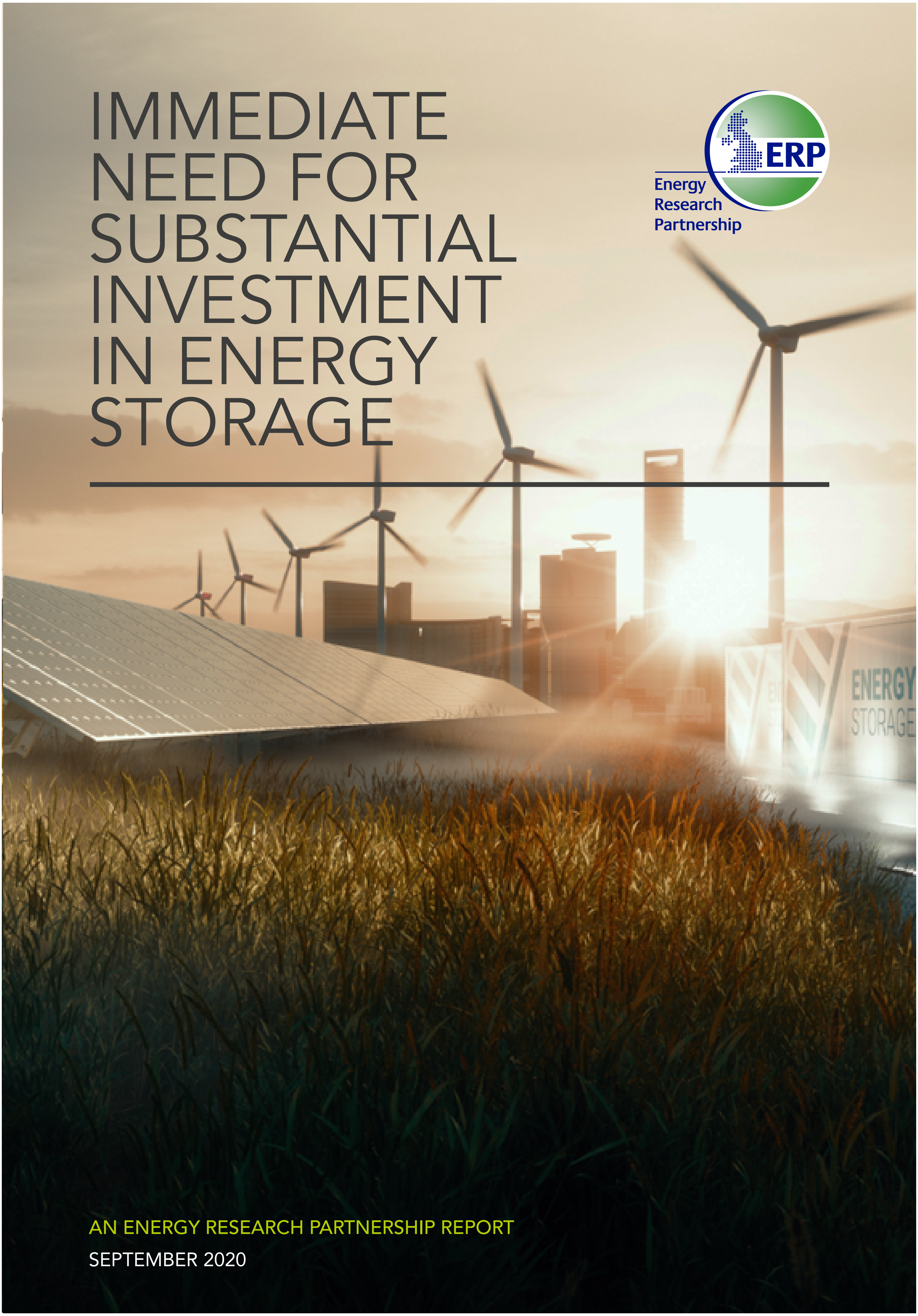
IMMEDIATE NEED FOR SUBSTANTIAL INVESTMENT IN ENERGY STORAGE

Energy Research Partnership



AN ENERGY RESEARCH PARTNERSHIP REPORT

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INTRODUCTION

With the transition towards Net-Zero, our increasing reliance on weather dependent energy generation will leave a significant gap in the UK's energy supply without continuing to use existing fossil fuel reserves.

Increasingly the UK's electricity supply is reliant upon gas and diesel reciprocating engines to plug the gap when renewable generation is limited due to weather conditions. Short-term engine operating cycles of less than ten minutes result in very **low electrical efficiencies and high levels of localised air pollution.**

Market uncertainty has slowed the roll-out of battery energy storage assets which are required to replace gas and diesel engines in Fast Response Contracts. Battery energy storage technology (Li-ion) is limited to operating periods of less than 2 hours and are generally **unable to access around 50% of the installed capacity due to technical constraints.**

Reduced renewable energy generation in excess of 2 hours is reliant on gas and diesel reciprocating engines due to CCGT and Nuclear power generation availability at short notice. **Further increases of up to 8GW in electrical demand by 2030 is expected due to the forecasted growth in electric powered vehicles.** Electrical storage using pumped hydro in the UK has lacked investment and electro-mechanical technologies are still in their infancy, **lacking industry and government focus.**

Around 80% of the UK's heat demand is currently supplied by natural gas which is unlikely to be compatible with the Government's 'Net-Zero 2050' target. The expected growth in heat pump deployment for hot water and space heating will add significant electrical demand on the system particularly during periods of low solar electrical energy availability. Although the efficiency of heat pumps is well proven, retrofitting this technology within older properties will require further investment in improving insulation and heat storage.

EXECUTIVE SUMMARY

Immediate and substantial sums of government and private investment (through research, development and guaranteed market pricing) is needed to transform the current capacity for future energy storage to one that is fit for purpose in 30 years' time. Without urgent action, the UK is on the path to missing the Net-Zero target by 2050 despite how much green energy we can generate. Current storage models alone, are not robust enough or meet the economies of scale needed for future energy demands and generation scenarios.

The outcomes of this report advise that in order to drive the investment requirements as stated to the left:

- BEIS and Energy Systems Catapult (ESC) should convene a Working Group focussed on analytical and modelling frameworks that include thermal, mobility and power services, to assess the potential contribution of energy storage and its technical characteristics.

- BEIS and Ofgem should convene Working Groups to develop strategies which will attract and secure private investment in infrastructure across the UK network.

The objectives of these working groups are to focus on the following areas of storage:

Markets	• Secure, long-term market mechanisms are required to attract private investment in expanding the existing storage capacity and attract funding to develop emerging technologies. • Government must decide on the route-to-market for low-carbon electricity incorporating not only energy storage, but also considering the contribution hydrogen will make for direct use or as a storage option.
Technology	• BEIS, UKRI and Ofgem need to coordinate innovation and R&D funding to strengthen support for medium to long duration electricity and thermal storage technologies. • Specific support is needed for research to develop, improve and validate performance using large scale pilot plants to better understand the true costs. Export opportunities will emerge for companies who develop cutting edge technologies as Global demand for low-carbon energy systems increases.
Global Supply and Demand	• Development of electricity interconnectors with Northern Europe and Scandinavia would give the UK access to low-carbon energy and pumped-hydro stores with the option to export surplus UK generation. • As demand for hydrogen is expected to increase, importation from counties where production would be more efficient from renewables (primarily solar) is a viable option.

Based on the progress of these working groups, the ERP will review the industry and industry achievements against these recommendations over the next 12 months to ensure momentum is maintained within the ERP membership to review how we as members and influencers can stimulate further investment in the energy storage space. We welcome your thoughts and input also!

1. NET-ZERO WILL CHANGE HOW AND WHERE ENERGY IS STORED

Storage plays an important role in helping balance the supply of energy across the multiple demands of the modern economy for electricity, heat and transport. Different types of storage provide a range of services, operating over a range of timescales, filling gaps and operating in timeframes that would be difficult or expensive for alternatives to fulfil. The daily evening peak in electricity demand may increase the load by about 3 GW (the output of two large gas-turbine power stations) for a few hours – about 10 GWh of energy (see page 9). Similar peaks in winter space heating can see gas demand tripling over 3 hours, a rise that can be as high as 100GW.

Heating is also strongly seasonal with about 75% consumed in winter compared to summer (about 200 TWh more), supplied mainly by imported gas.

As in other markets, being able to store the product allows the process to be managed, but also has an associated cost. With a wide range of energy supplies, vectors and uses, the characteristics of energy storage that meet the multitude of system needs are equally varied (Table 1). In the transition to net-zero, the patterns of both energy supply and demand will change radically, and so we need to rethink what role storage has here.

SERVICE NEEDS	DESCRIPTION	TYPE OF STORAGE	TIMEFRAME
GEOPOLITICAL SECURITY	Manage disruptions to imported energy.	Long	Months
ECONOMIC SECURITY	Fuel bought in advance hedges against price swings.	Medium - Long	Weeks – Months
SEASONAL HEAT DEMAND	UK Seasonal demand for heat. Reduced PV generation in winter.	Medium - Long	Weeks – Months
MEETING DAILY PEAK DEMAND	Provide energy to meet peak demand - heat or electricity	Short - medium	Minutes – Hours
SYSTEM RESILIENCE	Provide security of energy supply for unexpected loss of generation or extreme weather conditions.	Short - medium	Minutes – Hours
RENEWABLES INTEGRATION	Large-scale variability in output from wind and solar due to UK weather patterns	Medium	Hours – days – minutes
	Short, hourly variations in weather - sunlight (PV generation) and wind	Short - Medium	Minutes – hours
	Reduce curtailment of wind & solar - capture 'surplus' energy when generation is higher than demand	Short - long	Minutes – hours
SYSTEM AND SECTOR INTEGRATION	Coupling energy sectors – transfer between sectors where the time and scale of use or location may be different to point of supply e.g. heat, hot water and transport.	Short - medium	Hours – days
NETWORK UPGRADE DEFERRAL	Delay or avoid network investments by 'peak shaving' to reduce peaks in demand and extending the life of existing infrastructure configuration.	Short	Seconds to hours
ELECTRICITY SYSTEM SERVICES	Stabilise electricity networks - manage very short-term variations in supply and demand. Synthetic inertia: smooth very-short changes in supply - a service that was inherent in conventional power generation, but not in renewables.	Very-short	Milli-seconds to seconds

Table 1 Storage options to meet the needs of the system.

Currently, stored energy provides short-timescale flexibility and longer term security of supply across the energy system, mostly in the form of 'primary' fossil fuels – oil, natural gas and coal which are energy dense (hence high value) and easily stored. Energy converted into electricity has also been stored using pumped-hydro technologies to support the power system, in particular to meet daily peak loads and ensure grid stability.

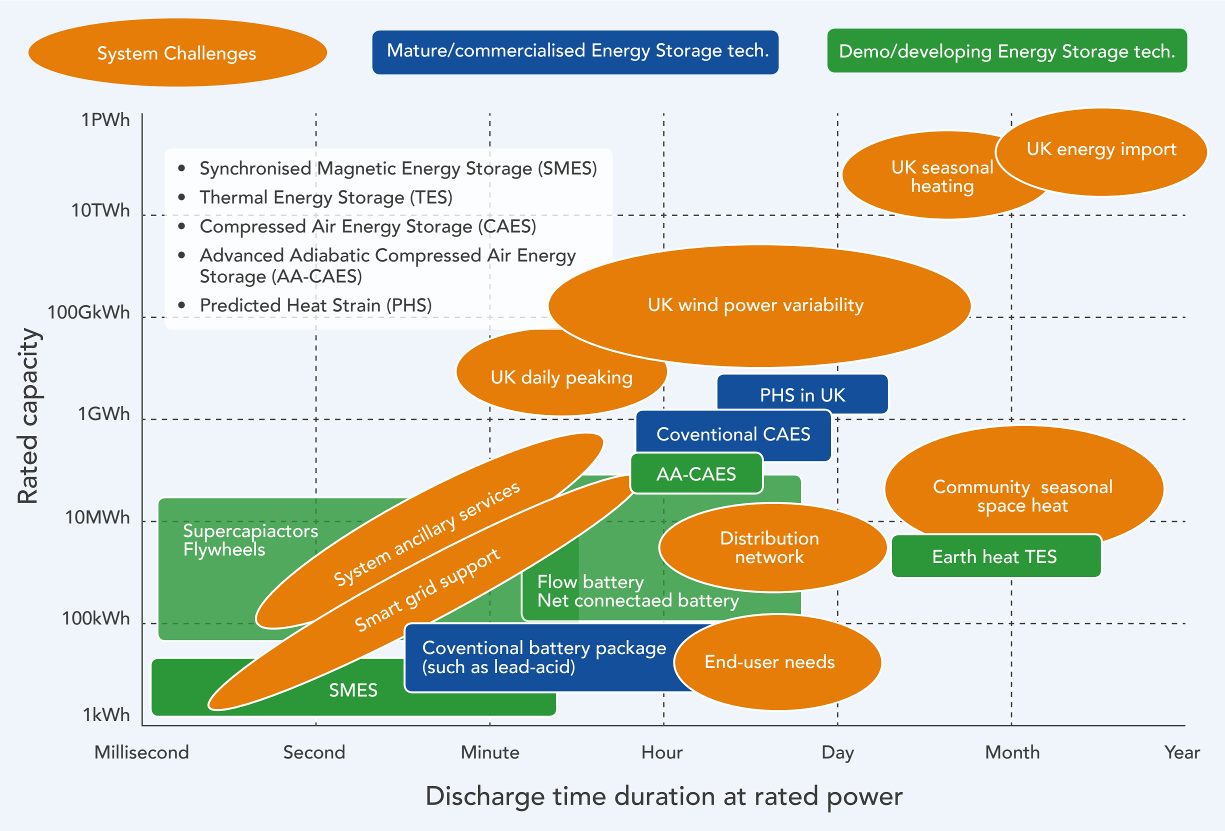


Figure 1: Electrical energy storage technologies with challenges to the UK energy systems[1].
Note: the axis are not linear, so the amount of energy represented by the bubbles in the top right is enormous.

The system is already changing driven by concerns about emissions and changes in the market for fossil fuels. Net zero will drive some of these changes faster. Over the last 15 years, the UK's central stocks of stored energy have reduced by 35%. Declining demand for coal for electricity generation has led to a 68% drop in stocks, while changes in the supply of natural gas has seen a 43% drop in storage: declining domestic reserves have led to increases in imports of LNG and additional pipelines between the UK and mainland Europe. The main role of large stores is geopolitical energy security. Large stores allow the UK to maintain energy supply for months (Figure 2). How long is determined politically.

Storage of heat at a household level has been common in the UK, but is also reducing. Many British homes have traditionally had hot water tanks, and a significant proportion have used electrical storage heaters for space heating. However, the rise of combination boilers to provide instantaneous hot water has reduced the embedded thermal storage, with 40% of (English) households having a hot water tank in 2017[2], down from 62% in 2007.

Storage has a cost: there are inefficiencies when converting between forms of energy, or in the processes associated with storage. The capital costs can also be significant, such as constructing

[1] Xing Luo et al 2015, Overview of current development in electrical energy storage technologies and the application potential in power system operation
[2] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/817757/EHS_2017-18_Energy_Report.pdf

reservoirs or underground caverns. A more efficient system may therefore seek to reduce storage in the short run. However, there may be longer term consequences to giving up one of the tools of providing reliability and security in a period of system transition.

In the future, with energy supplied predominantly from renewable sources, storage to provide long-term security (against import disruption and fuel price changes) will become less necessary. However, the other purposes for storage at shorter timescale will remain and are likely to increase, but will have to be provided by non-fossil fuels.

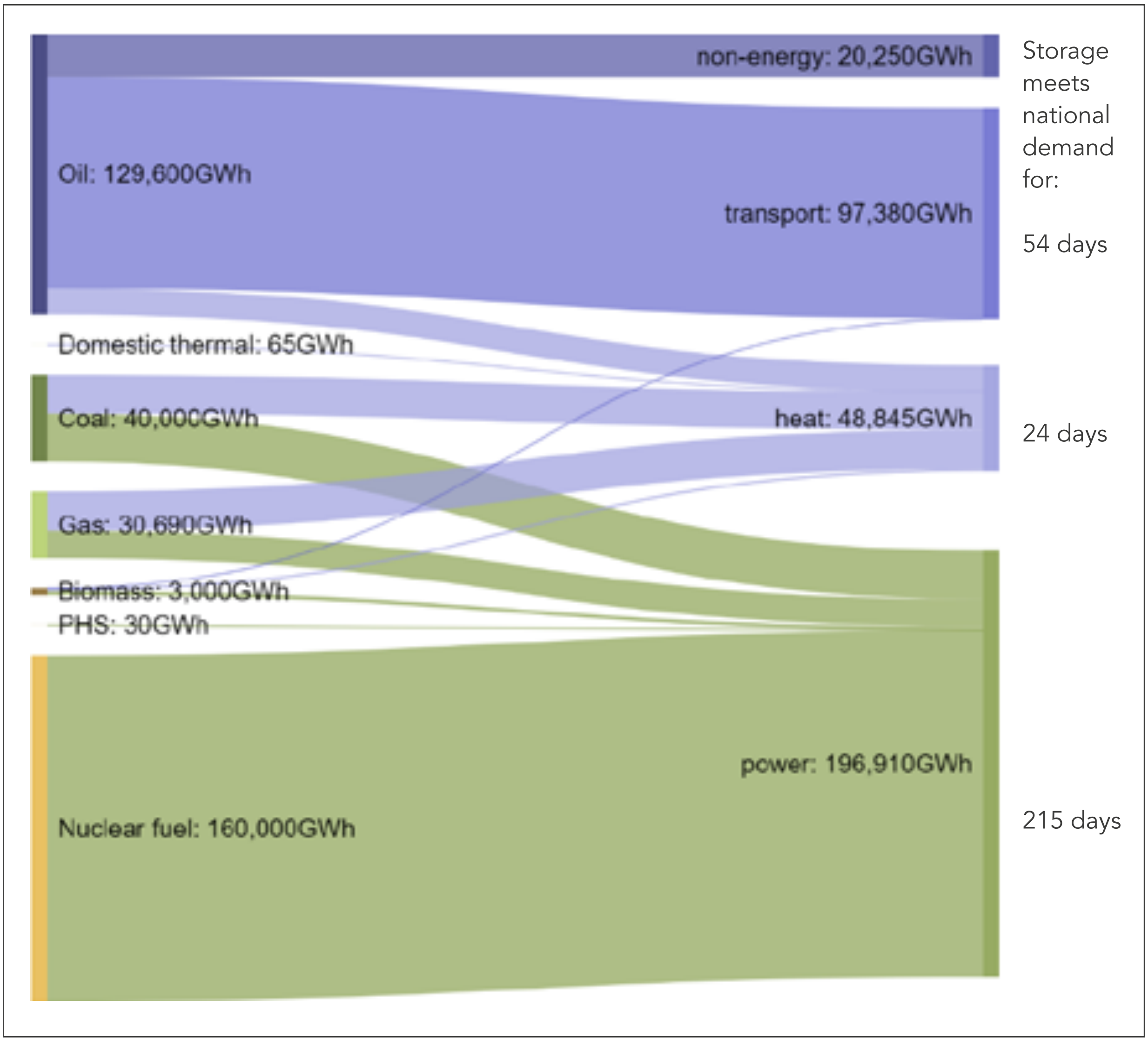


Figure 2: Energy stored and its end-use (2019 data from Wilson et al, 2020)

ENERGY STORAGE

There are two key factors that characterise energy storage:

- Capacity - the rate at which energy can be delivered from storage
- Duration - the length of time it can sustain that rate of output, which is determined by the amount of energy stored.

An analogy is water held in a reservoir – the diameter of the pipe determines the rate the water comes out (capacity using units of GW, MW), while the amount of water held in the reservoir determines the length of time the water will flow (duration, minutes, hours, days etc). The total amount of energy held in the store has units TW-hours, GWh.

Another key factor that distinguishes each type of storage option is:

- Response time – how quickly the storage unit can reach its full output capacity. Ranging from milliseconds to minutes.
- Recharge period – the ability for the storage medium to be fully discharged and recharged in the shortest cycle time (including cooling and stabilisation period)

Very rapid response is required for the constant management of the electricity system, which is highly sensitive to small changes in supply and demand. Batteries are primarily used for controlling frequency at 50Hz using the Fast Frequency Response (FFR) and Enhanced Frequency Response (EFR) grid mechanisms.

Energy storage has to be replenished, which requires energy to be available that can be stored. It also needs enough equipment to be available to capture it at the rate it is being produced. Every year there are a few very windy days, which, for a few hours, could produce peaks of electricity way above average supply. But is it economic to build the storage capacity just to capture these few hours of excess? Given the electricity is free, it will mean the resale price of the energy will have to be high enough to cover the additional cost of the extra capacity that was built to capture all the excess.

- Efficiency, how much energy is lost during conversion,
- Retention – how long the energy can be stored for before it degrades e.g. rate of leakage or evaporation of water from the reservoir.

And of course the costs. While costs may be high

- Utilisation – how often will it be accessed, and what is the value of the payment for the energy delivered. E.g. how often will the reservoir be emptied, either partly or completely: every day or only twice a year - but the payment is high enough to outweigh the cost.
- Cost of construction – construction and material costs e.g. how much it costs to build the reservoir and pipe system.
- Cost of operation – maintenance, longevity and operational costs e.g. cost of turning the water flow on and off, maintaining the reservoir, refilling it and lifetime of components.

It may be that these requirements can be met by other options, such as reducing energy demand when there is a shortfall in supply, increasing energy efficiency to lessen the impacts of variations, buying energy from somewhere else (imports), but this assumes the energy will be available and secured.

2. DECARBONISATION OF SUPPLY WILL DRIVE NEED FOR STORAGE

Decarbonisation of the energy system towards net-zero, and beyond, will lead to substantial changes in where energy comes from, how it is supplied and the technologies that use it. Current efforts indicate that the UK electricity system could become almost fully decarbonised by 2030, with fossil fuels displaced by increases in renewables (wind and PV) and some other low-carbon generation. This will lead to much greater variability in supply, over periods of minutes through to several days, possibly weeks. The reduction in the use and availability of flexible generation, such as gas generation will require new interventions to help manage the electricity grid. Maintaining the reliability and resilience of the electricity system should be a priority for the 2020s.

Decarbonisation of transport and space heating is expected to impact on the energy system beyond 2030, as the replacement of fossil fuels options with low-carbon technologies accelerates. Decarbonising heat could bring the biggest challenges, given the scale and variability of thermal demand. Improving energy efficiency, particularly of domestic buildings, should be at the heart of any energy strategy.

Decarbonisation of demand could lead to closer integration of the electricity, heat and transport sectors, which with fossil fuels have traditionally been segregated. This could open up new opportunities for managing the system and for storage. The technologies used will be a strong determinant of the services needed on the energy system and how it is managed. However, there is a myriad of ways of connecting them together and delivering these different services, creating huge uncertainty about what the future system will look like, and where the energy will be stored.

Electrification of heat and transport would put additional pressure on managing the electricity system and balancing the variable supply from renewables with increasing demand. Alternatively, other energy vectors could be used, such as hydrogen or biomethane, which could alter the demands on the electricity system, and possibly interact with it to help manage the grid and networks.

The net-zero energy system will need to meet some of the same demands as the current fossil fuelled system, but it will also create new challenges which as yet are not clearly defined or understood. New forms of large-scale energy storage will be vital to enable the different technology options to develop.

2.1. SUPPLY

During the 2020s as the planned wind and solar generation come online, and fossil fuels will be phased out, the proportion of electricity generated from zero-carbon sources (including gas with CCS) doubles or more – the first gas-free hour is expected by 2025[3] (Figure 3). Supply will therefore be less flexible, dominated by a combination of inflexible baseload (nuclear) and weather-dependent renewables.

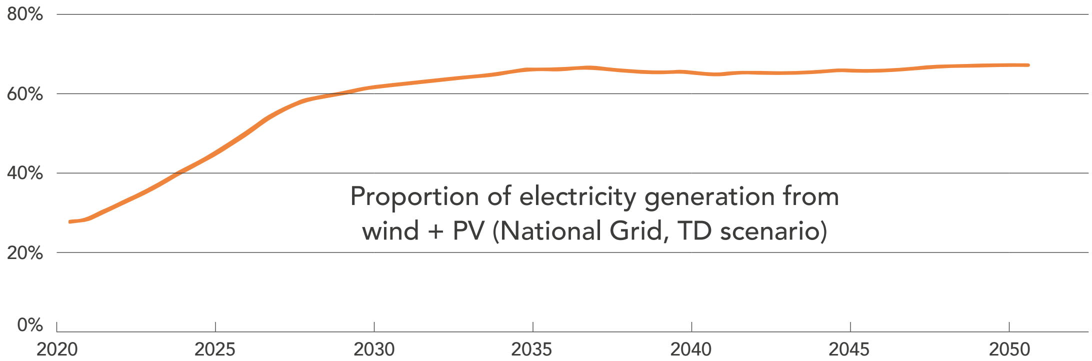


Figure 3: National Grid Two-Degrees scenario indicating possible proportion of electricity generated from variable renewables (wind+solar PV)[4].

Need for short-term storage to manage variability on grid and networks

Batteries are increasingly being used to provide short-term flexibility, up to a few tens of minutes, with the longer variations in renewables output filled in with gas-powered generation. National Grid ESO is developing new markets to support the operability of the high-voltage electricity transmission network, taking advantage of the exceptionally fast capabilities of Li-ion batteries and this progress should be prioritised.

Medium-term variability

By 2030 the current plans and proposals suggest that onshore and offshore wind capacity will increase to over 50GW, with further growth in solar PV. Using the weather conditions for 12 days in January 2020, Figure 4 illustrates how a four-day lull in wind output can create a substantial gap in energy generation. It illustrates how wind output from the expanded generation capacity can drop to as low as 5% of its maximum capacity – more than 30 percentage points (about 17GW) below its average output. Being winter the solar output is insufficient to compensate for this drop in output. It assumes that all of the interconnectors will have access to reliable electricity supply and deliver at full capacity in time of need. The brown line shows how a surplus of electricity generation turns negative for five days. The black line illustrates how 735 GWh of "surplus" electricity is accumulated over the first five days, but is rapidly used up as the wind output drops, to become a deficit of over 2.0 TWh in 6 days.

In the current fossil fuel system this gap is managed by gas generation, but by 2030 if the intention is to reduce carbon emissions as low as possible then the number of hours a gas power station could operate will be very limited, so other options will need to be available.

Dedicated electricity storage could be used. Compared to current levels of storage, this represents a 5-8 times increase in capacity (GW) and over 200-times increase in volume of energy stored (GWh). This would be equivalent to each home in the UK having 7 Tesla Powerwalls, or more than 2 Nissan Leaf electric vehicles, to maintain the supply.

[3] https://www.nationalgrid.com/document/126541/download, https://www.telegraph.co.uk/business/2020/06/13/britains-electricity-have-first-gas-free-hours-2025/

[4] National Grid ESO: Future Energy Scenarios http://fes.nationalgrid.com/fes-document/

[5] https://www.iea.org/commentaries/battery-storage-is-almost-ready-to-play-the-flexibility-game

Medium-term energy storage technologies would be required, which could be built to deliver sufficient capacity (GW) and could store enough energy (GWh) for several days. Batteries would be an expensive option for balancing supply and demand at this scale – at $200/kWh[5], 200 GWh of storage would cost $40bn. The world's largest battery energy storage facility will be that built by Tesla in South Australia, at almost 200 MWh.

Alternatively, thermal power station using gas with CCS or hydrogen, known as "peaking plant", could be used, although it is not clear if either will be available at the scale require by 2030. In the longer term, both these options could be useful in a zero-carbon energy system, possibly displacing medium-term energy storage, although the cost and efficiency may be prohibitive.

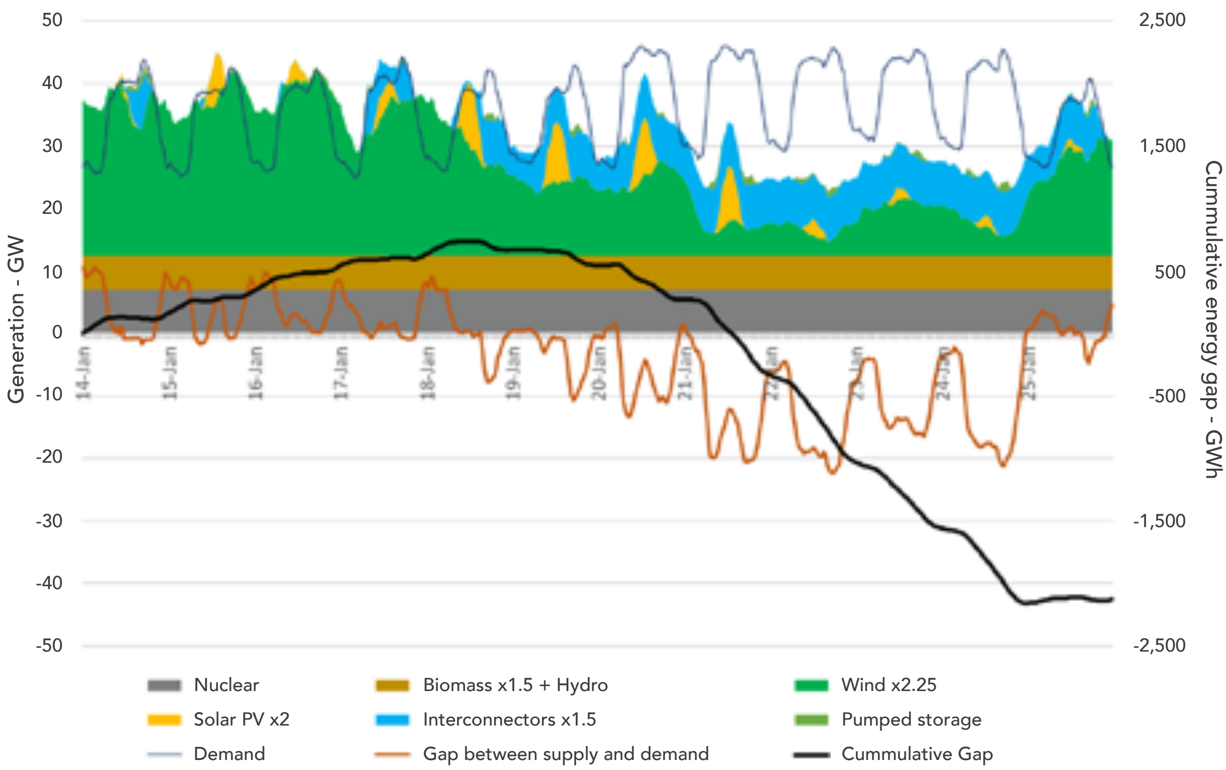


Figure 4: Illustration of low-carbon generation expanded to 2030 capacity. Assumes demand unchanged from January 2020. Interconnectors are used to respond to short-fall in zero-carbon generation.

Reaching net-zero, across the whole energy system, is likely to require even larger volumes of generation from wind and solar, which will make the lulls ever more material. Furthermore, it is possible that the future climate may make these wind lulls more frequent or longer.

With increasing amounts of variable and non-dispatchable generation through the 2020s, and rising demand for electrified heat and transport, the energy system will need to be flexible to cope with the potential imbalances across different timescales and geographies. Generally speaking, energy demand has a daily, weekly, and seasonal profile. The generation from renewable energy (e.g. wind and PV) is variable but has a pattern and can be forecast to an extent.
Although wind generation has slight positive correlation to heat demand on a seasonal timescale, there will be significant imbalances on an hourly to weekly timescale. Daily wind generation in winter can vary over 8-fold in a week and the daily heat demand can be tripled in 3 hours in the cold winter morning[6].

[6] Challenges for the decarbonisation of heat https://ukerc.ac.uk/publications/local-gas-demand-vs-electricity-supply/

3. DECARBONISATION OF DEMAND ACCELERATES BEYOND 2030

In general, most scenarios show overall demand for electricity remaining stable to 2030, based on the assumption that it will take time for the deployment of electric vehicles and heat pumps to become established. If electrification dominates the decarbonisation of demand, then the overall amount of electricity generated could more than double (Figure 5).

For the UK, it is the scale and variability of demand for heat that poses the critical challenge – more than three times the energy supplied by electricity in the winter, with a daily swing that can reach 25% of demand, and winter demand double that of the summer.

Whilst demand is currently met by natural gas, an energy dense and storable fuel, scenarios show decarbonised heat provided by a mix of heat pumps and hydrogen, alongside a more efficient building stock. The timing and scale of deployment is uncertain, but scenarios from National Grid and Energy Systems Catapult (ESC) shows this occurring at scale from 2030, using decarbonised electricity. ESC scenarios include over 200 TWh heat produced from heat pumps and electric heaters annually by 2050. Electric vehicles also demand more electricity in winter as up to 40% of the battery's energy is used for heating in cold weather[7].

Meeting this growth in demand will require an increase in generating capacity. Expanding the amount of renewables will mean that the lulls in output will require larger amounts of energy to fill the gaps.

However, it is not just a matter of an equal increase in generating capacity, as the nature of demand will also change, presenting new service needs to the energy system.

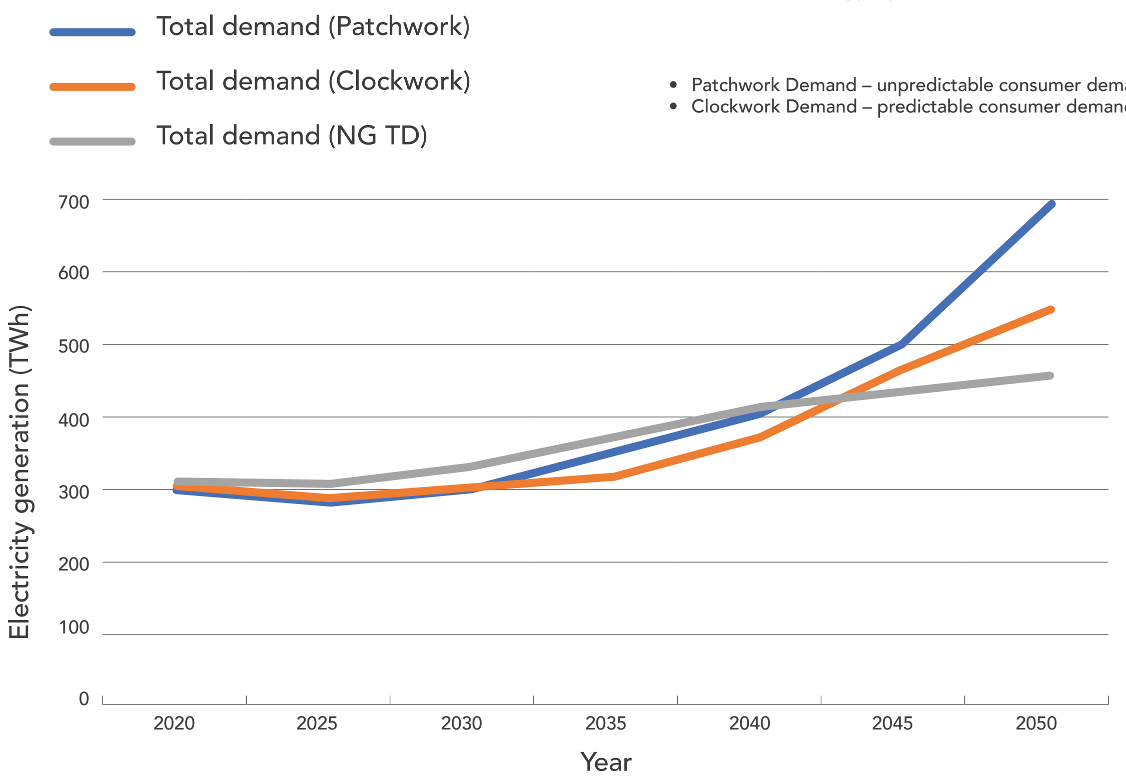


Figure 5: Electricity demand increases beyond 2030

[7] Research report: EV Range Testing https://www.scribd.com/document/399096994/

3.1 DECARBONISING HEAT WILL PRESENT CRITICAL NEW DEMANDS ON THE ENERGY SYSTEM

One of the biggest challenges to decarbonisation, for the UK, is replacing natural gas in the provision of space heating and hot water. The scale and variability of demand for heat during the day and between seasons pose the critical challenges.

Natural gas provides heating for 85% of households, accounting for 37% of the UK's carbon emissions - 17% of emissions come from space heating alone.

Daily variability

On a cold winter morning, gas demand for space heating can increase over 100 GW (125%) within 3 hours, met by increasing the pressure in the gas pipelines beforehand, known as 'line-pack' (Wilson et al, 2018, see Figure 6). The national transmission system and local gas networks can provide within-day flexibility of up to 690 GWh, although over 4,800 GWh of gas can be stored in the pipes (enough to meet over 3 days of average UK consumption), except the need to retain pressure prevents it all being utilised.

In a net-zero energy system a range of options could be used to deliver decarbonised heat, including heat pumps, biomethane, district heating and hydrogen, alongside a more efficient building stock.

Heat pumps are energy efficient but could increase morning peak demand significantly if heat demand is transferred directly to electricity. The peak could be reduced by integrating the heat pump with heat storage (e.g. hot water tanks), which would charge for a few hours before the peak. However, this comes with economic and technical challenges, and not all homes may have the space. Heat pumps generally produce low temperature heat (e.g. <40°C), which requires a large tank to store the necessary heat. Electric storage heaters retain heat at a much higher

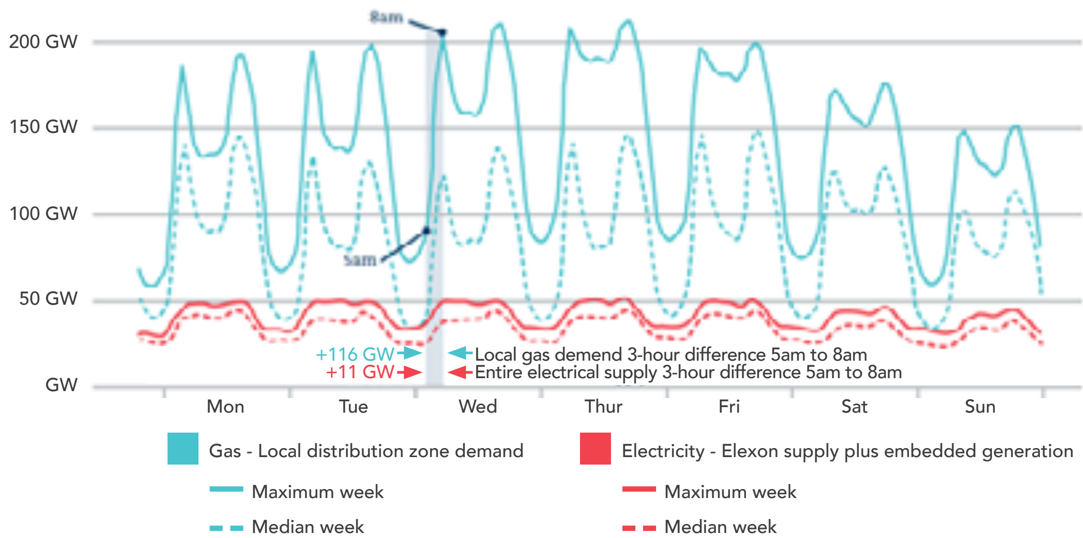


Figure 6: Britain's local gas demand and electrical system supply in 2017-2018 heating season[8].

[8] https://ukerc.ac.uk/publications/local-gas-demand-vs-electricity-supply/

temperature (e.g. >600°C) and require much less space for storage, but the heat production is less efficient than heat pumps.

Innovation is reducing the system cost and device size, which would help increase the deployment of thermal storage. Phase-Change Materials are being developed that can deliver high density heat storage to replace water tanks. The units are not yet commercial.

Alternatively, some homes could be well-insulated to reduce heat loss, allowing the heat pump to run continuously at a low level. This could even be turned off for short periods in response to peak demands on the electricity system. Insulation would also reduce the overall demand for energy for heating.

On very cold days the efficiency of the heat pump is greatly reduced, which would raise overall demand. One solution could be a hybrid heating system that uses a heat pump for most of the heat, but for peak demand includes a boiler that runs on either biomethane or hydrogen. Although the low-carbon gases would have to be stored for long periods until they are needed. This could be an expensive option for consumers, who would need to buy and maintain two units, although the cost could be subsidised by the savings to the energy system which the service provides.

District heat network that use low-carbon heat sources (e.g. renewable energy, wasted heat from power stations) can be another option for decarbonising heating sector. Integrating thermal energy storage into a district heat network can improve efficiency and flexibility of the system. Large-scale heat storage can be more economically feasible than small scale, but it still requires high investment cost and space for the device[9].

Seasonal Heat Challenge

Analysis suggests that switching to primarily heat pumps would mean that energy supplied by electricity would increase more than three times, with a daily swing in demand that can be as high as 25%, with winter demand double that of the summer. Meeting this demand could mean installing large amounts of generation capacity that operate primarily in winter to respond to seasonal and weather swings. Storage could be effective for balancing on both the supply and demand side.

Whilst technologies exist for storing heat for a few hours and between days near the end user, they are not a solution to addressing the challenge of seasonal variability in heat, because of their low energy density, and the sheer quantity of heat that needs to be stored. Innovation is developing low cost and high energy density seasonal heat storage (e.g. thermochemical heat storage) to decouple heat demand from electricity system.

Using hydrogen to provide heat could avoid the additional stress on the electricity system, as it could provide similar flexibility as the current gas networks. However, it cannot be stored in the pipe networks to the same extent as natural gas (line-pack), so hydrogen storage facilities would have to be built to meet the daily and seasonal variability in demand. The potential of hydrogen is considered in the next section, alongside other options for storing energy.

[9] Potential of Thermal Energy Storage for a District Heating System Utilizing Industrial Waste Heat (https://www.mdpi.com/1996-1073/13/15/3923)

4. ENERGY STORAGE TECHNOLOGIES ARE EMERGING AS A WAY OF PROVIDING FLEXIBILITY AND RESILIENCE

Managing the evolving supply and demand patterns in the energy system can be achieved by several means, including demand side response/ management, interconnection with other markets, more flexible generation, and energy storage. Each option will have a role to play in the future. Post-conversion energy storage has a number of features that makes it attractive in principle, though as we explore in this report, there are challenges to its large-scale deployment.

The defining characteristic of such 'secondary' energy storage is the ability to capture energy when it is supplied from primary (zero-carbon) sources to meet demand at a later time, thus decoupling supply and demand. A number of technologies allow this to occur across different timescales, from milliseconds, to year-to-year variation providing flexibility and resilience [ref ERP resilience report][10].

[10] https://erpuk.org/project/future-resilience-of-the-uk-electricity-system/

4.1. ENERGY STORAGE TECHNOLOGIES

Energy can be stored in different forms, such as mechanical (e.g. pumped hydro, flywheels), thermo-mechanical (e.g. liquid air and compressed air energy storage), electrical (e.g. capacitor), electrochemical (e.g. lithium-ion battery), thermal energy storage (e.g. hot water tanks, underground thermal stores), and chemical (e.g. fossil fuels, hydrogen). Each energy storage technology has different characteristics with no single solution to cover all the applications (see Table 2).

Apart from fossil fuels, water is the most common medium for storing energy, as pumped hydro storage and thermal storage in water tanks or reservoirs. However, its relatively low energy density, mean those technologies require large amounts of space, which limits its deployment and application. Batteries have higher energy density and are used commercially in mobile devices/vehicles and stationary electricity storage at domestic/grid scale where the value of storage is greater.

Medium-term storage

Some new longer duration energy storage technologies are being commercially deployed, or are at the early stage of commercialisation, such as liquid air energy storage (LAES)[11] and large-scale 'sensible' heat storage (e.g. tank/ underground thermal energy storage).[12] Although their technical feasibility has been demonstrated, the current energy market and business case limits their deployment beyond niches. Several technologies and concepts have been studied or demonstrated for their capability for medium/ long duration storage (see Annex 2), each has its advantages and limitations.

Long-term seasonal storage

For long-term seasonal storage the technologies are mainly in the early stage of research, but are showing potential, such as the chemical, ammonia-based, energy storage and thermochemical storage[13]. These need more research to drive the development to the next level, and then to demonstrate at scale.

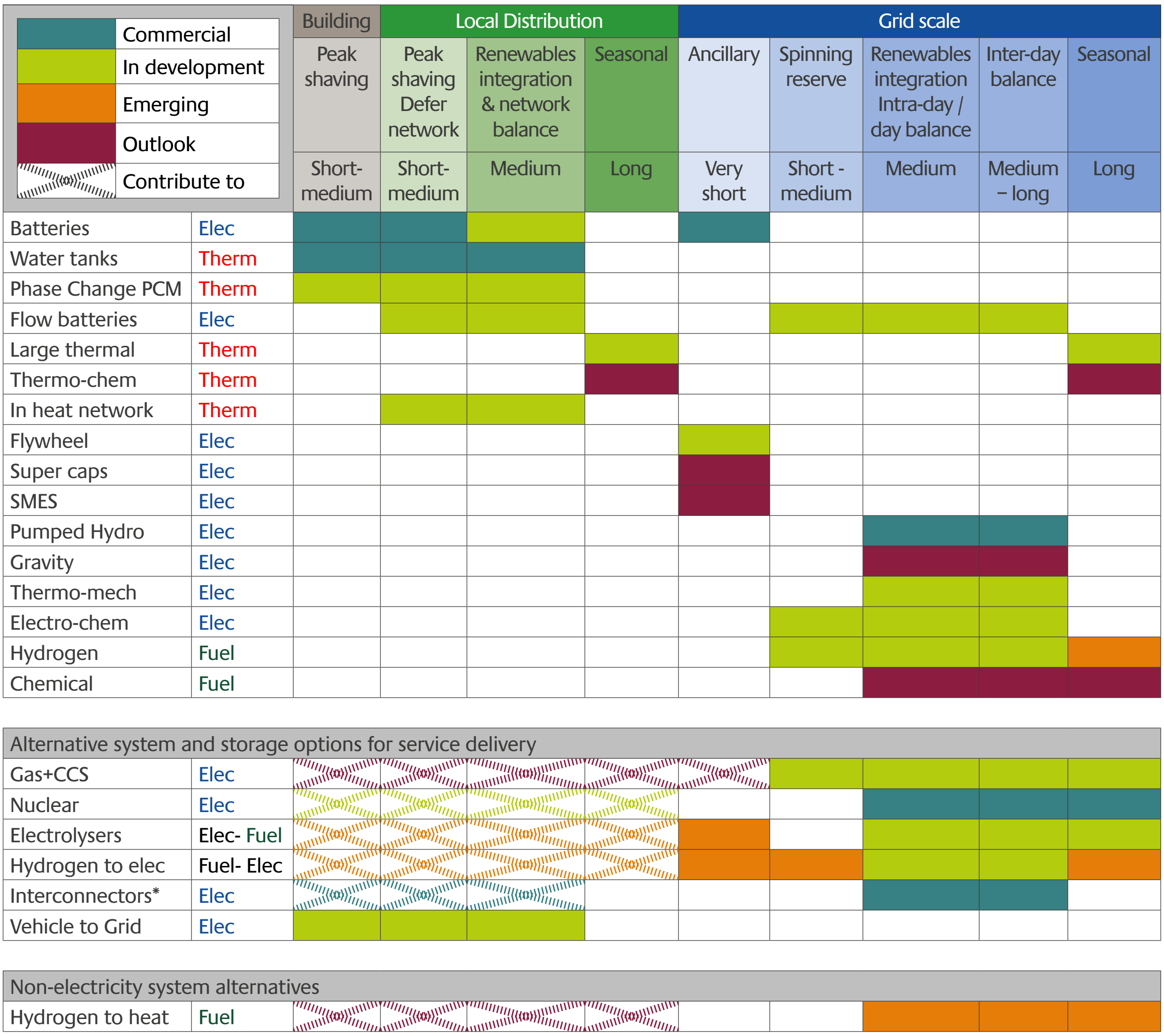


Table 2 Energy Storage application, scale, technology & state of maturity. (colours indicate maturity of technology) *Interconnectors should not be treated as a firm source of electricity, but can provide services to the electricity grid.

[11] https://highviewpower.com/news_announcement/highview-power-awarded-10-million-grant-from-uk-government-for-first-commercial-cryobattery-facility/

[12] Medium duration energy storage – kingpin of net zero energy, April 2020; University of Nottingham https://www.nottingham.ac.uk/research/research-areas/energy-technologies/news-and-events/news/medium-duration-energy-storage.aspx

[13] Medium duration energy storage – kingpin of net zero energy, April 2020; University of Nottingham https://www.nottingham.ac.uk/research/research-areas/energy-technologies/news-and-events/news/medium-duration-energy-storage.aspx

4.2 ROLE OF HYDROGEN IN MANAGING THE ENERGY SYSTEM

Hydrogen is being considered for power generation, heating, and transport, and is suitable for long-term storage at very large scale (e.g. GWhs in salt caverns). Hydrogen produced by electrolysis can be used to absorb surplus electricity from the grid, reducing the need to curtail generation from renewables. This hydrogen could either be converted back to electricity or used for heat, industry or transport. But the amount of surplus electricity is unclear as it would be competing with other storage options and demand side users that could benefit from zero or negatively priced electricity. National Grid's analysis of their scenarios suggested 6% of electricity (20-25TWh) in their Community Renewables scenario could be lost. Not all of it may be capturable as it may come in large, short gluts, which would require large banks of electrolysers that are used very infrequently.

The Energy System Catapult's analysis of the energy system deploys a significant amount of energy storage, e.g. 4-8 GW and 29-35 GWh electricity storage, over 200 GW and 600 GWh of heat storage, but also uses hydrogen storage with over 150 GW and 660 GWh[14]. Hydrogen is used alongside electricity storage to help meet the highest peaks in demand alongside natural gas with CCS. These are used very infrequently, operating for about 1% of the year, but can provide up to 50GW of electricity. The electricity generated would be very expensive, but this is affordable given the critical importance maintaining a reliable supply of electricity. To reduce the peak in heat demand the scenario also suggests that about 10-15% of heat demand is met by hydrogen (about 25TWh) using hybrid domestic boilers, which can switch to hydrogen to reduce electricity peaks and when the efficiency

[14] Innovating to Net Zero https://es.catapult.org.uk/reports/innovating-to-net-zero/

of the heat pump drops too low when the outdoor temperature falls to low.

Using hydrogen to meet demand in other sectors could also reduce the pressures on the electricity system. A recent study analysed the impacts of converting half of domestic heat demand to hydrogen boilers by 2050, along with parts of industry and transport. It suggested that hydrogen demand could be up to 500 TWh in a year (Figure 12). However, in order to meet the peak demand in winter these scenarios may require up to 19 TWh of hydrogen storage[15], requiring a substantial increase in salt cavern development[16].

However, it is unclear how quickly, and therefore how much, of the gas network could be converted by 2050. Furthermore, it is not clear where the energy to produce the hydrogen at this scale would come from. Producing it from natural gas with CCS will not be zero-carbon[17], and using renewable energy would require a major increase in wind capacity. One option that is being proposed is to import the majority of the hydrogen, in the same way that LNG is delivered. Production could be more efficient from renewables (primarily solar) in Southern Europe or North Africa it could be shipped via marine vessels or delivered by pipeline into Europe and the UK.

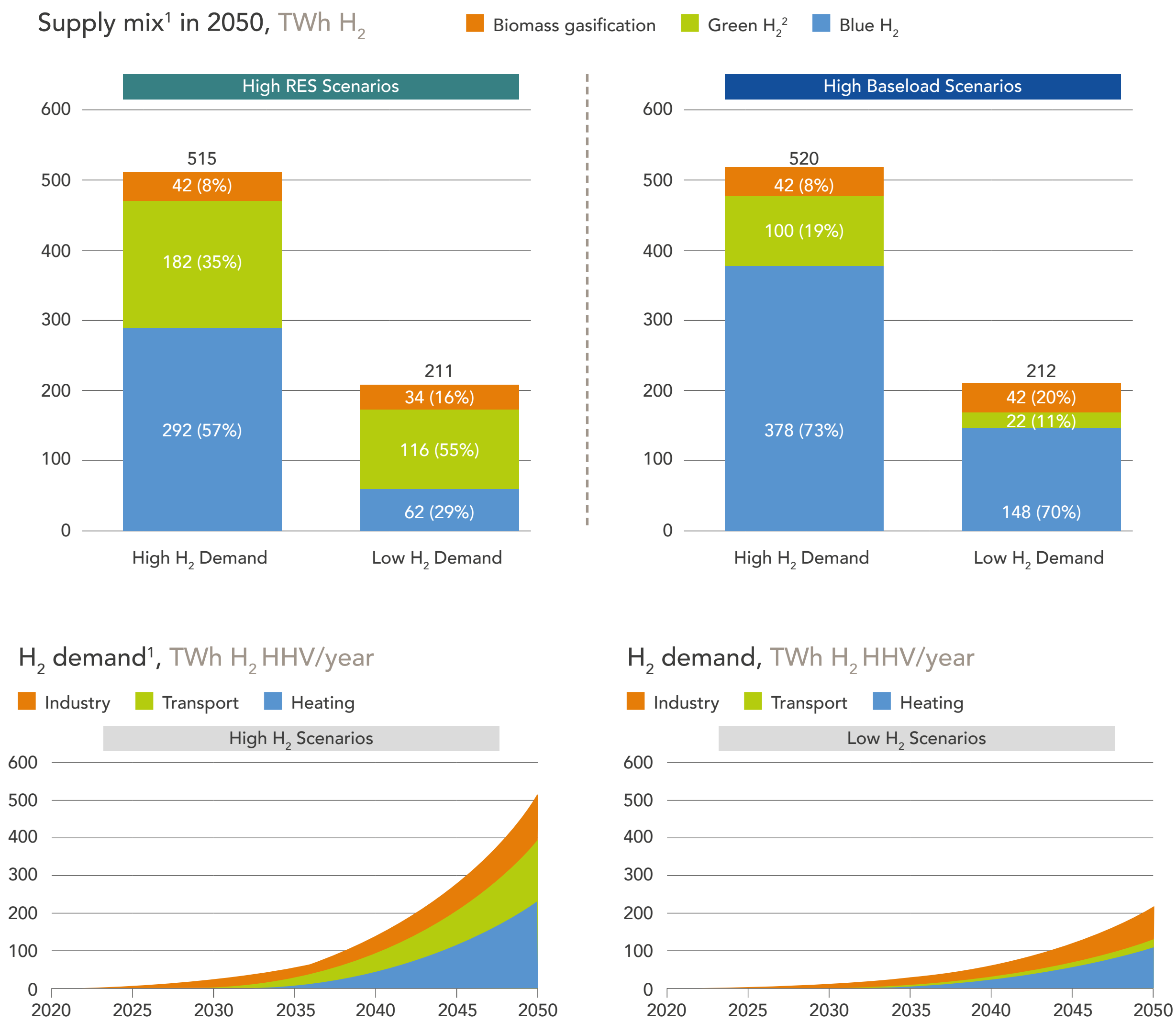


Figure 7: Hydrogen generation for decarbonising industry, transport, and heating[18].

[15] Hydrogen for a Net Zero GB https://www.auroraer.com/insight/hydrogen-for-a-net-zero-gb/

[16] ERP 2016, Potential Role of Hydrogen in the UK Energy System https://erpuk.org/project/hydrogen/

[17] ERP 2016, Role of Hydrogen in the UK energy system

[18] Hydrogen for a Net Zero GB https://www.auroraer.com/insight/hydrogen-for-a-net-zero-gb/

5. RISKS AND UNCERTAINTIES AFFECTING INVESTMENT IN ENERGY STORAGE

The precise role and scale of energy storage, and the various energy storage technologies, is uncertain in the transition to net zero, partly because the value is correlated to the shifts in generation (e.g. capacity change in wind, solar, and nuclear) and demand (e.g. electrification of transportation and heating sectors; behaviour changes). Intrinsic technical developments will affect cost and performance compared to alternative source of flexibility or resilience – there will inevitably be trade-offs in decision-making to take into account the costs of providing storage against the emissions reductions that it allows.

The development of different energy storage technologies will also have an impact on which 'succeed' – with battery costs reducing, they are becoming more cost-effective at longer timescales; and if a hydrogen economy were to take-off, its use to provide shorter timescale services may become more viable. Under such circumstances, the space for medium-duration energy storage could be squeezed. The cost of energy storage technologies is expected to be reduced but with high uncertainty (see Figure 8, IEA[19]). Modelling results suggest that the deployment of energy storage in different timescale is very sensitive to the cost of each technologies. (ESC: non-battery electrical storage, 2020).

Medium-duration energy storage sits between the technologies providing high value ancillary services to the network over short periods, such as batteries (cost effective with high charging/discharging cycle); and long-term storage such as hydrogen, which may have low round-trip efficiency, but with few other options available to such a level of demand (see Figure 9).

The deployment of the alternatives that provide flexibility affects the need for energy storage.

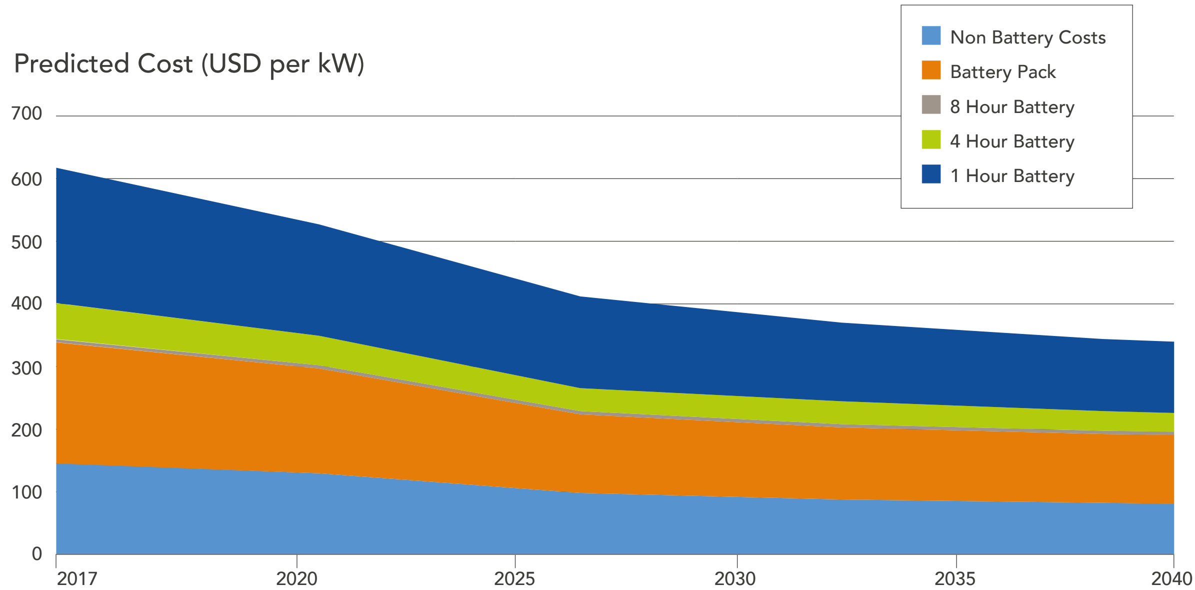


Figure 8: Battery cost projections[19].

Data taken from IEA Report 'Capital cost of utility-scale battery storage systems in the New Policies Scenario, 2017-2040'

[19] IEA, Capital cost of utility-scale battery storage systems in the New Policies Scenario, 2017-2040, IEA, Paris https://www.iea.org/data-and-statistics/charts/capital-cost-of-utility-scale-battery-storage-systems-in-the-new-policies-scenario-2017-2040

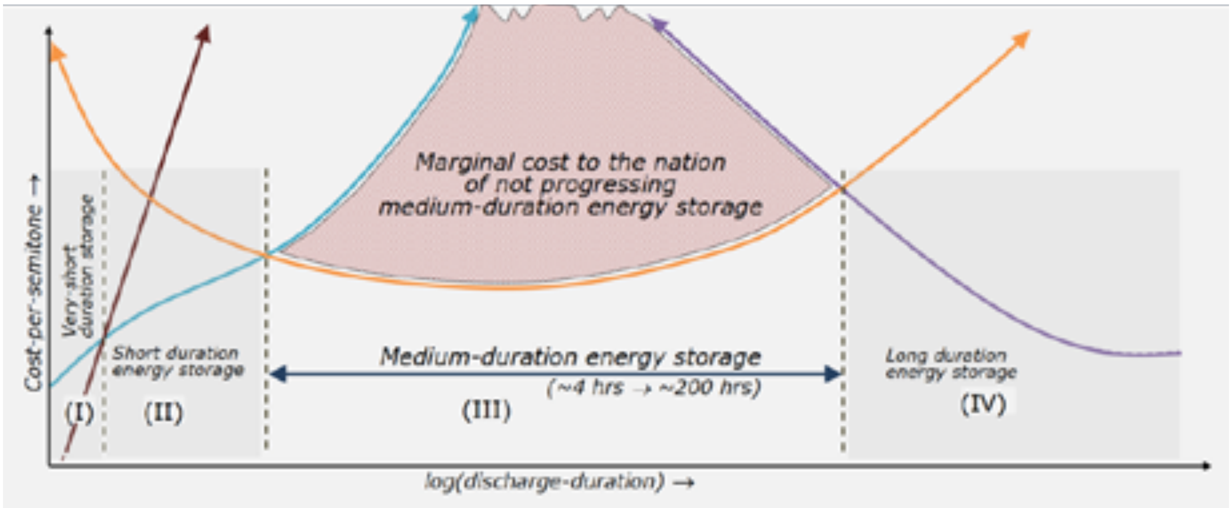


Figure 9: Cost of energy storage vs discharge duration. (Garvey, 2020[20])

Electricity interconnectors could be used to help balance the grid, off-loading surplus electricity, or, if the generation capacity is available, filling in any shortfalls. Capacity is expected to increase from 4 GW to 20 GW with demand-side response increasing from 1 GW to 6 GW by 2050 (NG FES, 2019), equivalent to 20% of the estimated peak demand in 2050.

Gas generation may continue to provide dispatchable power with the development of Carbon Capture and Storage (CCS), although its role in may depend on whether the CO_2 capture rate will be high enough (99%). Similar flexibility may be available from the deployment of Bioenergy with CCS (BECCS), which is being developed to provide negative emissions to help decarbonise hard to treat processes. CCS is likely to be important for producing low-carbon hydrogen since the cost is lower than electrolysis. (ESC: innovating to net zero).

The number of electric vehicles on the road is expected to increase from 2+ million in 2030 to 35+ million in 2050. This not only increases the electricity demand, but also the cumulative battery capacity in EVs from 100+ GWh to and 1500+ GWh. Meanwhile, the potential capacity for Vehicle-to-Grid (around 1/8 of battery capacity) will increase dramatically from 2030 to 2050. In principle, the scale of EV battery capacity could meet that needed on the grid [ref Vivid & Imperial report for CCC].

The installation of energy storage requires high upfront cost and its revenue is determined by how the energy market is designed, in particular how renewable generation that would otherwise be constrained-off is valued. This makes the investment of energy storage can be financial/ business risk if no support from the government. The energy policy can influence the deployment of energy storage significantly.

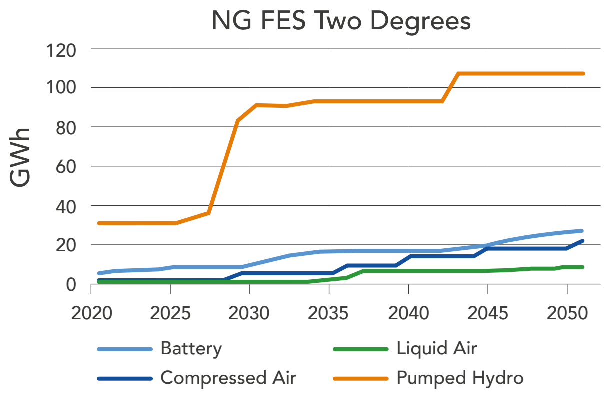
[20] Medium duration energy storage – kingpin of net zero energy, April 2020; University of Nottingham https://www.nottingham.ac.uk/research/research-areas/energy-technologies/news-and-events/news/medium-duration-energy-storage.aspx

5.1. THE ROLE OF ENERGY STORAGE IN SCENARIOS

Although the benefits that energy storage can bring to the energy system are understood, the complexity of the energy system transition means that its precise role and scale is hard to determine. Energy system modelling has been used to evaluate the role of energy storage but is limited in its ability to represent the temporal and geographic granularity necessary to capture its benefits. Several scenarios have been created and modelled to understand the potential need and role of energy storage:

Data created by National Grid Future Energy Scenarios, though not meeting the net-zero target, indicate that storage capacity on the electricity system will need to increase substantially compared to current levels (Figure 7). In the Community Renewables scenario, where a higher proportion of the renewable generation is micro-generation or distributed, the storage units are smaller, providing shorter duration outputs. The Two Degrees scenario has 30% more large-scale variable renewables, which feed into central transmission grid. Although the peak demand is 10GW higher, the storage capacity is lower and the projects tend to be bigger, with longer duration, such as transmission-connected pumped hydro. Two Degrees also has half the amount of electric domestic heat and nearly twice that coming from hydrogen for heat.

National Grid's analysis indicates that the impact of heat pumps on peak electricity demand can be lowered by increasing the thermal efficiency of buildings and using heat storage. In the other two scenarios, renewables continue to grow but decarbonisation on the demand side is much slower, and do not achieve the 2050 emission targets, but an increase in storage is still needed to support the electricity grid.



Energy storage could improve the use of existing generation facilities by reducing their curtailment during periods of high renewables output[21]. It also provide load-shifting to reduce the need for other investments in generation or network upgrades, which could save up to £7 billion per year for UK's electricity system by 2030[22,23].

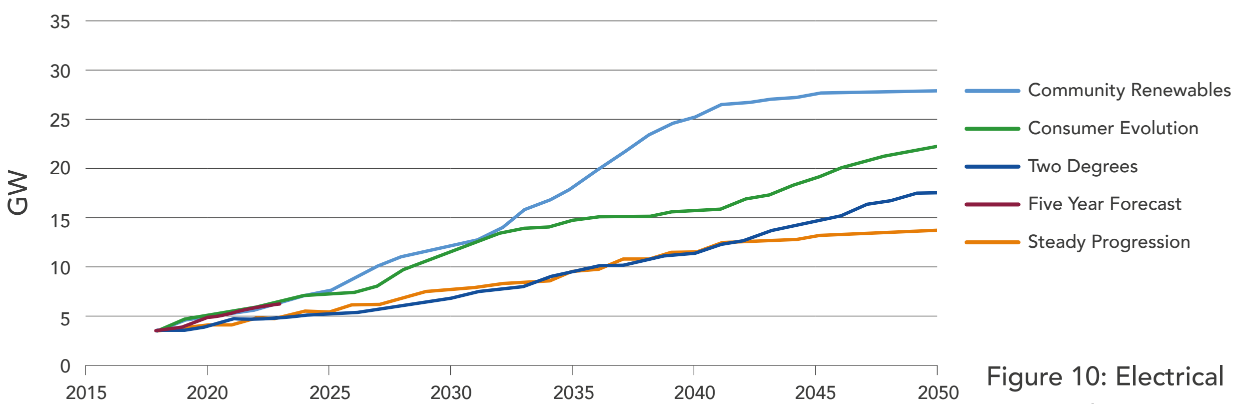


Figure 10: Electrical energy storage growth to 2050 from National Grid scenarios,[24].

[21] Carbon Trust and Imperial College Can storage help reduce the cost of a future UK electricity system? https://www.carbontrust.com/resources/energy-storage-report-can-storage-help-reduce-the-cost-of-a-future-uk-electricity-system

[22] Carbon Trust and Imperial College Can storage help reduce the cost of a future UK electricity system? https://www.carbontrust.com/resources/energy-storage-report-can-storage-help-reduce-the-cost-of-a-future-uk-electricity-system

[23] https://www.carbontrust.com/news-and-events/news/capturing-the-benefit-of-a-smart-flexible-energy-system

[24] https://www.carbontrust.com/news-and-events/news/capturing-the-benefit-of-a-smart-flexible-energy-system

6. ENERGY STORAGE WILL FACE COMMERCIAL DEPLOYMENT BARRIERS WITHOUT GOVERNMENT ACTION

The lack of business case that can benefit both the energy system and investors is the main challenge for energy storage deployment beyond ancillary services for the grid. To remove this barrier requires both the costs of storage to come down and for the value of the services it provides to go up. UK industry developing new storage technologies could benefit from a strong domestic market.

Research and innovation funding has increased globally since the mid-2000s and led to significant cost reductions. Recent government competitions have funded some demonstration of large-scale energy storage, but support has been focused on battery developments, driven by the market pull of the EV sector (see Figure 11). As a result, batteries are being deployed commercially for short time-scale responses (See Figure 12), up to a few hours, responding to new markets in e.g. Enhanced Frequency Response, Capacity Market; 'behind-the-meter' to reduce energy costs; and for network support[25].

To fill the gap in medium-long duration energy storage by the time it is needed will require an innovations systems approach, including support from research through to deployment. New energy market frameworks that provide revenue streams for other energy storage services, and give equal opportunity for different solutions in the markets will provide the pull for further private sector investment[26].

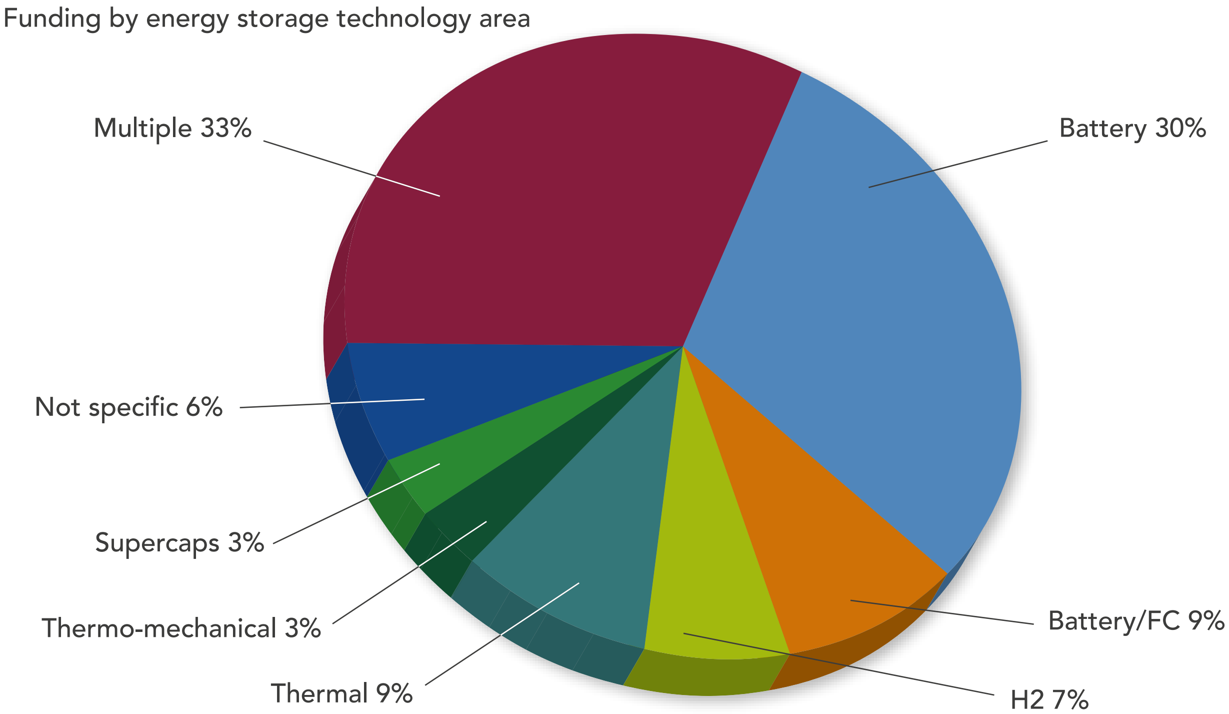


Figure 11a: UK research council project funding by technology area.

[25] https://www.ukpowernetworks.co.uk/internet/en/news-and-press/press-releases/UK-Power-Networks-announces-results-of-UKs-biggest-ever-competitive-Flexibility-tender.html

[26] Study on energy storage https://op.europa.eu/en/publication-detail/-/publication/a6eba083-932e-11ea-aac4-01aa75ed71a1

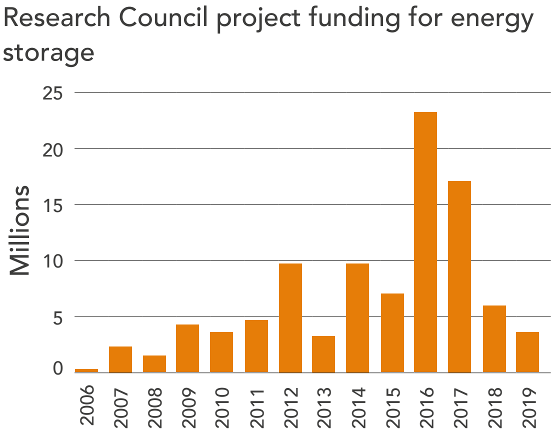


Figure 11b: UK research council project funding by award date. Not including Faraday Institute (£75m, 2018) and capital grants (£30m, 2013).

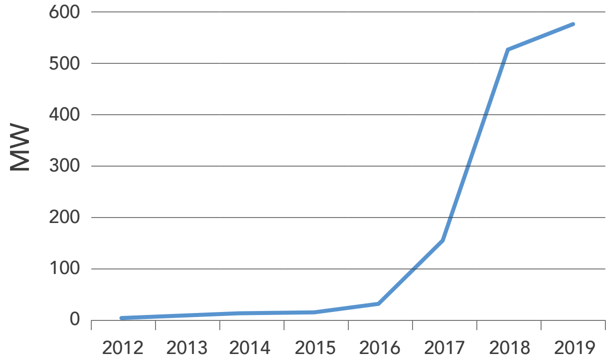


Figure 12: Operational battery capacity in the UK

Lack of social acceptance of energy storage could also hamper its deployment. A UK study shows the awareness of the need for storage in the transition to low-carbon energy system was low, and the social perspectives to each technology could be very different. While the government is supporting the deployment of energy storage through making new regulations and incentives, key criteria in the lens of social acceptance (e.g. fairness, independence and control, and convenience) should be taken into account[27].

The UK needs more flexibility than most of European countries due to lack of interconnectors and pumped hydro resources. The global electrical energy storage market is expected to growth rapidly to reach 3,000 GWh (or £546 billion) on 2035, with the annual growth rate of 20%[28]. With several technology companies developing energy storage solutions, the UK has potential to be a leader. However, there is also a history of companies that have failed when there was not a market to provide a revenue stream.

[27] Deliberating the social acceptability of energy storage in the UK https://www.sciencedirect.com/science/article/pii/S0301421519304860

[28] Global Energy Storage Market 2019 https://www.luxresearchinc.com/global-energy-storage-market-forecast-executive-summary

7. ANNEX 1 - THERMAL ENERGY STORAGE

Thermal Energy Storage (TES) technologies can be classified into three types:

"Sensible" heat storage

Thermal energy is stored in forms where the heat can be felt, known as "sensible" heat. This creates a temperature difference between the storage media and environment. In general, it has low energy density but also low cost and easy to obtain.

The most common heat storage in UK's households is hot water tanks and storage heaters, which heat up bricks. Thermal energy can be stored in underground TES (e.g. boreholes and aquifers), pit TES (e.g. packed-bed rocks with water), and tank TES (e.g. large water tanks, often integrate with combine heat & power plant). Those have been used in several countries with large scale (up to 200,000 m3)[29].

Phase change material (PCM) storage

Thermal energy is stored in the phase change between liquid and solid with no significant temperature change in the material. In a small temperature range, PCMs can store several times more energy than sensible heat, and make it suitable for the application with limited space (e.g. plats and vehicles). Ice storage is the most common PCMs to store cold. PCM-base heat storage is commercial available to replace hot water tanks in households.

Thermochemical storage

The reaction heat of reversible chemical reactions can be used to store thermal energy with high energy density and efficiency. Many materials and technologies have been studied but most of them are still in development due to the complexity of the system. Salt hydrates have been demonstrated for inter-seasonal storage to large buildings in the UK[30].

[29] Medium duration energy storage – kingpin of net zero energy, April 2020; University of Nottingham https://www.nottingham.ac.uk/research/research-areas/energy-technologies/news-and-events/news/medium-duration-energy-storage.aspx

[30] https://www.specific.eu.com/thermal-storage/

8. ANNEX 2 - POTENTIAL MEDIUM – LONG DURATION TECHNOLOGIES

Thermo-mechanical: liquid air (LAES), compressed air (CAES), pumped heat (PHES)

Energy is stored in hot/cold storage and/or high pressure vessels through compression and expansion processes. The round-trip efficiency is not high (40-80%), but it is suitable for long duration due to its low cost per energy capacity at large-scale. It can also couple with heating and cooling sectors to improve the flexibility and efficiency of the system. The first grid-scale LAES plant (50 MW and 250+ MWh) is currently under construction in the UK[31].

Electrochemical: Flow batteries, Sodium-Sulphur (NaS) batteries[32]

Electricity is charged/discharged through reversible electrochemical reactions. Flow batteries store energy in two liquid chemical components, and the power and energy can be decoupled by the size of storage tanks. NaS batteries has a solid electrolyte between two liquids, and becomes more economical at large-scale. The round-trip efficiency of both technologies is fairly high (70-80%), but also high cost.

Mechanical: pumped hydro storage (PHS), gravity storage

Energy is stored by lifting water or solid objects to a higher elevation. Pumped hydro storage has been widely used worldwide but has geographical constrains. Novel gravity storage concepts, for example lifting heavy concrete blocks up and down shafts, can have fewer limitations on location. The round-trip efficiency is high (80-90%).

Chemical: hydrogen, ammonia

Hydrogen can be produced by electrolysis from low-carbon electricity. Hydrogen gas has very low volumetric density, so extra processes are needed to reduce the volume, such as compression, liquefaction, storing on/with solid materials, or synthesis of ammonia. Those methods require additional energy or material costs. The round-trip efficiency is low (25-40%) but has low energy loss over time and the potential to store at very large scale (100s GWh).

Thermal energy storage (TES): large-scale sensible storage, thermochemical

Usually integrated with CHP plants in district heating networks, hot water accumulators allow heat and power production to be decoupled. Large amounts of thermal energy that are enough to provide heating/cooling for the whole season can be stored as sensible heat storage (e.g. underground TES, pit TES) and thermochemical storage. Heat/cold can be stored by using heat pumps powered by renewable energy in summer/winter, and uses in another season.

[31] https://highviewpower.com/news_announcement/highview-power-awarded-10-million-grant-from-uk-government-for-first-commercial-cryobattery-facility/

[32] https://energystorage.org/why-energy-storage/technologies/sodium-sulfur-nas-batteries/

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