Batteries

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Capitalist Solutions to Climate Change

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Introduction

Batteries are already ubiquitous in everyday life, surrounded as we are by countless electronic devices powered by them. Helped by this mass adoption in consumer electronic devices, batteries are now spreading into other, larger-scale applications, key amongst them electric vehicles (EVs) and stationary battery electricity storage systems (BESSs).

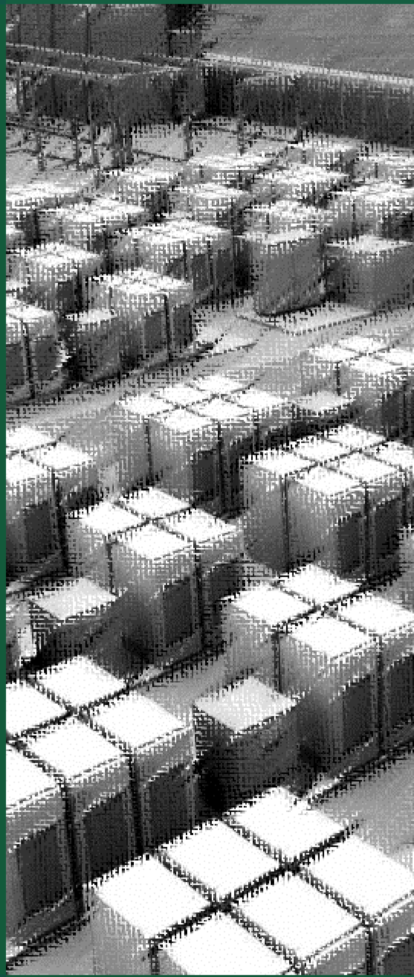
This report provides a brief introduction to BESSs. We cover the technology and its applications, as well as historical, current and potential future deployment.

BESSs are fundamentally a tool for providing low-carbon, quick-responding, short-duration, electricity system flexibility. Flexibility is something that is naturally being lost from electricity systems as the shift to low-carbon electricity generation proceeds at pace. Traditional thermal power plants are closing and weather-dependent renewables are taking their place. Loss of flexibility makes it harder to keep electricity grids functioning and to do so at a reasonable price.

While by no means the only way of providing low-carbon flexibility or implementing electricity storage, BESSs are one of the more powerful. Reasons for this include BESSs being rapidly deployable across a large number of potential sites, at a wide range of scales, and at an increasingly competitive price.

Whilst we touch on the global market for BESSs, our focus in this report is on the UK, one of the leading European BESS markets. The UK recently became one of the first countries to set a legally-binding net-zero greenhouse gas emissions target. It is reasonable to assume that BESSs will play a key role in enabling this 2050 target to be met, alongside a hefty build-out in renewables. In the process, National Grid ESO forecasts that the UK's BESS market could expand about 25 times in power and 50 times in energy terms by 2050.

Contents



Basics

In this section we cover the basics of batteries, BESSs and the energy storage market. We start by looking at how batteries work, the types that exist, as well as their key properties. If you are not interested in the technical side of things, you can skip ahead.

Battery Basics

Batteries are a surprisingly complex technology in practice, even though the basic theory is simple enough to understand. Batteries work by the exchange of electrons between two chemical reactions, an oxidation reaction, which produces electrons, and a reduction reaction, which consumes them; collectively these are known as redox reactions. By guiding electrons through an external electrical circuit between these opposite reactions, a direct electrical current (DC) is generated, which can be used to power an electrical load. With batteries that are rechargeable, the reactions can be reversed by attaching an appropriate electrical source - rather than a load - to the external electrical circuit. Within limits, rechargeable batteries can therefore convert back and forth between energy in chemical and electrical forms. Other types of storage technologies exist that convert electricity to and store energy in different forms, e.g. thermal, mechanical or electrical. We cover a few later.

There are numerous types of battery, all of which follow the basic operating principles given above. For ESS applications, two distinct forms of battery are employed - what we will call 'standard' rechargeable batteries, and, less commonly, flow batteries.

Standard Batteries

A conventional rechargeable battery consists of one or more electrochemical cells - see **Figure 1** - plus components for external connection and housing at a minimum.

The main components of each electrochemical cell are two electrodes, known as the anode and the cathode, and a connecting electrolyte (or sometimes two compartmentalised but electrically-connected electrolytes).

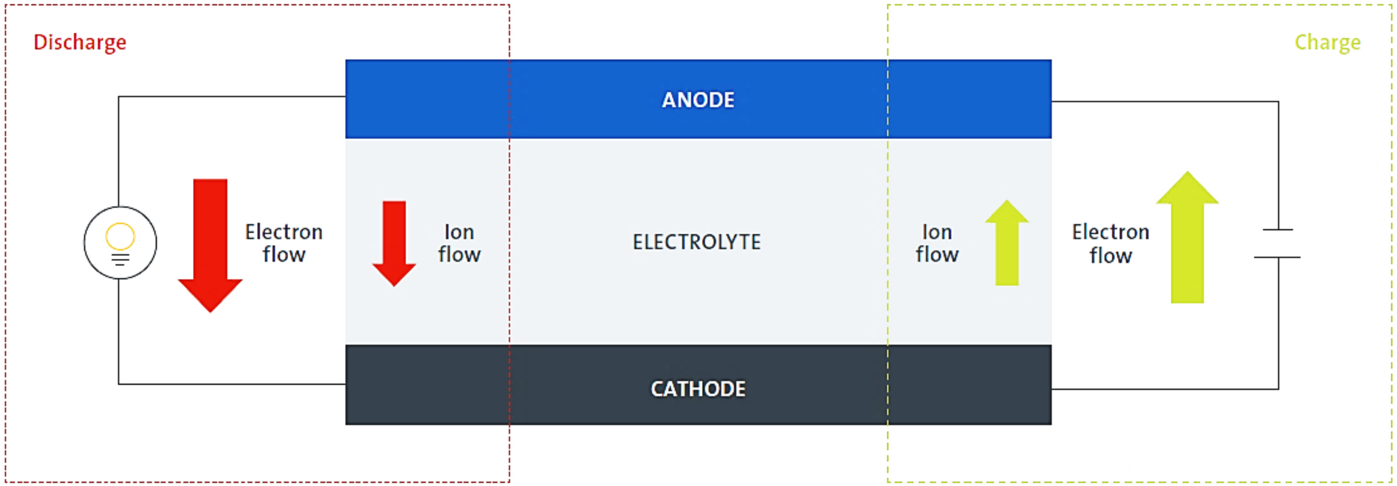


Figure 1 - representative diagram of an electrochemical cell found in a standard rechargeable battery. Source: Innovation in Batteries and Electricity Storage, IEA, 2020.

Electrodes are typically made from two dissimilar metals or metal oxides. These are the electroactive materials that participate in the redox reactions. During cell discharge, oxidation occurs at the electrode we define as the anode, whilst reduction occurs at the electrode we define as the cathode. The cell's electrical current arises from the transfer of electrons from the anode to the cathode via the external electrical circuit.

The electrolyte provides a medium through which positively-charged ions, known as cations, which also participate in the redox reactions alongside the negatively-charged electrons, can move between the electrodes internally to the cell. You need the movement of *both* electrons *and* cations for the cell to work. **Figure 1**, on the previous page, shows the direction of flow of electrons and cations during cell charge and discharge. Note that electrons cannot move through the electrolyte, just as cations cannot move through the external electrical circuit. In some types of cell, the electrolyte may also directly participate in the redox reactions, in addition to being the cation transport medium. Although not shown in **Figure 1**, physical contact between the electrodes, which can be very close, is prevented by the insertion of a thin, porous membrane between the electrodes.

Certain fundamental properties of a cell - e.g. voltage - are determined by its chemistry; that is, by which redox reactions occur, which is in turn determined by the materials used for the electrodes (and possibly electrolyte). Other properties, including energy capacity and charge/discharge performance, are determined by the physical configuration of the battery; for example, by the amount of material in the battery, or the geometry of the electrodes. We explore battery properties shortly.

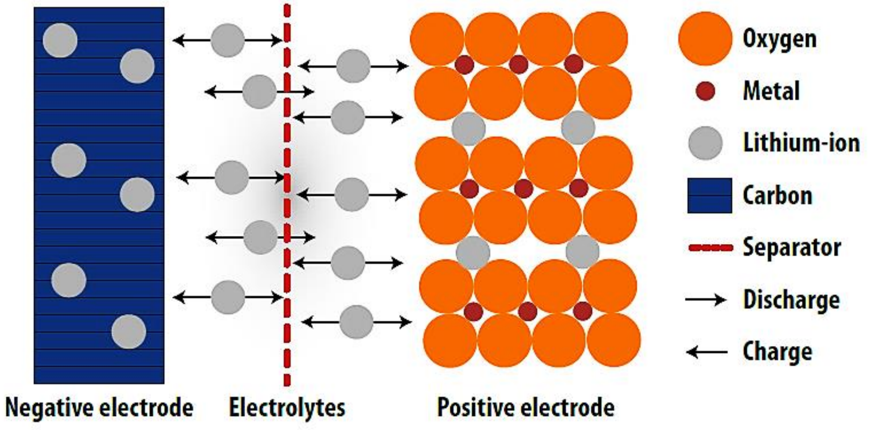


Figure 2 - main components and operating principle of a lithium-ion electrochemical cell with a metal oxide cathode and carbon-based anode. Source: Electricity Storage and Renewables: Costs and Markets to 2030, IRENA (International Renewable Energy Agency), 2017.

Types

There are numerous types of standard rechargeable batteries. For BESS applications, some notable examples include:

Lithium-ion. The term lithium-ion does not refer to a single battery chemistry, rather it refers to all the chemistries that employ lithium ions as the cation. A standard lithium-ion battery has a solid graphite anode, a solid lithium metal oxide cathode, and a liquid electrolyte containing dissolved lithium salts. See **Figure 2**. We look in detail at lithium-ion batteries later.

Lead-acid. The term lead-acid refers to a less diverse class of batteries than the lithium-ion group. In this case the name describes both the electrode material and the electrolyte. A standard example has a solid lead anode, a solid lead oxide cathode, and a liquid electrolyte containing sulphuric acid. This is largely a legacy technology.

High temperature. This class of batteries operates at a few hundred degrees Celsius, in contrast to most standard batteries, which operate near room temperature. Typically, the electrodes are liquid and are separated by a solid electrolyte. Examples include sodium sulphur (NaS) and sodium nickel chloride ($NaNiCl_2$) batteries.

Other types are also used but these are currently less commercially significant.

Flow Batteries

In a flow battery, the processes of energy storage and extraction that are combined in a standard battery are instead separated out. One or more of the electroactive materials are stored externally to the flow cell, the place where energy is extracted from the electroactive materials. A flow cell still has electrodes like a standard cell, but these are simply the locations where the redox reactions occur; they do not participate in them.

There are several categories of flow batteries, the most common of which is the 'redox flow' category, in which all electroactive materials are dissolved in liquids and stored separately from the flow cell. Vanadium redox flow batteries are the most common implementation of this type. Other categories break one or other of these restraints, e.g. 'hybrid flow' batteries, typified by zinc bromine, in which one of the electroactive materials is stored within the cell.

Figure 3 shows the layout of a typical redox flow battery, with only one flow cell shown for simplicity, though there may be many in practice. The electroactive materials used in this case are commonly metals dissolved in aqueous acid or alkali solutions. The resultant electroactive solutions can flip between two oxidation states (known as redox pairs) and therefore participate in redox reactions. Two electroactive solutions - called electrolytes in this context, though their function is more than just as a cation transport medium, the sole function of electrolytes in most standard rechargeable batteries - are used, with each stored in a separate tank external to the flow cell, one connected at the anode side and the other at the cathode side. During battery operation, the electrolytes are pumped from their respective tanks into the flow cell.

The flow cell itself consists of two half cells, each connected to one of the electrolyte tanks, and each with a porous electrode, typically made from carbon felt. To repeat, the electrodes are the sites for the redox reactions but are not altered by them; the two electrolytes are the things that are altered as they flip between oxidation states. The half cells are separated by a porous membrane to prevent the electrolytes mixing, whilst still permitting the selective passage of cations across the membrane, crucial to battery operation, as it was for standard batteries.

The direction of flow of electrons and ions during charge and discharge is equivalent

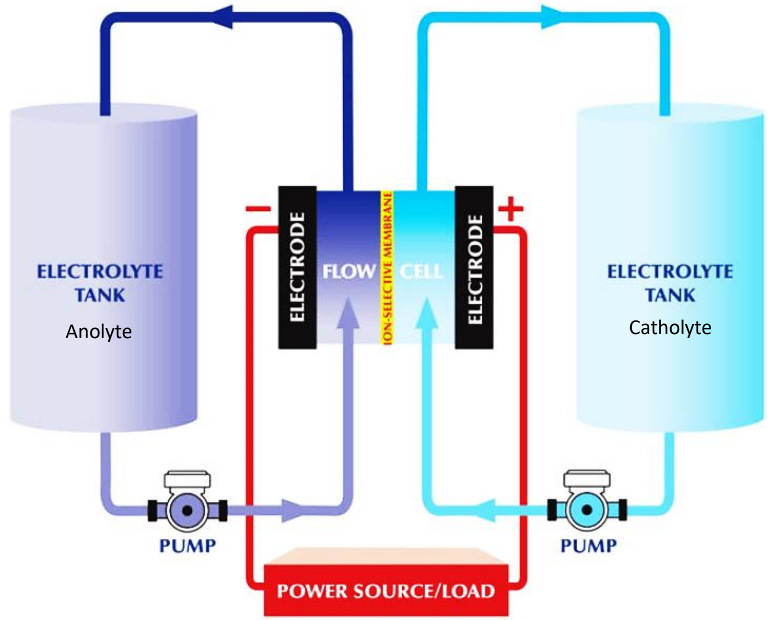


Figure 3 - schematic of a redox flow battery. Source: [What is a flow battery?](), International Flow Battery Forum.

to that shown for a standard battery in **Figure 1**, e.g. during discharge, electrons flow from the anode to the cathode via the external circuit, while cations make the same journey within the flow cell.

Interestingly, as well as being able to recharge a flow battery like you would a standard rechargeable battery, it is also possible to restore the flow battery to its charged state by simply replacing the spent electrolyte with new, charged electrolyte. This is conceptually similar to how fuel cells work (see our hydrogen report for a primer on fuel cells). Flow batteries are therefore sometimes described as a cross between standard rechargeable batteries and fuel cells. We say more about flow batteries in the next section and elsewhere in this report.

Battery Technical Properties

Batteries have a range of technical properties that must be taken into account when establishing suitability for a particular application. Whilst some of these can be improved through innovation in manufacturing and engineering, basic science limits the extent of such improvements, as do economic considerations.

Applications differ significantly in the properties that are most important to them. For ESS applications, key properties include:

- **Efficiency** (%) - the ratio of output to input energy after completing a charge/discharge cycle. Clearly, you want this to be as high as possible, but some loss in unavoidable.
- **Energy capacity** (Wh) - how much energy a battery can store. Although batteries have a nominal rated energy capacity, measured under standard conditions, capacity is not a fixed quantity - it depends on various factors including how fast a battery is charged/discharged, and the age and history of the battery. With most standard batteries, the full capacity cannot be withdrawn without causing damage. The maximum **Depth of Discharge** (DoD) (%) is the fraction of energy capacity that can be safely withdrawn from the battery.
- **Power** (W) - how fast a battery stores/releases energy. Although batteries used in BESSs are given a nominal rated power - a maximal power that can be sustained under normal operating conditions without damage - power is obviously and usefully not a fixed quantity, rather the product of voltage and current:

    Voltage (V) - the amount of energy per unit of electrical charge. Different cell chemistries naturally provide different voltages, though multiple cells used in combination can reach any desired battery voltage. Although batteries have a nominal rated voltage, the actual voltage under current flow may differ substantially from this.

    Current (A) - the amount of charge per unit time. Batteries can be made to charge/discharge across a range of currents and therefore at different speeds, though there is an optimal and an upper current, above which damage is likely to occur. In general, higher currents reduce the usable energy capacity of a battery and its lifetime, defined on the next page. Battery currents are often given relative to the energy capacity, defining what is known as the C-rate (see this link for more).

- **Duration** (hours) - how long a fully charged battery takes to discharge to its maximum depth of discharge (DoD). A nominal duration can be calculated using the nominal energy capacity, nominal power and DoD.
- **Lifetime** (cycles) - how many charge/discharge cycles a battery can survive before end-of-life. Every time you cycle a battery its energy capacity and efficiency decrease a bit; this is known as degradation. End-of-life is usually defined as a percentage loss of energy capacity relative to the battery's capacity when new. With standard batteries, lifetime is significantly affected by DoD, with greater DoD lowering lifetime. Lithium-ion batteries used in large-scale BESS applications need to be replaced after roughly 8-10 years of use.
- **Thermal stability** - how susceptible a battery is to thermal runaway. All charging and discharging of batteries generates internal heat, which, as well as leading to degradation, can also lead to an outright fire in the extreme case. This has historically been an issue with certain types of lithium-ion battery.
- **Power** and **energy volume density** (W/m^3, Wh/m^3) - how much power or energy can be stored per unit volume. It is obviously preferable if the same power or energy can be supplied by a smaller volume of batteries. Less so for BESS applications but for EV applications **power** and **energy mass density** (W/kg, Wh/kg) are also very important properties.

For a range of battery and other storage technologies, representative values for some of these technical properties, as well as some additional commercial properties, can be found in the Appendix.

As we quantify later, although lithium-ion batteries dominate BESS deployment, other battery types have also found some commercial success. Returning to flow batteries as one example of this, technical reasons given in favour of potentially deploying a flow battery instead of a lithium-ion battery for BESS applications include:

- Superior thermal stability.
- Longer lifetime (though this depends on exactly which type of batteries you are comparing), with low degradation even under full discharge.
- The possibility of scaling the power and energy capacity independently, something you cannot do with standard batteries.

Expanding on this last point, with a flow battery energy capacity can be increased simply by scaling the electrolyte volume and storage tanks, while power can be increased independently by adding flow cells. This potentially makes flow batteries more economically competitive for longer-duration applications (~6 hours+), though, as we explore later, shorter-duration applications (<4 hours) are the current market focus and where lithium-ion dominates. For a fuller discussion of flow versus lithium-ion batteries, see this article.

BESS Basics

Although we will largely skip over the details, a BESS is more than simply a collection of electrochemical cells connected to one another and usually also to the electrical grid. To illustrate this, **Figure 4**, below, shows a schematic of a typical grid-connected, large-scale ESS built from flow batteries, while **Figure 5**, overpage, shows the standard battery equivalent. Our description will focus on **Figure 5** but, beyond adaptations for the battery type, these are essentially the same.

Although we focus on large-scale BESSs here, BESSs exist at scales ranging from a few kW to hundreds of MW, with 1 to 4 hours duration typical across all scales. Smaller systems, such as those used in homes, are of course simpler than those described here.

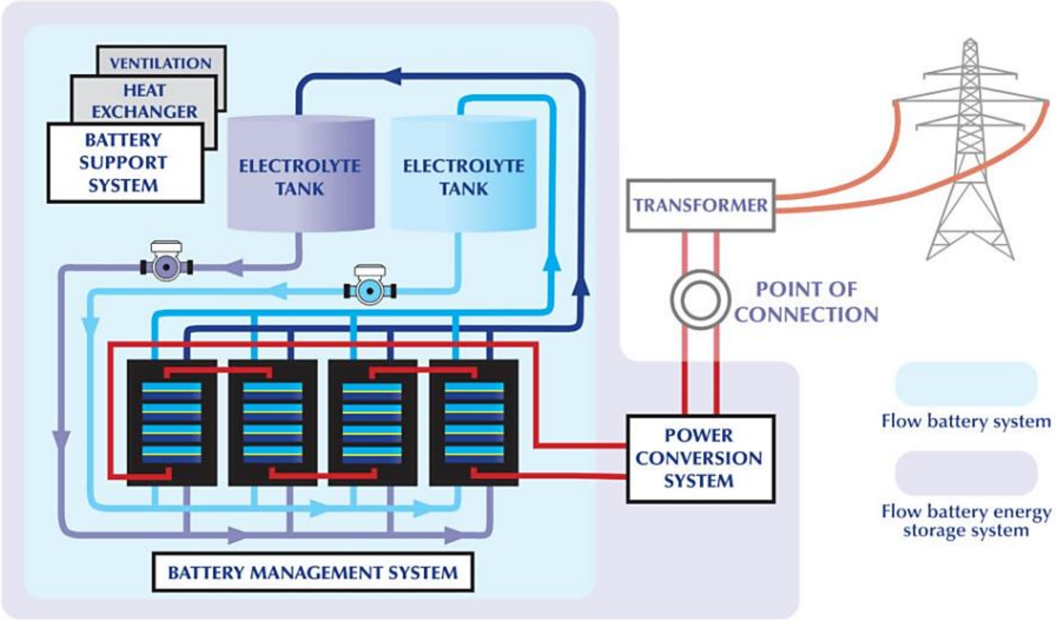


Figure 4 - schematic of a typical BESS (that employs flow batteries, compare **Figure 5**). Source: [What is a flow battery?](), International Flow Battery Forum.

In **Figure 5**, the smallest unit is the humble electrochemical cell. Multiple cells are grouped into an entity known as a pack or tray; pack is the term used in EV applications, but a pack and a tray are essentially the same thing. A BESS of appropriate scale is built from racks and racks of trays - see the image on the previous page - together with several other key systems, collectively known as the balance-of-system equipment. These are a mixture of hardware and software that perform various important functions, including:

Battery management - monitoring and managing the low-level behaviour of the BESS. Specific tasks might include reporting on the state of cells and ensuring that: (a) cells do not operate outside of safe parameters, e.g. current, voltage, DoD; (b) cell operation is otherwise optimised, e.g. by balancing charge between cells.

Energy management - monitoring and managing the high-level behaviour of the BESS, i.e. whether the BESS is charging or discharging and at what rate. Much of the complexity of operating a BESS comes from the decision-making process behind this task, which need not be performed on-site, or necessarily by the company who owns the BESS, and which may involve cutting-edge software technologies such as artificial intelligence. BESSs are as much about data collection and processing as they are about electrical engineering.

Thermal management / fire protection - controlling the temperature of the cells so that they operate most efficiently and do not suffer from thermal runaway. This can be an passive or active process, and the cooling medium can be either air, liquid or a phase change. If the thermal management system fails, the fire protection systems steps in by detecting and hopefully extinguishing any fire that occurs.

Power conversion - converting between the DC electricity used by the BESS and the AC electricity used by the grid, and separately

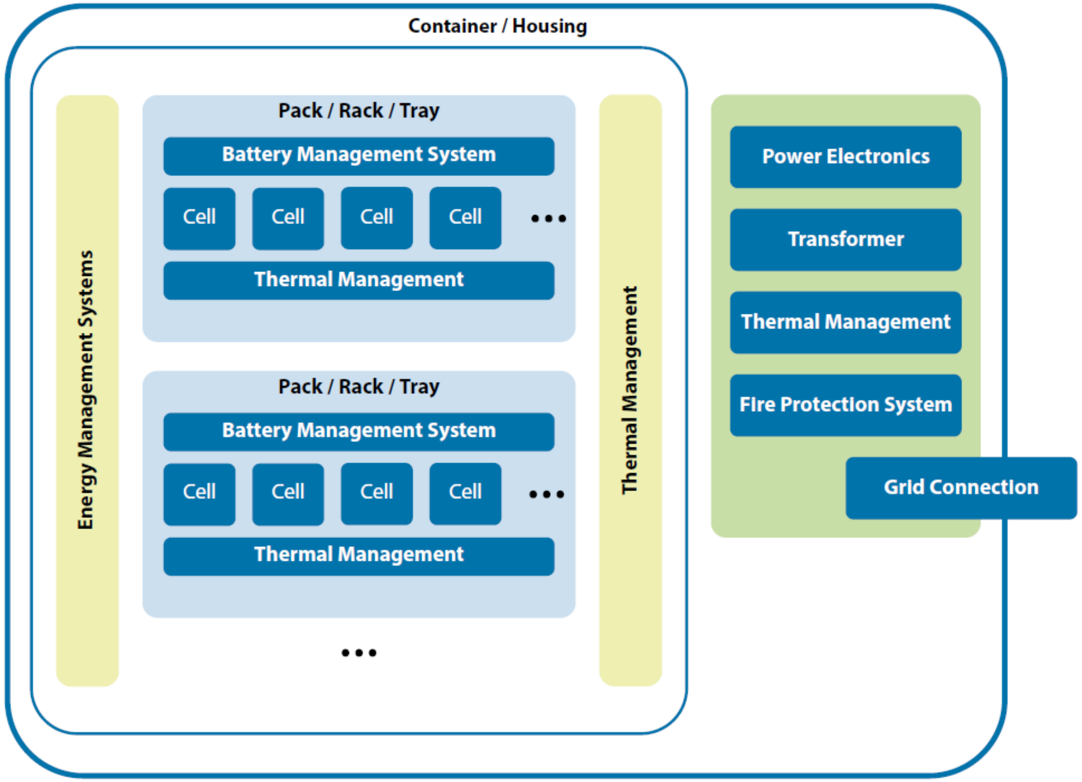


Figure 5 - schematic of a typical BESS (that employs standard rechargeable batteries, compare **Figure 4**). Source: [Electricity Storage and Renewables: Costs and Markets to 2030], IRENA (International Renewable Energy Agency), 2017.

converting between the voltage used internally and externally to the BESS. A BESS can be connected either to a lower-voltage, distribution grid, or a higher-voltage, transmission grid.

As should be obvious from the above description, the cost and performance of the BESS is determined by more than simply the cost and performance of the batteries. The balance-of-system equipment contributes significantly to the overall cost - as we quantify later - and also acts as a parasitic load, reducing the performance obtained from the batteries.

Value Chain

A large collection of companies are involved in the birth of a fully-functional BESS. Ignoring those companies involved in the extraction of raw materials, **Figure 6** shows the categories of companies involved in a typical large-scale BESS project. The upstream part of this 'value chain' turns raw materials (plus know-how and money) into the hardware and software needed to build a BESS. The downstream part of the value chain take these basic components (and more money and know-how) and outputs an operational BESS; this involves everything from securing investment, to obtaining a permitted site, to constructing the BESS, to running the BESS once built. Such a diverse value chain presents a range of opportunities for investors, above and beyond direct equity or debt investment in a specific BESS project.

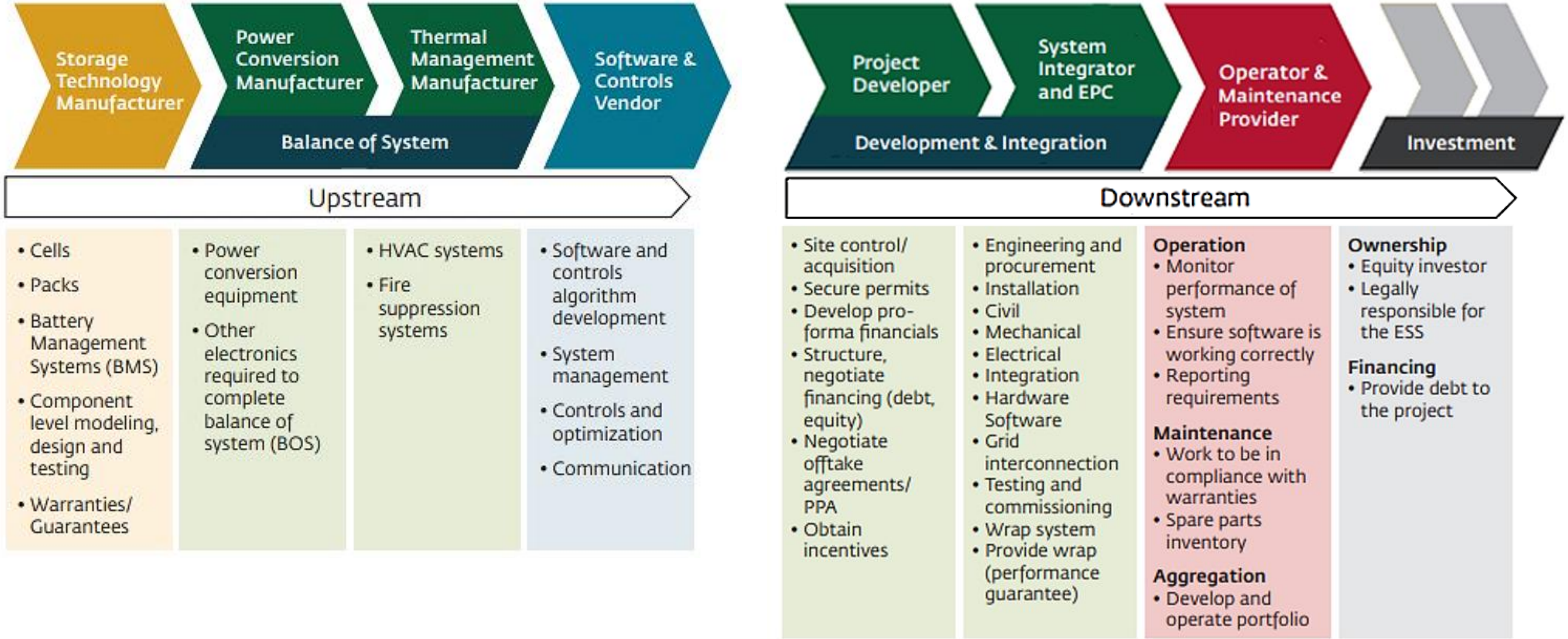


Figure 6 - the BESS value chain for a large-scale BESS, divided into upstream and downstream parts. Source: Energy Storage Trends and Opportunities in Emerging Markets, ESMAP (Energy Sector Management Assistance Program) and IFC (International Finance Corporation), 2017. HVAC - heating ventilation and air conditioning. PPA - power purchase agreement.

Broad Motivation for BESS Use

Having sketched out what a BESS is, we now outline the high-level motivation behind their use - providing electricity system flexibility. We have covered this area repeatedly in previous 350 PPM sector research, so we give a shortened version here. We delve into specific BESS applications later.

The Need for Flexibility

The strengthening political will to fight climate change, coupled with the declining cost of renewables, has made it increasingly likely that the global energy system will be completely decarbonised over the next few decades. Whilst this is undoubtably great for the planet, this transformation comes with its challenges. Chief amongst these is a loss of electricity system flexibility that goes hand-in-hand with this transformation. This mainly means the loss of an ability to adjust electricity supply so that it matches demand in real-time - which it must - and so that the physical infrastructure that transports the electricity - the wires, substations, etc. - is not overwhelmed. Adjusting demand to supply can also help with this task but to a lesser extent. A loss of flexibility makes it harder to keep the electricity system stable and operating, and to do so at a reasonable cost, with electricity consumers ultimately paying the price. On the supply side, the current and expected further loss of flexibility stems from the replacement of centralised, thermal generation - coal and nuclear in particular - with decentralised, weather-dependent renewables, mainly wind and solar. **Figure 7** and **Figure 8** forecast two aspects of what this might mean for the E7, the group consisting of the largest seven European countries, in 2030:

- A large, effective loss of generation capacity compared with today. Renewables only generate when conditions allow and are not forecast to be built at a rate that would make up for the capacity of closing thermal generation.
- A significant increase in intra-day generation swings due to solar and wind capacity build-out. This includes an approximate tripling in intra-day swings due to solar (though in the UK, wind will likely be more of an issue).

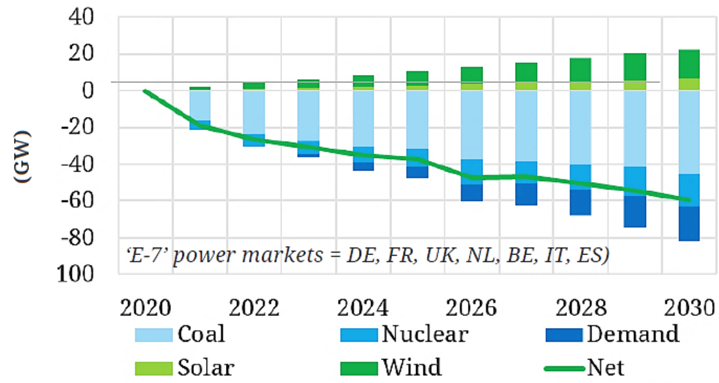


Figure 7 - forecast E-7 changes in de-rated capacity (GW). De-rated capacity corrects for the fact that power sources do not generate all the time. Source: European battery investment wave, Timera Energy, Oct 2020.

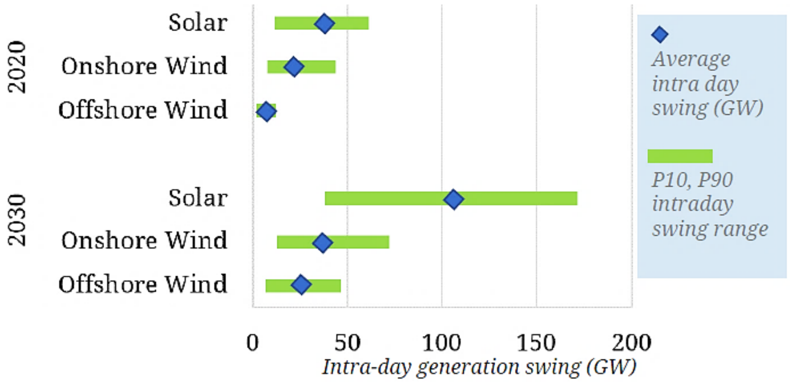


Figure 8 - 2020 and forecast 2030 E-7 intra-day generation swings (GW). Source: same as **Figure 7**.

On the demand side, population and economic growth, as well as the ongoing process of electrification, most notably in the transport and heat sectors, are expected to push up electricity demand considerably. Some of this demand is potentially flexible - EV charging in particular - but some is not, and this will only exacerbate the difficulty in matching demand with an increasingly variable and unpredictable supply.

Types of Flexibility

Thankfully, there are a number of ways of increasing electricity and wider energy system flexibility. Given the scale of the problem we are likely to need them all. These methods are summarised neatly in **Figure 9**. We will not discuss non-BESS solutions in any detail in this report, but it is worth pointing out what makes BESSs a useful source of flexibility, particularly in comparison to what is usually touted as their main competitor - the installation of new gas-powered generation to meet peak demand; these are known as 'gas peakers'. BESSs are, among other things:

- **Low carbon**. BESSs generate no direct emissions but may have emissions associated with their electricity consumption (and manufacture and construction).
- **Versatile**. BESSs are able to provide both supply- and demand-side flexibility across a range of potential locations, scales and use cases. We cover use cases later.
- **Quickly** and **easily deployable**. BESSs usually come in modular form and a large-scale facility can be built in a few months, quicker than most alternatives.
- Very **quick-responding** and **accurately-controllable**. BESSs can respond in fractions of a second, as fast or faster than alternatives.
- **Low cost**. BESSs, either in standalone form or co-located with renewables, are increasingly competitive versus alternatives, gas peakers most notably. We look at cost in more detail later.

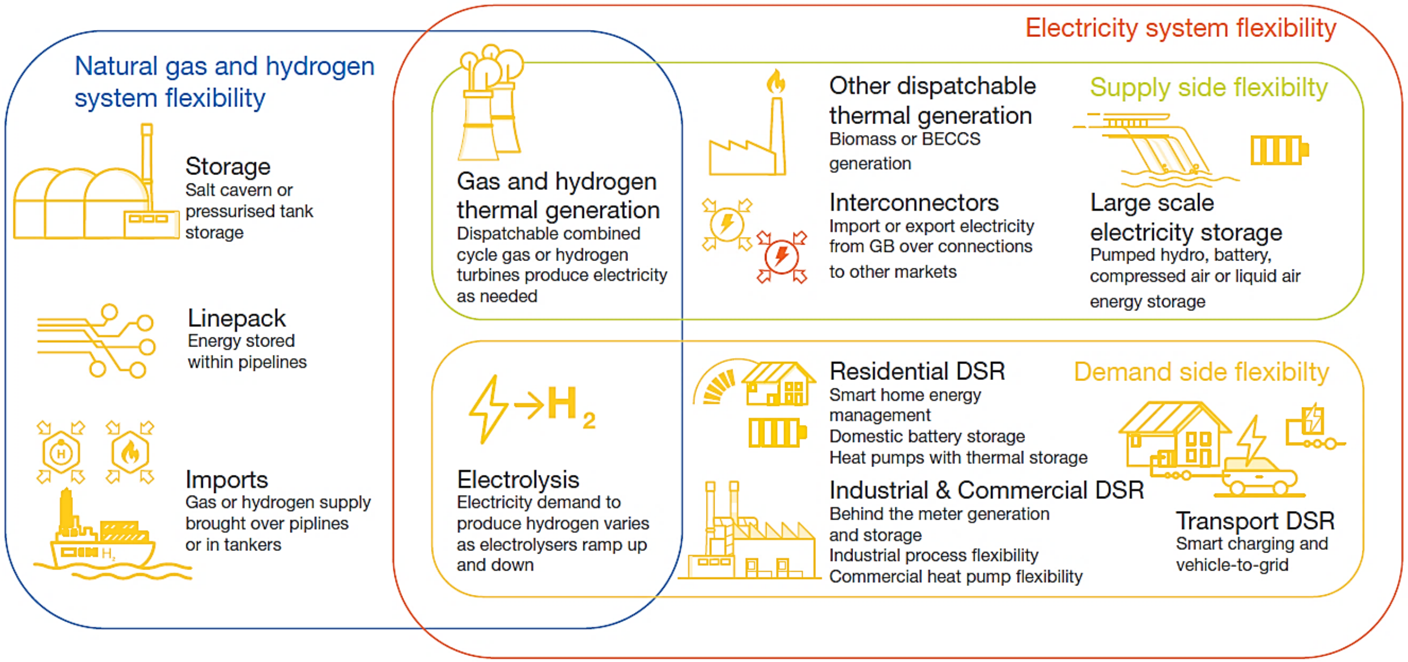


Figure 9 - types of networked energy system flexibility. Source: Future Energy Scenarios 2020 Interactive, National Grid ESO, August 2020. DSR - Demand Side Response; BECCS - Bio-energy with Carbon Capture and Storage.

ESS Market Outline

Before moving onto discuss BESSs in more detail, it is worth briefly considering how they fit into the wider ESS market, some examples of which were included in **Figure 9**, on the previous page.

Types of Electricity Storage

As pointed out earlier, one of the most fundamental ways of grouping ESS technologies is by the form of energy into which the electricity is converted for storage (chemical, electrical, mechanical, etc). Another way of grouping ESSs, which neatly maps onto potential applications, is the nominal duration of the technology. To recap, nominal duration is the length of time that a battery can supply nominal power for, starting fully charged.

At one extreme are short-duration technologies. These can typically only supply their nominal power for seconds to minutes. Examples include flywheels and supercapacitors, which store energy in mechanical (rotating mass) and electrical forms respectively, and neither of which are widely deployed. These technologies have very high power capabilities, supplying a lot of energy very quickly, and are therefore used in what are termed 'power' applications.

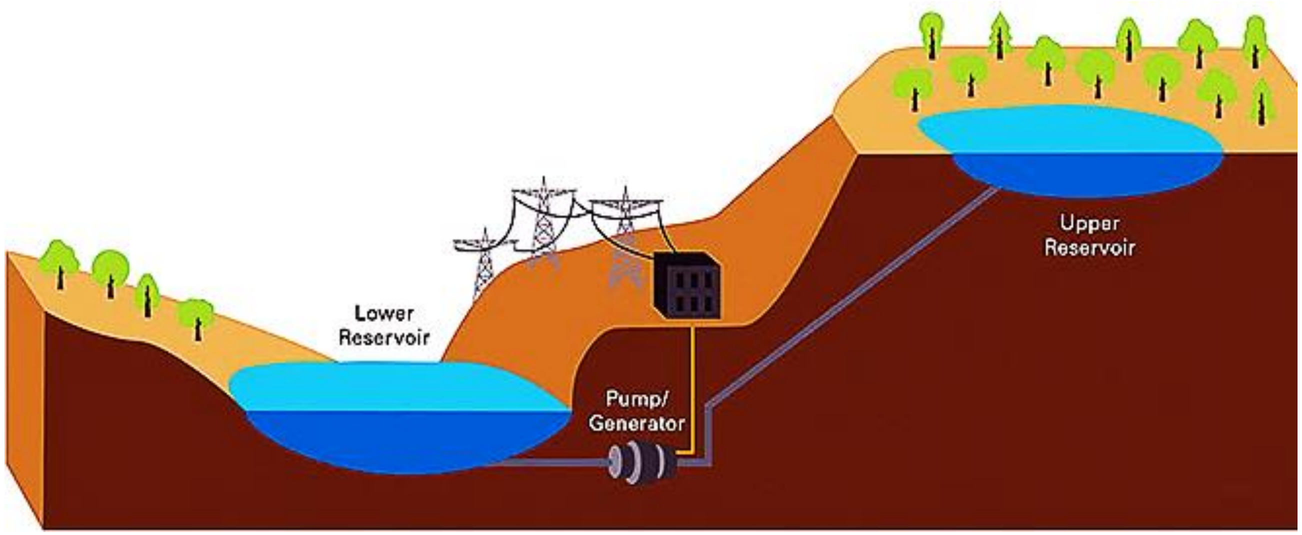


Figure 10 - diagram of a pumped hydro storage facility. Source: theengineer.co.uk.

At the other extreme are long-duration technologies, where the nominal power can potentially be supplied for days, though greater than 6 hours is commonly taken as the definition of long-duration. These are used in so-called 'energy' applications. The most widely-deployed, long-duration capable technology is pumped hydro. Pumped hydro stores energy in the gravitational potential of water, see **Figure 10**. Pumped hydro plants currently operational in the UK have an average duration of about 10 hours. Other - less used - long-duration ESS examples include flow batteries and ESS technologies that store energy in compressed or liquid air forms (CAES and LAES). As noted earlier, it is relatively easy to scale the duration of flow batteries, and to do this independently of scaling the power. This is true - to some extent at least - for all these technologies.

Standard batteries, typified by lithium-ion, sit somewhere between these two extremes of duration. Although not a technical limit, batteries in commercial use generally top out at about 4 hours of duration, with shorter durations more common. Standard battery BESSs can therefore be employed for some subset of the full range of both power and energy applications you could possibly imagine, and are often the commercially optimal solution for most of the currently remunerated applications. We explore BESS applications in detail later.

Over the long term, the additional concept of seasonal storage may become important, whereby energy is stored at scale with potentially months between the energy storage and retrieval processes (this is a different concept to that of storage duration, though the two are often conflated). The storage of electricity in hydrogen form is the most hyped example of this. Learn more about hydrogen in our separate report on the subject.

Current ESS Deployment

According to BloombergNEF (New Energy Finance), storage accounted for just 2% of the global electricity capacity mix in 2019. This means that out of the ~7500 GW of total capacity, ~150 GW was storage. It is perhaps easier to grasp quite how insignificant this amount of storage is using energy rather than power terms - according to the IEA (International Energy Agency), global storage energy capacity stood at ~200 GWh in 2020, equivalent to storing the world's electricity requirements for a measly six seconds.

Of the installed ESS capacity, over 90% is pumped hydro, while BESSs account for less than 3%. See **Figure 11**. This significant difference is a reflection of the fact that pumped hydro has been commercially viable for decades, whereas - as we detail later - BESSs have only emerged as a commercially viable option within the last decade, and have only been deployed at any significant scale within the last few years.

If we look at what is currently going on in the ESS market, we find a completely different picture to that presented in **Figure 11**. In 2019, for example, only ~300 MW of new pumped hydro was added globally, according to the IHA (International Hydro Association), whereas BESSs added roughly ten times this amount (~3 GW), according to the IEA (we have switched from energy to power terms but the point remains valid). In other words, BESSs now dominate the market.

Reasons for the current dominance of BESS over pumped hydro include that pumped hydro projects:

- Can only be built at a very limited number of locations with specific topography (see **Figure 10**, on the previous page).
- Are only built at scale. Together with topographical limitations, this reduces the use cases for pumped hydro.
- Are major civil engineering projects that take years to build.

Contrast this list with that for BESSs a couple of pages back. Pumped hydro projects are also typically more capital intensive than BESS projects, which - as we quantify later - are rapidly falling in cost. However, as pumped hydro projects last decades longer than BESS projects, and, as a more mature technology, may be able to secure more favourable financing, may be cheaper on a Levelised Cost basis. Levelised Cost of Storage looks at the $/MWh and $/kW-year needed to achieve a healthy equity return.

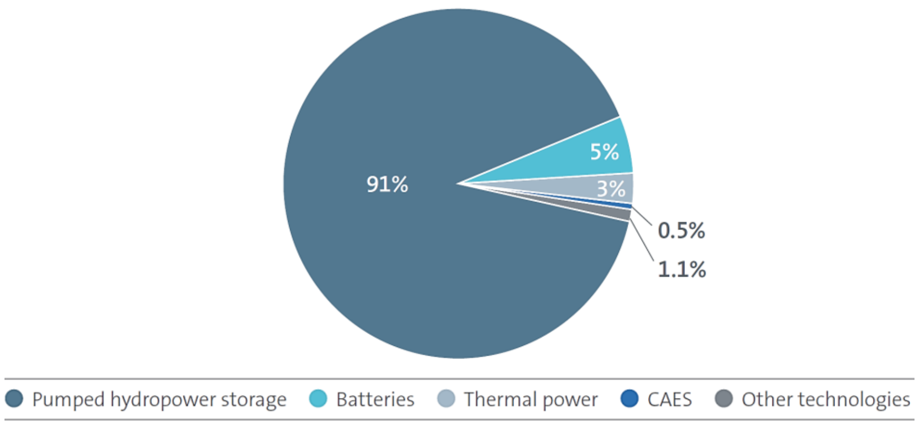


Figure 11 - installed global energy storage capacity by technology, 2019. Source: Innovation in Batteries and Electricity Storage, IEA (International Energy Agency), 2020. CAES - Compressed Air Energy Storage.

Lithium-ion Batteries

In this section we look at lithium-ion batteries in more detail, starting with their various commercial uses, of which BESSs remain a minor one.

Applications

Lithium-ion batteries have been in commercial use for three decades. For two of those decades their main use was in consumer electronics. As recently as 2013, nearly 90% of all battery manufacturing - mainly lithium-ion plus nickel-cadmium and nickel-metal hydride - supplied this market, see **Figure 12**.

More forward just 4 years, to 2017, and EVs have became the largest consumers of batteries; by 2019 their share had increased to two-thirds. EVs use lithium-ion batteries almost exclusively.

The BESS market is the youngest and smallest of the current-day battery applications shown in **Figure 12**, roughly a tenth of the size of the passenger EV market. As we quantity overpage, lithium-ion dominates the BESS market too, largely as a result of piggy-backing on the cost and performance improvements seen in the consumer electronics and EV markets; battery packs used in EV applications are the same or similar to those used in BESS applications. Having overlapping supply chains with these other, larger markets has its complications as well as benefits. For example, it ties the BESS industry more closely to the research, development and innovation goals of these parallel spaces. For EVs this means a focus on properties such as power and energy mass density, not as relevant for BESS applications. As the BESS market grows in size, it is likely that it will become more independent from the other applications' supply chains, switching over to alternative lithium chemistries that suit its purposes more closely. We look at this potential market bifurcation in more detail shortly.

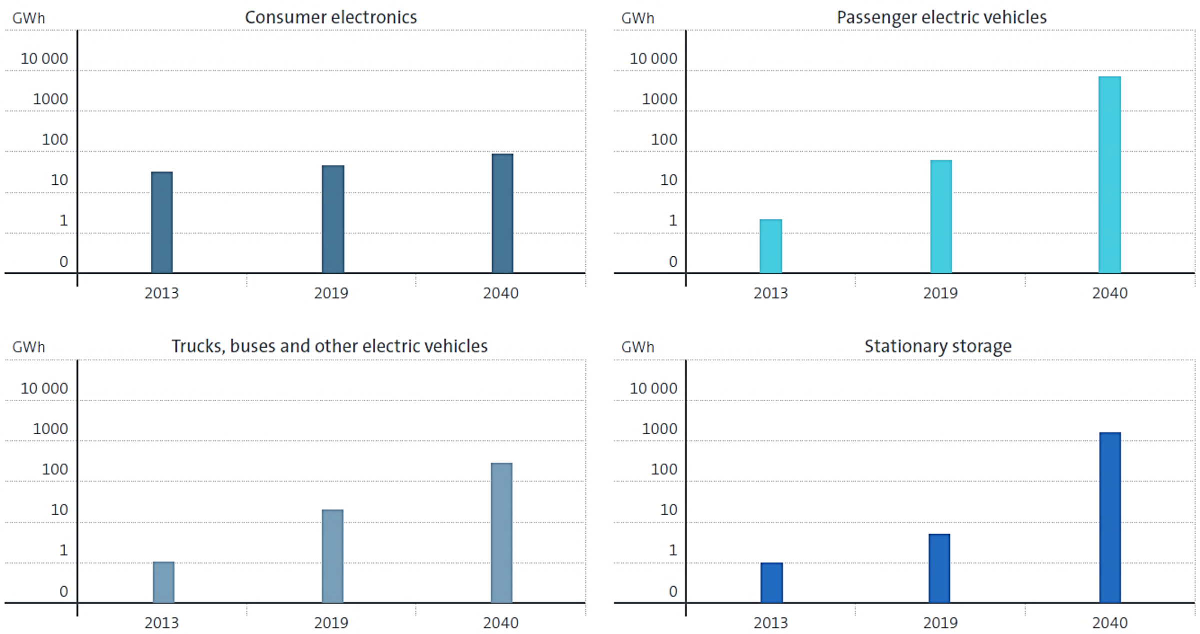


Figure 12 - annual demand for batteries across key applications in the IEA's Sustainable Development Scenario (SDS). Source: Innovation in Batteries and Electricity Storage, IEA, Sept 2020.

Figure 12, on the previous page, looks forward as well as back, estimating that the BESS market is set for considerable growth, scaling by more than two orders of magnitude by 2040, overtaking consumer electronics as the second largest application, but still being dwarfed by the gargantuan EV market. Most cars should be electric by this time, so this seems like a reasonable guess. Clearly, production of lithium-ion batteries will need to scale rapidly, and there are various challenges associated with this, as we discuss shortly. The last section of this report has more to say about the future of the BESS market.

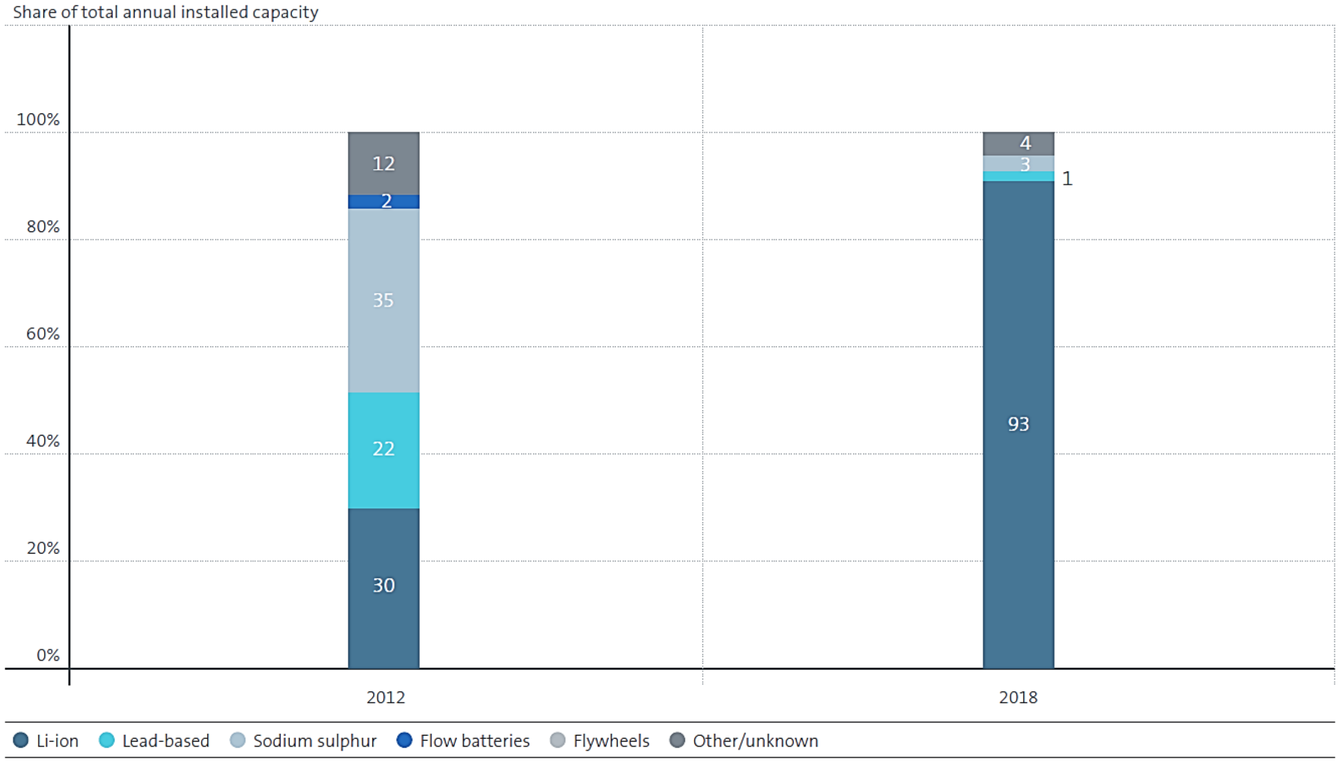


Figure 13 - ESS technology mix excluding pumped hydro, 2012 and 2018. Source: [Innovation in batteries and electricity storage](), International Energy Agency (IEA), Sept 2020.

BESS Market Share

To recap, pumped hydro dominates the ESS market in terms of cumulative installations, whilst BESSs dominate in terms of recent installations. But if we put pumped hydro to one side, what does the ESS market look like, and how is it evolving? This question is addressed in **Figure 13**.

As previously suggested, the BESS market barely existed in 2012. However, lithium-ion did not dominate what was deployed in that year. **Figure 13** shows that other types of battery - namely lead-based, sodium-sulphur and flow batteries - made up a significant share of the then tiny market.

Move forward to 2018, though, and, benefiting from the rise of EVs, lithium-ion now accounts for more than 90% of annual ESS installations (and ~80% of cumulative BESS capacity). This trend has continued through to today, with lithium-ion completely dominant in the short-duration applications at which it excels and which are the revenue focus of today's market, as we see later. Competing types of battery are less attractive for most applications, given lithium-ion's advantages across a range of technical and economic factors, including: efficiency, energy and power volume density, price, commercial acceptance and availability. See the Appendix for a detailed comparison between types of storage.

Types

As noted earlier, the term lithium-ion refers to a group of batteries that all use lithium as the cation. The standard approach, used since the early days of lithium-ion, is to employ a graphite anode combined with a metal oxide cathode. Precisely which metal oxide is used is the main differentiating factor between types of lithium-ion batteries. Each metal oxide uses a different blend of raw materials and has different cost, performance and safety characteristics. The main types of cathode, used in both EV and BESS applications, are:

- Lithium nickel manganese cobalt (NMC). This comes in various blends, with different ratios between nickel, manganese and cobalt (e.g. NMC 811 has the ratio 8 Ni : 1 Mn : 1 Co).
- Lithium nickel cobalt aluminium (NCA).
- Lithium iron phosphate (LFP).

Figure 14 shows which cathodes are currently used in EV and BESS applications, and forecasts how this might change in the future. The picture today is that around 60% of BESSs currently use NMC cathodes, not coincidentally also the technology of choice - with roughly an 80% market share - for EVs. Looking ahead, **Figure 14** suggests that what is currently quite a similar market between the two applications will bifurcate by 2030, due to the different priorities highlighted earlier. For BESS applications, LFP is forecast to overtake NMC by 2030. This seems reasonable given the momentum LFP currently has in the market. This momentum can be explained by various factors, including:

- Supply constraints for NMC batteries in late 2018 and 2019 pushing people towards the available supply of LFP. In addition, the raw materials used in LFP are more readily available and otherwise less problematic than those used in NMC, see overpage.
- LFP is less expensive than NMC, see later section on cost.
- LFP has higher thermal stability than NMC, particularly touted as an advantage for residential applications.
- Segments of the vehicle market are also adopting LFP, creating the potential for continued scale benefits from EV adoption (though **Figure 14** does not see this happening).

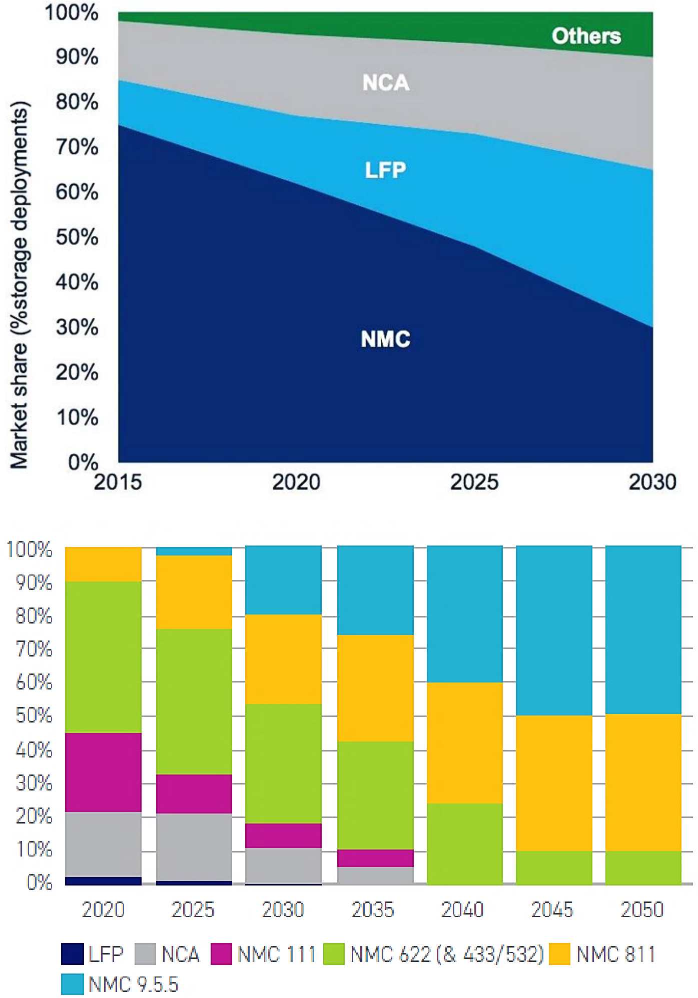


Figure 14 - top, BESS market share by chemistry (%); bottom, EV market share by chemistry (%). Top graph source: Can LFP technology retain its battery market share?, Wood Mackenzie, July 2020. Bottom graph source: Lithium, Cobalt and Nickel: The Gold Rush of the 21st Century, the Faraday Institution, April 2020.

Supply Chain and Resource Considerations

Today, the combined annual demand for batteries relevant to the clean energy transition stands at roughly 200 GWh. If we take **Figure 12**, three pages back, as our guide, this will need to scale by a couple of orders of magnitude by 2040, with this scaling likely front-loaded as motor manufacturers rush to switch to all-EV production, and as BESS deployment takes off. The natural question to ask is: is this rapid scale-up even possible? Summarising a range of opinions, the answer appears to be yes - probably - but there will be challenges along the way.

Research firm Wood Mackenzie's 'ForeSight 2020: Storage' report states that "it is not immediately clear that supply can meet surging demand {for batteries}, particularly given the dramatic upsides possible amidst the accelerated energy transition". The key issue, according to the Faraday Institute's report 'Lithium, Cobalt and Nickel: The Gold Rush of the 21st Century', appears to be about scaling up all along the battery supply chain, rather than whether the world has enough resources in the ground; specifically enough lithium, cobalt and nickel, of which there is a limited supply. Whilst it is true that the current annual production of these raw materials is far from adequate to meet anticipated future demand, according to the Faraday Institution's modelling there are more than enough resources in the ground to supply the manufacture of EV batteries to 2050 (and by implication also for other applications). If we look at these metals in turn…

Today**, Nickel** has a large global supply relative to its use in batteries, and also compared with supplies of nickel and cobalt. Nickel supply is therefore not likely to be a limiting factor for BESS manufacture. In any case, nickel could be replaced with copper and iron in the long term.

Cobalt is potentially more problematic than nickel as it has much lower global resources, the mining capacity is lower, it is expensive, and over 60% of its supply comes from just one country - the Democratic Republic of Congo, where there are social and human rights issues associated with cobalt mining, which is low-tech and labour intensive. For all these reasons, lithium-ion is already evolving away from high-cobalt systems, and, as suggested by **Figure 15**, this trend is likely to continue. The cobalt shortage is therefore expected to be manageable.

Although to a lesser extent than cobalt, **lithium** is also a relatively rare metal with supply concentration issues; key quantities of lithium are found in Chile, Australia and Argentina. Without switching to a type of battery that uses a different cation - for example, switching to flow batteries, some types of which use abundant and relatively inexpensive raw materials - there is no way around lithium use as there is with cobalt. However, the Faraday Institution does not see a long-term shortage of lithium, though they do see a shorter-term challenge in converting it into a battery-grade product - in many cases the available lithium supply is not suitable for the battery industry.

In addition, there are a number of other reasons not to worry too much about resource availability limiting the BESS industry long term, though that does not mean there will not be supply bottlenecks and associated price spikes along the way:

- Batteries are improving in longevity as the technology improves, and this trend is likely to continue, meaning fewer batteries will need to be manufactured.
- Within the next 5-10 years, long before ground resources become an issue, it is likely that battery recycling emerges at scale. Batteries themselves will add to the raw material supply for the next generation. As one example of developments in this area, the Faraday Institutions's ReLib project is 'developing the technological, economic and legal infrastructure to allow close to 100% of the materials in lithium-ion batteries to be recycled'.

Even before battery recycling becomes the norm, there is the possibility of using batteries in second-life applications, with the first life an exhausting EV application and the second life a less demanding BESS application.

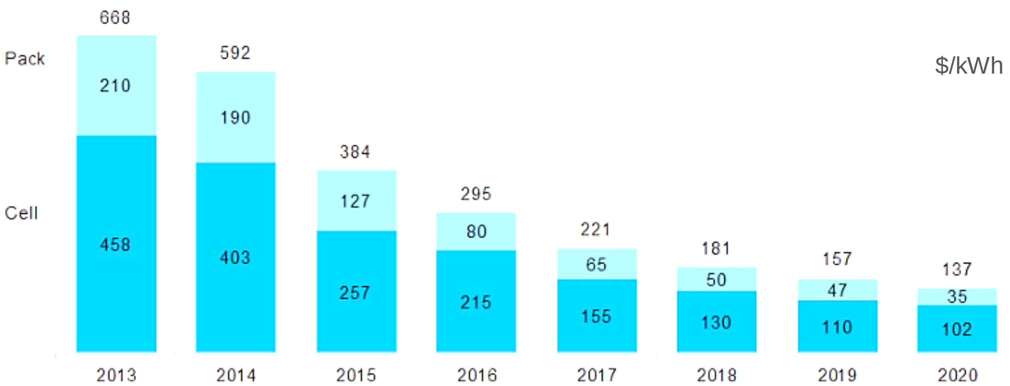


Figure 15 - historical volume-weighted average pack and cell price split for EV and ESS applications (real 2020 $/kWh). Source: BloombergNEF blog, December 2020.

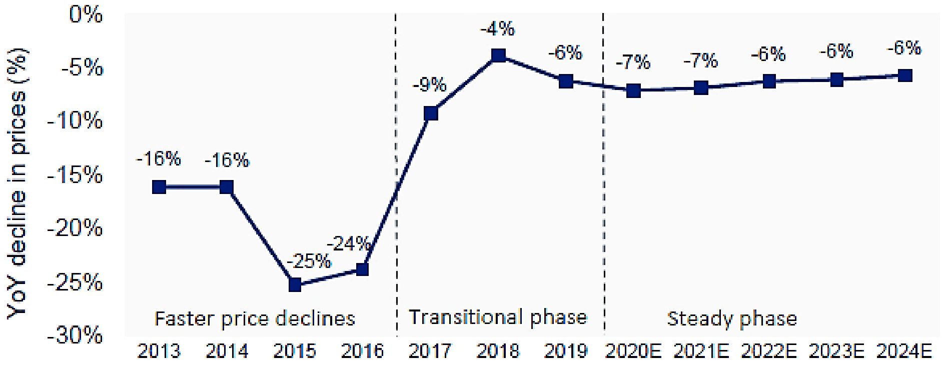


Figure 16 - historical and forecast year-over-year BESS price change (%). Source: Foresight 20/20: Storage, Wood Mackenzie, February 2020.

Cost

Pack Price

In tandem with a massive ramp-up in manufacturing capacity and the associated economics of scale, the cost of lithium-ion packs has fallen about 90% over the last decade, an 18% fall for every doubling of cumulative manufactured volume. This is according to BloombergNEF's Battery Price Survey, which puts the average pack prices for ESS and EV applications at $137/kWh in 2020, see **Figure 15**. There is a wide range of prices around this average, with LFP contributing to the lowest reported prices (though research firm Wood Mackenzie see this price advantage narrowing over the next few years). According to Greentech Media, developers of BESSs may in practice see substantially higher battery pack prices than this average, with size of project being a key determinant of price (smaller = more expensive).

BloombergNEF expects that prices will continue to fall, with the same relationship to manufactured volume holding for at least the next 10 years. This would mean an average pack price of ~$60/kWh in 2030. It is in 2030 that research firm IHS Markit believes that flow batteries could become broadly competitive with lithium-ion, for 8 hour duration applications.

BESS Price

Although battery pack price is important to overall BESS price, balance-of-system components contribute over half of total equipment costs. **Figure 16**, from Wood Mackenzie, shows that, after rapid annual price declines from 2013-16, overall BESS prices have steadied recently, but are still forecast to continue to decline by ~6% annually over the next few years.

There are a number of ways of quantifying the value of BESSs; just looking at their price is not very informative. These include Lazard's Levelised Cost of Storage measure, mentioned earlier. We will largely not use this concept due to the very market-specific nature of storage revenue streams. We instead present some illustrative business models and their expected IRRs (Internal Rates of Return) later.

BESS Applications

Earlier we outlined the broad motivation behind the use of BESSs - providing energy system flexibility. In this section, we connect the dots between this system-level motivation and the reality that BESSs are selfish entities that need to make money for - or at least to offer tangible value to - their owner. We start by outlining the multitude of possible BESS use cases and services, then focus in on what it takes to turn a given use case into a viable business model.

Use Cases

There are several distinct ways of using BESSs. At the highest level, these 'use cases' can be divided into **on-grid** or **off-grid** categories, either of which can exist in **standalone** or in **hybrid** forms. 'Hybrid form' means the BESS is co-located with a power generation asset. Renewable power sources - solar in particular - are the most obvious fit, though any type of variable generation could potentially benefit. As we clarify shortly, there are a couple of ways that this hybridisation can be implemented.

Narrowing our focus to just on-grid use cases, these can also be divided into **front-of-the-meter (FTM)** or smaller-scale, **behind-the-meter (BTM)** variants. BTM means being located on the customer side of the connection point between the electrical grid and the customer; FTM means on the grid side. BTM use cases can be located on **commercial and industrial** (C&I) or **residential** premises.

Figure 17 shows some examples of typical on-grid use cases. It makes the additional distinction between FTM systems either being connected to the **distribution** or **transmission** grid.

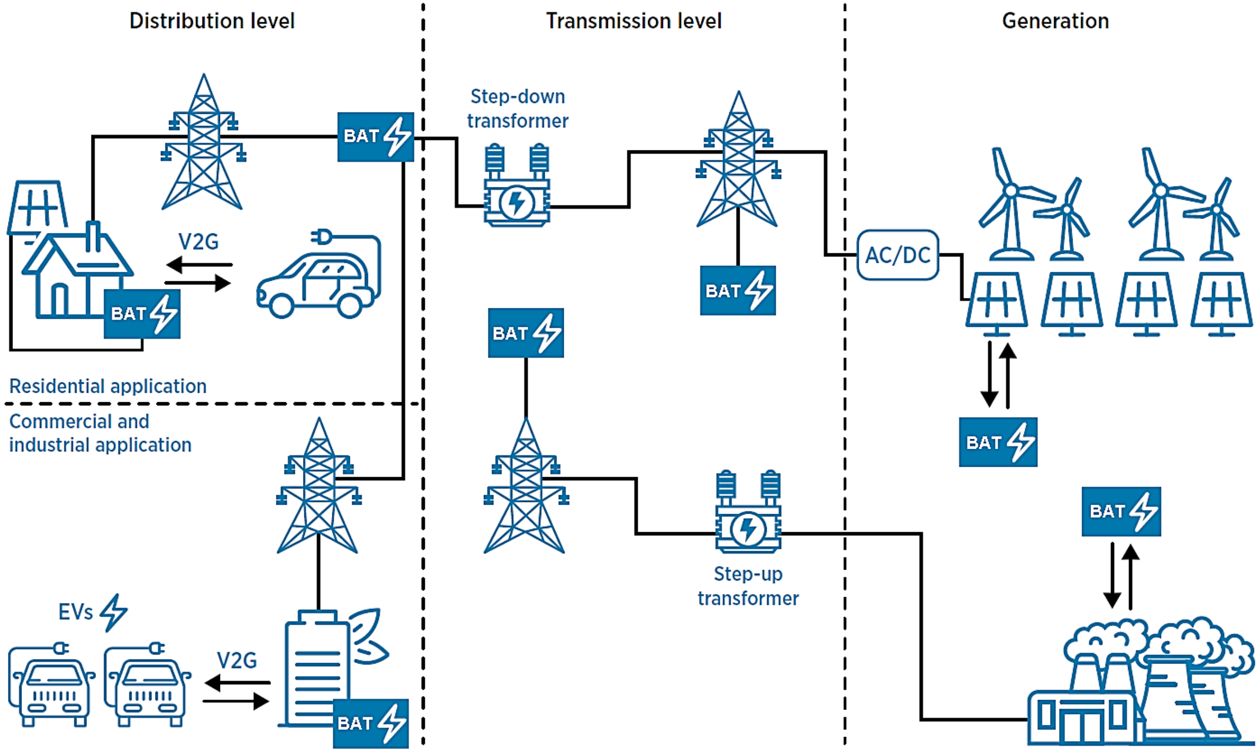


Figure 17 - example on-grid BESS use cases. Source: Electricity Storage Valuation Framework: Assessing system value and ensuring project viability, IRENA, 2020. V2G - vehicle-to-grid.

Having defined the broad categories of use case, we now outline the services that can potentially be provided by each. Some services are unique to a category, whilst others can potentially be provided across multiple categories. Some services are insular, in that the person paying for and benefiting from the service are the same entity - the storage owner -, whilst in other cases, the service is solicited by a external stakeholder - such as an electricity system operator, grid infrastructure owner or government - and its provision benefits multiple parties. For the storage owner, service provision may be beneficial due to the availability of a direct revenue stream, or because of indirect benefits such as avoided costs (or fluffy things like peace of mind). In practice, storage business models often involve the provision of multiple services in parallel, referred to as service or revenue stacking.

On-grid, Front-of-the-meter

Standalone

Large-scale, standalone, FTM BESSs (also called grid-scale or utility-scale) can and do in practice provide a wide range of services, including:

Energy arbitrage - buying and selling electricity in wholesale electricity markets. Electricity is traded ahead of its generation for delivery across a range of timescales, from months ahead to just prior to delivery. Energy arbitrage is the process of buying low - charging - and selling high - discharging - in short-term electricity markets. We expand on this key revenue stream later.

Capacity provision (also called resource adequacy) - providing long-term - usually multi-year - electricity supply availability. Examples of this include: (a) direct replacement of a retiring fossil fuel plant with a BESS, ensuring some level of capacity at a local level; (b) at the opposite end of the scale, government procurement of capacity on a national basis, perhaps for only certain times of the year.

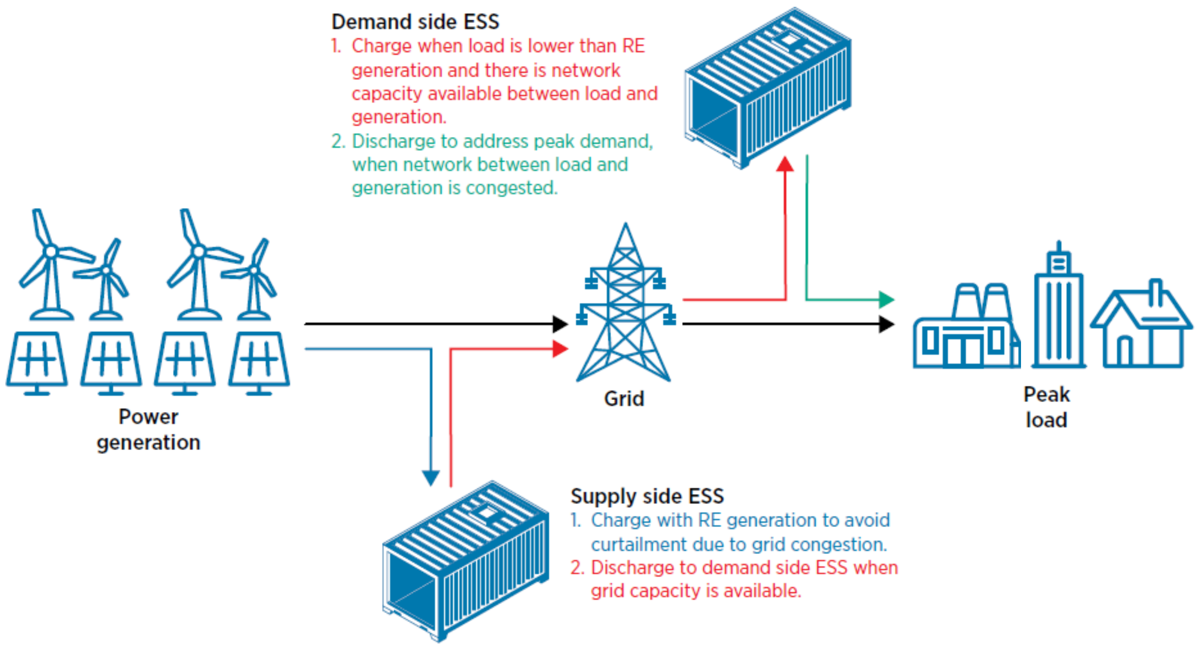


Figure 18 - battery storage for distribution/transmission upgrade deferral. Source: [Electricity Storage Valuation Framework: Assessing system value and ensuring project viability](), IRENA (International Renewable Energy Agency), 2020. V2G - Vehicle-to-grid; EV - Electric Vehicle.

Grid infrastructure upgrade deferral or **avoidance** - using a BESS - or pair of them, see **Figure 18** - to adjust the load on a section of the grid such that the grid is not overwhelmed. This has benefits both for the system operator and the grid infrastructure owner. For the grid infrastructure owner, grid upgrades that would otherwise be needed are delayed or no longer necessary, saving money. This service is less common than the other FTM services described here.

Grid service provision (also called ancillary, balancing or flexibility services) - supplying services to the system / transmission network / distribution network operator to help maintain grid stability (unstable grid = blackout in the extreme case). BESSs can provide most of the grid services that operators might need to procure, including:

- **Frequency response** - keeping the grid operating at its target frequency (50 Hz in the UK), both under normal operating conditions and after a fault. The fast response speed of batteries is particularly suited to the provision of the fastest of frequency response services, especially important after a major fault.
- **Reserve** - providing back-up power in the event of an unforeseen change in demand or generation. Reserve is a slower acting but longer duration service than frequency response. In our earlier language, it is an energy application, while frequency response is a power application.
- **Voltage support** - keeping all areas of the grid close to its target voltage (different parts operate at different voltages). Unlike frequency, voltage varies across the grid, even in sections with the same target voltage. Voltage is kept close to target by controlling the ratio of the two types of power on the system - active power (the power that we are familiar with and that powers lightbulbs) and the more mysterious reactive power (the power that moves active power from power plant to bulb).
- **Black start** - the ability to repower the grid in the event of a total shutdown. A total shutdown is particularly problematic because you need some power to get back up and running, but where does this power come from if you are totally shutdown? Charged batteries are one solution.

Figure 19 - example large-scale solar plus storage installation.

Hybrid

A FTM, hybrid BESS, consisting of a co-located BESS and large-scale generation asset - be it solar park, wind farm, or other asset - are typically implemented in one of two ways. In both cases the grid connection is usually shared.

In the first case, the BESS operates more or less independently from the generation asset, acting similarly to a standalone BESS. This might seem like an odd thing to do but can be a neat way of improving the return and reducing the risk on the combined asset. These benefits are explained in more detail in this article.

Alternatively, the BESS and generation asset interact, with the BESS's main role typically being to provide a buffering service for the generation asset, storing electricity when the grid does not need it - when prices are low and the asset might even be curtailed (told to stop exporting to the grid) - and releasing previously stored electricity when it does, and prices are higher. In theory, this is how you might imagine getting to a 100% carbon-free grid - just add storage to all renewable assets. Alas, the commercial reality is that - in the UK, at least - independent BESS and asset operation is currently the norm.

On-grid, Behind-the-meter

Standalone

With the possible exception of the grid infrastructure upgrade deferral or avoidance service, all services previously listed for standalone, FTM use cases could theoretically be implemented BTM, though not necessarily with the same level of cost or effectiveness. The possibility of implementing these BTM will depend on the market, with implementation more probable for larger C&I rather than domestic systems (unless aggregated together, see overpage). In addition, some services can *only* be provided BTM. These BTM-unique services are insular, focussed on providing services to the household or business where the BESS is located, rather than the wider electricity system (though there may be system benefits too). Examples include:

Bill management - minimising a site's electricity bill. Exactly how this is done will depend on how a site is charged for electricity, but common examples include *demand charge reduction* - typically reducing the peak load a site draws from the grid - and *time-of-use bill management* - shifting when electricity is imported from the grid to make best use of time-of-use variation in the electricity tariff.

Backup power - providing an alternative power source in the case of a blackout. BESSs offer a low-carbon alternative to other possible backup technologies, such as diesel generators. BESSs usually have to be designed and scaled specifically to provide this service, and, in most cases, will only be able to deal with power outages lasting a few hours, perhaps only for a critical subset of the total load.

Power quality - improving the ability of electrical equipment at a site to consume the energy being supplied to it. A number of power quality issues, including electrical harmonics, poor power factor, and voltage instability and imbalance - none of which we will explain here - impact on the efficiency of electrical equipment. High power quality is particularly important for some industrial electrical equipment as it prevents undue wear and tear and reduces equipment downtime.

Hybrid

By combining a BTM BESS with an on-site renewables installation, most commonly rooftop solar, a new service emerges, in addition to those already described for standalone systems - **maximising self-consumption**. This means maximising the amount of electricity produced on-site that is consumed on-site, rather than exported to and later imported from the grid. A BESS makes this possible by time-shifting electricity from when it is produced in excess - and might otherwise be exported - to when it is most needed - and might otherwise have to be imported. For example, from the middle of a sunny day to the evening. This usually makes financial sense as electricity produced on-site is essentially free (once a system is installed and paid

Figure 20 - example domestic solar plus storage installation (the white box on the wall is a Tesla Powerwall).

for), and its export value is usually considerably less than the cost of importing electricity. In some markets, exporting to the grid is financially rewarded, e.g. through a feed-in tariff or net metering system (see our EU solar report), which may reduce or eliminate the financial benefit of self-consumption. One particularly neat use of delayed self-consumption is the overnight charging of an EV using solar. Speaking of EVs, these are really just BESSs on wheels, so when stationary can potentially provide standard BESS services, though battery degradation is an issue. This setup is called **vehicle-to-grid** (V2G). It is not a mainstream use case, yet.

Off-grid

All our previous use cases were on-grid, though the idea of reducing reliance on the grid was seen as a useful application BTM. This hints at the existence of additional use cases for BESSs in off-grid and weak-grid applications. The need for such applications is greatest in developing countries. Almost 1 billion of the world's population still do not have access to electricity, most of whom live in rural areas. Where electricity is accessible, a major challenge is the reliability of supply and related dependence on diesel generators. BESSs potentially provide a solution, more so as costs continue to fall. Specifically, BESSs could provide services such as enabling entirely **solar-powered homes** and **increasing the share of renewables in mini-grids**, local grids used to power individual communities not connected to a national grid. Even in the richest countries, weak grids are not uncommon, particularly in areas that suffer from extreme weather and related issues such as wild fires. Climate change is only likely to make these once rare occurrences more common. Plus, some people just want to be grid-independent, even in reliable areas.

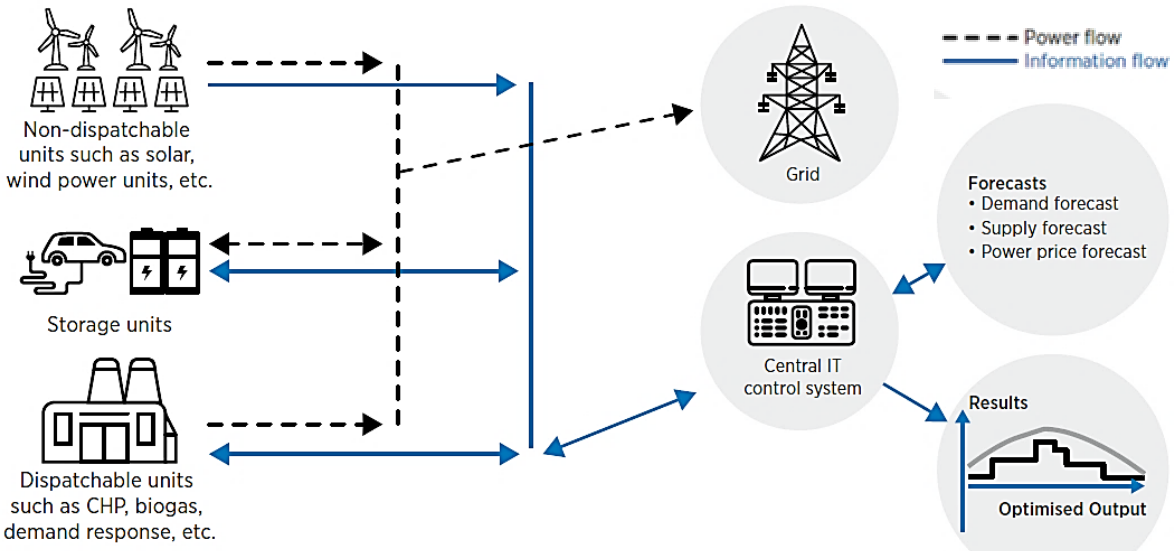


Figure 21 - one way of implementing the aggregation use case. Source: Electricity Storage Valuation Framework: Assessing system value and ensuring project viability, IRENA, 2020. CHP - combined heat and power.

On-grid, Aggregation

Most of our previous use cases were focussed on the action of a single BESS. Our final use case is the practice of aggregation, involving multiple distributed energy resources acting together as one virtual power plant (VPP). BESSs are one type of distributed energy resource that can be aggregated this way. **Figure 21** outlines how this aggregation might work. Aggregation potentially enables the provision of services that the individual assets acting alone could not.

For distributed energy resources, participation in a VPP has the potential to optimise revenue generation. In particular, for BTM BESSs participation may provide access to markets that would otherwise not be accessible.

Use Case to Business Model

The use cases given in the preceding section will not, in general, be deployed unless there is a viable business model associated with them. This is certainly the case for FTM use cases; these will simply not get financed. At the other end of the spectrum, you could imagine a homeowner installing a domestic BESS even if the economics do not strictly pencil out, if there are subjectively strong non-monetary considerations involved, e.g. love of new technology, desire for grid independence and/or to run solely on renewable power, or peace of mind from having backup power available.

BESS business models tend to be very region-specific, with a complex web of factors determining whether a given business model is theoretically possible and profitable in a given region. Very briefly, for a standalone, FTM system, these factors include (there are more):

Electricity market structure - how the electricity market is organised and regulated. A liberalised and unbundled market with an independent regulator is often quoted as an important prerequisite for BESS adoption.

Definition of storage - how storage is defined in regulation, e.g. as generation, load, both, or a separate entity unto itself. In the UK this has practical implications relating to grid fees and planning permission.

Ownership - the type of entities who are allowed by regulation to own a BESS. This may be linked to the definition of storage and is particularly relevant to the grid infrastructure upgrade deferral or avoidance service.

BESS properties - the scale, cost and performance of the BESS. Key cost and performance factors are highlighted in the Appendix. Storage capex and lifetime are key.

Planning and grid connection - whether and how quickly and cheaply a BESS can get planning permission and connected to the grid.

Market existence - the existence of markets that remunerate the services a BESS can provide. Not all the conceivable services that BESSs can potentially provide necessarily have a market attached to them.

Market access - the ability of BESSs and other technologies to access markets that remunerate the services BESSs can provide. This may be a question of whether BESS can access the market *at all*, or access it on a level playing field with other technologies. At the other extreme, the market may explicitly or effectively be a BESS-only market (due to demanding technical requirements, such as response speed).

Market profitability - how profitable BESS-accessible markets are. This depends on a multitude of factors, including: the BESS, the region, the service type, the level of competition and market prices, the last two of which may be closely related. Some services yield a guaranteed minimum level of profitability, while others provide no guarantee of returns, with returns instead determined by a combination of price dynamics and trading expertise. We expand on this in a UK context shortly.

Revenue stacking - the extent to which multiple services can be provided in parallel. This is determined by the services' contractual obligations. Stacking has the potential to increase overall profitability, assuming minimal interference between services. FTM business models typically stack energy arbitrage with one or more additional services, commonly frequency regulation.

Taxes and subsidies - the extent to which government policy tweaks a business model's viability. Storage subsidies are not as common as they are (or were at least) for wind or solar, but are important where they are available. Forms of subsidy in somewhat common use include tax incentives and inclusion in government renewables auctions (often for hybrid BESS only); examples later.

Availability and cost of financing - linked to all of the above, the availability of reasonably-priced debt and/or equity financing for a given business model.

Hybrid installations have additional complexity related to the co-located asset.

UK FTM Business Model

If the last page was rather abstract, hopefully looking at the specifics of the UK market will help. In the UK, FTM BESSs are typically deployed either standalone or in hybrid form where the BESS and the renewable asset operate more or less independently from each other. Investment is currently focussed on lithium-ion projects in the 1 to 4 hour duration range. Energy consultants Timera Energy estimate the IRR of such projects in the 8-12% range (unlevered nominal).

Other than a low-value capacity provision payment - from the Capacity Market, where short-duration storage is heavily de-rated - no government support mechanisms are available to BESSs. Viable business models are instead constructed by co-optimising between two main revenue streams: (a) energy arbitrage, the primary driver of returns for most battery projects; (b) the provision of one or more grid services, often including a frequency response service; this can provide supplementary income but faces increasing risk of cannibalisation as BESS volumes grow. The resultant revenue stack has significant exposure to wholesale electricity (and grid service auction) prices. This means future returns cannot be guaranteed, though the probability distribution of those returns can be estimated. One consequence of this uncertainty is that, to reduce risk and maximise returns, expert trading capability is required, either in-house or via a third party contract. Another consequence is that these types of project can be more difficult and expensive to finance than projects with guaranteed returns.

Energy Arbitrage

The basic concept of energy arbitrage is easy enough to understand, even if the practical details about how it is implemented are quite complex, involving sophisticated modelling of the energy system and electricity markets. Money is made by capturing price spreads; that is, by buying electricity at a low price to charge the battery and later discharging the battery to sell electricity at a higher price. As long as the price spread between the low and high prices is greater than the costs incurred during the charging cycle, then you make money. This is illustrated in **Figure 22**.

Costs incurred when cycling the batteries include:

- **Efficiency losses** - all batteries have less than 100% efficiency, meaning energy is unavoidably lost during the cycle. At the end of the cycle you have less electricity to sell than you bought at the beginning.
- **Variable charges** - for example, BESSs are charged for use of the grid.
- **Degradation charge** - battery cells degrade every time you use them, so eventually have to be replaced, typically after 8-10 years. Some fraction of this replacement cost is incurred during each cycle. More aggressive cycling leads to a higher degradation charge as the batteries lifetime is shortened by such use.

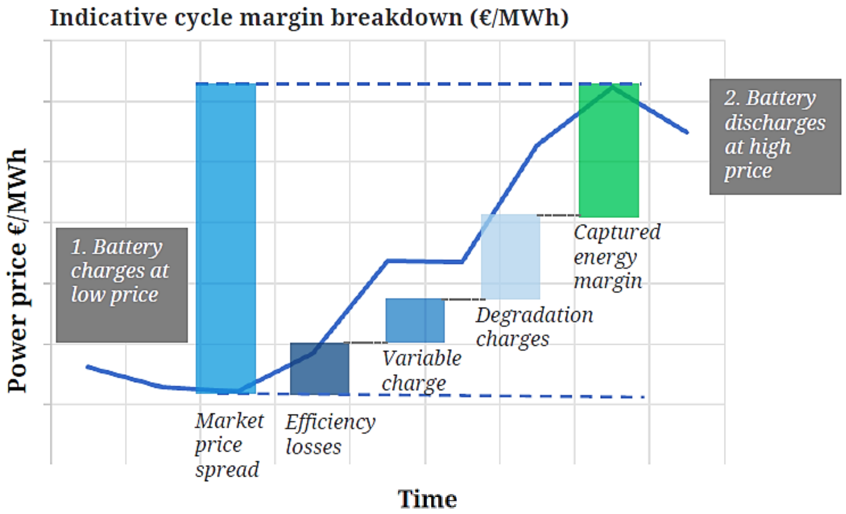


Figure 22 - illustration of the economics of energy arbitrage. Source: European Battery Investment Wave: Understanding and Quantifying Battery Value, Timera Energy, Oct 2020.

Some of the practical complexity of energy arbitrage comes from the existence of multiple markets from which a BESS can attempt to capture price spreads. Each of these markets has a different delay between fixing the price and the subsequent physical delivery of the electricity. Sophisticated trading strategies will attempt to co-optimise price spread capture across all these markets, potentially using multiple battery cycles a day. See the source for **Figure 23** for an example of how this is done. Available markets in the UK include a:

- **Day-ahead market** - relatively liquid, lower risk, but lower volatility.
- **Intraday market** - less liquid, higher risk, somewhat higher volatility.
- **Balancing Mechanism** - high volatility but high forecast / dispatch risk. This is a market used by the system operator, National Grid ESO, as a last resort to balance supply and demand just prior to physical delivery. National Grid ESO has been expanding access to the Balancing Mechanism over the past couple of years; this is beneficial for BESSs.

Assuming you have a reasonable trading strategy, then revenues from a given market are a function of how much prices change in that market. To make the most revenue, you want the prices to change as much as possible. Prices can change more in a couple of different ways: (a) a steepening in the intraday price shape (the repeated pattern that overlays electricity prices every day, peaking in periods of demand and falling at other times); (b) increased price volatility.

Price volatility is arguably the key driver of overall BESS revenue generation ability. It is largely driven by shorter-term uncertainty around wind, solar and load patterns. As renewables penetration increases and thermal plants close, it is reasonable to suggest that this will drive a structural uptrend in power price volatility, supporting battery value capture. A way of seeing that this should be the case is by looking at what happens to prices in periods when there is lots of wind and sun, and periods when there is none:

During high wind/sun periods - renewable capacity, which has very low marginal costs, sets the marginal power price. This leads to low or even negative power prices, ideal for a BESS to charge. Negative prices mean a BESS is paid to charge.

During low wind/sun periods - high variable cost peaking capacity (batteries, gas peakers and demand response) sets the marginal power price. This leads to high prices and occasionally very high price spikes, ideal for a previously charged BESS to discharge.

Grid Services

In today's markets, provision of grid services potentially provides a substantial supplementary income for BESSs, in addition to that from energy arbitrage. Grid service revenues are often split into a guaranteed component, paid simply to be available to provide a service, and a conditional component, paid if drawn upon to provide the service. **Figure 23**, a forecast from Timera Energy, suggests that in 2021 grid services could provide a little under half of the margin for a typical FTM BESS. Looking further out, this forecast sees the grid service margin declining as competition increases and market saturation occurs. However, for the structural reasons covered on the previous page, it still sees overall margin increasing as energy arbitrage becomes more valuable.

Grid services in the UK have traditionally only been tendered by the national Electricity System Operator - National Grid ESO. Whilst this is no longer the case - all Distribution Network Operators are also now running auctions to procure local grid services - National Grid services - particularly frequency response - remain where the bulk of the value is for most projects.

The arrival of a long-term contract frequency response market in 2016 precipitated the first wave of BESS projects in the UK. This initial market became saturated in subsequent years, driving down the price, and contract lengths have since been shortened to a month. However, growing system stability issues saw the introduction of a new frequency product called Dynamic Containment (DC) in Q4 2020, in addition to the standard frequency response product. According to Timera, DC is an important service for BESSs near-term because:

- Due to tough technical requirements, it is effectively a BESS-only service, eliminating competition from other technologies.
- Demand is currently a lot lower than supply. National Grid has a maximum requirement of between 1.1-1.4 GW of DC a month over 2021. In February 2021, the procured volume of DC topped out at just 400 MW.
- Related to this demand-supply balance, the price is currently very high. Auctions have been clearing at around 17 £/MW/h since the service was introduced. This is the equivalent of just under 150 £/kW/yr of revenue for a 1 hour duration battery, well in excess of the required annual return to support investment. This high price also pulls capacity away from the standard frequency service, supporting prices received for that service.

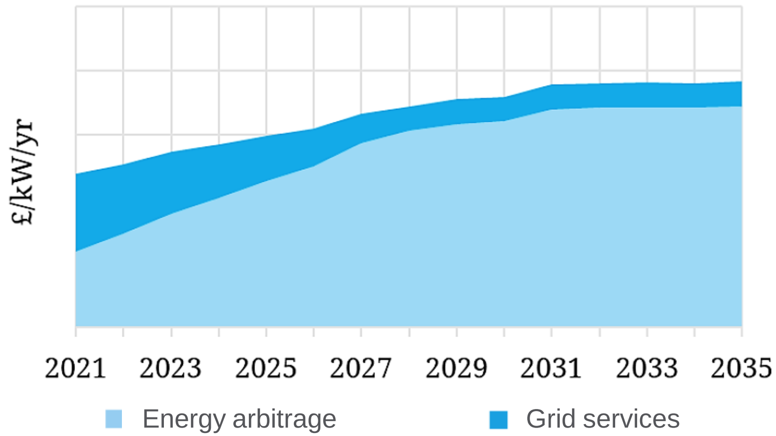


Figure 23 - forecast battery margin evolution for a typical UK FTM BESS. Source: European Battery Investment Wave: Understanding and Quantifying Battery Value, Timera Energy, Oct 2020.

- Operators have recently been allowed to stack the DC service with entry into the Balancing Mechanism.

Frequency response is an important near-term bridge to support battery investment cases across the early to mid 2020s. However, it would be wrong to suggest it is the only game in town. Although less lucrative, FTM BESSs can access other established grid service markets, such as reserve. In addition, as the need increases, new National Grid services are opening up, some with long-term contracts available. Examples include constraint management, providing flexibility to deal with localised constraints on the transmission grid, voltage control, outlined earlier, and the provision of inertia. Inertia is roughly the momentum of the electricity system; with appropriate momentum, the system is less liable to harmful frequency deviation.

Illustrative Business Models

Although the preceding UK example illustrated some general principles that apply beyond the UK's shores, it is worth repeating that storage business models are very region-specific. To emphasise this, the table to the left lists a selection of illustrative business models, covering the most common use cases. Most use cases have a US and an outside-the-US example.

It is hard to conclude anything about a general relationship between use case and IRR from this table, given the differences in IRR between locations. Things are clearer when doing a Levelised Cost of Storage comparison, with FTM use cases providing better value on a $/MWh and $/kW-year basis, most likely due to economies of scale. See the source for **Figure 24** for more details.

Use Case	Location	Project Size	Key Revenue Streams	IRR (%)
FTM, standalone	US, California	50 MW / 200 MWh	energy arbitrage, frequency regulation, reserve, capacity provision	23.3
	Germany	50 MW / 200 MWh	energy arbitrage, frequency regulation	4.3
FTM, standalone, grid upgrade deferral	US, Massachusetts	10 MW / 60 MWh	frequency regulation, distribution deferral, demand response	8.1
-	-	-	-	-
FTM, hybrid with solar	US, South Texas	100 MW / 200 MWh, 100 MW PV	energy arbitrage, reserve	22.3
	Australia	100 MW / 200 MWh, 100 MW PV	energy arbitrage, frequency regulation, capacity provision	11.9
BTM, commercial & industrial, standalone	US, San Francisco	1 MW / 2 MWh	demand response*, bill management, local subsidy	33.7
	Canada	1 MW / 2 MWh	bill management	13.1
BTM, commercial & industrial, hybrid with solar	US, San Francisco	0.5 MW / 2 MWh, 1 MW PV	demand response*, bill management, local subsidy	26.2
	Australia	0.5 MW / 2 MWh, 1 MW PV	bill management	28.0
BTM, residential, hybrid with solar	US, Hawaii	0.006 MW / 0.025 MWh, 0.010 MW PV	bill management	14.9
	Germany	0.006 MW / 0.025 MWh, 0.010 MW PV	bill management, local subsidy	4.4

* demand response is a service whereby electricity usage is adjusted as instructed by the service procurer.

Figure 24 - a selection of illustrative business models. Source: [Lazard's Levelized Cost of Storage Analysis - Version 6.0], Lazard, 2020.

Current BESS Market

In this section we look fleetingly at the history and current state of the global BESS market, before delving into the UK market in a little more detail.

Global Market

In the last decade, the global BESS market has transitioned from its infancy to true scale, even as the industry and policymakers still work to fully understand and value the technology. Getting accurate deployment figures is a challenge, especially BTM, but, based on multiple sources, it is reasonable to estimate that the cumulative global installed BESS capacity grew to well over 10 GW in 2020, from a near-zero base a decade ago. **Figure 25** shows when and where growth in the global ESS market has taken place. We assume this figure includes pumped hydro, but as we covered earlier, the BESS market now dominates the ESS market in terms of annual additions, so this is not greatly important. **Figure 25** shows the market expanding from annual additions in the 100s of MW in 2013, to about 3 GW in 2019. It also highlights that growth took a hit in 2019 compared to 2018, partly as a result of the fallout from several fires that happened at FTM BESSs in 2018 and 2019. More recent figures from IHS Market suggest that - despite the pandemic - the market expanded by a record-breaking 4.5 GW in 2020. Finally, **Figure 25** makes it clear that the BESS market is highly concentrated in a few key markets, namely: South Korea, China, the US and Germany. Other significant but smaller markets include, in alphabetical order: Australia, Chile, France, India, Italy, Japan, Spain, and the UK, amongst others.

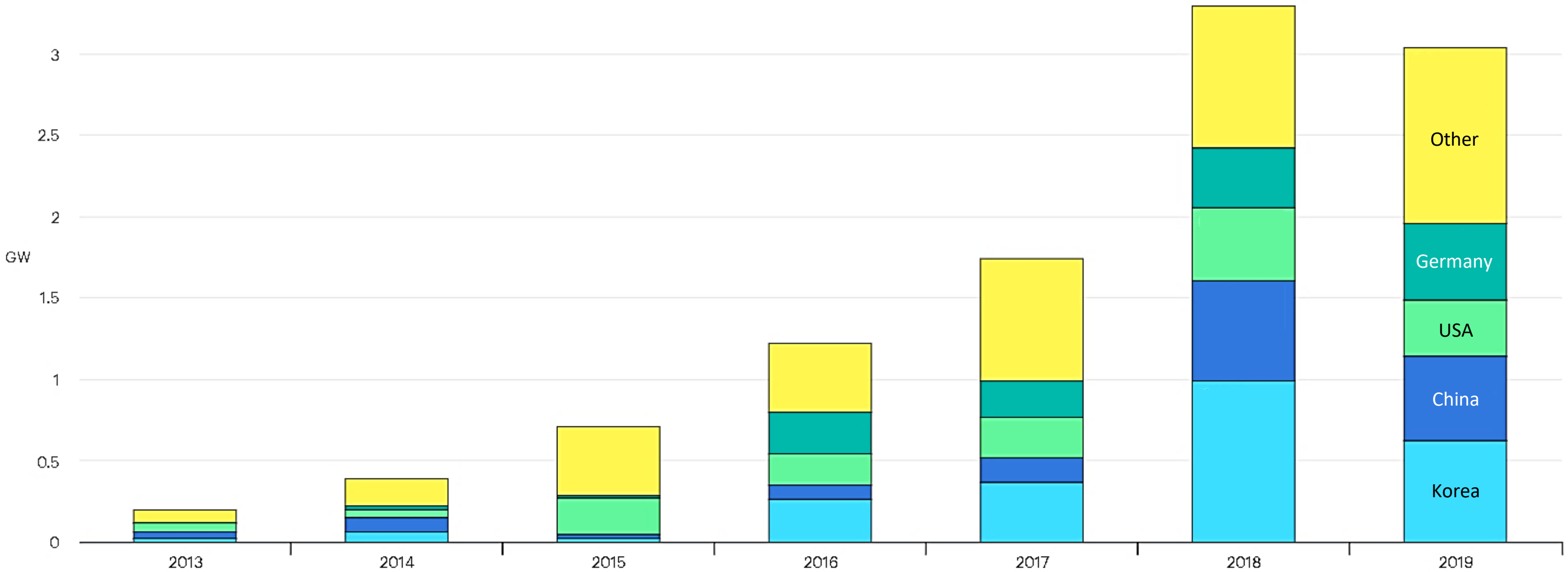


Figure 25 - global annual ESS deployment by country, 2013-2019. Source: Energy Storage Tracking Report, IEA, June 2020.

Market Drivers

We highlighted earlier some of the factors that make operating a FTM BESS possible and profitable. The expansion of the BESS market shown in **Figure 25**, on the previous page, is being driven by many of these factors, as well as an overlapping set for BTM, moving in BESS's favour, particularly in the markets highlighted above. Where these factors have not moved in BESS's favour they act as barriers to deployment. The specifics vary by country and use case but we can attempt to construct a broad narrative describing what is driving the BESS market…

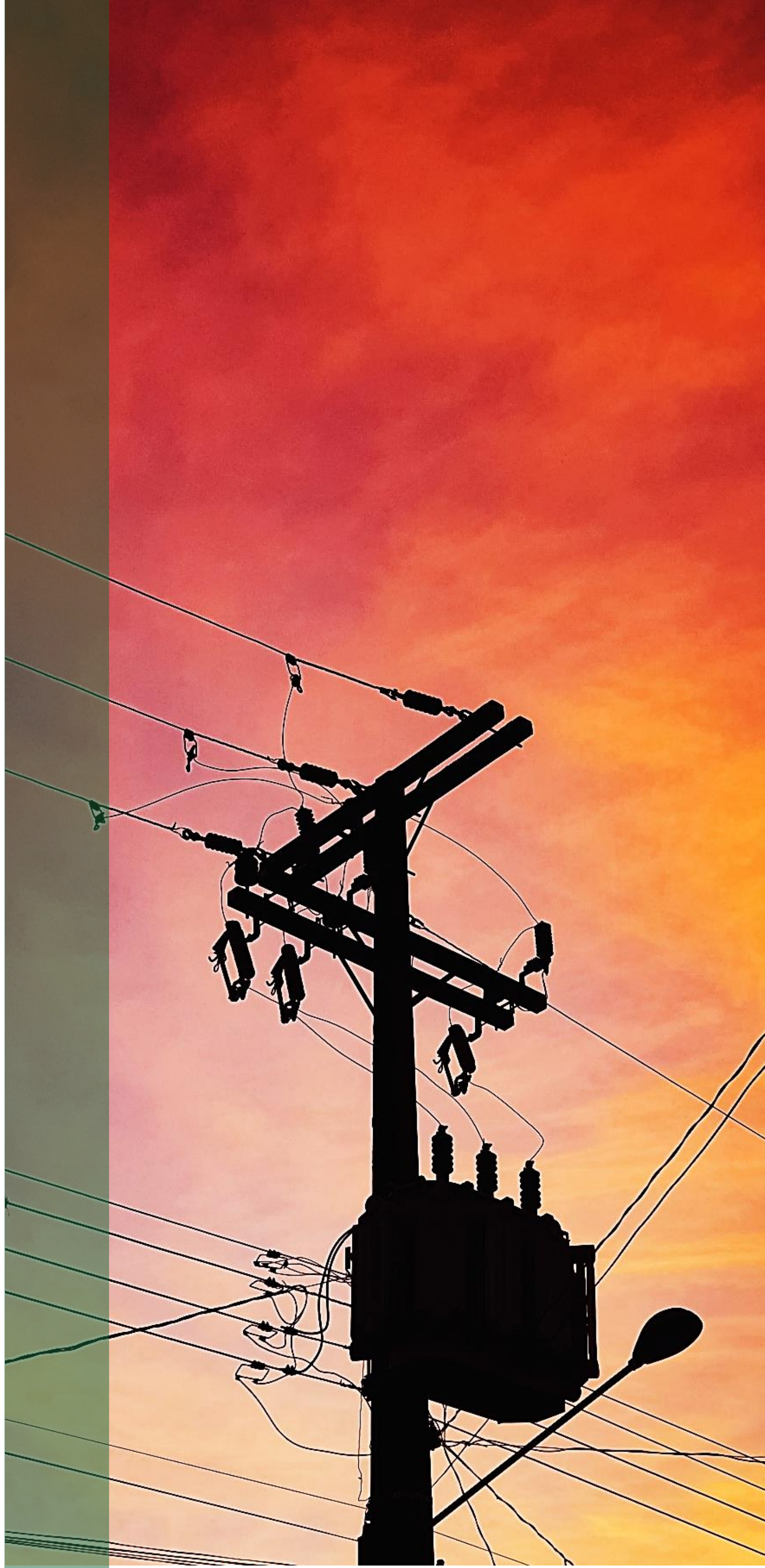
- Climate change and the related global movement towards decarbonised and decentralised sources of power have led to a need for: (a) electricity system flexibility and new ways of providing this; (b) modernisation of grid infrastructure, meaning both an expansion of carrying capacity - where needed - and a transition to smarter grids. The term 'smart grid' is explained at this link.
- There has been a growing recognition among key enabling stakeholders, including governments, regulators and system operators, that storage is well suited to helping on both of these fronts (in the specific ways described earlier).
- In some regions, this recognition has to the removal of regulatory barriers, the opening up of existing markets to BESSs, and the creation of new markets, some targeted specifically at BESSs. This process has been aided by the move to smarter grids. As one example of this, the installation of smart meters in customer premises opens up the possibility of granular time-of-use billing and associated BESS services.
- Combined with dramatic battery cost (Figure 16) and performance improvements, this opening up process - where necessary - has led to the emergence of viable BESS business models and subsequent deployment.
- Deployment has been aided by financial incentives for storage in some regions. These incentives appear to favour hybrid BESSs, and be particularly generous in countries with a greater system need for storage, or with an economic stake in battery manufacturing. As an aside, several major governments are also notably supporting early-stage innovation in storage technologies, including long-duration storage.

A few, non-exhaustive examples of financial incentives that have been important in shaping global BESS deployment include:

- USA - up to 30% investment tax credit for the storage part of solar plus storage. Extension of this tax credit to cover standalone storage is in the works.
- South Korea - financial incentives related to renewable energy certificates for utility-scale renewables plus storage. South Korea is home to some of the largest battery manufacturers in the world, e.g. Samsung, LG Chem and SK Innovation.
- Regional level across EU countries, including Germany, Italy, Austria and Belgium - direct upfront subsidies for the storage part of residential solar plus storage.
- India - government renewables auctions for utility-scale solar plus storage, which mandate storage equal to 50% of solar generation capacity.
- Italy - 50% tax deduction for the storage part of residential solar plus storage. Italy also allows the tax deduction of 110% of the storage price if a house receives an efficiency renovation (i.e. free storage).
- California - solar mandate for new-build housing where it is possible to trade in obligatory solar credits through storage credits.

As well as market push from governments, there is also notable market pull from those looking to profit directly from BESSs, as well as from corporations whose main area of business is not storage, for example from:

- Big Tech and other large corporations, who are almost universally moving to obtain 100% of their power from renewable sources. As one example, Google is already obtaining all its power from renewables, but now it wants to match electricity usage and renewables supply in real-time; this requires storage.
- Investment companies divesting from fossil fuel related investments.
- Oil majors attempting to rebuild themselves as clean energy companies.
- Entities large and small who are involved with developing wind and solar installations, particularly in countries that are terminating subsidies for these renewables. As we highlighted earlier, a BESS potentially provides a way of optimising a renewable asset. Recent examples of countries removing small-scale solar subsidies include: Japan, Australia, Germany and the UK.



Usage

Figure 26, below, is similar to **Figure 25**, three pages back, but this time the data is divided by storage type. **Figure 26** shows that FTM installations have dominated the market historically, though more recently BTM installations have gained some ground. Another source, Wood Mackenzie's Global Energy Storage Outlook 2019, states that in 2019 FTM was the biggest segment, with 55% of the global market, while residential - largely government subsidised solar plus storage - had 23%, and commercial and industrial, 22% (we assume these percentages relate to cumulative capacity). From other sources it is clear that BTM growth has been focussed in particular countries - Italy, the UK, Germany, South Korea, Japan, Australia and California, amongst others. Each of these markets has its own set of BTM drivers. For example, unreliable grids related to wild fires are driving self-sufficiency installations in Australia and California.

Throughout most of the 2010s, FTM systems were limited to durations on the order of 20-30 minutes. However, in the last few years, systems with durations over 1 hour and up to 4 hours have become more common. In general, systems are getting bigger in both power and energy terms, especially FTM. This trend is most publicised at the top end of FTM systems - the largest in development are now 100s of MW and over a GWh.

It is not easy to find up-to-date information on the services being provided by BESS installations. That said, for FTM installations, the 2010s 'belonged to' grid services, 'the lowest-hanging fruit of the storage tree', according to a report from Deloitte, the accountancy firm. **Figure 27**, overpage, provides some confirmation of this.

Figure 27 breaks down global BESS capacity by primary service provided. As a caveat, this data is from 2017 and likely flawed in other ways. Beyond frequency regulation, important services at the time were what we would call reserve, bill management, energy arbitrage and capacity provision. The names they use are a bit different but most match with ours.

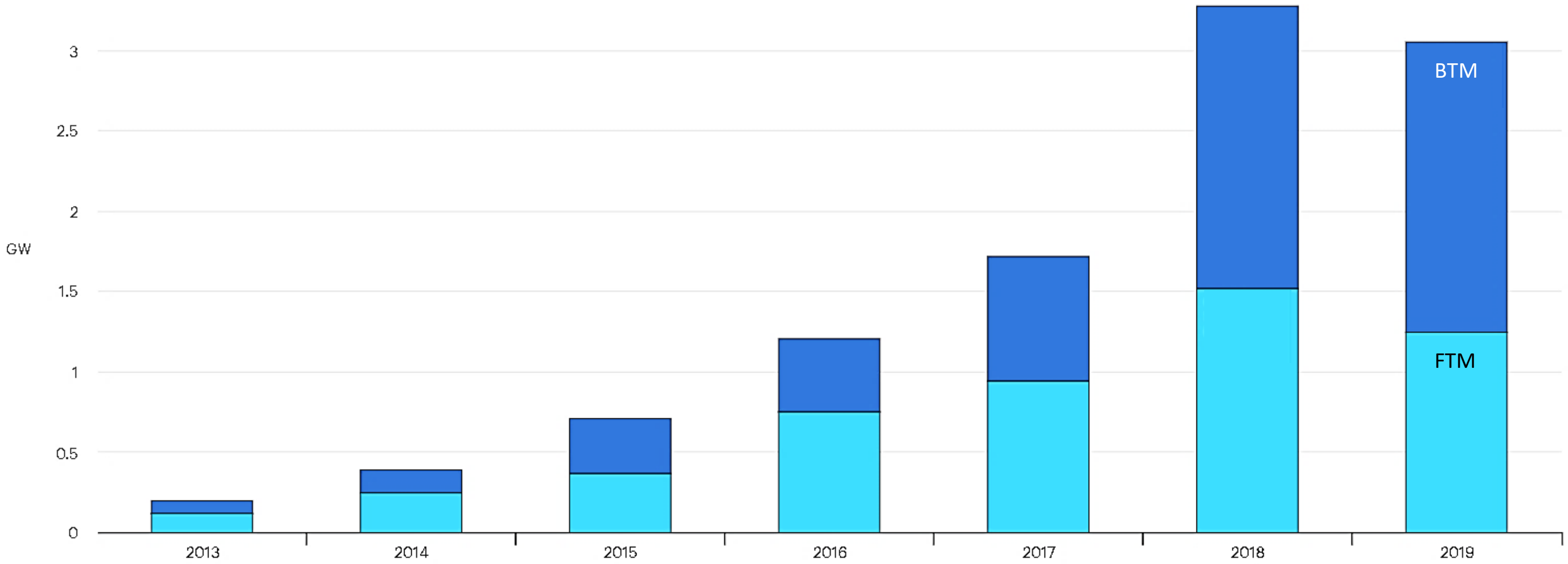


Figure 26 - global annual ESS deployment by type. Source: Energy Storage Tracking Report, IEA, June 2020.

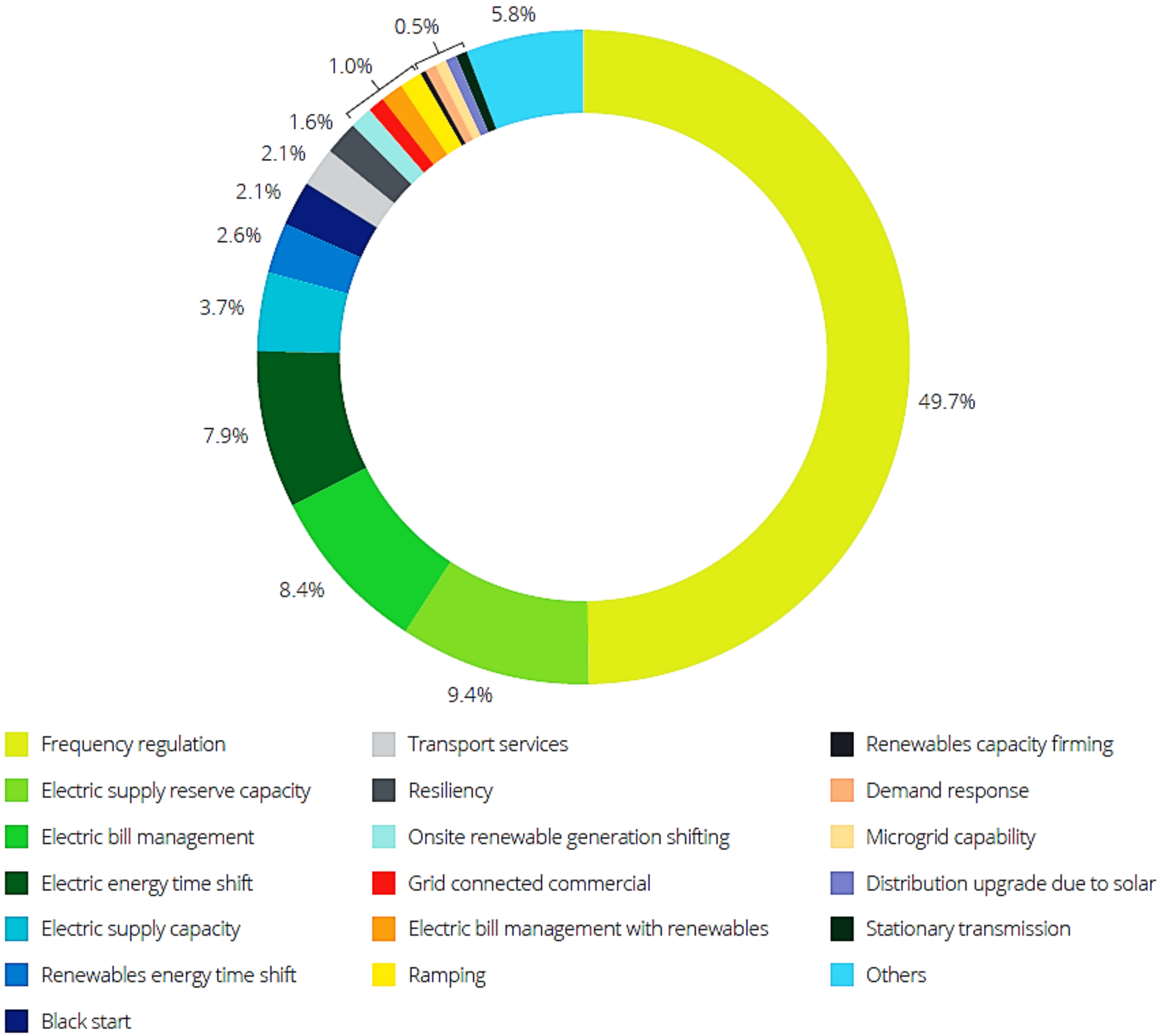
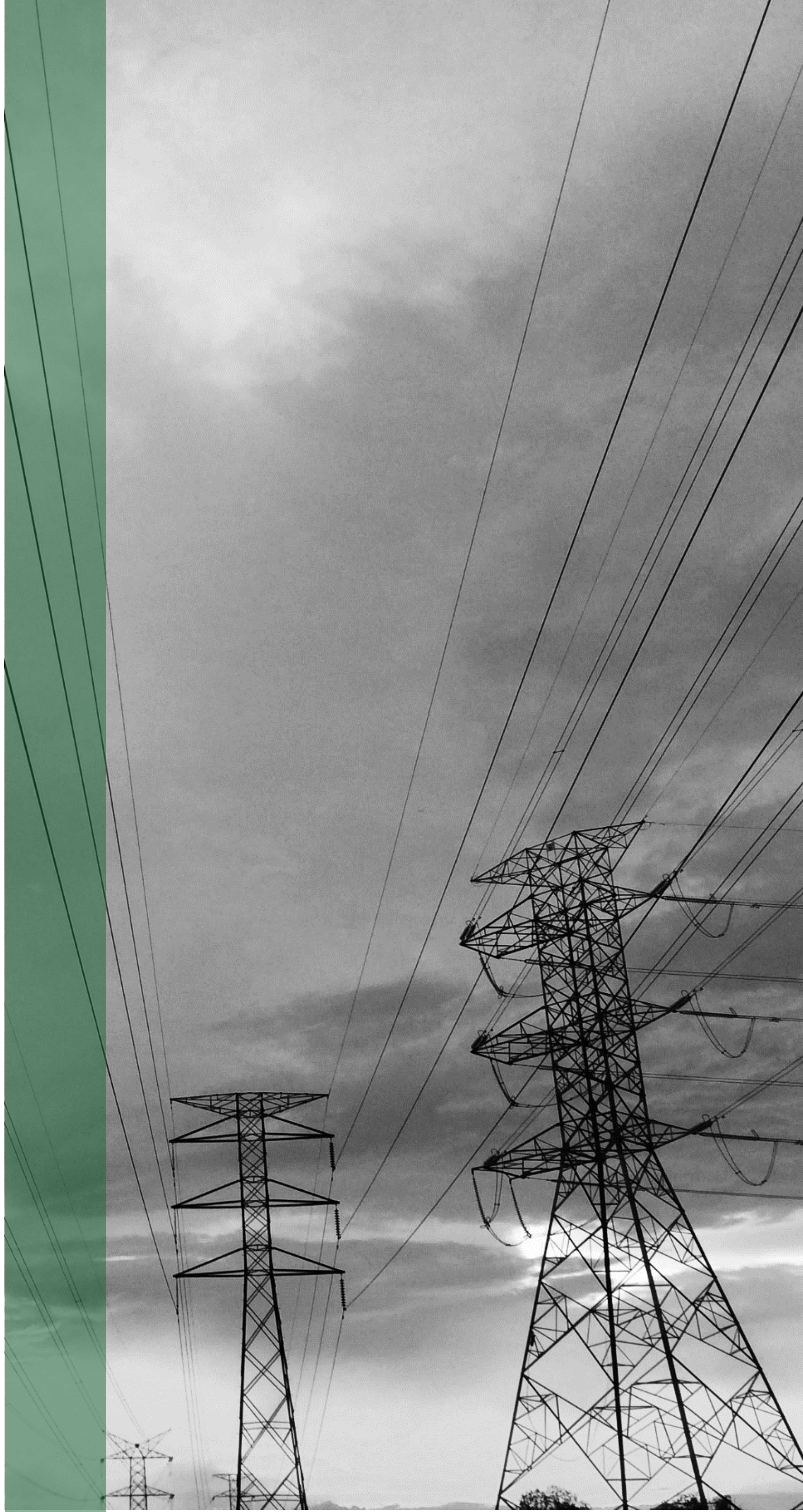


Figure 27 - global BESS capacity by primary service (%). Source: Electricity Storage and Renewables: Costs and markets to 2030, International Renewable Energy Agency (IRENA), October 2017.



UK Market

Deployment

Pumped hydro storage has been operating in the UK for decades; there are four installations in Scotland and Wales, totalling 2.7 GW and 38.4 GWh, according to National Grid ESO. By contrast, BESSs are a much more recent phenomenon, with FTM deployments starting in 2013 but only really taking off in 2017, alongside price declines and the availability of long-term frequency response contracts.

At the beginning of 2017, only five FTM BESS projects totalling 28 MW had been deployed. However, by the end of 2020, operational projects had grown more than 27 times, to nearly 1.2 GW of capacity, across many tens of installations, with 2018 being the key year for growth, with ~450 MW added that year, according to Solar Media. Despite the pandemic, about 250 MW was added in 2020, a touch more than in 2019.

The vast majority of operational projects are distribution-connected, standalone systems, with an average duration of about an hour. While a broad mix of project sizes has been deployed, operational capacity is dominated by projects larger than 30 MW. As is happening globally, projects are getting larger, with 50 MW the most common size for recent standalone projects, whereas hybrid projects vary in size but are usually much smaller (co-location with solar is most common).

Looking ahead, there is a famously large and growing collection of FTM projects in the pipeline, with 1.8 GW ready-to-build or under construction, and 6.9 GW with planning consent, according to Solar Media, though some experts are sceptical all of these will get built. The average timeline for projects - from planning submission to final commissioning - is about three years.

Figure 28 shows some of the larger ESS installations in the UK. The South East region has the largest operational capacity. A complete database of UK BESSs at all stages of development is available from Solar Media, which you have to pay to access.

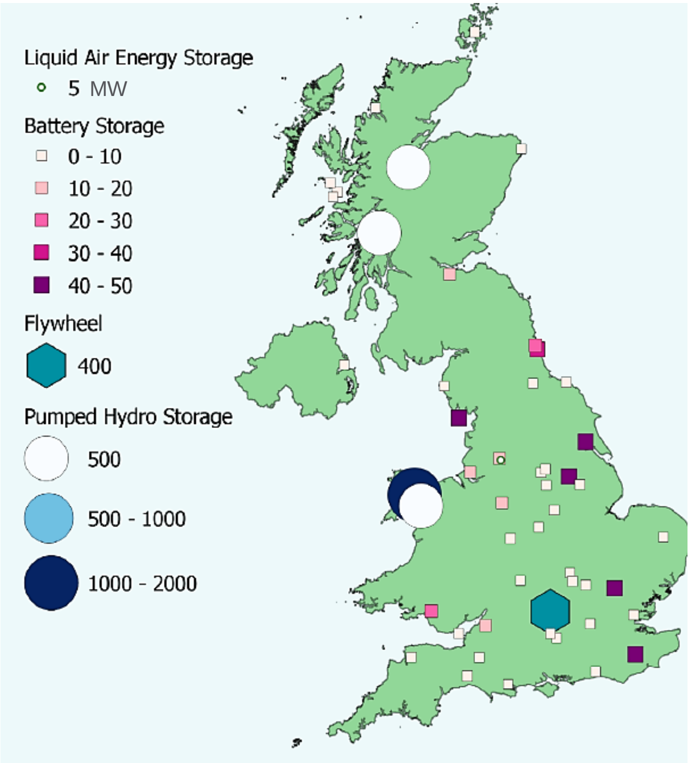


Figure 28 - map of some of the larger UK ESS installations. Source: Electricity Storage: Pathways to a net Zero Future, The Electricity Storage Network, June 2020.

In the residential BTM segment, at the end of 2019 approximately 23,000 units had been installed - mostly solar plus storage - with a cumulative energy capacity of 260 MWh, according to SolarPower Europe. Growth was strong from 2015 to 2017, before levelling off thereafter, alongside a slowing in demand for solar installs due to the winding down and them removal of the associated feed-in tariff in 2019. This government subsidy was replaced with a scheme called the Smart Export Guarantee (SEG) , which enables solar owners to get paid a market price for electricity exported to the grid. SEG tariffs can include and be optimised for storage. More at the above link.

Need for Flexibility

The scale of deployment highlighted on the previous page makes the UK one of the top European BESS markets, alongside Germany. At the highest level, the UK and BESS are a natural fit due a particularly strong need for flexibility. Reasons for this include the UK's:

Island grid nature. Unlike many countries in mainland Europe, the UK has relatively limited interconnector capacity to neighbouring countries (~5 GW). This means flexibility largely has to be provided from within the UK.

High and increasing renewables penetration. Renewable energy sources provided about 40% of total electricity in 2019, including from 13 GW of solar and 22 GW of wind capacity, 9 GW of this offshore, the largest offshore wind capacity of any country in the world. Even the least optimistic scenario from National Grid ESO's Future Energy Scenarios 2020 has renewables providing about 60% of total electricity in 2030 (the most optimistic is close to 100%). For traditional generation we already know that:

- Coal plants are being phased out by 2025, though most of the 10 GW of capacity that existed a decade ago has already gone, and after September 2022 only one 2 GW plant is expected still to be open.
- With the exception of Sizewell B and Hinkley Point C (under construction), all existing nuclear power plants are to be closed by the end of 2030, leading to a decline in overall nuclear capacity in the 2020s.

Concentration of renewables supply in the North. Due to better wind resources, wind generation has largely been added in Northern parts of the UK. However, much of the demand is down South. The existing grid infrastructure was not designed to move large amounts of power across the length of the UK.

Alongside simple economics, the shift towards renewables is being helped along by the UK government. Sitting behind everything is the UK's legally-binding net-zero greenhouse gas target; the UK was one of the first developed nations to adopt such a target. This 2050 target is already shaping policy and investment, and is a great long-term driver for BESS deployment. Recent policies relating to net-zero include the government reintroducing onshore wind and solar to the Contracts for Difference (CfD) auctions (a subsidy for large-scale renewables), and increasing the ambition of its 2030 offshore wind target from 30 GW to 40 GW. By contrast, new-build, small-scale solar remains subsidy-free, since the cancellation of the feed-in tariff scheme.

It is worth stressing that the UK's lack of electricity system flexibility has been demonstrated repeatedly over the past few years; this is not just a theoretical risk. For example, in 2019 a major blackout occurred across significant areas of the UK, after two large generators both went offline almost simultaneously. This incident highlighted the fragility of the electricity system - with lack of inertia one of the key problems - and also the lack of fast-responding flexibility to limit the fallout from faults when they do occur. This incident led to the introduction of the Dynamic Containment frequency response service, mentioned earlier as a currently lucrative revenue source for FTM BESS.

In 2020, low demand due to the pandemic, combined with historically high generation from renewables, demonstrated that high renewables penetration *is* possible but that it goes hand-in-hand with power price volatility. In the early stages of the pandemic, negative power prices were seen much more frequently than usual, due to low demand relative to supply. During the winter pandemic months, however, low supply has been more of an issue, with 6 energy market notices issued to signal insufficient capacity on the system (due to low wind capacity and other issues, e.g. nuclear plants offline, mothballing of the Calon CCGTs (Combined Cycle Gas Turbine) and a prolonged outage of the BritNed interconnector). To give some context, the last energy market notice was issued five years ago. Related to this lack of capacity, wholesale prices, which normally live at about 50 £/MWh, spiked to over 1400 £/MWh, with Balancing Mechanism prices spiking to 4000 £/MWh (good news for BESSs).

Companies

A list of some of the companies involved in the UK storage and related smart energy sectors is available from Regen. Other companies active on the trading side can be found through the publicly-available lists of companies that have won Capacity Market auctions, and similar lists for other auctions. Although many of the companies involved in the storage sector are private, investors do have access to two stock exchange-listed investment funds focussing on the UK storage sector - the Gresham House Energy Storage Fund and the…
Gore Street Energy Storage Fund.

Market Drivers and Barriers

Beyond the broad narrative already presented, BESS deployment in the UK is being affected by a range of specific factors. Below we highlight a few of these, some of which we have already mentioned. This list is not exhaustive. The barriers we present are mostly inspired by the Electricity Storage Network (ESN).

Drivers

Strengthening revenue potential. The revenue outlook is arguably strong and improving for BESSs, FTM in particular. Reasons include:

- Wider access to and use of the Balancing Mechanism.
- Increasing Balancing Mechanism and wholesale price volatility, pushing up potential energy arbitrage revenues. This is a structural trend.
- Availability of new, lucrative grid services from National Grid ESO as it strives to keep the grid stable and ultimately operate the grid with zero carbon by 2025.

Credible off-taker structure emerging. Although the revenue potential exists, operating a BESS profitability is not easy. However, BESS owners have the option of employing one of an increasingly sophisticated set of companies who can trade the BESS on their behalf, either in isolation, or in aggregation, as part of a virtual power plant. These companies can provide demonstrable track records, increasing investor confidence, and therefore the likelihood of a BESS getting funded and built in the first place.

Increasing appetite for hybrid BESSs. This is especially true for solar projects of all sizes, in part because of the UK's transition to a subsidy-free solar regime (well, before subsidies were reintroduced for large-scale solar). As covered earlier, adding a BESS is potentially advantageous both FTM and BTM, more so in a subsidy-free regime.

50 MW local planning cap removed. Previously batteries above this size had to be given permission by central government, which resulted in a more time consuming, complex and expensive process for developers. This limited the size of projects being built. Now projects up to 100 MW are in the pipeline.

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Barriers

There is no government storage plan or target. Whilst it is clear that the UK government supports the idea of storage, it has provided no clear long-term plan or targets related to storage. Long-duration storage in particular, which is struggling due to a lack of revenues that reward their duration, could benefit from direction and assistance from government.

Storage is not defined separately in legislation. Storage has recently been included as a subset of generation in the electricity generation licence, which, amongst other things, removes an issue related to the double charging of certain grid fees. However, many in the industry are pushing for storage to have a licence of its own, with separate rules, codes and guidance. The claim is this could lead to new markets and increased deployment.

Some markets are still not accessible or fair. Although the situation is improving, small, non-fossil fuel assets are still struggling to access some markets, and where access is possible, to compete with large, incumbent providers. One issue is that low carbon intensity is not rewarded.

Business rates are high. Business rates make up a significant proportion of the business model for storage, particularly BTM. The current rate calculation needs improving as it is over-generalised and does not take into account the wide variation between assets.

C&I BTM business models have been hurt by Ofgem's network charging reforms. These reforms will reduce or remove entirely the ability of BESSs to save a site money by avoiding certain grid charges. More here.

GB's smart meter rollout is not complete. Specifics here. As discussed earlier, the provision of some BTM services requires a smart meter.

BESS Market Forecast

In this section we present a few forecasts for the global and UK ESS/BESS markets. To spoil the obvious punchline, significant growth is expected. Although we are largely just going to present the headline results unquestioningly, it is worth stressing that market forecasts in relation to clean energy technologies are almost always wrong, often underestimating the speed and scale of deployment over longer timescales. Note that we sneaked in some related forecasts earlier: E-7 generation capacity, E-7 intraday generation swings, annual demand for batteries, lithium-ion deployment by type, lithium-ion and BESS cost and UK FTM margin evolution.

Global Forecast

To 2030

The headline from Wood Mackenzie's Global Energy Storage Outlook: H2 2020 report is the forecast that global ESS capacity could grow at a compound annual growth rate (CAGR) of 31% in the 2020s, reaching 741 GWh of cumulative capacity by 2030. See **Figure 29**. The exact definition of ESS here is unclear. This 31% CAGR is considerably slower than the 66% seen over the past decade, but is still impressive growth by most standards. Importantly, the pandemic is not seen as having a lasting, detrimental impact on the transition to renewables, or the growth of the ESS market. However, ESS growth is expected to be relatively subdued in the early 2020s, before accelerating later in the 2020s as the energy transition picks up pace.

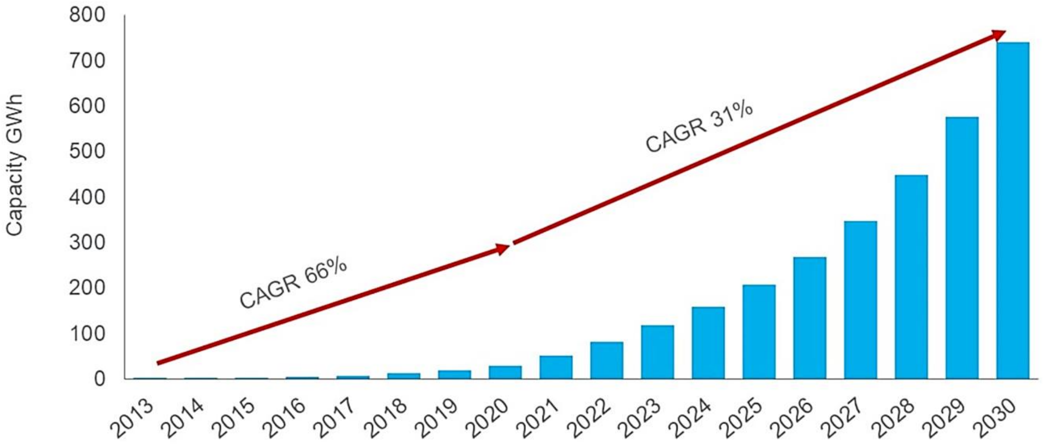


Figure 29 - global cumulative ESS capacity, 2013-2030. Source: Global energy storage capacity to grow at CAGR of 31% to 2030, Wood Mackenzie, Sept 2020.

Beyond this headline, Wood Mackenzie add a little colour about the nature of the expected deployment. In terms of deployment type, the forecast is for FTM to dominate, accounting for up to 70% of annual total capacity additions to the end of the decade (this somewhat goes against the trend to BTM implied by **Figure 26**). In terms of where the deployment is expected to occur, the US and China are together expected to account for 70% of global cumulative capacity by 2030, with the US alone accounting for 50%. Meanwhile, Europe is expected to grow more slowly than its global counterparts. Within Europe, the UK and Germany are forecast to continue dominating the FTM market out to 2025, with frequency response remaining a key revenue stream. Beyond these top markets, France and Italy are highlighted as being in the process of opening up to BESS, with both capacity and ancillary service markets open or opening. Spain and the rest of continental Europe are expected to follow, with potential help from the European Green Deal.

To 2050

To provide a single cross-check with the 2030 forecast from Wood Mackenzie on the previous page, and to extend our reach to 2050, we now bring in a second report, BloombergNEF's New Energy Outlook 2020.

By luck or judgement, our two forecasts are in the same ballpark in terms of 2030 global installed energy capacity, which arguably increases the credibility of both, though it is not clear if they are measuring exactly the same thing. See **Figure 30**. Both forecasts also agree that FTM will dominate capacity additions.

Looking out to 2050, BloombergNEF see installed BESS (not ESS) capacity further expanding to 4500 GWh. This implies a CAGR of ~10% from 2030-50, somewhat slower than our previous 2020-30 CAGR prediction. In power terms, storage is predicted to go from 2% of global electricity generation capacity (~150 GW) in 2019, to 8% of capacity (~1600 GW) in 2050. This implies average annual additions of ~50 GW, compared with 4.5 GW in 2020. Finally, to make this 2050 prediction a reality, how much investment is required? The staggering estimate: $1.2 trillion from 2020-50, or about $40 billion a year on average.

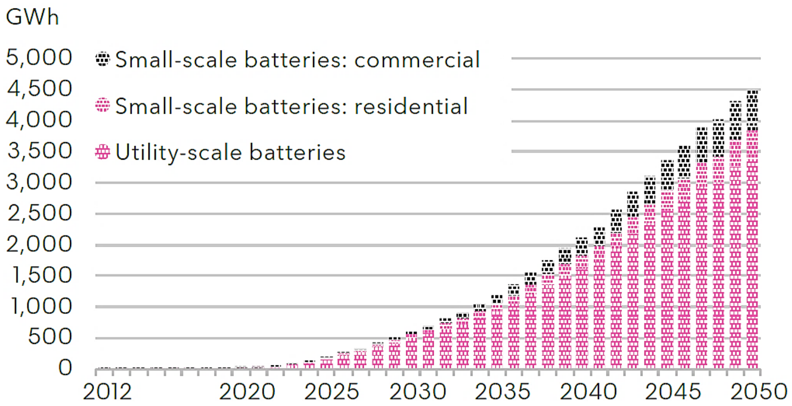


Figure 30 - global cumulative BESS capacity, 2012-2050. Source: New Energy Outlook 2020 Executive Summary, BloombergNEF, Oct 2020.

UK Forecast

To close out this report we look at the UK ESS and BESS market forecasts included as part of National Grid ESO's [Future Energy Scenarios (FES) 2020 report](), a report which looks at the future of the UK's energy system more broadly.

To give a credible range of forecasts in the face of considerable uncertainty, FES 2020 models the development of the UK's energy system under four scenarios. We will focus mainly on the two most extreme scenarios, as these define the upper and lower bounds on forecast energy storage deployment. One scenario, dubbed 'Steady Progression', does not meet the UK's 2050 net-zero goal, due to a slow speed of decarbonisation - with no progress made on heat decarbonisation at all - and minimal societal behaviour change. At the other end of the scale is the 'Leading the Way' scenario, which meets the 2050 net-zero goal via the fastest credible route. This involves significant societal change and heat being fully decarbonised by a mix of electrification and hydrogen. The other scenarios sit somewhere in-between these two scenarios (see the source for more detail).

Figure 31 shows that, from a base of about 4 GW in 2019, the four scenarios forecast a range of ESS power capacities roughly between 20 and 40 GW in 2050. At the lower end of this range this is a 5-fold increase in power; at the higher end, a 10-fold increase. Note that in all scenarios the pace of deployment is slower during the first part of the 2020s, after which deployment takes off at a faster, more or less constant, pace.

As an aside, interconnectors are forecast to be another significant source of flexibility over this period, providing between 16 and 27 GW in 2050, from ~5 GW today.

Figure 32, overpage, shows the energy capacity equivalent of **Figure 31**. From a base of about 40 GWh in 2019, almost all of this from pumped hydro installations, it forecasts a range of energy capacities

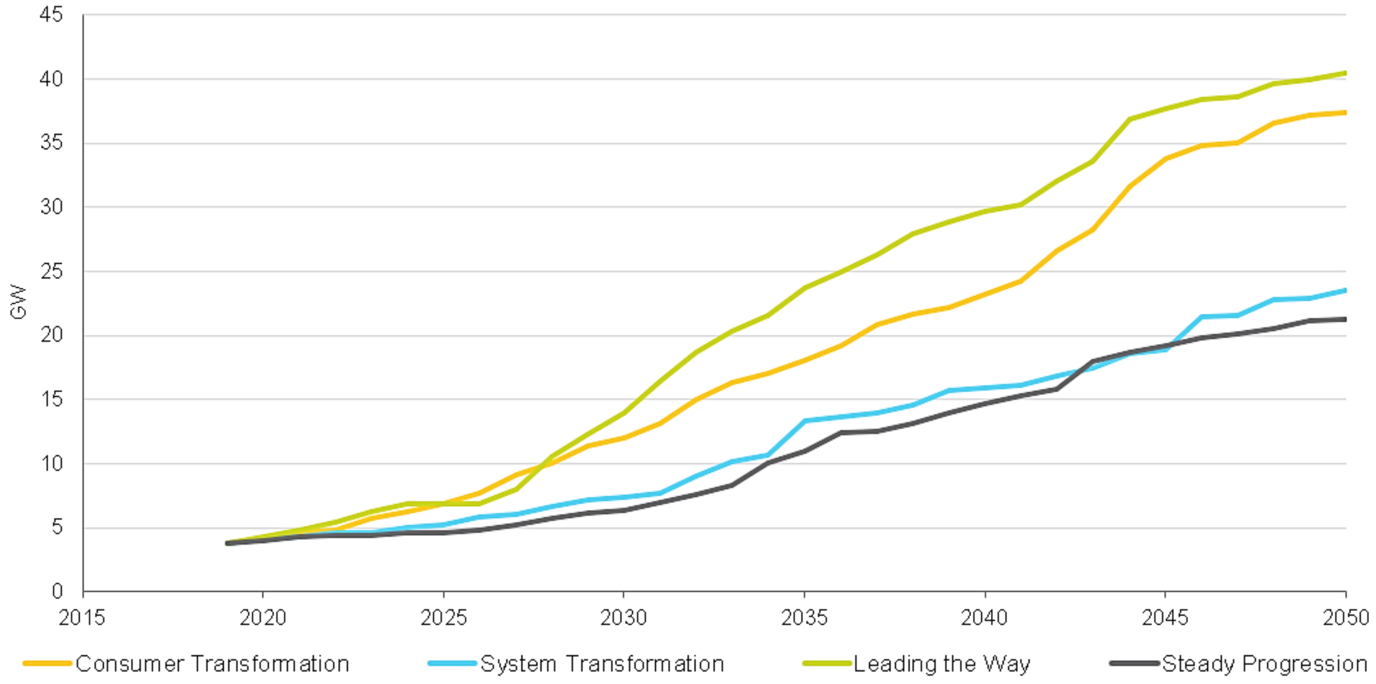


Figure 31 - installed ESS power capacity forecast under 4 scenarios. Excludes vehicle-to-grid. Source: [Future Energy Scenarios 2020](), National Grid ESO, 2020.

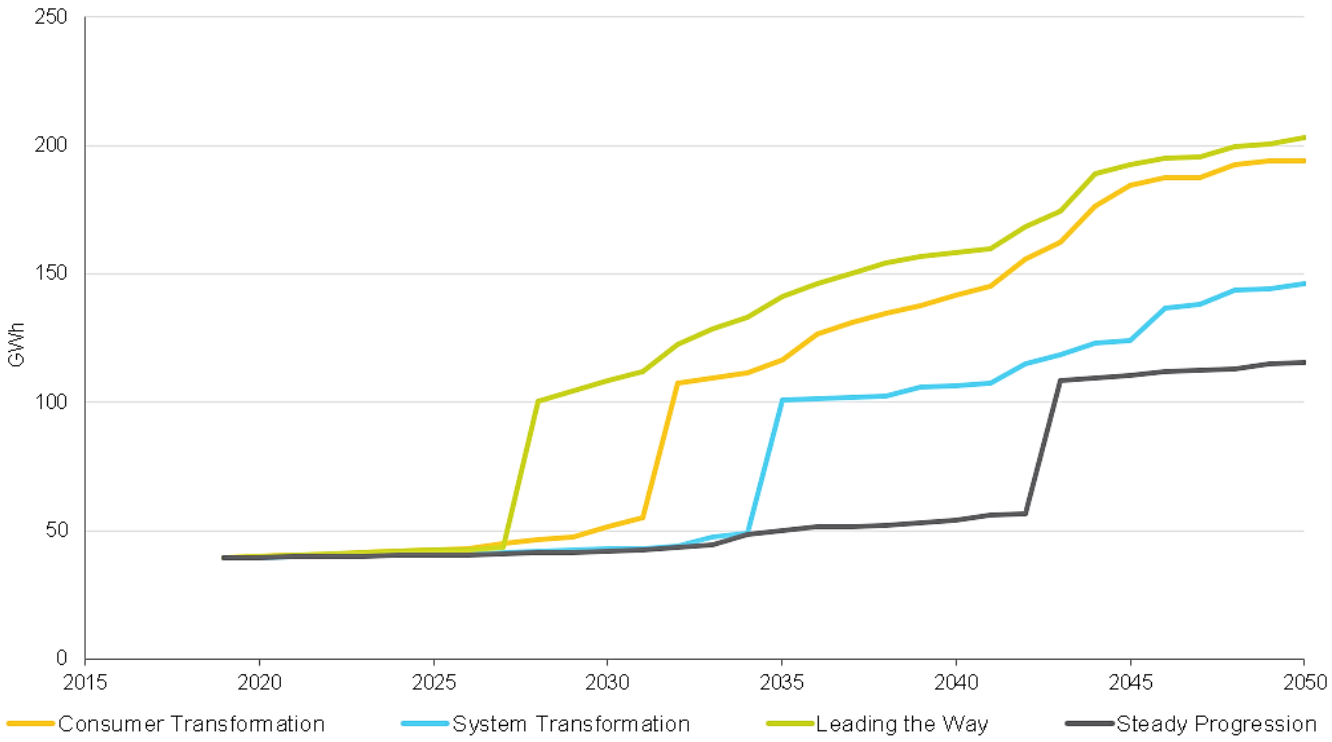


Figure 32 - above, installed ESS energy capacity forecast under 4 scenarios. Excludes vehicle-to-grid. Source: see **Figure 31**.

between about 100 and 200 GWh in 2050. At the lower end of this range this is a 2.5-fold increase in energy capacity; at the higher end, a 5-fold increase.

Unlike **Figure 31**, which has quite a smooth ramping up of power capacity, **Figure 32** has an occasional jump in energy capacity. These jumps are due to the addition of high energy capacity technologies, chiefly pumped hydro. New pumped hydro plants are assumed to have double the duration (~20 hours) of currently-operational plants.

For the Leading the Way scenario, **Figure 33**, below, shows which technologies are providing the power and energy capacities in 2019, 2030 and 2050. This is shown graphically for 2030 and 2050 in the top part of **Figure 34**, overpage. The bottom part of

Figure 33 - below, installed ESS capacity in the 'Leading the Way' scenario by technology. Source: see **Figure 31**.

Leading the Way		2019		2030		2050	
Storage Type	Short name	Storage Capacity (GWh)	Capacity (GW)	Storage Capacity (GWh)	Capacity (GW)	Storage Capacity (GWh)	Capacity (GW)
Battery storage	Battery	0.9	1.0	11.4	8.7	56.2	25.3
Liquid air storage	LAES	0.0	0.0	0.0	0.0	15.6	3.9
Compressed air storage	CAES	0.0	0.0	5.0	1.0	32.5	6.5
Pumped Hydro	Pumped Hydro	38.4	2.7	91.8	4.3	98.6	4.7
Vehicle-to-grid	V2G	0.0	0.0	21.7	1.5	272.9	19.1

Figure 34 shows the 2050 technology market share in both power and energy terms.

To summarise the key points from **Figures 33** and **34**, National Grid's most optimistic scenario for ESS is decidedly optimistic for BESS in particular. From a base of about 1 GW and 1 GWh in 2019, the forecast is for BESS to grow ~25-fold in power and over 50-fold in energy terms (meaning the average duration doubles to 2 hours). Of all the storage technologies, BESS is expected to dominate the ESS market in power terms but remain a fairly minor part in energy terms, with pumped hydro and vehicle-to-grid dominating here (although, of course, vehicle-to-grid is just BESS on wheels).

Credible forecast such as these, showing BESS as potentially a key net-zero-goal-enabling technology in the UK, add to our confidence in concluding that the outlook for the BESS sector in the UK - and indeed in many other markets - is very rosy indeed. We do not give investment advice but investors have a range of options for getting involved should they so wish after conducting their own research. These include [two exchange-traded investment funds targeting the UK storage sector].

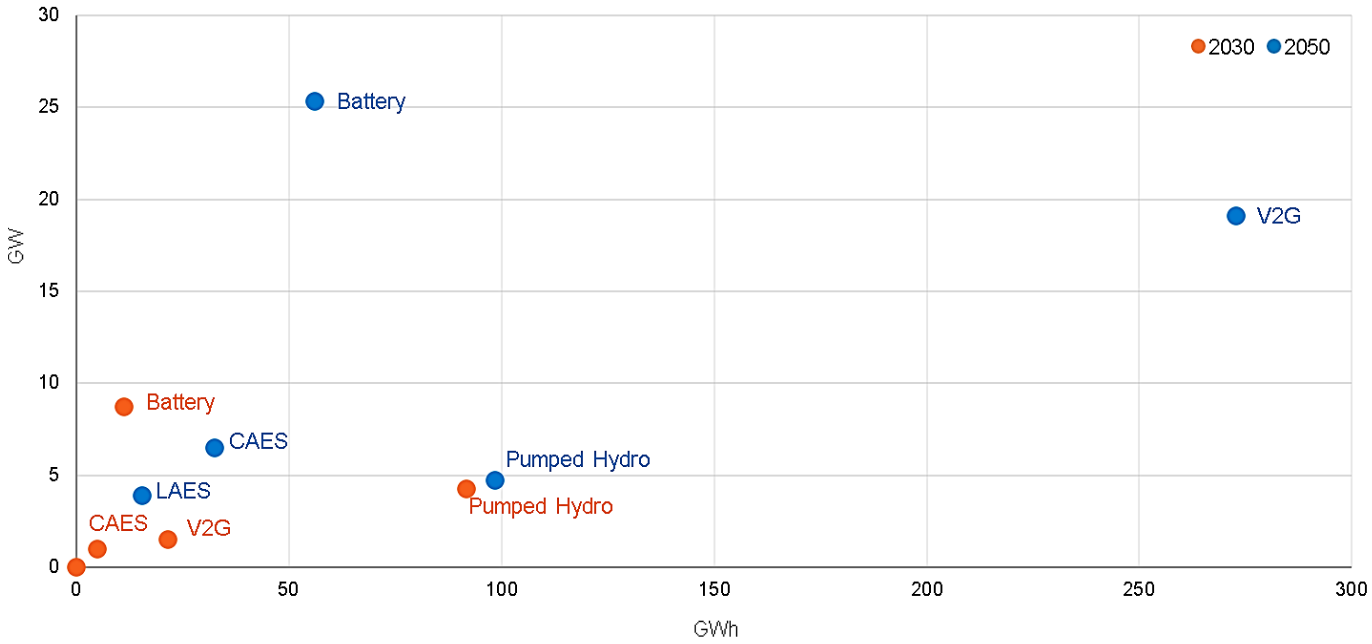
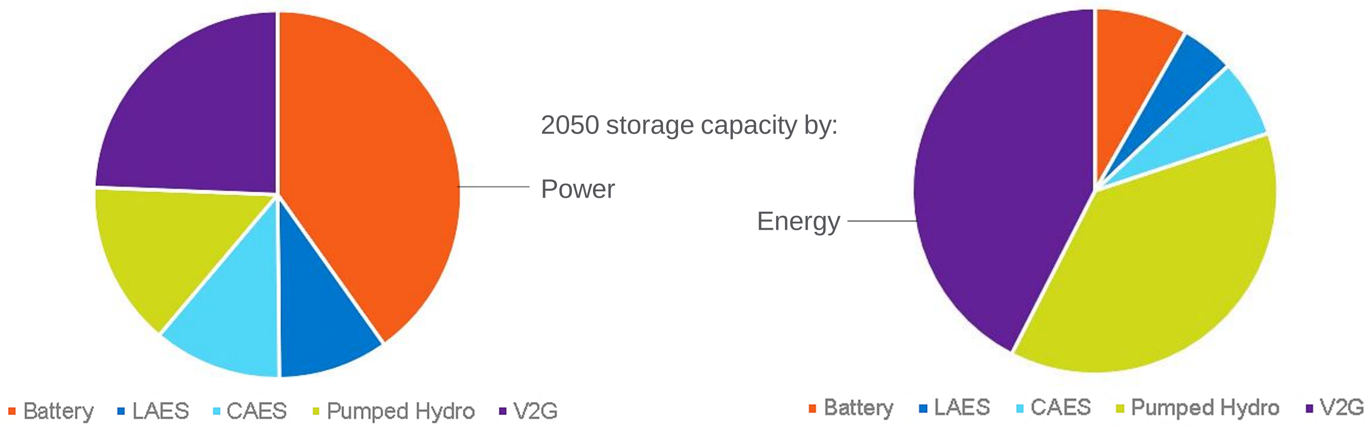


Figure 34 - top, forecast installed ESS capacity by technology in the 'Leading the Way' scenario in 2030 and 2050; bottom, market share by technology in the Leading the Way scenario in 2050. Source: see **Figure 31**.



Appendix: Storage Properties

Parameters	VRLA	Pumped Hydro	CAES	Flywheels	NMC	NCA	LFP	LTO	NaS	NaNiCl2 (Zebra)	ZBB	VRB
Technical												
Efficiency (AC-to-AC) (%)	81%	80%	64%	85%	92%	92%	86%	96%	81%	85%	72%	72%
C-Rate min	C/10	C/20	C/10	1C	C/4	C/4	C/4	C/4	C/8	C/8	C/8	C/8
C-Rate max	2C	C/6	C/4	4C	2C	1C	2C	10C	C/6	C/6	C/4	C/4
DOD (%)	50%	90%	40%	85%	90%	90%	90%	95%	100%	100%	100%	100%
Max. Operating Temperature (°C)	50	NA	NA	NA	55	55	65	65	NA	NA	50	50
Safety (Thermal Stability)	High	NA	NA	NA	Medium	Low	High	High	Medium	Medium	Medium	High
Commercial												
Storage Capex ($/kWh)	226	21	48	2 656	339	284	466	880	436	323	696	268
Development & Construction (Years)	0.25	5	3	1	0.5	0.5	0.5	0.5	0.5	0.5	1	1
Operating Cost ($/kWh)	3	2	1	80	8	8	8	6	8	8	15	11
Energy Density (Wh/L)	75	1	4	110	470	410	410	410	220	215	45	42.5
Power Density (W/L)	355	NA	NA	7 500	5 050	5 050	5 050	5 050	140	210	13	2
Life (full equivalent cycles)	500	20 000	20 000	>100 000	3 500	1 500	3 500	10 000	5 000	3 500	4 000	10 000
Maturity of Technology	M	M	C	EC	C	C	C	EC	C	D	EC	EC

Notes: kg = kilogram; kW = kilowatt; kWh = kilowatt hour; L = litre; VRB = vanadium redox battery; W = watt; Wh = watt hour; ZBB = zinc bromine battery.

Sources: Customized Energy Solutions (CES) market expertise for "Development and Construction", data sheets of key manufacturers for "C-Rate","Max. Operating Temperature" and "Life" and IRENA (2017a) for the rest.

Source: Electricity Storage Valuation Framework: Assessing system value and ensuring project viability, IRENA, 2020.

These are default values used by IRENA in assessing the relative merits of storage types in the above source. These figures are slightly dated, but comparisons between storage types should still be mostly valid.

Additional acronyms:

VRLA - valve-regulated lead-acid

CAES - compressed air energy storage

NMC - lithium nickel manganese cobalt oxide

NCA - lithium nickel cobalt aluminium oxide

LFP - lithium iron phosphate

LTO - lithium titanate oxide

NaS - sodium sulphur

NaNiCl2 - sodium nickel chloride

M - mature

C - commercialisation

EC - early commercialisation

D - demonstration

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