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Renewable energy risk and reward

Integrating renewables into grids and the role of storage

Imperial College London Consultants

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1. Introduction

Increased amounts of grid connected electricity storage are often assumed to be essential if renewables are to play a substantial role in the energy system, due to the variable output from wind and solar energy. Grid connected storage capacity has indeed been expanding in recent years, and prices of battery storage have been falling – down around 80% since 2010. However, it is important to be careful when assessing the need for storage to integrate variable renewables. Storage can provide important system services but is not essential to renewables integration, at least in the short term. To understand this, it is necessary to start with some of the principles of operation of conventional power grids, then consider what changes with the addition of variable renewables. Based on this it is possible to consider the economics of storage, different applications for storage and the global market, considering the falling prices of some types of batteries. In what follows we explore:

Operation of electricity networks with and without renewables; the economics of electricity storage; the role of storage in electricity markets; other battery applications; and the risks associated with electricity storage.

The operation of electricity networks with and without variable renewables

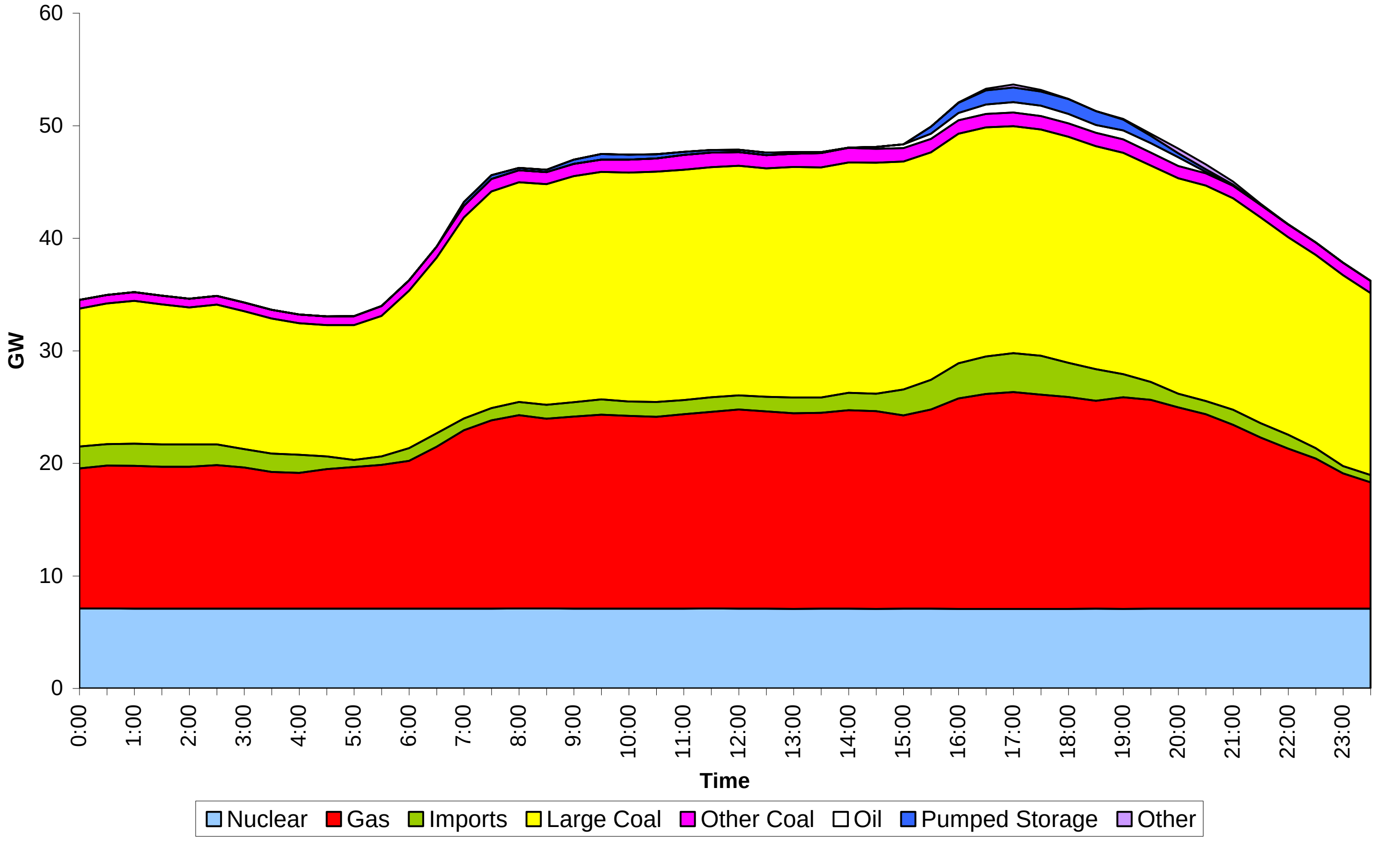
Electricity demand changes continuously. It fluctuates from second to second and can go through very large swings over a few hours – for example at the start of the working day. Whilst the general direction of demand changes each day and at different times of the year are well understood, demand can still change unexpectedly. It is necessary to ensure increased electricity generation as demand increases, and reductions as demand falls[1]. This adjustment must be continuous, and almost instantaneous if problems with power system operation are to be avoided.

No generator can operate 100% of the time; all plants require periodic planned maintenance, and every power station will suffer occasional unplanned outages due to a fault. As a result, power systems have long been engineered to cope with both predicted and unpredicted demand fluctuations, unexpected power station breakdowns and periods when several power stations are unavailable due to planned maintenance.

A range of power stations are used to meet different portions of the daily demand curve – from a very flexible plant able to meet rapid swings in demand to an inflexible plant that runs all the time. Historically, before power markets were liberalised in most countries, a central System Operator would decide which power plants to run based upon their marginal running costs – the so called 'merit order'. Centralised dispatch of power stations is still used in many countries irrespective of whether generators are owned by the government or private companies. In more market-based systems power station operators enter into contracts with electricity suppliers, power may be traded in various exchanges, and the System Operator steps in the hours or minutes ahead of real time to ensure that the system is balanced. In all cases the principles are the same. The plants with the lowest running costs are used first, with successively higher running costs used to fill the gaps in the demand curve (BEIS & Ofgem, 2016). Finally, the System Operator contracts for a range of what are called ancillary services, such as short term operating reserve, which can be dispatched at short notice to make up for any unexpected shortfalls. Figure 1 provides an illustration of a system with little or no variable renewables – the 24-hour 'load profile' on the British electricity system in 2004 (National Grid, 2004).

[1] Supply side adjustments are the current norm because most consumers are not under the control of system operators or direct participants in wholesale electricity markets. Large consumers (such as steel works or chemical plants) can participate in wholesale markets and reduce demands in response to high prices, or contract to respond to requests from the system operator (BEIS and Ofgem, 2016). The role of smaller consumers in demand response is widely expected to increase in future as new opportunities for smarter management of loads such as electric vehicle charging and heat pumps expand, together with the role out of smart meters.

Figure 1: Winter 24-hour load profile on the UK National Grid system prior to the introduction of large amounts of wind and solar



Source: National Grid, 2004

Changes to the generation mix as the share of variable renewables rises

In recent years the share of wind and solar in many countries has grown dramatically. For example, on the British system they have increased from negligible levels at the beginning of the century to meet around 20% of annual demand in 2018 (Staffell *et al.*, 2018). Large biomass fired power stations have also been introduced, and the amount of interconnection to mainland Europe has increased. Figure 1 shows demand and the mix of wind solar and conventional demonstration across a range of days in Britain during 2016. Changed generation patterns also exist in a other countries where there has been rapid growth in renewables – examples include Ireland, Denmark, Germany, Portugal and parts of the United States or Australia (REN21, 2017).

As the share of renewables increases the mix of generation meeting demand changes. The daily load curve does not change (although gross demand has been falling in recent years in the UK (BEIS, 2017), but the fraction of demand met by renewables varies during the day or over a series of days, with the output from conventional generation flexing to accommodate it. The contribution from variable renewables depends on whether it is windy or sunny, and the share that renewables contribute at any one time will depend upon the net difference between demand and renewable output. The variability of wind and solar output and how it interacts with demand and affects the operation of conventional generators is illustrated in Figure 2a and 2b. Thus we can see that the diurnal variation illustrated in Figure 2a and 2b is retained but at some of the time the operation of conventional generation is substantially reduced due to the availability of renewable power. This gives rise to a range of impacts and we explore them in the sub-sections that follow.

Figure 2a: Average winter day load profiles in 2018/19 with renewables, shows dramatic drop in coal use from figure 1 and illustrates that Gas is the fuel used for rapid response

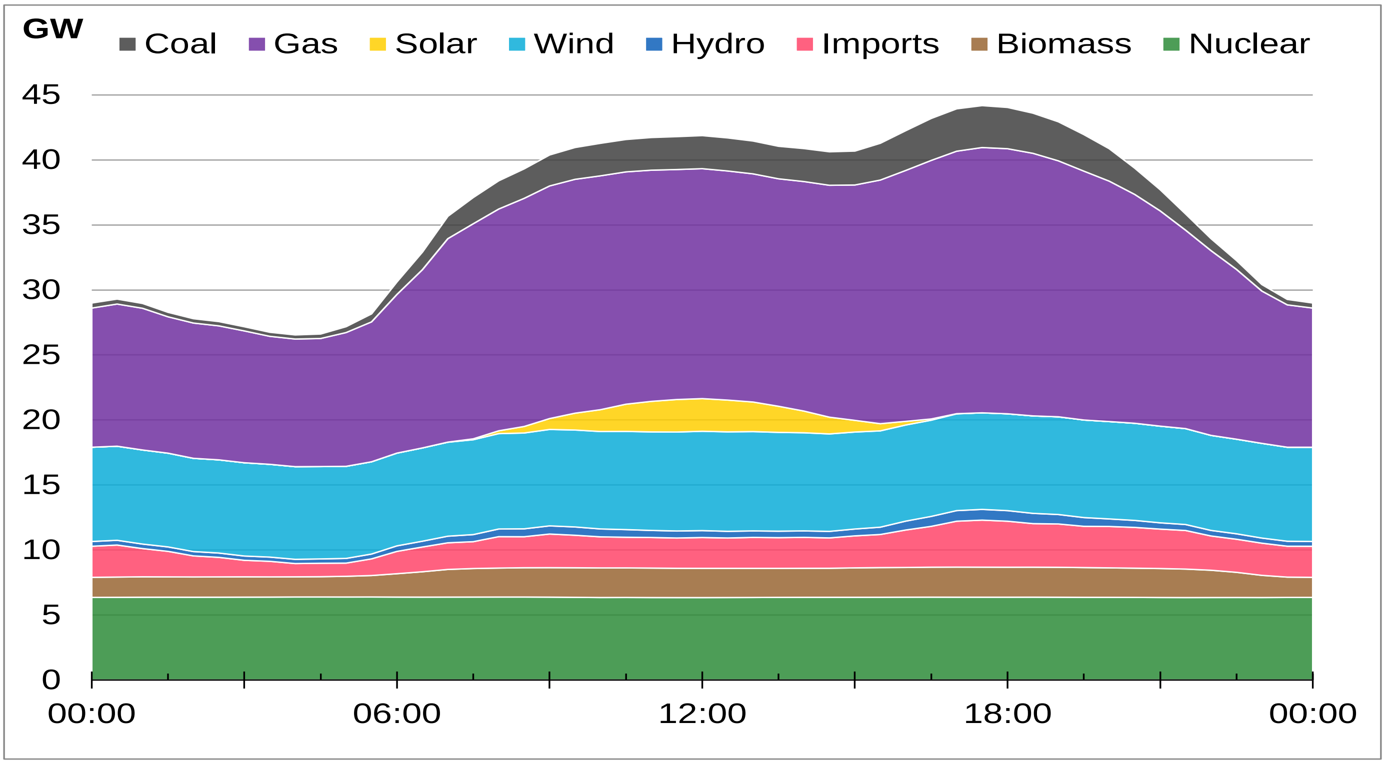
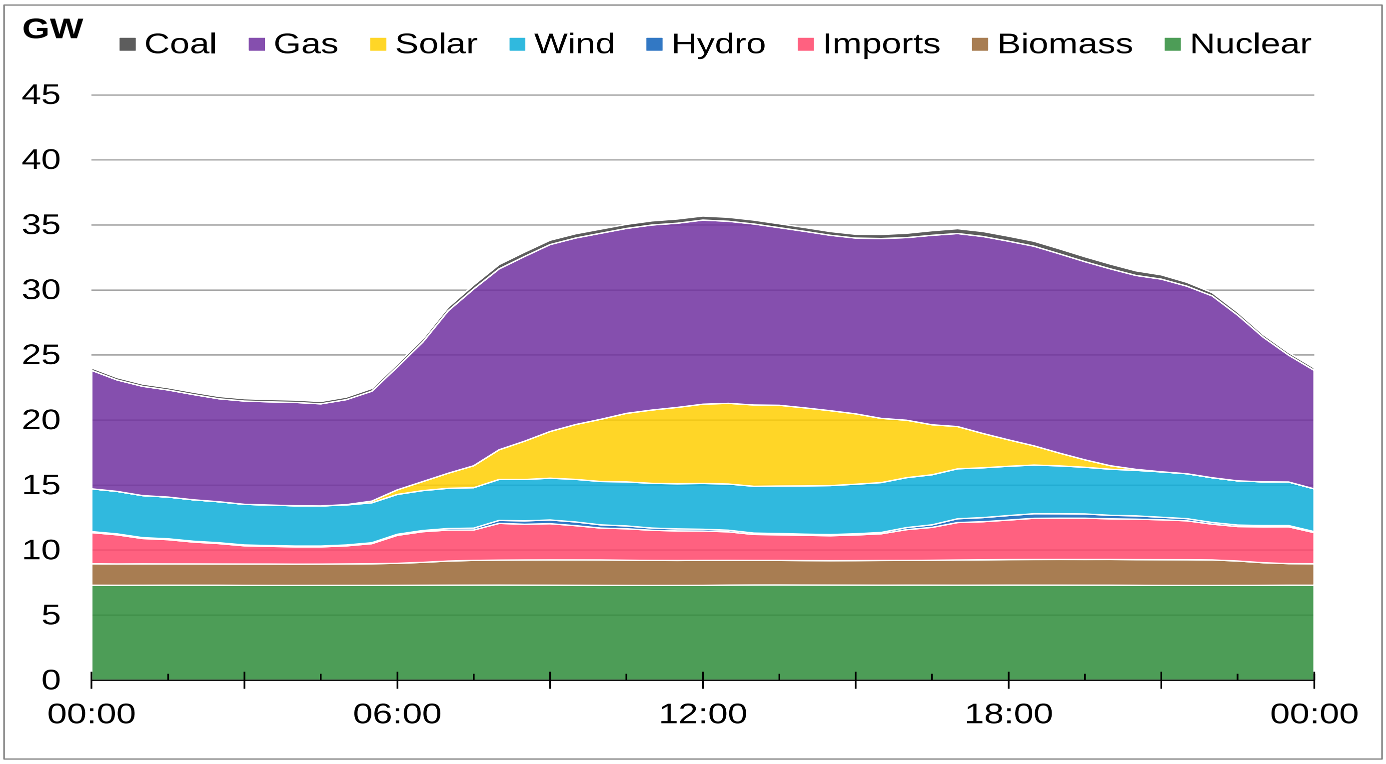


Figure 2b: Average summer day load profiles in 2018/19 with renewables, renewables growth has been rapid and taken significant share of power generation share.



Source: Electricinsights.co.uk, 2019

Impacts on conventional generators and markets

The net load for conventional generators is reduced. This of course has benefits, notably in terms of reducing emissions of CO_2, the principal reason that renewables have been introduced (Staffell, 2017). It may also reduce average wholesale power prices, since renewables have zero marginal costs (the so called merit order effect, (Newbery, 2016). Whether this serves to reduce customer bills will depend on the extent to which renewable generation is subsidised, since lower wholesale prices and subsidies to renewables tend to offset one another (Green & Vasilakos, 2009).

As the share of wind and solar rises power prices also tend to become more 'spiky' – showing larger swings between high and low-price periods. This is because conventional generators may need to come onto the system quickly, for example in the evening as solar output disappears and demand increases (see Box 1). Some fossil fuel power stations will need to recover their costs over a shorter operating period, also tending to increase prices during those periods where demand is high and renewable output is low. Over time it is possible that some conventional power stations will close and that the mix of generation will change, to reflect the price signals created by the more variable net load, need for greater flexibility or shorter operating hours created by the presence of renewables.

As the share of variable renewables rises, a key requirement is to make a power system more flexible. This is to ensure that the output from variable renewables can be used (even when demand might otherwise be low) and that other sources of supply are available for periods when variable renewables are not generating. Flexibility can be provided by conventional power stations, for example, modern gas turbines are designed to operate at high efficiency over a wider range of outputs than older gas turbines. Another option is demand response, for example offering householders or industrial consumers incentives to move demand from peak to off-peak periods. Interconnection with neighbouring systems offers another option, allowing access to sources of flexibility from a wider geographical area. There are limits, however, to the ability of geographical dispersion to smooth wind outputs. Storage is also an option, but a key issue is whether it can provide flexibility more cheaply than the other options.

In Britain and many countries, historically much of the load following has been provided by gas and coal fired generators. At present in Britain coal fired power stations tend to run at low load factors, with the role from coal often limited to peak demand periods and when renewable output is low. This is because Britain's Carbon Price Floor has made it cheaper to burn gas for much of the time (Staffell, 2017), coal power stations are also amongst the oldest power sources in Britain and some have restricted hours of operation due to environmental regulations.

Response and reserve services

In addition to the changes in the operation of power stations and wholesale market prices, increasing the share of variable renewables leads to changes in the actions that the system operator must take to ensure that supplies are reliable. These issues are discussed in detail in the UKERC report, Costs and Impacts of Intermittency (Gross *et al.*, 2006; Heptonstall, Steiner and Gross, 2017). A short summary is provided in Appendix 3. .

Other impacts

Adding renewables to a power grid may also require upgrading of transmission or distribution networks – renewables may be remote and need new transmission lines or be decentralised and require extra distribution network capacity. Renewables may at times be curtailed to ensure that the system stays within operational limits or because of limited transmission capacity. Finally increasing the range of outputs from conventional generators may reduce the efficiency with which they operate, though the evidence suggests that the absolute impact of this would be small (Heptonstall, Steiner and Gross, 2017).

The changing shape of transmission and distribution networks

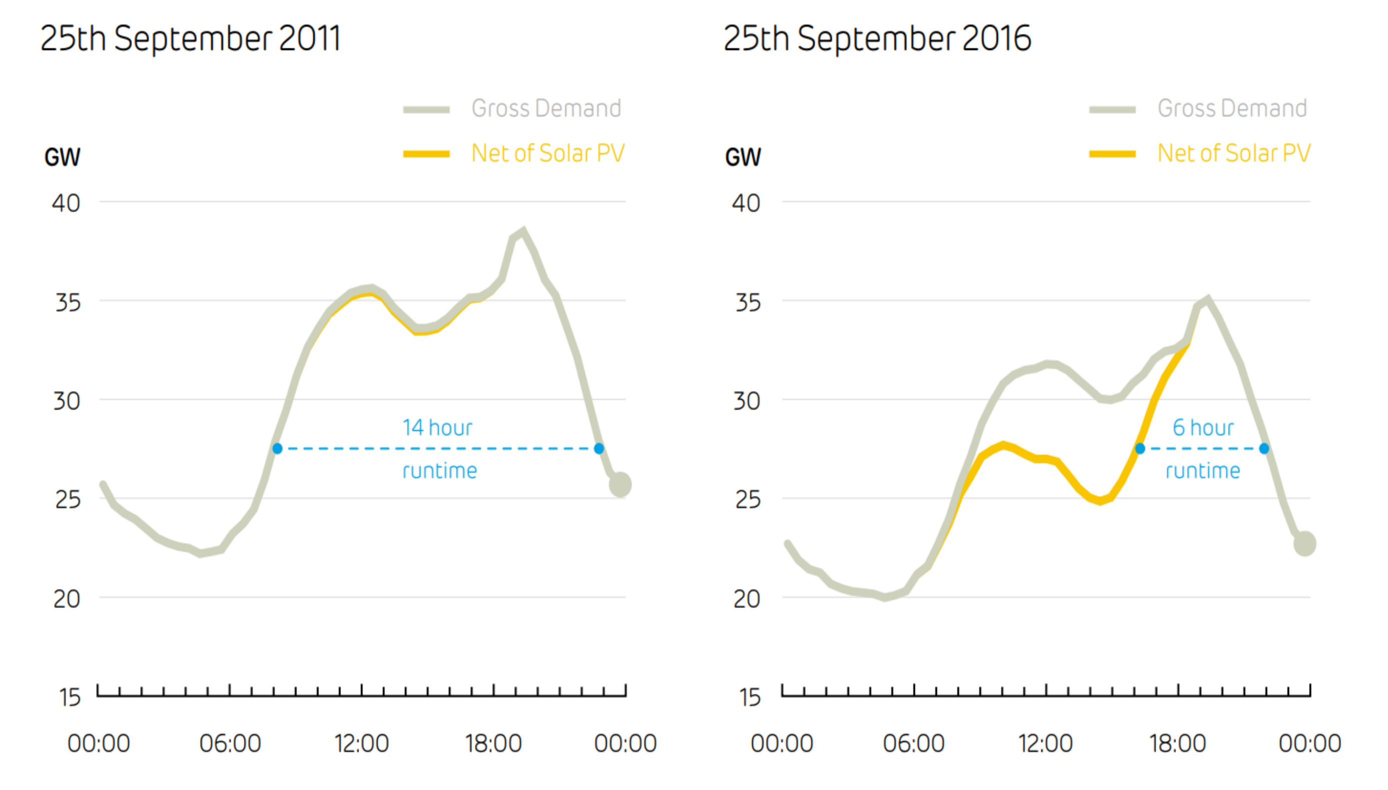
The growth of renewables has led to both an expansion of smaller scale generation, closer to demand, and to the growth of wind farms and other developments in remote locations. However, the notion that renewables are inherently more decentralised is less true of recent developments than it might have been at the beginning of the expansion of wind and solar energy. This is because wind and solar farms exhibit considerable economies of scale, meaning it is often more cost effective to develop a large ground mounted site than it is to embed large numbers of solar generators in the urban environment, for example. Nevertheless, the need to upgrade local networks is an important corollary of expanded renewable energy, as is the need to upgrade longer distance transmission – both to access remote wind or other resources and to help balance the outputs of variable generators. In some regions there has been growth of distribution network connected generation, for example the expansion of solar power in South Australia. System operators make provision to ensure that reliability standards are maintained. Indeed, the growth of batteries to provide fast frequency response (see below) has taken place in part because system operators have tendered for new system services that can replace the reducing amount of 'inertia' on the system. As the share of wind or solar expands and the share of conventional generators falls inertia may decline and this may make it harder to manage system frequency – inertia is the physical rotating mass in the form of conventional power stations. This is one driver of the growth in battery capacity connected to power systems, which we explore below.

Changing the demand curve and role of conventional generators

The chart below compares September 25th in 2011 and 2016: both Sundays which averaged 15.5–16°C. Demand was 3 GW lower in 2016 because of improving efficiency and other societal changes. Solar PV reduced net demand by a further 5.5 GW at its peak, pulling daytime demand down to levels previously seen overnight.

The resulting shape of net demand (orange line), which dispatchable generators (Gas) must follow, is very different from five years ago. The daytime peak from 8 AM to 10 PM has been replaced by a much shorter evening peak starting at 4 PM. 10 GW of dispatchable plant had to ramp up in the afternoon, but these were only needed for six hours instead of 12 hours or more, meaning they have to charge more per hour to recover their start-up costs.

Figure 3: Electricity demand, gross and net of solar output on the same day, five years apart demonstrates renewables impact with significant reduction in runtime for dispatchable generators fuelled by fossil fuels



Source: ElectricInsights.co.uk, 2019

2. Energy storage technologies

International markets for storage technologies have seen strong growth in grid connected batteries and the emergence of 'behind the meter' storage in homes and businesses, yet the vast majority of storage schemes installed internationally are pumped hydro, a large scale and traditional storage option that has been installed by power companies for many decades. In this section we explain recent developments in storage markets, how these link to renewable energy growth and what the future might hold. We start by explaining some of the main technology options.

Overview of current energy storage technology options

This section provides a short overview of major technologies, their advantages, disadvantages and level of commercialisation.

Batteries

Lead acid. Commercialised and stable with little opportunity for further improvement. Limited energy density and cycle life. Environmental issues associated with end of life disposal (although well-established recycling pipeline currently operates).

Lithium ion. Commercialised with significant growth in volume, becoming 85% less expensive since 2010 (Economist, 2019). High energy density. Good cycle life possible at expense of high energy density. Some safety issues associated with use of organic electrolytes and thermal stability. Some materials (e.g. cobalt) pose a resource constraint due to their source.

Sodium sulphur. Commercialised. High temperature (~200 ^{o}C) battery technology with good cycle life v. good energy density although somewhat poor power density. Low cost with resource abundant materials. Some safety concerns associated with very exothermic reaction between molten sodium and molten sulphur which has led to some spectacular accidents. High self-discharge rates due to need to keep system hot.

Redox flow. (e.g. all vanadium system) Commercialised. Utilises liquid electrolyte storage external to battery electrodes. Intrinsic safety.Very good cycle life and long term operation. Low cost. Suffers from lower energy and power density compared to lithium ion. Suits larger scale systems.

Zinc air. Early stage commercial systems. Low power but high energy density. Intrinsically safe. Poor cycle life at the moment. Prospects for low cost systems with further development.

Sodium ion. Pre-commercial. Compatriot to lithium ion but using less expensive and more abundant sodium. Prospects for lower cost than lithium ion over the long term, but at lower energy and power density and also probably lower cycle life.

Others

Pumped Hydro

Pumped hydro is a widely commercialised and mature technology in which water is pumped upwards from a base reservoir to a holding reservoir at a higher altitude. It has high power and energy density. Water is pumped upwards at times of low electricity demand and/or costs, and then allowed to flow back down to the base reservoir at times of high demand and cost, generating electricity by passing through hydroelectric turbines on the way. This technology makes up the vast majority of current global installed storage capacity, however future deployment is limited by the number of suitable sites and by high upfront capital costs and lengthy build times.

Compressed air

Late-stage demonstration/early commercialisation. Variable power and energy density depending on siting. Similar in concept to pumped hydro, compressed air storage works by pumping air into a container or underground space until a high-pressure level is achieved. When electricity is needed, the compressed air is allowed to flow outwards through a turbine. Large-scale applications are limited by the availability of suitable underground space. Round trip efficiency currently quite low.

Flywheels

Commercialised and mature, high power output and low energy density. Flywheels store energy in mechanical inertia and tend to be used in localised industrial or transportation applications to smooth energy outputs. Only suitable for short periods – minutes-hours due to high rate of self discharge.

Power to hydrogen/gas

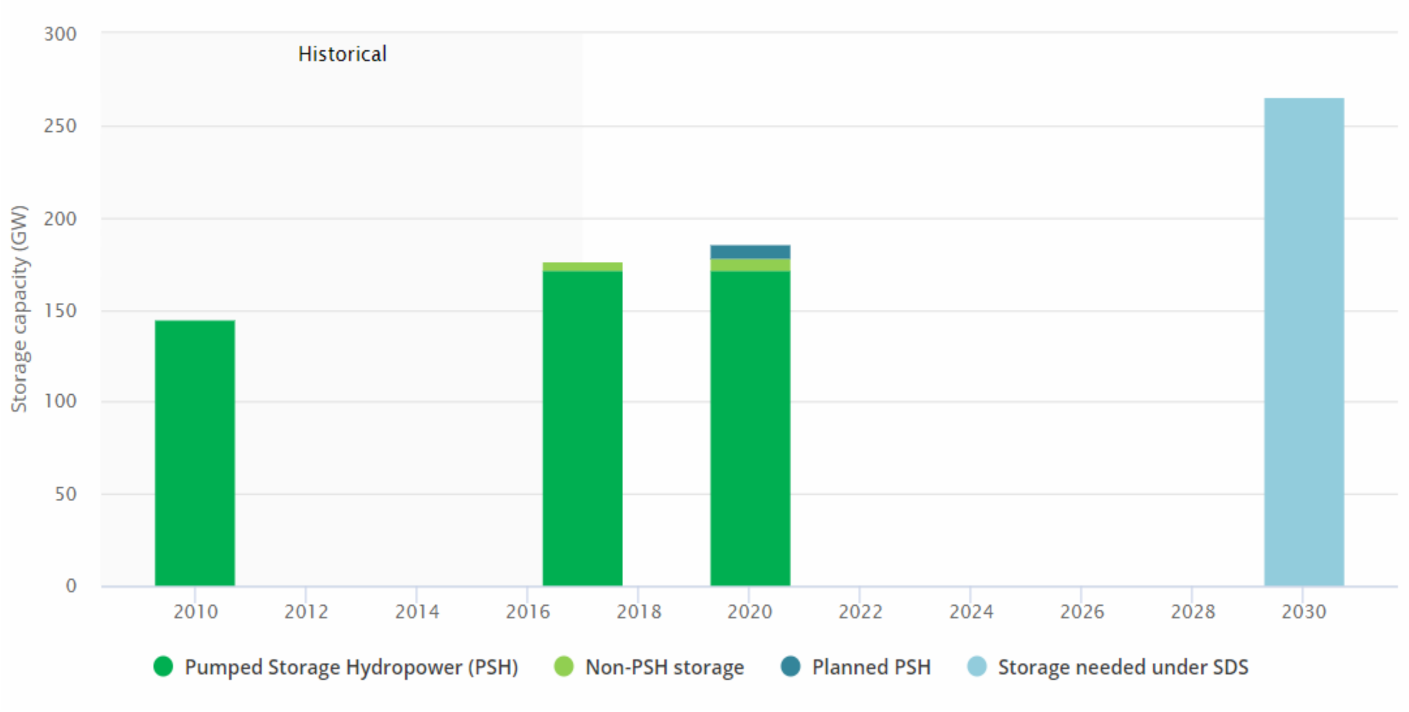
Demonstration/early-stage commercialisation. Low round-trip efficiency. Uses excess energy, for example from wind turbines, to perform electrolysis on water to produce hydrogen or methane (with the addition of carbon dioxide). Hydrogen production is well commercialised, methane still in R&D/demonstration phase.

Current market shares of key technologies

Globally a total of just over 176 GW of storage capacity was connected to electricity networks at the end of 2017 (International Energy Agency, 2018). Of this, in excess of 170 GW is pumped hydro, the 'traditional' form of energy storage often constructed by monopoly utilities. Batteries, compressed air and other non-pumped-hydro capacity amounted to around 4.5 GW at the end of 2017 (IEA Tracking progress (International Energy Agency, 2017). New forms of storage are growing rapidly however. During 2017 630 MWh of grid connected batteries were installed, a similar installation volume to 2016, taking total non-hydro capacity to around 15,000 MWh. As recently as 2010 there was hardly any capacity of non-hydro grid-connected storage capacity installed world-wide. There has also been growth in 'behind the meter' battery installations, for example by householders. In absolute terms the capacity installed is small at a few tens of MW but the potential paradigm shift for households going 'off-grid' has elicited considerable attention and discussion. The IEA estimates that around 80 GW additional storage capacity will be needed by 2030 if global energy system is to be on track for holding climate to change to below 2 degrees C (International Energy Agency, 2017).

The majority of batteries currently installed by capacity are in grid-connected network installations, either for frequency-regulation or peak-levelling functions. These are typically installed in specialist cabinets or buildings close to transmission or distribution facilities. A smaller share of the market, currently less than 10% globally, is made up of domestic behind-the-meter storage, mostly used in conjunction with PV generation (IRENA, 2017). This is currently a fast-growing market segment however, with more than half of battery storage added in 2018, 1.9GW, added behind-the-meter (IEA, 2018). There is considerable uncertainty over the quantity of behind-the-meter storage to be added over the next decade, especially with the potential for electric vehicles to be used as storage. A recent Bloomberg NEF report forecasts relatively slow growth of the behind-the-meter segment over the next decade, but faster growth throughout the 2030s with smart grid functionality enabling customers to engage in energy arbitrage markets. They predict over 500GW of battery storage, 40% of total installed capacity, to be installed behind-the-meter cumulatively by 2050, though the vast majority of this, over 90%, is expected to come from vehicle-to-grid. (Bloomberg, 2018).

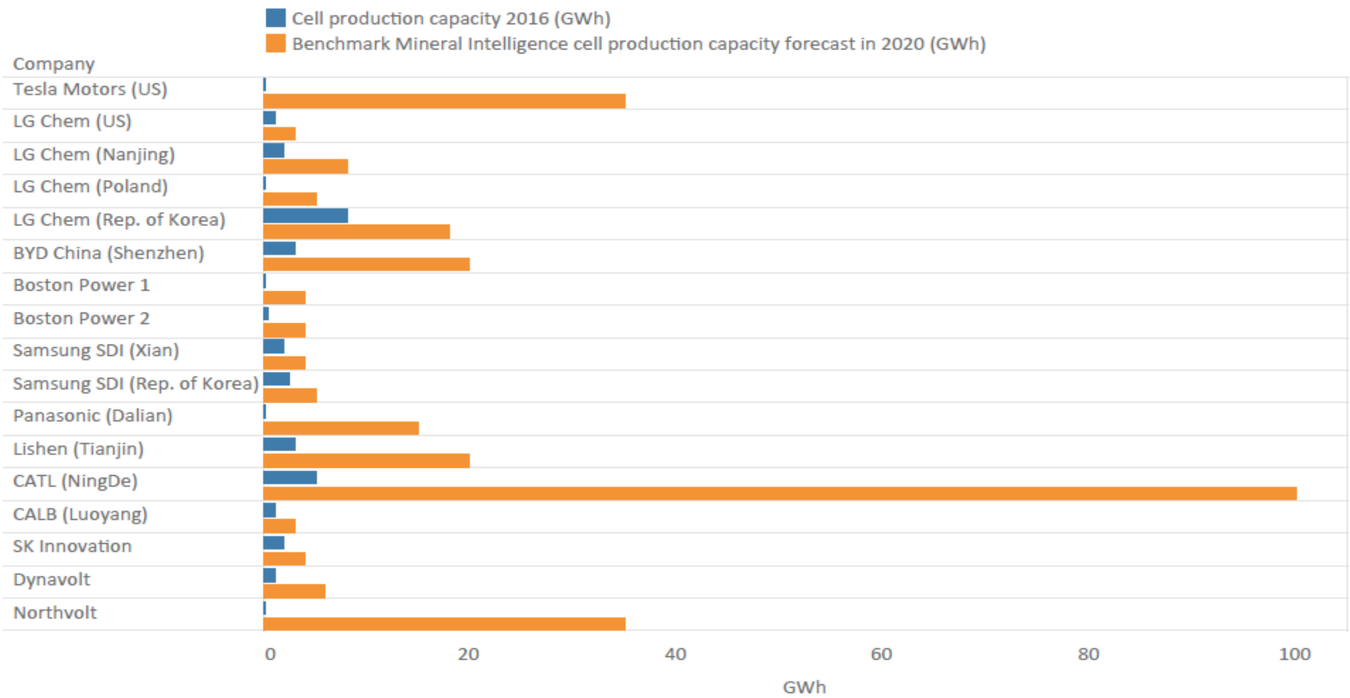
Figure 4: Total non-pumped-hydro storage installations in 2016, over half of the storage needed for sustainable development scenarios (SDS) reached already but still requires big jump in storage capacity by 2030.



Source: EIA, 2017

Recent trends show a massive expansion of lithium-ion manufacturing capacity around the world. The 35 GWh Tesla "Gigafactory" captured headlines in 2016; planned capacity expansions by 2021 now total over 220 GWh, with more than half planned in China (IRENA, 2017) (see Figure 5).

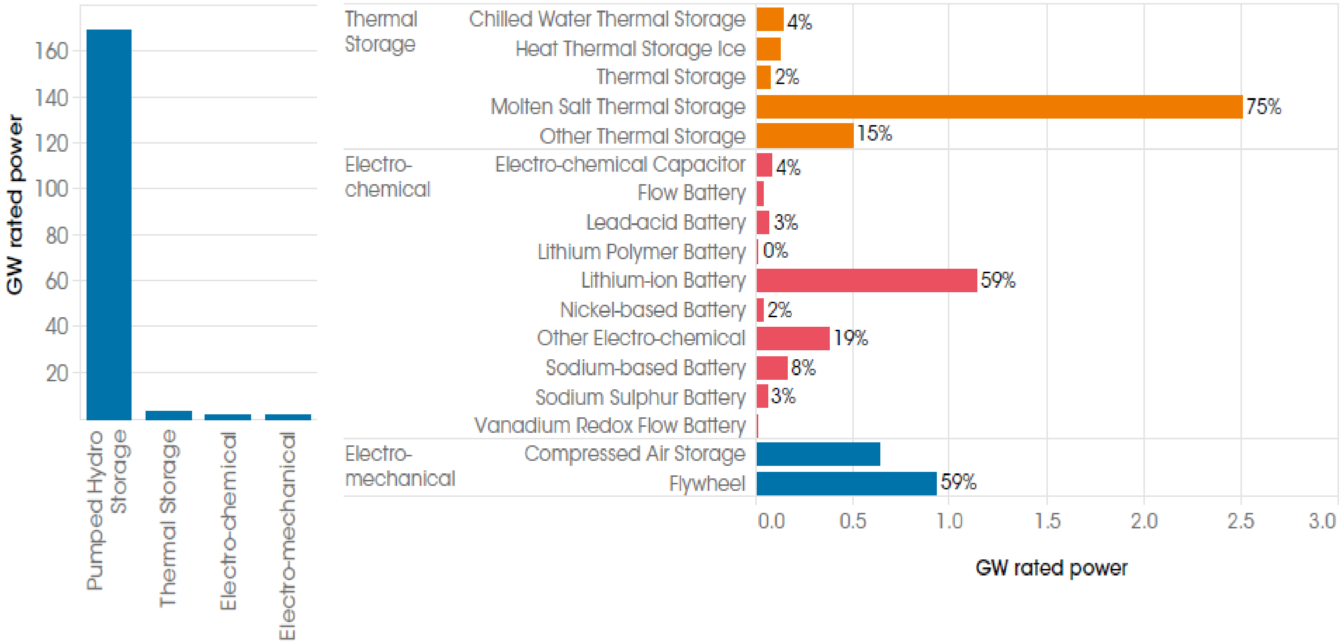
Figure 5: Lithium-ion yearly production capacity expansion, showimg significantly more batteries estimated to be produced in 2020 than 2016



Source: IRENA, 2017

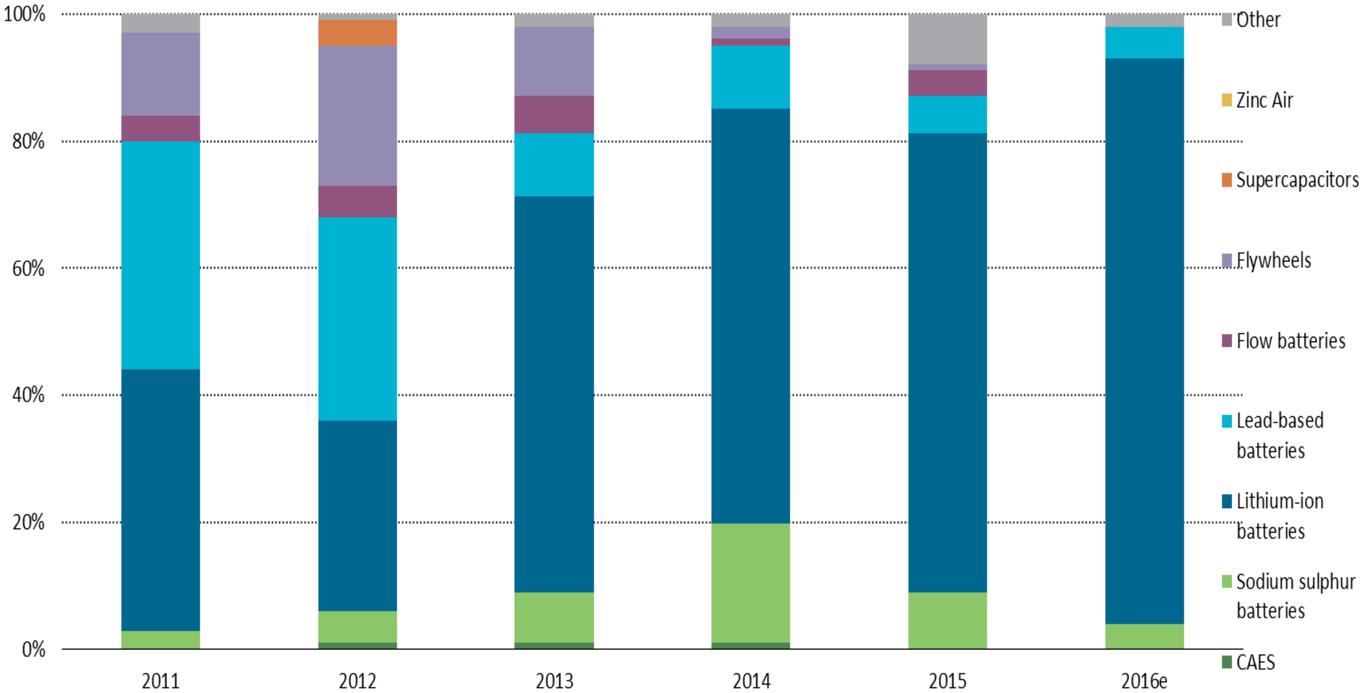
For new storage methods Lithium-ion continued to crowd out other major chemistries, accounting for nearly 90% of utility-scale batteries commissioned in 2017. IEA data demonstrates the rising dominance of lithium chemistries in the period since 2011 (Figure 7). However as of 2016 other technologies accounted for around 60% of total installed capacity (Figure 6) due to legacy methods which are still in use.

Figure 6: Global operational electricity storage power capacity by technology, mid-2017, pumped storage dominates current storage.



Source: IRENA, 2017

Figure 7: Split of new storage capacity added each year. Lithium-ion becoming the most popular source of new storage technology.

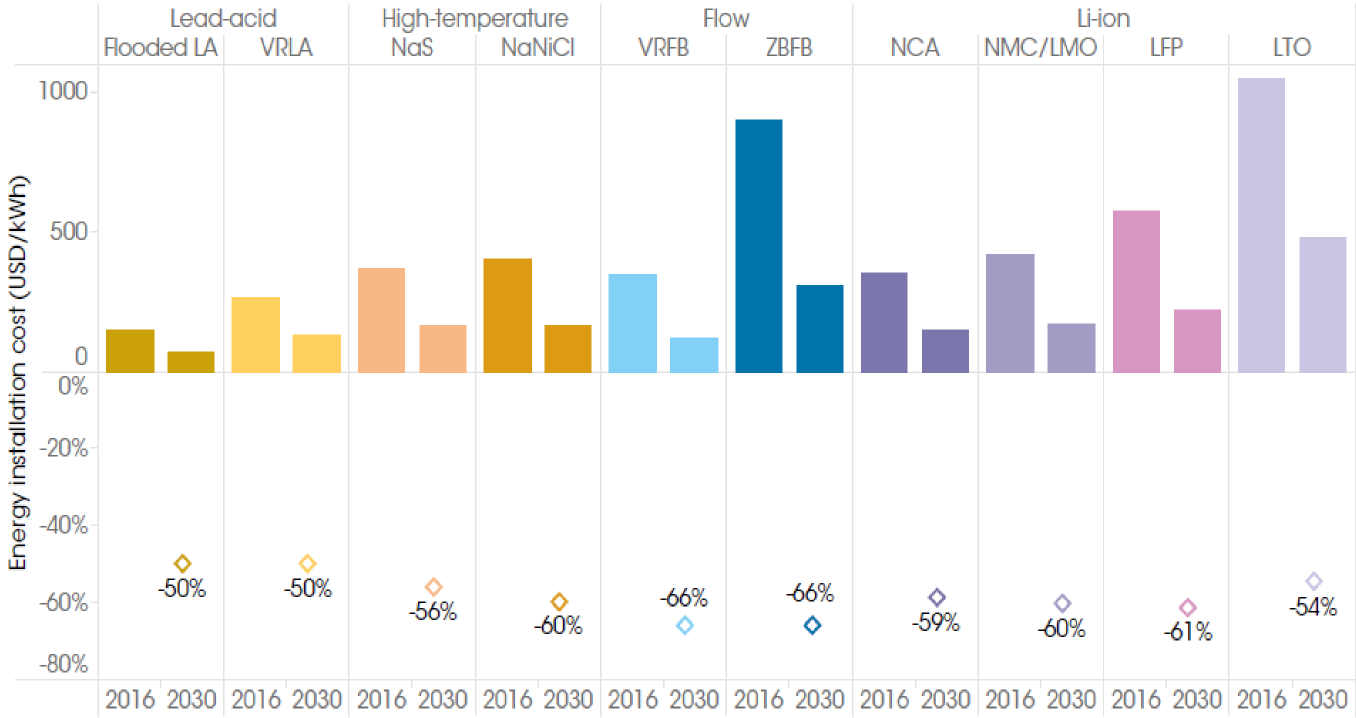


Source: International Energy Agency, 2017

Battery storage – future cost reductions

There are several reasons to expect steep reductions in the cost of battery electric storage in the period to 2030. Economies of scale caused by the commissioning of major new manufacturing facilities, advances in the materials science allowing cheaper electrodes and electrolyte substrates capable of supporting more charge cycles and improvements in the surrounding power electronics and monitoring systems could see battery costs for stationary storage sharply fall by 2030. Lithium-ion batteries for stationary storage systems, helped in part by economies of scale from the growth in the EV market, could see a drop of between 54-61% by 2030 (IRENA, 2017). Round-trip efficiencies for Lithium-ion batteries are already high and not expected to improve greatly, but the number of full cycles possible could improve by up to 90%, increasing lifetimes substantially. Significant cost reductions of about 2/3 for redox flow storage systems are also expected, assuming improvements in electrode and membrane design allowing round-trip efficiencies to improve from 60-85% currently to 67-95% by 2030, meaning that these technologies play larger roles in storage systems in the future.

Figure 8: Installation costs of each technology is expected to fall by least 50%. The most popular technologies will typically see the largest reduction.



Note: LA = lead-acid; VRLA = valve-regulated lead-acid; NaS = sodium sulphur; NaNiCl = sodium nickel chloride; VRFB = vanadium redox flow battery; ZBFB = zinc bromine flow battery; NCA = nickel cobalt aluminium; NMC/LMO = nickel manganese cobalt oxide/lithium manganese oxide; LFP = lithium iron phosphate; LTO = lithium titanate.

Source: IRENA, 2017

3. The economics of storage

Basic principles – the economics of arbitrage

Integrating variable renewables entails changes to the output of conventional stations, with both reduced overall output and increased flexibility in operation. It also affects the level of reserve and response services. Does this mean that renewables need storage or that the presence of renewables improves the economics of storage? The answer to the first question is no, and to the second, is that it may do, but that does not mean storage will be cost effective relative to other options. The key question is what options are available to manage and integrate renewables at least cost. For example, if the presence of renewables lead to a shorter peak period with increased ramp rate (see Box 3), it may be that the cheapest way to meet this is through relatively low capital cost open cycle gas fired power plants. New storage plants would need to recover their capital costs through electricity sales during the high price period, having paid to charge during the low-price period when renewables were generating. Revenue for the storage plant depends upon arbitrage – high prices minus low prices. However, the gas fired plant could set marginal price, based largely upon fuel costs. Whether the arbitrage revenue is sufficient to reward investment in storage will depend upon the capital cost of the storage capacity and the gas price.

Simply put, if the main role is to use storage for arbitrage across peak and off-peak prices it is likely that gas peaking plants are currently cheaper than storage plants (with the exception of older hydro schemes that have long since paid off their capital costs). However, the role of storage is more complex than this. It may be able to offer a range of system services and the economics will be different for different scales, locations and types of grid.

Additional value streams - other system services and market opportunities

There is a multitude of power system services required to balance electricity supply with demand. These services differ in purpose and technical requirements such as size, response time, duration and number of events (Table X, below) (Huff *et al.*, 2013; IEA, 2014; Fitzgerald *et al.*, 2015). For example, electricity arbitrage does not require a fast response, but rather large systems that can store electricity for many hours, possibly once a day. In contrast, frequency regulation requires a very fast response to provide electricity for only minutes, several times a day. Customer-side backup power may only be required a few times per year, but for as long as the outage lasts, which could be several hours. Tables in Appendix 4 provide a breakdown of system services and their characteristics. Investment in any battery system will be determined by which these services the storage installation is serving (possibly several, known as value stacking).

Matching batteries to services

Different storage types/battery chemistries have different characteristics, which affect the economics of use in different applications. Some electricity storage technologies like capacitors and coils are relatively small and respond and charge / discharge ultra-fast. By contrast, mechanical, thermal and chemical storage technologies like pumped hydro, district heat storage or power-to-gas, respond more slowly, have larger storage capacities and can provide electricity for many hours or even longer. Electrochemical storage technologies (i.e. batteries) tend to lie between these extremes, responding very fast and featuring moderate electricity storage capacities and discharge durations.

The challenge is in matching technologies and applications by optimizing technology cost and performance parameters to application requirements. The choice of electricity storage technologies must be appropriate for the required size of the system, the required electricity discharge duration and the discharge events per year.

Battery and thermal technologies are most cost-effective for residential / commercial applications, with lithium-ion and lead-acid most suitable for short discharge durations and thermal, vanadium redox-flow and sodium-sulfur for long discharge durations with many cycles. Outcompeting lithium-ion that currently cannot sustain comparable cycles throughout its lifetime. Lead-acid is most cost-effective for long discharge durations with relatively few cycles.

Electrical technologies (magnetic coils and super-capacitors), flywheels and lithium-ion batteries are most cost-competitive for industry / utility applications with many cycles and short discharge durations. The main criteria here are low investment costs per unit of power output, and a high cycle life. However, it is also important to consider the rapid cost reductions being experienced by certain technologies. By 2030 and 2040, current cost projections suggest that the economics of vanadium redox-flow and particularly lithium-ion will improve and make them most suitable for all residential and commercial applications and for industry/utility applications

Mechanical, chemical and thermal storage technologies are more suitable for long discharge duration applications due to their relatively low investment costs per unit of electricity stored. Again, the substantial investment cost reduction projected for lithium-ion batteries, and potentially also vanadium redox-flow batteries, could challenge this dominance. Vanadium redox-flow has a good cycle life and its electricity storage capacity can be increased independently from its power output (which is not the case for lithium-ion), allowing economies of scale for large electricity storage capacity systems. However, without a sizable current market, future investment cost reductions are less certain than for lithium-ion (cost reductions are discussed in more detail below).

Optimising the economics

The complexity of electricity storage cost and performance parameters and different application requirements make it challenging to identify the most economic storage solution. The Levelized Cost of Storage (LCOS) accounts for all technical and economic parameters affecting the lifetime cost of discharging stored electricity in a specific application, and therefore represents an appropriate tool for comparing the effective cost of storage technologies (Lazard, 2016, 2017; Schmidt *et al.*, 2018).

$$LCOS\left[\frac{\$}{MWh}\right] = \frac{Investment\ +\ Operation\ +Charging\ +\ End\_of\_life}{Electricity\ discharged}$$

The following sections review the growing role of storage in international electricity markets.

4. The role of storage in electricity markets

Table 1: Announced, contracted and under-construction storage by technology type

Counrty	Electro-chemical (Unspecified)	Electro-chemical Capacitor	Lithium ion Battery	Flow battery	Vanadium Redox Flow Battery	Lead-acid Battery	Metal-Air Battery	Sodium-based Battery	Total (kW)
United States	500398		61959	3030	20250	21500	14250		621387
Australia	122010		9400						131410
Germany	30000		92000	210					122210
India	110000		125						110125
Republic of Korea		48500							48500
Canada	12150		12010	4000	5000				33160
Egypt			30000						30000
Italy		1920	20000	1950				4000	27870
Kazakhstan				25000					25000
United Kingdom	1000		20300	140					21440
Top 10	775558	1920	294294	34330	25250	21500	14250	4000	1171102
World	784258	2920	333404	34965	25250	21500	5650	4800	1212747

Source: US DoE, 2017

The changing roles of electricity storage

Pumped hydro installations are often large capacity and construction usually entails significant civil engineering in the form of reservoir construction. Once operational, pumped hydro can offer considerable benefits, but the large capital costs and long payback periods mean capacity in some countries tends to date from the pre-liberalised era when investment was underwritten by state-owned entities and pumped hydro could be justified through a portfolio analysis of an integrated monopoly industry. The UK's pumped hydro provides an example. The most recent installation, Dinorwig, was opened in 1984, after a 10-year £425m (approximately £1.3 billion in today's money) construction programme financed by the British government. The station was developed by the then state-owned national utility in part in anticipation of a large fleet of new nuclear power stations, with concomitant system balancing challenges. In the event, the electricity industry was privatised in 1989 and the all but one of the anticipated new nuclear stations were never built.

Growing interest in new, smaller scale, forms of storage such as batteries is being driven by a combination of falling costs and new or extended categories of system service created by system operators to assist in integrating variable renewables. Several countries have explicitly created incentives to encourage deployment of battery storage, for example in California a 1.2 GW target has been encouraged by state mandate. There is a widespread variation in the amount of new storage capacity under development internationally.

Regional/country breakdown of installed storage capacity

A favourable policy environment in Korea – including discounted retail rates, low-cost credit and eligibility for renewable energy certificates – led to record deployments and a near tripling of the installed base in 2017. World-leading domestic manufacturers, coupled with the large number of projects in the pipeline – including an announced 150 MW megabattery, which would become the largest system in the world – signal that the trend in Korea is likely to continue.

In Australia, while the commissioning of the Tesla 100 MW megabattery captured headlines, several pumped hydro projects were announced in 2017, including a 2 GW expansion of a facility in the Snowy Mountains. If completed, all announced pumped hydro projects would provide 50 times the capacity of the Tesla battery installation.

In the United States, creation of storage markets is state driven. New York announced a 1.5 GW storage target by 2025, and Arizona proposed a 3 GW storage mandate by 2030. Regulatory changes in California, where a storage mandate is already in place, created a more favourable environment for storage players.

Deployment slowed significantly in the European Union and Japan in 2017.

In the United Kingdom, despite strong initial interest in storage in the 2017 capacity auction, just over 10% of pre-qualified storage capacity cleared the market. More positive trends were seen in Germany and Italy, where high retail prices and a positive regulatory framework led to an uptick in residential energy storage. Despite planned rollbacks of incentives in Germany, the growth in storage systems again reached record numbers, with over 30 000 systems installed.

Other battery applications – power grids, cars and electronics

It is important to note that the discussion above is focused on the use of storage in power grids. However large markets for batteries exist for use in consumer electronics, electric vehicles and other applications. A report by Umicore (Vandeputte, 2016) forecasts an exponential growth in batteries for electric vehicles, from a market of less than 25GWh in 2015 to one of over 450GWh by 2025. The consumer electronics market shows a doubling from 50GWh in 2015 to 100GWh in 2025, while batteries for stationary energy storage grow from a negligible capacity in 2015 to approximately 45GWh in 2025.

Electric vehicles – Are we equipped for the future?

Electric vehicles are becoming popular as a more environmentally friendly mode of transport with huge potential, however there are challenges surrounding the logistics of charging these vehicles. In the UK the largest emitter of greenhouse gasses is the transport sector therefore the move towards EVs can make a sizable impact when reducing the greenhouse gas emissions of the country (Department for Business, Energy and Industrial Strategy, 2018). An opportunity arising from the increasing number of plug in electric vehicles is their ability to act as a behind-the-meter storage, with the potential to add to the storage capacity of the grid. The addition of more behind the grid storage capacity connected to the grid can provide opportunities for energy arbitrage and can reduce the issues surrounding solar PV intermittent power output. Though there are unanswered issues regarding grid storage capacity supplementation with electric vehicles such as the deterioration of the battery and the issue surrounding a discharged battery when an emergency journey is needed (ITM Power, 2018).

There are two types of purely electric vehicle; a Battery Electric Vehicle (BEV) and a Fuel Cell Electric Vehicle (FCEV). The current trend in electric vehicle adoption is heavily weighted towards BEVs, with approximately 223,000 plug in cars registered in the UK in June 2019 (Next Green Car, 2019), compared to only 11,200 FCEVs across the world (Fukui, Lucchese, & Bennett, 2019). The fact that there is a current move towards BEVs allows for the exploration into the potential for Vehicle-to-grid storage, as a result the UK Government has recently invested £30 Million in Vehicle-to-grid R&D (House of Commons, 2018) . Although the move towards BEVs will reduce direct transportation emissions the increased power demand needed to charge these vehicles may incur indirect emissions from extra power generation needed from non-renewable sources. To fully charge a depleted BEV from home uses the equivalent daily energy consumption of between 5-10 conventional households; putting serious strain on the Low Voltage distribution networks connecting residential areas. This also increases the plateau demand in the typical electricity demand profile therefore requiring increased fossil fuel generation. In the long term, there are people betting that the only option for a low emissions transport network is to adopt hydrogen Fuel cell technology. With these FCEVs they run off Hydrogen which is produced by hydrolysis purposely at times when the grid demand profile is lowest. This hydrogen is then distributed in a similar way to traditional vehicle fuels, with cars being refuelled at hydrogen filling stations in a matter of minutes, considerably shorter than for BEVs. Hydrogen fuelling stations also present a more practical solution compared to charging from home when households have multiple cars and lack the infrastructure to charge one or both simultaneously (ITM Power, 2018).

Table 2 below shows the battery requirements for different systems in order to compare the required performance with the application. The description provides information about the application and the required size of the energy store. Linked to the application are requirements such as the response time. For mobile applications response time needs to be very fast, but for other applications, they might be quite slow. For firming up power from renewable resources there the requirement of a fast response time, although for some large-scale power stores – e.g. ones for communities, the response is orders of magnitude slower. Typical discharge times are for a few hours' worth of power. For mobile applications, efficiency is necessarily high to present extra mass requirements (poorer efficiency equates to more batteries and a greater requirement for cooling), whereas for stationary power stores, the requirements for high roundtrip efficiency are reduced. However, it is typically expected that calendar life and cycle life for stationary application needs to be higher in order to offset the fixed costs.

Based on the requirements of the different applications, it turns out that there is not one battery system which is best. The different battery chemistries including future contenders are expanded upon in the following table with further details below.

Table 2: Comparison between different battery technologies in terms of cell performance, safety and environmental Impact [2]

	Current RT Batteries	High temp.	Redox-Flow	Future prospects		
	Lead acid	Lithium ion	Sodium Sulfur	All vanadium	Zinc-air	Sodium ion[d]
Specific power W/kg	75-300	200-2000	90-230	50-150	30-50	
Specific energy Wh/kg	20-50	50-200	150-240	15-25	110-(3000)	100-200
Power density kW m^{-3}	90-700	1000-4000	120-240	0.5-25		
Energy density kWh m^{-3}	75	100-450	<400	15-35		
Lifetime cycles	500-2000	1000-3000	2500-4500	>10000	100-300	<100
Roundtrip efficiency[a] / %	70-92	85-90	86	65-85	50	80
Self-discharge % per day	0.1-0.3	0.1-0.3	20[b]	0		
Safety	++	+	-	++	++	-
Environmental impact[c]	-	+	+	++	++	+
Resource constraints[e]	++	+	+++	--	+++	(++)[f]

Bracketed figures are estimated from literature and should be considered limiting or maximum values.

[2] [a] at battery - DC
[b] to maintain temperature
[c] Information taken from [2] and [3] or estimated where required
[d] Information from [4] and based on laboratory cells
[e] Information from [5]
[f] Limited by composition of electrode materials rather than ion
[g] Taken as H_2-Br as a suitable example [6]
[h] Figure taken from Enstorage publicity material[2]

5. Risks associated with electricity storage systems

Catastrophic failure

The use of batteries in a large-scale energy store requires careful thought and design to avoid a catastrophic fire which cascades from battery pack to battery pack, as was the case for a massive fire in a failed NGK-manufactured battery installed outside of Mitsubishi Materials Corporation's Tsukuba Plant 7. Apart from that accident, there is relatively little public knowledge or evidence concerning accidents in this area, although for automotive systems there are a number of examples of battery pack failure leading to a fire which destroys the car.

Safety represents a significant area of concern for lithium-ion batteries. Cells contain flammable liquid electrolytes, leading to the possibility of failure causing combustion and harm to both people and assets. Non-flammable solid electrolytes, liquid electrolytes with a larger temperature window or with the ability to prevent lithium plating through rapid solid electrode interphase formation offer potential solutions to the flammability issue (Goodenough & Kim 2010). Present-day separators are inadequate when tasked with preventing short circuits, thermal runaway and cell failure upon penetration. Ionically-conductive solid electrolytes provide the potential for relief in this area. Improved battery management systems will make an incremental improvement to safety through more timely prediction of failure-events and better parameter estimation. The intelligent design of battery packs to ensure individual cell failures are sufficiently isolated from the remainder of the pack can further improve safety. However, the progression towards higher energy density cells and highly-reactive lithium metal anodes poses a set of new safety challenges.

Safety standards for lithium -ion batteries, including fire standards, have been developed at national and international levels (Intertek, 2014). The Underwriters Laboratories (UL) and the International Electrotechnical Consortium (IEC) have produced standards for lithium-ion batteries. Relevant standards are UL 1642 (Lithium Batteries), UL 2054 (Household and Commercial Batteries, IEC 60086-4 (Primary Batteries) and IEC 62133 (Secondary Batteries containing Non-acid Electrolytes). In the UK, the BSI group has adopted the IEC standards as British Standards.

Fire risks from grid-connected battery storage systems can be managed with appropriate planning and construction measures. It is essential to carry out a full assessment of the type of battery to be installed, as different battery chemistries require different fire extinguishing methods. (AIG 2017) Battery fires can also burn very intensely and emit toxic gas and liquids, so suitable protective equipment should be available on site and buildings should be constructed with this in mind. Battery systems should be physically isolated from other equipment such as battery management systems or electrical switches in separate cabinets, and preferably in separate rooms or buildings, which should have appropriate ratings to contain lithium battery fires for at least 90 minutes (Denios 2018). Battery Cabinets should contain appropriate fire detection and alert systems, as well as an explosion relief hatch to relieve internal pressure during the thermal-runaway stage of a fire.

End of life/toxicity/damage to the environment or during manufacturing

Lithium-ion batteries are classified as Class 9 miscellaneous hazardous materials, and there are different challenges in terms of size, shape, complexity of the used materials, as well as the fact that recycling lithium from pyrometallurgical processes is not an energy- and cost-efficient process. In the event of an accident there must be some way of safely discharging the batteries as they can remain dangerous for some time after an accident (e.g. a Tesla car bursting into flames after fire has been put out and the car moved to a separate location). Recycling Li-ion batteries is important due to the quantities of metals – cobalt, coper and nickel in addition to lithium - which they contain. Li-ion batteries cannot be landfilled due to toxic materials and the danger of fire or explosion, and cannot be incinerated, again due to the toxicity of the materials. (European Commission, 2018) Lithium batteries must be decommissioned carefully, as improperly treated batteries can cause heavy metal, $LiPF_6$ or PVDF contamination as well as risks relating to sudden power discharge, chemical reactions and dangers with batteries which have suffered water ingress (Weiping, Wang and Zhishan, 2018). Decommissioning lithium batteries at end-of-life is an important part of the process, and currently as few as 5% of LI-ion batteries in the EU are recycled (FOE Europe, 2014). This is due to the cost of recycling, which almost always is higher than the cost of obtaining the raw materials from mining. Subsidies are currently needed to make operations viable, though this could change in the future as resource prices fluctuate and a high volume of standardised EV and grid storage batteries reach end-of-life.

Use of critical raw materials

Worldwide production capacity of lithium will increase at a rate of 12% compounded annual growth rate to meet demand from battery technologies through 2020, involving an increasing extraction from hard rock sources. China currently contains the majority of global lithium refining plants, while Chile is currently the world's leading supplier of unrefined lithium, with 66% of the total (EC, 2018). Lithium supplies look robust for the near future, due to spare capacity in mining and refining and large quantities of proven reserves (McKinsey 2018). The large amount of cobalt required is potentially more concerning, as the worldwide cobalt demand is substantially sourced (64%) from the vast reserves in the Democratic Republic of Congo (DRC), a region of the world characterised by military conflict and significant human rights abuses upon workers, raising ethical as well as reliance issues. Supply is predicted to be even more dominated in the DRC in the future, up to approximately 75% by 2025. Graphite sourcing, required for electrodes, is currently dominated by China (66%) and it equally raised ethical and environmental issues. For redox flow batteries, the major materials used are vanadium which suffers from being almost exclusively mined in China leading to an issue of availability and associated price volatility. Work is ongoing to use metals other than vanadium in these systems to reduce cost and improve availability. More information about the importance of the mining sector's ability to extract and provide the resources necessary to build clean, renewable energy technologies can be found in Lloyd's report *'Unearthing Opportunities'* produced in collaboration with Satarla.

BESS Battery Insurance Product

Efficient electricity storage is one of the key long-term factors to consistent delivery of energy from renewable sources, during peak demand. Like all technologies early in their development, Battery Energy Storage Systems (BESS) present unique and challenging risks, which can be mitigated with the aid of appropriate insurance.

With the production and deployment of BESS steadily increasing, there is a growing need for insurance products that focus on BESS as a standalone product, helping companies to transfer their risk. For this reason AXIS, an insurer of renewable energy projects, including wind and solar, has created a bespoke insurance product for BESS.

BESS risks fall into four broad categories: technical, commercial, market, and natural..

1. Technical risks
   Due to the chemical nature of batteries, the leading technical risk is fire. This places a heavy emphasis on maintaining conditions including ambient temperature, humidity, condensation and charge level. These can be controlled and maintained using a Battery Management System (BMS), which mitigates risks
2. Commercial risks
   Commercial risks are led by loss of income. Loss of income can occur due to issues with system integration, an inability to collect revenue from the grid and penalties from unavailability to the grid, amongst others.
3. Market risks
   Market risks focus on possible overcapacity, caused by supply outweighing demand, lack of supply chains in project localities and the ability to rely on suppliers for the long term.
4. Natural event risks
   Natural event risks are the most easily mitigated. Projects can be built to withstand extreme weather. Constructing housing facilities for windstorm and placing batteries above water flood levels can help to mitigate these risks.

AXIS is an insurer of renewable energy projects, including wind, solar and BESS. Their BESS insurance product can provide specialised property coverage for:

- Physical Damage and revenue protection
- Marine Delay in Start up
- Construction All Risks
- Operation All Risks
- Business Interruption
- Contingent Business Interruption
- Third Party Liability
- General Liability

AXIS insures projects from development through to operation, on risks ranging from standalone projects to utility scale portfolios. Clients include project developers, operators, independent power producers, EPC's and utility companies around the world.

Learn more at https://www.axiscapital.com/

6. Conclusions

The principles involved in operating power grids with increasing penetrations of variable renewables are well understood and the costs of introducing renewables are relatively modest at current penetrations. Wind and solar are providing upwards of 20% of annual electricity demand in leading countries. For the most part this has been achieved with little change to the balance of plants on the system in each country. Greater flexibility in operation is needed at larger penetrations and this can be provided by demand response, interconnection, and more flexible fossil power plants – as well as storage. The traditional form of storage is pumped hydro, and this still dominates the installed capacity of all forms of storage worldwide.

Storage can provide a variety of system services and batteries have been installed in several countries in increasing amounts in recent years to provide fast frequency response and other system services. It is important to match battery type to system requirement because different batteries offer different capabilities, though there is evidence of Lithium -ion chemistries playing increasingly dominant role across many market segments and countries. Yet, for economic reasons there is little use of batteries to provide bulk storage of electricity on existing power grids – for example to provide inter-day storage. Behind the meter storage also remains a small fraction of total installed storage capacity. Nevertheless, the capacity of grid connected batteries is widely projected to expand considerably in the next few years as costs fall and insurers can support the deployment of this technology to improve and secure revenue for future renewable energy projects.

Appendix A

Short term system balancing requirements

System balancing reserves are needed to deal with unexpected short-term fluctuations (minutes to hours) caused by unanticipated demand changes, or faults at power stations or power lines. The amount of reserves needed to handle unpredicted short-term variations is calculated or simulated using statistical principles. The objective is to ensure that operating reserves are available that can deal with almost all the unpredicted fluctuations that can be envisaged (Gross *et al.*, 2006; Heptonstall, Steiner and Gross, 2017).

Historically, reserves have been sized to cover approximately ±3 standard deviations (SD) of the potential uncertain fluctuations that arise from this combined risk of demand prediction error and generation plant failure, plus provision for the sudden loss of the largest single generating unit (n-1 criteria, or disturbance reserve). The ±3 SD criteria ensure 99% of unpredicted demand or supply fluctuations are covered by reserves: Reserves = $\pm 3\sqrt{(\sigma_d^2 + \sigma_s^2)}$ (plus disturbance reserve) where $\sigma_d \sigma_s$ represent the standard deviations of demand and supply fluctuations[3] (Anderson, 2006).

Additional short run fluctuations in output due to variable renewables will increase the use of reserve capacity, for example the utilisation of automatic controls on the output of conventional power stations. It may also be necessary to have more part loaded plant running that can rapidly *ramp up* or *ramp down* (change output). Three interrelated factors determine the amount of extra reserve required when variable generation is added to the system (Gross et al., 2006):

1. The extent of unpredicted variations in variable plant output, which has two aspects: Firstly, how *rapidly* the outputs of different types of variable plant will fluctuate. Secondly, the possible scale of *total,* system-wide, changes in a given period. This requires a representation of the aggregated behaviour of individual variable plants, based on weather data, size of units, inertia, and the scope for 'smoothing' of outputs – for example by geographical dispersion. These data provide an indication of the variability of renewable generators such as wind or solar.
2. How accurately fluctuations over the minutes-to-hours timescale can be forecast. The more accurate the forecasting the greater the opportunity to use lower cost, *planned* changes as opposed to holding reserve plant in readiness, which can be costly and less efficient. In market terms, the effects of predicted fluctuations can be contractually committed prior to gate closure, which should permit the market to reveal the most cost-effective means to manage these variations. Again, it is the prediction accuracy of total aggregated variable generation that is relevant; forecasting for a large amount of widely distributed resources reduces forecast errors.
3. How the timing of demand variations compares with that of variable renewable output. If for example load and output are highly correlated, their variations may act to cancel each other out and reduce reserve requirements.

In all cases analysis requires a statistical treatment of both demand and variable generation, since we are dealing with *probabilities* rather than determinate functions. Using the analytical approach described earlier, we can see that adding variable generation increases the variance of the supply side term. This is usually estimated by adding the squared standard deviation of unpredicted fluctuations in variable supply to the sum of squared standard deviations of demand and conventional supply (Gross *et al.*, 2006).

Two factors are notable: First that even for a relatively unpredictable source like wind power the standard deviation of fluctuations in the period from minutes to a few hours is relatively modest. This is because there is considerable smoothing of outputs in the sub-hourly

[3] The analytical approach presented here provides an explanation of the underlying principles and approximate results; simulations are needed to deal with more complex situations.

timeframe, and considerable prediction accuracy over a few hours. Secondly, variance of unexpected wind or solar fluctuations must be combined statistically with the variance of demand and conventional supply, meaning that the absolute impact on reserves is muted. The implications of this are that the amount of additional reserve services needed for renewables has tended to be relatively modest, indeed there is evidence that they have been stable or falling even as the share of renewables has grown (Joos and Staffell, 2018). Regulatory changes (notably reducing the time period between market closure and real time) have helped to ensure that more of the fluctuations can be managed by the market. Improved forecasting techniques have also played an important role.

Longer term system reliability requirements

In addition to the short term reserves a larger 'system margin'[4] of maximum possible supply over peak demand is needed to ensure that peak demand can be reliably met, even if some power stations are unavailable, for example because of a fault. In England and Wales, the practice before liberalisation was to plan for and invest in installed capacity approximately 20% larger than expected peak demand. Current practice by the System Operator is to procure sufficient firm capacity for peak winter periods utilising the Capacity Market, a competitive auctioning process. (DECC, 2014). The Capacity Market is designed to utilise existing firm capacity (conventional generation, embedded generation) and incentivise the construction of new capacity, including demand-side response and storage.

It might be thought that variable renewable plant cannot contribute to reliability at all since in most cases we cannot be certain that it will be available at any specific time, including at system peaks. However, there is a possibility that *any* plant on the system will fail unexpectedly and reliability is always calculated using probabilities. Variable renewable generators can contribute to reliability provided there is some probability that they will be operational during peak periods. The fraction of capacity that can be relied upon statistically is called capacity credit. The key determinants of capacity credit are as follows (Gross et al., 2006):

1. The degree of *correlation* between demand peaks and variable output. The greater the correlation the greater the capacity credit. For example, photovoltaic (PV) has zero capacity credit in the UK because demand peaks occur in winter evenings, when it is dark. But PV can have a high capacity credit in sunnier regions where demand peaks are driven by daytime air conditioning loads that are well correlated with PV output.
2. The *average* level of output. A higher level of average output over peak periods will tend to increase capacity credit. Taking UK wind as an example, there is little correlation between wind output and demand. However, wind farm outputs are generally higher in winter than they are in summer. For this reason, analysts use winter quarter wind output to calculate capacity credit.
3. The *range* of variable outputs. Where demand and renewable output are largely uncorrelated a decrease in the range of variable renewable output levels will tend to increase capacity credit, because the *variance* decreases. More *consistent* wind regimes decrease variance and increase capacity credit. Geographical dispersion of plants can smooth outputs and decrease overall variation as can increasing the variety of types of renewable plant on a system.

Capacity credit is determined by considering the total variance of both supply and demand, including variable renewable options on the supply side, and then comparing this to an all fossil/no renewable case. Because the variance at peak demand is generally larger for wind/solar than for conventional stations, the capacity credit of variable sources tends to be lower than their installed capacity. Capacity credit is solely a measure of probable contribution to demand during peak periods and should not be confused with capacity factor – a measure of the average output over a year, and neither should be conflated with conversion of energy capture efficiency or used as a measure of how much of the time a wind farm might be generating.

[4] System margin is the current UK Grid Code term. The concept has been referred to historically as variously 'capacity margin', 'system reserves' and 'plant margin'.

Appendix B

Additional value streams – other system services and market opportunities

Table 3: ISO/RTO Services

Energy Arbitrage	The purchase of wholesale electricity while the locational marginal price (LMP) of energy is low (typically during night time hours) and sale of electricity back to the wholesale market when LMPs are highest. Load following, which manages the difference between day-ahead scheduled generator output, actual generator output and actual demand, is treated as a subset of energy arbitrage in this report.
Frequency Regulation	Frequency regulation is the immediate and automatic response of power to a change in locally sensed system frequency. Regulation is required to ensure that system-wide generation is perfectly matched with system-level load on a moment-by moment basis to avoid system-level frequency spikes or dips, which create grid instability.
Spinning/Non-spinning Reserves	Spinning reserve is the generation capacity that is online and able to serve load immediately in response to an unexpected contingency event, such as an unplanned generation outage. Non-spinning reserve is generation capacity that can respond to contingency events within a short period, typically less than ten minutes, but is not instantaneously available.
Voltage Support	Voltage regulation ensures reliable and continuous electricity flow across the power grid. Voltage on the transmission and distribution system must be maintained within an acceptable range to ensure that both real and reactive power production are matched with demand.
Black Start	In the event of a grid outage, black start generation assets are needed to restore operation to larger power stations in order to bring the regional grid back online. In some cases, large power stations are themselves black start capable.

Source: Fitzgerald *et al.*, 2015

Table 4: Utility Services

Resource Adequacy	Instead of investing in new natural gas combustion turbines to meet generation requirements during peak electricity-consumption hours, grid operators and utilities can pay for other assets, including energy storage, to incrementally defer or reduce the need for new generation capacity and minimize the risk of overinvestment in that area.
Distribution Deferral	Delaying, reducing the size of, or entirely avoiding utility investments in distribution system upgrades necessary to meet projected load growth on specific regions of the grid.
Transmission Congestion Relief	ISOs charge utilities to use congested transmission corridors during certain times of the day. Assets including energy storage can be deployed downstream of congested transmission corridors to discharge during congested periods and minimize congestion in the transmission system.
Transmission Deferral	Delaying, reducing the size of, or entirely avoiding utility investments in transmission system upgrades necessary to meet projected load growth on specific regions of the grid.

Source: Fitzgerald *et al.*, 2015

Table 5: Customer services

Time-Of-Use Bill Management	By minimizing electricity purchases during peak electricity-consumption hours when time-of-use(TOU) rates are highest and shifting these purchase to periods of lower rates, behind-the-meter customers can use energy storage systems to reduce their bill.
Increased PV Self-Consumption	Minimizing export of electricity generated by behind-the-meter photovoltaic (PV) systems to maximize the financial benefit of solar PV in areas with utility rate structures that are unfavourable to distributed PV (e.g., non-export tariffs).
Backup Power	In the event of grid failure, energy storage paired with a local generator can provide backup power at multiple scales, ranging from second-to-second power quality maintenance for industrial operations to daily backup for residential customers.

Source: Fitzgerald *et al.*, 2015

Table 6: System services

Application	Size (MW)	Duration (hours)	Cycles (per year)	Response Time (seconds)
Energy arbitrage	0.001-2,000	1-24	50-400	>10
Frequency regulation	1-2,000	0.02-1	250-5,000	<10
Voltage support	1-2,000	0.02-1	250-5,000	<10
Spin / Non-spin reserve	10-2,000	0.25-1	20-1,000	>10
Resource Adequacy	5-1,000	>1.5	20-50	>10
Black start	0.1-400	0.25-4	1-20	>10
Seasonal storage	500-2,000	24-2000	1-5	>10
T&D upgrade deferral	1-500	2-8	10-500	>10
Congestion management	1-500	1-4	50-500	>10
Time-of-Use bill management	0.001-10	1-6	50-500	>10
Power quality	0.05-10	0.003-0.5	10-200	<10
Demand charge reduction	0.05-10	0.003-0.5	10-200	<10
Backup power	0.001-10	2-10	50-400	>10

Source: Fitzgerald *et al.*, 2015

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