IRENA
International Renewable Energy Agency

ELECTRICITY STORAGE AND RENEWABLES:

COSTS AND MARKETS TO 2030

October 2017
www.irena.org

ISBN 978-92-9260-038-9

Citation: IRENA (2017), Electricity Storage and Renewables: Costs and Markets to 2030, International Renewable Energy Agency, Abu Dhabi.

About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and it serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. **www.irena.org**

Acknowledgements

IRENA is grateful for the the reviews and comments of numerous experts, including Mark Higgins (Strategen Consulting), Akari Nagoshi (NEDO), Jens Noack (Fraunhofer Institute for Chemical Technology ICT), Kai-Philipp Kairies (Institute for Power Electronics and Electrical Drives, RWTH Aachen University), Samuel Portebos (Clean Horizon), Keith Pullen (City, University of London), Oliver Schmidt (Imperial College London, Grantham Institute - Climate Change and the Environment), Sayaka Shishido (METI) and Maria Skyllas-Kazacos (University of New South Wales).

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Executive Summary

Electricity storage will play a crucial role in enabling the next phase of the energy transition. Along with boosting solar and wind power generation, it will allow sharp decarbonisation in key segments of the energy market.

The 2015 United Nations Climate Change Conference in Paris set the framework for a rapid global shift to a sustainable energy system in order to avoid the risk of catastrophic climate change. The challenge for governments has shifted, from discussing what might be achieved to determining how to meet collective goals for a sustainable energy system.

This is a task that demands urgent action. Greenhouse gas emissions must peak in the near future if the world is to steer clear of the costly and dangerous effects of climate change.

Given the sharp, and often rapid, decline in the cost of renewable power generation technologies in recent years, the electricity sector has made concrete progress on decarbonisation. Renewable power deployment, however, needs to accelerate. Decarbonisation in the end-use sectors, such as direct energy uses in industry, transport and residential and commercial buildings, also has to speed up given that progress is lagging in these areas.

All this has brought into sharp relief the significant potential, and the crucial importance, of electricity storage to facilitate deep decarbonisation. Storage based on rapidly improving batteries and other technologies will permit greater system flexibility – a key asset as the share of variable renewable electricity (VRE) increases. More directly, electricity storage makes possible a transport sector dominated by electric vehicles (EVs), enables effective, 24-hour off-grid solar home systems and supports 100% renewable mini-grids.

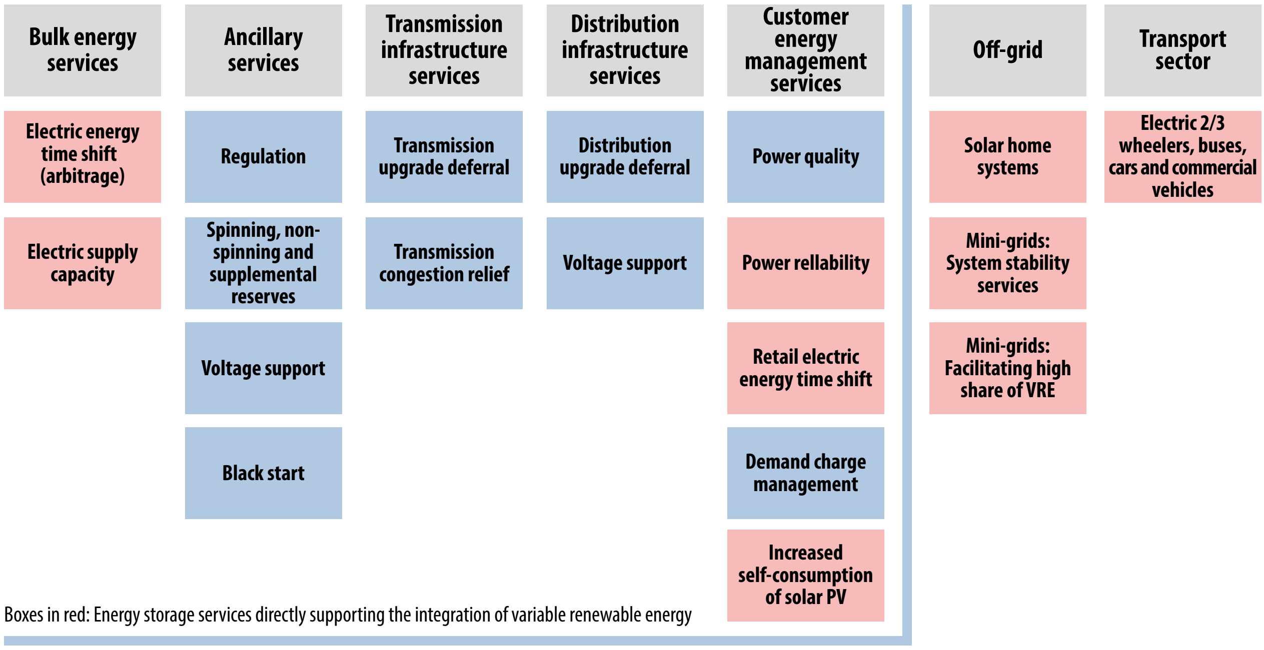
As variable renewables grow to substantial levels, electricity systems will require greater flexibility. At very high shares of VRE, electricity will need to be stored over days, weeks or months. By providing these essential services, electricity storage can drive serious electricity decarbonisation and help transform the whole energy sector.

Electricity systems already require a range of ancillary services to ensure smooth and reliable operation (Figure ES1). Supply and demand need to be balanced in real time in order to ensure supply quality (e.g., maintaining constant voltage and frequency), avoid damage to electrical appliances and maintain supply to all users. All electricity systems require a degree of flexibility services, which allow grid operators to react to unexpected changes in demand or to the loss of large chunks of supply (e.g. large stations tripping offline, loss of an interconnection). Flexibility gives operators the tools to rapidly restore system equilibrium.

In today's power systems, solar and wind power still have limited impact on grid operation. As the share of VRE rises, however, electricity systems will need not only more flexibility services, but potentially a different mix that favours the rapid response capabilities of electricity storage. This key shift in system operation needs to be part of the energy planning process. The International Renewable Energy Agency (IRENA), analysing the effects of the energy transition until 2050 in a recent study for the G20, found that over 80% of the world's electricity could derive from renewable sources by that date. Solar photovoltaic (PV) and wind power would at that point account for 52% of total electricity generation.

Electricity storage will be at the heart of the energy transition, providing services throughout the electricity system value chain and into the end-use sectors. Electricity storage capacity

Figure ES1: The range of services that can be provided by electricity storage



can reduce constraints on the transmission network and can defer the need for major infrastructure investment. This also applies to distribution, regardless of whether constraints reflect growth in renewables or a change in demand patterns. Behind-the-meter applications allow consumers to manage their bills, reducing peak demand charges and increasing "self-consumption" from rooftop PV panels. Along with providing multiple services and user benefits, an electricity storage project can unlock multiple revenue streams from the provision of a range of services. With the very high shares of wind and solar PV power expected beyond 2030 (e.g. 70-80% in some cases), the need for long-term energy storage becomes crucial to smooth supply fluctuations over days, weeks or months. Along with high system flexibility, this calls for storage technologies with low energy costs and discharge rates, like pumped hydro systems, or new innovations to store electricity economically over longer periods. Although such challenges extend beyond the time horizon of this report and, hence, the scope of the present analysis, they need to be kept in mind, as foreseeing future needs sheds light on long-term market potential. This, in turn, gives the necessary impetus for storage development today. Research and development in the period to 2030 is therefore vital to ensure future solutions are available, have been demonstrated and are ready to scale up when needed.[1]

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[1] There are a range of solutions to this requirement to smooth the variability of solar and wind over a longer time horizon that spans not only electricity storage. It could be, for instance, economically viable to use bioenergy plants (i.e. solid or biogas) in what currently would be termed "peaker roles"; that is, high-capacity plants that are used for relatively few hours during the year. An alternative is "power-to-X" pathways, where surplus VRE is used to produce renewable gas or hydrogen, which is then stored for later use (a power-to-fuel approach). Similarly, electricity could provide heat or cooling with highly efficient heat pumps, stored for short or long periods (e.g. existing seasonal thermal energy stores) before being released to the end-user as required. Given that thermal energy stores are significantly less expensive than electrical energy storage, this could make sense.

Electricity storage can directly drive rapid decarbonisation in key segments of energy use. In transport, the viability of battery electricity storage in electric vehicles is improving rapidly. Batteries in solar home systems and off-grid mini-grids, meanwhile, are decarbonising systems that were heavily reliant on diesel fuel, while also providing clear socio-economic benefits.

Electricity storage technologies are emerging as a critical part of the solution to increase access to electricity in conjunction with solar PV in solar home systems, as well as providing stability services to mini-grids, improving the power quality and increasing the potential share of variable renewables in such remote grids. At the end of 2016, as many as 55 million households, or 275 million people, benefitted from the electricity or light provided by solar lanterns, solar home systems and PV mini-grids. This has been driven by the fall in the cost of solar PV and the price reductions which have made these systems more affordable. For instance, in Africa, solar home systems using small batteries are now able to provide better quality energy services to off-grid households at an annual cost that is less than what they already pay for inferior lighting (e.g. kerosene lanterns) and other energy services (IRENA, 2016a).

Decarbonising the transport sector — for long, a challenge — is also gathering momentum, with the scale-up of EV deployment and the drive to lower battery costs. The cost of an EV battery fell by 73% between 2010 and 2016 (BNEF, 2017), and, at the end of 2016, the total stock of electric cars reached 2 million after having gone beyond the level of 1 million in 2015 (OECD/IEA, 2017). Smaller, two- and three-wheel EV numbers have surpassed 250 million globally, while there now are 300 000 electric buses in China alone.

While the focus of this report is on electricity storage in stationary applications, the sheer volume of batteries needed for the transport sector — if the sector is to be decarbonised — implies the essentiality of including total market figures in any analysis of the electricity storage market. To ensure a consistent and integrated global perspective, this report applies transport sector projections for all types of EV from IRENAs REmap analysis (IRENA, 2016b and 2017a). As EVs are unlikely to be passive participants in the process towards energy transformation, their potential to provide vehicle-to-grid flexibility services will also become a significant factor to consider. A number of pilot projects have been implemented to integrate demand-side management and vehicle-to-grid services to be able to manage the demand and provide electricity to the grid during peak demand hours or when flexibility services are called for.

Stationary electricity storage can provide a range of key energy services in an affordable manner. As the cost of emerging technologies falls further, storage will become increasingly competitive, and the range of economical services it can provide will only increase.

Electricity storage is currently an economic solution off-grid in solar home systems and mini-grids where it can also increase the fraction of renewable energy in the system to as high as 100% (IRENA, 2016c). The same applies in the case of islands or other isolated grids that are reliant on diesel-fired electricity (IRENA, 2016a; IRENA, 2016d). Emerging market segments include the pairing of storage with residential or commercial rooftop solar PV to increase self-consumption of PV electricity and/or to avoid peak demand charges by levelling load. For instance, with some financial support for battery storage, approximately 40% of small-scale solar PV systems in Germany have been installed with battery systems in the last few years. In Australia, with no financial support in place, approximately 7 000 small-scale battery systems were installed in 2016.

Pumped hydro storage historically has been implemented to shift the electricity supply from times of low demand to times of high demand to reduce generation costs (Figure ES2). The economics of providing grid services is more challenging today for batteries and other mechanical and thermal storage systems for electricity. Relatively high costs and often low-cost alternative flexibility options mean that current economics are very much market-specific. Despite this, battery electricity storage technologies are providing a range of services competitively today and this will only grow in the future as costs fall and performance improves. On a utility scale, competitive projects are becoming increasingly common. To name just a few examples: the recent UK capacity auction saw winning bids from 225 megawatts (MW) of electricity storage; Tesla will establish a 100 MW battery system in South Australia; and grid-scale projects are on the increase in Germany.

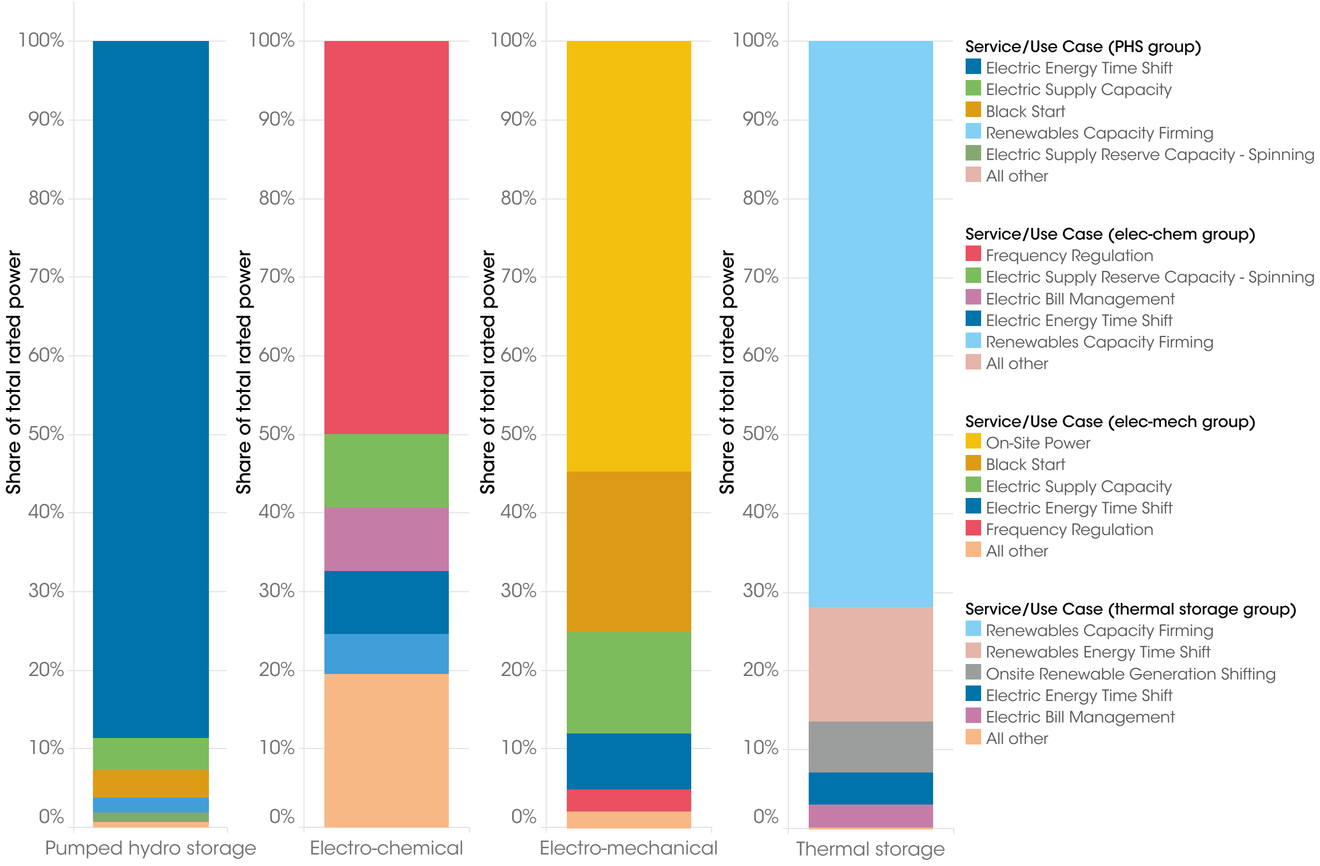

Figure ES2: Global energy storage power capacity shares by main-use case and technology group, mid-2017

A critical issue for electricity storage that will assist in its economics is the ability to derive multiple value streams by providing a range of services with one storage system. This will enable the "stacking" of revenue streams and improve project revenues. In many countries, this will require changes to market structure and regulations, or the creation of new markets for ancillary grid services. It will also, ideally, require behind-the-meter applications to have access to utility-scale markets through aggregators to maximise the potential for storage to contribute fully. Alternatively, in more regulated markets, the applicable valuation tools available to assess the potential multiple cost savings from battery systems from generation system ancillary services, transmission and distribution congestion relief, investment deferral and energy time shift, among others, need to be robust and easily available in order to compare storage options to the alternatives (IRENA, 2015a).

Future energy systems will rely on a large array of services based on effective, economical electricity storage. This plethora of service needs, with varying performance requirements, suggests an important role for many different storage technologies.

The growth in the electricity storage market to 2030 is not likely to be a one-horse race. Although lithium-ion (Li-ion) batteries are likely to dominate the EV market, this is not necessarily going to be the case in stationary applications. The very different requirements of the range of services that electricity storage can provide — and the varying performance characteristics of each group of electricity storage technologies — means that a diverse group of storage technologies will prosper.

It is therefore likely that a range of technologies will find different market segments where they can compete on performance and cost. The electricity storage market in stationary applications will therefore remain a diverse one to 2030 and beyond.

Ancillary grid services, such as primary (fast) frequency regulation, secondary frequency regulation, voltage support, capacity reserve and spinning reserve, among others, will grow in significance as VRE penetration increases, although they have different dynamics in terms of performance, varying by market and time of year. Some applications require high power for short durations (e.g. fast frequency regulation response), while others call for power over longer periods (e.g. firm capacity supply). These different services imply various charge/discharge cycles. In some cases, uniform charge and discharge cycles are likely to be the norm (e.g. in electricity time shift) while in others, highly variable charge/discharge patterns could be the standard.

This has implications in terms of which electricity storage technologies are most economically suited to provide this array of services. For instance, contrast between (i) pumped hydro storage with very low "self-discharge" rates at idle that are well suited to longer storage durations and (ii) flywheels that have very high discharge rates at idle, but have high power ratings and can be distributed within the electricity system to provide high power/rapid discharge services, such as frequency or voltage regulation.

There are also practical considerations that impact the most appropriate electricity storage technology. In residential applications or in densely populated cities, for example, space may be a constraint, and technologies with a higher electricity storage density may have an economic advantage. Similarly, in very hot or cold environments, the performance characteristics and lifetime of the battery can be affected.

The result of these varied application requirements, performance characteristics of electricity storage systems and the practical or environmental considerations that need to be taken into account when matching a storage technology to an application is that there is likely to be a diverse eco-system of electricity storage technologies and application combinations that will support the economic future of a wide range of storage technologies.

Total electricity storage capacity appears set to triple in energy terms by 2030, if countries proceed to double the share of renewables in the world's energy system.

With growing demand for electricity storage from stationary and mobile applications, the total stock of electricity storage capacity in energy terms will need to grow from an estimated 4.67 terawatt-hours (TWh) in 2017 to 11.89-15.72 TWh (155-227% higher than in 2017) if the share of renewable energy in the energy system is to be doubled by 2030.

Today, an estimated 4.67 TWh of electricity storage exists. This number remains highly uncertain, however, given the lack of comprehensive statistics for renewable energy storage capacity in energy rather than power terms. The estimated gigawatt-hour (GWh) storage capacity currently is dominated by pumped hydro storage, with approximately 96% of the total. By 2030, pumped hydro storage capacity will increase by 1 560-2 340 GWh above 2017 levels in the REmap Doubling case. The more rapid growth of other sources of electricity storage will see its share fall to 45-51% by 2030 in the REmap Doubling case.

In IRENAs REmap analysis of a pathway to double the share of renewable energy in the global energy system by 2030, electricity storage will grow as EVs decarbonise the transport sector, concentrating solar power (CSP) is deployed at increasing scale and electricity system flexibility needs increase. At the same time, falling battery costs will open up new economic opportunities for storage technologies to provide a wide range of grid services and boost the economic value of using distributed batteries to increase the self-consumption of rooftop solar PV. The result of this is that non-pumped hydro electricity storage will grow from an estimated 162 GWh in 2017 to 5 821-8 426 GWh in 2030 (Figure ES3).

The storage capacity of battery electricity storage (BES) systems in stationary applications by 2030 has to increase by a factor of at least 17 compared to today's estimated level, to meet the requirements for doubling renewables in the global

Figure ES3: Electricity storage energy capacity growth by source, 2017-2030

energy mix. This boom in storage will be driven by the rapid growth of utility-scale and behind-the-meter applications.

Focusing on the battery electricity storage market in stationary applications to 2030 highlights that there is significant potential for growth in applications behind-the-meter, notably in order to increase the self-consumption share of the output of rooftop solar PV. There may also be emerging demand driven by incentives from distribution or generation companies to manage grid feed-in (Figure ES4). At present, where the right regulatory structure is in place (e.g. Germany) or in areas with high electricity prices, excellent solar resources and relatively low grid feed-in remuneration (e.g. Australia), significant battery storage with regard to new PV installations is taking place.

Total battery capacity in stationary applications could increase from a current estimate of 11 GWh to between 100 GWh and 167 GWh in 2030 in the Reference case and to as much as 181-421 GWh in the REmap Doubling case. This represents a 9- to 15-fold increase over the present in the REmap Reference case and a 17- to 38-fold increase in the REmap Doubling case.[2]

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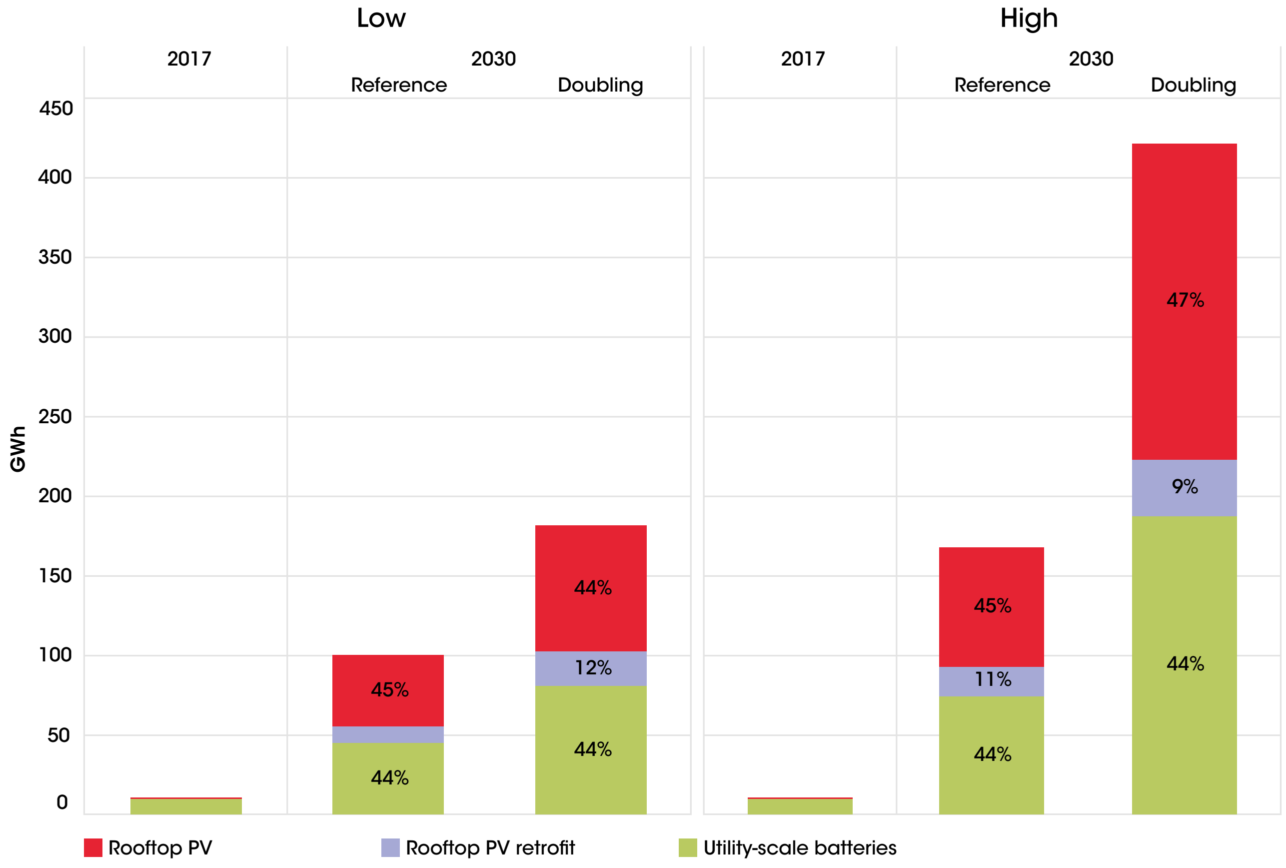
[2] The high and low variations to the REmap Reference and Doubling cases are based on varying the extent of storage used in each application. There remains significant uncertainty, for instance, about what will be the average residential battery pack size in 2030 on a global basis. Similarly, the actual mix of EVs deployed by 2030 is uncertain; it is neither clear whether the current sales mix will be representative (e.g. in terms of EV class size), nor to what extent falling battery costs will result in increased battery size to extend the range. This uncertainty is explored in the high and low cases.

The largest market for BES in the period to 2030 may be the pairing of BES systems with the installation of new small-scale solar PV systems. The economics of BES in these applications could improve dramatically in the next few years, especially in Europe and elsewhere where there are high residential and commercial electricity rates; competitive cost structures for solar PV; and low — and often declining — levels of remuneration for grid feed-in. Similarly, high and increasing electricity rates, combined with competitive solar PV costs and excellent solar resources make Australia a potentially large battery storage market. Japan could also emerge as a new, important market. As rooftop solar PV dominates deployment in Japan and if support levels begin to decline, the economics of storage could change dramatically, given the high electricity rates also experienced in that country.

The utility-scale market for BES will grow strongly, from an estimated 10 GWh in mid-2017 to between 45 GWh and 74 GWh in the Reference case and 81-187 GWh in the REmap Doubling case. As an increasing number of countries begin to identify market reforms to support higher shares of VRE, new and more transparent markets for ancillary services are emerging, often at a very granular level (e.g. primary and secondary frequency reserves, firm capacity, etc.). This will open up new opportunities for BES deployment, given that battery storage will increasingly offer competitive services to these markets. At the same time, renewable capacity firming or time shift services from battery storage technologies will also expand.

Figure ES4: Battery electricity storage energy capacity growth in stationary applications by sector, 2017-2030

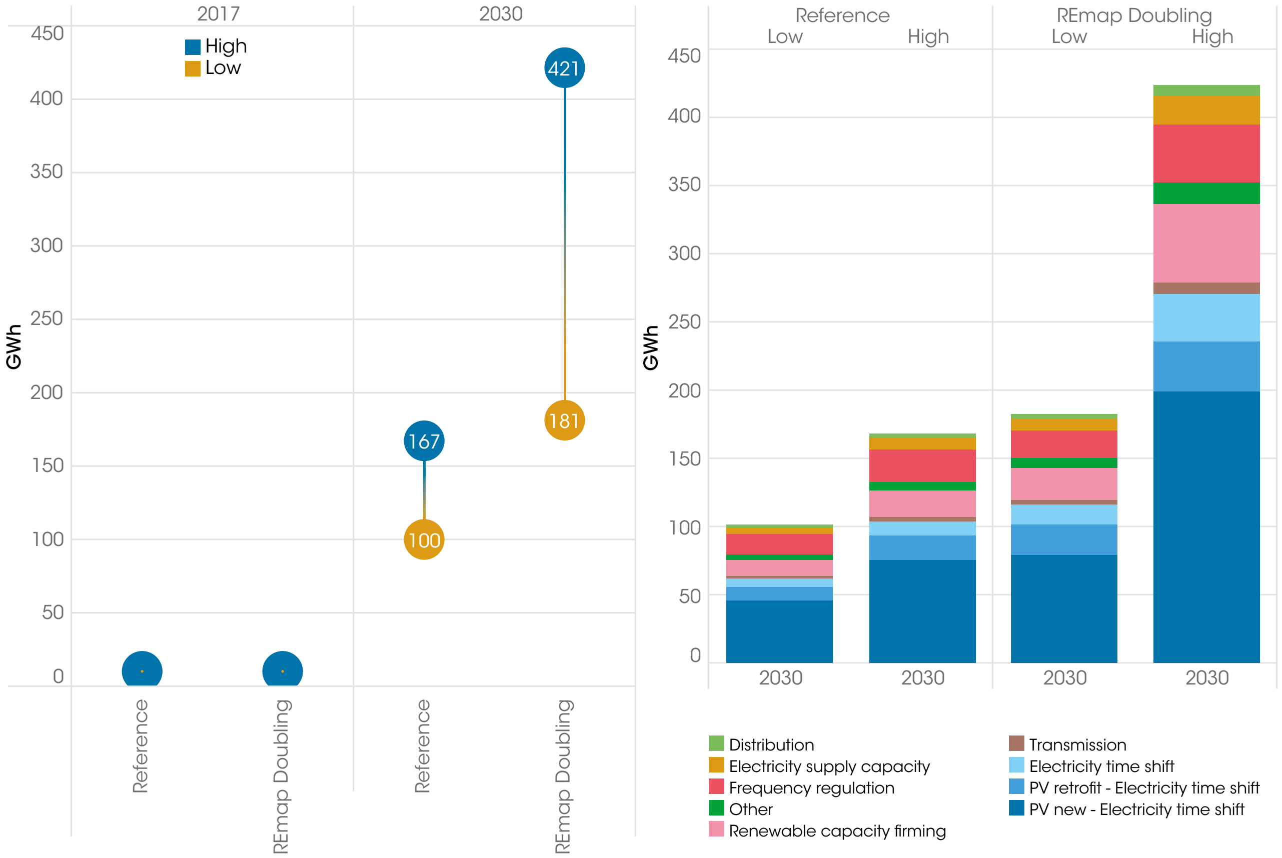


In terms of the services battery electricity storage systems could provide, the economics of behind-the-meter storage opportunities — notably when paired with new PV installations — could make this application the largest driver of battery storage growth. Behind-the-meter storage could become the primary-use case for 60-64% of total BES energy capacity in stationary applications in 2030.

The main-use case for battery storage to 2030 is likely to be influenced by the economic opportunities to provide electricity time-shift services to increase self-consumption or avoid peak demand charges in the residential and commercial sectors. Moreover, providing renewable capacity firming at the utility scale will effectively contribute to between 11% and 14% of total battery electricity storage capacity in 2030, depending on the case.

Frequency regulation is another market where BES is likely to become increasingly competitive as costs fall, given its rapid response characteristics. By 2030, the primary use case of frequency regulation could account for 10-15% of total installed BES capacity. It is worth noting that these are the primary services that BES systems provide. Their ability, in some cases, to provide multiple grid services will enable some systems to "stack" the value of multiple services, so as to capture higher revenue streams and improve the economics of BES projects. This will be of particular importance in the short- to medium-term, as costs continue to decrease and BES projects compete in a challenging environment.

Figure ES5: Battery electricity storage energy capacity growth in stationary applications by main-use case, 2017-2030

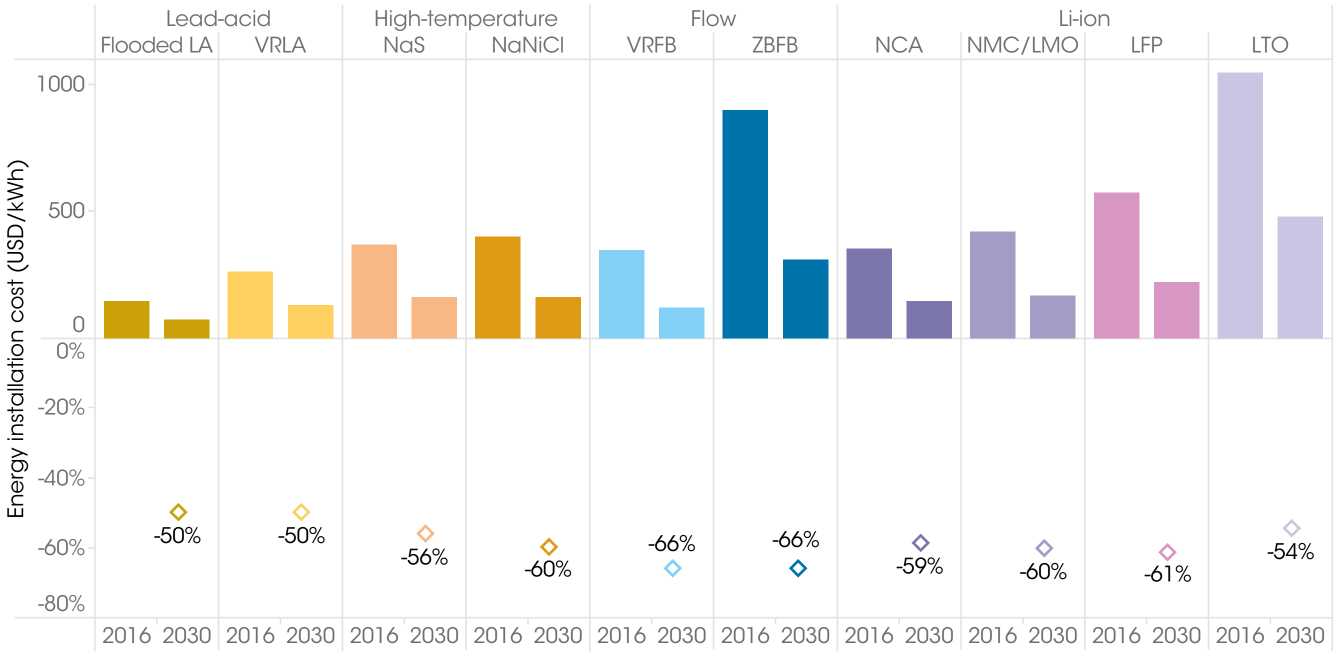


The cost reduction potential for new and emerging electricity storage technologies is significant. The total installed cost of a Li-ion battery could fall by an additional 54-61% by 2030 in stationary applications.

Although pumped hydro storage is the largest single source of electricity storage capacity today, it is a mature technology with site-specific cost. There is little potential to reduce the total installed cost from a technology perspective; lead times for project development tend to be long, and it is not as modular as some of the new and emerging electricity storage technologies, which can scale down to very small sizes.

The cost of Li-ion batteries have fallen by as much as 73% between 2010 and 2016 for transport applications. Li-ion batteries in stationary applications have a higher installed cost than those used in EVs due to the more challenging charge/discharge cycles that require more expensive battery management systems and hardware. In Germany, however, small-scale Li-ion battery systems have seen their total installed cost fall by 60% between Q4 2014 and Q2 2017. Benefitting from the growth in scale of Li-ion battery manufacturing for EVs, the cost could decrease in stationary applications by another 54-61% by 2030. This would reflect a drop in the total installed cost for Li-ion batteries for stationary applications to between USD 145 per kilowatt-hour (kWh) and USD 480/kWh, depending on battery chemistry (Figure ES6).

Figure ES6: Battery electricity storage system installed energy cost reduction potential, 2016-2030

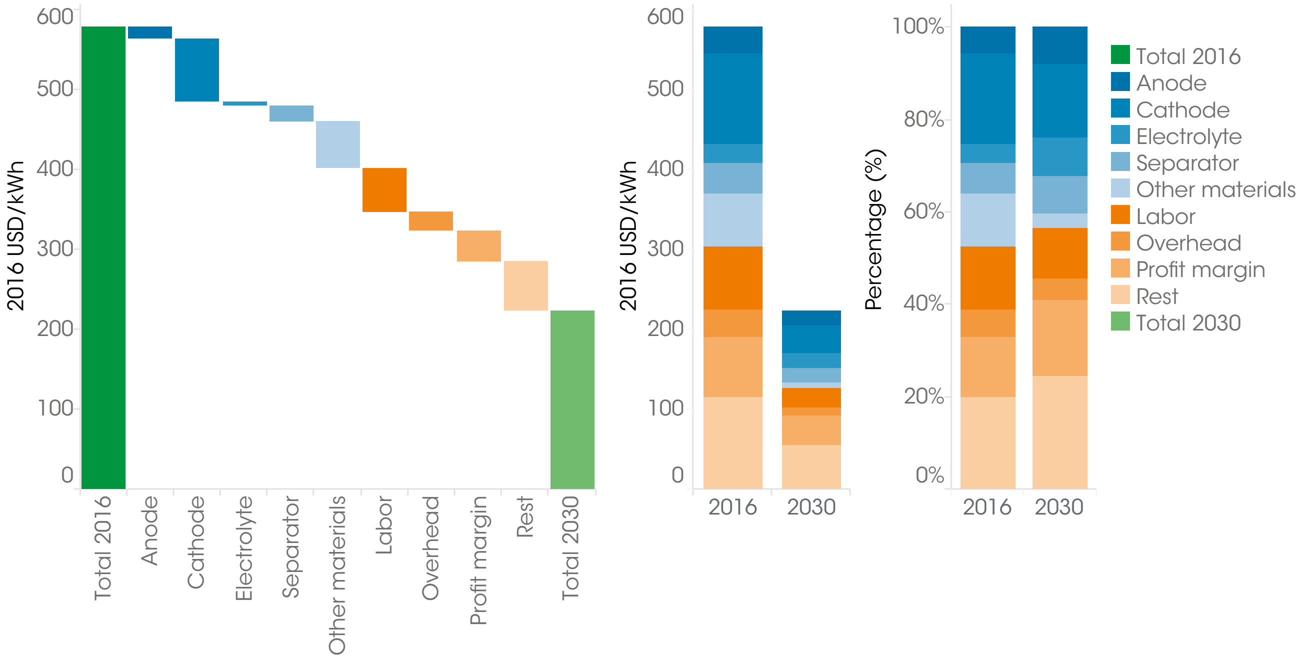


Note: LA = lead-acid; VRLA = valve-regulated lead-acid; NaS = sodium sulphur; NaNiCl = sodium nickel chloride; VRFB = vanadium redox flow battery; ZBFB = zinc bromine flow battery; NCA = nickel cobalt aluminium; NMC/LMO = nickel manganese cobalt oxide/lithium manganese oxide; LFP = lithium iron phosphate;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

While economies of scale and technology improvements that reduce material needs will drive overall cost reductions, cost decreases also still occur across the manufacturing value chain, as in the example of lithium iron phosphate batteries (Figure ES7).

Given the present small scale of development and the rapid growth, significant uncertainty remains around these numbers, and higher or lower values for each battery storage family are possible.

Figure ES7: Cost reduction potential by source of lithium iron phosphate battery energy storage systems, 2016 and 2030



As installed costs decrease, continued improvement in technology will increase performance. The calendar life of Li-ion batteries could increase by approximately 50% by 2030, while the number of full cycles possible could potentially increase by as much as 90%. At the same time, round-trip efficiencies[3] will improve a couple of percentage points to between 88% and 98%, depending on battery chemistry.

Other battery storage technologies also offer large cost reduction potential. The total installed cost of "flow batteries" could drop two-thirds by 2030. These batteries themselves offer valuable operational advantages, since they work at ambient temperatures, and their power and energy storage characteristics are independently scalable.

Flow batteries differ from conventional rechargeable batteries in that the electroactive materials are not all stored within the electrode but, instead, are dissolved in electrolyte solutions that are stored in tanks (i.e. one each on the anode and cathode sides). These tanks are separate from the main regenerative cell stack, and their contents are pumped into the cell stacks (i.e. reaction unit) as required during charging and discharging of the system. Flow batteries have a lower energy density than Li-ion batteries, but the advantage of operating at close to ambient temperatures and are able to independently scale their energy and power characteristics, as previously mentioned.

The two main flow battery technologies — vanadium redox flow and zinc bromine flow — had total installation costs in 2016 of between USD 315 and USD 1 680/kWh. By 2030, the cost is expected to come down to between USD 108 and USD 576/kWh. Round-trip efficiencies for these particular flow batteries are expected to improve from between 60% and 85% in 2016 to between 67% and 95% by 2030, as a result of improved electrode, flow and membrane design.

Although they presently indicate high upfront investment costs compared to other technologies, these batteries often exceed 10 000 full cycles, enabling them to make up for the high initial cost through very high lifetime energy throughputs. Their long-term electrolyte stability, however, is key to this longevity and is the focus of an important avenue of research effort.

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[3] Expressed in DC-to-DC terms, the DC-to-AC efficiency depends on the inverter losses.

High-temperature sodium sulphur (NaS) and sodium nickel chloride batteries will also become much more affordable. Their installed cost could fall 56-60% by 2030, at the same time that their performance improves.

High-temperature batteries utilise liquid active materials and a solid ceramic electrolyte made of beta-aluminium that also serves as the separator between the battery electrodes. Typically, the anode material in these systems is molten sodium and the anodes rely on sodium-ion transport across the membrane to store and release energy. In the case of the NaS battery, the cathode for the most common configuration is molten sulphur, although there is also the sodium nickel chloride battery.

NaS batteries have been providing grid services in Japan (e.g.-load levelling at wind farms) since the 1990s, with more than 300 MW of NaS storage power installed in more than 170 projects throughout the country. For example, the Tokyo Electric Power Company has been operating a 6 MW/48 megawatt-hour system for load levelling in Tokyo, since the 1990s. In recent years, deployment has increased and the technology is now used more widely. Advantages of the NaS battery include its relatively high energy density, which is at the low end of Li-ion batteries, but significantly higher than the redox-flow and lead-acid technologies. It also benefits from using non-toxic materials.

Currently, the total energy installation cost for an NaS BES system ranges between USD 263 and USD 735/kWh, although data suggest that typical systems are able to be installed for below USD 400/kWh. While the NaS battery offers the potential for high cycle lifetimes at comparably low costs, there are nevertheless some challenges. The main disadvantage of the NaS system is the relatively high annual operating cost, which can be USD 40-80/kW/year, mostly for heating.

Corrosion issues are a major ageing mechanism of high-temperature cells. To achieve lower production costs, there is a need to continue developing robust materials, coatings and joints to address the corrosion issue and, hence, increase the lifetime of the battery. Another avenue of research focuses on lowering the high operating temperature needed to achieve satisfactory electrochemical activity in the battery by improving ion transfer through the ceramic electrolyte.

Cost reductions of up to 75% could be achieved by 2030, with NaS battery installation cost decreasing to between USD 120 and USD 330/kWh. In parallel, the energy installation cost of the sodium nickel chloride high-temperature battery could fall from the current USD 315 to USD 490/kWh to between USD 130 and USD 200/kWh by 2030.

Flywheels could see their installed cost fall by 35% by 2030. Compressed air energy storage (CAES), although based on a combination of mature technologies, could see a 17% cost decline by 2030.

Flywheels store energy as rotational kinetic energy by accelerating and braking a rotating mass. They have a high power potential. Due to their high energy installation cost, which ranges between USD 1 500 and USD 6 000/kWh, and their very high self-discharge of up to 15% per hour, they are most suitable for short-term storage applications. The energy installation cost of a flywheel system is expected to decline to a range of between USD 1 000 and 3 900/kWh by 2030. The cycle lifetime will extend as materials and efficiencies improve as efforts to reduce friction losses bear fruit (i.e. notably with regard to the magnetic bearings).

CAES systems store energy in the form of compressed air (i.e. potential elastic energy) in a reservoir and works in a similar way to conventional gas turbines. To charge a CAES system, excess or off-peak power is directed towards a motor that drives a chain of compressors to store air in the reservoir. When discharging, the compressed air is released from the reservoir (i.e. expanded), cooling down in the process, and needs to be reheated. This is achieved by mixing compressed air with fuel (e.g. natural gas) in a combustion chamber that drives the turbine system. Similar to pumped hydro, accurately estimating the cost of a CAES system is extremely challenging, as the cost is site-specific and depends largely on local environmental constraints for the reservoir. The typical installation cost is estimated to be approximately USD 50/kWh, possibly dropping to USD 40/kWh if an existing reservoir is available. The disadvantage of this system is the relatively low rate of discharge and the poor round-trip efficiency that raises the cost of service.

Materials availability is unlikely to be a constraint on the growth of battery electricity storage technologies in the period to at least 2025. Systems for the end-of-life recycling, reuse and disposal of battery packs are being tested and will need to scale in the 2020s.

With the increased uptake of BES technologies, the availability of raw materials — particularly for use in Li-ion BES systems — has gained much attention in the last few years as question marks over the availability of sufficient supply to scale up BES have been raised. While often mentioned, it appears unlikely that a shortage of lithium will occur in the near future.

Recent analysis suggests total demand for lithium could increase to 80 150 tonnes (t) per annum by 2025, while a conservative supply expansion scenario indicates total lithium extraction could reach 88 000 t per annum by 2025. Under a more optimistic supply scenario the surplus of supply over demand in 2025, of around 8 000 t in the conservative supply estimate, could rise five-fold to around 40 000 t in 2025, or 50% higher than projected demand. However, uncertainty in both the supply and demand evolution remains, and short-term supply and demand imbalances could lead to volatile prices. A similar situation could conceivably play out for the production of cobalt – also extensively used in some battery chemistries – as this is usually obtained as a by-product of nickel and copper mining and supply growth will require some forward planning.

Currently, the recycling of lead-acid batteries is economical and widely undertaken (e.g. a recycling rate of more than 99% in Europe). Academia and industry have become active in seeking recycling paths for other chemistries, including the Li-ion family. The initial focus has been on portable technologies, given that the current volume of batteries being sent to end-of-life processes is too low to justify distributed sites. Much progress in recycling methods continues for Li-ion, with demonstrations now taking place. Larger battery formats and the diversity of Li-ion chemistries, however, pose added challenges to their recycling, but promising pathways are being explored that provide different trade-offs in terms of costs and materials recovery. These will need to begin to scale commercially in the 2020s as larger volumes of batteries reach the end of their calendar life.

There is significant confusion regarding when electricity storage is essential in the energy transition, as opposed to when it is an economic opportunity. Pumped hydro storage can be economic at present when providing flexibility to the electricity system. Battery costs — although falling rapidly — remain high at present with their economic applications mainly found in off-grid markets, transport and, increasingly, behind-the-meter uses. As costs fall further, batteries will provide more grid services.

The confusion about the role and necessity of electricity storage in the energy transition, particularly in terms of BES, is natural, since these technologies (aside from pumped hydro) are nascent in terms of deployment. In some ways, this fact mirrors the uncertainty that relates to the role of onshore wind and solar PV, 5, 10 or 15 years ago, when these technologies were also in their infancy and costs were higher and performance lower. IRENAs analysis highlights the important role that electricity storage can play in the energy transition and shows the contribution that storage will play in different sectors and applications.

Pumped hydro storage currently dominates total installed storage power capacity, with 96% of the total of 176 gigawatts (GW) installed globally in mid-2017. The other electricity storage technologies already in significant use around the world include thermal storage, with 3.3 GW (1.9%); batteries, with 1.9 GW (1.1%) and other mechanical storage with 1.6 GW (0.9%).

Pumped hydro storage is a commercially mature technology that dominates both the total installed power capacity (in GW) and the energy storage capacity (in GWh). Over three-quarters of energy storage power capacity was installed in only ten countries, with only three – China (32.1 GW), Japan (28.5 GW) and the United States (24.2 GW) – accounting for almost half (48%) of global energy storage capacity. These countries are home to the largest capacities of pumped hydro storage, although they are emerging as significant locations for new and emerging electricity storage technologies.

Thermal electricity storage, batteries and non-pumped hydro mechanical electricity storage technologies contribute a total of 6.8 GW of energy storage globally (Figure ES8). Thermal energy storage applications, at present, are dominated by CSP plants, with the storage enabling them to dispatch electricity into the evening or around the clock. Molten salt technologies are the dominant commercial solution deployed today and they account for three-quarters of the globally deployed thermal energy storage used for electricity applications. Other mechanical storage deployment, to date, is the result of a relatively small number of projects, with total installed power capacity of flywheels at 0.9 GW and CAES at 0.6 GW. In both technologies, two-to-three large projects dominate total deployment.

Electro-chemical storage is one of the most rapidly growing market segments, although operational installed battery

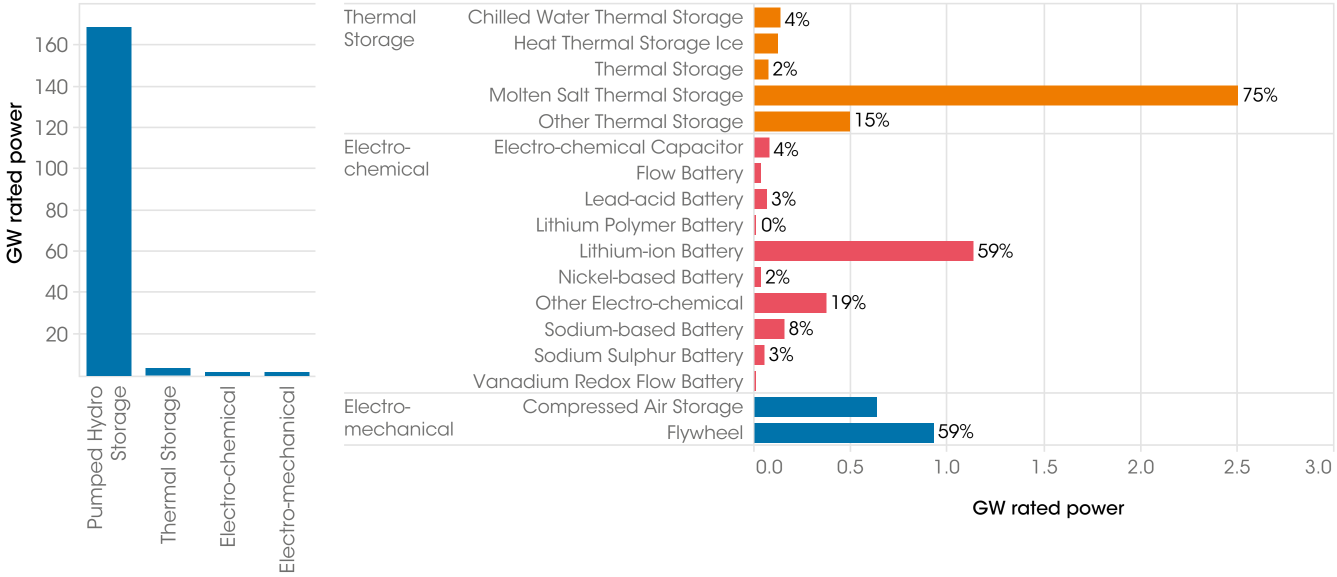

Figure ES8: Global operational electricity storage power capacity by technology, mid-2017

storage power capacity is only approximately 1.9 GW. Although there are a number of emerging battery electricity storage technologies with great potential for further development, Li-ion batteries account for the largest share (59%) of operational installed capacity at mid-2017. There also are small but important contributions from high-temperature NaS batteries, capacitors and flow batteries.

Abbreviations

°C	degree Celsius
AA-CAES	advanced adiabatic compressed energy storage
AC	alternating current
BASE	beta-aluminium solid electrolyte
BES	battery electricity storage
BEV	battery electric vehicle
CAES	compressed air energy storage
CO_2	carbon dioxide
CSP	concentrating solar power
DC	direct current
DOE	Department of Energy, United States
E/P	energy-to-power ratio
ESS	electricity storage system
EV	electric vehicle
FES	flywheel energy storage
GBP	British pound
GW	gigawatt
GWh	gigawatt-hour
HEV	hybrid-electric vehicle
IRENA	International Renewable Energy Agency
k	kilogram
kWh	kilowatt-hour
L	litre
LA	lead-acid
LCO	lithium cobalt oxide
LDV	light-duty vehicle
LED	light-emitting diode
LFP	lithium iron phosphate
Li-ion	lithium-ion
LMO	lithium manganese oxide
LTO	lithium titanate
MPa	megapascal
MW	megawatt
MWh	megawatt-hour
NaNiCl	sodium nickel chloride flow battery
NaS	sodium sulphur
NCA	nickel cobalt aluminium
NMC	nickel manganese cobalt
PHEV	plug-in hybrid-electric vehicle
PHS	pumped hydro storage
PV	photovoltaic
RE	renewable energy
t	tonne
TES	thermal energy storage
TWh	terawatt-hour
UK	United Kingdom
US DOE	United States Department of Energy
US	United States
USD	United States dollar
V2G	vehicle to grid
VRE	variable renewable electricity
VRFB	vanadium redox flow battery
VRLA	valve-regulated lead-acid
Wh	watt-hour
ZBFB	zinc bromine flow battery

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