IRENA
International Renewable Energy Agency

BATTERY STORAGE FOR RENEWABLES: MARKET STATUS AND TECHNOLOGY OUTLOOK

JANUARY 2015

About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international cooperation, 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.

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LIST OF ACRONYMS

AC	Alternating current
ARRA	American Recovery and Reinvestment Act
BNEF	Bloomberg New Energy Finance
CPUC	California Public Utilities Commission
DoD	Depth of discharge
DC	Direct current
DOE	U.S Department of Energy
EIA	Energy Information Administration
EPRI	Electric Power Research Institute
EV	Electric vehicle
ERCOT	Electric Reliability Council of Texas
FERC	Federal Energy Regulatory Commission
FiT	Feed-in tariff
GW	Gigawatt
GWh	Gigawatt hour
GWEC	Global Wind Energy Council
Hz	Hertz
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
KfW	Kreditanstalt für Wiederaufbau
KEA	Kodiak Electric Association
kW	Kilowatt
kWh	Kilowatt hours
kWp	Kilowatt peak
MW	Megawatt
MWh	Megawatt hour
MT	Metric tonnes
NREL	National Renewable Energy Laboratory
PV	Photovoltaic
REN21	Renewable Energy Policy Network for the 21st Century
U.S.A.	United States of America
Wh	Watt hour

1 EXECUTIVE SUMMARY

For over a century, energy storage in the power sector has been dominated by one technology – pumped hydropower storage. Along with the rest of the sector, that is beginning to change. Renewable energy deployment and policies to modernise electricity production and consumption are propelling numerous advances, including increased battery storage. This technology stores energy chemically and can be located at the point of demand or at the grid level. Its use can allow for greater amounts of renewable electricity and contribute to system reliability.

From a technological perspective, battery storage is mature and there are hundreds of suppliers providing reliable systems. However, several barriers have to be overcome before battery storage is fully integrated as a mainstream option in the power sector. These include performance and safety issues, regulatory barriers, and utility acceptance. Nevertheless, recent developments have demonstrated that these barriers can be and in many instances are being overcome. In multiple application areas around the world, batteries have been deployed to aid the integration of renewable energy, especially solar and wind power. Those two resources are also known as variable renewable energy as their production fluctuates depending on the availability of the resource. Costs are coming down, and technological progress is improving performance. Recent progress is also making batteries safer and more efficient. Regulatory barriers and traditional structures based around fossil fuel power plants are being challenged.

This Market Status and Technology Outlook aims to improve the understanding of the key considerations and drivers of battery storage for renewables. It also aims to provide a timely update on market developments. This provides policy makers and stakeholders a fundamental basis for understanding this technology and the role it can play in integrating and accelerating renewable energy deployment. Based on operational project case studies and a market analysis, the report identifies four applications in which batteries are deployed to increase the share of variable renewable energy and improve electricity supply reliability. These application areas are listed below.

- island systems and off-grid/rural electrification with renewable energy deployment
- households with solar photovoltaic (PV)
- variable renewable energy smoothing and energy supply shift (see figure 10 and 11 for examples)
- fast, short-term electricity balancing in ancillary markets

Key drivers to battery deployment vary by application and requirements are unique to each location. For islands and off-grid applications, they include the high cost of diesel fuel and a desire to integrate greater amounts of variable renewable energy while maintaining electricity supply reliability. Solar PV and battery storage at the household level is driven by government support, concerns over electricity supply in areas with a weak grid and economic trends. These include decreasing costs of small-scale battery systems, falling feed-in tariffs (FiTs) and rising retail electricity prices. Batteries are being used for a number of purposes. These include smoothing and energy supply shift applications driven by incentive programmes and regulatory requirements to increase renewables use. Other drivers are the need to control variable renewable energy feed-in to minimise variability and better match renewable electricity supply with area demand. Fast frequency regulation, technology developments and regulatory changes to compensate short-term balancing for fast and accurate response are also driving implementation.

In addition, this report identifies a number of countries leading on battery storage deployment. These are China, Germany, Japan, and the United States (U.S.). Activities in India, Italy, South Korea, and other areas, including island systems, are also discussed, due to their recent emphasis on battery storage implementation.

The analysis presented here also illuminates several key findings on the battery storage market. Government support for development and demonstration has increased deployment and established a foundation of operational experience. This has helped bring costs down, complemented by manufacturing support programmes for lithium-ion chemistries. In recent years, it is evident that the market has shifted from sodium-sulphur battery deployment to other types, namely lithium-ion batteries. These have proven favourable on a cost and performance basis compared to other types. But batteries can be used in multiple ways, so different types offer their own relative advantages. This means a whole range will continue to be active in the market. Examples include advanced lead-acid and flow batteries.

The report demonstrates that islands and remote areas represent one of the most attractive opportunities for battery storage implementation in conjunction with variable renewable energy deployment. The use of batteries for self-consumption of renewables could revolutionise the electricity system. In some specific situations, battery storage may also be the preferred solution for fast, short-term regulation within seconds. This could replace, or avoid having to build, fossil fuel plants.

Despite positive trends identified in the report, it is also clear that the decision to implement battery storage is not straightforward. In many countries and areas, dispatchable plants, interconnection and demand side management already provide the necessary resources to accommodate a significantly higher share of renewables. Nevertheless, the versatility of battery storage in the power sector, greater operational experience and market developments mean the technology will be deployed to a much greater extent than in the past. It is therefore worth exploring potential synergies between renewables and battery deployment.

2 INTRODUCTION AND BACKGROUND

Renewable energy deployment in the electricity sector is catalysing efforts to modernise the electricity grid, including the increased implementation of battery storage. Driven by policy and technological progress, renewable energy has been installed at unprecedented rates in recent years. This is particularly true of variable renewable energy like wind and solar PV. In 2006-12, solar PV and wind energy experienced an annual capacity growth rate worldwide of 190% and 40% respectively. They both present the fastest growth of all types of renewable energy according to IRENA's publication REthinking Energy. The growth in variable renewable energy is expected to continue. The International Renewable Energy Agency (IRENA) global renewable energy road map analysed the possibility of doubling the global share of renewable energy by 2030. Its authors foresee wind and solar power capacity growing to 1635 and 1250 gigawatts (GW), respectively (IRENA, 2014a). This would mean wind capacity would be five and solar PV capacity nine times higher than in 2013 (REN21, 2014). However, the road map showed that out of the 26 countries analysed, only a few are expected to reach or exceed 30% variable renewable energy production in their electricity system by 2030. These are Australia, Denmark, Germany, Morocco, Tonga and the United Kingdom (IRENA, 2014b). Nevertheless, many regions, islands and local area grids will see significant deployment of variable renewable energy, particularly as it becomes cheaper and regulatory environments become more favourable. For example, many of the 51 small island developing states have ambitious targets for renewable energy. In some cases, variable renewable energy shares of 50% or more can be expected.

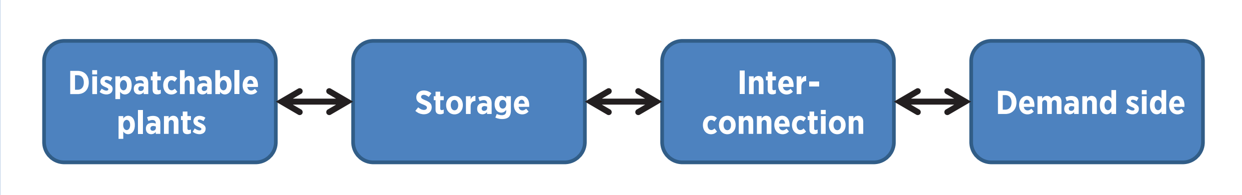
Unlike traditional fossil fuel plants and some forms of renewable electricity production (*i.e.* biomass, pumped hydropower and geothermal), the wind and the sun provide power only when the renewable resource is available. This makes them less predictable. Variability in electricity supply must be accounted for to maximises renewable energy penetration into the electricity system and ensures a match between electricity supply and demand at all times. Modularity is another characteristic of some renewable energy types, especially PV and wind. This means incremental capacity can be easily added and may be deployed at the site of electricity demand. These 'behind the meter' or distributed generation installations range from small kilowatt (kW) sized installations to megawatt (MW)-scale industrial projects. They are put on a roof (typical of household applications) or next to a commercial or industrial facility. Distributed generation upends the traditional model, which is to connect large power generation facilities to demand centres over large distances.

The variable and decentralised nature of renewable energy deployment presents unique challenges to maximise and ensure reliable electricity supply. At high levels of penetration, increased electricity production fluctuations may increase the risk to reliable supply of electricity. This is because supply and demand of electricity must be balanced at all times. The definition of high penetration varies among electricity systems (IRENA, 2013a). System operators measure the balance by monitoring system frequency. In Europe, the system target is a grid-level frequency of around 50 Hertz (Hz); in North America it is 60 Hz. Failure to operate the system at its required frequency can disrupt the operation of equipment, disconnect power plants to prevent damage and lead to large-scale blackouts (Eto *et al.*, 2010).

Increasing amounts of fluctuating renewables thus place a greater emphasis on grid flexibility, which ensures electricity supply reliability. An illustration of the various forms of system flexibility available is presented in figure 1. Fossil fuel power plants and interconnectors provide most of the necessary flexibility at the moment to maintain system frequency. The use of more renewable energy therefore draws greater attention to any available alternative.

A range of facilities play an important role in providing electricity system flexibility. These include dispatchable plants, grid transmission lines to connect supply and demand (interconnection), energy storage, and demand side measures such as distributed generation. These sources of flexibility must be evaluated for individual systems given the diverging characteristics of various parts of the world. The IEA provides calculations, an

Figure 1: Flexibility resources in the electricity system



Source: Based on IEA, 2011

approach and background for assessing the flexibility of a system (IEA, 2011; 2014a). Each of these sources of flexibility has advantages and disadvantages. While battery storage is an important option, it may not be relevant in all systems or under all scenarios.

The technical term for describing the ability of an electricity system to resist changes in frequency is inertia. It is determined by the characteristics of the generators and loads in a system (Eto *et al.*, 2010). Broadly, this is understood through the degree of spinning masses and motors synchronised to system frequency (Kirby *et al.*, 2002). Low inertia can be expected in a small system such as an island with limited interconnection and few power plants. On the other hand, interconnected grids with ample generation assets, such as the German network, have high inertia. Systems with high inertia recover more quickly from initial frequency changes stemming from unexpected supply and/or demand deviations.

In large interconnected systems the first instance of response to frequency changes occurs automatically and immediately, and is known as governor control. Synchronous generators (power plants whose rotational speed is synchronised to grid frequency, *i.e.* 60 Hz) generally have some capacity set aside to respond to sudden changes in system frequency. The collective action of synchronous generation governor control has the ability to oppose frequency changes automatically, and is available to the system within seconds (Eto *et al.*, 2010). Wind turbines and solar PV are not synchronous generators, but can mimic synchronous generation with power electronics. This issue takes on greater importance at high levels of variable renewable energy penetration (EIRGRID and System Operator for Northern Ireland, 2011). Although renewables can provide the same functions as synchronous generators, there are no examples yet of large interconnected systems that are balanced through renewable power.

Implementation planning and physically interconnecting generation to demand centres helps reduce the necessity for additional flexibility. For instance, renewable generation geographically dispersed and interconnected across a larger area allows less variability in supply (Delucchi and Jacobson, 2011). This is also true of wind and solar generation (IEA, 2013; 2014). Wind and solar are also able to incorporate power electronics and storage to provide automatic adjustments. These mimic traditional power plants, according to the U.S National Renewable Energy Laboratory (NREL, 2012a).

Storage may be essential to reliably integrate power generated from renewable energy in systems that have weak interconnection. Dispatchable plants, which can be called upon to increase or decrease electricity production, have traditionally been driven by fossil fuels. However, battery storage may mitigate frequency deviations at the grid level. It can also make variable renewables more dispatchable by storing excess electricity production on site.

Energy storage consists of a suite of technologies at various stages of development. The most mature energy storage technology is pumped hydropower, generally utilized for longer periods of charge and discharge (multiple hours). Pumped hydropower represents the vast majority (99%) of storage in use (IEA, 2014b). It is economically and technically proven throughout the world. By contrast, battery storage is a new market development. Examples of other emerging storage technologies are adiabatic compressed air energy storage, flywheels, power to gas and supercapacitors (Fuchs *et al.*, 2012; IRENA, 2012a). Electricity can also be stored in thermal form using boilers, heat pumps, ice or chilled water, for instance. Thermal storage can be integrated with combined heat and power production and utilised to maximise wind resource penetration (Sorknaes *et al*., 2013). Thermal energy storage options are often cheaper than other forms of storage, though it is more difficult to reverse heat storage back into electricity (IRENA, 2013b). Typically, electric energy converted to a thermal medium is used at another time as thermal energy, either for space heating, cooling or in industrial processes.

The types of batteries discussed in this report are secondary (rechargeable) batteries, unlike the non-rechargeable batteries used in some consumer applications. These batteries store energy chemically. They are low temperature (lithium-ion, lead-acid, nickel-cadmium), high temperature (sodium nickel chloride, sodium-sulphur) or redox flow (vanadium, zinc bromine) (Fuchs *et al*., 2012). Component materials are sourced from various locations around the world, and their availability or scarcity has an impact on the cost and sustainability of the battery – see box 4. Battery storage is one option that can mitigate both the short (defined here as seconds) and long-term (defined here as several hours) fluctuation of renewable energy. It does this through several different applications and locations in the electricity system, including battery storage in distribution networks or households. Batteries are generally not suited to medium and longer-term or seasonal storage lasting several months. This can be provided by compressed air energy storage, power to gas or other technologies not discussed in this report.

Battery storage in the power sector needs to overcome many barriers before it can be integrated as a mainstream option. One barrier is the lack of monetary compensations schemes available for the benefits of battery storage systems. Cost-competitiveness, validated performance and safety are others, as is a regulatory environment built around a legacy system of centralised generation and load-driven planning and operations. Similarly, general lack of industry/utility acceptance is also a barrier, according to the U.S Department of Energy (DOE, 2013a) and Sioshansi *et al.* in 2012. As with all less established forms of technology, traditional project financing may be difficult or costly to obtain. Furthermore, common approaches and standards for quality, testing and manufacturing must be established to ensure product data reliability and transparency. Section 3.1 presents an overview and analysis of the key concepts underlying battery storage.

The aim of this report is to provide policy makers and stakeholders a fundamental basis from which to understand battery storage and the role it can play in integrating renewable energy. What applications are most helpful for integrating renewable energy? How has the market developed in recent years for the various types of batteries? Which countries are leading the implementation of battery storage and what are the key drivers? Methods employed include a literature review and market analysis, discussions with researchers and industry participants, and an analysis of case studies that demonstrate operational projects. Case study information was gathered via a questionnaire sent to battery storage companies and through publicly available information.

Section 3 presents an overview of battery storage, including a discussion of the important technical aspects of batteries and key considerations for battery selection. Section 4 provides an overview of battery storage applications most relevant for renewable energy integration. Section 5 discusses the recent developments and current status of the battery storage market and analyses technological trends and developments at country level. Case studies are presented throughout the report, and a separate addendum provides additional details and operational projects. A summary and conclusion from the analysis are presented in section 6.

3 OVERVIEW OF BATTERY STORAGE

Batteries are not a new technology. The Italian physicist Alessandro Volta is credited with their invention in 1799. Lead-acid batteries provided electricity at night time in New York in the 1880s according to the Electric Power Research Institute (EPRI) and DOE in 2013. The cathode (the positive part) is separated from the anode (the negative part) by a porous separator, and ions are allowed to flow between the two charges via an electrolyte. The chemical reaction creates current and voltage (which together create power) that can be supplied to a load (EPRI and DOE, 2013). In flow batteries, the electrolyte is stored in external tanks and is pumped through a central reaction unit. This consists of a cathode and anode through which a current is either taken in (charged) or supplied (discharged) to the external demand/supply source (Fuchs *et al*., 2012).

Since batteries are composed of chemicals, the manner and conditions under which they are used affects their performance, cost and life time. For instance, in many cases the amount of a battery's capacity used, also known as depth of discharge (DoD), dramatically affects its operational life. This is measured in charge cycles (see below). A battery's capacity is often referred to in energy terms as power over a specified time. Megawatt hours (MWh) or kilowatt hours (kWh) are examples. Another important metric is power capability, which is the amount of power an installation can provide. Power capability is denoted in MW or kW.

Ambient conditions like temperature also have an important effect in many battery types. Definitions of these concepts must thus be understood when approaching the topic of battery storage. These are presented below and are based on studies by IRENA (2012), EPRI and DOE (2003). It is important to note that different battery types have unique attributes. In addition, manufacturers of batteries differ. The characteristics of the leading market batteries – sodium-sulphur, advanced lead-acid, lithium-ion and flow batteries – are presented in annex A. Novel and alternative types are also discussed in that section.

Calendar and cycle life

The cycle life of a battery is the number of charge and discharge cycles a battery can complete before losing considerable performance. It is specified at a certain DoD and temperature. The necessary performance depends on the application and relative size of the installation. However, a fully charged battery that can only deliver 60-80% of its original capacity may be considered at the end of its cycle life. Calendar life is the number of years the battery can operate before losing considerable performance capability. The primary parameters are temperature and time.

Depth of discharge

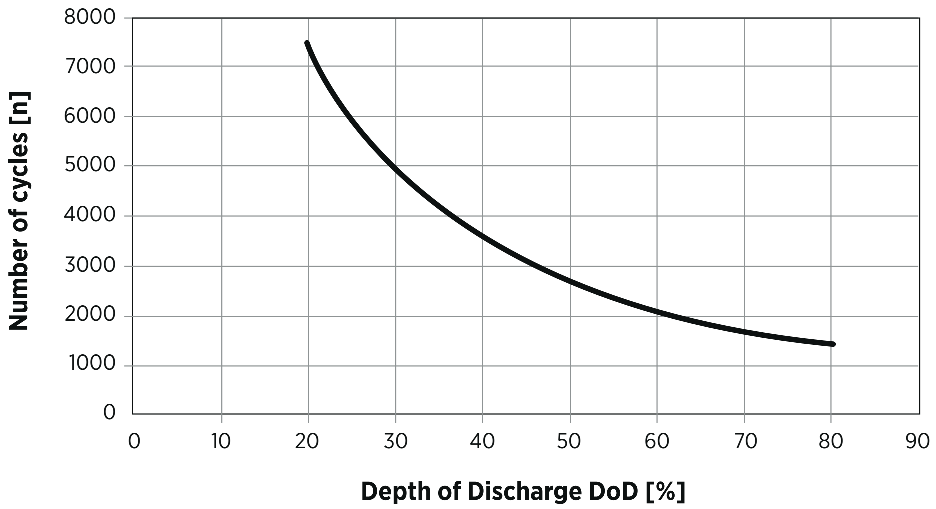
This refers to the amount of the battery's capacity that has been utilised. It is expressed as a percentage of the battery's full energy capacity. The deeper a battery's discharge, the shorter the expected life time. This is true of several cell-based batteries due to cell degradation, including lead-acid and lithium-ion.[1] For example, if a battery discharges 10% of its full energy capacity, 90% of the full capacity is unused. This corresponds to 10% DoD. This battery will be able to complete more charging cycles (defined above) than a battery cycled at deep discharge. Deep cycle is often defined as 80% or more DoD. Each battery type and chemistry is affected differently. Other conditions, such as temperature, also play a role. Flow batteries are not affected by DoD to the same extent as some cell-based batteries. Figure 2 provides an illustration of the effect of DoD (the x axis) on cycle life (y axis).

Ambient temperature

Ambient temperature may have an important effect on battery performance. High ambient temperatures cause internal reactions to occur, and many batteries lose capacity more rapidly in hotter climates. High

1 This is not necessarily the case for some cell-based batteries, like nickel-cadmium, which perform well under deep discharge cycles.

Figure 2: Illustration of depth of discharge versus cycle life - Hoppecke Opzv lead-acid sun-power pack



Source: Hoppecke (2014)

temperatures may also cause corrosion and and the creation of gases requiring ventilation. Reactions may be sluggish in very cold climates, and discharge may stop altogether. The electrolyte may also freeze. Some battery types, like lithium-ion and lead-acid, may require integrated temperature management in the battery installation for optimal performance and safety. However, lithium-ion batteries are generally not as sensitive to temperature as lead-acid batteries (see annex A). In figure 2 above, cycle life tests are usually conducted at various temperatures and DoD. Higher temperatures may cause faster cell degradation, increasing the gradient of the line.

Service provided

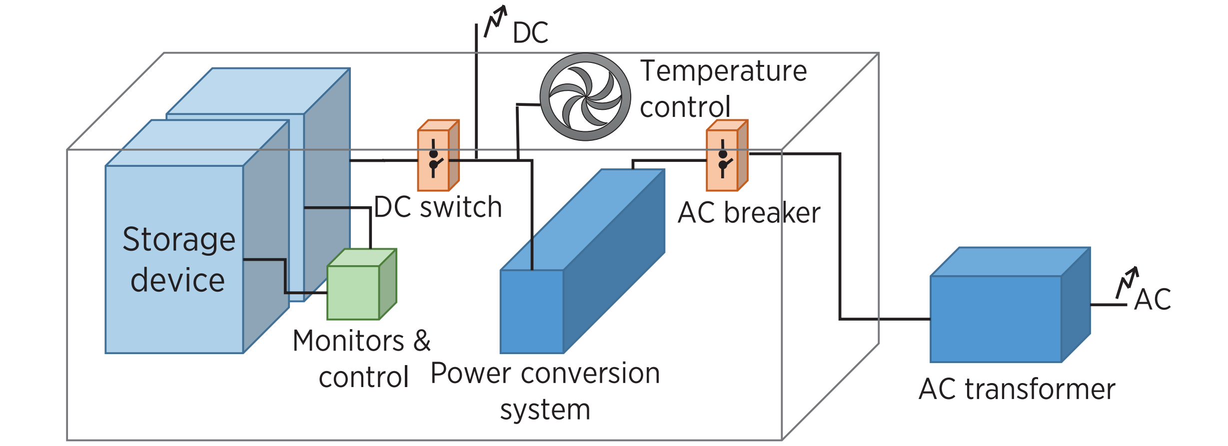
Various electric system services require different charging and discharging profiles, as well as power requirements. For instance, frequency regulation, which provides and takes away power over a short time period (in seconds) requires many fast charge and discharge cycles. It may also have significant power requirements over short periods. Energy supply shift, also known as load shifting, stores excess renewable energy for later use. This requires longer charge and discharge cycles. Some battery types and designs may be better suited to certain requirements from a performance and life time standpoint than others. This report describes battery storage application areas and considers one or more services batteries provide for renewable energy integration.

Battery storage system

The battery is only one part of a larger battery storage system, displayed and described below.

A battery storage system contains several primary components, including the battery, monitoring and control systems, and a power conversion system. Cell-based batteries consist of individual cells connected into modules and then into packs. Flow batteries consist of external tanks filled with an electrolyte which flows through a reaction stack (see annex A for a technical description). Monitoring and control systems, referred to as the battery management system, ensure safety and maximise performance. The battery management system prevents individual cells from overcharging, and controls charge and discharge of the battery. This is important for safety and performance. Battery cells and component monitoring may vary to some degree, in that different types require emphasis on particular issues. For instance, lithium-ion battery packs must emphasise thermal monitoring and controls, given a

Figure 3: Battery storage system and primary power components



Source: Based on EPRI and DOE, 2013

tendency to overheat (see annex A). In many of the new devices that are entering on the market, the storage system is also coupled to an inverter to provide one integrated product.

In addition, the system may need to incorporate power electronics to communicate with the area utility and adhere to local grid interconnection requirements. For example, while the majority of conventional electric systems run on alternating current (AC), batteries deliver electricity as direct current (DC). This means a power conversion system is required, which contains bi-directional inverters. The power conversion system in this case converts DC power from the battery to AC power for grid use or site demand. With the use of a rectifier, AC flows back to the battery for charging after conversion to DC power (EPRI and DOE, 2013).

Battery management systems are increasingly complex and expensive for larger battery solutions. For example, one new development is the integration of software technologies and tools to allow for remote tracking, control and management of battery storage systems. With up to date information about wind and sun forecasts, the charging level, expected electricity demand and information about the state of charge of other battery systems, it will become possible to optimise and create intelligent demand and supply assets to manage load. For example, Panasonic has developed the so-called LiEDO platform to remote control distributed li-ion batteries deployed in solar-equipped buildings. Furthermore, Panasonic is working on the integration of artificial intelligence into control systems to optimise their services (Katsufumi, 2014).At the same time, significant advances have been made over the last six years. For example, in 2008 a 22-foot containers with li-ion battery storage systems provided 500 kW, while the same container in 2014 can provide up to 2 MW of capacity.

3.1 Factors affecting battery selection

In most reports, a number of key technical features are used to compare different energy storage options. In particular, energy storage technologies are often displayed on the basis of power in MW and/or energy in MWh on the x-axis, set against discharge time (seconds to hours) on the y-axis (for example in IRENA, 2012b, p. 9). However, significant overlap between the categories for battery storage makes the comparison rather trivial (see Annex for a more detailed discussion). As a guide for a more nuanced perspective, some of the most significant considerations for battery selection are presented in figure 4.

Figure 4: Important considerations for battery selection

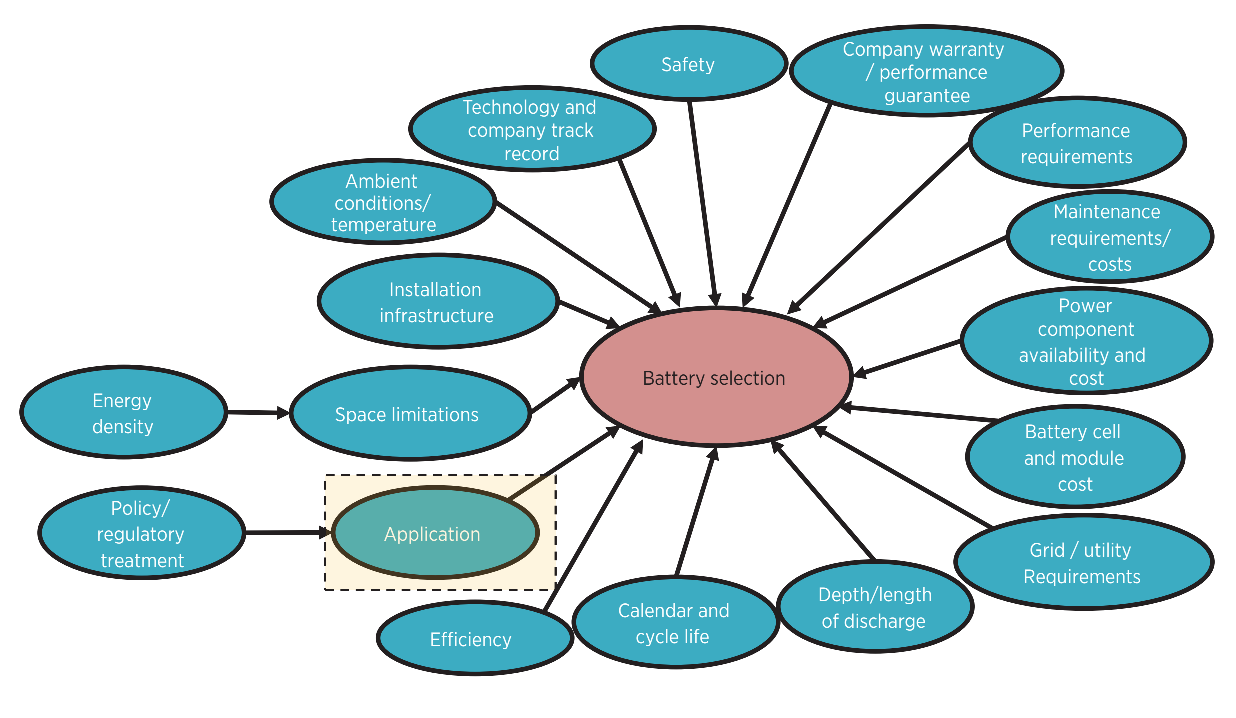
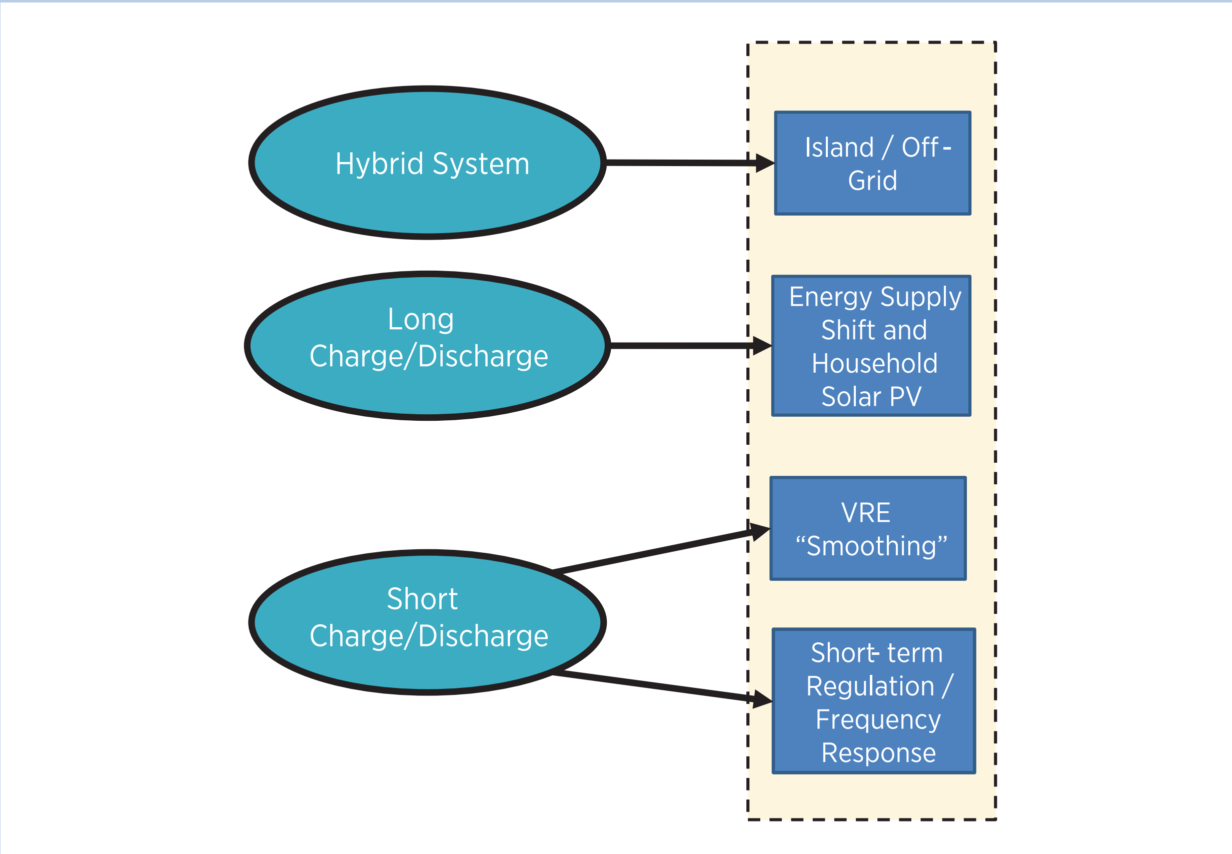


Figure 5: Important considerations for battery selection by application



Some of these considerations relate to the life and performance of the battery, such as DoD, temperature, calendar and cycle life, as well as efficiency and performance requirements. Others are related to the specific location in which the battery is required, such as space limitations, installation infrastructure and ambient conditions. Other considerations are economic. These relate to battery cell and module cost, power component availability and cost, and maintenance costs. Others relate to risks concerning the manufacturer and vendor. Technology and company track record as well as a warranty may be significant criteria to ensure individual product quality and performance and to hedge against the financial cost of defective components. Safety is an important consideration in all situations. Finally, the specific application of storage is affected by the local policy and regulatory environment. This affects incentives, remuneration, interconnection standards and other considerations.

Besides the large number of factors impacting the choice of batteries for renewables integration, battery cost and performance statistics are complex and nuanced. This means that focusing on a single cost statistic may be misleading, especially when comparing manufacturers. This is discussed in more detail in section 5.2. While cost is an important aspect of battery choice, other considerations may take on equal if not greater importance. Figure 4 outlines the important considerations for battery selection for the benefit of policy and decision-makers.

A number of additional performance considerations come into play for battery systems supporting renewables deployment. These are displayed in figure 5. For regulation and smoothing, fast reaction times and the ability to withstand many short charge/discharge cycles are important features. For some frequency response situations the ability to provide a large amount of power over a short period may also an important factor (see box 1 for an example). Alternatively, battery storage for supply shift must be suited to long charge/discharge cycles. Island systems may require a mix of both short and long-term power fluctuation. Additional information about these applications is presented in section 4.

Figure 4 emphasises the point that a single focus on cost for battery selection tends to be too simplistic. A survey commissioned by the U.S Sandia National Laboratories stakeholders showed that other considerations are equal or more important than cost, though this aspect of battery selection was still significant. (NAATBatt, 2014). Other considerations included safety, grid requirements and other factors. Criteria that take the context into account, affected by several considerations presented in figure 4, must therefore be considered.

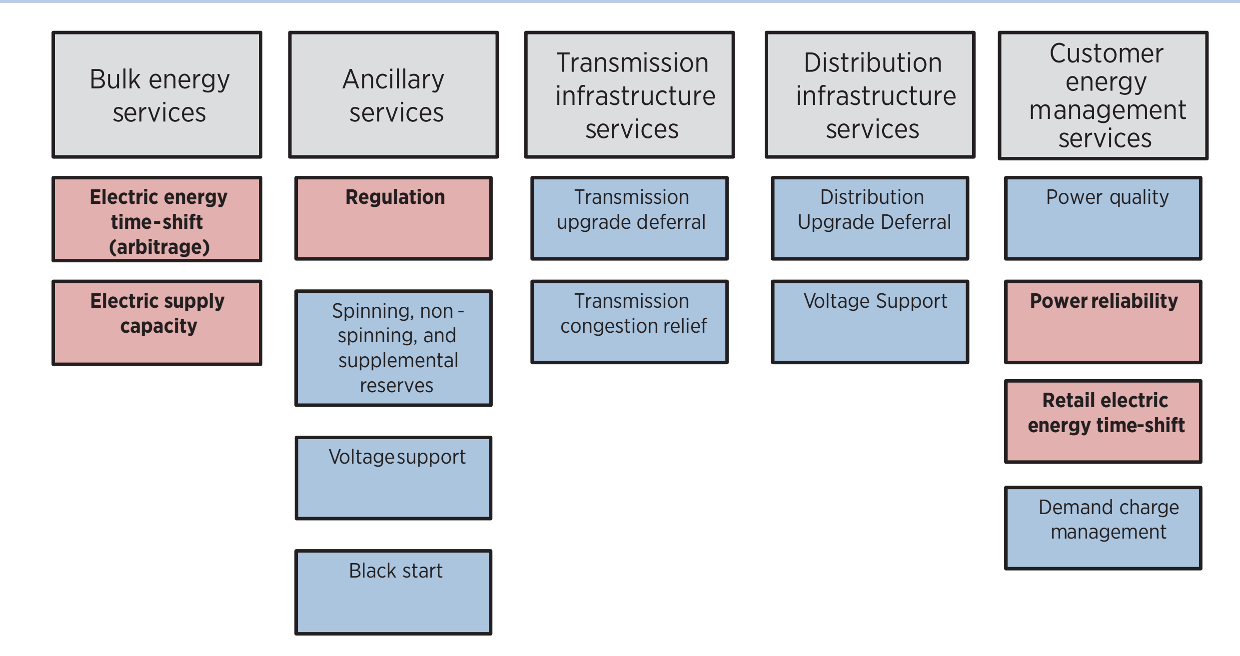
4 APPLICATIONS OF BATTERY STORAGE FOR RENEWABLE INTEGRATION

Battery storage in the power sector can be employed in a variety of ways over multiple time periods, ranging from seconds to hours. EPRI and DOE (2013) describe 14 services under five umbrella groups that can generally be provided by energy storage. These include bulk energy, ancillary services, transmission infrastructure, distribution infrastructure and customer management services. Battery storage can, in principle, provide all these services. Figure 6 below outlines the categories and subcategories of these services. This report focuses on those highlighted in red through the application areas presented below.

The application areas discussed here were determined by examining the applications of battery storage most directly related to wind and solar PV power integration. The emphasis was on those that have been demonstrated and/or deployed in the market. These applications compensate for the variable nature of wind and solar power. They match supply of renewable resources with demand, and optimise variable renewable energy feed-in to the grid. They also provide or take away power when supply and demand become out of balance. It is important to note that a single battery installation can serve multiple uses. A combination of value streams may benefit the economics of an installation.

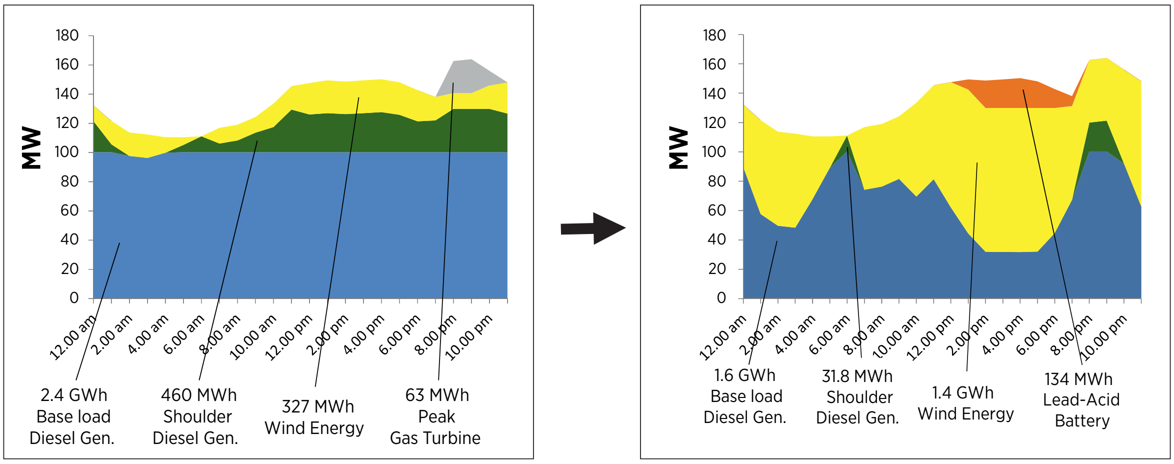
In the following section, the use of battery storage is discussed for the several applications. These are islands and off-grid scenarios (which can encompass all the services highlighted in red in figure 6), and households with solar PV (power reliability and retail electric energy time shift). Additionally, variable renewable energy smoothing and supply shift (electric energy time shift are discussed). Finally, regulation (ancillary services) in grids with high variable renewable energy shares is explored, with emphasis on short-term regulation at the grid level.

Figure 6: Services provided by energy storage



Source: Based on EPRI and DOE, 2013

Figure 7: Island renewable energy production, impact of battery storage



Source: Balza, et al. 2014

4.1 Battery storage – islands and off-grid applications

Islands and rural/off-grid electrification present unique opportunities and challenges for the integration of variable renewable energy. Most islands and many off-grid areas are powered by diesel generation. This is often oversized to meet peak demand and not meant to operate below 30% of capacity. This form of generation is expensive and has high emissions. If initial investment is included, it may cost more than USD 0.35[2]/kWh to run diesel generators whilst most utility-scale renewable power generation have levelised costs in the range of USD 0.05–0.25 /kWh (IRENA, 2013c). The remote location, as well as the lack of infrastructure means constant diesel imports are costly and a risk to security of supply. Diesel generation has traditionally been used as the most accessible and cost-effective solution. It also responds flexibly to highly variable demand, which fluctuates hourly, daily and seasonally due to weather, tourism and lack of baseload industrial demand.

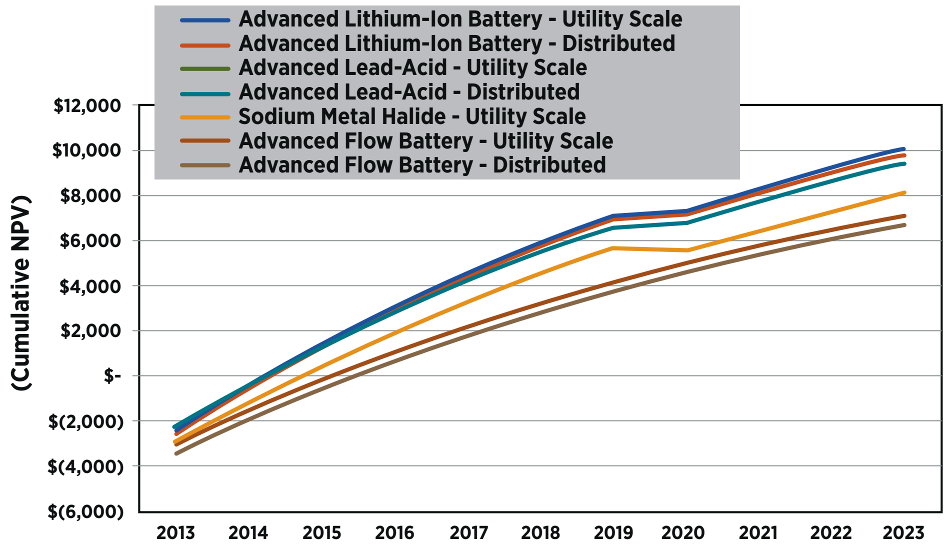
Islands represent a unique opportunity for battery storage. The technology may be utilized to help integrate renewable energy, reduce reliance on diesel and gas generation, and in some cases lower costs. Many islands operate mini-grids, have weak interconnection and a lack of flexible power sources. This means they would benefit from storage to reliably integrate significant amounts of solar or wind power. This starts in some instances from a 15% share of variable renewable energy generation in the system. Figure 7 shows the increased integration of variable renewable energy when combining utility-scale wind with diesel power and a lead-acid battery in an island scenario (Balza *et al.*, 2014).[3]

The figure demonstrates the ability of battery storage (in this case a 134 MWh lead-acid battery) to economically increase renewable energy penetration and decrease diesel and peak gas use. The figure on the left in figure 5 shows a 'business as usual' case with no storage. Here, wind power contributes to peak demand, but its penetration is restricted by the 15% constraint. Adding storage increases the amount of renewables by one gigawatt hour (1 GWh) per day. It also reduces carbon dioxide emissions by 1423 metric tonnes (mt) per day. In addition, it provides a net benefit of around USD 80 000 in avoided generation costs, taking into account the cost of additional storage. Costly peak demand can be supplied by the renewable resource and storage. Variable renewable energy penetration cannot economically reach 100% penetration due to the cost of required storage. Nevertheless, it is an economically viable option for achieving much greater utilisation of renewable energy by displacing diesel and

2 All dollar figures in this report are in US Dollars (USD).

3 Balza assumes maximum renewable penetration of 15% without storage, a realistic estimate for many islands.

Figure 8: Net Present Value of energy storage technologies integrated in remote microgrid world markets, 2013-23



Source: Navigant Research (Dehamna, 2014)

gas generation. This is particularly true at times of peak demand. Box 1 provides an illustration.

Though the scenario presented in figure 7 uses a lead-acid battery, this may not necessarily be the only option. Traditional lead-acid batteries are a mature technology and generally the cheapest option. Advanced chemistries developed in the last two decades may also provide cost-effective solutions. An analysis by Navigant shows a payback period of less than four years for all advanced chemistries. However, these results are based on some simplifying assumptions such as the battery replacement after seven years (though this varies by type, location and application) and the cost of USD 1.0/litre of diesel remaining constant over a ten-year period. The payback period is even shorter with an increase in diesel price. At USD 1.36/litre, all technologies have a payback period of three years or less. At USD 1.64/litre, this falls to two years or less (Dehamna, 2014).

Hybrid systems, consisting of both short and long-term storage, may be both economic and sustainable solutions to replace greater amounts of diesel generation. For example, figure 7 demonstrates the increased benefits from using a lead-acid battery for short-term peak electricity supply. However, longer-term storage could also be used for relatively low, stable demand during off-peak times (*i.e.* at night) when the renewable energy source will not be operating. In this case, the diesel generator would be primarily used in emergency situations.

Similar situations occur when the grid is weak and unreliable. In India, for instance, industrial clusters have begun to produce their own renewable electricity coupled with battery storage to improve security of supply. It is apparent that the cost of blackouts for industrial operations promotes distributed generation with storage as an option to increase electricity supply reliability (USAID, 2014). Similarly, cell phone masts and other telecommunication towers require reliable electricity supply. In many off-grid areas they use diesel generation to secure this. According to industrial company General Electric, this costs USD 20 000-30 000 and produces 50 million tonnes of carbon dioxide per site annually (General Electric, 2014). Solar PV with battery storage may, therefore, represent a cost-effective and more sustainable alternative.

Islands also present a significant market opportunity. One estimate calculates that islands have an overall energy storage capacity potential of 5.3 GWh. If storage is introduced with renewable energy, this could increase their share of electricity penetration by more

Box 1: Case study: Alaska, U.S, island frequency response

In Alaska, a local utility called Kodiak Electric Association (KEA) sought to add an additional 4.5 MW to existing wind resources of 4.5 MW. The KEA system has a peak load of about 27 MW. Given system size and available resources, the utility faced reliability concerns in integrating additional wind. One traditional option was to bring additional diesel generation online as a spinning reserve. This would mean curtailing the wind resource and consuming additional diesel fuel. This would raise costs for electricity supplied, reduce wind resource integration and increase pollution.

Instead, the utility selected Xtreme Power, recently acquired by Younicos, to deliver a 3 MW/750 kWh advanced lead-acid battery solution. Average DoD is expected to be around 5% and the system is used frequently – around 285 times per day. The inside of the container is kept at 20-30 degrees Celsius (°C). In the first six months of operation, KEA benefited from 8 million additional kWh of wind integration, displacing USD 560 000 of equivalent diesel generation costs.

Installation and maintenance requirements were significant considerations given the remote location. The system usually experiences shallow discharge but has significant power requirements during some periods. Temperature, the most important operating condition for performance and cycle life of the lead-acid battery, was also a major consideration. See figures 4 and 5 for important factors related to battery selection and requirements concerning specific applications.

Case study 1 in the addendum to this report presents additional project information.

Source: information provided by Younicos.

than 20% (Blechinger *et al*., 2014). These areas also represent significant market opportunities. In 2011, the African market showed the largest annual growth in volume for European battery systems.[4] Much of this continent has weak or no interconnection. In 2012-13, an Asian company distributed around 2.7 million lead-acid batteries to customers with solar PV in Bangladesh, Nepal and India (Alliance for Rural Electrification, 2013). Rural areas in these countries have weak or little grid interconnection.

Battery storage in island and off-grid scenarios discussed above offer many advantages. However, their unique challenges cannot be ignored. A remote location means there is increased emphasis on cycle life so that there is a less frequent need for replacement. Other challenges are the ambient conditions (particularly temperature), lack of installation infrastructure for equipment transportation and costly maintenance due to travel requirements. Shipping may be difficult due to government restrictions. Meanwhile, the weak macroeconomic performance of some of these countries may limit incentives and government support. See figure 5 for an overview of important factors for battery selection.

4 EUROBAT surveyed 18 African countries.

Nevertheless, for many island and off-grid locations, battery storage is a significant opportunity. It will ensure balance between production and consumption of electricity along with variable renewable energy penetration. This is necessary to guarantee stable operation of the electricity grid. Battery storage can help maximise the use of renewable resources and reduce diesel fuel import and consumption. Other flexible options may also be relevant solutions. They include interconnection, demand response and dispatchable plants (including renewable energy sources like biomass and geothermal) as well as other storage technologies.

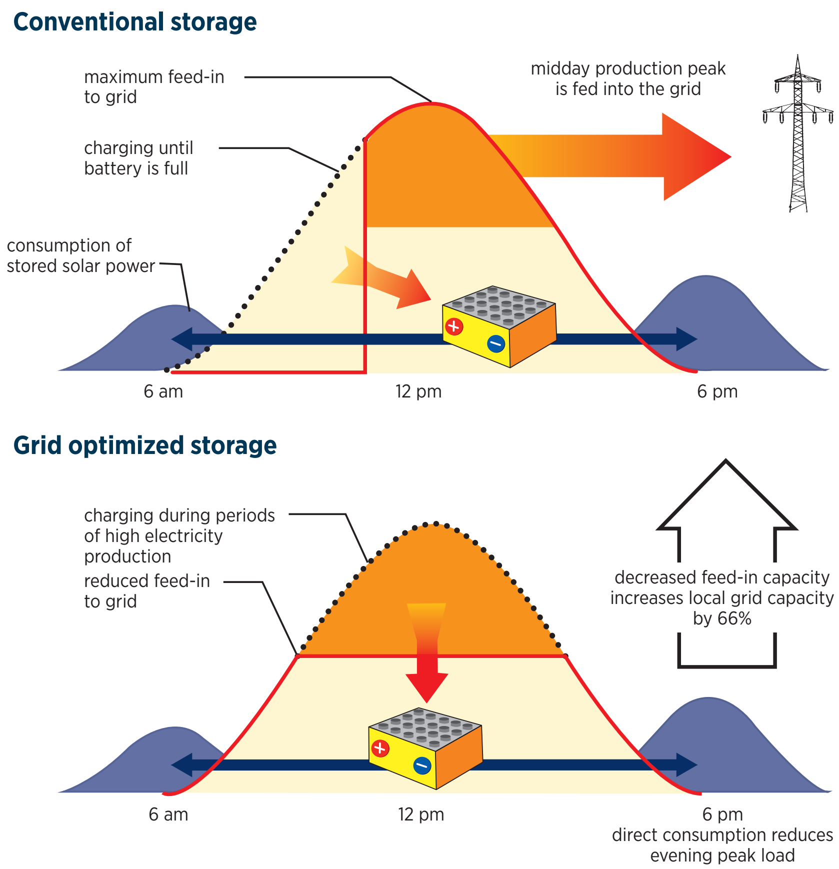
4.2 Household solar PV

Battery storage at a household allows greater self-consumption of electricity produced by solar PV. It can also help relieve local grid capacity constraints. This is accomplished by using storage to align the user's electricity demand with solar production. Solar PV feed-in to the grid may be restricted if it does not coincide with peak demand periods (Fraunhofer ISE, 2013a; BSW, 2013). The application discussed here is similar to the supply shift discussed below, but at a smaller scale for household solar PV.

Figure 9 demonstrates the difference between uncontrolled battery charging and charging and solar PV production that takes grid demand into account. As figure 9 below demonstrates, optimising self-consumption of solar PV is just one aspect of household battery storage. Local area grid demand must also be taken into account if solar PV and storage are to benefit both the user and local grid. Peak solar radiation usually occurs at or just before noon. If solar PV output and battery charging profiles are not controlled, the battery will charge in the morning and become fully charged. This may mean peak solar power production is exported to the grid during its maximum output. This export may not correspond to grid peak demand periods. This results in an oversupply of renewable energy in relation to demand, especially in distribution networks, which can potentially leading to voltages that exceed tolerable limits and curtailment of renewable energy resources. If a large number of distributed solar PV systems are running in a specific area, this practice may also limit renewable energy deployment.

The Fraunhofer Institute in Germany calculates that up to 66% more solar PV can be installed in a given area under circumstances where peak solar PV production is not exported to the grid. This is possible when solar feed-in to the grid is restrained, and battery supply matched to household demand. This means self-consumption of solar power can at least double depending on the size of the solar PV installation and battery. For example, a five kilowatt peak (kWp) PV installation with a 4 kWh battery can increase the household's consumption of PV power from 30% to 60% (Fraunhofer, 2013a; Fraunhofer,

Figure 9: Solar PV and battery storage



Source: Bundesverband Solarwirtschaft, 2014

Box 2: Case study: New Mexico, US, solar PV smoothing and energy shift

Commissioned in 2011, Ecoult (acquired by East Penn Manufacturing in 2010) supplied PNM, a utility in New Mexico, with its advanced lead-acid battery solution. The battery provides 500 kW of smoothing capability and 250 kW/1MWh of energy shifting potential for a 500 kW solar PV plant owned by PNM. Eight battery containers were delivered in trucks to the site for installation.

The battery installation allows better alignment of PV output and system peaks and smooths the volatile ramp rates of the solar PV resource. It demonstrates a dispatchable renewable resource. Data are collected to optimise control algorithms for better system performance and to quantify the benefits such a system can bring to grid stability. The battery installation was supported in part by the US American Recovery and Reinvestment Act (ARRA), a 2009 stimulus bill. The solar PV installation did not receive government funds.

Some of the most important requirements for the installation were to incorporate both short and long charge and discharge, and power and control components. Integrating the policy-regulatory treatment of the application was another important requirement, as was considering installation infrastructure for large shipments. See figures 4 and 5 for an overview of battery installation considerations.

Case study 6 in the addendum to this report provides additional information.

Sources: Ecoult (2013), EPRI (2012).

2014). Thus, this application, unique to battery storage, increases household solar power penetration and allows more solar PV in a particular area while ensuring grid stability.

Depending on individual system characteristics, grid optimal charging patterns can vary. The German government has linked battery incentives to grid-optimal solar PV feed-in, which is expected to encourage the type of charging profiles seen in figure 9. On the other hand, the German government (and also other governments) are introducing taxes on self-consumption and increased connection fees discouraging residential electricity storage. See box 8 for a discussion of the German battery storage incentive programme.

The attractiveness of residential battery storage also depends on the correspondence of peak solar production with peak system demand. If close, this makes grid export during these times helpful rather than harmful. In some Gulf countries, solar corresponds with demand due to demand for air-conditioning.[5] Furthermore, some households may experience peak demand during the day. Thus, optimal charging and discharging algorithms will vary according to the particular electricity system and area, household, and time of year.

Some of the most important factors for battery selection at the household level include cost and economic benefits of the system. Conservative estimates for residential battery storage systems in Europe and Australia are around EUR 2000/kWh for up to 10 kWh systems with estimates of around EUR 900/kWh by 2020. This means that the payback time for these system could reduce from 15 years today to 9 years in 2020 (Goldie-Scot, 2014; BNEF, 2014b). In contrast, some residential battery storage systems are already selling at EUR 1000/kWh at the end of 2014. Others suggest battery storage costs of EUR 200/kWh and payback times of around 6 to 8 years for European countries (Parkinson, 2014). Other potentially attractive markets for batteries coupled to rooftop solar PV systems are Brazil, India, Japan, and certain states in the United States.

Other important considerations for battery storage at households include comparable and reliable information and data sheets, company track record, product warranty, and safety and maintenance requirements. Some vendors are now offering extended warranties of 15 years for residential systems (Goldie-Scot 2014). Furthermore, a key issue for future deployment of

5 Given a delay of one to two hours between the sunniest and hottest times of day, peak solar PV production and peak grid demand may not exactly match.

residential battery storage systems is the issue of liability. If network operators will make consumers responsible for the impact of battery storage systems on the network, then this will change the risk profile for households and possible insurance/finance options for battery storage technologies (Crossley, 2014). Figure 4 provides an overview of the important factors.

In addition to governmental support, other factors are driving this application in many markets throughout the world. They include decreasing solar PV prices, increasing retail electricity prices, decreasing battery costs and consumer desire for energy self-sufficiency. These trends in favour of battery storage mean this application is set to expand significantly in coming years.

4.3 Variable renewable energy smoothing and supply shift

Battery storage can be located at the centralised wind and solar power production site to smooth variable generation output as it is fed into the grid. It can also store excess renewable production for later periods. This process, in which excess renewable energy production is matched to periods of higher demand, is known as energy supply shift. These applications are distinguished from regulation, described below, because they occur on the renewable energy production side, storing energy directly generated from the specific renewable energy resource. By contrast, battery storage regulation services operate at the grid level.

Solar PV and wind power may quickly ramp up or down. This can have negative consequences for system voltage levels in the distribution network and overall stability of the system, depending on the size and ability of the system to cope with unexpected supply and demand changes. A large cloud that blocks the sun may cause the output of a PV panel to fall as much as 90% almost instantly. A similar, though slower, loss of wind resources can cause an unexpected decrease in wind energy output (Jaffe and Adamson, 2014). Smoothing renewable energy production helps maintain system reliability and voltage concerns. It does so by mitigating the very short-term fluctuating nature of variable renewable energy before feeding it into the grid.

Smaller mini-grids, areas of weak interconnection and islands face more serious impacts from rapid fluctuations in output from individual generators. Figure 7 illustrates how storage can be used to smooth the output of a variable renewable energy generator.

The red line in figure 10 represents the normal output of centralised PV production on a Hawaiian island. Battery storage is deployed to charge and discharge in order to smooth this output (bottom blue line), helping integrate the renewable resource to optimise grid stability. The result is the top blue line, demonstrating smoother output that allows for wind and solar resources to be more easily integrated into the electricity network.

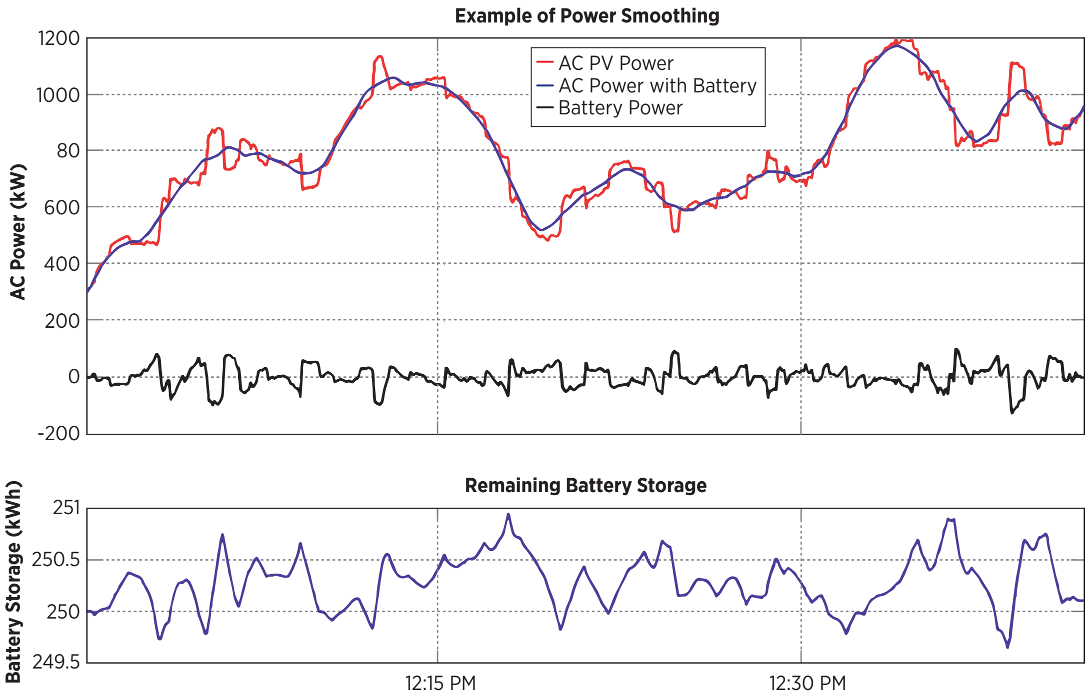
Given the vulnerability of island and off-grid systems to fluctuations in variable renewable energy feed-in, islands have paid particular attention to this issue. For instance, French island systems required storage in conjunction with solar PV installations in their 2012 call for tenders. These battery installations were expected to smooth power fluctuations as well as provide frequency response, as discussed in the following section (Shakarchi, 2014). Puerto Rico introduced similar storage requirements for smoothing, discussed in section 5.3.

Battery storage may also be utilised at the variable renewable energy production site for longer supply shifts. Here, it is used to store excess renewable energy production for times when demand increases. This may not be necessary for system stability, given that other grid-level system resources may be able to provide this service economically (Sioshansi *et al.*, 2012). If necessary, excess renewable energy storage integrates more of the renewable resource, decreases reliance on fossil fuel power plants and ensures system stability while avoiding curtailing wind or solar power. In some markets this makes economic sense. The battery is charged when prices are relatively low, corresponding with low residual demand.[6] It discharges electricity when prices are higher, during times of high (or peak) electricity demand.

In Italy, innovative policies and increased renewable energy development is driving battery storage projects. In particular, Italy's net metering scheme *Scambio Sul Posto* provides economic compensation for feeding in renewable electricity depending on the time of day and demand. According to the national regulation approved

6 Also referred to as 'net load,' residual demand is defined as the amount of demand remaining after subtracting renewable electricity supply.

Figure 10: Illustration of battery storage power smoothing



Source: Johnson et al. (2011)

by the Italian Energy Regulator in November 2014, battery storage systems could be used to regulate the amount of electricity consumed and fed into the grid, depending on the capacity of the plant and on the applying supporting scheme (Toxiri, 2014). Can't be existing and planned. One of the existing battery storage systems in Italy uses energy time shift methods to make electricity supply from renewable energy sources more predictable. The plan is for NGK Insulators to provide a sodium-sulphur battery (1-7 MWh) to correct forecast errors for a 30 MW wind park, allowing wind power supply to become more dispatchable. With an estimated investment of EUR 4.5 million, however, the project may not be economic even with the savings arising from avoided prediction penalties (Mazzochi, 2014).

In figure 11, night-time refers to a period of low demand and relatively low prices. Renewable energy is stored at this time and released when demand is higher, corresponding to relatively higher prices and greater stress on the system. Energy supply shift may also occur over a smaller time frame (*i.e.* 15 minutes to one hour) to avoid curtailment. Over this shorter period, it may display similar economic characteristics.

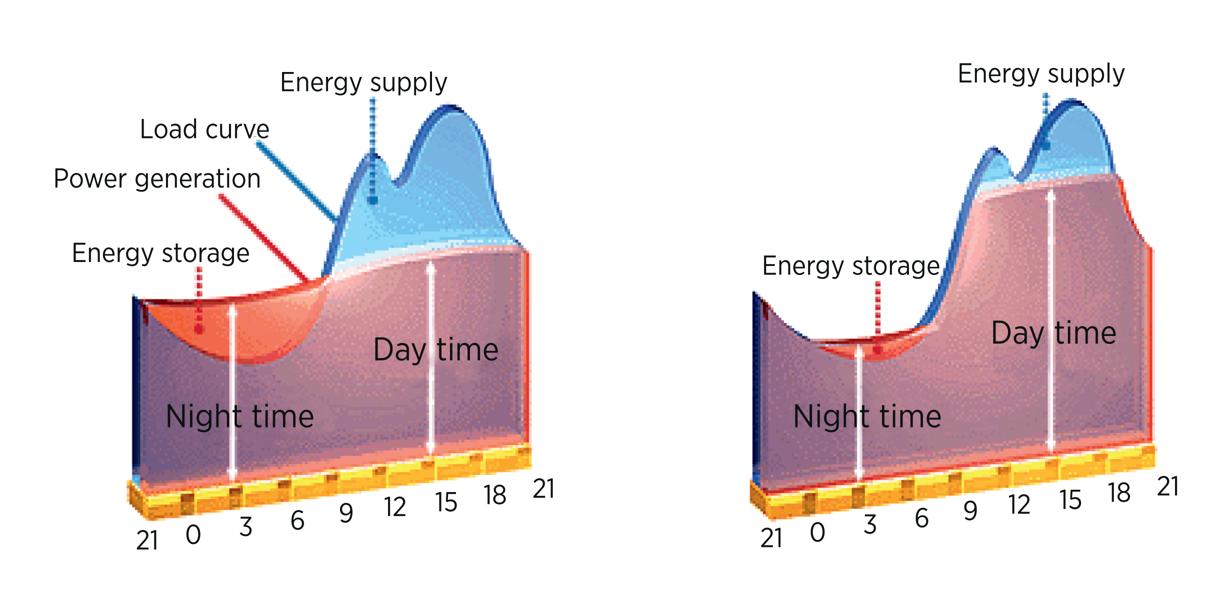
Battery storage may be applied to grid-level storage as well as renewable energy production. In this case, several variable renewable energy and other generators supply the battery with an electrical charge during periods of low demand. At that point, when prices and demand are higher, electricity is released from the storage system.

The smoothing application is well suited to battery storage, given the need for rapid, quick charging and discharging (see figure 4). Many storage technologies can provide energy time shift. In fact, shifting renewable energy production over a period of time is unique to energy storage. No other flexibility measure can provide this facility.

4.4 Fast regulation in grids with high variable renewable energy shares

Along with other storage technologies, battery storage is well suited to a range of ancillary services. These are defined here as facilities that enhance the security and reliability of the electricity system as well as servicing

Figure 11: Illustration of energy supply shift



Carnegie, et al. (2013)

the normal production and consumption of electricity. This application is also useful in islands - see box 1 for an example.

This report focuses on balancing or controlling power meant to solve short-term active power imbalances (over seconds to hours) that cause the system frequency to diverge from its target (Hirth and Ziegenhagen, 2013). These services are generally categorised according to the time frame for which power is provided or taken away. The exact definition varies among systems. The discussion in this section focuses on short-term regulation or frequency/primary response (in seconds). This is an important ancillary service needed in systems

Box 3: Case study: Doha, Qatar, frequency response and other ancillary services

As a climate change conference got underway in late 2012, BYD launched its lithium-ion phosphate battery solution at the Qatar Science and Technology Park. The battery is 500 kWh and is charged by an adjacent solar PV installation and diesel generator.

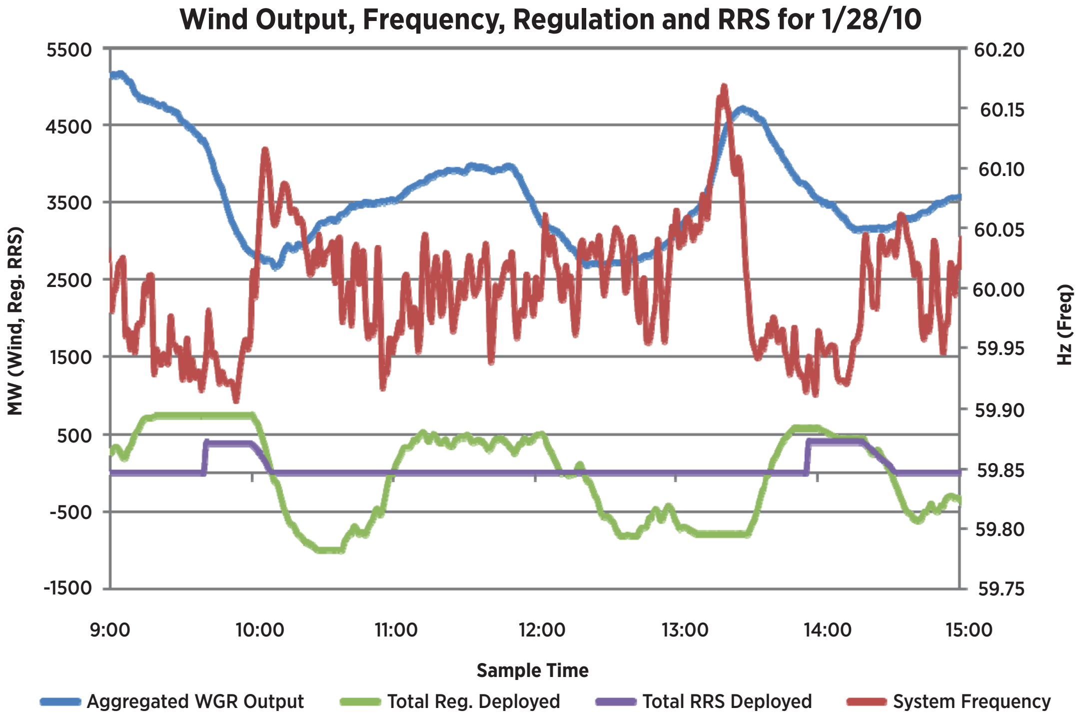
The project provides an interesting hybrid system with benefits for both on and off-grid applications. These include voltage/reactive power support, frequency regulation and black start capabilities. Black start is when a power station restarts without the external electricity grid due to a total or partial shutdown of the transmission system. The project represents an interesting bundle of ancillary services. Battery storage can take over at least some of these, in addition to frequency response.

Some of the most important project criteria were ambient conditions and temperature management in a desert environment location and bundling of services. Performance requirements were another, including the ability to deliver power quickly and stay highly charged in order to supply black start capability. See figures 4 and 5 for an overview of factors significant for battery selection.

Case study 12 in the addendum to this report provides additional information.

Sources: BYD Energy (2012; 2014).

Figure 12: Illustration of fast response wind output and deployed regulation in Texas



Source: Eto et al. (2010)

with a high share of variable renewable. Primary reserve needs to respond immediately when plants are (unexpectedly) brought offline to restore the balance. Case studies discussed in this report demonstrate battery storage can provide primary reserve and applications are operational in many areas of the world.

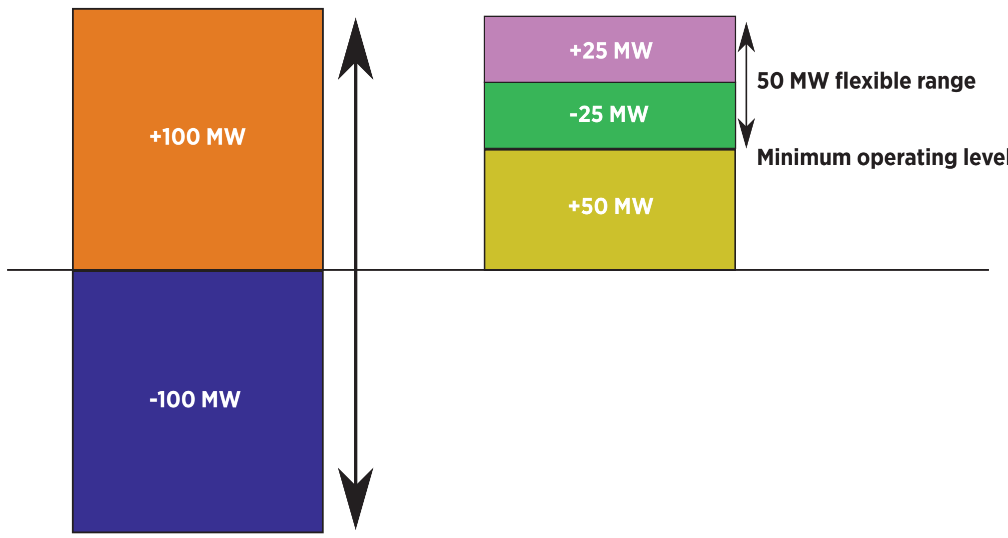
In North America, primary control is deployed over 10-60 seconds (frequency response), secondary control over a maximum of ten minutes (regulation) and tertiary control over a period of ten minutes to several hours (imbalance/reserves). Frequency response refers to the shortest time frame of control. It is important because it begins the process of bringing frequency back towards the system target (*i.e.* 50 or 60 Hz) (NETL, 2011). Battery storage can provide balancing power over all of these time frames. The role of a battery installation depends on other flexibility options available to the system. For example, island systems often have no secondary control options. The ramp rate is the time it takes for an individual resource to increase and decrease supply of electricity.

Spinning reserves are power plants kept operational (spinning) and connected to the grid. These are expected to respond as quickly as primary response. Alternatively, they can respond over a slightly longer time frame for secondary response. Spinning reserves can provide large amounts of energy once needed. Nevertheless, they burn costly and polluting fossil fuels. It is expected that battery storage could be used for this service, though this is not yet commonplace (Jaffe and Adamson, 2014).[7]

In the context of regulation, battery storage is often referred to as a fast response resource. Response time may refer to the time it takes for a power resource to respond initially to the utility signal or to the time it takes to reach a desired end state. In either definition, battery storage responds quickly. This is because storage can

7 Non-spinning (peak) reserves are another service that can be provided by storage, including batteries. Supplemental reserves, black start, load following and ramping support for renewables are others (EPRI and DOE, 2013).

Figure 13: 100 MW Battery storage (left) versus 100 MW gas turbine (right)



Source: Vassallo, A. (2013)

charge and discharge energy in seconds or less, faster and more accurately than thermal power plants.

An electricity system benefits in several ways from the fast, accurate ramping provided by battery storage. The battery can quickly and accurately compensate for short-term output deviations from variable renewable energy generators in order to maintain system frequency. This concept is illustrated in figure 12. It shows wind output in the Texas system and corresponding regulation employed to maintain a frequency of 60 Hz., the system target in the U.S.

Figure 12 illustrates the concept of frequency response in an interconnected system. It shows significant downward ramps of wind in the Electric Reliability Council of Texas (ERCOT) system. These start at around 9 am and 1.30 pm. It also shows the required deployment of rapid response reserves or primary frequency response. The red line depicts system frequency. This is seen to fall as the slope of aggregated wind generation resource output decreases, indicated by the blue line. The purple line illustrates primary frequency response deployed (rapid response reserve) due to the decline in frequency from the 60 Hz target. The need for this short-term regulation is probably related to errors in forecasting peaks and troughs in the wind resource. Though the rapid response reserve depicted here is probably not battery storage, batteries are well suited to this application. Other types of regulation are also being deployed by fossil fuel plants. This is the aggregate amount indicated by the green line. This application occurs at the aggregated grid level and is therefore distinguished from variable renewable energy smoothing (as displayed in figure 10) which is employed at the renewable energy installation site. Texas has around 12 GW of wind capacity according to the Energy Information Administration (EIA, 2014a) and peak demand of 50-70 GW (winter and summer) (ERCOT, 2014).

Battery storage offers its full negative and positive capacity for regulation, as well as a faster ramp rate than fossil fuel power plants. By contrast, a fossil fuel plant is constrained by a minimum operating level requirement below which operation and maintenance costs would suffer (see figure 13).

The battery resource needs less capacity than its fossil fuel regulation equivalent due to its positive regulation attributes. This is because battery storage is faster, more accurate and able to provide its full capacity[8] for positive

8 The actual economic range of operation provided by a battery depends on the technology (cycle life, DoD limitations *etc.*) and how remuneration for these services is calculated.

and negative regulation. These attributes allow it to be utilised more often than a fossil fuel plant for regulation due to the ramping constraints of these resources. Moreover, fossil fuel regulation services may induce a greater requirement for regulation service because they are slower to respond to the operator signal. In this case, they require increased and unnecessary frequency reserve than a resource that can provide more accurate regulation (KEMA, 2010; California Energy Storage Alliance, 2011).

In addition, battery storage may avert the need to keep combustion turbines online. This avoids the emission of more greenhouse gases from these additional conventional generation plants. In a case where incremental regulation service comes from a natural gas or diesel power plant rather than battery storage, comparative emissions may be significant (KEMA, 2010). Frequency regulation provided by conventional plants may also accelerate equipment degradation due to ramping requirements of frequency regulation. This increases maintenance costs for these plants and, therefore, the overall cost of the ancillary service.

The battery storage market for some ancillary services, such as spinning reserve, is expected to become viable in the near future. In Germany, average annual revenue in the primary control reserve market is around EUR 150 000/MWh/year, while annualised costs of energy storage are around EUR 91 000/MWh/year (BNEF, 2014c). In the United States, the market for frequency regulation is currently under way. For instance, the Pennsylvania, New Jersey, Maryland, and other Midwest and mid-Atlantic states market has provided a special fast response signal known as RegD for the provision of this service. This is due to federal regulatory changes described in section 5.3. This alone has spurred around 100 MW of battery storage (Beacon Power, 2014; Jaffe and Adamson, 2014). The market is already viable, as illustrated.

Short-term regulation can also be provided by demand response and fossil fuel power plants. The advantages and disadvantages of battery storage over fossil fuel options are described above. Battery storage represents a compelling option that ought to be considered along with other options to ensure grid stability. This is particularly true as increasing amounts of renewable energy are integrated into the electricity system. Batteries used for this application must be able to withstand multiple charge and discharge cycles as well as providing a significant amount of power when necessary over a short time period. See figure 5.

Box 4: Sustainability of batteries and access to raw materials

A life cycle analysis must be conducted to determine a battery's effect on the environment. This is accomplished by assessing the impacts of raw material acquisition, manufacturing (materials, product, packaging and distribution), consumption and recycling/waste management. A key metric is the energy and emissions from each process. Long-distance transportation of raw materials or manufactured components contributes to impacts. However, this may not be a deciding factor when compared with other energy inputs (Dunn and Gaines, 2013; Weissbach et al., 2013).

Recycling battery materials helps improve material availability, bring down materials costs and reduce the environmental impacts of production. For lead-acid batteries, the selection of partially recycled over virgin materials allows an approximately 40% reduction in energy input. These include 50% recycled lead and 100% recycled plastic (Sullivan and Gaines, 2010). Due to these advantages, some novel chemistries focus on component sustainability, such as zinc air batteries which do not contain toxic components and are 100% recyclable (EPRI and DOE, 2013).

The life cycle analysis is also useful for identifying key raw materials whose scarcity or abundance affects the cost of the battery and potential supply constraints. Lithium is not expected to face supply constraints even under a high demand scenario. However, the expense, safety concerns and relative difficulty in obtaining cobalt (a key component of a popular lithium-ion chemistry) has prompted researchers to look for alternatives (NREL, 2012b; Gaines, 2011). Similarly, a number of new flow batteries are avoiding vanadium because of its limited availability.

5 BATTERY STORAGE IN THE POWER SECTOR, MARKET ANALYSIS

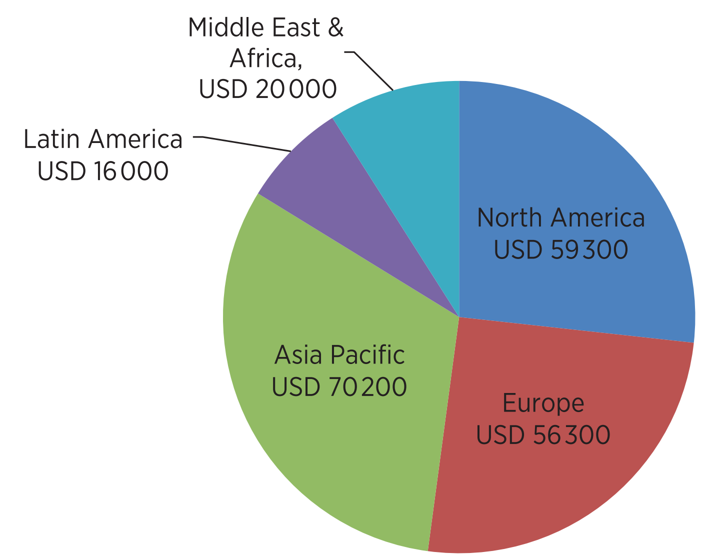
In the power sector battery storage market, batteries are used for a variety of applications, including those presented in section 4. No clear pattern or preferred application has emerged. This no doubt indicates the strong influence of local policy, regulatory and market drivers that differ across energy systems. According to Bloomberg New Energy Finance (BNEF), two applications described in this report comprise the majority of storage projects announced in Q2 2013-Q1 2014 (BNEF, 2014).[9] These are renewable energy integration (which includes smoothing and energy supply shift) and frequency regulation.

Section 5 provides a market analysis of battery storage in the power sector. First, an overview is presented, including a forecast, the supply chain and market participants (5.1). Market activity for different battery types is then discussed (5.2). Finally, the market at country level is explored, analysing key drivers and the context underpinning countries leading in battery storage deployment. These are the U.S, Japan, Germany and China. Activities in India, Italy and South Korea are also discussed.

5.1 Market overview

Propelled initially by government subsidies and research and demonstration programs, many of the technical challenges of battery storage are being overcome. Increased knowledge of how these installations function allow utilities to become more comfortable with their utilization. Cost reductions, described below, are allowing batteries to be increasingly competitive in

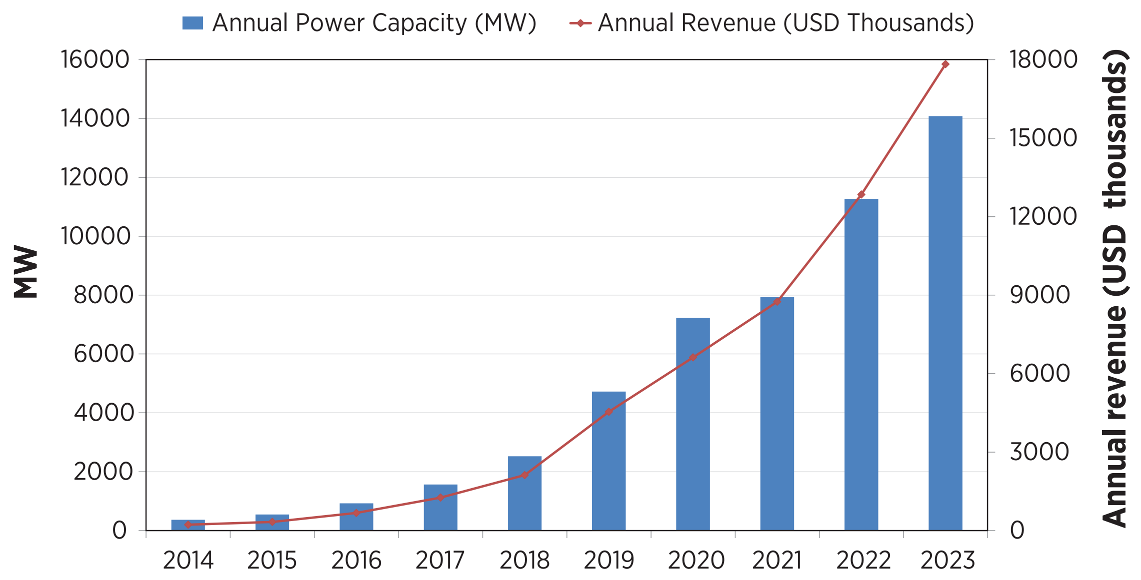
Figure 14: 2014 regional battery storage cell sales for utility-scale applications (USD thousands)



Source: Data from Navigant Research (Jaffe and Adamson, 2014)

9 For a project with multiple applications, BNEF counts the full capacity of the project towards each of the application areas provided by the project.

Figure 15: Worldwide forecast of battery storage capacity (MW) and annual revenue (USD) for utility-scale applications



Source: Data from Navigant Research (Jaffe and Adamson, 2014)

the market. Further, regulations are beginning to move away from an approach to grid services centred on fossil fuels. All these factors will continue to drive the use of battery storage in the electricity grid to unprecedented levels, albeit starting from a very low baseline.

The battery storage market in the power sector has seen significant growth in recent years. For utility-scale applications (excluding battery storage installed behind-the-meter), global 2014 revenue was around USD 220 million, according to Navigant research. Asia Pacific, Europe and North America are first movers in the market. A country analysis, including drivers, is presented in section 5.3.

This market is expected to grow in coming years. Figure 14 shows Navigant's worldwide sales estimate for cells used in utility-scale projects (data excludes batteries with solar PV system behind the meter). The annual revenue for all applications is expected to increase from USD 220 million in 2014 to USD 18 billion in 2023. Annual battery storage capacity will rise from 360 MW to 14 GW over the same period. For utility-scale projects, Navigant expects battery use for renewables integration in 2014 to comprise 29% of the total. This is followed by peak shaving (20%),[10] load shift (18%, similar to the energy supply shift application discussed in this report), ancillary services (17%) and other applications (16%). Renewables integration is expected to remain a primary application in 2023, providing 40% of cell-based revenue. This will be followed by load shifting application (37%), peak shaving (15%), ancillary services (3%) and others (5%) (Jaffe and Adamson, 2014). However, these numbers do not include household solar PV installations, which represents a significant market opportunity.

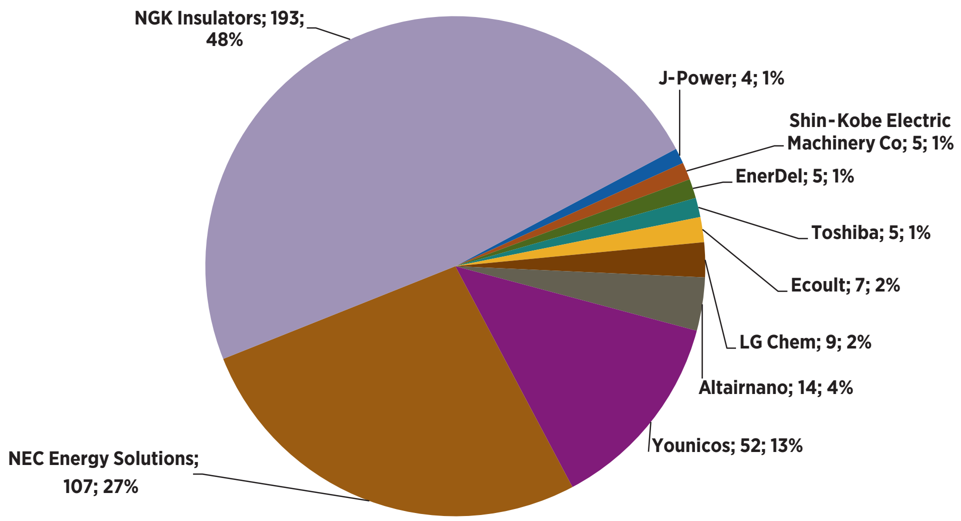
The strong upward trend is noteworthy, although future revenue will differ from figure 15 estimates above due to the complexity of predicting energy sector development. Several steps are needed to manufacture and sell the batteries. This involves many industry players, as illustrated in figure 16.

10 Peak shaving refers to utilisation of battery storage to reduce a facility's peak demand. The application is primarily for commercial and industrial customers in developed grids who face high peak demand charges.

Figure 16: Battery market supply chain

Chemical supply	Battery production	Integration	Use	Recycle / re-use
Chemicals and compounds from around the world are mined, sourced and sold. These are used for the anode, cathode, separator, and electrolyte solution.	For batteries composed of cells, such as lithium-ion, these are constructed from chemical components and arranged into modules, which may include sensors and controls. Modules are then combined into packs and additional hardware/software that manages power, charging, and temperature. Flow batteries integrate chemical components and are not composed of individual cells. Example companies listed here vary in which portion of battery production (cell/module/pack/integration) they serve, and many serve multiple.	Systems are selected and integrated with power components (inverters, etc.) to meet project specifications and are installed following local regulations and requirements. Integrators include project integrators - utilities or energy generation companies that purchase storage assets - and product integrators, which aid project developers to integrate battery storage systems.	Systems are used and maintenance is conducted as-necessary.	Battery components must be recycled to the greatest extent possible to ensure minimal environmental impact and preservation of natural resources. Parts or all of the facility may be refurbished or re-used.
Example companies: Asahi Kasei Chemicals, BSAF, Hitachi Chemicals, Mitsubishi Chemical, Sumitomo Chemicals	**Example companies** A123, AES Corp., BYD, Ecoult, FIAMM, Hoppecke, GS Yuasa, Johnson Controls, LG Chem, NEC/AESC, NGK Insulators, Panasonic/Sanyo, Saft, Sumitomo, Samsung SDI, Younicos		**Example customers:** Local and regional utilities, commercial enterprises, renewable energy companies, households.	

Figure 17: Advanced battery storage technologies for utility-scale applications[11], installed capacity (MW) by top ten companies[12] in 2014



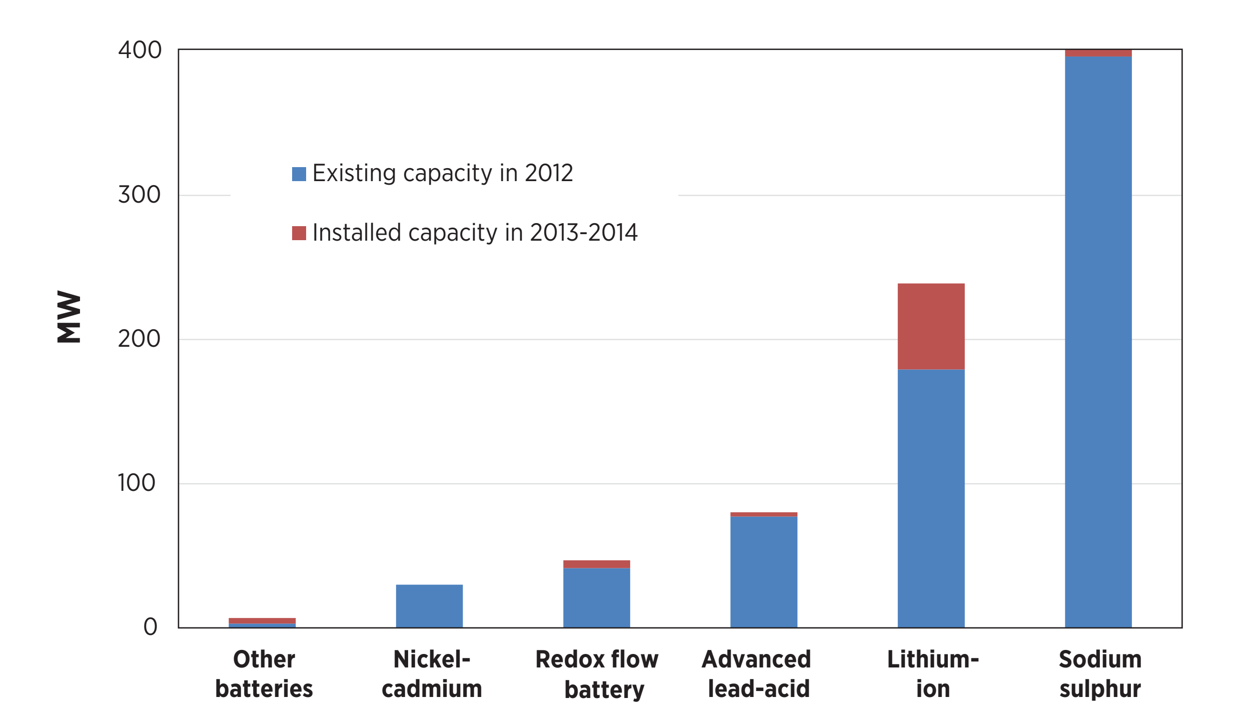
Source: Data from Navigant Research (Dehamna, et al., 2014)

11 Navigant defines utility-scale applications as projects on the utility-side of the meter in the market segments for ancillary services, bulk storage, and community storage and defines advanced batteries as rechargeable battery chemistries that have been developed for mass manufacture only in the last two decades.

12 Xtreme Power entered bankruptcy in 2013, and was recently acquired by Younicos. A123 entered bankruptcy in 2012, and was acquired by NEC Energy solutions.

The production chain integrates chemicals into battery modules, packs and power and control components. Flow batteries require external tanks and pumps/valves to circulate the electrolyte (see annex A). While this report focuses on the battery storage market and its capability to integrate variable renewable energy, the

Figure 18: Estimated installed battery capacity and commissions (MW) in the power sector by type, 2014[13]



Source: Navigant Research (Dehmana, et al. 2014)

sustainability of the batteries themselves must also be considered. This is highlighted by the recycle/reuse phase of figure 16. Box 4 gives an overview of how to assess battery sustainability.

Figure 17 shows some of the companies providing advanced battery storage technologies for utility-scale applications. NGK insulators is the market leader with almost 350 MW of installed battery storage systems, of which around 200 MW in utility-scale applications. This market has changed dramatically in recent years. Common in new and developing markets, some companies have gone bankrupt. Several of these have re-emerged as a different company or through acquisition. These include A123 Systems (which sold its grid storage unit to NEC), Xtreme Power (acquired by Younicos), Valence Technology, Exide and others.

13 The data has been verified and augmented with data from the DOE global database for capacity installed to date (lithium-ion, vanadium redox flow, zinc bromine redox flow and nickel-cadmium) for operational projects.

Recent developments for battery types present in the power sector are described in section 5.2, which includes cost trends and statistics.

5.2 Analysis of battery types

A few years in the energy sector is usually considered a blink of an eye. This makes the rapid transformation of the battery storage market in recent years even more remarkable. The battery storage landscape in the electricity sector is moving away from the former market concentration of sodium-sulphur batteries provided by NGK Insulators, still the world's only provider of this type. It has shifted towards lithium-ion batteries, as well as advanced lead-acid. This is depicted in figure 18. For many applications, lithium-ion has proved preferable to other chemistries with respect to energy and power density, cycle and calendar life, and cost.

The capacity estimates above do not include small solar PV installations coupled with battery storage at the household level. They also exclude a recent 35 MW

Box 5: Case study: Rokkasho, Aomori, Japan, wind energy time shift and frequency response

Commissioned in 2008, NGK Insulators supplied 34 MW/204 MWh of sodium-sulphur batteries connected to a 51 MW wind farm in northern Japan. The installation provides increased wind integration for electricity produced at night during periods of low demand. This is stored and then sold during the day when demand for electricity is greater. In addition, the batteries can be used for ancillary services like frequency response to maintain system stability.

The batteries are housed to protect them from the corrosive salty atmosphere typical of the area. They consist of 17 sets of 2 MW battery units. Sodium-sulphur batteries operate at 300-350 °C and provide around six hours of storage.

As shown in figures 4 and 5, key considerations included long charge/discharge cycles and protection from the salty sea air.

Case study 7 in the addendum to this report provides additional information.

Sources: Abe (2013); Clean Energy Action Project (2014).

sodium-sulphur order from Italy's transmission system operator, Terna, discussed in the following section.

Overall, the market has shifted towards lithium-ion away from sole market penetration by sodium-sulphur. This, however, remains an important battery type produced by NGK Insulators. The shift is due to cost and performance advantages and the industry's further development. The lithium-ion deep discharge cycle life, energy and power density, and other attributes have proved preferable over other battery types. In conjunction with rapid cost decreases, this has led to increased deployment. The driving factors of lithium-ion cost decreases are discussed below. The advanced lead-acid market has been driven primarily by Xtreme Power, which has several projects in Hawaii for smoothing and supply shift. It also has a large installation in Texas for supply shift, smoothing and frequency response. This is discussed in case study 8 in the addendum. However, the company's technology and use of its advanced lead-acid product may shift due to bankruptcy, fire incidents and the subsequent takeover by German battery storage company Younicos (St. John, 2014). Advances in lead-acid batteries with the use of carbon are discussed in appendix A.

While flow batteries comprise a small portion of the market, they are a promising longer-term battery storage solution (four hours or more). This is due to the technology's ability to handle large energy capacity. This is easily multiplied with the addition of external tanks that store the electrolyte. Flow batteries have in the past suffered from the premature degradation of membrane materials and high costs. This must be improved if they are to become more widespread. Installations are at present relatively low. Nevertheless, this is expected to change over the next decade, as the technology shows considerable promise. Navigant estimates that around 4% of installations in 2014 will be flow battery installations in terms of installed capacity (on a power (MW) basis). This share is expected to increase to 19% by 2023 for utility-scale applications (Jaffe and Adamson, 2014). The most mature flow battery chemistries at the moment are vanadium redox flow and zinc bromine redox batteries. Some other chemistries are being developed, such as iron-chromium redox flow by Enervault and zinc-iron redox flow by ViZn Energy. See annex A for a technical overview.

The cost of battery systems has fallen in recent years due to increased deployment and renewed interest in storage for variable renewable energy integration. For example, in Germany the prices for battery storage systems connected to solar PV system dropped by 25% in 2014 (BSW-Solar, 2014b). Economies of scale, manufacturing capacity, the development of electric

Box 6: Battery system costs and Levelised Cost of Energy (LCOE)

As discussed in section 3, a battery installation is comprised of several components. These include battery cells (for cell-based batteries), a power conversion system, materials in the module, a battery management system and other components. In addition, labour, maintenance and other variable costs must be taken into account. While individual cell costs (for cell-based batteries) may be a good economic indicator for comparison purposes, they only represent around 20% of all relevant costs. Total system and variable costs depend on location, application, additional equipment needed, vendors, commercial availability, size of the system and other variables.

There are a number of indicators used for cost comparison, such as cost per kW (power), cost per kWh (energy), or cost per kWh per cycle. Table 1 shows the data for three battery storage systems available in the German market. All battery systems can provide a nominal power of 5 kW, but the capacity, maximum depth-of-discharge determining the usable capacity, the number of cycles, and the prices are different (Photovoltaic, 2012). The data shows that the li-ion battery with the highest system price actually provides the lowest cost per cycle.

Table 1: Calculating cost of battery storage systems available in the German market

battery technology	lead-acid	li-ion	li-ion
battery power	5	5	5
battery capacity (kWh)	14.4	5.5	8
usable capacity (kWh)	7.2	4.4	8
cycles	2800	3000	6000
price (EUR)	8900	7500	18900
EUR/kW	1780	1500	3780
EUR/kWh	618	1364	2363
EUR/useable kWh	1236	1705	2363
EUR/useable kWh/cycle	0.44	0.57	0.39

Furthermore, the cost of a complete system can be represented by the calculation of the LCOE. This is determined by adding all relevant initial, variable and end-of-life costs for an installation. This is then divided by the life time output of electricity, measured in kWh or MWh. The calculation takes into account the time value of money with an appropriate discount rate over the life of the system. EPRI and DOE provide LCOE statistics in their 2013 storage handbook for specific applications. Vendors are anonymous. For instance, lithium-ion batteries utilised for distributed energy storage applications of various capacities and power output ranged from about USD 0.5-2/kWh and upwards (EPRI and DOE, 2013, p.106).

The LCOE statistic must be viewed with caution as it does not necessarily represent the value of the service provided. For instance, a backup storage facility not often used will have a very high LCOE but may provide a valuable service. These types of installations may be economic if flexibility is accurately valued and compensated for under the local market and regulatory structure.

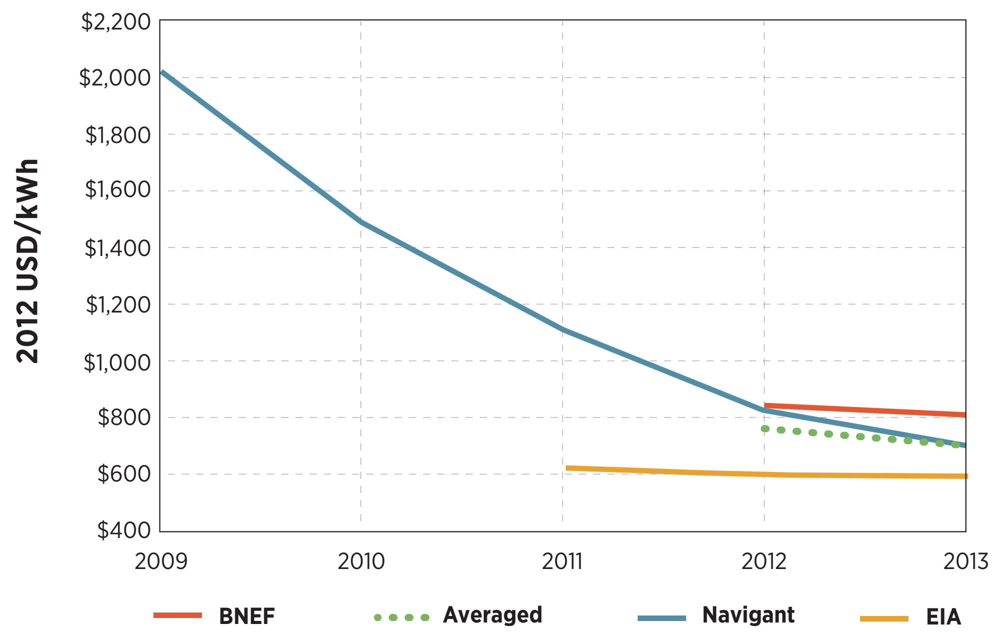
vehicles (EV) and other trends are other reasons for this. The most dramatic cost developments have been for lithium-ion chemistries, driven by policies to deploy the technology in the electricity sector and EV market. Other drivers are developments in the consumer electronics sector, where lithium-ion cells are a clear favourite for portable electronic devices. This is because of their energy density (they are small but have significant energy capacity) and relative performance. Lithium-ion cell manufacturing in Japan, South Korea, China and the U.S has experienced significant overcapacity in recent years as government stimulus programmes in these countries pursue increased manufacturing capability (Jaffe and Adamson, 2013). BNEF estimates that

33 GWh of manufacturing capacity was available for lithium-ion cells in 2013. This compares with a demand closer to 5 GWh (Sun, 2014) from EVs. This has reduced prices for lithium-ion chemistries as companies decrease margins to increase sales volumes. Continued EV adoption will have a direct impact on economies of scale in manufacturing. It will also directly affect technological progress on density, safety and thermal management. This is primarily the case for lithium-ion batteries but is also true for other chemistries. This is expected to continue over the next few years. However, growth in EV deployment means battery cell price decreases are not a long-term trend as excess manufacturing capacity becomes utilised (Sun, 2014). Though the EV market is just 0.02% of total passenger vehicles, sales more than doubled in 2011-12 (IEA, 2013c).

These trends refer primarily to lithium-ion cells, which have experienced the most rapid cost decline in recent years. Advanced lead-acid, flow batteries, and other types have come down in cost in a less pronounced manner. However, they will continue to experience cost improvements given higher deployment, competition and technology improvement. Sodium-sulphur batteries, a more mature battery, are not expected to experience significant cost reductions (Sun, 2011). Nevertheless, favourable characteristics, including the long-term storage capability of flow batteries (over four hours) and strong power performance of advanced lead-acid batteries, allow them to remain competitive. This is despite the fact that they are relatively more costly than some lithium-ion batteries. While cost is an important variable, other factors may take on equal or greater importance. Figures 4 and 5 display many of the most important factors.

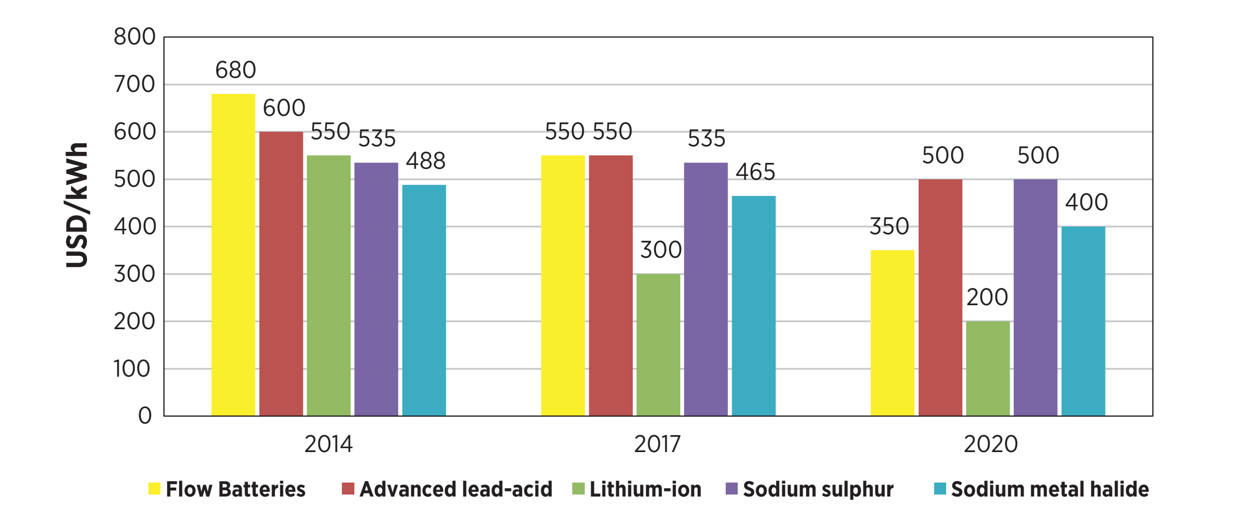
Though estimates are presented in this report, cost statistics should be viewed with care, as they are difficult to assess objectively. This is due to the current lack of defined standards and approaches by which companies provide cost and performance data. This includes lack of reference duty cycles and the environmental conditions under which testing is performed. Multiple assumptions must be made to calculate cost. The most significant of these are temperature, DoD, cycle and, if applicable, calendar life (see section 3). Metrics chosen by a manufacturer may not reflect actual operational performance. Therefore, precise comparison of data among manufacturers and vendors is difficult. The development of a standard of this kind, or at the least an accepted common approach, will be a critical development for long-term success and transparency

Figure 19: Recent lithium-ion battery cost developments



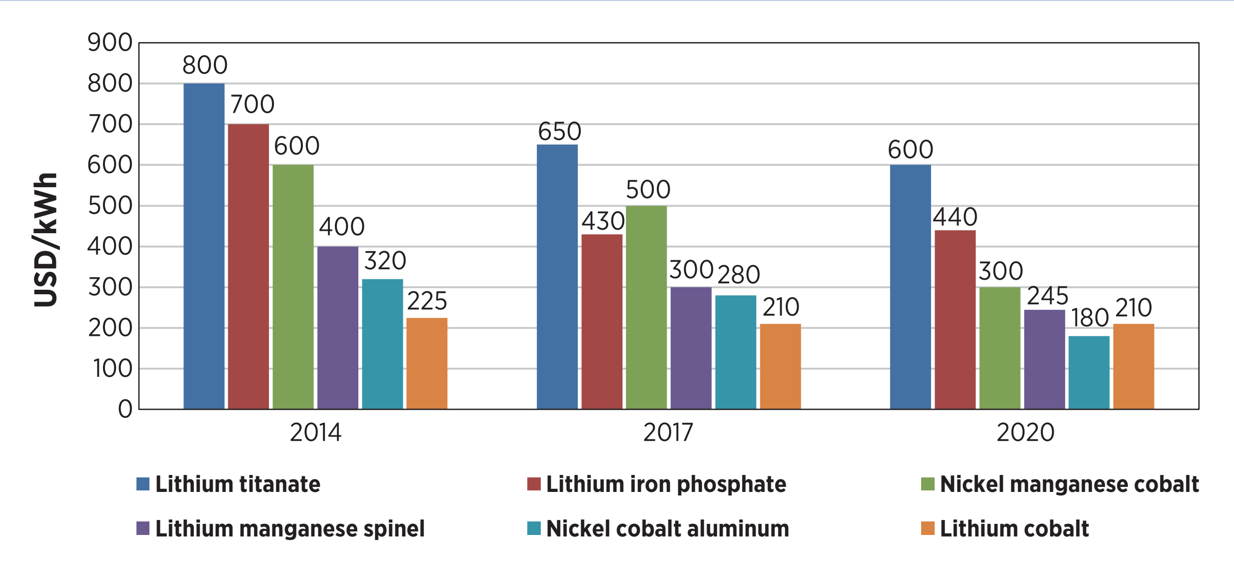
Source: RMI, et al. (2014)

Figure 20: Lowest current and projected battery cell price by type for utility-scale applications



Source: Navigant Research (Jaffe and Adamson, 2014)

Figure 21: Lowest cell price of lithium-ion chemistries for utility-scale applications



Source: Navigant Research (Jaffe and Adamson, 2014)

in the industry. Development of common cost and performance approaches are under way, including work led by the Electric Power Research Institute (EPRI) through the Energy Storage Integration Council in the U.S. Universities and government-supported research facilities are also investigating the cost and performance of various battery types under a range of conditions. Nevertheless, there is a lack of data transparency in the sector. Many battery companies conduct their own independent testing. This adds to the cost of installations and decreases efficiency in the sector.

Costs at the cell level are presented in figures 19-21. However, the battery modules and containers, power components, thermal management systems and other factors add to the overall cost. The total also depends on the size and complexity of a given project. For example, to compare flow batteries with other types

Box 7: Case study: Angola, off-grid school lighting

AllCell supplied a school in Angola, with 200 Watt (W)/1300 Watt hours (Wh) of lithium-nickel-cobalt-aluminum batteries coupled with electricity generated using solar PV for off-grid lighting. The school previously had no lighting or electrical power. By adding lighting, the school is able to stay open later and provide more services. The estimated cost to light four classrooms for up to eight hours per day is USD 2 per day.

This battery type was selected because it is more resilient to high temperatures than lead-acid, very important in this hot environment. Given lithium's tendency to overheat, the batteries are protected by AllCell's thermal management material and placed in the shade. No other voltage or temperature control was employed.

Among the considerations highlighted in figures 4 and 5, the most important in this case are temperature and long charge and discharge cycles. The remote location also imposes unique maintenance requirements. Hands-on maintenance is not possible, and it is less expensive to replace the batteries than provide maintenance.

Case study 2 in the addendum to this report provides additional information.

Source: Information provided by AllCell.

of batteries, Navigant Consulting assumes containers with eight hours of electrolyte storage. See box 6 for more on this subject. Information provided by Younicos indicates that for a lead-acid installation in Alaska, the battery represented around 40% of installation costs (see box 1). For a small project in Africa, battery cells provided to AllCell Technologies were about 50% of the system's cost (see box 7). These percentages may not be representative of all installations.

Annex A provides an overview of technical characteristics for multiple chemistries.

Lithium-cobalt has become a standardised chemistry used to a large extent for consumer portable electronic devices and also EVs. Lithium-ion cells face a floor at the bottom of their cost curve due to material costs. Figure 21 suggests costs of about USD 200/kWh for lithium-cobalt chemistries.

5.3 Country analysis

Japan and the U.S lead the world in battery storage implementation thus far. However, other countries are also increasing deployment, including Germany and China. Figure 22 shows an estimate of the total MW of battery storage installed and planned by country.

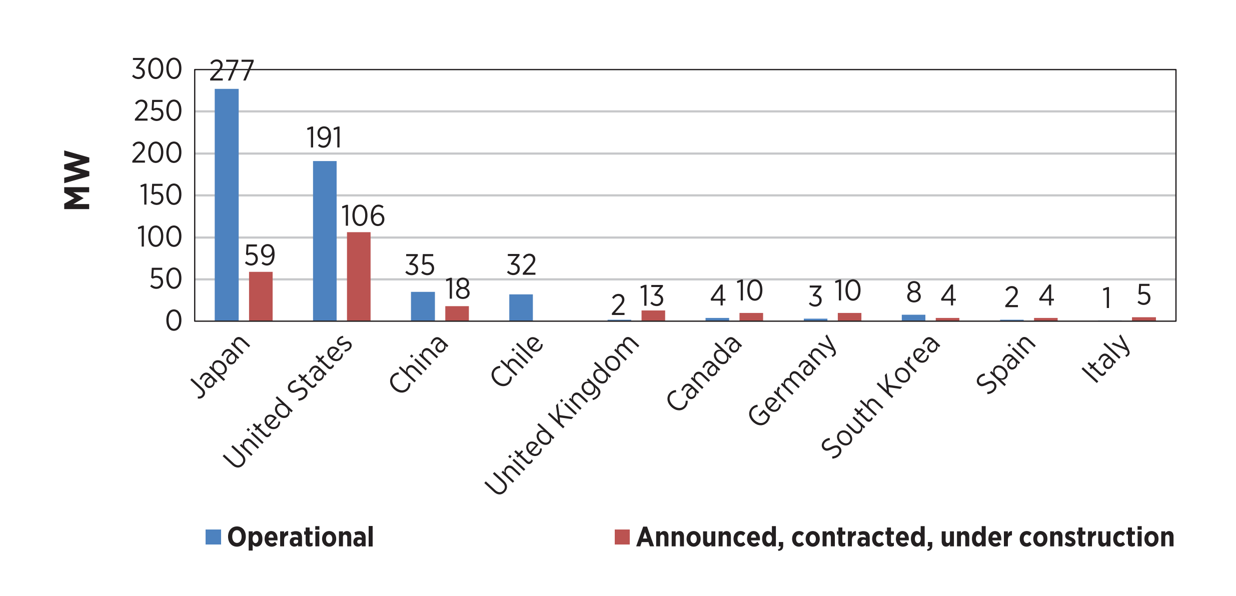
The data presented in figure 22 underestimate battery storage because they do not include decentralized installations, such as at households or commercial facilities. The small size and private nature of these installations often do not show up in datasets. However, taken together they are significant and an important market opportunity. Small island battery storage is also not represented, though taken together these installations may be significant.

The primary drivers of battery installations in leading countries U.S, Japan, China and Germany are presented below. This creates an understanding of factors propelling the market in these countries, both now and in the near future. Although these countries have taken the lead, others will benefit from the technological advancements, know-how and cost decreases established by these first movers.

U.S.A.

The U.S.A is a market leader in battery storage implementation, though installations represent a small fraction of overall system size. Growth has been driven

Figure 22: Estimate of operational and planned battery storage (MW) in the power sector by country[14]



Source: Abe, H. (2013), and DOE (2012)

by the country's 2009 federal stimulus package, the American Recovery and Reinvestment Act (ARRA). It is also driven by regulatory changes helping to integrate and value services provided by battery storage. Other drivers are grid reliability issues in parts of the country, state-level storage mandates and renewable support programmes.[14]

ARRA provided about USD 100 million for power sector battery storage projects. These were matched by private funds to make a total of USD 222 million towards battery storage implementation. This accounts for about 75 MW of battery storage projects, primarily for renewable energy integration and smart grid demonstration. The stimulus also encouraged the development of U.S EV manufacturing capabilities. It provided USD 2.4 billion for this purpose, a portion of which went to battery manufacturing capability (Borden and Schill, 2013; Electric Advisory Committee, 2011).

In addition, constraints on generation and transmission capacity (including retiring capacity) and the integration of variable renewable energy has created grid reliability issues. This has drawn attention to the need to level the regulatory playing field and compensate non-traditional flexibility measures for the benefits they provide. In 2007, the Federal Energy Regulatory Commission (FERC) passed Order 890. This required that applicable markets consider non-generation resources such as energy storage and demand response for ancillary and grid services. This opened the door for battery and other storage technologies to provide and get paid for grid services.

FERC has also taken a position on how these resources should be paid. In 2011, FERC 755 was issued, requiring wholesale markets to pay for the actual quantity and accuracy to the utility signal provided by a frequency regulation resource. The commission found compensation in most ancillary markets was not adequately set (FERC, 2011).[15]

14 Project information is in various stages of verification. All data points, other than operational projects in Japan, are from the DOE global storage database.

15 Each regional transmission Organization (RTO) and independent system operator (ISO) has different ancillary market rules. For instance, in some markets, up and down frequency regulation was netted and therefore did not pay for quick up and down performance or accuracy to signal response. Nevertheless, each market will implement FERC 755 in a unique way, which must be subsequently approved by FERC. FERC Order 784 clarified accounting and reporting rules for energy storage in ancillary markets (FERC, 2013).

Table 2: Procurement of energy storage by Southern California Edison in 2014

Seller	Resource type	MW
Ice Energy Holdings, Inc.	Behind-the-Meter Thermal Energy Storage	25.6
Advanced Microgrid Solutions	Behind-the-Meter Battery Energy Storage	50
Stem	Behind-the-Meter Battery Energy Storage	85
AES	In-Front-of-Meter Battery Energy Storage	100

States and areas with relatively high penetration of renewable energy have demonstrated and funded battery storage to help integrate variable renewable energy. Texas, the U.S state with the largest wind generation capacity, has, for example, installed battery storage with large wind farms. This is used for smoothing. It includes the Duke Energy project at the Notrees wind farm in West Texas supported by ARRA (see addendum) and GE Durathon batteries in Mills County, Texas (DOE, 2013b; Gates, 2011). Islands in the U.S such as Hawaii have also installed battery storage for renewable integration. This includes around 16 planned and operational projects for wind and PV integration with lithium-ion and lead-acid batteries. Some of these received ARRA funding (Hawaii State Energy Office *et al.*, 2013). The government-run utility commission in Puerto Rico, the Puerto Rico Electric Power Authority, has recently mandated energy storage for renewable energy projects. It requires that individual projects have sufficient energy storage for smoothing 45% of the variable renewable energy resources' maximum capacity. It also requires them to have sufficient energy storage to discharge in ten minutes or less for frequency response for 30% of the rated capacity (St. John, 2013). These cases illustrate the particular importance of storage in island and off-grid situations, discussed in section 4.

California has the most ambitious plans for advanced energy storage in the U.S. It recently approved a requirement for utilities to procure 1.3 GW of primarily non-pumped hydropower storage.[16] This follows Assembly Bill 2514, according to the California Public Utilities Commission (Charles, 2014). The state also subsidises battery installations by around USD 1.6/Watt through its self-generation incentive program. This varies according to specific conditions and programme budget (CPUC, 2013). Based partially on this mandate, the Californian utility Southern Californa Edision has already procured 261 MW of storage, of which 100 MW is front-of-meter battery storage, and 135 MW of behind-the-meter battery storage.

New York is another state moving aggressively to promote battery storage. It has created the New York Battery and Energy Storage Technology Consortium and is introducing incentives. These include a planned USD 2100/KW battery storage incentive for 50% of the project cost for summer peak demand reduction. This is granted by the state's research and development institution NYSERDA[17], and major utility ConEdison (NY-BEST, 2014).

Innovative financing models for storage in California include third-party leasing of solar and battery storage from SolarCity. This requires no upfront cost for the battery system (similar to Japanese company plans outlined below). After SolarCity and other private enterprises became frustrated with utility interconnection fees and time lag, the state energy commission stepped in to resolve the issues, largely in favour of companies like SolarCity (CPUC, 2014). This demonstrates the important role local regulations play, even when policy seeks to promote battery storage. California's mandate, renewable energy objectives, incentives and increasingly favourable economics will drive U.S battery storage implementation and innovation in the power sector in the near future.

Lithium-ion battery manufacturing is another notable development. This is traditionally concentrated in Asia with Samsung SDI, LG Chemicals, and Panasonic as major producers. Tesla Motors, an EV producer that uses lithium-ion batteries in its vehicles, is building a

16 Small pumped hydropower projects, 50 MW and below, may be included in utility procurement.

17 New York State Energy Research and Development Authority

production facility in the American state of Nevada to produce 35 GWh of battery cells (equal to global li-ion cell production in 2013), and 50 GWh of battery packs by 2020. The batteries would be used primarily for the company's EV fleet but could also be sold into the power sector and for consumer electronics. While predictions of widespread cost reductions are speculative, the plan illustrates a potential future model for battery innovation. It also shows the interaction between the automotive and power sector battery storage market segments (Wesoff, 2014). Establishing a manufacturing base of lithium-ion development in the U.S would also make this technology even more accessible.

There are many reasons the U.S will continue to be a leader in the implementation of battery storage. Drivers in the near future include increased variable renewable energy due to state renewable portfolio standards and regulations that value and pay for fast frequency response. Other drivers are the falling costs of solar PV power, increasing retail electricity rates and the cost and technological development of battery storage.

Japan

Battery development in Japan has centred on Tokyo Electric Power Company's large sodium-sulphur installations. These were supplied by NGK Insulators. Concerns over the country's reliance on pumped hydropower storage prompted this battery development. It was seen as an attractive alternative for relatively long periods of electricity supply (multiple hours). However, the batteries can also provide energy quickly (EPRI and DOE, 2003). See annex A for further discussion on sodium-sulphur batteries.

Along with the rest of the electricity sector in Japan, this primary driver of battery storage has changed in recent years. The 2011 earthquake and subsequent tsunami resulted in a devastating nuclear reactor meltdown. Subsequently Japan's nuclear reactors have been shut down. It is unclear what portion of this capacity will come back online due to safety concerns and public resistance. In 2010, nuclear energy provided over 25% of electricity supply, and the country has limited natural resources (IEA, 2013b; EIA, 2013).

These factors have motivated greater emphasis on renewable energy. This includes solar, geothermal, wind and biomass. These provide the majority of renewables in Japan at present. Renewables are incentivised through a FiT. This pays a high fixed price for renewable energy sources over a period of ten or 20 years. This incentive is currently around USD 0.37/kWh for solar PV panel installations of less than 10 kW. This compares to a household retail electricity price of around USD 0.21/kWh[18] (IEA, 2013d). This has spurred a rapid growth in solar PV, with 1.7 GW installed in 2012 to more than 10 GW at the end of 2014. Despite high FiTs, implementation of household battery storage has followed, fueled by a desire for security of electricity supply given the recent nuclear shutdown. Other motivating factors include government subsidies and the avoidance of high retail electricity prices by increasing solar self-consumption. In March 2014, Japan's Ministry of Economy, Trade and Industry announced a lithium-ion battery subsidy programme worth USD 100 million, and the total volume of applications received has already exceeded the allocated budget before the end of 2014 (BNEF, 2014c). Subsidy payouts are limited to around USD 10 000 for individuals and around USD 980 000 for businesses, and may cover up to two thirds of the costs (Colthorpe, 2014). Subsidies available in 2013 prompted more than 100 MWh in household storage installation. This is expected to increase in coming years (Jaffe and Adamson, 2014). Additional subsidies include support for stand-alone renewable energy generation with batteries. The total programme is worth just under USD 300 000. The Ministry of Economy, Trade and Industry also grants subsidies for renewables with batteries in areas affected by earthquakes. The Ministry of Environment runs additional programmes to support batteries with renewable generation (Tomita, 2014).

In the hope of capturing the benefits of the trends described above, business innovation is further driving household battery storage implementation in Japan. In September 2013, Japanese companies ORIX Corporation, NEC Corporation and EPCO Incorporated announced a joint venture called One Energy Corporation. This offers consumers with solar PV panels the ability to rent a NEC battery with 5.53 kWh capacity. They pay no initial cost but are charged around USD 30-50[19] per

18 2011 average price. Japanese Yen (JPY) have been converted to USD at an exchange rate of 0.0099 JPY/USD.

19 The Tokyo-only plan is for no initial cost and a monthly fee of JPY 3 045 incl. tax. Outside Tokyo, the basic plan also cuts out any initial cost and includes a monthly fee of JPY 5145, incl. tax. JPY have been converted to USD at an exchange rate of JPY 0.0099/USD. These plans are subject to various conditions. An initial fee may apply for some households.

month over ten years. This is subject to various conditions. The consumer monitors energy consumption and battery output through a 'smart house' app provided by the company and developed by EPCO. The venture offers to rent the rooftop of households without a solar PV panel. Subject to an initial fee, the company offers to install solar PV, making a monthly payment to the consumer if the roof's shape, direction and electricity generation volume is favourable. Consumers in a household with a south-facing roof are expected to receive around USD 25 per month over a ten year period following the installation of a 4 kW PV panel. These customers may also rent a battery alongside this. The solar PV panel is used partly for the household's self-consumption. However, it seems the company expects to benefit from the country's FiT tariff mechanism by selling exported electricity to the grid (ORIX, 2013).

Storage at the grid level is also being explored for larger-scale renewable energy integration. Japan has several isolated grids with insufficient transmission. Battery storage thus represents a valuable option for grid stability and renewable resource integration, and several projects are in place or under construction. For instance, a project in Rokkasho, northern Japan, combines a 51 MW wind farm with 34 MW sodium-sulphur battery. This is primarily charged at night when demand is low. See box 5 and case study 7 in the addendum.

Lithium-ion battery production is heavily concentrated in the region (Japan and South Korea), and Japan is home to the only provider of utility-scale sodium-sulphur batteries – NGK Insulators. This, along with increasing renewable energy, stability of electricity supply issues, island and off-grid scenarios, as well as government support, will continue to drive battery storage implementation in Japan.

Germany

Germany is a worldwide leader in renewable energy implementation. The country has a goal of 80% renewable electricity by 2050 according to the economic ministry (Bundesministerium für die Wirtschaft) and environment ministry (Bundesministerium für die Umwelt) in 2010. This has been incentivised by a FiT, which pays renewable generation a fixed price over 20 years. Several German nuclear reactors were shut down after the Japanese nuclear meltdown in 2011, and the rest are to be phased out by 2022. As in Japan, nuclear power had previously contributed about 25% of annual electricity production.

Germany has a highly interconnected transmission grid. At present levels of about 30% renewable energy penetration (mainly wind and solar), the system has faced very few reliability issues. Renewable energy is rarely curtailed, according to the federal energy network agency (Bundesnetzagentur) and competition authority (Bundeskartellamt) in 2013.[20] As wind and solar power increase in penetration, and fossil fuel plants go offline, battery storage may become an important option for short and long-term supply fluctuations. This has prompted demonstration projects and research funding for battery storage implementation. A newly contracted 5 MW/ 5 MWh li-ion battery park from supplier Younicos will assist distribution grid WEMAG AG to manage frequency regulation and integrate wind power into their system in Schwering (Younicos, 2013). Energiequelle and ENERCON are installing a 10 MW li-ion battery storage system to provide primary control and to assist the 100% renewable-energy sources town of Feldheim (ENERCON, 2014). Another hybrid li-ion and lead-acid 5 MW facility will be operational in 2015, and provide testing, demonstration and frequency balancing in the city of Aachen (SMA Group, 2014).

Nevertheless, the current drivers of battery storage complement solar PV implementation at the household level. Germany is a world leader in this area. In 2013, the country had the most solar PV capacity installed on a total and per capita basis (REN21, 2014). General economic trends support greater implementation of solar PV with battery storage in Germany in the near future. These include falling FiTs for solar PV generation (an opportunity cost for storage), rising retail rates for electricity consumed from the grid and decreasing battery costs. Storage allows greater self-consumption of solar PV power, avoiding retail electricity rates. A proposal now under consideration to tax electricity

20 For plants governed by the Erneuerbare-Energien-Gesetz, Germany's Renewable Energy Act, 0.33% of total renewable energy production was curtailed in 2012. High wind production in the North of Germany and lack of interconnection to demand centres in the South have created loop flows. These are deviations between the scheduled (market-based) and physical flow of electricity. This has affected neighbouring markets negatively in recent years. Better price signals, stronger interconnection and integrated markets can help alleviate this issue in future (THEMA, 2013).

Box 8: Case study: Germany, support for household solar and battery storage

Since May 2013 the German government has supported the installation of battery storage systems coupled with solar PV panels at the household level. The programme received EUR 25 million in initial funding; it is unclear whether additional funds will become available. Basic programme requirements include:

- PV installations must be smaller than 30 kWp, and batteries must be used for at least five years.
- PV systems must have been installed by 31 December, 2012 to receive the battery incentive.
- The PV installation feed-in to the grid must not exceed 60% of its nominal power rating over its whole lifetime, or at least for 20 years. This encourages optimal charging behaviour.
- Total subsidies are capped at EUR 600/kWp for PV systems operating within the previous six months.

Case study 11 in the addendum to this report provides additional information.

Sources: Kreditanstalt für Wiederaufbau (KfW), 2014; Goldie-Scot, 2013; Bundesministerium für die Umwelt, 2013; BNEF, 2014.

self-consumption would alter this formula, negatively affecting the economics of storage with solar PV power.

Battery subsidies are accelerating the trends listed above. From May 2013, the German government provides a grant of 30% of the battery cost. It also grants low interest loans for the balance for PV panels installed after 2012, according to German development bank KfW in 2013. Its aim is to encourage battery storage adoption with PV systems (see box 8). In 2013, around 2 700 installations were installed. By October 2014, around 6 500 battery storage systems with solar PV had been installed as a result of the subsidy, with demand increasing by more than 30% in the last quarter of 2014 (KfW, 2013b; BSW Solar, 2014a; BSW Solar, 2014b). Around 4 000 systems have also been installed without governmental subsidy; 85% of the total volume of units installed were lead-acid batteries (Sonne Wind & Wärme, 2014). This means that at the end of 2014 around 12% of solar PV systems were installed with a battery system, and many solar PV suppliers are now offering integrated systems. Eligible types include lithium-polymer, lithium titanate, lead-acid and lead-acid gel batteries (BNEF, 2014c).

Battery storage is generally not yet economic for new solar PV systems. However, rising retail prices, falling FiTs and decreasing battery costs supplemented by governmental support mean solar PV with battery storage will become increasingly financially attractive. For older solar PV systems unable to capture a FiT, batteries provide an economically attractive way to increase self-consumption and avoid high electricity charges. These now stand at about EUR 0.29/kWh. The consultancy firm UBS provides a range of LCOE estimates for solar PV and battery systems in Germany to 2020, as well as a discussion on current trends (Hummel *et al.*, 2013).

China

China is the world's largest producer and consumer of energy and plays an important role in all global energy markets. Traditionally, growth and development in the power sector has focused on fossil fuels, especially coal. However, the focus has shifted. This is due to the continued growth in electricity demand, supply security concerns, increased attention on energy source diversification and environmental concerns. Natural gas, nuclear and renewables are now in the spotlight. Spurred by a variety of financial and government programmes, China's renewable energy capacity has grown exponentially in recent years. By the end of 2013, China had the highest installed wind capacity in the world and the second highest solar PV capacity (REN21, 2014). Nevertheless, these sources still represent a relatively small percentage of the electricity sector – less than 3% of total production in 2013 (IRENA, 2014d).

Lack of transmission infrastructure has already obstructed renewable energy integration. Total installed wind capacity was 75 GW in 2012. However, only 61 GW could be utilised (EIA, 2014b). Given China's declared goals, the emphasis is on additional transmission along with storage. This is because the country aims to increase wind capacity to 150 GW by 2020 (IRENA and GWEC, 2012) and solar generation capacity to 70 GW by 2017.

Box 9: Case study: Zhangbei, China, wind energy time shift and ancillary services

Commissioned in 2011 in collaboration with China Electric Power Research Institute, Prudent Energy provided a 500 kW/1 MWh vanadium redox flow battery to China's Wind Power Research and Testing Centre. The battery is used to integrate the centre's 78 MW of wind and 640 kW of solar PV. It stores excess electricity during times of low demand and discharges when demand increases. The installation can also provide services over a shorter time scale, including load following and voltage support. The facility is meant to test the battery's operation. This allows the local utility, the State Grid Corporation of China, to test the technology's compatibility with China's system.

The vanadium redox flow battery represents a relatively developed type of flow battery technology. It uses external tanks and pumps to store the electrolyte pumped through a cell stack during charge and discharge cycles. The systems operate at room temperature.

Key considerations affecting battery selection included long/deep charge and discharge, as well as power requirements – criteria discussed in figures 4 and 5.

Case study 9 in the addendum provides additional information.

Sources: DOE (2013c); Prudent Energy (2012a; 2012b; 2013).

This is from a baseline of 3 GW in 2012 (Deutsche Bank, 2012; EIA, 2014b; Hall, 2014). According to Bloomberg New Energy Finance (BNEF), at least 180 MW of storage has been commissioned or announced in China. The country is concentrating on lithium-ion technology, with 101 MW of storage capacity to come from lithium-ion batteries and another 30 MW from flow battery technology (Littlewood, 2013). Installed projects include a 6 MWh lithium-ion-phosphate battery system in Zhangbei county provided by BYD Energy. This is part of the Golden Sun programme, which provides subsidies for up to 50% of total solar PV system cost in both urban and rural applications (IRENA, 2014). Smart grid test projects are also in progress. The battery provides smoothing, peak shaving and frequency regulation in combination with 100 MW of wind power and 50 MW of solar (BYD Energy, 2011). An overview of the flow battery installation in China is presented in box 9.

Grid restrictions (particularly in the North), increasing wind and solar generation as well as changing demand patterns will drive battery and other types of electricity storage in coming years (Littlewood, 2013). Renewables must be connected to demand centres, and the Chinese grid must be expanded and made more flexible. Battery storage will play a role in achieving this in the short to medium term.

India, Italy and South Korea

Though not discussed in detail in this report, other notable countries include India, Italy (a case study is presented in section 4.3) and South Korea.

India's power system is growing by about 25 gigawatts (GW) per year, which is more than the total installed capacity in countries like Belgium or Austria. Furthermore, India has ambitious plans to accelerate the deployment of solar energy from the initial 20GW planned for 2022 to more than 100GW, and already has problems to transmit wind power from wind-rich states like Tamil Nadu and Gujarat. Finally, India has ambitious plans to provide access to the 43% of households that are not connected yet through decentralized and distributed renewable power generation (USAID, 2014). Battery storage is already popular in India with more than 100 million households using batteries as back-up in case of black-outs or load shedding. Furthermore, batteries provide an economical alternative to diesel-generators that are used for rural electrification, power

Table 3: Overview of battery storage projects in South Korea

Storage Type	Program/Owner	Capacity	Funding Source
Li-ion Battery ESS	2012 Smartgrid program	0.5	KSGI and End user
Li-ion Battery ESS	2013 Smartgrid program	5	KSGI and End user
Li-ion Battery ESS	2014 Smartgrid program	5	KSGI and End user
Li-ion Battery ESS	KEPCO Frequency regulation	52	KEPCO
Li-ion Battery ESS	Island projects	3	KETEP, KEMCO, Provincial Gov.
Li-ion Battery ESS	Samsung SDI	5.5	Samsung SDI
Li-ion Battery ESS	LG Chem	5	LG Chem
Li-ion Battery ESS	HHI	1	KETEP, HHI, Kokam
Li-ion Battery ESS	LSIS	2	LSIS
Li-ion Battery ESS	KPX FR	8	KETEP, KPX, Hyosung
Li-ion Battery ESS	KEPCO Jochun S/S	4	KETEP, KEPCO, Hyosung, Samsung SDI
Lead-acid	Woojin IS	0.5	Woojin IS
Lead-acid	KERI	0.5	
ETC(Li-ion, Lead-acid)	Jeju Smartgrid Demonstration	5	KSGI and Private
Total battery storage projects		97.0	

Source: ESS Committee of KSGA and Hyosung Corporation

supply to telecom towers[21], and to provide power supply (UPS) to industries during load shedding or peak hours[22].

Renewables growth in Italy, particularly from solar PV, is placing increased emphasis on battery storage for frequency regulation and power reserves. Solar PV meets around 8% of power demand in Italy. At the end of 2013, the country had the third greatest solar PV capacity in the world and the second greatest per capita (REN21, 2014). This has prompted Terna, a major transmission system operator, to begin procuring battery storage assets. So far, 51 MW have been approved for procurement, 35 MW of which will be in the form of sodium-sulphur batteries from NGK Insulators. These will be used for power reserve and transmission investment deferral (BNEF, 2013a). The other procured contracts are 5 li-ion projects, and two projects with ZEBRA batteries (BNEF, 2014c).

South Korea also has ambitious plans for energy storage. Electricity demand has grown fourfold from 1990 to 2012, especially due to growth by large industrial consumers. The country has 4.7 GW of pumped hydro to provide storage, but requires additional storage capacity to ensure power quality, save on frequency regulation payments to thermal generators, and integrate renewables. Already, South Korea announced funds for research, development and demonstration in 2011. Table 2 provides a list of some of the battery storage projects in South Korea. Additionally, there are a number of smaller projects in Korea's research institutes, as part of Korea's smart grid programme, and on some of Korea's islands.

The largest project is a 52 MW lithium-ion battery project (24 and 28 MW) to support the grid around Seoul. Many of the battery projects are using lithium-ion chemistries, given government support driving the market and the presence of domestic producers Samsung SDI, LG Chem, and SK Innovation (BNEF, 2013a). The country also aims to reach 2 GW of storage by 2020. It is too early to ascertain whether this target is over-ambitious.

21 In 2013, 9000 towers were operated with renewable energy (Scientific America, 2013)

22 Many Indian states charge higher prices for electricity consumed during peak hours in the range of 3.5-4 US cents per kWh.

6 SUMMARY AND CONCLUSION

The rapid growth in variable renewable energy, namely solar PV and wind, is catalysing efforts to modernise the electricity system. At high levels of penetration, variable renewable energy increases the need for resources that contribute to system flexibility. This ensures that system stability is maintained by matching supply and demand of electricity. Battery storage is one of the options for enhancing system flexibility in these circumstances by managing electricity supply fluctuations. Battery storage can also increase local penetration and self-consumption from small solar PV facility installed at commercial facilities and at households.

There are already hundreds of different suppliers providing battery storage systems, and renewable energy technology providers have started to integrate storage solutions into their rooftop solar PV systems and wind turbines. Though battery storage technology has made significant strides, several key concerns must continue to be resolved for the technology to achieve its potential. These include continued safety and performance improvement, continued cost declines, and the development of international standards for data presentation. Another problem is the availability of detailed project information. Safety concerns must be constantly evaluated, and novel, improved batteries must be researched, developed and demonstrated. Sustainability and access to component materials will also become increasingly important as the technologies become a more mainstream solution to grid flexibility. Non-traditional forms of flexibility like battery storage must be adequately compensated under governing regulatory structures to help modernise the electricity grid.

Government support has been a key driver for demonstration projects all over the world, and these have built a productive foundation of operational knowledge, data and industry participation. The U.S, China, Japan and Germany are leading the implementation of battery storage. Other countries, including Italy and South Korea, are following close behind. It is clear that increased variable renewable energy is one key driver everywhere as countries seek to improve system flexibility, maximise renewable resource feed-in and develop alternative technologies. The regulatory landscape in some countries is beginning to recognise the benefits of non-fossil fuel assets for grid stability. This is noticeable in the U.S, where recent rulings require remuneration for fast, accurate response in ancillary markets.

The report emphasizes that focusing on cost alone may be insufficient to accurately assess battery storage options. The application areas and case studies discussed in this report demonstrate that cost is just one of a large number of parameters determining battery choice. For islands, cycle life, ambient conditions (particularly temperature), installation infrastructure and maintenance requirements are likely key criteria for battery selection. For household solar PV integration, cost, space requirements, safety, maintenance and warranty issues are likely to be significant. For frequency regulation and variable renewable energy smoothing, short charge and discharge performance is important. Some instances of frequency response may also require significant power availability over a short period.

As the case studies and market analysis shows, the market for battery storage technologies has developed rapidly over the last couple of years. There is sufficient evidence to show that industry participants can deliver operational solutions for the applications discussed, as well as others throughout the world. Previously, the market for power sector battery storage was dominated by sodium-sulphur batteries made by NGK Insulators in Japan. This has shifted recently towards lithium-ion chemistries due to current cost, performance and safety advantages over other battery types. The shift has been incentivised by governmental support and the influence of other sectors. The overall market is set to expand dramatically in the coming decade. A variety of battery types and designs will remain active in various niches of the field. While lithium-ion is a popular battery at present, advanced lead-acid, flow batteries and less developed batteries have also made significant progress. A healthy diversity of options will remain given the versatility of battery technology in a variety of applications.

Given the preceding analysis and discussion, we conclude that choosing batteries to support renewable energy deployment is not a straightforward matter. In many places, dispatchable plants, interconnection and demand side management can already provide the necessary flexibility to accommodate even a significantly higher share of renewables. Though installations of batteries have increased dramatically, countries are still at the MW stage of deployment. Batteries are not a significant feature of most grids. Nevertheless, battery storage technology is an increasingly attractive solution. This is because more variable renewable energy is coming on stream, the technology's cost is declining and performance is continually improving. It is also more attractive if installations can be used simultaneously for multiple purposes that add value for the customer or grid. Examples include variable renewable energy integration, decentralised production and consumption of power and/or the provision of multiple ancillary services to the grid. The case studies in which a single installation is often used for more than one application demonstrate this. This enhances its benefit and value. If local market and regulatory structures value the services provided by storage and other non-fossil fuel flexibility assets, the benefit can accrue to storage operators.

The analysis in this report also demonstrates that the use of battery storage on islands and in remote areas presents one of the ripest applications for expansion. Diesel generation is costly and polluting, and fuel imports create supply risk. More renewable energy with batteries at the grid level and/or at the production site can decrease the necessity of diesel generation, increase clean renewable energy supply and enhance system stability. Project finance may be a particular problem in countries experiencing weak macroeconomic conditions. Nevertheless, finance options and new business models are expected to grow in coming years. For variable renewable energy smoothing and supply shift, government regulation on curtailment, negative pricing and predictable generation demand may be important drivers of deployment. Predictable generation requirements are particularly relevant to small island systems with weak interconnection. For example, in a number of French and U.S islands, regulators require renewables to adhere to strict production profiles that only allow for predetermined variation in output. This means that in most cases RE generation will have to be coupled to an energy storage technology, whereby batteries are the best storage technology from an economic and performance standpoint.

In addition to subsidies and consumer demand, the declining costs of solar PV systems and batteries are revolutionising this market. The combination of solar PV systems and batteries is still more expensive in many areas than retail electricity prices. However, this combination will become cost-competitive in some areas over the next few years in an environment of rising retail prices and falling FiTs. The initial increase in battery deployment with solar PV, spurred by innovative company products and government support, is encouraging. However, it will be important to consider how regulators and local utilities deal with this trend. Onerous regulatory barriers play a significant role in this market. They are as important as underlying economics and governmental incentives. If utilities and regulators were to compensate distributed resources for their contribution to grid stability, solar PV and storage would become even more financially attractive.

Another important battery storage application demonstrated in the preceding analysis is the ability to mitigate short-term imbalances in electricity supply and demand. This is achieved by regulation in ancillary markets. Improved regulatory structures have proved a significant catalyst in the U.S. where new regulations have specifically valued swift, accurate and responsive resources. This role has traditionally been fulfilled by fossil fuel plants. Batteries generally provide fast regulation more quickly and accurately than fossil fuel generators, because they can utilise more of their capacity than a fossil fuel plant. This helps decrease fossil fuel utilisation and increase variable renewable energy penetration while ensuring grid reliability.

In conclusion, batteries are already facilitating the transition towards a renewables-based power system in islands, rural areas and local households. Various projects around the world have also demonstrated that batteries are capable of supporting such a transition in larger interconnected networks. This report shows that cost reductions are not the only parameter that will determine the future deployment levels of different battery storage systems. Instead, the deployment and value of battery storage technologies for renewable integration will depend on the creation of an appropriate ecosystem with significant interplay between policy, regulation, business models, and consumers. For policy makers, it is important to pro-actively engage in the development of these ecosystems to ensure that batteries support the transition towards renewables while maximising value for society.

ANNEX A

Overview of technical characteristics for particular battery types

There are hundreds of different batteries available in the market today, and the technical characteristics and performance differ per technology, per manufacturer, and per supplier. Their discharge time ranges from one second to a day, while their capacity ranges from one kW to tens of MWs. Furthermore, there are variations within each technology depending on the voltage level, the desired depth-of-discharge, and maintenance and load requirements. Therefore, there is no single battery technology that serves a particular application, but rather a multitude of options depending on the decision criteria as outlined in Figure 4. Furthermore, there are a number of projects where batteries are combined to achieve the required functionality (the so-called hybrid storage solutions). For example, a battery storage system connected to a wind turbine park in Braderup combines a 2 MWh li-ion battery with a 1 Mwh vanadium redox flow battery.

Lead-acid batteries

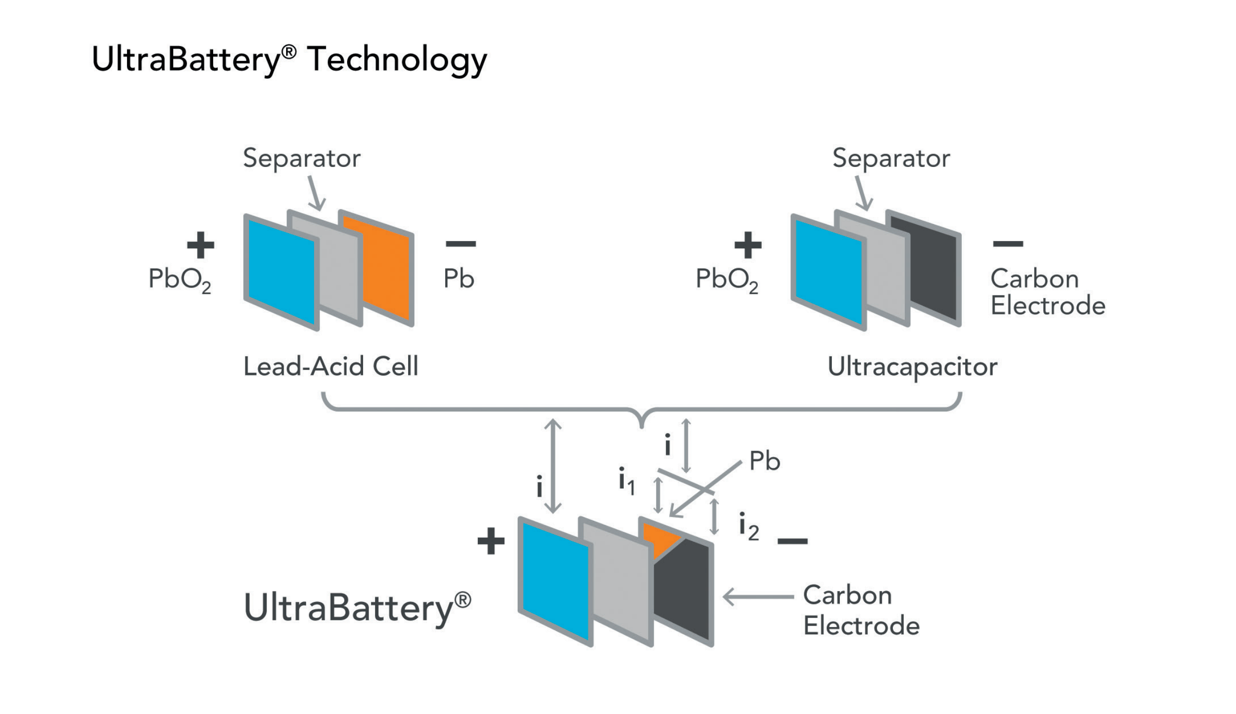
Lead-acid batteries are already deployed extensively to support renewables deployment. For example, between 1995 and 2009 Morocco deployed around 50 000 solar home systems coupled to batteries to provide rural electrification. In Bangladesh, already 3.5 million solar home systems are installed each coupled to a battery. In most cases, sealed valve-regulated lead-acid (VRLA) or flooded lead-acid batteries are used. The latter are cheaper, but require at least monthly maintenance to check and refill the battery with distilled water in case the water levels drop below the plates. Furthermore, they need to be operated in vented locations due to the production of flammable gases. The choice for VLRA versus flooded batteries does not only depend on their technical specifications, but also on the institutional framework, such as subsidy schemes or recycling requirements (Morris, 2009). Many lead-acid batteries still suffer from low depth of discharge (<20%), low cycle numbers (<500) and a limited life time of 3-4 years, also due to poor maintenance. Their energy density (around 50 Wh/kg) is generally lower than li-ion batteries. However, more recent versions can achieve 2 800 cycles at a 50% Depth of Discharge and ensure a service life up to 17 years for industrial systems (Garcia, 2013).

Advanced lead-acid

Lead-acid batteries are a mature technology that has been widely adopted given their relative cost advantage compared to other types. This is primarily in the conventional automotive market but also in the power market. The low-cost, traditional lead-acid option includes valve-regulated lead-acid batteries, which have been on the market since the 1960s, and advanced glass mat lead-acid. This has been commercially available since the 1980s (Jaffe and Adamson, 2013). These conventional batteries may still be appropriate in developing nations and emerging markets. However, they suffer from technical drawbacks, of which the main ones are short cycle life, slow charging and maintenance requirements. More advanced versions of this conventional form of battery are taking over (Navigant, 2014; EPRI, 2010, p. 4-7).

More recent advanced lead-acid options involve the use of carbon in one or both electrodes. These are being introduced by Ecoult/East Penn, Axion Power International and Xtreme Power (EPRI and DOE, 2013). The latter is a leader in advanced lead-acid battery installations that recently went bankrupt and was acquired by Younicos. However, this puts into question the status of Xtreme Power's advanced lead-acid battery, exacerbated by recent safety concerns. Axion Power's technology is called PbC®. It utilises the standard lead-acid composition's positive electrode along with an ultracapacitor negative electrode consisting of five layers (also referred to as a supercapacitor) made of activated carbon (Axion, 2014). The 'Ultrabattery' composition by Ecoult/East Penn is also based on a hybrid lead-acid and ultracapacitor design, but its negative electrode consists of only two layers as shown in Figure 1.

Annex A, Figure 1: Advanced lead-acid battery design – Ultrabattery



Source: Ecoult (2014)

The 'Ultrabattery' was developed by the Commonwealth Scientific and Industrial Research Organisation of Australia. This lead-acid composition uses an ultracapacitor which enables the battery to operate longer and more effectively in partial state of charge applications than traditional lead-acid batteries. This is achieved in two ways. First, the carbon-based ultracapacitor inhibits the sulphation that usually occurs in traditional lead-acid batteries. Sulphation is a process through which sulphate crystals grow on the negative electrode. They eventually become larger and do not fully dissolve during the charging process. This leads to greater internal resistance and decreased performance. Secondly, the battery operates at a lower state of charge than traditional lead-acid batteries. This means electrolysis, when water is split into oxygen and hydrogen, occurs less frequently. As a result, the positive electrode experiences less corrosion and dries out more slowly than conventional VRLA[23] batteries (Ultrabattery, 2014). The intention is to dramatically improve the performance and durability of the traditional lead-acid battery design.

23 valve-regulated lead-acid battery

This battery has been tested for hybrid vehicles but has been proposed and demonstrated for power sector applications including frequency response and smoothing (Ecoult, 2014).

Molten salt batteries

Sodium-sulphur batteries, sodium metal halide (also known as ZEBRA[24] batteries), and a number of other battery varieties use molten salt as an electrolyte, and therefore have to operate under high temperatures. Sodium-sulphur batteries are a relatively mature composition in the power market. They were demonstrated and used in Japan by utility Tokyo Electric Power Company and NGK Insulators in the late 1990s. They have been commercially available since 2002 (EPRI and DOE, 2003). The batteries operate at high temperatures – over 300°C. They are generally used for long periods of discharge lasting six hours or even longer given

24 Invented by the Zeolite Battery Research Africa Project (ZEBRA) at the Council for Scientific and Industrial Research in Pretoria, South Africa.

sufficient capacity (EPRI and DOE, 2013). Like lead-acid batteries, sodium-sulphur batteries have a limited cycle life. They are able to charge and discharge a limited number of times before substantially degrading (IEA, 2013b). Their advantage over flow batteries (see below) is that any degradation of the electrodes (ie. cracks) are automatically repaired every time the NaS electrodes are liquefied. They have an energy density of around 60 Wh per kilogramme (kg), a cycle life of 1500-3000 cycles and cost of around USD 600/kWh in 2014 (Jaffe and Adamson, 2014). The ZEBRA battery uses molten sodium aluminiumchloride as its electrolyte. Sodium-nickel batteries are produced by FIAMM SONICK and GE.

Lithium-ion

Lithium-ion batteries have a high energy density (energy in relation to volume) as well as power density (rate at which energy changes) compared to other batteries[25]. This allows them to take up minimum physical space while providing high energy and power. Density and power performance continue to improve, which makes them so popular for consumer electronic and power sector applications. They are also highly efficient – 80-90%. The batteries are best suited to relatively short discharge cycles of less than four hours (EPRI and DOE, 2003). Their high power and energy density mean they are ideal for frequency regulation and other applications requiring relatively short discharge and high power performance.

Lithium-ion batteries consists of a range of different chemistries, each with unique cost and performance characteristics. These can generally be grouped into two categories of cathode materials to complement lithium: iron phosphate and mixed metal (cobalt and manganese oxide) (Albright and Al-Hallaj, 2012). Titanate is an anode material that can complement lithium with relatively low energy density and very high cycle life, however also most expensive.

One of the greatest obstacles facing lithium-ion is safety. The energy density of the cells and combustibility of lithium, as well as the presence of oxygen, mean cells can overheat and catch fire. This can lead to a situation known as thermal runaway when neighbouring cells also overheat. This leads to leaks, smoke, gas venting and/or the cell pack coming alight. A variety of external conditions may cause this, leading to internal cell distress. These include for instance external

Annex A, Table 1: Lithium-ion subcategory characteristics

	Cathode	Anode	Electrolyte	Energy density	Cycle life	2014 price per kWh	Prominent manufacturers
Lithium iron phosphate	LFP	Graphite	Lithium carbonate	85-105 Wh/kg	200-2000	USD550-USD850	A123 Systems, BYD, Amperex, Lishen
Lithium manganese spinel	LMO	Graphite	Lithium carbonate	140-180 Wh/kg	800-2000	USD450-USD700	LG Chem, AESC, Samsung SDI
Lithium titanate	LMO	LTO	Lithium carbonate	80-95 Wh/kg	2000-25000	USD900-USD2,200	ATL, Toshiba, Leclanché, Microvast
Lithium cobalt oxide	LCO	Graphite	Lithium polymer	140-200 Wh/kg	300-800	USD250-USD500	Samsung SDI, BYD, LG Chem, Panasonic, ATL, Lishen
Lithium nickel cobalt aluminum	NCA	Graphite	Lithium carbonate	120-160 Wh/kg	800-5000	USD240-USD380	Panasonic, Samsung SDI
Lithium nickel manganese cobalt	NMC	Graphite, silicon	Lithium carbonate	120-140 Wh/kg	800-2000	USD550-USD750	Johnson Controls, Saft

Source: Based on Jaffe, S. and Adamson, K.A. (2014)

25 Energy density of about 120 Wh/kg for lithium-ion compared to 35 Wh/kg energy density for lead-acid.

heating, overcharging, overdischarging, and high current charging (Albright and Al-Hallaj, 2012). Design and thermal management integrating performance characteristics by limiting DoD, for example, must therefore be considered.

Flow batteries

Flow batteries are reaction stacks separated from one or more of the electrolytes held in external storage tanks. Either one or both active materials are in solution in the electrolyte at all times. Flow batteries have unique characteristics in terms of the power (rate at which energy changes) and energy (volume of energy) they provide. Power (in kW) is a function of the number of cells that are stacked, whilst energy (kWh) is a function of the electrolyte volume, which is circulated by pumps. Flow batteries are generally less affected by overcharge or discharge. This means they can be used without significant degradation of performance. This is even the case when using the majority of energy capacity (deep discharge) uncommon for most battery types and a distinct advantage for this type of battery. On the other hand, plumbing and pipework ads to the cost, and the electrolyte may be prone to leaks and must be contained (EPRI, 2003).

Membrane materials have up till now been susceptible to premature degradation and contamination and/or are expensive. Flow batteries are often used for storing and discharging long durations of energy supply (typically between two and 10 hours). Leading chemistries at the moment include vanadium redox and zinc bromine redox flow batteries. Vanadium redox flow batteries use one element in both external tanks. This is preferable because cross-contamination does not occur, unlike when two electrolytes are used (as in most redox flow batteries). The technology has in the past suffered from energy density limits. This is because the electrolyte, a sulphuric acid solution, becomes oversaturated and is also sensitive to temperature. Furthermore, expensive polymer membranes have been needed because of the acidic environment. Companies and government institutions are working on these problems (DOE, 2012b). Other upcoming chemistries, like hydrogen bromine or iron-chromium, promise to improve the state-of-art flow battery.

Additional types

While the batteries presented in the previous subsections are currently the most advanced in terms of research, development and commercialisation, other competitors are emerging. They include iron-chromium (flow battery), lithium NMC with silicon anodes, lithium-sulphur, solid electrolyte batteries, magnesium-ion and metal air batteries (Jaffe and Myron, 2014). Aqueous hybrid ion from Aquion is a novel battery that focuses on component sustainability. Aquion's battery solution is described in case study 5 in the addendum. Innovation is driven by the desire to improve safety, address material shortages, reduce cost, improve performance and increase the sustainability of batteries.

Battery data sheets

In order to illustrate some of the technical concepts presented in this report, a sample battery data sheet is reproduced in figure 2. This is for a Hoppecke Sun.power battery pack, a lead-acid battery intended for use by households for PV storage.

The data sheet in figure 2 presents basic information about a Hoppecke battery solution for household solar PV storage. It includes nominal capacity over a certain number of hours. C10 refers to ten hours of discharge. It also includes expected voltage at this rate of discharge and system dimensions. Calendar life, ten years, is indicated at the bottom of the sheet. Cycle life at various DoD is displayed. At deeper levels of discharge, cycle life decreases. This is presumably over the ten-hour discharge level. Cycle life at various temperatures is not described, though temperature will also play an important role. Different discharge times (C5, C3 *etc.*) are also absent though they may be available from the manufacturer. Efficiency is not noted. The data sheet provides some helpful basic information about the system, but actual system performance in various external conditions and for alternative applications will probably differ. Many battery vendors carry out independent tests.

Annex A, Figure 2: Sample battery data sheet, Hoppecke

HOPPECKE
POWER FROM INNOVATION

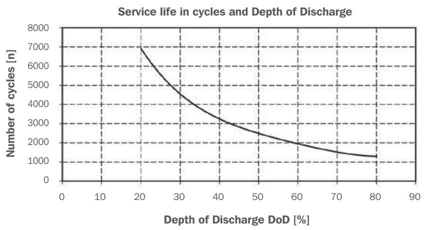
sun.power pack

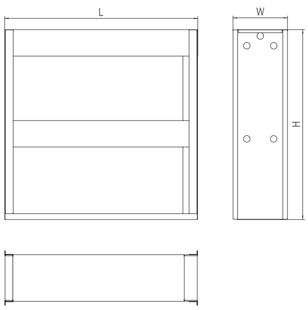
Type overview

Capacities, dimensions and weights

	Total energy content (C_{10}) **kWh**	Nominal voltage **V**	Type of battery*	Number of racks, Connection type	Block batteries **Pc**	Length L **mm**	Width W **mm**	Height H **mm**	Weight **kg**
sun.power pack 4.9/24	4.9	24	6 V 4 OPzV bloc solar.power 250	1	4	660	247	862	270
sun.power pack 4.9/48	4.9	48	12 V 2 OPzV bloc solar.power 120	1	4	660	247	862	325
sun.power pack 6.0/24	6.0	24	6 V 5 OPzV bloc solar.power 300	1	4	876	247	862	325
sun.power pack 7.4/24	7.4	24	6 V 6 OPzV bloc solar.power 370	1	4	876	247	862	360
sun.power pack 7.4/48	7.4	48	12 V 3 OPzV bloc solar.power 180	1	4	876	247	862	350
sun.power pack 9.8/24	9.8	24	6 V 4 OPzV bloc solar.power 250	2, parallel	8	660**	247**	862**	510
sun.power pack 12.0/24	12.0	24	6 V 5 OPzV bloc solar.power 300	2, parallel	8	876**	247**	862**	510
sun.power pack 12.0/48	12.0	48	6 V 5 OPzV bloc solar.power 300	2, serial	8	876**	247**	862**	620
sun.power pack 14.8/24	14.8	24	6 V 6 OPzV bloc solar.power 370	2, parallel	8	876**	247**	862**	670
sun.power pack 14.8/48	14.8	48	12 V 3 OPzV bloc solar.power 180	2, parallel	8	876**	247**	862**	690
sun.power pack 14.8/48	14.8	48	6 V 6 OPzV bloc solar.power 370	2, serial	8	876**	247**	862**	680

* maintenance-free gel battery for cyclic application
** In parallel and serial connection of 2 racks the dimensions are to be multiply by 2





Design life: 10 years

Optimal environmental compatibility - closed loop for recovery of materials in an accredited recycling system

IEC 60896-21
IEC 61427

[1] Back-up function is only possible with appropriate inverter

HOPPECKE
POWER FROM INNOVATION

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Source: Hoppecke (2014)

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