IRENA

Overview of Technical Characteristics for Batteries

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. 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

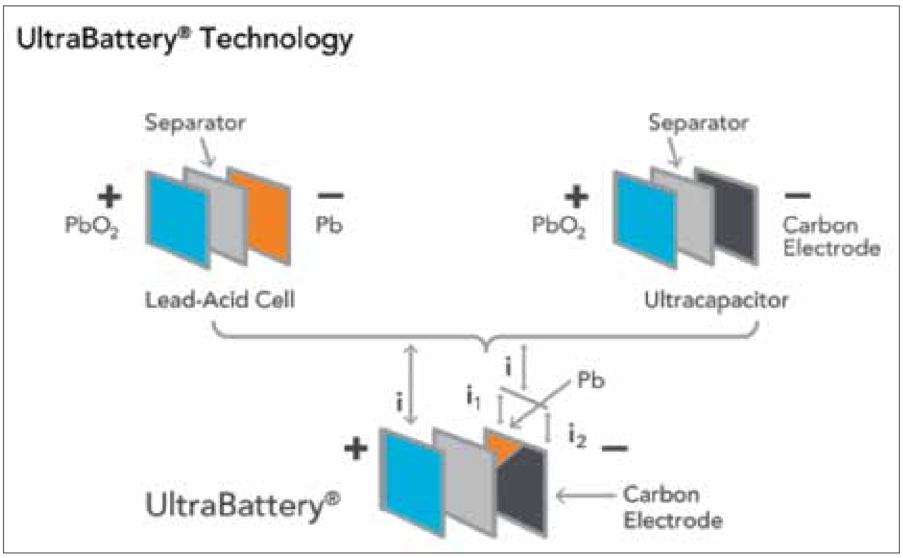
Lead-acid batteries are already deployed extensively to support renewables deployment. For example, between 1995 and 2009 Morocco deployed around 50 000 solar home systems coupled to batteries to provide rural electrification. In Bangladesh, already 3.5 million solar home systems are installed each coupled 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. 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.

More recent advanced lead-acid options involve the use of carbon in one or both



Lithium-ion subcategory characteristics.

electrodes. These are being introduced by Ecoult/East Penn, Axion Power International and Xtreme Power. 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 leadacid composition's positive electrode along with an ultracapacitor negative electrode consisting of five layers (also referred to as a supercapacitor) made of activated carbon. 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.

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 leadacid 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 VRLA23 batteries. The intention is to dramatically improve the performance and durability of the traditional lead-acid battery design.

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

Molten salt batteries

Sodium-sulphur batteries, sodium metal halide (also known as ZEBRA24 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. 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 sufficient capacity. 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. 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 1 500-3 000 cycles and cost of around USD 600/kWh in 2014. The ZEBRA battery uses molten sodium aluminium chloride 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 batteries25. 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

	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

Advanced lead-acid battery design –Ultra battery.

short discharge cycles of less than four hours. 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). 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 heating, overcharging, overdischarging, and high current charging. 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.

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.

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, lithiumsulphur, solid electrolyte batteries, magnesium-ion and metal air batteries. Aqueous hybrid ion from Aquion is a novel battery that focuses on component sustainability. Innovation is driven by the desire to improve safety, address material shortages, reduce cost, improve performance and increase the sustainability of batteries