Chapter 3

Characteristics of Storage Technologies

3-1 Overview of Energy Storage Technologies

Major energy storage technologies today can be categorised as either mechanical storage, thermal storage, or chemical storage. For example, pumped storage hydropower (PSH), compressed air energy storage (CAES), and flywheel are mechanical storage technologies. Those technologies convert electricity to mechanical energy.

Thermal storage technologies convert electricity into thermal energy (hot water, ice) for heating or cooling purpose, or absorb and store renewable heat and use the heat for power generation (concentrated solar power).

Batteries are chemical storage technologies using electro-chemical reaction to store (charge) or release (discharge) electricity. Chemical storage technologies also include hydrogen (although this has other applications besides energy storage).

Pumped storage hydropower is the most mature energy storage technology and has the largest installed capacity at present. However, given their flexibility and continuing cost reduction, batteries are rapidly increasing their share of the energy storage market. The choice of energy storage technologies to use depends on the technologies' characteristics vis-à-vis specific requirements from energy services.

In this chapter, the following terms and definitions are used:

Power rating (or rated output/size, kW) is the instantaneous demand requirement the storage module can supply.

Energy capacity (kWh) is the total amount of energy the storage module can deliver.

E/P ratio is the storage module's energy capacity divided by its power rating (= energy capacity/power rating). The E/P ratio represents the duration (hours, minutes, or seconds) the storage module can operate while delivering its rated output.

3-2 Characteristics of Selected Energy Storage Technologies

(1) Pumped storage hydropower

Pumped storage hydropower is a mature technology. It stores electricity in the form of gravitational potential energy. There are two reservoirs of different heights. When electricity demand is low, water is pumped from the lower reservoir to higher reservoir. During discharging, water is released from the higher reservoir to the lower reservoir, passing through turbine for electricity generation.

Until mid-2017, global PSH capacity was around 170 GW, which represents more than 95% of the total energy storage capacity. About half of the PSH capacity is in China (32.1 GW), Japan (28.5 GW), and the United States (24.2 GW).

At present, PSH is mainly used for time shifting of electricity energy; that is, storing electricity when demand is low (for example, during night time) and discharging when demand is high. Other applications of PSH are supply capacity firming and black-start. Traditionally, PSH is used to maximise the economics of nuclear or thermal power generation. However, with the expanding deployment of variable renewable energy technologies such as solar PV and wind, the use of PSH dedicated to RE is also increasing.

Pumped storage hydropower can discharge for tens of hours economically and is capable of providing energy storage for days or even weeks. However, PSH plants require a large area of land and a high initial investment. Due to its size and location constraints, PSH is usually not feasible as on-site energy storage for small-scale renewable power generation plants.

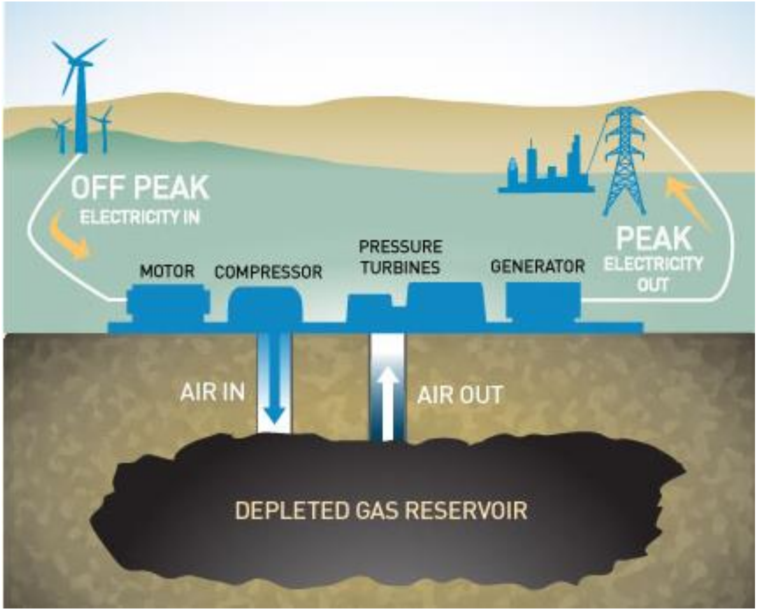
(2) Compressed Air Energy Storage (CAES)

Compressed air energy storage stores energy by compressing air in a cavern. In a CAES plant, ambient air is compressed and stored in underground caverns during off-peak periods, and the air is released to drive a gas turbine for electricity generation when electricity demand is high. Using existing suitable caverns such as depleted gas fields could significantly reduce the cost.

As of 2016, only two large-scale CAES plants are connected to the grid: one (290 MW) in Huntorf in Germany and the other (270 MW) in Alabama in the United States.

Similar to PSH, CAES is typically used for managing large amounts of energy. However, location constraints and high initial investment requirement limit CAES's applications.

Figure 3-1. Operation Mechanism of CAES



CAES = compressed air energy storage.

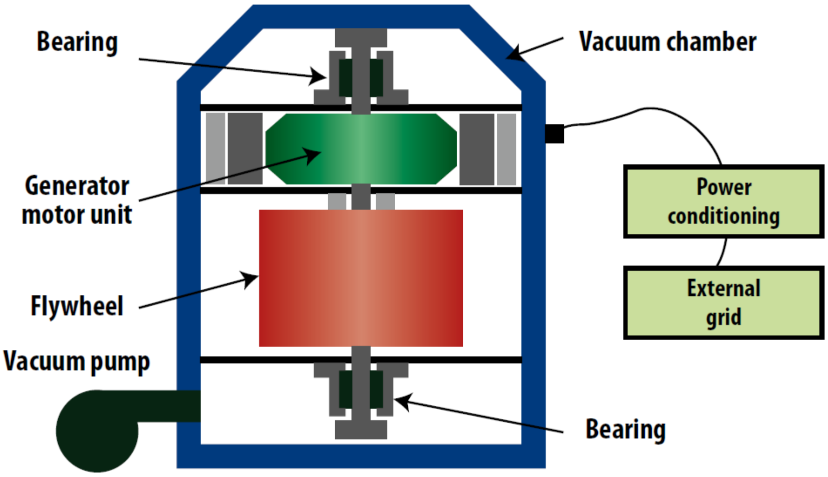
Source: Pacific Gas and Electric Company.

(3) Flywheel

Flywheels store energy in the form of rotational kinetic energy. The central part of the flywheel energy storage system is a rotating mass (flywheel). The rotating mass is accelerated during charging while the high-speed rotating mass will drive the generator motor during discharging. The energy that can be stored in the flywheel system depends mainly on the weight of the rotating mass and the speed at which it rotates.

Flywheel systems have very fast charging/discharging response and a high rated power. However, because of its high self-discharging rate, the discharge time at rated power for flywheels usually takes seconds long, which means that the energy density of flywheel is low. Given these characteristics, the flywheel is suitable for applications that require high response speed and high power such as frequency response. Applications like energy shifting, which requires higher energy density (i.e. longer discharge time at the rated power) is not the match for flywheels.

Figure 3-2. Flywheel Energy Storage System



Source: IRENA (2017).

(4) Ice storage

Ice storage keeps electricity in the form of cold energy. When electricity demand is low, the ice storage system uses electricity to produce ice that can be used for space cooling. Using stored ice for cooling could help save the fuel that would otherwise be consumed for cooling purpose.

Ice storage is a demand-side energy management measure for energy shifting in buildings. Ice storage is typically employed to produce ice during midnight, when electricity price is low; and to cool the building during daytime, when electricity tariff is high. Since the output of solar PV peaks during daytime, the combination of solar PV and ice storage is only economically suitable for buildings that have a cooling demand during the night or early in the morning (for example, households in tropical regions).

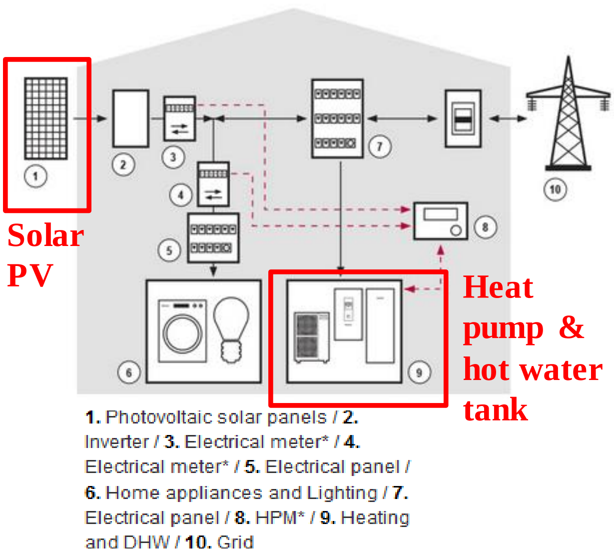
(5) Hot water storage

Electricity can also be stored in the form of hot water, which will require an electric water heater and a water tank. The electric water heater can be traditional electric resistance water heaters or heat pump water heaters.

Heat pump water heaters can use a small amount of power to move a larger amount of thermal energy for space heating, space cooling, and/or water heating. They use electricity to move heat from one place to another rather than generating heat directly and is more efficient than traditional water heaters using electric resistance.

Combining solar PV with heat pump (i.e. with hot water tanks) can not only provide clean electricity for buildings but also reduce the buildings' energy demand for heating. In particular, heat pump water heaters with hot water tanks can store huge solar power during the daytime and help improve the self-consumption rate of rooftop solar PV panels.

Figure 3-3. Example of Solar PV and Heat Pump System for Home Energy Supply

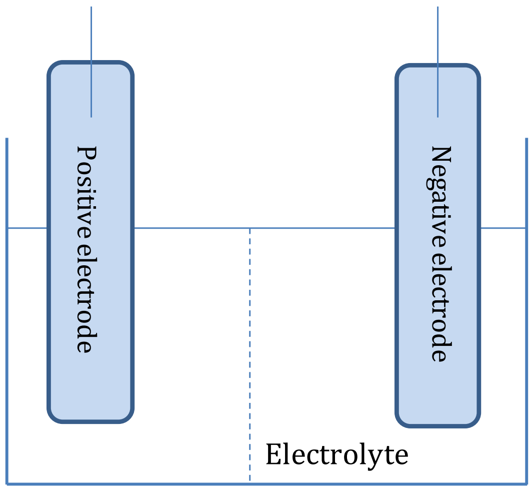


Source: Panasonic website.

(6) Batteries

The basic structure of batteries consists of a negative electrode (cathode), a positive electrode (anode), and the electrolyte. In its electro-chemical reaction, electrons (–)/ions (+) moving between the two electrodes pass through the electrolyte. Charging and discharging represent opposite direction of the electrons (–) or ions (+)'s movement. Batteries in the market vary based on their material and the design of the cathode, anode, and electrolyte. They vary significantly in characteristics such as energy density, power density, life span, safety, and cost.

Figure 3-4. Basic Structure of Batteries



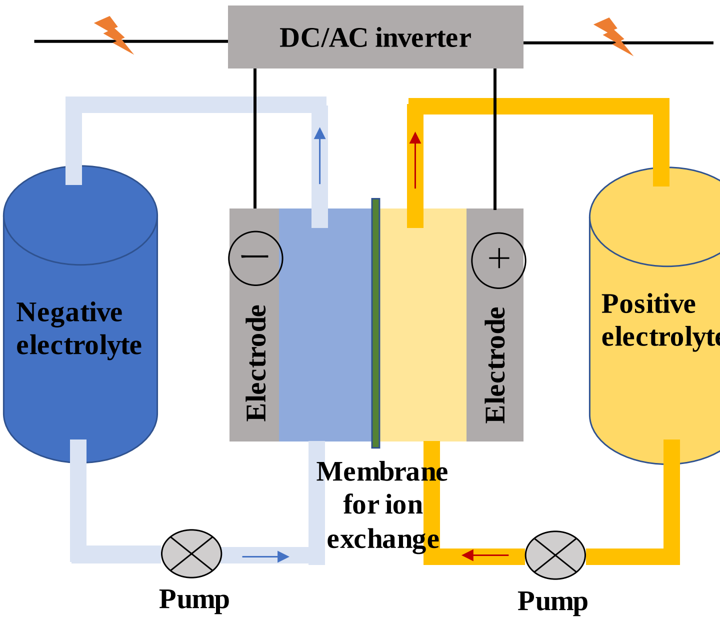
Source: Authors.

Lead-acid batteries are the oldest and most widely deployed rechargeable battery. Their installation cost is the lowest amongst all the current battery technologies. However, the energy density of lead-acid batteries is relative low, and the cycle life is shorter than most other types of batteries.

Given its high energy density, Lithium-ion (Li-ion) batteries are widely used in consumer electronics. In recent years, Li-ion battery installations have seen rapid growth in other fields such as electrical vehicles and stationery storage. Besides having a high energy density, Li-ion batteries also exhibit advantages such as high power density, good round-trip efficiency, relative long lifetime, and low self-discharge rate. However, issues with Li-ion batteries such as thermal stability and safety still persist.

With the increasing need to maintain the grid's stability as more variable REs connect to grids, batteries with large capacity such as flow batteries are also emerging in the market. Unlike traditional battery designs, which hold the electroactive materials at the electrodes, flow batteries store electroactive materials in the electrolyte solutions (Figure 3-5). Since the electrolyte and electrodes are separately stored, the energy capacity and rated power of flow batteries can be adjusted independently according to the specific requirement of the application.[2] Flow batteries can provide large energy capacities for large-scale applications and have longer cycle lifetimes than other technologies. However, the round-trip efficiency of flow batteries is lower than that of Li-ion batteries. Also, the system design of flow batteries is more complex.

Figure 3-5. Mechanism of Flow Battery



Source: Authors.

High temperature batteries – where the NaS battery and $NaNiCl_2$ battery (also known as ZEBRA) are the best-known commercial types – are also being used for grid services. High temperature batteries have an energy density higher than that of flow batteries but still lower than the average level for Li-ion batteries. They have installation costs that can compete with that of Li-ion batteries and longer cycle lifetimes than most Li-ion batteries.

(7) Hydrogen

Renewable electricity can be absorbed by producing hydrogen through water electrolysis. Hydrogen is a promising option for large-scale, long-term, and seasonal renewable storage.

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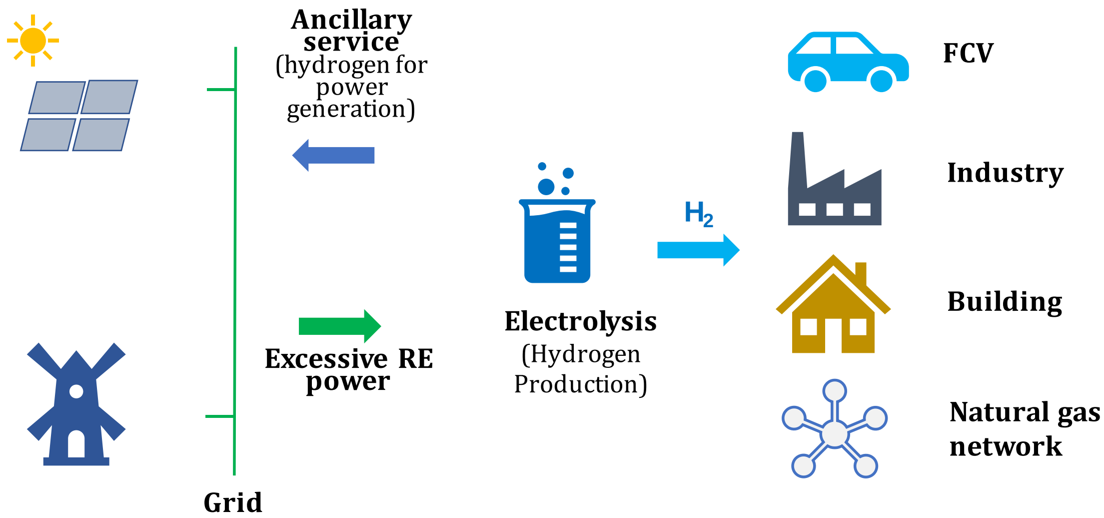
[2] The rated power can be scaled by increasing the electrode surface, while the energy capacity can be expanded by increasing the volume of electrolyte in the tank.

Since hydrogen does not emit carbon at usage, it has the potential to replace fossil fuel in many final energy applications such as transportation (Fuel cell vehicles, industries (both as industrial gas and as fuel), and heating for buildings. Hydrogen can also be injected into natural gas pipelines (up to a certain percentage) and is used for power generation either through fuel cells or hydrogen turbine (note: not commercialised yet).

With the increasing deployment of variable renewable technologies, the concept of 'power-to-gas' (Figure 3-6) as an energy of the future is drawing much attention. Pilot projects are underway in Japan, Europe, and the United States. However, the power-to-gas concept of the future requires technology breakthrough, commercialisation and cost reduction, and new infrastructure to be in place before it can be realised.

Figure 3-6. Image of Power-to-Gas System



Source: Author.

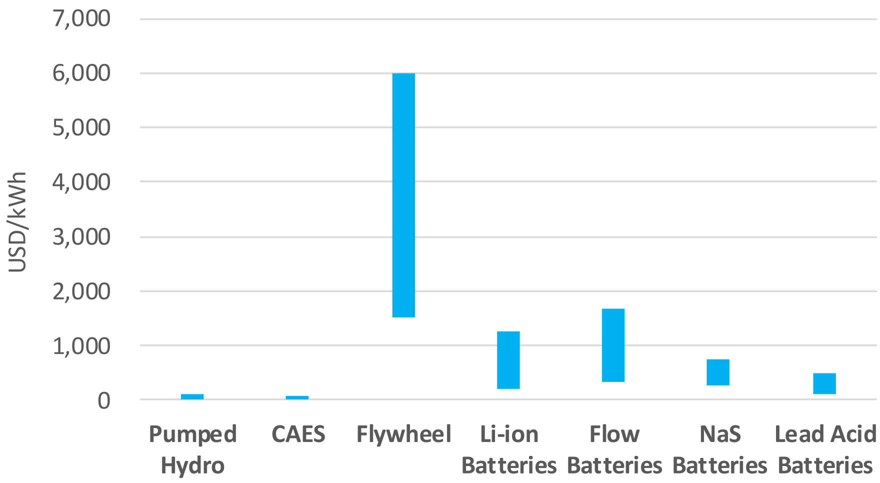
3-3 Overview of Cost and Characteristics of Various Energy Storage Technologies

(1) Cost

Data on installation costs of various storage technologies are well documented (Figure 3-7). However, that of the levelised service cost (i.e. the cost per kWh of power generation) is dependent on the cycle lifetimes of the storage technology and its operational pattern.

Pumped storage hydropower stands out as the technology with the lowest unit installation cost (US$/kWh).[3] Its scale, however, is usually bigger than other technologies, which means that the total initial investment requirement per project using pumped storage hydropower is very high.

Figure 3-7. Unit Installation Cost of Various Storage Technologies as of 2016



Source: Compiled by author based on IRENA (2017).

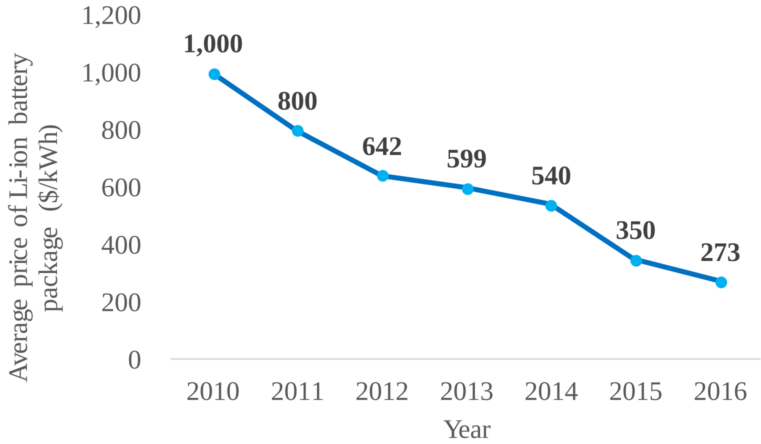
Prices of batteries, especially Li-ion batteries, have seen steep cost reductions in recent years (Figure 3-8). Such cost reduction is expected to continue in the future (Figure 3-9), driven by performance improvements, learning effects as well as economies of scale.

(2) Overview of characteristics of various energy storage technologies and applications

Different energy storage technologies are suitable for distinct applications. For example, when mapping various energy storage applications (stationery) and technologies by power capacity and discharge duration (Figure 3-10), one can see that while battery is suitable for various applications and almost have no site constraints, it is unable to provide inter-seasonal or seasonal energy storage. Hydrogen is the only technology that can hold seasonal energy storage.

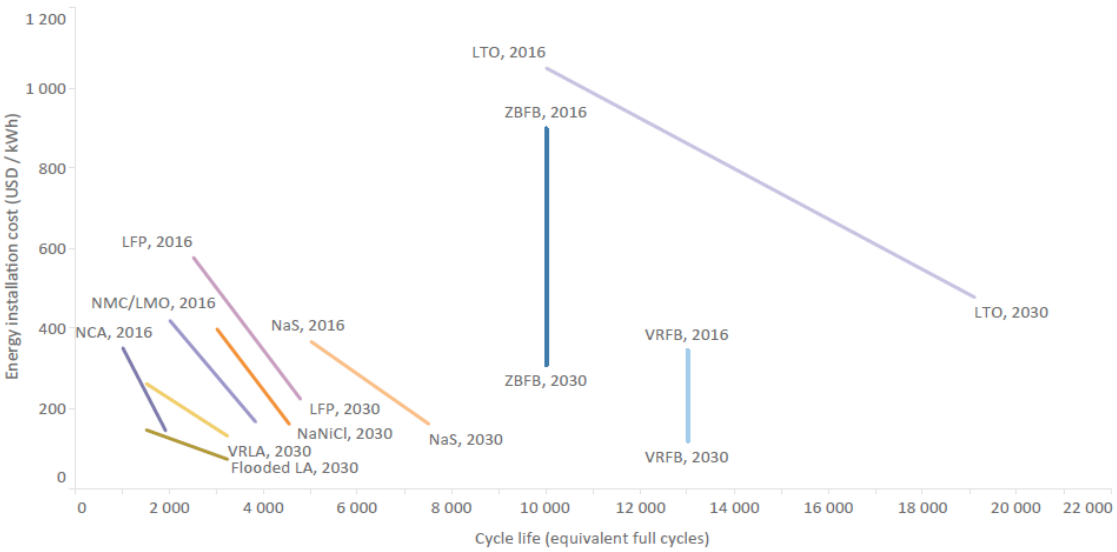
[3] 'kWh' here represents the capacity of energy storage rather than power generation.

Figure 3-8. Price Reduction of Li-Ion Battery From 2010 to 2016



Source: Bloomberg New Energy Finance (2017)

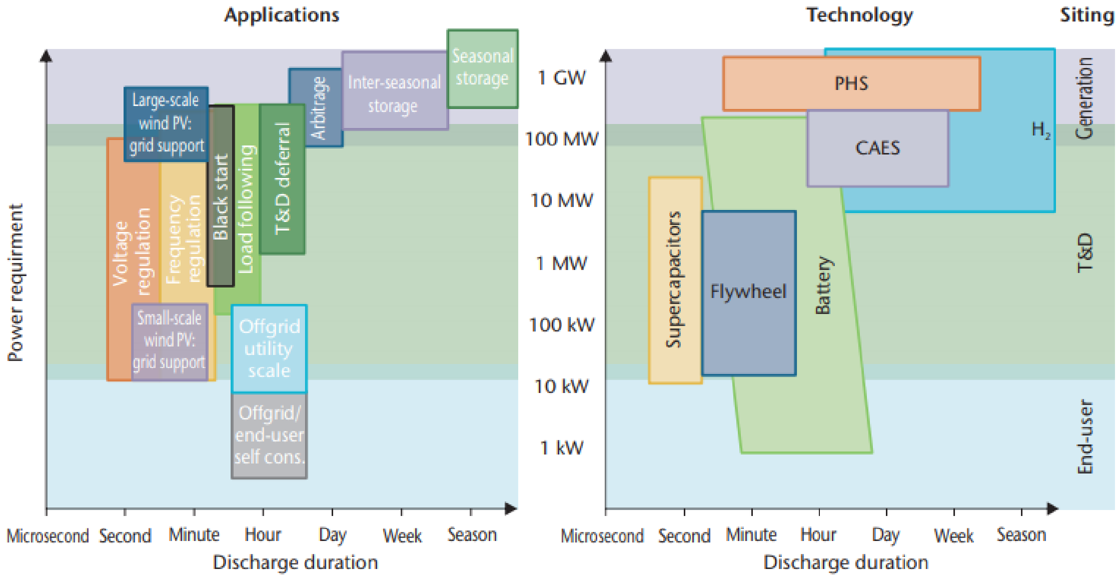
Figure 3-9. Cost Reduction and Cycle Life Improvement of Various Battery Technologies Through 2030



Note: Li-ion battery sub-technologies: NCA=nickel cobalt aluminium, NMC/LMO=nickel manganese cobalt oxide/lithium manganese oxide, LFP=lithium iron phosphate, LTO=lithium titanate; Flow battery sub-technologies: VRFB=vanadium redox flow battery, ZBFB=zinc bromine flow battery; High temperature battery sub-technologies; Lead-acid battery sub-technologies: VRLA=valve-regulated lead-acid, Flooded LA=lead-acid.

Source: IRENA (2017).

Figure 3-10. Mapping of Energy Storage Applications and Technologies by Power Capacity and Discharge Duration



Source: IEA (2015).

The choice of energy storage technology for a specific energy service need depends on many factors, including technology suitability, cost, service lifetime, space and location constraints, and safety considerations. For example, for mobile and consumer electronics application, high-energy capacity in a compact space is required, which means batteries with high energy density (kWh/litre) is preferable – even if it sometimes means a tradeoff with cost.

Besides discharging duration and cost, other characteristics of select storage technologies featured in this report are summarised in Table 3-1.

Table 3-1. Summary of Other Characteristics of Selected Storage Technologies (2016)

Storage technology	Round trip efficiency	Cycle life (full cycles)	Energy density (kWh/litre)	Self discharge (%/day)
Pumped storage hydro	80%	50,000	2	0.01
CAES	60%	50,000	2~6	0.5
Flywheel	84%	200,000	20~200	60
Li-ion batteries	>90%	1,000~10000	200~735	0.05~0.2
Flow batteries	70%	10,000~13,000	15~70	VRFB: 0.15 ZBFB: 15
NaS batteries	80%	5,000	140~300	0.05
Lead-acid batteries	80%	1,500	50~100	0.09

VRFB = vanadium redox flow battery; ZBFB = zinc bromine flow battery; CAES = compressed air energy storage; NaS = sodium sulphur.

Source: Compiled by author based on IRENA (2017).