Comparative Study of Energy Storage Systems (ESSs)

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Abstract. Renewable energy (RE) resources have shown impressive growth globally, as these sources do not provide enough amount that is readily adaptable to consumer needs, it can rarely allow an immediate response to demand. However, intermittency in RE supply (RES) sources, combined with fluctuating demand shifts over time, has caused a high risk of sustaining system reliability to provide customers with sufficient supply. The excess energy produced by RESs can be stored in a myriad of ways and used later during shortages or intermittent periods. This study was carried out to understand how to provide energy storage to create a future built environment where RE systems play an essential role. There are different types of a storage system with different characteristic, parameters, and costs. This paper highlights the chronology, classification, characteristic, comparison, and assessment of ESSs and energy storage systems deployment.

1. Introduction

Engineers and policymakers are increasingly focusing on energy storage due to rising attention about the environmental consequences of fossil fuels and the efficiency and durability of energy grids worldwide. In fact, energy storage can help resolve the intermittent nature of wind power and solar; in some instances, it can also respond quickly to significant demand changes, make the grid reacting quickly and minimize the need to install backup power plants. An energy storage facility’s efficiency is determined by how rapidly it can respond to demand changes, its total capacity to store energy, the rate of energy lost in the storage process, and how easily it can be recharged.

Solar PV only supplies power throughout the day with the peak. Total production is different every day. Wind production is unpredictable but can be distributed 24 hours per day. However, average performance can vary dramatically; for example, in one region of Germany alone, there can be almost 20 GW change over a day [1]. Intermittent growth in renewable energy leads to challenges in maintaining the balance within supply and demand. The closure of conventional power plants decreases the frequency control capability, which is why energy storage is needed.

Energy storage can also satisfy the need for electricity at peak times, i.e., when air conditioners blast during summer time or when households turn on the lights and appliances at night. As power plants need to scale up production to meet the increased energy use during peak times, electricity becomes more costly. Energy storage provides higher grid efficiency because utilities can purchase electricity at off-peak hours when energy is cheap and sell it to the grid when it is more in demand [2].
2. Overview of Energy Storage Systems

2.1. Chronological order of Energy Storage Systems

The processes of electro-chemicals energy storage started to develop very rapidly in the late 19th century. In 1749, American scientist Benjamin Franklin first used the word "battery" as he was doing experiments with electricity using a set of linked capacitors. The Italian physicist Alessandro Volta invented the first real battery in 1800 [3].

Table 1. Chronological order of ESS

| Year  | Types of battery | Description | Ref |
|-------|------------------|-------------|-----|
| 1800  | Volta cell       | The invention of the first battery led to the Volta cell, which used a brine solution as an electrolyte and had alternating copper and zinc discs divided by cardboard. | [7, 8] |
| 1836  | Daniel cell      | Regularly identified as a zinc-copper battery that takes advantage of a porous barrier between two electrolytes, the Volta cell developed into the Daniel cell. John Frederic Daniell, a British chemist, invented the Daniel Cell. | [9] |
| 1866  | Leclanche cell   | Daniel cell transforms into a Leclanche cell invented by a French engineer containing an ammonium chloride conducting solution: the electrolyte, a negative zinc terminal and a positive manganese dioxide terminal. | [10] |
| 1859  | Lead-acid        | The first rechargeable battery based on lead-acid was invented by the French physician Gaston Planté, a still used device. They were all primary batteries until then, meaning they were not typically rechargeable. | [7, 8] |
| 1899  | Nickel-cadmium (NiCd) | The nickel-cadmium (NiCd) battery using nickel as the positive electrode (cathode) and cadmium as the negative electrode (anode) was invented by Sweden’s Waldemar Jungner. | [11] |
| 1901  | Nickel-iron (NiFe) | Thomas Edison replaced cadmium with iron, which was called nickel-iron (NiFe). | [8, 11] |
| 1967  | Nickel-metal hydride, NiMH | Nickel-metal-hydride development began in 1967. It acts as a substitute for NiCd because it only has mild toxic metals and provides higher specific energy. | [12] |
| 1980  | Li-ion           | American physicist John Bannister Goodenough invented the lithium-ion nervous system. | [13] |
| 1980  | Lithium-polymer  | The lithium-polymer battery invention came in the 1980s. Sony integrated Goodenough’s cathode and a carbon anode into the world’s first commercial lithium-ion rechargeable battery in 1991. | [14] |
| 1954 - latest | Solar fuel | Solar fuels, inspired by environmental concerns, have recently gained interest. This is still under development and study. In the 1950s, Bell Laboratories discovered that semiconducting materials were more powerful than selenium, such as silicon. They succeeded in making a solar cell that was 6percent efficient. The brains behind the silicon solar cell at Bell Labs were inventors Daryl Chapin, Calvin Fuller and Gerald Pearson. | [15] |

These first measures were identified with the names of Luigi Galvani (1737-1798) and Alessandro Conte di Volta (1745-1827), which remain in history through the words we use today: "galvanic element" and "volt". Galvani found that if death meets various metals, a frog leg begins to move. On the contrary, Volta studied the outcomes obtained when certain
salt solutions are inserted into various metals. The lead/acid/lead dioxide (lead-acid battery) mechanism will not be found without these tests [4]. Table 1 shows the chronology of the energy storage system.

2.2. Comparison and characteristic of Energy Storage System
Therefore, it is crucial to critically analyze the fundamental characteristics of ESSs to create benchmarks for selecting the best technology. These ESSs can also be defined by their technical specifications, i.e., max power rating, discharge time, energy density and efficiency. Table 2 concentrates in ESSs currently proficient of giving critical storage capacities of at least 20 MW. A glossary of technical data ESSs is given to help any beginner clearly understand the characteristics [5,6].

|                                | Max Power Rating (MW) | Discharge time | Max cycles or lifetime | Energy density (watt-hour per liter) | Efficiency |
|--------------------------------|-----------------------|----------------|------------------------|--------------------------------------|------------|
| Pumped hydro                   | 3,000                 | 4h-16h         | 30-60 years            | 0.2-2                                | 70-85%     |
| Compressed air                 | 1,000                 | 2h-30h         | 20-40 years            | 2-6                                  | 40-70%     |
| Molten salt                    | 150                   | hours          | 30 years               | 70-210                               | 80-90%     |
| Li-ion battery                 | 100                   | 1min-8h        | 1,000-10,000 years     | 200-400                              | 85-95%     |
| Lead-acid                      | 100                   | 1min-8h        | 6-40 years             | 50-80                                | 80-90%     |
| Flow battery                   | 100                   | hours          | 12,000-14,000 years    | 20-70                                | 60-85%     |
| Hydrogen                       | 100                   | min-week       | 5-30 years             | 600(at bar)                          | 25-45%     |
| Flywheel                       | 20                    | secs-mins      | 20,000-100,000 years   | 20-80                                | 70-95%     |

**Max power rating (MW or kW):** Max power rating for a storage system determines the rate of energy storage in the storage medium. It is also commonly determined as average value and a peak value that is often used to indicate maximum power, $P_{max}(W)$.

**Discharge time (energy per unit):** The amount of time taken to fully discharge energy at its rated power by the storage system is called discharge time. The maximum-power for the duration of the discharge, $\tau(s) = Wst/P_{max}$, where $Wst$ is total energy stored and $P_{max}$ is maximum discharge power.

**Max cycles / Lifetime (cycles/years):** The lifetime for a storage system is to estimate its performance and be specified as the number of years according to its rated capacity and rated power.

**Energy density (kWh/L):** The amount of energy that can be contained in the storage material per unit volume is referred to as the energy density.

**Efficiency (%):** The ratio between energy that the ESS discharged and the amount of energy contained in it is referred to as the ESS discharge efficiency. The ratio of released energy and stored energy is $n = W_{ut}/Wst$, where $W_{ut}$ is usable released energy and $Wst$ is total energy stored.

2.3. Classification of ESSs
The growing need for energy storage has pushed into a never-ending effort to find new storage system solutions that are more effective and cater to specific requirements. There are many types
of ESS technologies coexisting and can be classified on the basis of their particular functions, response time, the form of energy stored, storage duration and etc., [5]. The energy storage system may be used for a range of applications. Some of them may be precisely selected for a particular application. On the other hand, some others are the framework in question in a broader framework.

The ESS classification is broadly determined based on the form of converted energy. Energy can be converted either in the form of thermal, chemical, mechanical, or electrochemical energy or magnetic or electrical fields. Figure 1 illustrates the ESS’s classification.

![Figure 1. The classification of energy storage systems.](image-url)

### 3. Comparison and Assessment of ESSs

Many studies have been performed specifically for the purpose of drawing up a thorough comparison between the various types of ESS.

#### 3.1. Comparison between power density and energy density

Figure 2 shows the comparison of ESS technologies between energy density and power density. When the density of energy and power is more significant, the storage system’s volume is lower. On the top right, highly dense ESS technologies which are ideal for mobile applications. The extensive and high-volume storage system is located at the bottom left. Flow batteries, CAES and PHS, have a low energy density and are extensive area. The volume of it consumes more storage systems. On the other hand, Li-ion batteries have a large energy density and a high-power density, so Li-ion is currently used in many applications.
3.2. Comparison between the system power rating and discharge time

Figure 3 shows the application of the ESSs generally classified into large, medium, and small scales based on the discharge time at rated power and power rating.

Electrochemical storage systems such as lithium (Li-ion), lead-acid and NaS batteries are primarily appropriate for applications with a medium discharge time of minutes to hours. For a short discharge time at rated power applications, all technologies for high-power storage such as Flywheels, Supercapacitor and SMES are suitable. PHS and CAES are located between medium discharge times of storage system and large scale for discharge times at rated power.

ESSs currently available for use in applications involving power quality are Supercapacitors, Ni-Cd, lead-acid battery and Li-ion battery, and Flywheels also appear to be a promising system for those applications.

3.3. Comparison of life expectancy and efficiency of energy

Figure 4 represents the comparison between life expectancy and energy efficiency of ESSs. Before choosing a storage technology, this two-parameter is vital to consider, among others, as it affects the total storage costs.

Both ESS high-power technologies, i.e., Flywheels and EC Capacitors, are distinguished by their performance, ranging from 90-95% and 84-97%, respectively. Currently, diabatic CAES systems have a low efficiency of less than 55%. However, the new adiabatic CAES plant is presumed to achieve an efficiency of around 70% [16]. Li-ion batteries have the highest efficiency of the electrochemical storage system, estimated to be over 90% or even 97%. PHS systems will run at 70-87% efficiency, and the use of an adjustable speed machine can increase efficiency in the future.

Life expectancy can be given either in cycles or years for ESSs. In traditional battery
technology, lead-acid batteries in the order of 2000 cycles have the longest cycle life. However, more cycles can be reached by Li-on and NAS than lead-acid batteries. CAES, PHS and flywheels are technologies with a very long-life cycle of between 10,000 and 30,000 cycles, while
EC Capacitors are about 100,000 cycles [5].

3.4. Comparison of the investment cost of ESSs
The investment costs of ESSs are compared in Figure 5. Storage-related investment costs are a significant economic parameter and impact the overall cost of energy production. Hence, certain types of storage systems can only become profitable if supplied with a certain minimum of resources. To achieve a precise cost analysis, the total cost of the system must be appraised.

Figure 5. Comparison between Capital Cost per Unit Energy and Capital Cost per Unit Power [6].

Concerning the capital cost per unit of energy, EC capacitors and high-power flywheels have the greatest investment cost of some thousand \$/kWh. At the same time, metal-air batteries are the lower-priced storage option. CAES also have a meagre cost for the storage system. Long-duration flywheels, Li-ion and the zinc-air battery are most-costly technologies in the capital cost per unit power. Apart from long-duration EC capacitors and high-power flywheels, high-power EC capacitors are the most affordable.

Data in 2018 and prediction in 2025 for cost and parameters (power conversion system, capital cost–energy capacity, the balance of plant, construction and commissioning) ranges by technologies is shown in Figure 6 [18].

3.5. Comparison based on specific power and energy
Between technologies for high-power, the capacitor has the highest specific power of more than 100,000 (W/kg), while TES is the lowest specific power which is 10-30 (W/kg) [5]. In the range of 800-10,000 (Wh/kg), the fuel cell exhibits exceptionally high specific energy. Higher specific energy gives an impact on storage weight. Figure 7 shows the comparison between specific power and energy.
Figure 6. Overview of the 2018 data and 2025 forecasts compiled by technology for parameter ranges [18].

Figure 7. Comparison between specific power and energy.
4. Deployment of ESSs
For the first-ever in ten years, the global storage market is diminishing. In 2019, electricity systems worldwide had added 2.9 GW’s storage capacity, nearly 30% lower than in 2018. The reasons behind this bottom-line mark how much storage, present in just a few key markets and profoundly reliant based on policy support, continues as an early-stage technology. However, if adequately deployed, energy storage provides system operators with flexible and quick response capability to efficiently manage generation and load variability. ESSs have recently undergone an accelerated decrease in cost, reflecting the learning crescents seen over the past decade from wind and solar generation.

The installment of energy storage has started to gain market popularity over the last few years. Figure 8 shows the IEA’s current data, which illustrates the stride of battery energy storage deployments, except in 2019. 2016 is the first year in which the annual deployment for energy storage has reached 1 GW. In Korea, annual deployments decreased by 80 per cent after the 2018 reporting year when Korea accounted for one-third of all installed capacity globally. The decrease arose from increasing concern in 2018 over multiple fires at storage plants in a grid-scale. While a large-scale review of the fires and safety measures was carried out, in 2019, five more fires broke out. The co-location of RE generation facilities with energy storage assets, which helps stabilize generation and assures more robust capacity during high demand times, has been a critical driver of energy storage growth. Large-scale auction with a 1.2 GW of solar-plus-storage, India expressly started rewarding this application in 2019, require the storage capacity for 50% of the installed generation. Singapore has declared a goal for 2025, which is 200 MW of storage. IHS Markit’s Energy Storage Business, a global information provider headquartered in London, records global installations rising by more than 5 GW in 2020 [20]. The other substantial potential implementation of ESS is in the mobile communication area. The studies

Figure 8. The 2013-2019 annual deployment of ESS by the country [19].
in [21–28] consider cloud radio access network (C-RAN), where the remote radio heads (RRHs) are equipped with renewable energy resources and can trade energy with the grid. However, in their proposed systems, RRHs are not installed with frequently rechargeable storage devices. ESSs can be installed at the master base station (MBS) in the C-RAN or can be employed at the RRHs with the advancement of battery technologies. The self energy storage management is expected to control unequal local renewable energy generation to match the energy request by receiving terminals that always change over time.

5. Conclusion

Viewing the previous work on ESSs and the reliability of the power grid, this paper covers a great deal of critical knowledge on ESSs. The world is obliged to be enticed further towards ESSs to move towards renewable energy sources, which will need a full understanding of this technology’s perspectives. Several types of technical parameters have been compared, which will encourage a specific type based on the main specifications. A brief insight has been presented about the annual deployment of ESS. The most appealing solution and long term for other storage systems competing today might not always be the ESS. However, this implies that even if the flexibleness’s investment signals are currently lacking, assessing the regional and country potential will be important in the long term.

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