Journal of Energy Storage 39 (2021) 102591

Contents lists available at ScienceDirect

Journal of Energy Storage

journal homepage: www.elsevier.com/locate/est

Empowering smart grid: A comprehensive review of energy storage technology and application with renewable energy integration

Kang Miao Tan [a,*], Thanikanti Sudhakar Babu [b], Vigna K. Ramachandaramurthy [a], Padmanathan Kasinathan [c], Sunil G. Solanki [a], Shangari K. Raveendran [a]

[a] *Institute of Power Engineering, Department of Electrical Power Engineering, College of Engineering, Universiti Tenaga Nasional, 43000 Kajang, Selangor, Malaysia*
[b] *Department of Electrical and Electronics Engineering, Chaitanya Bharathi Institute of Technology (CBIT), Hyderabad, 500075, India*
[c] *Department of Electrical and Electronics Engineering and Center for Research and Development, Agni College of Technology, Thalambur, Chennai, Tamil Nadu 600130, India*

ARTICLE INFO

Keywords:
Energy management
Energy storage system
Microgrid
Renewable energy
Smart grid

ABSTRACT

The rapid growth in the usage and development of renewable energy sources in the present day electrical grid mandates the exploitation of energy storage technologies to eradicate the dissimilarities of intermittent power. The energy storage technologies provide support by stabilizing the power production and energy demand. This is achieved by storing excessive or unused energy and supplying to the grid or customers whenever it is required. Further, in future electric grid, energy storage systems can be treated as the main electricity sources. Researchers and industrial experts have worked on various energy storage technologies by integrating different renewable energy resources into energy storage systems. Due to the wide range of developments in energy storage technologies, in this article, authors have considered various types of energy storage technologies, namely battery, thermochemical, thermal, pumped energy storage, compressed air, hydrogen, chemical, magnetic energy storage, and a few others. These energy storage technologies were critically reviewed; categorized and comparative studies have been performed to understand each energy storage system's features, limitations, and advantages. Further, different energy storage system frameworks have been suggested based on its application. Therefore, this paper acts as a guide to the new researchers who work in energy storage technologies. The future scope suggests that researchers shall develop innovative energy storage systems to face challenges in power system networks, to maintain reliability and power quality, as well as to meet the energy demand.

1. Introduction

Renewable Energy Sources (RES) are increasing rapidly in the electrical grid due to the reduced dependency on conventional energy resources and the high demand of power to meet the requirements. The microgrid can be used to integrate renewable energy resources and the Energy Storage Systems (ESS) efficiently. Industries such as manufacturing, transportation and communication have significantly increased the demand of electrical energy [1]. To meet this high energy demand, RES play a crucial role. The usage of RESs is critical as they are abundant in nature, eco-friendly, scalable and can be applied in industrial, commercial, agricultural and residential areas [2]. However, RES are non-dispatchable and exhibits poor load following. The successful implementation of ESS can overcome these limitations. There are several options to store the energy generated from RES: batteries, flow batteries and supercapacitors. Supercapacitors have capabilities more than conventional capacitors and secondary ion batteries [3,4].

Thereby, ESS plays a significant role in power generation by supporting different energy sources to meet the requirement of loads. ESS can resolve power intermittency issues as most RES produce power based on atmospheric conditions. Hence, to produce continuous power supply to the customer, ESS such as batteries, ultracapacitors, flywheel and thermochemical storage systems can be widely used. Traditionally, fossil fuels are capable of generating power whenever the customer requires, and these resources can be stored easily. Unlike fossil fuel, RES produces energy only when the wind blows or the sun shines. Hence, ESS can store the energy during excessive generation or when energy is not in use. ESS can also help provide power quality improvement, frequency and voltage regulation, power variations and ancillary services [5]. With this motivation, an array of energy storage technologies have been

---

* Corresponding author.
E-mail address: tankangmiao@gmail.com (K.M. Tan).

https://doi.org/10.1016/j.est.2021.102591
Received 9 February 2021; Received in revised form 16 April 2021; Accepted 17 April 2021

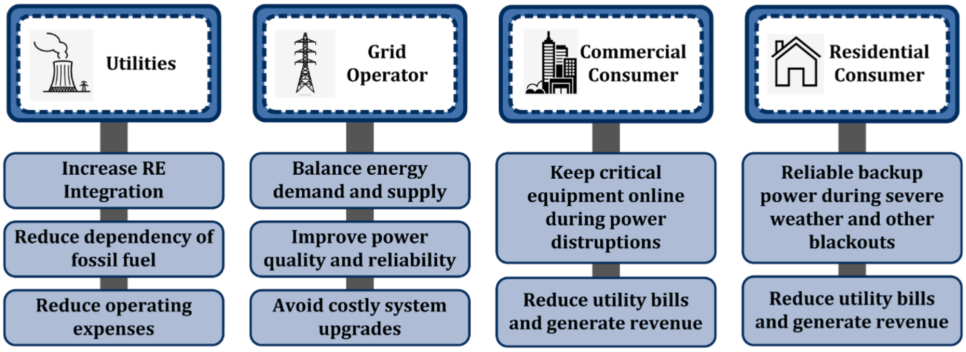


Fig. 1. Value of battery energy storage system [11].

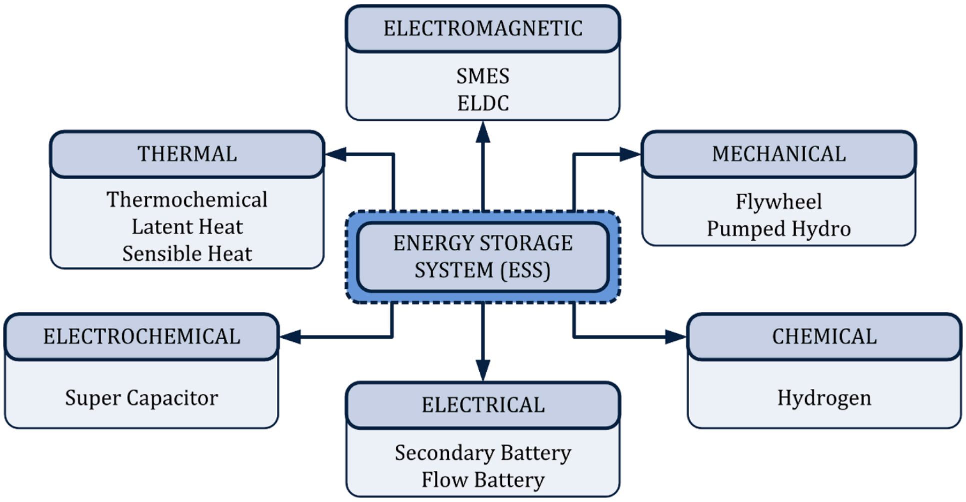


Fig. 2. ESS technology classification.

developed such as batteries, supercapacitors, flywheels, Superconducting Magnetic Energy Storage (SMES), Compressed-Air Energy Storage (CAES), pumped hydro and hydrogen storage systems. These technologies are mainly categorized as chemical, electrochemical, mechanical, and electrical. Among the ESS technologies, batteries are considered a prominent ESS to maintain power system stability [6]. Besides, ESS plays a crucial role in off-grid systems in regulating frequency, power fluctuations and stability. In addition, the combination of different energy storage systems are useful for storing and controlling the power, for use at the time of need [7]. McKinsey refers battery energy storage system as a “disruptive innovation in the power sector”. As per the reports presented in [8], minimized cost of energy storage system could change the future power landscape. The implications are listed as follows:

- At the present lower costs, storage is beginning to assume a more extensive part in energy markets, moving from specialty uses, for example, grid balancing to more extensive ones, for example, substituting regular power generators for reliability, giving power quality services, and supporting integration of renewables [9].
- The installations of battery has increased by 27 percent to 431 MWh in 2017 and the capacity has doubled in 2018 [9].
- As per the reports from Brattle Group, the storage market potential could grow by 55,000 MW in the next decade if the storage cost continues to drop, assisted by state administrative policies [10].

Battery energy storage system has evolved in the last few decades [11]. The innovation is expected to change certain areas of the economy, with the possibility to decarbonize of our energy system. Fig. 1 shows the value that can be derived from battery energy storage system.

Fig. 1 shows the vital role of battery storage system in all fields and applications. This article collates numerous functionalities of ESS. Furthermore, different ESS features and limitations are critically reviewed and highlighted in this paper. Besides, various applications of ESS are discussed together with the challenges and future direction.

The remaining sections of the article are as follows: Section 2 discusses the types of energy storage, whereas the application of ESS to improve the reliability of power grid is detailed in Section 3. In Section 4, the future of renewable energy via innovative energy storage technologies is discussed. The challenges and future direction of ESS are presented in Section 5. Finally, the notable points and conclusion derived from this review article are listed in Section 6.

2. Classification of major energy storage types

Energy storage systems (ESS) can be classified into various types according to their form of energy. The application of these ESS technologies depends on the charging and discharging rate and depth of the system. Fig. 2 shows the ESS technology classification.

2.1. Electrochemical and electrical energy storage system

Capacitors and batteries can store electrical energy in the electrochemical form. Capacitors are widely classified into three types, which are electrochemical, electrolytic, and electrostatic capacitors. Among the capacitor mentioned above types, electrochemical capacitors may have a savvy structure of the electrode; thus, it has a high capacity per unit volume. These capacitors are also called ultracapacitors (UC) or supercapacitors (SC). Batteries have matured technology and high energy densities. Many types of batteries are available in the market for various applications. To name a few, there are flow batteries, nickel-cadmium, lithium-particle, sodium-sulfur, zebra, lead-carbon, and stream batteries. A few new electrolytes and terminal materials have been inspected and proposed to enhance the battery's cost, power, energy density, safety, and life. In [12], the authors presented an overview and comparative studies on different electrochemical energy storage advancements, including leading corrosive batteries and nickel hybrid-related batteries. The authors' discussion on recent advancements in battery technologies was highlighted in [13] to improve the battery technologies' performance. In [14], the authors highlighted new initiatives by cutting down the dimensions of active materials, functionalization, doping, development of coatings over active materials, and moderation of electrolytes.

Furthermore, the latest technologies, challenges, and features of cathode and anode materials for lithium batteries were also described in detail. Amid the different types of batteries, lithium-based (Li-based) batteries play a big role in ESS since they exhibit high energy density and specific energy. A charged Li-air battery can replace gasoline to drive an electric vehicle in terms of usable energy density.

Before using the Li-air batteries, there exist few technical challenges which must be tended to (i) cathode structure reformation, (ii) downplay the compositions of electrolyte, and (iii) enlighten the chemical reactions while charging the discharging of batteries more easily [14-16]. Before using Li-air batteries, the authors attempted to present a comprehensive review in [14,15] for a clear understating of features, limitations, and challenges. Bruce et al. [17] performed the critical analysis by considering Li-air and Li-sulfur batteries and compared their features with Li-ion batteries and also possibilities to increase the advancements of Li-ion batteries. From their analysis, it was found that Li-air and Li-sulfur were cost-effective than Li-ion batteries. But there is a good scope of research to analyze the chemistry involved in Li-air and Li-sulfur batteries. Authors in [18] elaborated on the factors that influence the solid electrolyte interface and its influence on battery performance. A verifiable outline of lithium-ion batteries and their current trends can be seen in [19]. Because of the accessibility and low cost of sodium (Na) and the comparability of the chemical inclusion of lithium and sodium, Na-ions could be utilized in forthcoming batteries that may minimize the cost of smart grid integration into RES. With the active involvement of researchers and industrial experts, a good quantum of work has been done in the field of Li-ion and Na-ion technologies to fulfil the requirements of energy storage. Extensive research on ionic liquids has been carried-out by Watanabe et al. [20], who suggested using Li-ion, Na-ion, or Li-sulphur batteries for high ESS applications. In addition, authors in [20] also focussed on inimitable ionic liquids such as high thermal stability, ionic conductivity, and non-volatility. From the examinations done in [21], it was found that aluminium ion batteries can be treated as the most appropriate contender to supplant Li-ion batteries because of their extensive assets, economy, and ecological cordiality, together with its potential for faster-charging speeds and long run. These extensive features can help in the application of RES.

Moreover, there is still room to improve its cell capacity, energy density, and stability as per the market trends. Further, selecting appropriate electrolytes and materials for the electrodes is still challenging, and these are still in the theoretical stage. The experimentations carried-out found that electrolytes made with aluminium chloride, sulfide, and carbonaceous materials are most suitable for positive electrodes. Electrochemical capacitors based energy storage devices will achieve storage efficiency higher than 95%. These types of batteries can run for a long time without losing their storage capacity. Even though these capacitors exhibit high efficiency, there may be chances of self-discharging, and operating voltages cannot exceed potential in the process of chemical reactions.

To overcome these low voltage levels, electrolytic capacitors can be combined with batteries. With the presently available technology of electrochemical capacitors, they can store 1 or 2 orders of energy magnitude less than batteries [20]. Improving the nanoscale energy and power densities of electrochemical capacitors have become a popular research area in recent years. A complete review of principles and future applications of electrochemical capacitors was done in [22].

The development of nanoscale energy storage using electrolytic capacitors was highlighted Lu et al. [23]. Electrochemical capacitors are categorized based on the storage mechanism and type of electrode materials used. They are namely pseudocapacitors, double layer electro capacitors, or a combination of these two. In double layer electrochemical capacitors, the conversion of solvated ions into electrolytes occurs faster. The formation of a double-layer behaves like two capacitors connected in series via the electrolyte, and it endures charged even after the circuit is opened. Double layer electrochemical capacitors enhance the cell capacity. This supports the usage of electrode materials made with metal oxides, carbon, conductive and hybrid polymers. Authors in [24] examined different electrochemical double-layer capacitors technology and voltage levels testing. From the analysis, it is observed that the gradient of temperature and aging of cells results in variable capacitance. This can be observed clearly in double-layer capacitors. Voltage differentiation between layers can be avoided by using voltage equalization circuits [25].

Batteries can store nearly 30 times higher charges than SC that has the same amount of mass. This high energy density can be achieved by storing charges in various materials. However, SC can deliver higher power than batteries as they can store energy in the electrode. Electrochemical capacitors can run for longer duration or years when compared to batteries. To prove this, Miller and Simon in [26] executed a thorough comparative analysis between batteries and supercapacitors. The results shared in [27] show that the multi-electronic chemistry of electrolytes and electrode materials will increase the percentage of energy stored. Further, it is suggested that, by combining features of metal-ion batteries and electrochemical capacitors, hybrid devices can be derived to accommodate future energy storage requirements.

Fixed electrode batteries may exhibit less energy density, and it can be compensated by solar or wind power for short time regulation. Flow batteries can serve as a proper solution for this. These flow batteries comprise two electrolyte reservoirs for electrolyte flow, and the membrane can separate the anode and cathode. The energy density of these batteries depends on the storage volume of the electrolyte. Further, it is self-reliant on size and electrochemical cell design, which characterizes the power density. For the storage applications with RES, a redox flow battery is most suitable. Redox vanadium (VRB), polysulphide bromide (PSB), and zinc bromide (ZnBr) can be used for the design of flux batteries.

Comparison of different redox flow battery innovations that emphasized cell configuration, including the cell parts of electrolytes, terminals, and layers, for both watery and non-fluid systems was discussed in [28,29]. These days, new technologies for redox flux batteries have been introduced, along with integrated electrochemical solid oxide cell with a redox cycle unit [30], a trapezoidal flow-through battery [31], and hybrid membranes for VRB [32]. These technologies enhanced the power capacity, density, efficiency, charging and discharge rates, electrolytes, non-toxic material usage, and the development of low-cost heavy metals.

2.2. Thermal energy storage system

Thermal energy storage is nothing but storing cold or heat in a medium-size storeroom. It mainly comprises of storage elements and a device to extract or inject heat from the storage medium. The storage medium can be a structure made with soil, or it can also be a container that avoids losses or adds heat from the atmosphere. There are three major thermochemical, latent, and sensible modes in a thermal energy storage system. Generally, the heat is stored in moderate heat, which helps to increase the containers' heat. Storage of hot water,

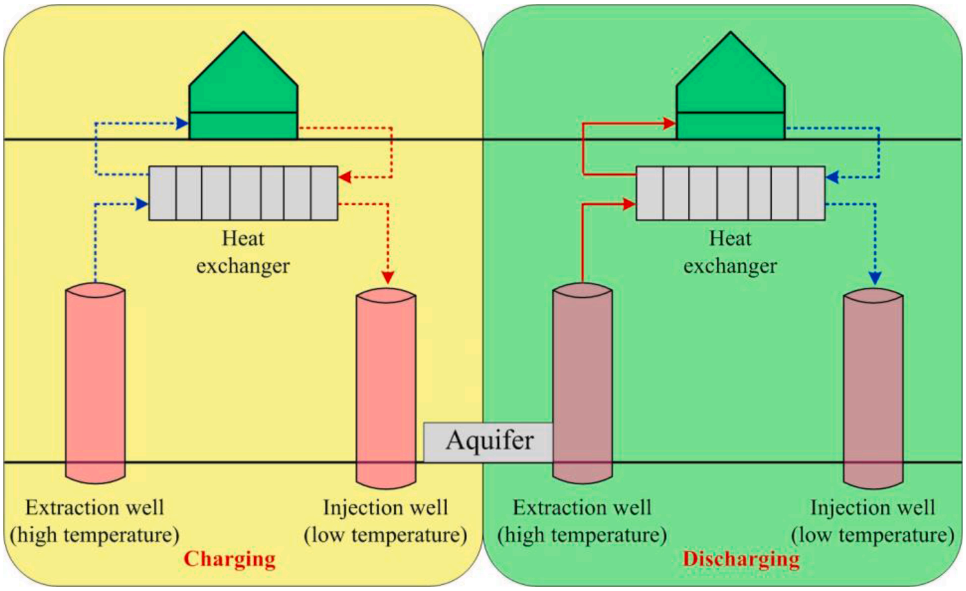


Fig. 3. Aquifer heat storage.

underground thermal energy storage [33], and rock-filled storage are examples of thermal energy storage systems. The latent heat storage is a technique that incorporates changing period of storage material, regularly among strong and fluid stages, albeit accessible stage change of liquid, solid-gas, and solid-solid is additionally found. The latent heat storage system has received high consideration as of late, generally because of the isothermal nature of the stage change cycle and its less weight per capacity limit and conservativeness. Its thermal features improved in contrast with judicious heat storage materials, namely, high latent heat and stable phase change temperature. Phase change materials that are used as storage medium comprise of esters, fatty acids, water, eutectic salts, and paraffin waxes.

In the heat energy storage systems, variations in the supply of heat may occur seasonally or in fewer periods. The highest energy can maintain the heat required for storage systems use after a long duration. Ground heat storage is an example of this, where it is connected to the building to accumulate the heat. In this system, heat can be released during summer, and during frozen months, heat can be used. A comparative idea can be applied by stockpiling solar thermal energy in summer for winter. The systems store energy, generally in less capacities, and hold heat for a couple of hours to a couple of days. Such systems can be utilized to store solar thermal energy during the day, and it can be utilized during colder hours in case of necessity. In houses, thermal energy storage systems can be used to minimize electricity costs by storing thermal energy during day time.

Various advancements for heat energy storage systems has been detailed in [34–38]. These authors have discussed the thermal energy storage modes, heat material properties, design approaches, thermal improvement techniques for latent and sensitive heat energy storage systems. The research for latent heat-storing systems is of utmost importance for developing new storage media and enhancing thermodynamic media features [39]. Recently authors in [40] introduced fatty acids from animal and vegetable oils to develop phase change materials. Nazir et al. [41] carried out extensive research on applying various phase change materials based on the thermophysical, conductive, and energy thermal density. The carried-out studies found that phase change materials can be used in smart heating networks, including RES. To improve the usage of thermal energy storage systems, a critical review on terrestrial heat exchanger - models and their applications was dealt with by authors Florid et al. in [42]. The approach uses spaces to store sensible heat, such as heat storage systems in aquifers, wells, water tanks, and pits [37]. Water tanks are the most recommended alternative from the thermodynamic perspective because of the high specific heat of the water and discharge energy and high capacity [37,43].

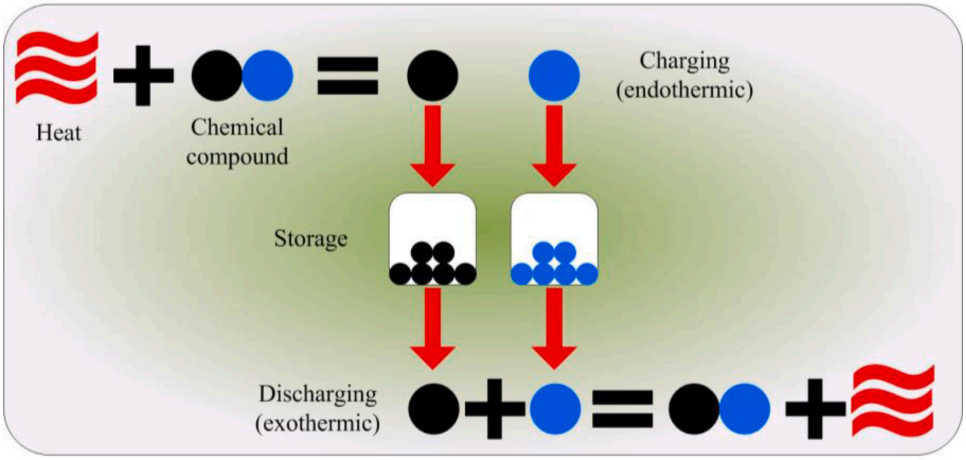


Fig. 4. Processes involved in a thermochemical energy storage cycle.

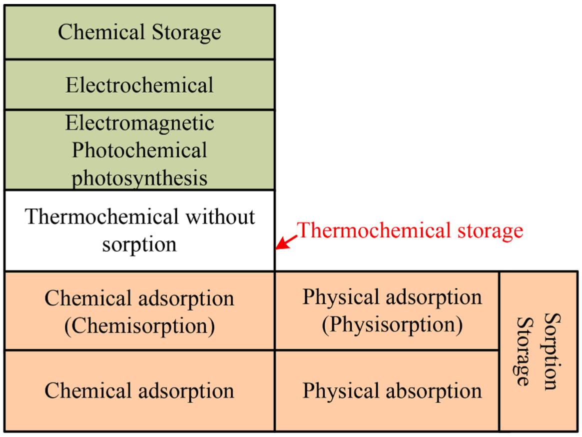


Fig. 5. Chemical storage and sorption storage classification.

Aquifer Heat Storage Systems (ATES) shown in Fig. 3 use regular water in an underground layer as a storage medium [43,44]. In light of a country-specific analysis to eradicate the market nation's detailed and measurable investigation, Feluchaus et al. [44] entered the market blockade by distinguishing a commercialization level from a developing business viewpoint sector, a development stage, and a developing stage. They noticed that, due to technical feasibility, lack of knowledge causes obstacles in the market trend. A technology grows towards the advanced stage, high initial cost, policy regulations, and legislation are noticeable barriers.

Chemical reactions can be used to generate or consume thermal energy in thermochemical energy storage systems. These systems comprise of three stages, namely response items capacity, exothermic response, and endothermic separation. These processes are shown in Fig. 4.

In the final stage, the materials are reproduced with the goal that the cycle can be rehashed. Thermochemical energy storage systems can be categorized into different types, appearing in Fig. 5. These systems may exhibit high storage density compared to latent and sensitive thermal energy storage systems. This reduces space consumption. This helps significantly in such applications where storage space is bounded and costlier. Thermochemical storage systems have attained high priority since it can run for long life than latent or sensitive thermal energy storage [45].

Nonetheless, thermochemical energy storage systems face a few difficulties in achieving effective operation. Appropriate materials or combinations are required to store energy with less heat losses and deliver it effectively. The materials used for the thermochemical system involves $Ca(OH)_2$, $MgSO_4{\cdot}7H_2O$, $CaSO_4{\cdot}2H_2O$, and $FeCO_3$.

Lefevbre et al., in [46], proposed that combinations and materials with salt impregnations are reasonable for use in thermal chemicals. For thermochemical storage systems, enhancing the long run by adding salt to the adsorbent materials is the popular research topic. In [47], the authors reviewed the advancements and principles of thermochemical energy storage systems and correlated these with different thermal energy storage systems. Because of the high material expenses and operational issues, few thermochemical energy storage systems were in usage. Some investigations depict the physicochemical and thermodynamic properties of materials appropriate for long-term thermal energy storage [34,48]. Innovative technology for energy storage based on microwaves induced CO_2 fumigations of carbon materials was proposed by Bermudez et al. [49]. Different carbon materials are to be examined for the consumption of energy. Two microwave heating techniques, namely multimode and single-mode ovens, were tested to identify FFI deficiencies regarding energy utilization and recovery. With the developed technology, 45% of energy-efficient defects were rectified on a laboratory scale.

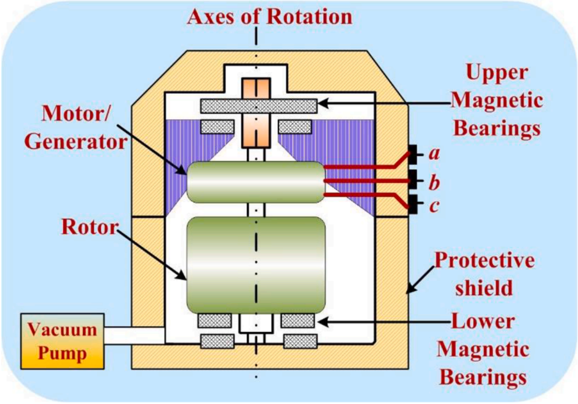


Fig. 6. functional diagram of a Flywheel.

2.3. Mechanical energy storage system

Kinetic Energy (KE) storage is also known as a flywheel energy storage system. It is a mechanical energy storage that contributes to high energy and performance. In this system, KE is conveyed in and out of the flywheel with an electric machine that behaves like a generator or motor based on discharge/charging mode. Permanent magnet machines are regularly used as flywheels due to their high-efficiency defects, fewer rotor losses, and high power density [50]. Charging power in the rotating mass of a developed flywheel is stored in the form of kinetic energy. This stored energy can be utilized during the required time. The rotational mass is handled by magnetic bearings that work under vacuum to eradicate frictional losses [51]. The rotational bearing system is a mechanical or magnetic system or hybrid by having both properties. Magnetic bearings are free from frictional losses as no need for lubrication. However, it consists of a complex control system and requires additional power to operate.

Superconducting magnetic bearings are widely used for high-speed applications, although it needs electricity to operate a cryogenic cooling system. Density flywheels are most appropriate for attaining high speed and power since energy storage is proportional to the speed's square and linearly proportional to the mass [13]. Flywheel rotors and their casings are made-up of composite materials, stainless steel alloys; with these materials, 10,000 RPM can also be achieved [50]. Fig. 6 indicates complete functional diagram of a Flywheel with its components.

Flywheels store the energy in the form of kinetic energy in a rotating mass. It can be defined as a function of the angular velocity and the moment of inertia. The energy storage equation for flywheel is as follows:

$$E = \frac{1}{2} I \times \omega^2 \ J \tag{1}$$

Where ω is the angular velocity and I is the moment of inertia. The moment of inertia is defined by the principal rotational axis, shape and mass of the flywheel. It can be given as in Eq. (2)

$$I = \int x^2 dm_x \ \ \text{kg.m}^2 \tag{2}$$

Where x is the distance from the rotational axis of the differential mass dm_x

The utilization of composite materials empowers high speed at higher power densities over chemical batteries. The high power density is attractive in vehicles application. The high power is required while accelerating, and the high power is accessible in a brief timeframe while slowing down [52]. In contrast with batteries and supercapacitors, flywheel energy systems have lower power density and higher noise, cost, support, and well-being concerns [53,54]. To improve the power density, Toodeji [54] suggested s plan for a joint system wherein the

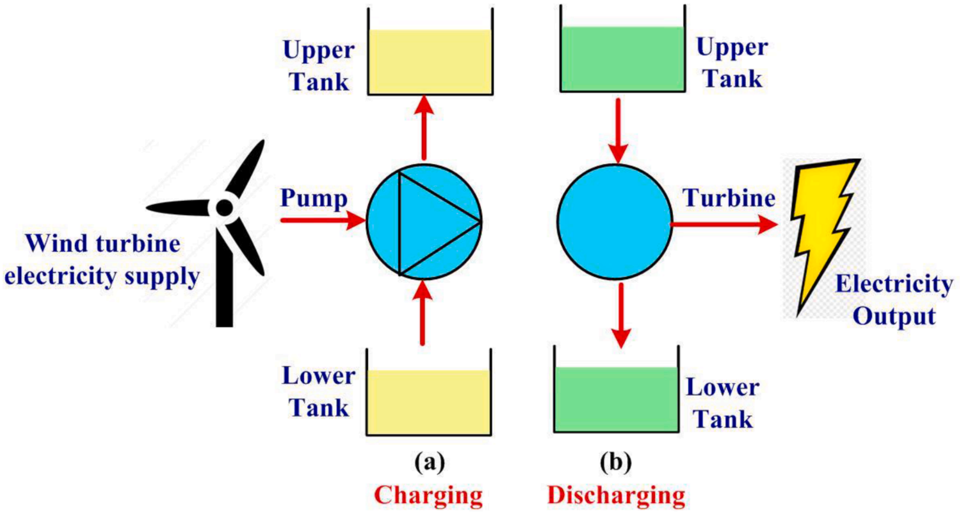


Fig. 7. Illustration of pumped hydro storage with the pumping energy supplied by wind turbines: (a) charging at off-peak hours, (b) discharging at peak hours.

supercapacitor contains a rotating plate flywheel. This empowers the trading of pulsed energy with high energy capacity.

Pumped Hydro Energy Storage (PHES) systems store electrical energy in the form of hydro potential energy via an electric pump which transfers water from a stored container at low height via a pipe to a higher water tank; its representation is shown in Fig. 7 Energy can be generated by passing water to flow from a high to a lower altitude with hydraulic turbines. The channel flow of water to the turbine can be controlled, utilizing gates to permit variable output power.

To regulate power while charging, frequency converters can be used. For effective operation and suitability of PHES, the following criteria should meet, such as place availability, different elevation to fetch water. Fulfilling these criteria is suitable for RES along with the grid. Its efficiency may vary between 70 to 80% [55]. Further, PHES can run for longer years, about 70 to 100 years, and involves less maintenance and operating costs. However, limitations of PHES are the high capital cost and suitability of topographical conditions. Underground PHES systems can overcome these challenges by adapting underground reservoirs [56].

From the above discussion, it is understood that PHES consists of a separate motor unit and turbine or generator unit together with RES to meet the required energy demand. The total stored energy in the active volume of a reservoir can be given as in Eq. (3)

$$E^t = \eta_t \times \rho \times g \times H \times V = c_t \times V \, kWh \tag{3}$$

where H is the net head (m), $\eta_t$is the efficiency of generator/turbine, V is the storage capacity in m^3, g is the acceleration due to gravity in m/s^2, c_t is the generator/turbine generating coefficient in kWh/m^3, ρ is the water density in kg/m^3.

Furthermore, the energy used to pump the water to a particular height with specific pumping efficiency can be described as shown in Eq. 4.

$$E^p = \frac{\rho \times g \times H \times V}{\eta_p} = c_p \times V \; kWh \tag{4}$$

where η_p is the pumping efficiency, H is the pumping head in m, c_p is the water pumping coefficient of the motor/pump unit in m^3/kWh.

There were many research done to identify suitable locations viable for the installation of PHES [55]. The authors presented various methods and technical challenges to identify locations and advanced techniques in [57]. For less rated capacities, PHES systems' design varies from 60% to full capacity, and generating capacity varies from 20% to full capacity [58]. The efficiency of individual PHES systems will be limited;

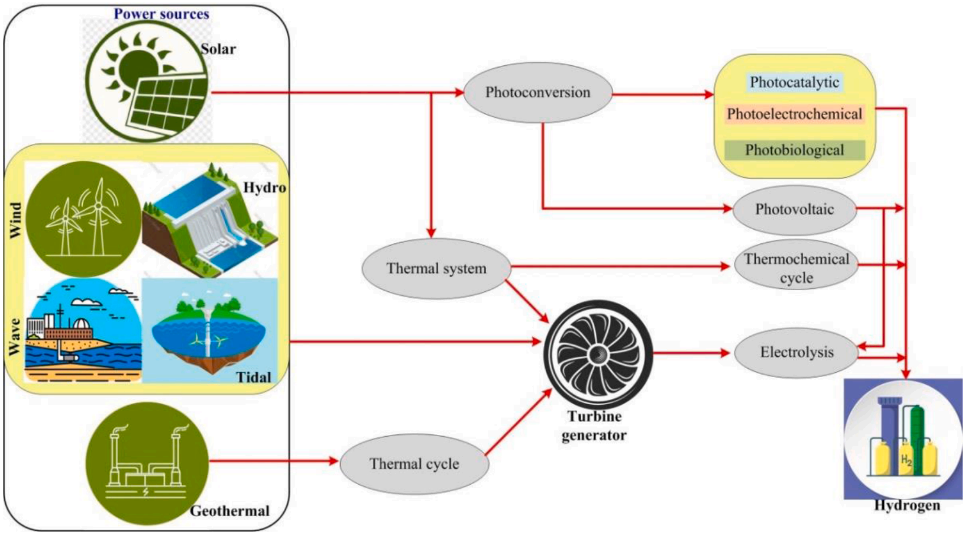


Fig. 8. Production of hydrogen using RES.

however, when multiple machines' capacities vary with different configurations [58]. A few control systems for various suitable levels for variable speed activity of PHESs have additionally been created [59]. The high performance of PHES systems with variable speed was shown in comparison among PHES systems with variable and consistent speed for managing wind power [60]. Power converters' involvement also gives fast response in both phase and pump generation modes than mechanical-based fixed-speed control systems. This helps the microgrids explore the capability of converters and controls to strengthen a PHES system and organization in various working modes. As seen in regular usage, a prototyping climate is created [61].

Yang and Jackson [62] believed in the historical improvement of pumped water storage in the United States and new advancement activities in PHES technology. To overcome the climatic difficulties of PHES systems, researchers proposed ingenious steps, along with maximum usage of wastewater in PHES applications. Due to the rapid usage of ESS, the development of new methods were attracted by researchers. PHES can be widely used to couple recurrent RES. The advanced techniques proposed by authors in [63] solves the limitations of conventional PHES. These advancements help to abolish larger water tanks, long pipes and also can be designed for various capacities.

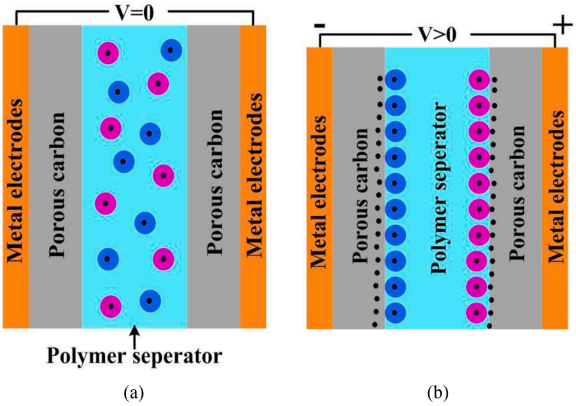
2.4. Chemical energy storage system

Chemical energy storage systems can be utilized as a reversible chemical reaction where a high amount of energy is consumed to store energy. The chemical energy storage systems can be categorized in terms of energy consumption, like electrochemical energy storage.

In a hydrogen energy storage system, hydrogen is produced by an electrolytic process, direct or stored for some duration of time, and oxidized. The process is shown in Fig. 8. Hydrogen generates from the process of chemical reactions. For many years, electricity has been treated as a primary source than hydrogen. Hydrogen exhibits features that complement that of electricity. Researchers proposed the hydrogen economy, which consists of hydrogen energy and utilization, production, distribution, and storage [64]. Authors in [65] characterize the environmental relevance, hydrogen economy, and atmospheric conditions. its impact in the decarbonization of fossil-fuel power plants and electrical novel related non-heat motor energy converter power module in compact gadgets, in fixed and versatile applications.

A typical technique for generating hydrogen is by separating the water. The energy required for this procedure can emerge out of petroleum derivatives and RES. RES is intermittent in nature and temporary; thereby, it needs to be stored for longer usage. Environmentally friendly power is regularly brief and should be put away before it is required. Authors in [66] discussed the production of hydrogen from solar energy by considering the steps mentioned below: combining an electrolyzer with a solar cell, a combination of the solar thermal system along with electrolyzer and turbine; photo conversion, and a combo of solar concentration system with a thermochemical water-splitting cycle. The production of hydrogen from other sources was also discussed in [66]. Besides, RES like hydro, geothermal, ocean, wind, biomass waste was detailed for the reader's clear understanding. Photovoltaic (PV) process and photosynthetic receives energy from the sun; at certain times, these two can be compared for understanding its process. However, these two works in different and release various products. Blankenship et al. [67] contrasted with normal photosynthesis, flow innovations for photovoltaic water electrolysis to control hydrogen production, and show that electrolysis PV is fuelled and productive yearly premise. Manners by which new advancements in manufactured science can improve solar energy transformation proficiency are examining common photosynthesis.

The development of innovations for hydrogen storage is a challenging task, specifically for automotive applications. As hydrogen has less volume density than other fuels, it requires larger tanks for vehicles than vehicles run with diesel. Further, hydrogen is the lightest element due to this difficulty to liquefy than methane and propane.



(a) (b)

Fig. 9. An electrical double layer capacitor (a) un-charged, (b) charged.

2.5. Electromagnetic energy storage system

Electromagnetic energy can be contained in an electromagnet or in an electric field, including superconducting magnetic double-layer capacitors (SMES). The two technologies are somewhat elementary: Electrical Double Layer Capacitor (EDLC) places energy between two oppositely charged electrodes separated by an insulator, whereas SMES uses current running a superconducting wire through a current to generate a magnetic field. Both of these storage systems have very high-power density, efficient use of energy and good tolerance to de-/charging after multiple cycles.

In ordinary capacitors, the electrolyte is in contact with the electrodes. The construction of an EDLC contains two electrodes connected by a porous material. The separator is a polymer membrane with a hundred nanometres thickness to keep the electrodes from touching each other. It is an electrolyte, allowing free passage of ions but blocking electronic movement Often known as supercapacitors or ultracapacitors, these capacitors have a very high capacitance. They are sealed up and put into a cylindrical jar with electrodes. This will make the corresponding electric field ions travel to the electrode surfaces when a voltage is applied to the electrolyte. A colloidal carbonized base has pores and can receive ions but does not contribute much to the build-up of electrostatic charge. Ionic layers therefore allow successful two layers of charges to form at the electrode surfaces, which results in the capacitor's 2-layer name (see Fig. 9).

Although the applied voltage can go as high as 1–3 V [68], the distance between separated charges is measured in nanometres. which generates a strong electric field in the two upper and lower layers ($\approx$ 109 V/m), which in turn results in high energy concentration.

The energy density of EDLC can be given as in Eq. (5):

$$E = \frac{CV^2}{2} \tag{5}$$

where E is the energy stored in the capacitor, V is the applied voltage and C is the capacitance.

The EDLCs are made up of porous carbons, like actuated carbons. The high capacitance i.e., 100–200 F g^{-1} is gotten from the high explicit surface area i.e., >1000 m^2 g^{-1} in microporosity [68]. As a rule, it is accepted that there is a relative connection between's specific surface area and the EDLC of actuated carbons as dependent on the accompanying condition.:

$$C = \int \frac{\varepsilon_0 \varepsilon_r}{\delta} dS \tag{6}$$

where C is specific capacitance, ε_0 is permittivity in vacuum, ε_r, δ are the relative permittivity and thickness of the double layer, and S is specific surface area.

Characteristics of electrical double-layer capacitors:

In a double-layer capacitor, there are no chemical reactions taking place. The charge and discharge period therefore have virtually no effect on the lifespan of the battery, and it is expected to last for more than a million cycles. Here EDLCs are good for applications where high throughputs are needed. In general, EDLCs work above the defined temperature range for batteries. It has a wide surface area, and is more resistant to electrical fields, leading to low losses. That gives an efficiency of 95–99 percent and reduced internal heat.

Application areas:

- A battery that is connected in parallel with an EDLC is smaller, less expensive, and lasts longer. The EDLC can provide short bursts of high-level power during discharge. There are occasions where EDLC chargers can increase the battery life of the battery by smoothing damaging potentially damaging charges.
- EDLCs processed renewable fuels can be used in situations where the power-to-energy ratio is very high, and the storage time is low. Transport applications that require regular acceleration include, for example, city buses, streetcars and local rail systems.
- The EDLCs can be used to compensate for regenerative braking currents, and then use the energy that has been stored, in order to help accelerate.
- The EDLC model focuses on power efficiency and voltage support of applications such as power improvements, sudden load shifts, and transient phenomena. In companies such as Maxwell Technology, EDs, backup power, self-surge power, and regenerative power have already been introduced. EDLC would cost about $350/kWh in the next decade [69].

Future possibilities:

Today, an EDLC has a one percent of the energy density of a typical Li-ion battery. EDLCs aren't widely used because of their limited energy density. Intended to combine the properties of capacitors and batteries, on-going research is currently aimed at better combining them. With improved parameters, there is the potential for high-power devices with broad energy storage capacities, limited power use, wide operating temperature ranges, and little degradation. If materials research results in commercially available devices with substantially increased energy density, EDs will explode in value. Compatible designs in the transport and energy storage on hours-long timescale would open the door to higher capacity and low-price alternatives on the power grid.

Superconducting Magnetic Energy Storage (SMES) systems comprise of a giant superconducting coil. The superconducting coil is kept up at a cryogenic temperature utilizing compartments of liquid helium or nitrogen. A portion of the energy losses are related to the cooling system that keeps the cryogenic temperature; however, the loop's energy losses are right around zero because superconductors offer no protection from electrons flow. SMES coils can download a lot of energy in a split second and go through a boundless number of cycles of charge and release high productivity. Coil configuration, the power capacity, operating temperature, and arrangement are the critical design parameters of the SMES.

SMES can be used for applications such as voltage, system stability, load levelling, frequency control, automatic generation control, and power quality enhancements. Different technology-based SMES like current source converter-based, voltage source converter-based, and thyristor-based were inspected by Hassan Ali et al. [70]. They recommended SMES technologies based on cost, energy storage, and power handling capacity. From the analysis, it was found that there exist substantial research possibilities in minimizing the cost of SMES. Further, authors in [71] reviewed SMES systems, which are most suitable for power system applications. The authors in [71] presented the necessity of developing practical applications of SMES, compared to various studies done via simulations. The authors advised that new advancements of SMES technologies should require efficient control. An important advancement for small companies would be a superconducting magnetic circuit diagram that involves a cryogenic enclosure, an electronic converter to connect the DC power in the superconducting part of the circuit to the AC power on the grid, and an electronic switch to regulate the flow of current through the magnet (see Fig. 10).

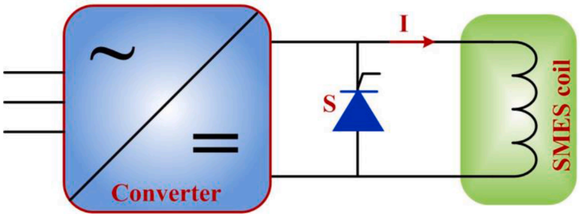


Fig. 10. Circuit diagram of SMES.

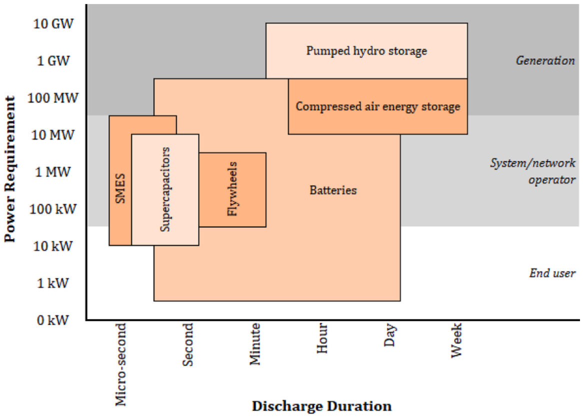


Fig. 11. ESS technology comparison.

Fig. 11 shows the comparison of different ESS technology in terms of their discharging power capability and discharging duration.

3. Energy storage system to support power grid operation

ESS is gaining popularity for its ability to support the power grid via services such as energy arbitrage, peak shaving, spinning reserve, load following, voltage regulation, frequency regulation and black start. Among all ESS types as presented in Section 2, Battery Energy Storage Systems (BESS) is gaining more popularity in recent years. This is mainly due to the following advantages of BESS:

- Flexible to construct into various size and shape as required for the ESS application.
- Unlike some ESS type, where specific location of installation is required (e.g. underground caverns, water dam, etc.), BESS can be installed almost anywhere.
- Along with the increase of battery demand, the technology development has become more mature. BESS's energy and power density is among the best options at a competitive price.

Hence, it is noticeable that the following assessment of the latest ESS application has greater interest to adopt BESS as their storage option.

3.1. Energy arbitrage

Energy arbitrage plays a major role in the economic perspective of the grid operation. ESS is used to gain monetary profit by selling and buying energy at the appropriate time. The main objective is to sell the

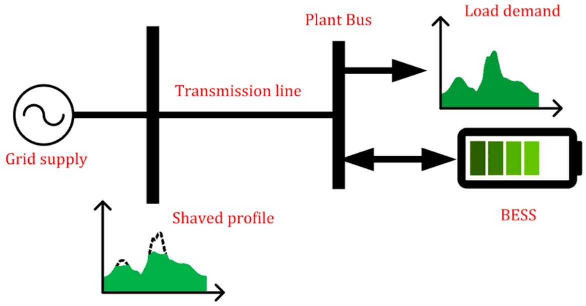


Fig. 12. Peak shaving using ESS.

energy at a high price and storage when the price is low [72]. Due to economics and technical benefits, ESS is widely deployed in American and European markets. Among ESS's advantages, one of them is to take part in a deregulated grid to maintain the grid's stability. Due to environmental concerns, RES is widely used for power generation. But the unmanageable behavior of RES has increased the volatility in price. This leads to negative prices at a time, making energy arbitrage even more attractive for managing the demand and supply of electrical power. Due to several emerging technologies and advances, ESS can benefit economically by maintaining the system's reliability and stability.

3.2. Peak shaving

Due to the rapid increase in commerce, industry, and population, energy demand is also increasing. Therefore, peak shaving is gaining interest to cover this extra energy demand with the help of ESS. The extensive increase and change in use have made a huge difference in the valley's peaks and load profiles. For many years, it has raised concerns about the reliable and stable operation of the network. Due to the increase in the number of load profiles and the differences in the valley, the effective control of storage has gained significant importance in the electrical system's operation [73].

Most industrial customers operate appliances and equipment that require large amounts of electricity in a relatively short period of time during a single day. Additional costs are accepted in maintaining peak demand in terms of customer demand fees. Therefore, industrial consumers are usually charged according to their maximum demand, and for energy consumption, that is averaged normally at a time period of 15 minutes. These peak demand charges can cover half of the budget bill. Peak shaving is quite similar to energy arbitrage; the difference is that in peak shaving, there is no economic objective such as energy arbitrage; it is only installed to cover the peak loads. Peak shaving supports the peak demand with the help of ESS. On the other hand, peak shaving applications are installed on the customer side, and energy arbitrage applications are installed on the supplier side. The basic concept of peak shaving is given in Fig. 12 [73].

Since peak power only occurs for a short interval of time, these peaks increase the stress and reduce the grid's overall efficiency. In some cases, microgrid operators keep their 10% capacity for peak shaving, which is done with diesel generators' help. The operating and maintenance cost of microgrid increases for supporting peak demands, due to extra fuel and CO_2 emissions. Therefore, peak shaving is an important area of research in the current era.

3.3. Spinning reserve

Ancillary services provide support for the system throughout the journey of electrical power from generation to utilization. This can also include backups and flexible adjustments in the grid variables using ESS. The spinning reserve is the part of the electrical system that is not used under normal conditions [74]. But this source is used only to cover the power shortage for a shorter period. The basic application of spinning reserve is to support the demand during the time of power outages. The spinning reserve must have the capability of supply power over at least 1 hour [75].

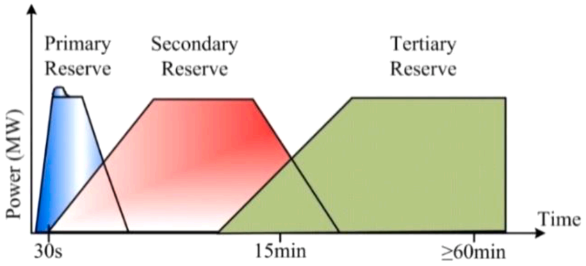


Fig. 13. Three levels of frequency control.

3.4. Load following

Frequent load variations are often observed in the electric power system, which causes various issues in the grid operation. ESS's quick and sudden variations are more responsive than other generation types [76]. The main function of ESS in this application is to maintain the harmony between generation and load [77]. ESS is also suitable for following the load variations in both up and down directions [78].

3.5. Voltage regulation

Voltage variation has a huge impact on the stability of the grid. Therefore, to maintain the system's stability, the voltage must be kept within its permissible limits. The voltage and reactive power are dependants on each other; therefore, reactive power must be maintained for voltage support in the system [76]. On the other hand, to transfer the reactive power over a long distance, voltage support is a need; for this, ESS can be used to support this application [78].

3.6. Frequency regulation

Frequency is a very important factor for maintaining the harmony between generation and load. Frequency controllers should be able to maintain the frequency within desirable limits, such as 50 Hz. To maintain the frequency in desirable limits, ESS is often used with frequency regulators. This regulation is usually very small; for example, frequency regulation of ±0.1 Hz is proposed in Northern Europe, ±0.2 Hz in continental Europe [79–81]. These frequency regulators are classified as primary, secondary, and tertiary controls, as shown in Fig. 13. Primary control tries to balance the system frequency in the range of 5 to 30 sec over 5 minutes. The function of secondary control is to keep an eye on primary control regulation and maintain frequency if the primary controller does not control that. The tertiary controller function is also similar to the secondary. Here, the tertiary controller monitors the control of the secondary controller and acts as a backup. When it comes into action, this controller will maintain the frequency from 15 to 60 minutes duration. Overall the combination of these frequency controllers together balances the system between generation and load.

3.7. Black start

In the power system, blackouts are caused due to power interruption of unplanned events in single parts or the whole system. These interruptions threaten the stability of the system and cause a blackout. Some applications of ESS are also found for a black start, where ESS supports the voltage, maintains the balance between grid and consumer, and also provides a starting point for conventional generators [82].

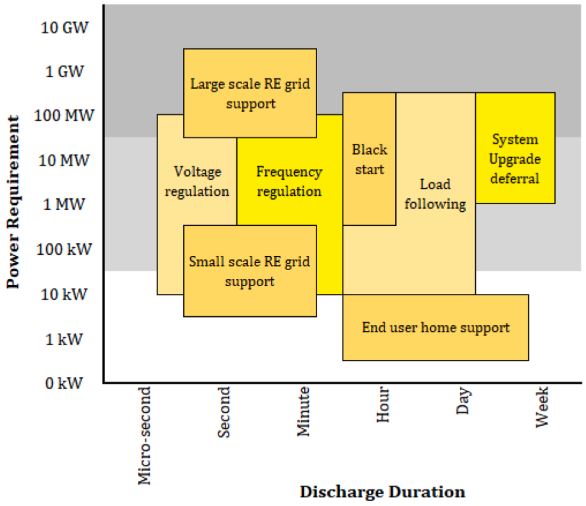


Fig. 14. Requirement comparison of ESS services.

3.8. *Summary*

Each ESS services has different power requirement and duration of storage discharging time. By understanding the requirement of these services will help when selecting the appropriate ESS type and sizing. Fig. 14 presents the comparison of ESS application in terms of power requirement and discharging duration. The summary of the ESS application without the integration of RES is provided in Table 1. From this review, it can be observed that the selection of ESS technology depends on available resources to the particular grid operator. It is also found that Pump Hydro Storage (PHS) is mostly deployed in China for energy arbitrage, while Compressed-Air Energy Storage (CAES) is more famous in Canada. On the other hand, the arbitrage business, especially BESS, has gained interest due to innovative advances in ESS technologies and power electronics.

4. Energy storage technologies and renewable energy

For many decades, the global electricity network has heavily depended on power generation from fossil fuels. As fuel depletion and environmental pollution issues arise, many nations are now switching their power generation option to RES. Nevertheless, with the increasing role of the intermittent generation from RE, retirements of fossil fuel generation, and the varying consumer demand profile, maintaining the balance between power generation and consumption becomes extra challenging. ESS is a key component in overcoming this challenge due to its flexibility in storing and dispatching energy at any time and place. Recently, energy storage technology, especially battery energy storage, is experiencing a tremendous drop in cost. Many researchers and stakeholders have noticed this great potential in BESS, which will become an inevitable electric technology in the future smart grid system. This section discusses the methodology implemented worldwide to strike for more RE integration to the electricity network.

4.1. *ESS services for RE integration*

The responsibility and function of the ESS technology depends on its application's location and scale. As shown in Fig. 15, the advantage of ESS to support RE integration to the power grid is achieved via the following operations:

- Solving intermittent generation of RE,
- Frequency stabilization,
- Voltage compensation,
- Prevent back feeding,
- Improve system flexibility and
- Improve system efficiency

4.1.1. *Solving intermittent generation of renewable energy*

Energy generation from RE is susceptible to environmental conditions such as wind speed, solar radiation, temperature, etc. This intermittent nature leads to an unpredictable fluctuation of RE power generation, which complicates its application in the power grid to meet electricity demand. Hence, ESS offers are generous to smooth the intermittent power produced from RE resources by regulating their power profiles [116]. Among many of the ESS technologies, BESS is a popular choice of ESS for regulating the RE intermittent generation. This is due to BESS's characteristic in providing high power density, modularization, and flexible installation. In [117], Xu and Shen demonstrated BESS's capability in solving RE intermittency in a microgrid. Centralized optimal energy management was used to control multiple distributed BESS in the microgrid to regulate the RE generation while minimizing the adjustment cost, considering the influences of the time-of-use tariff, power losses, and system efficiency.

Even though the battery is known for its large power density and flexible installation quality, it has a limited power density and response speed. An oversized battery design is required to cater to these constraints, which is a very cost-ineffective investment. Therefore, ESS's hybridization is a new technique utilized where multiple ESS technologies with complementing characteristics were combined to achieve a complete ESS system [118]. For instance, a battery has high energy density and low power density. In contrast, the supercapacitor has a high power density but low energy density. As presented in [119] and [120], battery and supercapacitor are proposed to use as a Hybrid Energy Storage System (HESS), which created a high power and high energy density ESS system. Research has shown that with HESS technology, the overall system stability was improved.

Meanwhile, paper [121] introduced a solution to mitigate RE intermittency using a household battery pack and Plug-in Electric Vehicle (PHEV). The decision making is based on the power difference between PV generation and household power demand. The PV generation is always fully utilized whenever the demand is greater than PV generation. Either ESS or the power grid will cover the shortfall of load demand. On the other hand, when the PV generation is greater than the load demand, excessive PV output will be stored in ESS or sold back to the power grid. The choice of power flow into ESS and the power grid is based on the building owner's optimal economic advantage.

4.1.2. *Frequency stabilization*

Frequency stabilization require energy injected into or withdrawn from the grid to regulate the system frequency. This service requires a fast response speed, which can take place within seconds and last for a few minutes. The ESS requires a fast response time, high-performance rate, and high power capability to achieve this. Frequency stabilization is especially important for microgrids or islanded power grids, where a stronger power system does not drive their system. Hence, whenever there are a mismatch or power generation and system demand, ESS must regulate the system frequency and maintain system stability [116]. Li and the team presented a microgrid frequency stabilization technique using supercapacitor and battery HESS in [122]. A dynamic droop control was utilized to manage power-sharing between the capacitor and battery ESS. In addition, HESS using supercapacitor and battery is shown to have better frequency stabilization performance than ESS using the pure battery.

4.1.3. *Voltage compensation*

With more and more integration of RE into the modern power grid, the distribution network has become an active grid, where the bus voltage at RE distribution generator integration can be higher than other upstream buses. This has disrupted traditional voltage compensation

Table 1
Summary of ESS application without RES integration.

Ref.	Objective	Algorithm / Model	ESS Technology	Description / Contribution	Content / Market
[73]	Peak load shaving	Dynamic programming	BESS	Increasing economic benefit for the consumer by reducing peak demand with optimal operation and sizing.	Simulation
[83]	Peak load shaving	Mixed integer programming, rolling load forecasting	BESS	Minimize the daily load variance by reducing the difference between peak load and valley load with an optimization model using the rolling load forecasting method.	Simulation (Billing Substation in Shen Zhen)
[84]	Load levelling	-	BESS	Less computational burden for peak shaving.	Simulation
[85]	Peak load shaving	Demand side management	Electric Vehicle (EV), BESS	Comparative study on DSM, EV, and BESS.	Review
[86]	Voltage regulation, peak load shaving	-	BESS	Sizing and cost-benefit analysis of BESS.	Simulation
[87]	Peak load shaving, power curve smoothing, voltage regulation	Parallel load forecasting using a linear regression method	BESS	Less computational burden for peak shaving.	Simulation, real data
[88]	Peak load shaving	Decision tree-based algorithm	BESS	Less computational burden and more cost-effective for peak shaving for islanded microgrids.	Simulation, real data
[89]	Peak load shaving	Day-ahead scheduling	Hydro power	Dependent on the forecasting model for accurate results.	Simulation, real data
[90]	Peak load shaving	Multi-objective optimization	Hydro power	Cost-effective solution for peak shaving.	Simulation, real data (China)
[91]	Peak load shaving	-	EV	The lower the cost of EV batteries, the more the net income of a single EV user.	Simulation
[92]	Peak load shaving	-	RCG, Rankine compression gas turbine	RCG applications for peak shaving and rapid transient response.	Hardware implementation of 5 kW system
[93]	Peak load shaving	Modified differential evolution	Hydro power	Minimum residential load variance with calculation precision and rapid convergence rate.	Simulation, case study
[94]	Peak load shaving	Dynamic voltage tracking	BESS	Easy computational for peak shaving.	Hardware
[95]	Peak load shaving	Feed-forward ANN for forecasting pattern recognition	BESS	Proposed ANN for peak shaving to limit the usage of diesel generators.	Simulation
[96]	Peak load shaving	Mathematical model representation of power plant	Nuclear power plant, PHS	Consideration of technical, environmental, and economics indexes for peak shaving.	Simulation, real grid data
[97]	Peak load shaving	Mixed integer linear programming	Thermal power plant	Reduces the peak valley difference in the East China power grid.	Case study of East China power grid
[98]	Peak load shaving	Efficiency model of large scale ESS	Vanadium redox battery (VRB)	Energy conversion efficiency is increased by 6.26 % on average compared to the conventional strategy.	Simulation
[99]	Peak load shaving	Multi-agent system (MAS) framework	-	Net demand profile (reduce by 3.75%) and peak to valley ratio (reduced by 7.32%) is significantly reduced.	Simulation
[100]	Peak load shaving	-	BESS	Efficiency enhancement and electricity cost reduction in Naresuan University, Thailand.	Simulation, real data
[101]	Peak load shaving	Adaptive dynamic programming	Modular lithium-ion battery	Total cost reduction by 8%.	-
[102]	Energy arbitrage	Hybrid stochastic-robust optimization	-	Participation in RTM produces more profit but affects the lifespan of the battery.	Simulation
[103]	Energy arbitrage	Mixed integer linear programming		According to the technological model, after 2024, lithium-ion arbitrage is going to be more profitable.	Simulation (Spain)
[104]	Energy arbitrage	-	PHS	Investigates the influence of parameters on profit.	Australia
[105]	Energy arbitrage	Economic dispatch model	-	Arbitrage influence on benefit and battery.	Alberta - Canada
[106]	Energy arbitrage	Technological model	CAES, PHS, ZEBRA	ESS has the greatest internal rate of return for arbitrage.	U.S. markets
[107]	Energy arbitrage	24 optimal strategy	PHS	The proposed optimal strategy is better for arbitrage than Prognostic and historical approaches.	11 countries
[108]	Energy arbitrage	-	NaS, PHS	PHS has more economic merit compared to emerging technologies such as NaS.	Alberta - Canada
[109]	Energy arbitrage	-	-	Discuss the condition and profitability of arbitrage.	Germany
[110]	Energy arbitrage	Benders decomposition	PHS	The demand curve for more than 300 generators are used for optimal sizing and maximizing the benefit.	Alberta - Canada
[111]	Energy arbitrage	Mixed integer linear programming	NMC-C, LFP-C, NCA-C, NCA-LTO, VRLA, VRFB	Profitability analysis considering 6 different types of batteries in community energy storage.	Switzerland
[112]	Energy arbitrage	-	NaS, Flywheel	Benefits of high power and energy density storage system over traditional lead-acid batteries.	New York
[113]	Energy arbitrage	-	BESS	Optimal sizing.	China
[114]	Energy arbitrage	Mixed integer linear programming, DTMC-based probabilistic model	CAES	Optimizing operational strategies for maximum profit.	Turkey
[115]	Energy arbitrage	-	CAES, LA, PHS, NaS, VRB	Optimal sizing.	Finland

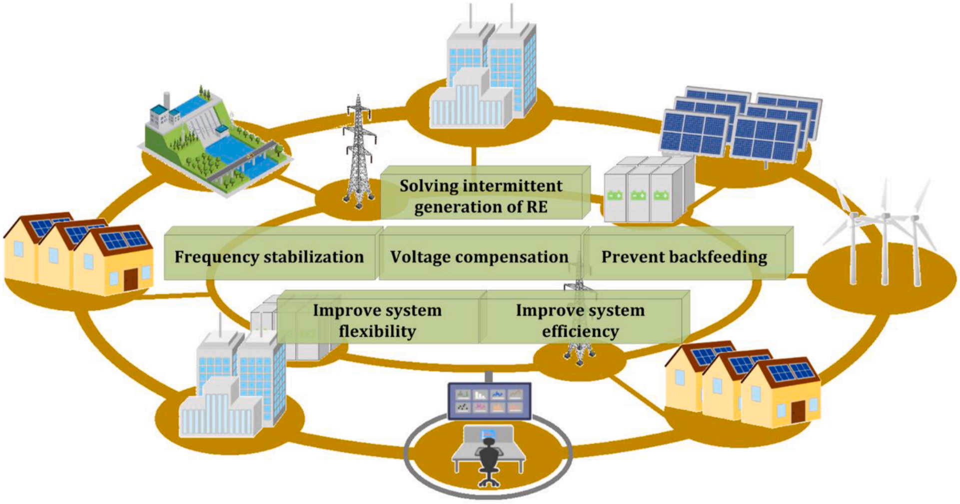


Fig. 15. Function of ESS to support RE in the power grid.

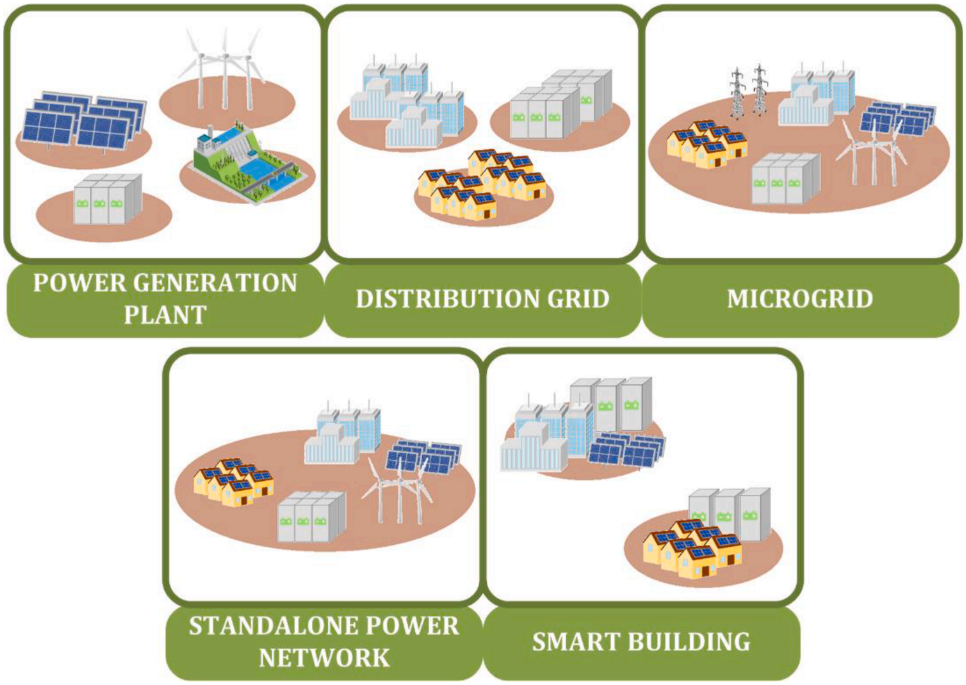


Fig. 16. Region of application for ESS in the power grid.

methods such as on-load tap changer and reactive power compensator [123]. The traditional method usually increases the voltage level at the upstream of the power network, which in turn level up the voltage of the entire feeder of the distribution network. Nevertheless, with RE's introduction into the system, voltage compensation at one node could result in a voltage violation at another system node. In [123], a coordinated voltage compensation method was introduced to regulated distribution network voltage by utilizing multiple distributed ESS. This method strategically divides the grid into multiple regions and implements each region's voltage compensation with a distributed ESS. Coordinated control is also inherited for system synchronization to prevent over-regulation and compensate each other whenever necessary. Distributed ESS was also utilized in [124] to achieve voltage compensation for a grid with concentrated RE penetration. The proposed method mange power outputs of each ESS using distributed control and localized State-of-Charge (SOC) control.

4.1.4. *Prevent backfeeding*

Backfeeding of power in the power network is known as the flow of electricity in the reverse direction of typical power flow. Unintentional backfeeding events can lead to unpredictable hazards to the system equipment and service personnel. As RE integration to the distribution power grid is growing, it has increased the risks of power backfeeding. The common practice to prevent reverse power flow due to the surplus of RE energy was to size the RE distributed generator smaller than the system through load, ensuring RE generation is always lower than energy demand. In the case of excessive RE production, energy curtailment will be conducted.

Nevertheless, these solutions limit the growth of RE and cause ineffective energy utilization. Therefore, ESS is utilized to attain high self-consumption of RE power and minimize RE production surplus. Ke Jia and the team demonstrated the utilization of ESS in [125] to increase RE self-consumption. Variable charging and discharging threshold method were adopted to manage the ESS, improve energy efficiency, and avoid

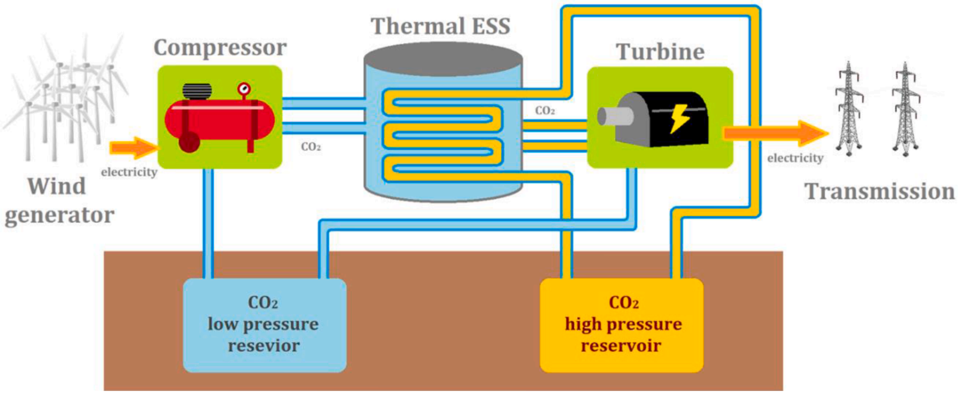


Fig. 17. Framework of a thermal-compressed supercritical carbon dioxide ESS to support wind turbine generation [126].

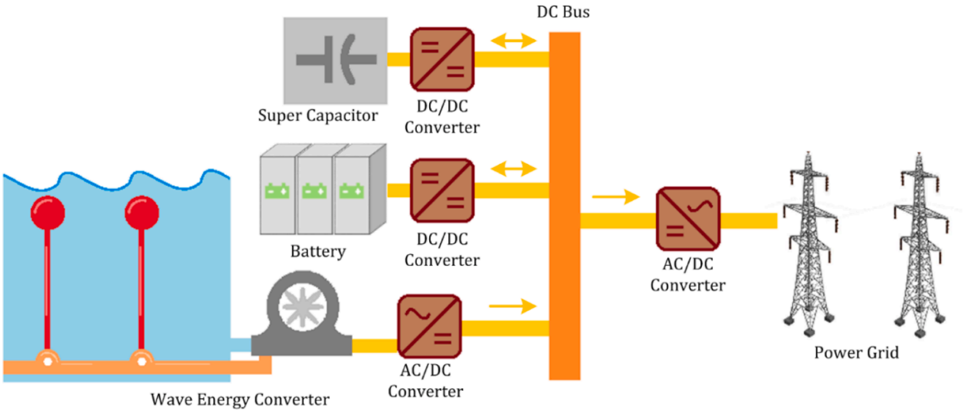


Fig. 18. Framework of a HESS to support wave energy plant [119].

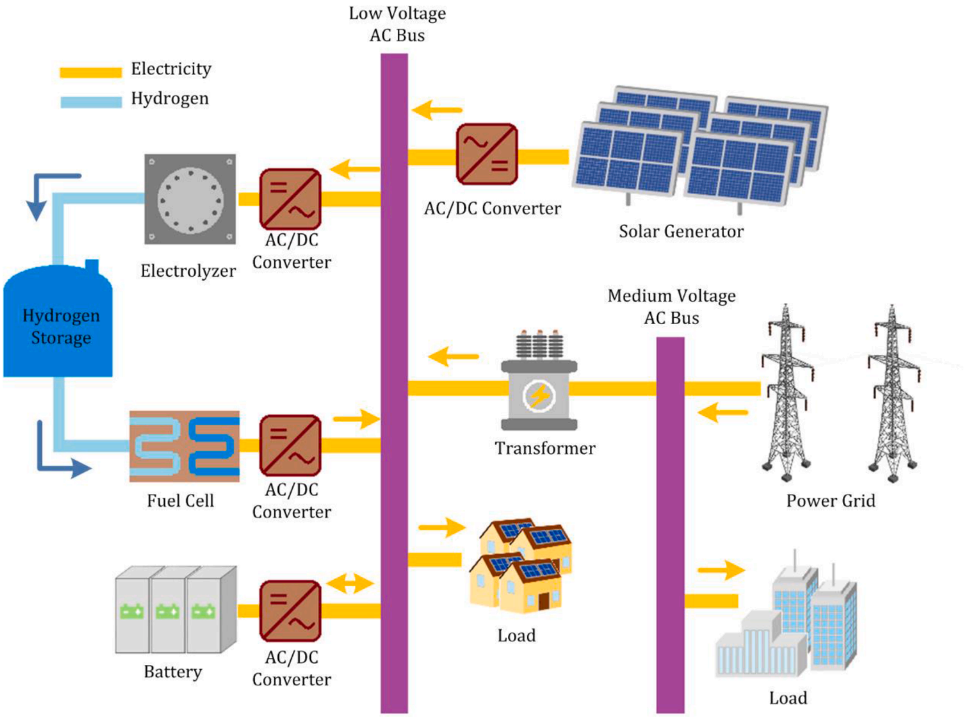


Fig. 19. Framework of a HESS to support solar distributed generator [127].

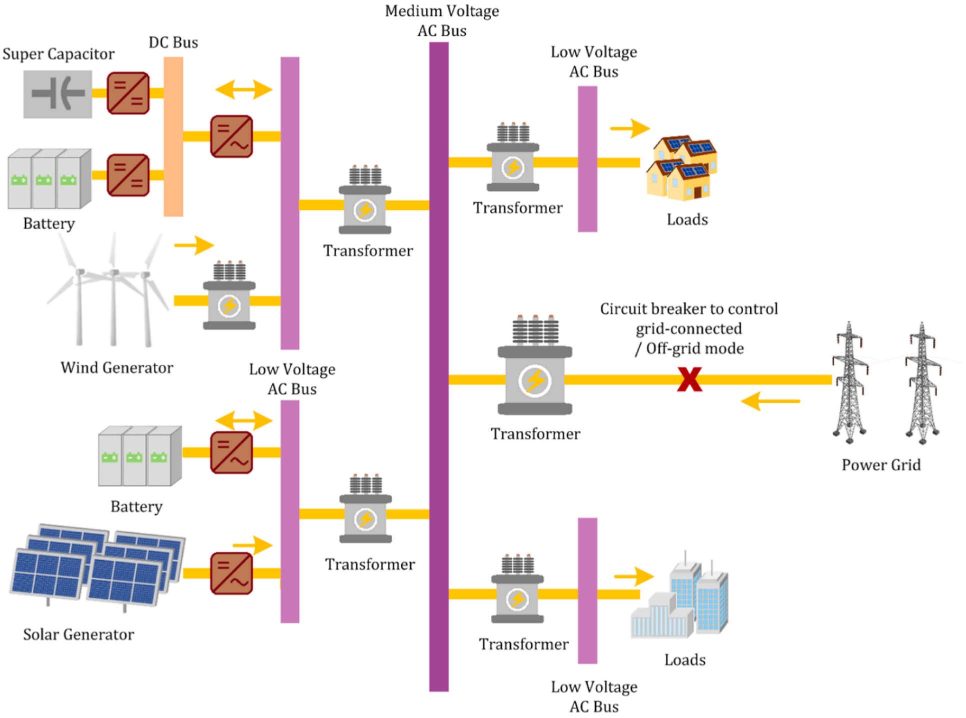


Fig. 20. Framework of a ESS to support a AC microgrid [117,122].

RE curtailment.

4.2. ESS framework for RE integration

The ESS contribution in supporting RE integration can occur in various power grid regions such as the power generation plant, distribution grid, AC/DC microgrid, standalone power network, and smart building, as illustrated in Fig. 16. This section discusses the various application frameworks for ESS in supporting the RE generation according to the integrated region.

4.2.1. Power generation plant

The inconsistent power production and high amplitude fluctuation are the main reasons for the restricted dispatchability characteristic of RE resources. These drawbacks limit the potential of RE penetration in the power grid. ESS is a promising solution to recover the mismatch between the RE inconsistent generation and varying electricity demand. As the RE generation plant's location and structure are not heavily

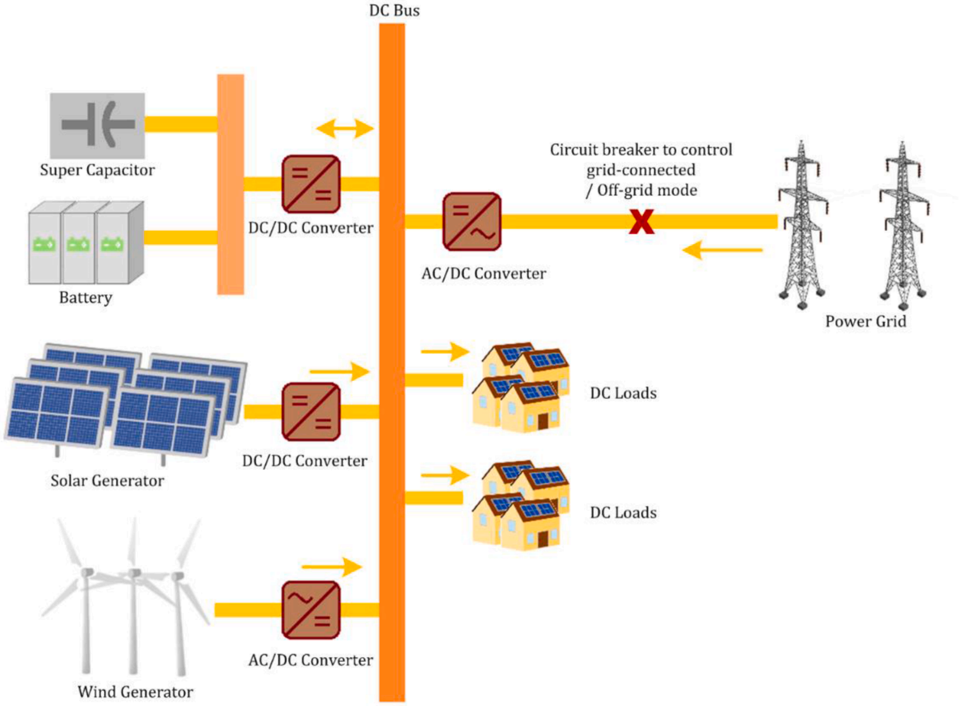


Fig. 21. Framework of a dual ESS to support a DC microgrid [128].

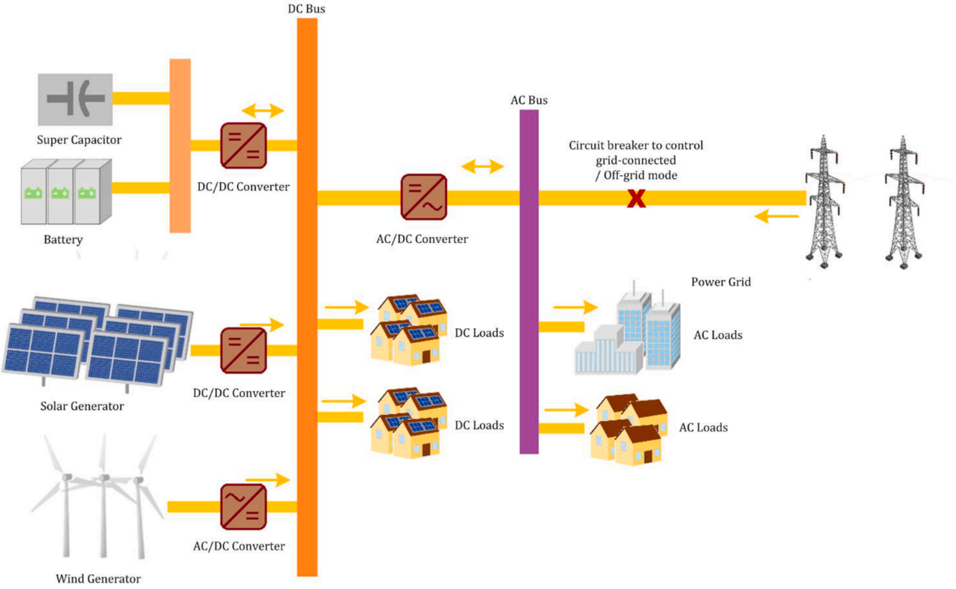


Fig. 22. Framework of a HESS to support an AC microgrid [120,129].

dependent on the location of loading, the utilization of ESS can be much flexible. For instance, thermal energy can be stored in compressed-air ESS, and kinetic energy can be stored in flywheel ESS, and electrical energy can be stored in BESS. In [126], a thermal-compressed supercritical carbon dioxide ESS (T-CCESS), as shown in Fig. 17, was proposed to store the wind turbine generation in the form of thermal energy. The T-CCESS consisted of two caverns for carbon dioxide (CO_2) storage, where one is in high pressure and another in low pressure. When there is excessive power generation, electricity produced is used by a compressor to compress CO_2 released from a low-pressure cavern and transferred to a high-pressure cavern. The heat generated during the compression is stored in the thermal ESS. In contrast, when energy demand increases, CO_2 from a high-pressure cavern is released and heated in the turbine to generate electricity.

Authors in [119] introduced the utilization of HESS to regulate the harvest of wave energy. The system framework of the wave energy plant is presented in Fig. 18. Wave energy converter is utilized to transform wave energy into AC electric energy. Meanwhile, the rectifier converts the AC power into DC power, which then stores in a BESS. This BESS can regulate the dispatchability of the power plant before transmitting the energy to load.

4.2.2. *Distribution grid*

Distributed generation using RE resources is gaining more attention recently. Electricity generation on a smaller scale and closer to the end-user can greatly reduce energy losses, improve grid resiliency, reduce carbon emissions, and defer transmission network upgrade. To increase RE distributed generation flexibility, authors in [127] proposed HESS track the feed-in schedules of a distributed solar generator. As shown in Fig. 19, HESS with a combination of hydrogen and battery ESS is adopted. This system conducted short term system regulation using batteries, which can provide a fast system response. Meanwhile, long term and large scale ESS are achieved using hydrogen ESS, which has a larger capacity and lower system losses.

4.2.3. *Microgrid*

A microgrid is a self-sufficient electricity network with a discrete geographic footprint such as a neighborhood, school, office building, or

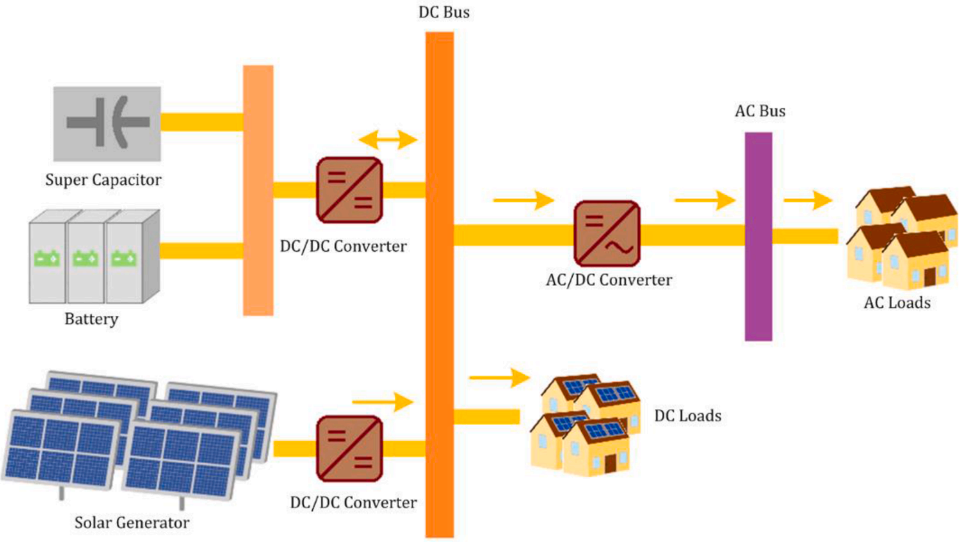


Fig. 23. Framework of a HESS to support a DC microgrid [130].

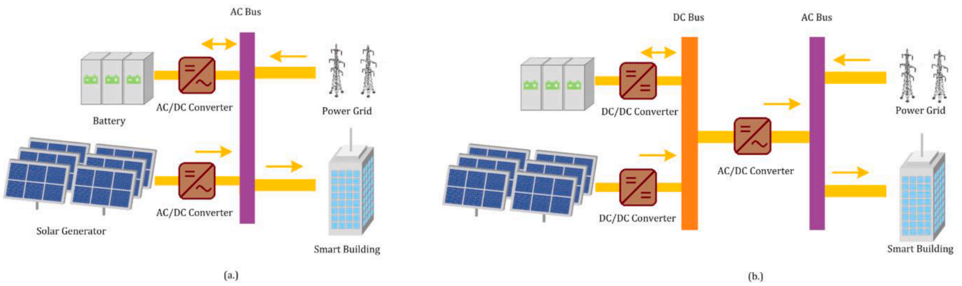


Fig. 24. Framework of ESS to support a smart building, (a) with common AC bus [116] and (b) with common DC bus [131].

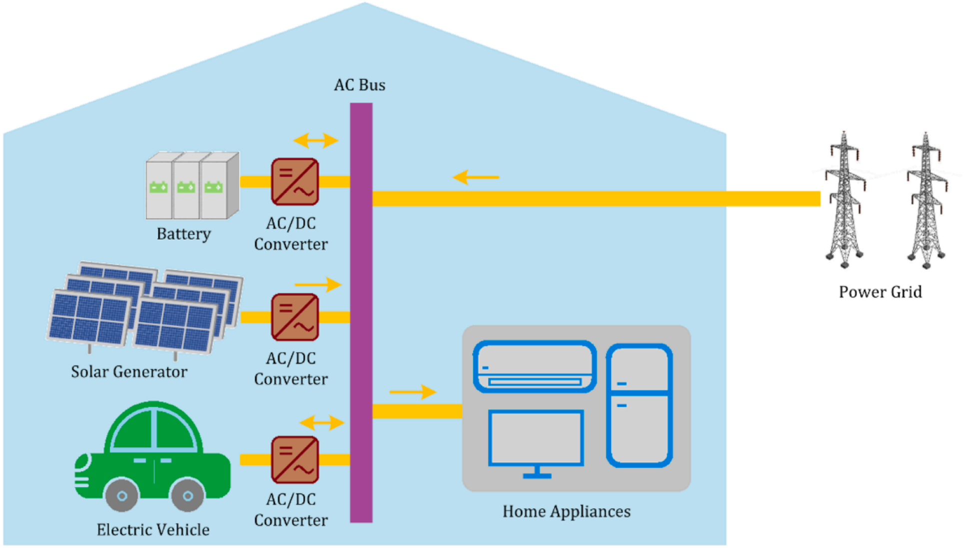


Fig. 25. Framework of EV to support a smart home [121].

hospital. This electric network consists of its own electric generator, distribution system, storage system, and loads. With an appropriate energy management system, the microgrid can achieve self-sustain, energy arbitrage, and carbon reduction benefits. A microgrid can operate in both grid-connected mode or islanded mode. Energy can be sold to or buy from the power grid whenever necessary. To achieve these functions, ESS is an inevitable element of a microgrid. In [122] and [117], the microgrid introduced was operated mainly in AC power mode. All power generated from wind and solar generators was converted into AC power and distributed to loads through AC bus. Fig. 20 illustrates the framework of AC microgrid with integrated ESS.

Subarto and the team proposed a dual ESS consists of a battery pack and supercapacitor for a DC microgrid [128]. The grid is powered by PV solar generator and supported DC loads, where the system framework is illustrated in Fig. 21. This DC microgrid has various benefits, including its effectiveness in utilizing solar power generators with fewer power converters required, simpler application structures, and higher power efficiency. In [120] and [129], the DC microgrid was modified to support both DC and AC loads. Hence, an AC/DC inverter was utilized to convert DC power into AC power, as shown in Fig. 22.

4.2.4. *Standalone power system*

Energy transmission to a rural area with low electricity demand is not a practical solution: a standalone power system or off-the-grid network is usually constructed in a remote area where electric networks are unavailable. A sufficient capacity of ESS is essential for a standalone network to sustain its electricity supply, especially when powered by intermittent RE resources. In [130], the authors introduced a standalone power network to support basic household appliances in a rural area. This standalone power network framework is shown in Fig. 23, where the system consists of a solar generator, ESS, and AC/DC inverter. This network can support both AC and DC loads. The ESS comprises both batteries and supercapacitor, which are passively connected to the common DC bus. This configuration increases the ESS flexibility and energy efficiency.

4.2.5. *Smart building*

Smart buildings and residential areas equipped with RE power sources, especially rooftop solar technology, are developing quickly in recent years. Depending on the RE sizing and generation output, the building demands will be supported by either RE itself or both RE and power grid. The power grid serves as a backup supply to the system whenever the RE generation is lower than the building demands. In general, there are two types of framework connections for a smart building with a solar generator and ESS, where both elements are having a common AC bus [116] or a common DC bus [131]. Fig. 24 illustrates both frameworks for a smart building. As solar generator outputs DC power, it is more energy and cost-efficient to utilize the common DC bus connection.

Electric Vehicle (EV) market is growing drastically in recent years. This trend has opened up a brand new concept, namely Vehicle-to-Grid (V2G) technology, where EV is utilized to replace ESS. Authors in [121] adopted this concept and successfully utilized EV to conduct energy management and mitigate a smart home's intermittency, as illustrated in Fig. 25. Table 2 summarizes the recent research and development of ESS technologies to support the deployment of RE integration.

Table 2
Summary of the research and development of ESS technologies to support the deployment of RE integration.

Ref.	Description	ESS type	Application network	Main Function of ESS
[132]	Proposed of a dynamic simulation model of a two-tank indirect thermal ESS for a solar power plant	Thermal ESS	Power generation plant	Mitigate RE intermittency
[119]	Energy management control for battery-super capacitor ESS for a grid-connected wave energy park	Battery - SC	Power generation plant	Mitigate RE intermittency
[126]	Designed a stochastic dynamic simulation system for a hybrid thermal-compressed carbon dioxide ESS integrated with a wind farm	Hybrid thermal-compressed carbon dioxide storage system	Power generation plant	Improve RE dispatchability
[116]	Evaluate the role of Lithium-Ion battery integration to large scale grid in an application such as frequency regulation, peak shifting, integration of RE, and energy management	Li-Ion battery	Distribution grid, grid-connected system	Frequency regulation, peak shifting, integration of RE and energy management
[123]	Coordinated control for voltage regulation of ESS and PV integrated distribution system	Battery	Distribution grid, grid-connected system	Voltage regulation
[124]	Coordinate control method with localized and distributed controls to achieve voltage regulation of distribution network with high penetration of rooftop solar panel using BESS.	Battery	Distribution grid, grid-connected system	Voltage regulation
[120]	Development of a smart energy management algorithm for an ESS in smart grid applications, mainly to support RE integration	Battery - SC	Distribution grid, grid-connected system	Mitigate RE intermittency
[133]	Optimal planning and scheduling of ESS for congestion management in electric power systems including generation from RE resources	ESS	Distribution grid, grid-connected system	Relief system congestion
[127]	Proposed of three-stage scheduling scheme for HESS to track scheduled feed-in solar generation		Distribution grid, grid-connected system	Improve system flexibility
[134]	Proposed of the distributed optimal solution for ESS to maintain generation and demand balance, while maximizing system efficiency of a microgrid	Battery	AC Microgrid	Improve system efficiency
[122]	Design of a HESS for primary frequency control using a dynamic droop method in microgrid	Battery -SMES	AC Microgrid	Frequency regulation
[125]	Design of adaptive Intelligent technique to improve the energy management efficiency of a microgrid	Battery - SC	AC Microgrid	Prevent backfeeding
[117]	Proposed optimal control-based energy management for a multi ESS to maintain the supply-demand balance in a microgrid.	Battery	AC Microgrid	Mitigate RE intermittency
[129]	Proposed of a Hierarchical Control Structure for Distributed ESS for a DC microgrid	Battery	DC Microgrid	Energy balancing and system stability
[128]	Development of an energy management system for a DC microgrid with dual ESSs	Battery - SC	DC Microgrid	System stability
[135]	Design of coordinated control strategy for DC microgrid with HESS to smooth solar and wind generation	Battery - SC	DC microgrid	Frequency regulation, system stability
[136]	Design and Implementation of BESS in DC microgrid utilizing fuzzy current and voltage control	Battery	DC microgrid	System stability
[130]	Study of HESS for standalone solar power generation plant in rural electrification network	Battery - SC	The standalone solar grid in a rural area	System stability
[137]	Techno-economic analysis of ESS to support wind generation	CAES and battery	Standalone power network	System stability
[131]	A heuristic control strategy to alleviate voltage fluctuation in distribution grid due to PV generation	Battery - SC	Smart building	Reduce voltage fluctuation

(*continued on next page*)

Table 2 (*continued*)

Ref.	Description	ESS type	Application network	Main Function of ESS
[121]	Energy management framework based on Energy Price Tag (EPT) of connected ESS to address the RE intermittency challenges.	Plug-in EV	Smart building	Mitigate RE intermittency

5. Challenges and future prospects

In the modern power network, ESS plays an inevitable role in maintaining the power grid reliability and sustainability. Nevertheless, the integration of ESS to the power grid can be challenging. Hence, to success the ESS integration, the following challenges shall be encountered.

5.1. Battery ESS degradation

As one of the most common ESS types adopted, the battery faces degradation problems, which can shorten the storage life span. This is due to the cycling of battery charging and discharging that elevated the battery temperature, and aging reduces the performance over time. In [138], the authors introduced a control strategy to centrally control a distributed BESS in a microgrid, which had the goal of enhancing the ESS life span. The proposed strategy evaluated the BESS status of health based on battery SOC and maximum capacity. The controller then prioritized the BESS with better health and higher capacity for power grid services and proven the concept had improved the overall BESS life span by 57%.

5.2. ESS energy efficiency

With respect to the application of ESS to support distributed RE generators, ESS was widely distributed installed to meet the local demand of energy consumers. Nevertheless, the uncoordinated control of these distributed ESS usually leads to unbalance SOC. This can result in certain ESS to quit operation due to low SOC; whilst some ESS with high SOC remains unused. This condition caused inefficient energy utilization. Wei Jiang and the team proposed a hierarchical control strategy in [129], which coordinated the operation of these distributed ESS to achieve higher system SOC and improved overall system efficiency. The control strategy allowed capacity sharing among ESS units using droop control, which successfully achieved balance SOC and improved all ESS efficiency.

5.3. ESS sizing and allocation

Sizing and allocation of ESS heavily depended on the system function. Inappropriate ESS sizing can lead to, inefficient system service, unnecessary energy curtailment, and insufficient energy supply. Hence, research was conducted to perform ESS sizing to determine the optimal system capacity to fulfill its application's technical requirements. In general, the methodology utilized to solve ESS sizing and allocation problem include the analytical method, mathematical programming, exhaustive search and heuristic methods [139]. For instance, authors in [140] demonstrated an ESS sizing and allocation technique using Parallel Particle Swarm Optimization – Genetic Algorithm (PPSO-GA) optimization method. The proposed algorithm deployed the battery and supercapacitor's output power according to the system operation period and cutoff frequency. Later, this information was utilized to deduce ESS's optimal sizing, which intended to achieve a balance system costs and lifetime.

BESS has limited lifespan, which can be affected by the frequency of charging/discharging cycle and its depth of discharge. Overtime, BESS maintenance and replacement is essential to maintain the system reliability and operational feasibility. Sizing and replacement plan of BESS for an off-grid microgrid application was presented in [141]. A multi-stage and multi-timescale BESS planning considered the short term random factors (e.g. fluctuation of RE generation, varying power demands, etc.) and long term dynamic factors (e.g. growth of power demand, BESS capacity degradation, etc.) was proposed to scale the investment required for BESS renewal and maintenance purposes.

ESS is also a key factor to enable regulation of RE generation, mainly for smoothing the power output. Throughout these ESS operation, battery SOC shall not be fully charged, nor fully discharge easily. Ideally, the storage SOC shall maintain around 50 percent to ensure good storage capacity to charge and discharge for effective RE output regulation. Authors in [142] developed a storage sizing method which aims to obtain a more dispatchable wind power system. The proposed control-based sizing method is capable of facilitating the robust unit commitment via regulating the generation of wind plant according to a preset system reference. The controller monitors the storage SOC throughout its operation to avoid it being fully charge during the regulation. Meanwhile, the simulation results are utilized to determine the optimal sizing for the ESS.

Financial risk analysis is always an important first step for any business investment. In [143], Zao Tang and team presented a bi-level optimal sizing approach for HESS integration to a high RE penetration distribution grid. The proposed dual layer sizing method can analyze the investment risks due to intermittent RE generation. The first layer investigate the economic composition related to HESS initial investment cost; whilst the second layer optimize the strategies to minimize the operation cost. In the meantime, Ahmad and team concerned about the development plan of joint transmission network and integrated energy storage in a wind powered grid [144]. Utilizing the conventional hourly discrete time model can lead to high operation cost and non-optimal system sizing and placement. Research in [144] presented a continuous-time hybrid robust optimization, which determine the optimal investment plan for transmission line and energy storage in a wind turbine powered grid.

5.4. ESS financial feasibility

ESS integration for smart grid advancement is a relatively new technology introduced in the latest decade. Besides understanding the technical aspect of this technology, its application's economic feasibility is also important to ensure the technology practicality. Nevertheless, ESS's economic studies were rather limited, where most of the case, only the system capital cost was addressed. For a comprehensive techno-economic analysis, the model shall include system capital investment, operational expenses, maintenance cost, and asset degradation loss.

Table 3 summarizes the research works conducted to overcome the ESS degradation, system efficiency, and financial feasibility challenges faced in the ESS technology rollout.

6. Conclusion

This article was intended to enhance the reader's understanding of the overall deployment of ESS technology. A comprehensive assessment of ESS, which is used to improve the smart grid reliability and sustainability, was presented. This review included the classifications and comparisons of various ESSs, including thermal, mechanical, electrochemical, electrical, and chemical ESS. Various combinations of HESS were also discussed where different ESS types were combined to achieve an improved version of energy storage. In general, ESS is utilized to support the power grid operation, as well as to enhance RES integration in the power grid. ESS obtained the former benefit via power grid

Table 3
Summary of ESS technology challenges and solutions.

Ref	Description	Challenge	Solution/ Objective of Research	ESS Technology	System Application	Technique
[145]	Optimal sizing of a HESS in PV household-prosumers to maximize self-consumption and self-sufficiency	High cost	Reduce system cost	Battery - SC	Household PV panel	The analytical methodology that assesses the techno-economic effect
[146]	Sizing of HESS to perform ramp-rate control in PV power plants	High cost, ESS degradation	Reduce system cost, prolong ESS lifespan	Battery - SC	PV power plant	The techno-economic model that can be used to measure the Net Present Cost over the project life
[147]	Sizing of HESS for a PV based microgrid	ESS degradation	Minimize annualized life-cycle costs	Battery - hydrogen storage	PV based microgrid	Generic sizing technique through design space approach
[148]	Optimum sizing and optimum energy management of a HESS	ESS degradation	Prolong ESS lifespan	Lithium battery - SC	RE power plant	Sizing optimization formulization based on the initial cost and the 10-year battery replacement cost
[149]	Sizing of battery and supercapacitor in a HESS for wind turbines	ESS degradation	Prolong ESS lifespan	Battery - SC	Wind power plant	Sizing method based on the average fluctuation of the wind
[150]	Optimal sizing and control for HESS with SMES and battery	High cost, Energy inefficiency	Reduce system cost, improve efficiency	SMES - lead-acid battery	Residential PV system	Optimization algorithm considering the price of the system and the power output reference.
[151]	Sizing a HESS for maintaining power balance of an isolated system with high penetration of wind generation	ESS degradation, System instability	Prolong ESS lifespan, improve system energy balance	Battery - SC	Wind power plant	Frequency-based approach algorithm
[152]	A statistical approach for HESS sizing based on capacity distributions in an autonomous PV/ Wind power generation system	High cost, Energy inefficiency	Improve efficiency, prolong ESS lifespan	Battery - SC	PV / wind power plant	Statistical methodology
[153]	Optimal sizing of hybrid fuel cell-supercapacitor storage system for off-grid renewable applications	System instability, High cost	Improve reliability and cost-effectiveness	Hydrogen fuel cell - SC	Off-grid RE system	Sensitivity analysis
[154]	HESS sizing and power splitting optimization for PHEV	High cost, Bulky system size	Minimize the cost weight and volume of ESS	Battery - SC	PHEV	Multi-objective optimization problem
[155]	Optimal sizing of HESS sub-systems in PV/diesel ship power system using frequency analysis	ESS degradation, High cost	Prolong ESS lifespan, reduce system cost	Lead Acid and Lithium-Ion battery - SC	PV system on shipboard	Discrete Fourier Transform (DFT) approach and Particle Swarm Optimization (PSO)
[156]	Optimizing size and cost of HESS with state of charge regulation for stand-alone direct current microgrids	ESS degradation	Prolong ESS lifespan	Battery - SC	PV standalone DC microgrid	Multi-objective genetic algorithms optimization
[157]	Techno-economic evaluation of HESS technologies for a solar–wind generation system	High cost	Study technical and financial feasibility of ESS technology	SMES, Flywheel, SC, and redox flow batteries	Solar/wind generation plant	Techno-economic analysis
[158]	Techno-economic analysis of storage degradation effect on Levelized cost of HESS	ESS degradation	Determine HESS combination with longest ESS lifespan	Hydrogen fuel cell - SC	Rural area electrification	Techno-economic analysis include system degradation and replacement costs
[159]	Assessing hybrid supercapacitor-battery energy storage for active power management in a wind-diesel system	ESS degradation	Reduce ESS operation stress	Battery - SC	Wind - diesel power plant	particle swarm optimization techniques
[160]	Optimization for a HESS in EV	ESS degradation	prolong ESS lifespan	Battery - SC	Electric city bus	dynamic programming approach optimization
[161]	The configuration method of HESS for high power density	Bulky system size, Energy inefficient	Reduce ESS weight and improve system efficiency	Battery - SC	Electric aircraft	
[140]	Investment planing considering the life cycle of BESS in a off-grid wind-solar-diesel microgrid	Energy inefficient	Ensure efficient and reliable microgrid operation via BESS sizing and allocation	Battery	Microgrid in remote area	Sizing and plancement using multi-stage multi-timescale decision framework
[142]	ESS sizing method for optimal wind farm energy efficiency	Energy inefficient	Facilitate robust unit commitment via regulating generation of wind source	Battery - SC	Wind farm	Control-based sizing algorithm
[143]	ESS sizing approach considering the financial risk analysis	High cost	Perform investment risk analysis	Battery	RE integrated distribution network	Bi-level optimal sizing approach
[144]	Optimal investment plan for transmission line and energy storage in a wind turbine powered grid	High cost	Determine optimal investment plan	Battery	Transmission line with wind powered generation	Continuous-time hybrid robust optimization

services such as energy arbitrage, peak shaving, load following, voltage regulation, frequency regulation, and black start. Meanwhile, the advantage of ESS to support RE integration is achieved by solving the intermittent generation of RE, frequency regulation, voltage regulation, prevent back feeding, improve system flexibility, and efficiency. Challenges and future prospects of ESS technology were also discussed to inspire the future research and development of the technology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This research is supported by Tenaga Nasional Berhad (TNB) Seeding Fund – Hybrid Energy Storage System to Enhance Renewable Energy Integration (U-TD-RD-19-22).

References

[1] J. Qian, X. Wu, D.S. Kim, D.W. Lee, Seesaw-structured triboelectric nanogenerator for scavenging electrical energy from rotational motion of mechanical systems, Sensors Actuators, A Phys 263 (2017) 600–609. Aug.
[2] Dalia Yousri, Thanikanti Sudhakar Babu, Dalia Allam, Vigna Ramachandaramurthy, Eman Beshr, Magdy Eteiba, Fractional chaos maps with flower pollination algorithm for partial shading mitigation of photovoltaic systems, Energies 12 (18) (2019) 3548.
[3] D.P. L.barelli, P.A.Ottaviano G.Bindini, Vanadium redox flow batteries application to electric buses propulsion: performance analysis of hybrid energy storage system, J. Energy Storage 24 (2019).
[4] H. Tao, X. Yang, Z. Li, T. Q. Zheng, X. You, and P. Kobrle, "Analysis and Control of Improved MMC with Symmetrical Super Capacitor Energy Storage System in EER Application," 2019 4th IEEE Work. Electron. Grid, eGRID 2019, December, 2019.
[5] L.W. Chong, Y.W. Wong, R.K. Rajkumar, R.K. Rajkumar, D. Isa, Hybrid energy storage systems and control strategies for standalone renewable energy power systems, Renew. Sustain. Energy Rev. 66 (2016) 174–189.
[6] G.J. May, A. Davidson, B. Monahov, Lead batteries for utility energy storage: a review, J. Energy Storage 15 (2018) 145–157.
[7] P. Roy, J. He, Y. Liao, Cost Minimization of Battery-Supercapacitor Hybrid Energy Storage for Hourly Dispatching Wind-Solar Hybrid Power System, IEEE Access 8 (2020) 210099–210115.
[8] David Frankel, Amy Wagner, Battery Storage: The Next Disruptive Technology in the Power Sector, McKinsey & Company (2017). June. www.mckinsey.com/business-functions/sustainability-and-resource-productivity/our-insights/battery-storage-the-next-disruptive-technology-in-the-power-sector.
[9] Chris Mooney, The U.S. Just Hit a Major Milestone for Energy Storage—Which is Also Great News for Solar, Washington Post (2018). March 6. https://www.washingtonpost.com/news/energy-environment/%20wp/2018/03/06/the-u-s-just-hit-a-major-milestone-for-energy-storage-which-is-also-great-news-for-solar/?utm_term=.39d2c74da45d.
[10] Brattle Study: FERC Order Sets Course for 50,000 MW U.S. Storage Market, Cision PR Newswire (2018). February 22. www.prnewswire.com/news-releases/brattle-study-ferc-order-sets-course-for-50000-mw-us-storage-market-300602866.html.
[11] Clean Energy Group, "Why Energy Storage is Important Now". https://www.cleanegroup.org/ceg-projects/energy-storage/background/#toggle-id-1.
[12] P.J. Hall, E.J. Bain, Energy-storage technologies and electricity generation, Energy Policy 36 (2008) 4352–4355.
[13] J. Baker, New technology and possible advances in energy storage, Energy Policy 36 (12) (2008) 4368–4373.
[14] N. Nitta, F. Wu, J.T. Lee, G. Yushin, Li-ion battery materials: present and future, Mater. Today 18 (5) (2015) 252–264.
[15] G. Girishkumar, B. McCloskey, A.C. Luntz, S. Swanson, W. Wilcke, Lithium−air battery: promise and challenges, J. Phys. Chem. Lett 1 (14) (2010) 2193–2203.
[16] L. Zhang, Z. Wang, D. Xu, X. Zhang, L. Wang, The development and challenges of rechargeable non-aqueous lithium–air batteries, Int. J. Smart Nano Mater. 4 (1) (2013) 27–46.
[17] P.G. Bruce, S.A. Freunberger, L.J. Hardwick, J. Tarascon, Li–O2 and Li–S batteries with high energy storage, Nat. Mater. 11 (1) (2012) 19–29.
[18] P. Verma, P. Maire, P. Novák, A review of the features and analyses of the solid electrolyte interphase in Li-ion batteries, Electrochim. Acta 55 (2010) 6332–6341.
[19] M.M. Thackeray, C. Wolverton, E.D. Isaacs, Electrical energy storage for transportation—approaching the limits of, and going beyond, lithium-ion batteries, Energy Environ. Sci. 5 (2012) 7854–7863.
[20] M. Watanabe, M.L. Thomas, S. Zhang, K. Ueno, T. Yasuda, K. Dokko, Application of ionic liquids to energy storage and conversion materials and devices, Chem. Rev. 117 (2017) 7190–7239.
[21] Y. Ru, S. Zheng, H. Xue, H. Pang, Different positive electrode materials in organic and aqueous systems for aluminium ion batteries, J. Mater. Chem. A 7 (2019) 14391.
[22] R. Kötz, M. Carlen, Principles and applications of electrochemical capacitors, Electrochim. Acta 45 (2000) 2483–2498.
[23] P. Lu, D. Xue, H. Yang, Y. Liu, Supercapacitor and nanoscale research towards electrochemical energy storage, Int. J. Smart Nano Mater. 4 (1) (2013) 2–26.
[24] P. Sharma, T.S. Bhatti, A review on electrochemical double-layer capacitors, Energy Conv. Manag. 51 (2010) 2901–2912.
[25] D. Qi, Y. Liu, Z. Liu, L. Zhang, X. Chen, Design of architectures and materials in in-plane micro-supercapacitors: current status and future challenges, Adv. Mater. 29 (5) (2017), 1602802.
[26] J.R. Miller, P. Simon, Electrochemical capacitors for energy management, Sci. Mag. 321 (5889) (2008) 651–652.
[27] M.R. Lukatskaya, B. Dunn, Y. Gogotsi, Multidimensional materials and device architectures for future hybrid energy storage, Nat. Commun. 7 (2016) 12647.
[28] A.Z. Weber, M.M. Mench, J.P. Meyers, P.N. Ross, J.T. Gostick, Q. Liu, Redox flow batteries: a review, J. Appl. Electrochem. 41 (10) (2011) 1137–1164.
[29] C. Choi, S. Kim, R. Kim, Y. Choi, S. Kim, H. Jung, J.H. Yang, H.T. Kim, A review of vanadium electrolytes for vanadium redox flow batteries, Renew. Sust. Energy Rev. 69 (2017) 263–274.
[30] N. Xu, X. Li, X. Zhao, J.B. Goodenough, K. Huang, A novel solid oxide redox flow battery for grid energy storage, Energy Environ. Sci. 4 (2011) 4942–4946.
[31] M. Yue, Q. Zheng, F. Xing, H. Zhang, X. Li, Z. Ma, Flow field design and optimization of high power density vanadium flow batteries: a novel trapezoid flow battery, AIChE J 64 (2) (2017) 782–795.
[32] R. Niu, L. Kong, L. Zheng, H. Wang, H. Shi, Novel graphitic carbon nitride nanosheets/sulfonated poly(ether ether ketone) acid-base hybrid membrane for vanadium redox flow battery, J. Membr. Sci. 525 (2017) 220–228.
[33] P. Fleuchaus, B. Godschalk, I. Stober, P. Blum, Worldwide application of aquifer thermal energy storage – A review, Renew. Sust. Energy Rev. 94 (2018) 861–876.
[34] P. Tatsidjodoung, N.Le Pierrès, L. Luo, A review of potential materials for thermal energy storage in building applications, Renew. Sust. Energy Rev. 18 (2013) 327–349.
[35] I. Sarbu, S. Sebarchievici, A comprehensive review of thermal energy storage, Sustainability 10 (1) (2018) 191–223.
[36] A. Gil, M. Medrano, I. Martorell, A. Lázaro, P. Dolado, B. Zalba, L.F. Cabeza, State of the art on high temperature thermal energy storage for power generation. Part 1—Concepts, materials and modellization, Renew. Sust. Energy Rev. 14 (1) (2010) 31–55.
[37] A.V. Novo, J.R. Bayon, D. Castro-Fresno, J. Rodriguez-Hernandez, Review of seasonal heat storage in large basins: water tanks and gravel–water pits, Appl. Energy 87 (2010) 390–397.
[38] F. Agyenim, N. Hewitt, P. Eames, M. Smyth, A review of materials, heat transfer and phase change problem formulation for latent heat thermal energy storage systems (LHTESS), Renew. Sust. Energy Rev. 14 (2010) 615–628.
[39] Y. Lin, Y. Jia, G. Alva, G. Fang, Review on thermal conductivity enhancement, thermal properties and applications of phase change materials in thermal energy storage, Renew. Sust. Energy Rev. 82 (3) (2018) 2730–2742.
[40] D. Rozanna, T.G. Chuah, A. Salmiah, T.S.Y. Choong, M. Sa'ari, Fatty acids as phase change materials (PCMs) for thermal energy storage: a review, Int. J. Green Energy 1 (4) (2005) 495–513.
[41] H. Nazir, M. Batool, F.J. Bolivar Osorio, M. Isaza-Ruiz, Z. Xu, K. Vignarooban, P. Phelan, K.a.n.n.a.n.A.M. Inamuddin, Recent developments in phase change materials for energy storage applications: a review, Int. J. Heat Mass Transf. 129 (2019) 491–523.
[42] G. Florides, S. Kalogirou, Ground heat exchangers—A review of systems, models and applications, Renew. Energy 32 (2007) 2461–2478.
[43] K.S. Lee, A review on concepts, applications, and models of aquifer thermal energy storage systems, Energies 3 (6) (2010) 1320–1334.
[44] P. Fleuchaus, B. Godschalk, I. Stober, P. Blum, Worldwide application of aquiferthermal energy storage – a review, Renew. Sust. Energy Rev. 94 (2018) 861–876.
[45] P. Pinel, C.A. Cruickshank, I. Beausoleil-Morrison, A. Wills, A review of available methods for seasonal storage of solar thermal energy in residential applications, Renew. Sust. Energy Rev. 15 (2011) 3341–3359.
[46] D. Lefebvre, F.H. Tezel, A review of energy storage technologies with a focus on adsorption thermal energy storage processes for heating applications, Renew. Sust. Energy Rev. 67 (2017) 116–125.
[47] A. Haji Abedin, M.A. Rosen, A critical review of thermochemical energy storage systems, Open Renew. Energy J. 4 (2011) 42–46.
[48] E. N'Tsoukpoe, H. Liu, N.Le Pierrès, L. Luo, A review on long-term sorption solar energy storage, Renew. Sust. Energy Rev. 13 (9) (2009) 2385–2396.
[49] J.M. Bermúdez, E. Ruisánchez, A. Arenillas, A.H. Moreno, J.A. Menéndez, New concept for energy storage: microwave-induced carbon gasification with CO2, Energy Conv. Manag. 78 (2014) 559–564.
[50] S.M. Mousavi, F. Faraji, A. Majazi, K. Al-Haddad, A comprehensive review of Flywheel Energy Storage System technology, Renew. Sust. Energy Rev. 67 (2017) 477–490.
[51] B. Bolund, H. Bernhoff, M. Leijon, Flywheel energy and power storage systems, Renew. Sust. Energy Rev. 11 (2007) 235–258.
[52] M.E. Amiryar, K.R. Pullen, A review of flywheel energy storage system technologies and their applications, Appl. Sci. 7 (3) (2017) 286–307.
[53] F. Meishner, D.U. Sauer, Wayside energy recovery systems in DC urban railway grids, eTransportation 1 (2019), 100001.
[54] H. Toodeji, A developed flywheel energy storage with built-in rotating supercapacitors, Turk. J. Elec. Eng. Comp. Sci. 27 (2019) 213–229.
[55] S. Rehman, L.M. Al-Hadhrami, M.M. Alam, Pumped hydro energy storage system: a technological review, Renew. Sust. Energy Rev. 44 (2015) 586–598.
[56] J. Menéndez, A. Ordóñez, R. Álvarez, A. Loredo, Energy from closed mines: underground energy storage and geothermal applications, Renew. Sust. Energy Rev. 108 (2019) 498–512.
[57] J.P. Deane, B.P. Ó Gallachóir, E.J. McKeogh, Techno-economic review of existing and new pumped hydro energy storage plant, Renew. Sust. Energy Rev. 14 (2010) 1293–1302.

[58] D. Beevers, L. Branchini, V. Orlandini, A. De Pascale, H. Perez-Blanco, Pumped hydro storage plants with improved operational flexibility using constant speed Francis runners, Appl. Energy 137 (2015) 629–637.

[59] R. Vasudevan Krishnakumar, K. Ramachandaramurthy Vigna, V. Gomathi, J. B. Ekanayake, S.K. Tiong, Modelling and simulation of variable speed pico hydel energy storage system for microgrid applications, J. Energy Storage 24 (2019), 100808.

[60] W. Yang, J. Yang, Advantage of variable-speed pumped storage plants for mitigating wind power variations: integrated modelling and performance assessment, Appl. Energy 237 (2019) 720–732.

[61] M. Mohanpurkar, A. Ouroua, R. Hovsapian, Y. Luo, M. Singh, E. Muljadi, V. Gevorgian, P. Donalek, Real-time co-simulation of adjustable-speed pumped storage hydro for transient stability analysis, Electric Power Syst. Res. 154 (2018) 276–286.

[62] C. Yang, R.B. Jackson, Opportunities and barriers to pumped-hydro energy storage in the United States, Renew. Sust. Energy Rev. 15 (2011) 839–844.

[63] A. Vasel-Be-Hagh, R. Carriveaua, D.S. Tinga, Energy storage using weights hydraulically lifted above ground, Int. J. Env. Stud. 70 (5) (2013) 792–799.

[64] M.A. Rosen, S. Koohi-Fayegh, The prospects for hydrogen as an energy carrier: an overview of hydrogen energy and hydrogen energy systems, Energy Ecol. Environ. 1 (1) (2016) 10–29.

[65] C.J. Winter, Hydrogen energy — abundant, efficient, clean: a debate over the energy-system-of-change, Int. J. Hydrog. Energy 34 (14) (2009) S1–S52. Supplement 1.

[66] T. Abbasi, S.A. Abbasi, Renewable' hydrogen: prospects and challenges, Renew. Sust. Energy Rev. 15 (6) (2011) 3034–3040.

[67] R.E. Blankenship, D.M. Tiede, J. Barber, G.W. Brudvig, G. Fleming, M. Ghirardi, M.R. Gunner, W. Junge, D.M. Kramer, A. Melis, T.A. Moore, C.C. Moser, D. G. Nocera, A.J. Nozik, D.R. Ort, W.W. Parson, R.C. Prince, R.T. Sayre, Comparing photosynthetic and photovoltaic efficiencies and recognizing the potential for improvement, Science 332 (6031) (2011) 805–809.

[68] M.F. El-Kady, V. Strong, S. Dubin, R.B. Kaner, Laser scribing of high-performance and flexible graphene-based electrochemical capacitors, Science 335 (2012) 1326–1330.

[69] Z. Styczynski, et. al., "Electric Energy Storage Systems", CIGRE Working group C6.15, Paris, 2011.

[70] M. Hasan Ali, B. Wu, R.A. Dougal, An overview of SMES applications in power and energy systems, IEEE Trans. Sustain. Energy 1 (1) (2010) 38–47.

[71] D. Sutanto, K.W.E. Cheng, Superconducting magnetic energy storage systems for power system applications, in: Proceedings of International Conference on Applied Superconductivity and Electromagnetic Devices, ASEMD, 2009, 2009.

[72] M. Bragard, N. Soltau, S. Thomas, R.W. De Doncker, The Balance of Renewable Sources and User Demands in Grids: Power Electronics for Modular Battery Energy Storage Systems, IEEE Trans. Power Electron. 25 (12) (2010) 3049–3056.

[73] A. Oudalov, R. Cherkaoui, A. Beguin, Sizing and Optimal Operation of Battery Energy Storage System for Peak Shaving Application, in: 2007 IEEE Lausanne Power Tech, 2007, pp. 621–625.

[74] F. Díaz-González, A. Sumper, O. Gomis-Bellmunt, R. Villafáfila-Robles, A review of energy storage technologies for wind power applications, Renew. Sustain. Energy Rev. 16 (4) (2012) 2154–2171.

[75] P.D. Brown, J.A.P. Lopes, M.A. Matos, Optimization of Pumped Storage Capacity in an Isolated Power System With Large Renewable Penetration, IEEE Trans. Power Syst. 23 (2) (2008) 523–531.

[76] A. Mohd, E. Ortjohann, A. Schmelter, N. Hamsic, D. Morton, Challenges in integrating distributed energy storage systems into future smart grid, in: 2008 IEEE international symposium on industrial electronics, 2008, pp. 1627–1632.

[77] E. Hirst, B. Kirby, Separating and measuring the regulation and load-following ancillary services, Util. Policy 8 (2) (1999) 75–81.

[78] J. Eyer, G. Corey, Energy storage for the electricity grid: Benefits and market potential assessment guide, Sandia Natl. Lab. 20 (10) (2010) 5.

[79] J.M. Guerrero, J.C. Vasquez, J. Matas, L.G. De Vicuña, M. Castilla, Hierarchical control of droop-controlled AC and DC microgrids—A general approach toward standardization, IEEE Trans. Ind. Electron. 58 (1) (2010) 158–172.

[80] J.M. Guerrero, P.C. Loh, T.-L. Lee, M. Chandorkar, Advanced control architectures for intelligent microgrids—Part II: Power quality, energy storage, and AC/DC microgrids, IEEE Trans. Ind. Electron. 60 (4) (2012) 1263–1270.

[81] J.M. Guerrero, M. Chandorkar, T.-L. Lee, P.C. Loh, Advanced control architectures for intelligent microgrids—Part I: Decentralized and hierarchical control, IEEE Trans. Ind. Electron. 60 (4) (2012) 1254–1262.

[82] A.A. Akhil, et al., DOE/EPRI 2013 electricity storage handbook in collaboration with NRECA, Sandia National Laboratories Albuquerque, NM, 2013.

[83] C. Lu, H. Xu, X. Pan, J. Song, Optimal sizing and control of battery energy storage system for peak load shaving, Energies 7 (12) (2014) 8396–8410.

[84] A. Rahimi, M. Zarghami, M. Vaziri, S. Vadhva, A simple and effective approach for peak load shaving using Battery Storage Systems, in: 2013 North American Power Symposium (NAPS), 2013, pp. 1–5.

[85] M. Uddin, M.F. Romlie, M.F. Abdullah, S. Abd Halim, A.H. Abu Bakar, T. Chia Kwang, A review on peak load shaving strategies, Renew. Sustain. Energy Rev. 82 (2018) 3323–3332.

[86] Y. Yang, H. Li, A. Aichhorn, J. Zheng, M. Greenleaf, Sizing Strategy of Distributed Battery Storage System With High Penetration of Photovoltaic for Voltage Regulation and Peak Load Shaving, IEEE Trans. Smart Grid 5 (2) (2014) 982–991.

[87] E. Reihani, S. Sepasi, L.R. Roose, M. Matsuura, Energy management at the distribution grid using a Battery Energy Storage System (BESS), Int. J. Electr. Power Energy Syst. 77 (2016) 337–344.

[88] M. Uddin, M.F. Romlie, M.F. Abdullah, C. Tan, G.M. Shafiullah, A.H.A. Bakar, A novel peak shaving algorithm for islanded microgrid using battery energy storage system, Energy 196 (2020), 117084.

[89] B. Liu, J.R. Lund, S. Liao, X. Jin, L. Liu, C. Cheng, Optimal power peak shaving using hydropower to complement wind and solar power uncertainty, Energy Convers. Manag. 209 (2020), 112628.

[90] J. Shen, C. Cheng, S. Wang, X. Yuan, L. Sun, J. Zhang, Multiobjective optimal operations for an interprovincial hydropower system considering peak-shaving demands, Renew. Sustain. Energy Rev. 120 (2020), 109617.

[91] X. Li, et al., A cost-benefit analysis of V2G electric vehicles supporting peak shaving in Shanghai, Electr. Power Syst. Res. 179 (2020), 106058.

[92] H.C. de Lange, H. Ouwerkerk, J. Schot, H.A.N. Abdelaal, Proof of concept of the Rankine Compression Gas Turbine (RCG) for a rapid peak-shaving response in industrial application, Appl. Therm. Eng. 173 (2020), 115251.

[93] S. Shu, L. Mo, Y. Wang, Peak Shaving Strategy of Wind-Solar-Hydro Hybrid Generation System Based on Modified Differential Evolution Algorithm, Energy Procedia 158 (2019) 3500–3505.

[94] M. García-Plaza, J. Eloy-García Carrasco, J. Alonso-Martínez, A. Peña Asensio, Peak shaving algorithm with dynamic minimum voltage tracking for battery storage systems in microgrid applications, J. Energy Storage 20 (2018) 41–48.

[95] S. Chapaloglou, et al., Smart energy management algorithm for load smoothing and peak shaving based on load forecasting of an island's power system, Appl. Energy 238 (2019) 627–642.

[96] Y. Gong, et al., Peak Shaving Benefits Assessment of Renewable Energy Source Considering Joint Operation of Nuclear and Pumped Storage Station, Energy Procedia 152 (2018) 953–958.

[97] Z. Feng, W. Niu, W. Wang, J. Zhou, C. Cheng, A mixed integer linear programming model for unit commitment of thermal plants with peak shaving operation aspect in regional power grid lack of flexible hydropower energy, Energy 175 (2019) 618–629.

[98] J. Li, et al., Optimal control strategy for large-scale VRB energy storage auxiliary power system in peak shaving, Int. J. Electr. Power Energy Syst. 120 (2020), 106007.

[99] Y. Wang, L. Liu, R. Wennersten, Q. Sun, Peak shaving and valley filling potential of energy management system in high-rise residential building, Energy Procedia 158 (2019) 6201–6207.

[100] U. Prasatsap, S. Kiravittaya, J. Polprasert, Determination of Optimal Energy Storage System for Peak Shaving to Reduce Electricity Cost in a University, Energy Procedia 138 (2017) 967–972.

[101] M. Böttiger, M. Paulitschke, R. Beyer, L. Neumann, T. Bocklisch, Modular hybrid battery storage system for peak-shaving and self-consumption optimization in industrial applications, Energy Procedia 155 (2018) 102–110.

[102] A. Akbari-Dibavar, K. Zare, S. Nojavan, A hybrid stochastic-robust optimization approach for energy storage arbitrage in day-ahead and real-time markets, Sustain. Cities Soc. 49 (2019), 101600.

[103] Á. Arcos-Vargas, D. Canca, F. Núñez, Impact of battery technological progress on electricity arbitrage: An application to the Iberian market, Appl. Energy 260 (2020), 114273.

[104] R. Sioshansi, P. Denholm, T. Jenkin, J. Weiss, Estimating the value of electricity storage in PJM: Arbitrage and some welfare effects, Energy Econ 31 (2) (2009) 269–277.

[105] A.I. Adebayo, P. Zamani-Dehkordi, H. Zareipour, A.M. Knight, Impacts of transmission tariff on price arbitrage operation of energy storage system in Alberta electricity market, Util. Policy 52 (2018) 1–12.

[106] K. Bradbury, L. Pratson, D. Patiño-Echeverri, Economic viability of energy storage systems based on price arbitrage potential in real-time U.S. electricity markets, Appl. Energy 114 (2014) 512–519.

[107] D. Connolly, H. Lund, P. Finn, B.V Mathiesen, M. Leahy, Practical operation strategies for pumped hydroelectric energy storage (PHES) utilizing electricity price arbitrage, Energy Policy 39 (7) (2011) 4189–4196.

[108] S.J. Kazempour, M.P. Moghaddam, M.R. Haghifam, G.R. Yousefi, Electric energy storage systems in a market-based economy: Comparison of emerging and traditional technologies, Renew. Energy 34 (12) (2009) 2630–2639.

[109] D. Metz, J.T. Saraiva, Use of battery storage systems for price arbitrage operations in the 15- and 60-min German intraday markets, Electr. Power Syst. Res. 160 (2018) 27–36.

[110] E. Nasrolahpour, S.J. Kazempour, H. Zareipour, W.D. Rosehart, Strategic sizing of energy storage facilities in electricity markets, IEEE Trans. Sustain. Energy 7 (4) (2016) 1462–1472.

[111] T. Terlouw, T. AlSkaif, C. Bauer, W. van Sark, Multi-objective optimization of energy arbitrage in community energy storage systems using different battery technologies, Appl. Energy 239 (2019) 356–372.

[112] R. Walawalkar, J. Apt, R. Mancini, Economics of electric energy storage for energy arbitrage and regulation in New York, Energy Policy 35 (4) (2007) 2558–2568.

[113] W. Wu, B. Lin, Application value of energy storage in power grid: a special case of China electricity market, Energy 165 (2018) 1191–1199.

[114] A. Yucekaya, The operational economics of compressed air energy storage systems under uncertainty, Renew. Sustain. Energy Rev. 22 (2013) 298–305.

[115] B. Zakeri, S. Syri, Economy of electricity storage in the Nordic electricity market: the case for Finland, in: 11th International conference on the European energy market (EEM14), 2014, pp. 1–6.

[116] Tianmei Chen, Yi Jin, Hanyu Lv, Antao Yang, Meiyi Liu, Bing Chen, Ying Xie, Qiang Chen, Applications of lithium-ion batteries in grid-scale energy storage systems, Transactions of Tianjin University 26 (3) (2020) 208–217.

[117] Yinliang Xu, Xinwei Shen, Optimal control based energy management of multiple energy storage systems in a microgrid, IEEE Access 6 (2018) 32925–32934.

[118] Muhammad. Khalid, A review on the selected applications of battery-supercapacitor hybrid energy storage systems for microgrids, Energies 12 (23) (2019) 4559.

[119] Arvind Parwal, Martin Fregelius, Irinia Temiz, Malin Göteman, Janaina G. de Oliveira, Cecilia Boström, Mats Leijon, Energy management for a grid-connected wave energy park through a hybrid energy storage system, Appl. Energy 231 (2018) 399–411.

[120] Ahmet Aktas, Koray Erhan, Sule Ozdemir, Engin Ozdemir, Experimental investigation of a new smart energy management algorithm for a hybrid energy storage system in smart grid applications, Electric Power Systems Res. 144 (2017) 185–196.

[121] Sima Aznavi, Poria Fajri, Reza Sabzehgar, Arash Asrari, Optimal management of residential energy storage systems in presence of intermittencies, J. Build. Eng. 29 (2020), 101149.

[122] Jianwei Li, Rui Xiong, Qingqing Yang, Fei Liang, Min Zhang, Weijia Yuan, Design/test of a hybrid energy storage system for primary frequency control using a dynamic droop method in an isolated microgrid power system, Appl. Energy 201 (2017) 257–269.

[123] Yu Wang, K.T. Tan, Xiao Yang Peng, Ping Lam So, Coordinated control of distributed energy-storage systems for voltage regulation in distribution networks, IEEE Trans. Power Deliv. 31 (3) (2015) 1132–1141.

[124] Delong Zhang, Jianlin Li, Dong Hui, Coordinated control for voltage regulation of distribution network voltage regulation by distributed energy storage systems, Protect. Control Modern Power Syst. 3 (1) (2018) 1–8.

[125] Ke Jia, Yiru Chen, Tianshu Bi, Yaoqi Lin, David Thomas, Mark Sumner, Historical-data-based energy management in a microgrid with a hybrid energy storage system, IEEE Trans. Ind. Inform. 13 (5) (2017) 2597–2605.

[126] Farzin Chaychizadeh, Hojat Dehghandorost, Abbas Aliabadi, Alireza Taklifi, Stochastic dynamic simulation of a novel hybrid thermal-compressed carbon dioxide energy storage system (T-CCES) integrated with a wind farm, Energy Convers. Manage. 166 (2018) 500–511.

[127] Zhirui Liang, Zhengxiang Song, Jianhua Wang, Xian Wang, Guogang Zhang, Three-stage scheduling scheme for hybrid energy storage systems to track scheduled feed-in PV power, Solar Energy 188 (2019) 1054–1067.

[128] Subarto Kumar Ghosh, Tushar Kanti Roy, Md Abu Hanif Pramanik, Ajay Krishno Sarkar, Md Mahmud, An Energy Management System-Based Control Strategy for DC Microgrids with Dual Energy Storage Systems, Energies 13 (11) (2020) 2992.

[129] Wei Jiang, Chen Yang, Zhong Liu, Ming Liang, Peipei Li, Guozheng Zhou, A hierarchical control structure for distributed energy storage system in DC micro-grid, IEEE Access 7 (2019) 128787–128795.

[130] Wenlong Jing, Chean Hung Lai, Wallace SH Wong, ML Dennis Wong, A comprehensive study of battery-supercapacitor hybrid energy storage system for standalone PV power system in rural electrification, Appl. Energy 224 (2018) 340–356.

[131] Prabha Ariyaratna, Kashem M. Muttaqi, Danny Sutanto, A novel control strategy to mitigate slow and fast fluctuations of the voltage profile at common coupling point of rooftop solar PV unit with an integrated hybrid energy storage system, J. Energy Storage 20 (2018) 409–417.

[132] Xiaolei Li, Ershu Xu, Shuang Song, Xiangyan Wang, Guofeng Yuan, Dynamic simulation of two-tank indirect thermal energy storage system with molten salt, Renew. Energy 113 (2017) 1311–1319.

[133] Reza Hemmati, Hedayat Saboori, Mehdi Ahmadi Jirdehi, Stochastic planning and scheduling of energy storage systems for congestion management in electric power systems including renewable energy resources, Energy 133 (2017) 380–387.

[134] Tianqiao Zhao, Zhengtao Ding, Cooperative optimal control of battery energy storage system under wind uncertainties in a microgrid, IEEE Trans. Power Syst. 33 (2) (2017) 2292–2300.

[135] Tiezhou Wu, Fanchao Ye, Yuehong Su, Yubo Wang, Saffa Riffat, Coordinated control strategy of DC microgrid with hybrid energy storage system to smooth power output fluctuation, Int. J. Low-Carbon Technol. 15 (1) (2020) 46–54.

[136] Yuan-Chih Chang, Hao-Chin Chang, Chien-Yu Huang, Design and Implementation of the Battery Energy Storage System in DC Micro-Grid Systems, Energies 11 (6) (2018) 1566.

[137] George Caralis, Theofanis Christakopoulos, Sotirios Karellas, Zhiqiu Gao, Analysis of energy storage systems to exploit wind energy curtailment in Crete, Renew. Sustain. Energy Rev. 103 (2019) 122–139.

[138] Asfand Yar Ali, Basit Abdul, Tanvir Ahmad, Affaq Qamar, Javed Iqbal, Optimizing coordinated control of distributed energy storage system in microgrid to improve battery life, Comput. Electr. Eng. 86 (2020), 106741.

[139] M. Zidar, P.S. Georgilakis, N.D. Hatziargyriou, T. Capuder, D Škrlec, Review of energy storage allocation in power distribution networks: applications, methods and future research, IET Gener. Transm. Distrib. 10 (2016) 645–652.

[140] Ming Pang, Yikai Shi, Wendong Wang, Shun Pang, Optimal sizing and control of hybrid energy storage system for wind power using hybrid parallel PSO-GA algorithm, Energy Explor. Exploit. 37 (1) (2019) 558–578.

[141] Y. Zhang, J. Wang, A. Berizzi, X. Cao, Life cycle planning of battery energy storage system in off-grid wind–solar–diesel microgrid, IET Gener. Transm. Distrib. 12 (2018) 4451–4461.

[142] Minjian. Cao, Qingshan. Xu, Hamidreza. Nazaripouya, Chi-Cheng. Chu, Hemanshu R. Pota, Rajit Gadh, Engineering energy storage sizing method considering the energy conversion loss on facilitating wind power integration, IET Gener. Transm. Distrib. 13 (9) (2019) 1693–1699.

[143] Zao. Tang, Junyong. Liu, Youbo. Liu, Yuan. Huang, Shafqat Jawad, Risk awareness enabled sizing approach for hybrid energy storage system in distribution network, IET Gener. Transm. Distrib. 13 (17) (2019) 3814–3822.

[144] Ahmad. Nikoobakht, Jamshid. Aghaei, Integrated transmission and storage systems investment planning hosting wind power generation: continuous-time hybrid stochastic/robust optimisation, IET Gener. Transm. Distrib. 13 (21) (2019) 4870–4879.

[145] J.C. Hernández, F. Sanchez-Sutil, F.J. Muñoz-Rodríguez, Design criteria for the optimal sizing of a hybrid energy storage system in PV household-prosumers to maximize self-consumption and self-sufficiency, Energy 186 (2019), 115827.

[146] Daniel Alvaro, Rafael Arranz, Jose A. Aguado, Sizing and operation of hybrid energy storage systems to perform ramp-rate control in PV power plants, Int. J. Electr. Power Energy Syst. 107 (2019) 589–596.

[147] Ammu Susanna Jacob, Rangan Banerjee, Prakash C. Ghosh, Sizing of hybrid energy storage system for a PV based microgrid through design space approach, Appl. Energy 212 (2018) 640–653.

[148] Masoud Masih-Tehrani, Mohammad-Reza Ha'iri-Yazdi, Vahid Esfahanian, Ali Safaei, Optimum sizing and optimum energy management of a hybrid energy storage system for lithium battery life improvement, J. Power Sources 244 (2013) 2–10.

[149] Hamed Babazadeh, Wenzhong Gao, Jin Lin, Lin Cheng, Sizing of battery and supercapacitor in a hybrid energy storage system for wind turbines. Pes T&d 2012, IEEE, 2012, pp. 1–7.

[150] SunHo Bae, Seoung Uk Jeon, Jung-Wook Park, A study on optimal sizing and control for hybrid energy storage system with SMES and battery, IFAC-PapersOnLine 48 (30) (2015) 507–511.

[151] Yi Liu, Wenjuan Du, Liye Xiao, Haifeng Wang, Siqi Bu, Jun Cao, Sizing a hybrid energy storage system for maintaining power balance of an isolated system with high penetration of wind generation, IEEE Trans. Power Syst. 31 (4) (2015) 3267–3275.

[152] Abdelkader Abbassi, Mohamed Ali Dami, Mohamed Jemli, A statistical approach for hybrid energy storage system sizing based on capacity distributions in an autonomous PV/Wind power generation system, Renew. Energy 103 (2017) 81–93.

[153] Doudou N. Luta, Atanda K. Raji, Optimal sizing of hybrid fuel cell-supercapacitor storage system for off-grid renewable applications, Energy 166 (2019) 530–540.

[154] Hassan H. Eldeeb, Ahmed T. Elsayed, Christopher R. Lashway, Osama Mohammed, Hybrid energy storage sizing and power splitting optimization for plug-in electric vehicles, IEEE Trans. Industry Appl. 55 (3) (2019) 2252–2262.

[155] Shuli Wen, Hai Lan, David C. Yu, Qiang Fu, Ying-Yi Hong, Lijun Yu, Ruirui Yang, Optimal sizing of hybrid energy storage sub-systems in PV/diesel ship power system using frequency analysis, Energy 140 (2017) 198–208.

[156] P.N.D. Premadasa, D.P. Chandima, An innovative approach of optimizing size and cost of hybrid energy storage system with state of charge regulation for stand-alone direct current microgrids, J. Energy Storage 32 (2020), 101703.

[157] L. Ren, Y. Tang, J. Shi, J. Dou, S. Zhou, T. Jin, Techno-economic evaluation of hybrid energy storage technologies for a solar–wind generation system, Physica C: Superconductivity 484 (2013) 272–275.

[158] Azizat O. Gbadegesin, Yanxia Sun, Nnamdi I. Nwulu, Techno-economic analysis of storage degradation effect on levelised cost of hybrid energy storage systems, Sustain. Energy Technol. Assess. 36 (2019), 100536.

[159] H. Shayeghi, F. Monfaredi, A. Dejamkhooy, M. Shafie-khah, J.P.S. Catalão, Assessing hybrid supercapacitor-battery energy storage for active power management in a wind-diesel system, Int. J. Electr. Power Energy Syst. 125 (2020), 106391.

[160] Ziyou Song, Heath Hofmann, Jianqiu Li, Xuebing Han, Minggao Ouyang, Optimization for a hybrid energy storage system in electric vehicles using dynamic programing approach, Appl. Energy 139 (2015) 151–162.

[161] Long Cheng, Fanghua Zhang, Shuo Liu, Zehua Zhang, Configuration method of hybrid energy storage system for high power density in More Electric Aircraft, J. Power Sources 445 (2020), 227322.