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Energy Storage in Power Systems

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ABSTRACT
Energy storage system is recognized as a fundamental technology for the power system to store electrical energy in several states and convert back the stored energy into electricity when required. The systems stand at the forefront of renewable energy innovation, offering a unified solution that encapsulates efficiency, reliability, and environmental stewardship. They have the potential to revolutionize the renewable energy landscape. The have become indispensable components in harnessing renewable energy sources since they serve as a vital link in our sustainable energy transition. This paper aims at providing a clear understanding of energy storage concepts, technologies, and potential applications in different sectors of the power industry.

KEYWORDS: *energy, energy storage, power systems, power industry*

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INTRODUCTION

Today, electrical energy is the main driving force in every step of life, consuming almost every sector from residential houses to large industries. The industries of developed and developing nations are consuming most of the electric energy. The conventional energy generation system mainly uses natural gas, coal, diesel, and so on, which is primarily responsible for carbon emissions and other greenhouse gasses. Due to the generation of non-renewable energy, the climate is changing and if it continues to change, the earth will be in danger. Low carbon emission, prevention of the temperature of the earth, maintenance cost reduction, power quality improvement, and so on can be achieved by using renewable energy (RE) generation in the state of conventional energy generation. Energy storage significantly facilitates large-scale RE integration [1].

The world is moving towards a sustainable future, and renewable energy sources like solar power are becoming increasingly popular. Renewable energy sources, such as solar and wind, are intermittent and unstable, making it difficult to meet the peaks and valleys of energy demand. Figure 1 shows solar power [2], while Figure 2 shows wind power generation [3]. In the world of renewable energy, the importance of efficient energy storage solutions cannot be overstated. The key advantage of an energy storage system lies in its ability to provide a continuous and reliable power supply, even during fluctuations in energy production, with electricity as the central form of energy.

WHAT IS ENERGY STORAGE?

Energy storage is a technology and equipment system that converts, transmits, transfers, manages, regulates, and controls power. It stores energy to meet people's energy needs by storing it and releasing it when needed, while achieving efficient use of energy. Energy storage is an indispensable component of modern power systems, enabling the efficient and reliable management of electricity supply and demand. It stores excess electricity generated during periods of low demand and makes it available during times of high demand or when intermittent renewable energy sources, such as solar or wind, are not available. Energy storage systems (ESS) are innovative solutions that combine multiple components of solar power generation and storage into one cohesive unit. These systems typically include solar panels, a battery pack, an inverter, and sometimes a charge controller, all integrated into a single, manageable system. A typical energy storage system is shown in Figure 3 [4].

The main objective of ESS is to ensure a consistent and reliable power supply, reducing dependence on the traditional power grid and maximizing the use of renewable energy. Some excellent characteristics such as availability, versatility, flexible performance, fleet response time, modularity etc., make ESS more attractive for power system applications. ESSs are not *primary* electricity generation sources. They must use electricity supplied by separate electricity generators or from an electric power grid to charge the storage system, which makes ESSs *secondary* generation sources. Locations of ESS for electricity generation on an electric grid are shown in Figure 4 [5].

Two basic ratings for ESS electricity generation capacity are [5]:

- *Power capacity*—the maximum instantaneous amount of electric power that can be generated on a continuous basis and is measured in units of watts (kilowatts [kW], megawatts [MW], or gigawatts [GW])
- *Energy capacity*—the total amount of energy that can be stored in or discharged from the storage system and is measured in units of watthours (kilowatthours [kWh], megawatthours [MWh], or gigawatthours [GWh])

Battery energy storage systems are generally designed to be able to output at their full rated power for several hours.

Various types of ESS are used to ensure optimal power system operation since electrical energy can be stored in different ways. Based on the operation, applications, raw materials, and structure, ESS can be classified into five categories: mechanical energy storage (MES), chemical energy storage (CES), electrical energy storage (ESS), electro-chemical energy storage (ECES), and thermal energy storage (TES). This leads to different types of energy storage.

TYPES OF ENERGY STORAGE

Energy storage technologies can be categorized into different types based on the method used to store energy. Storage options include batteries, thermal, or mechanical systems. Each type of energy storage has its own advantages, disadvantages, and suitability for different applications. These storage technologies can be paired with software that controls the charge and discharge of energy. The choice of energy storage solution depends on factors such as required energy capacity, duration of storage, cost-effectiveness, environmental impact, and the specific needs of the application or system. Common types of energy storage include the following [6,7]:

1. *Batteries*: Battery energy storage is one of the most widely used and versatile storage technologies. Batteries work by converting chemical energy into electrical energy and can be recharged multiple times. Battery energy storage systems are becoming increasingly popular as a means to store and utilize electrical energy. These systems are comprised of rechargeable batteries that can store electricity during periods of low demand and discharge it when demand exceeds supply. Different types of batteries exist, including lithium-ion, lead-acid, nickel-cadmium, sodium, and others designed to meet specific power and duration requirements. Batteries are commonly used in portable electronics, electric vehicles, and grid-scale energy storage systems. They are now playing a growing role as they can be installed anywhere in a wide range of capacities. Since battery storage plants are compact, they can be rapidly installed and placed if necessary within urban areas, close to customer load, or even inside customer premises. The battery energy storage system or battery management system fits into the power systems as illustrated in Figure 5 [8].
2. *Pumped Hydro Storage*: Pumped-storage is a common type of energy storage. Pumped hydro storage is a well-established and widely used method for storing energy. These ESS are the oldest and some of the largest type. Pumped hydroelectric facilities account for over 95% of the storage in use today. Pumped hydro storage is a mature and reliable technology that uses gravitational potential energy to store and generate electricity. It involves using excess electrical energy to pump water from a lower reservoir to a higher reservoir. When electricity demand is high, the water is released, flowing downhill through turbines to generate electricity.
3. *Compressed Air Energy Storage* (CAES): CAES involves compressing air and storing it in underground caverns or tanks. CAES systems store energy by compressing air into underground caverns and releasing it to generate electricity when needed. When electricity demand increases, the compressed air is released and expanded through a turbine to generate electricity. This technology is suitable for large-scale energy storage applications and can help balance fluctuations in electricity supply and demand.

4. *Thermal Energy Storage* (TES): Thermal systems use heating and cooling methods to store and release energy. They work by storing energy during periods of low demand and releasing it when needed. For example, molten salt stores solar-generated heat for use when there is no sunlight. TES has various applications, including heating and cooling buildings, industrial processes, and solar thermal power plants. Water tanks in buildings are simple examples of thermal energy storage systems. Thermal energy technologies allow renewable energy for heating and cooling, as typically shown in Figure 6 [9].
5. *Flywheel Energy Storage*: Flywheel energy storage devices turn electricity into kinetic energy in the form of spinning wheels, which can then be used to store grid energy. Flywheels store energy in a rapidly spinning mechanical rotor and are capable of absorbing and releasing high power for typically 15 minutes or less, although longer duration systems are being developed. Flywheel energy storage systems harness the energy of a rotating mass to store and release electricity. They store energy in a rotating mass. When excess energy is available, the flywheel spins at a high speed, storing energy in its rotational momentum. When needed, the stored energy is converted back to electricity. Figure 7 shows a typical flywheel energy storage [10].
6. *Hydrogen Storage*: Hydrogen has emerged as a potential energy carrier and storage medium that can facilitate the integration of renewable energy into various sectors. Hydrogen storage involves storing hydrogen gas for later use as an energy source. Hydrogen can be produced using various methods, such as electrolysis or steam methane reforming. It can be stored in tanks or used in fuel cells to generate electricity.
7. *Supercapacitors*: Supercapacitors store energy electrostatically. Unlike batteries, they store and release energy quickly, making them suitable for applications requiring high power bursts. Supercapacitors have a longer lifespan and can withstand a higher number of charge-discharge cycles than batteries, but they have lower energy density. Batteries can be replaced or integrated with supercapacitor modules in all newly developed consumer electronic products, particularly those that operate on dc voltage or electricity.
8. *Chemical Storage:* Chemical energy storage involves converting electrical energy into chemical energy for later use. This includes methods such as hydrogen production through electrolysis, fuel production through electrochemical processes, or other chemical reactions that store energy.

These energy storage technologies are illustrated in Figure 8 [5].

APPLICATIONS OF ENERGY STORAGE

An energy storage system (ESS) for electricity generation uses electricity (or some other energy source, such as solar-thermal energy) to charge an energy storage system or device, which is discharged to supply (generate) electricity when needed. Its potential applications could be found in the entire spectrum of power systems such as generation, transmission, distribution, and utilization. ESS applications are classified into two major categories: applications in power grids with and without RE systems and applications in detached electrification support. Common areas of application include the following:

- *Integration with Smart Grids:* Renewable energy sources are not always available, and grid-based energy storage directly tackles this issue. With the development of smart grid, supported by investment and government policies, the prospect of energy storage application are gradually emerging. As a flexible power source, energy storage has many potential applications in renewable energy generation grid integration, power transmission and distribution, distributed generation, micro grid and ancillary services such as frequency regulation. As smart grid technology evolves, energy storage systems will become more integrated with the grid, allowing for two-way communication. This will enable more dynamic energy management, including real-time energy trading and better grid stability.
- *Integration with Microgrids:* Microgrids are some small grids that supply electricity to commercial buildings, manufacturing plants or communities when connected to a larger grid. Autonomous microgrids can provide electricity to remote areas and communities such as islands. To maintain stable voltage and frequency of microgrid in different operational modes, microgrid has adopted with reasonable distributed generations and energy storage configuration in order to realize the transformation in different operational modes. ESSs are being integrated into microgrids that supply a relatively small geographic area or customer base to provide some or all of the uses and benefits of electricity storage. A microgrid ESS may be isolated from a larger grid, or it may be connected to a larger grid with automatic

isolation (disconnect) from the larger grid during grid supply interruptions.

- *Green Infrastructure:* Renewable energy sources like solar, wind, hydro, and geothermal replace traditional fossil fuels, reducing greenhouse gas emissions. They are inexhaustible and can be harnessed without depleting the planet's resources, making them a sustainable choice for energy production. As the world embraces cleaner alternatives, green infrastructure takes center stage. Imagine EV charging stations powered by renewable energy sources like solar panels and wind turbines. Energy storage systems ensure reliability, while efficient industrial motors drive progress to reduce energy consumption. Together, they create a green infrastructure that promotes sustainability, reduces environmental impact, and paves the way for a cleaner, greener future.
- *EV Charging*: The electric vehicle (EV) is able to be used as the energy storage unit connecting with power system. EV charging is the process of replenishing an EV's battery using electricity. Charging stations can be found at public locations, private homes, or workplaces, and they vary in charging speed. The widespread installation of EV charging points is crucial for the adoption of EVs.
- *Grid-scale Storage*: Grid-scale storage refers to technologies connected to the power grid that can store energy and then supply it back to the grid at a more advantageous time – for example, at night, when no solar power is available, or during a weather event that disrupts electricity generation. The most widely-used technology is pumped-storage hydropower, where water is pumped into a reservoir and then released to generate electricity at a different time. Figure 9 shows a grid energy storage [11].
- *Data Centers:* A rechargeable battery bank can be used in a data center. For safety and security, the actual batteries are housed in their own structures, like warehouses or containers.

BENEFITS

Energy storage systems allow excess energy produced by renewable sources to be stored and used when needed. This helps to balance supply and demand, stabilize the grid, and ensure a constant energy supply even when renewable energy sources are intermittent. ESSs are used for many purposes and provide a number of benefits to the electric power industry and electricity consumers. They can be used to help improve power system reliability by balancing utility grids and electricity distribution or smoothing the integration of renewable energy from sun, wind, and hydro power. Other benefits of ESSs include the following [12]:

- *Back-up power*: An ESS owned by on-grid electricity consumers can provide emergency back-up electricity during grid outages.
- *Efficiency*: By integrating solar panels, batteries, and inverters into a cohesive unit, energy storage systems minimize energy loss that typically occurs during the transfer of electricity between separate components. This seamless integration ensures that more of the generated solar power is used effectively. By effectively managing supply and demand imbalances, energy storage helps stabilize electric grids.
- *Energy Independence:* With the capability to generate, store, and manage power independently, energy storage systems significantly reduce reliance on the traditional power grid. This autonomy ensures a consistent energy supply, especially in areas prone to power outages or with unstable grid infrastructure.
- *Sustainability:* Energy storage systems not only streamline the integration of renewable sources into our daily energy consumption but also pave the way for a sustainable future. An energy storage systems harness solar power, one of the cleanest and most abundant renewable energy sources available. By using solar energy to its full potential, these systems significantly reduce the carbon footprint associated with energy consumption. Besides reducing greenhouse gas emissions, solar energy systems contribute to a decrease in air and water pollution that is often associated with fossil fuel energy production.
- *Decarbonization:* Developing countries are a crucial part of the global decarbonization challenge. Energy storage makes deep decarbonization of reliable electric power systems affordable.
- *Demand Response:* Energy storage systems will be capable of participating in demand response programs, automatically adjusting energy usage and storage in response to grid demands, which will optimize energy costs and contribute to grid reliability.

CHALLENGES

Although implementing ESS in power systems applications is undoubtedly advantageous, there are a few challenges. The major challenges from ESS are identified to be proper energy management, manufacturing, construction of ESS, the capacity of ESS, renewable energy integration, high maintenance and implementation cost of ESS, ESS degradation, waste management, and associated environmental pollution. There are also challenges in terms of technology and economy that need to be addressed to make the practical applications of ESS viable for power industries. The challenges can be classified into three groups: technological, economic, and social [13]:

- *Technology Challenges:* The development of energy storage technology requires the innovation and breakthrough in capacity, long-lifespan, low-cost, high-security for electrochemical energy storage. And also, physical storage technology with high-efficiency, low-cost is required. It is necessary to establish a complete and rigorous professional cohesion, reasonable classification, transparency, openness and energy storage standards, which will provide strong support for research and development, production and application of energy storage, and promote the development of energy storage technology and related industries.
- *Economic Challenges*: Energy storage industry is still facing with challenges of lack of policy support, high cost, unclear application value, unhealthy market mechanism and other issues. The suitable industry market mechanism and the subsidy policy should be promoted.
- *Social Challenges:* It is necessary to propose energy storage system solutions with the participations from electricity users, electrical enterprises, researcher, economical organizations and social originations. We should encourage numerous researches and applications of energy storage, establish a sustainable development model and achieve commercial operation of energy storage.

CONCLUSION

Energy storage is needed to efficiently manage the dynamics of demand and supply. Understanding energy storage systems and their potential applications in power systems is crucial for policymakers, grid operators, renewable energy project developers, and individuals interested in the transition toward a more sustainable and resilient energy future. As the demand for reliable and sustainable power continues to grow, the need for technology that can store and distribute energy effectively becomes urgent. This versatile system can seamlessly integrate with existing solar panels or other renewable energy sources to maximize efficiency and minimize waste.

Energy storage is going to be a quintessential part of the new power system architecture. It not only helps to balance out the variability in generation but could also enable consumption of a higher proportion of self-generated renewable power by consumers and reduce the need to feed excess electricity back into the grid. As the renewable power penetration increases, the operational dynamics of the power system will change drastically, requiring a change in the system architecture as well. More information on energy storage is available from the books in [14-24] and the following related journals:

- *Journal of Energy Storage*
- *Journal of Modern Power Systems and Clean Energy*
- *Energies*

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Figure 1 Solar power generation [2].

Figure 2 Wind power generation [3].

Figure 3 A typical energy storage system [4].

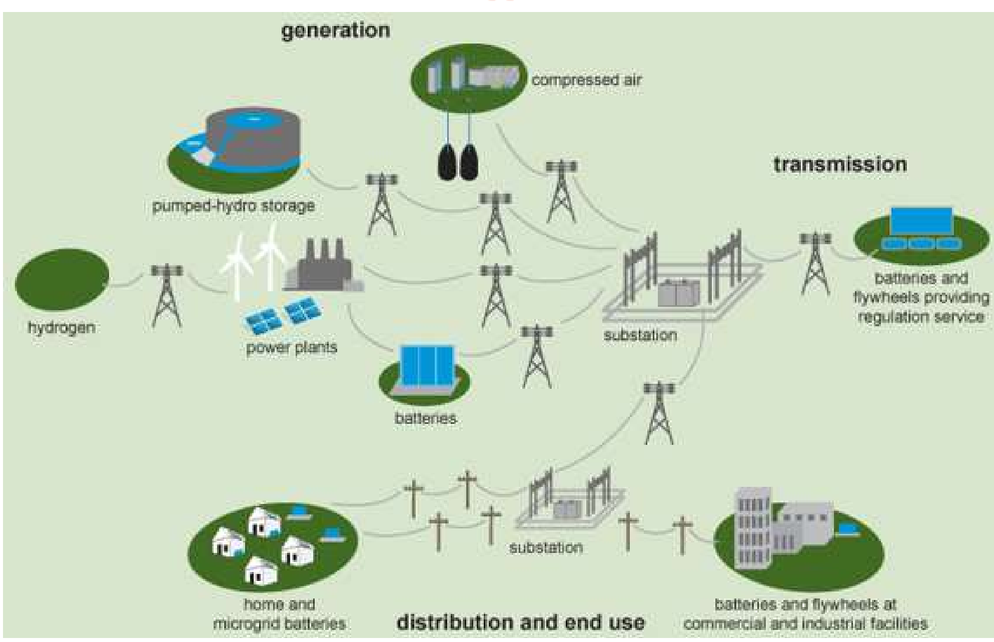

Figure 4 Locations of ESS for electricity generation on an electric grid [5].

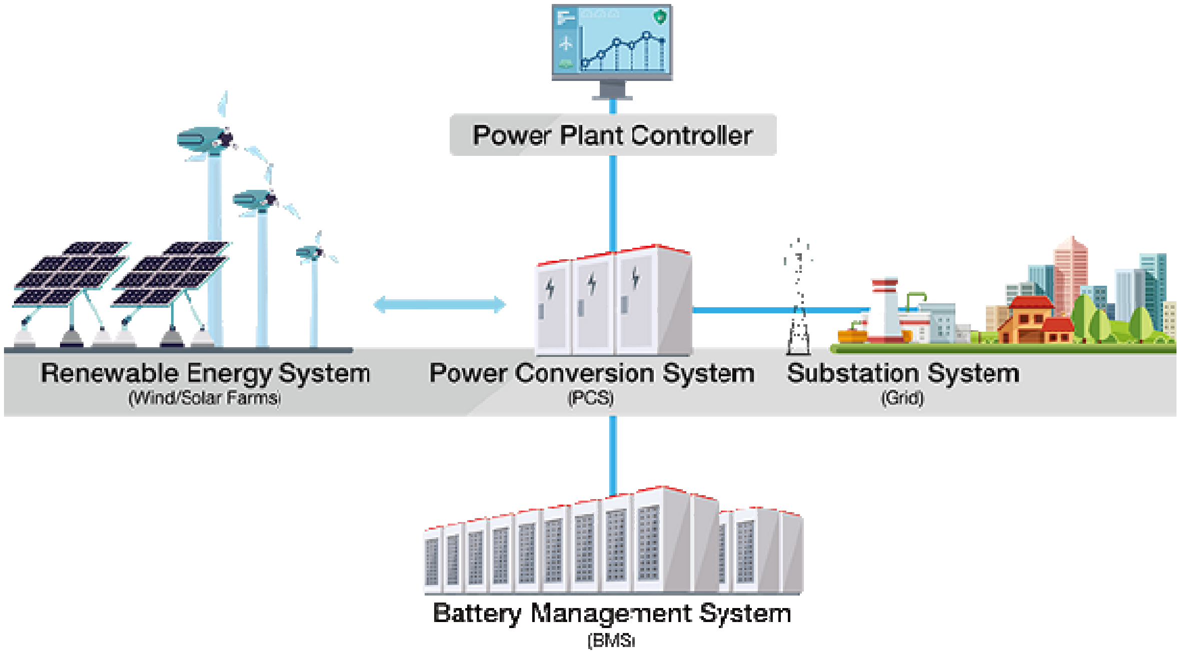

Figure 5 Battery management system in the power systems [8].

Figure 6 Thermal energy for healing and cooling [9].

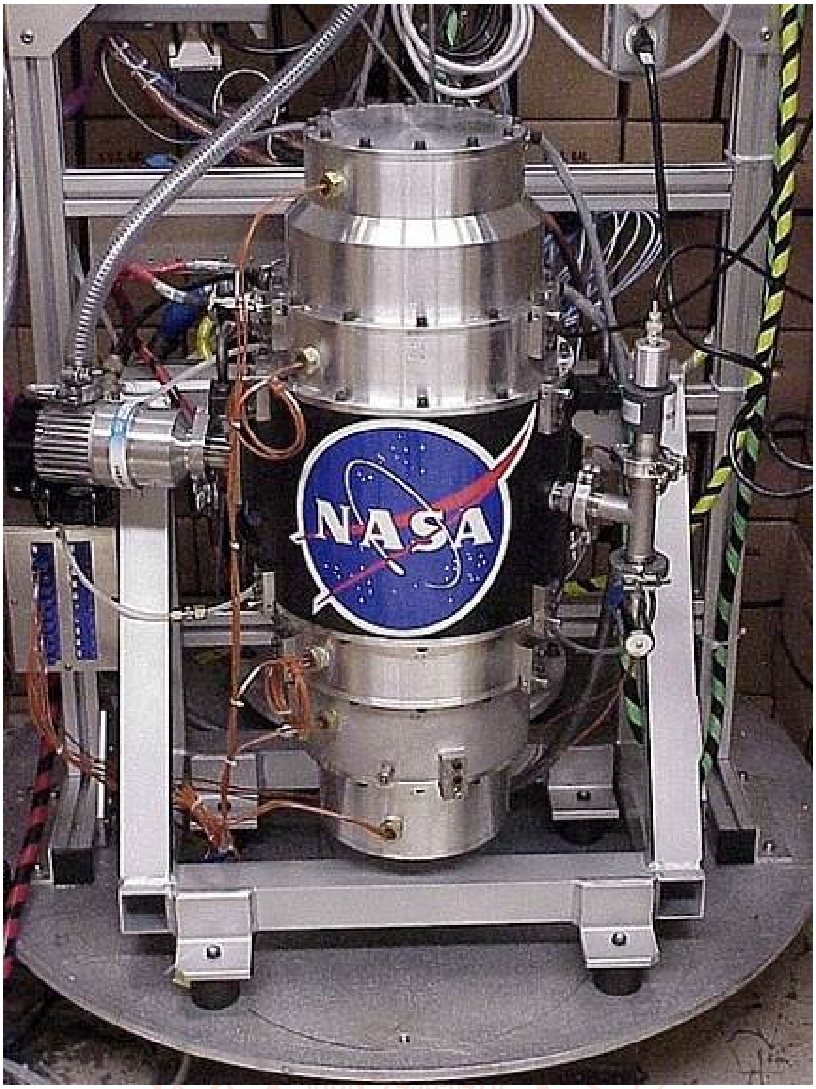

Figure 7 A typical flywheel energy storage [10].

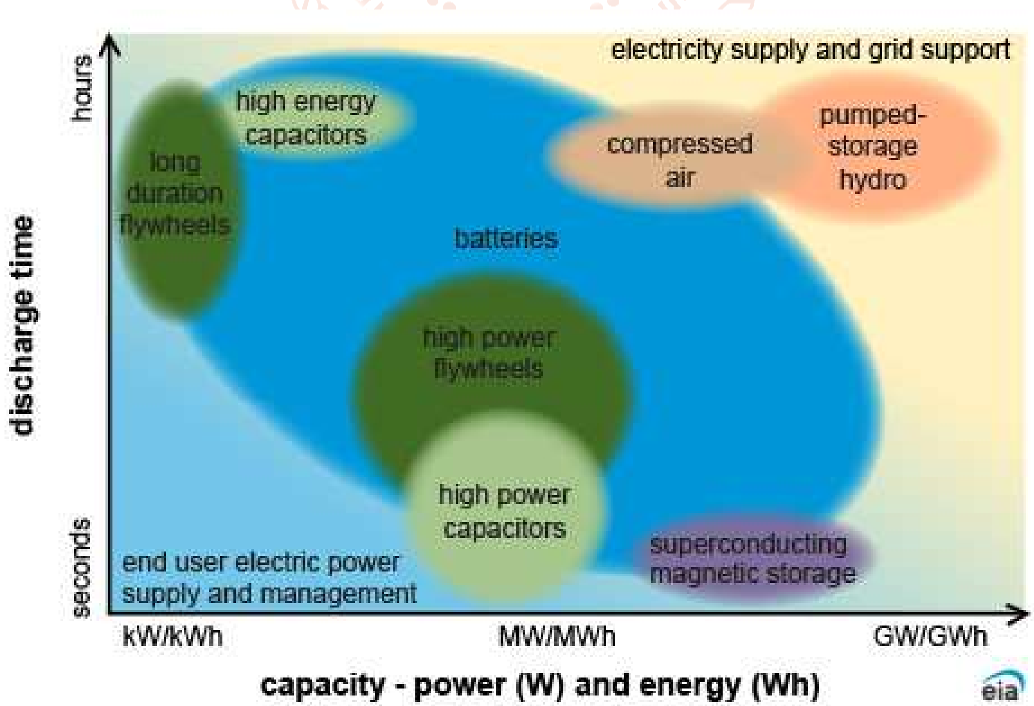

Figure 8 Energy storage technologies [5].

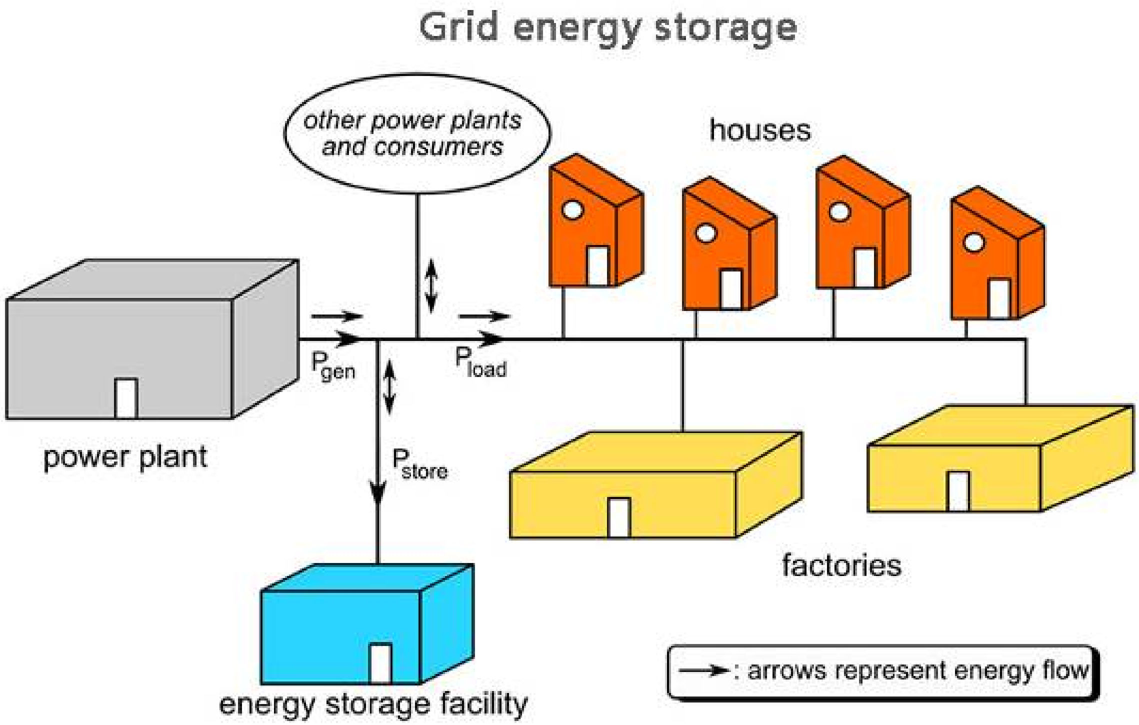

Figure 9 Grid energy storage [11].