

A Review of Energy Storage Technologies for Enhancing Grid Stability in Renewable Energy Systems

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Abstract: Modern power systems have undergone tremendous change as a result of the quick integration of renewable energy sources like wind and solar. However, maintaining grid stability, dependability, and power quality is made more difficult by the sporadic and irregular nature of these energy sources. In order to improve grid flexibility, balance supply and demand, and guarantee uninterrupted power delivery, energy storage technologies have become an essential option. This review study looks at a number of energy storage technologies, such as flywheel storage, compressed air energy storage, pumped hydro storage, battery energy storage systems, and supercapacitors. The paper outlines their benefits, drawbacks, and uses in the integration of renewable energy. The study also explores how these technologies are used in load balancing, peak shaving, voltage support, and frequency control. According to the results, grid stability may be greatly improved and the shift to sustainable energy systems can be supported by the strategic deployment of hybrid energy storage systems.

Keywords: Renewable Energy, Energy Storage Technologies, Grid Stability

I. INTRODUCTION

Globally, the use of renewable energy sources like solar photovoltaic and wind power has increased due to the growing need for sustainable and clean energy. Despite the fact that these sources greatly reduce greenhouse gas emissions, the stability and dependability of the electricity system are seriously threatened by their sporadic and unexpected character (Lund et al., 2015). To guarantee steady functioning, grid operators must constantly strike a balance between the production and consumption of power. Voltage instability, frequency variations, and even power outages can result from abrupt changes in renewable energy production.

By holding extra energy during times of high generation and releasing it during times of high demand, energy storage technologies are essential in tackling these issues. These technologies increase the dependability of renewable energy systems, mitigate power oscillations, and strengthen grid resilience (Chen et al., 2009). Numerous energy storage technologies have advanced significantly during the last ten years, each with special qualities appropriate for a range of grid applications.

Grid stability depends on ancillary services like reserve capacity, voltage management, and frequency regulation, all of which are supported by the integration of storage technologies (Divya & Østergaard, 2009). Energy storage also makes it possible to control peak loads and make effective use of renewable energy sources. The purpose of this review article is to examine various energy storage technologies and assess how well they work to improve grid stability in renewable energy systems. The main technologies covered in the study include flywheels, batteries, compressed air energy storage, pumped hydro storage, and supercapacitors.



IMPORTANCE OF ENERGY STORAGE FOR GRID STABILITY

Weather, seasonal changes, and erratic demand patterns are common causes of swings in renewable energy systems. In the absence of appropriate balancing measures, these variations might lead to power grid instability. Energy storage systems capture excess energy and release it when needed, offering a versatile and effective option. Grid stability is enhanced by energy storage in a number of ways. First, it facilitates frequency management, guaranteeing that, in spite of variations in generation or demand, the grid frequency stays within reasonable bounds (Aneke & Wang, 2016). Second, storage devices help stabilize voltage, especially in distribution networks where renewable energy is widely used. Third, they make it possible to shift peak loads, which lessens the need for costly and environmentally harmful backup power plants. The capacity to supply backup power during grid outages, which improves overall system dependability, is another significant advantage. Energy storage is anticipated to become even more important in preserving grid stability and operational flexibility as the use of renewable energy sources grows.

TYPES OF ENERGY STORAGE TECHNOLOGIES

Modern energy systems rely heavily on energy storage technology, especially when integrating renewable energy sources like solar and wind power. Since renewable energy generation is often intermittent and dependent on environmental conditions, energy storage systems help maintain a balance between electricity supply and demand. These technologies store excess energy produced during periods of high generation and release it when demand is high or generation is low. Over the years, various energy storage technologies have been developed, each with distinct characteristics, advantages, and applications in power systems.

BATTERY ENERGY STORAGE SYSTEMS

Battery Energy Storage Systems are among the most widely used energy storage technologies in renewable energy applications. When needed, batteries transform chemical electrical energy back into electrical energy. Lithium-ion batteries are the most common type used in modern energy storage systems due to their high energy density, long cycle life, and relatively high efficiency. These batteries are widely used in grid-scale storage projects, electric vehicles, and residential solar power systems. Other battery types include lead-acid batteries, sodium-sulfur batteries, and flow batteries. Battery storage systems are highly flexible and can respond quickly to fluctuations in electricity demand, making them suitable for applications such as frequency regulation, load balancing, and backup power. However, battery systems may involve high installation costs and require proper recycling and disposal to reduce environmental impacts.

PUMPED HYDRO ENERGY STORAGE

One of the earliest and most advanced large-scale energy storage systems is pumped hydro energy storage. It works by storing gravitational potential energy. During periods of low electricity demand or excess power generation, water is pumped from a lower reservoir to an upper reservoir using electric pumps. When electricity demand increases, the stored water is released back to the lower reservoir through turbines, generating electricity. Large quantities of energy may be stored for extended periods of time in pumped hydro storage systems, which can run effectively for many decades. These systems are essential for stabilizing power grids with increasing penetration of renewable energy because of their great capacity and dependability. However, the implementation of pumped hydro systems requires specific geographical conditions, such as suitable elevation differences and access to water resources, which may limit their widespread deployment.

COMPRESSED AIR ENERGY STORAGE

Another large-scale energy storage technology that improves grid stability is compressed air energy storage. In CAES systems, air is compressed using extra power and then stored in mines, underground caverns, or specifically constructed storage tanks. The compressed air is released, heated, and then expanded via turbines to produce energy as required. Long-term energy storage makes CAES systems ideal for balancing the production of huge amounts of renewable energy.



The technology's capacity to store substantial quantities of energy at comparatively cheap cost when compared to some battery systems is one of its main features. However, heat production during compression and expansion cycles may result in efficiency losses for CAES systems. Large-scale application also need appropriate subterranean storage locations.

FLYWHEEL ENERGY STORAGE SYSTEMS

Flywheel energy storage systems use a quickly rotating rotor to store energy as kinetic energy. An electric motor speeds the rotor to a high speed when power is applied to the system, storing energy as rotational motion. The rotor slows down and uses a generator to transform the stored kinetic energy back into electrical energy when power is needed. Flywheel systems are renowned for their extended operating longevity, excellent efficiency, and quick reaction times. In electrical grids, they are especially helpful for short-duration applications including voltage stability, frequency management, and power quality enhancement. In comparison to certain other storage technologies, flywheel systems also need very less maintenance. However, their usage in long-term energy storage applications is limited since their energy storage capacity is often smaller than that of batteries or pumped hydro systems.

SUPER CAPACITORS (ULTRA CAPACITORS)

Super capacitors, often referred to as ultra-capacitors, are sophisticated energy storage devices that use electrostatic charge buildup instead of chemical processes to store electrical energy. These devices can store and release energy very fast and are made up of two electrodes separated by an electrolyte. Super capacitors can charge and discharge far more quickly than conventional batteries and have a very high power density. They are often used in applications that need for quick power bursts, such power stabilization in renewable energy systems and regenerative braking systems in electric cars, because of their quick reaction and extended cycle life. To enhance overall system performance, super capacitors are often integrated with battery storage systems in hybrid setups. super capacitors have a low energy density, which restricts their capacity to store energy for long periods of time despite their benefits.

THERMAL ENERGY STORAGE

Thermal energy storage is the process of storing energy for later use as either heat or cold. District heating systems, solar thermal power plants, and industrial applications all make extensive use of this technology. Materials like water, molten salts, and phase-change materials which absorb and release heat during phase transitions can all store thermal energy. Molten salt is often used in concentrated solar power facilities to store heat produced by solar collectors. Even in the absence of sunshine, the stored heat may be used to create steam and produce power. Long-term energy storage is possible using thermal energy storage devices, which are also reasonably priced. Nevertheless, their use is often restricted to certain sectors of the economy or technology used in power generation.

HYDROGEN ENERGY STORAGE

An new technology that has received a lot of attention lately is hydrogen energy storage. This method uses extra power from renewable sources to create hydrogen by splitting water into hydrogen and oxygen via a process known as electrolysis. The generated hydrogen may be stored and then utilized as fuel in combustion engines or fuel cells to create energy. Hydrogen storage is appropriate for seasonal energy storage in renewable energy systems because it provides the benefit of long-term and large-scale energy storage. Additionally, it may facilitate the growth of an energy economy centered on hydrogen. For broad deployment, however, issues including high manufacturing costs, storage limitations, and infrastructural needs must be resolved.

GRAVITY-BASED ENERGY STORAGE

Gravity-based energy storage devices use excess power to raise heavy objects to a greater altitude in order to store energy. When energy is needed, the mass is reduced, and generators are propelled by gravity to create electricity. Although solid



masses are used in place of water, this idea is comparable to pumped hydro storage. Gravity storage systems may be used in places with limited water supplies since they are thought to be ecologically benign. The technology has prospective benefits including a long lifetime and no environmental effect, even though it is still in the early stages of research.

HYBRID ENERGY STORAGE SYSTEMS

In order to increase overall performance, dependability, and efficiency, hybrid energy storage systems integrate two or more storage technologies. Supercapacitors and batteries, for instance, may be combined to provide both high power density and high energy density. Similar to this, battery systems and pumped hydro storage may be combined to maximize both short-term and long-term energy management. In renewable energy grids, where both substantial storage capacity and quick response are needed, hybrid systems are very helpful. Hybrid storage systems may improve grid stability and overcome the drawbacks of individual storage options by integrating several technologies.

Modern power grids and renewable energy systems depend on energy storage technology to function effectively. Depending on its reaction time, capacity, and design, each storage technique has special advantages and drawbacks. While compressed air storage and pumped hydro provide large-scale energy storage capabilities, battery storage technologies offer adaptable and quick alternatives. While thermal storage systems and hydrogen provide possibilities for long-term energy storage, flywheels and super capacitors are perfect for short-term power control. The development and integration of cutting-edge energy storage technologies will become more crucial as the use of renewable energy sources increases in order to guarantee dependable, stable, and sustainable energy systems.

BATTERY ENERGY STORAGE SYSTEMS

Battery energy storage systems are among the most widely used storage technologies in renewable energy systems. Lithium-ion batteries are particularly popular due to their high energy density, long cycle life, and fast response time (Dunn et al., 2011). These batteries are commonly used in grid-scale storage projects and distributed energy systems. BESS can rapidly respond to changes in power demand, making them suitable for frequency regulation and load balancing. They are also widely deployed in microgrids and residential solar energy systems. However, challenges such as high costs, limited lifespan, and environmental concerns related to battery disposal remain significant barriers to widespread adoption.

Battery Energy Storage Systems have emerged as one of the most important technologies for supporting modern power systems, particularly with the increasing penetration of renewable energy sources such as solar and wind power. Renewable energy generation is inherently intermittent and dependent on environmental conditions. Solar power generation varies with sunlight availability, while wind power fluctuates with wind speed. These fluctuations create challenges in maintaining the balance between electricity generation and consumption. Battery Energy Storage Systems provide a reliable solution by storing excess electricity generated during periods of high production and releasing it when demand exceeds supply. As a result, BESS plays a critical role in enhancing grid stability, reliability, and energy efficiency (Dunn et al., 2011).

One of the major advantages of Battery Energy Storage Systems is their ability to respond quickly to changes in electricity demand and supply. Unlike traditional power plants that may require significant time to ramp up or down, batteries can respond almost instantly. This rapid response capability makes them highly effective for frequency regulation and voltage control in power grids. Frequency regulation is essential for maintaining the balance between electricity generation and consumption in real time. When the supply of electricity exceeds demand, the grid frequency increases, while a shortage of electricity causes the frequency to decrease. BESS can quickly absorb or release energy to stabilize the frequency and maintain grid reliability (Divya & Østergaard, 2009).

Battery Energy Storage Systems also play a significant role in facilitating the integration of renewable energy into power systems. Renewable energy generation often produces excess electricity during certain periods, such as midday for solar power or during strong wind conditions for wind farms. Without storage systems, this excess energy may be curtailed or wasted. BESS allows utilities and grid operators to store surplus electricity and utilize it later during periods of higher



demand. This process not only improves the efficiency of renewable energy utilization but also reduces the need for fossil-fuel-based backup power plants (Chen et al., 2009).

Several types of batteries are used in energy storage systems, each with unique characteristics and advantages. Lithium-ion batteries are currently the most widely used technology in grid-scale energy storage applications due to their high energy density, high efficiency, and long cycle life. These batteries are commonly used in electric vehicles, residential energy storage systems, and utility-scale storage projects. Their declining costs and continuous technological improvements have made them increasingly attractive for large-scale energy storage deployment (Luo et al., 2015).

Another type of battery used in energy storage systems is the lead-acid battery, which is one of the oldest and most mature battery technologies. Lead-acid batteries are relatively inexpensive and have been widely used in backup power systems and small-scale storage applications. However, they have lower energy density, shorter lifespan, and require regular maintenance compared to modern battery technologies. As a result, their use in large-scale renewable energy integration is gradually declining.

Flow batteries represent another promising category of energy storage technology. In flow batteries, energy is stored in liquid electrolytes contained in external tanks, which are circulated through the battery cell during operation. One of the main advantages of flow batteries is their ability to provide long-duration energy storage. They also offer longer cycle life and improved safety compared to conventional batteries. Vanadium redox flow batteries are among the most widely studied and deployed types of flow batteries for grid-scale applications. These batteries are particularly suitable for large renewable energy installations where long-term storage is required.

Battery Energy Storage Systems also support several important grid services beyond renewable energy integration. One of these services is peak shaving, which involves reducing electricity demand during peak consumption periods. During times of high electricity demand, power utilities often rely on expensive and less efficient power plants to meet the additional load. By discharging stored energy during peak hours, BESS can reduce peak demand and help utilities avoid the need for additional power generation capacity. This process can lead to significant cost savings and improved efficiency in power system operation.

Another important application of BESS is in microgrids and distributed energy systems. Microgrids are localized energy systems that can operate independently or in coordination with the main power grid. Battery storage plays a crucial role in maintaining the stability and reliability of microgrids, particularly in remote areas or regions with unreliable grid infrastructure. By storing locally generated renewable energy, batteries ensure a continuous power supply even during grid outages or periods of low renewable generation.

Despite the many advantages of Battery Energy Storage Systems, several challenges still need to be addressed to enable their widespread adoption. One of the main challenges is the relatively high initial investment cost associated with large-scale battery installations. Although the cost of lithium-ion batteries has decreased significantly over the past decade, large energy storage projects still require substantial capital investment. Continued research and technological advancements are expected to further reduce battery costs in the coming years.

PUMPED HYDRO ENERGY STORAGE

The most developed and extensively used large-scale energy storage technology is pumped hydro energy storage. When demand for power is low, it pumps water from a lower reservoir to a higher reservoir; when demand is high, it releases the water via turbines to produce energy (Lund et al., 2015). PHES has a huge storage capacity, extended operating life, and great efficiency. It is essential for maintaining the equilibrium of renewable energy systems, especially in areas with substantial hydropower infrastructure. However, the technique requires a substantial initial commitment as well as certain geographic circumstances.

COMPRESSED AIR ENERGY STORAGE

During times of surplus power production, compressed air energy storage stores energy by compressing air in storage tanks or subterranean caves. Later, the compressed air is released to power turbines and produce energy (Aneke & Wang,



2016). Large-scale grid applications may benefit from CAES systems' capacity to store substantial quantities of energy for extended periods of time. Their distribution may be limited by the availability of appropriate subterranean storage locations, and their efficiency is comparatively lower than that of other storage systems.

FLYWHEEL ENERGY STORAGE

Flywheel energy storage devices use very high rotor speeds to store energy as kinetic energy. The rotational energy is transformed back into electricity when energy is required. Flywheels have a long cycle life, great efficiency, and quick reaction times. For short-term uses like frequency control and power quality enhancement, they are very helpful (Chen et al., 2009). However, their employment in long-duration storage applications is limited by their very poor energy storage capacity.

SUPER CAPACITORS

Super capacitors, often referred to as ultra-capacitors, use electrostatic charge buildup to store electrical energy. These gadgets are perfect for applications that need quick power supply because of their very quick charging and discharging times. Because they can handle brief power fluctuations, super capacitors are often employed in hybrid energy storage systems to supplement batteries (Divya & Østergaard, 2009). Their low energy density limits their usage for long-term energy storage, notwithstanding their benefits.

Table 1: Comparison of Major Energy Storage Technologies

Energy Storage Technology	Energy Density	Response Time	Typical Applications	Advantages	Limitations
Battery Energy Storage	High	Fast	Grid balancing, renewable integration	High efficiency, flexible deployment	High cost, limited lifespan
Pumped Hydro Storage	Medium	Moderate	Large-scale grid storage	Long lifespan, high capacity	Requires suitable geography
Compressed Air Storage	Medium	Moderate	Large-scale energy storage	Large capacity, long duration	Lower efficiency
Flywheel Storage	Low	Very fast	Frequency regulation	High power output, long cycle life	Limited storage capacity
Super capacitors	Very low	Extremely fast	Power quality, short bursts	Rapid charging, long life	Low energy density

HYBRID ENERGY STORAGE SYSTEMS

To increase overall performance, hybrid energy storage systems integrate two or more storage technologies. Super capacitors and batteries, for instance, may be used to produce both high power density and high energy density. These solutions increase system efficiency and enable better handling of swings in renewable energy. According to research, hybrid storage technologies that provide both short-term and long-term energy balancing capabilities may improve grid stability (Luo et al., 2015). The use of these technologies in contemporary microgrids and smart grids is growing.

In contemporary power systems, especially those that include renewable energy sources like solar and wind power, hybrid energy storage systems provide a sophisticated method of energy management.

Because of environmental variables including weather and seasonal variations, the production of renewable energy is naturally sporadic and unpredictable. The maintenance of grid stability, voltage control, and a steady supply of power are severely hampered by these variations. By integrating two or more energy storage technologies to take advantage of their complementing benefits, hybrid energy storage systems solve these problems.



For instance, super capacitors and flywheels provide high power density and quick reaction times, whereas batteries offer high energy density appropriate for long-term storage. HESS enhances overall system performance, efficiency, and dependability via the integration of various technologies (Luo et al., 2015). Hybrid storage technologies are becoming more crucial for maintaining sustainable energy infrastructure and stabilizing power grids as global energy systems shift toward decarbonization and greater penetration of renewable energy sources.

COMPONENTS OF HYBRID ENERGY STORAGE SYSTEMS

Multiple energy storage devices, power electronic converters, and an intelligent energy management system are the usual components of a hybrid energy storage system. Lithium-ion batteries are most often used in conjunction with flywheel storage devices or super capacitors. Batteries are useful for load shifting and backup power applications because they can store a lot of energy and provide power for extended periods of time. super capacitors, on the other hand, are perfect for handling abrupt power changes and brief high-power demands since they can charge and discharge very fast (Dunn et al., 2011).

Flywheel systems are commonly utilized for power quality management and frequency regulation since they mechanically store energy as rotating kinetic energy. While the energy management system synchronizes the functioning of various storage components to maximize performance, power converters are in charge of regulating the flow of energy between storage devices and the grid. When combined, these elements provide a highly adaptable and effective energy storage system that can handle a variety of grid needs.

WORKING PRINCIPLE OF HYBRID ENERGY STORAGE SYSTEMS

The coordinated interplay of several storage technologies is the foundation for the functioning of hybrid energy storage systems. Excess power is stored in energy storage devices when the production of renewable energy surpasses the consumption. Due to their large energy capacity, batteries usually absorb the majority of the energy. Simultaneously, flywheels or super capacitors manage quick power swings brought on by abrupt shifts in load demand or generation. The stored energy is released back into the system at times of high power demand or low renewable output. Depending on the length and size of the demand, the energy management system chooses which storage component should provide electricity. Super capacitors or flywheels react fast to short-term high-power demands, while batteries provide energy for longer-term requirements (Aneke & Wang, 2016). The longevity of individual components is increased and effective use of storage resources is ensured by this coordinated operation.

ADVANTAGES OF HYBRID ENERGY STORAGE SYSTEMS

Compared to single-technology storage options, hybrid energy storage systems provide a number of benefits. Increased system efficiency is one of the biggest advantages. Hybrid systems increase operational efficiency and reduce energy losses by allocating energy storage chores across many devices according to their respective capabilities. Improved grid stability is an additional benefit. While batteries provide continuous energy assistance for extended periods of time, rapid-response devices like flywheels and super capacitors may swiftly adjust for abrupt power swings. By lowering the frequency of high-power charge and discharge cycles, which are normally managed by super capacitors, hybrid systems also extend the life of batteries (Chen et al., 2009). Moreover, hybrid storage systems provide additional operational flexibility, enabling them to concurrently carry out many grid tasks including voltage support, frequency control, peak shaving, and renewable energy smoothing. Hybrid storage systems are especially well-suited for distributed energy systems and contemporary smart grids because of these benefits.

APPLICATIONS IN RENEWABLE ENERGY SYSTEMS

In renewable energy applications, hybrid energy storage devices are often used to improve power generation's stability and dependability. Hybrid storage can control variations brought on by cloud cover or abrupt shifts in solar irradiation in solar photovoltaic systems. Super capacitors manage brief power fluctuations to ensure steady output, while batteries



store extra solar energy throughout the day. Similar to this, hybrid storage aids in balancing the erratic power production brought on by fluctuations in wind speed in wind power systems.

Microgrids also use hybrid energy storage devices, which enhance the integration of various renewable energy sources and provide dependable backup power. By storing energy during off-peak hours and providing it during times of high demand, hybrid storage in electric car charging infrastructure may lessen the strain on the electrical grid. These uses highlight the adaptability and efficiency of hybrid energy storage systems in facilitating the integration of renewable energy sources.

ROLE IN GRID STABILITY AND POWER QUALITY

Preserving power quality and grid stability is one of the most important functions of hybrid energy storage systems. To guarantee safe and dependable operation, power grids must adhere to stringent frequency and voltage constraints. Frequency variations and voltage fluctuations are often caused by the intermittent nature of renewable energy sources. Hybrid energy storage systems are able to react swiftly to these disruptions and bring the grid back into equilibrium.

Flywheels and super capacitors assist regulate frequency and lessen voltage swings by responding quickly to abrupt changes. Batteries, on the other hand, provide longer-term assistance to preserve the general equilibrium between the production and consumption of power (Divya & Østergaard, 2009). Hybrid systems provide a complete solution for preserving steady and dependable grid functioning by fusing fast-response and large-capacity storage devices.

ENERGY MANAGEMENT STRATEGIES IN HYBRID SYSTEMS

Optimizing the performance of hybrid energy storage systems requires efficient energy management. The distribution of energy among various storage components is decided by sophisticated control algorithms. These algorithms take into account variables including system efficiency, power fluctuations, energy demand, and state of charge. One popular approach is to use supercapacitors for high-power short-duration applications and batteries for lower-power long-duration energy supplies.

Another strategy makes use of predictive control techniques that project future energy consumption and renewable production by analyzing previous data. The energy management system may more effectively distribute resources and lessen the strain on individual storage components by foreseeing swings. In order to enhance decision-making and system optimization, hybrid energy management systems are progressively integrating contemporary smart grid technology and artificial intelligence approaches.

II. CONCLUSION

In renewable energy systems, energy storage solutions are essential for improving grid stability. In order to ensure dependable and effective power system operation, storage technologies are integrated to assist reduce the unpredictability and intermittency associated with renewable energy sources. Numerous technologies, including flywheels, compressed air energy storage, pumped hydro storage, battery storage, and super capacitors, have special benefits and uses. Although each method has significant drawbacks, the creation of hybrid energy storage systems offers a viable way to get beyond these issues. The significance of energy storage in attaining a sustainable and resilient energy future will be further strengthened by ongoing technology developments and favorable legislative frameworks.

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