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Technological Readiness and Scalability of Emerging Energy Storage Systems for Solar and Wind Integration

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ABSTRACT

"The need for efficient, scalable, and technologically sophisticated energy storage systems (ESS) is increasing as renewable energy sources, such as wind and solar, become increasingly integrated into power grids. This article focusses on the integration of solar and wind power systems, examining the technological readiness and scalability of many new energy storage technologies. The technologies include solid-state batteries, flow batteries, supercapacitors, hydrogen storage, compressed air energy storage (CAES), flywheels, and lithium-ion batteries. Technology Readiness Levels (TRLs) assess the developmental stage of a storage technology based on criteria such as energy density, power output, cycle life, response time, cost, and environmental impact. Lithium-ion batteries dominate the market due to their commercial maturity and exceptional efficiency. Nonetheless, their scalability is constrained by material limitations and safety concerns. Flow batteries include an extended cycle life and a modular design, making them appealing for large-scale grid applications. Nonetheless, they have some challenges regarding energy density and early capital expenditures". Despite being in the nascent phase of development, hydrogen storage, particularly via power-to-gas systems, has significant potential for long-term storage and seasonal equilibrium. Although CAES and flywheels serve certain functions, they are not consistently practicable owing to energy loss and infeasibility in some places or for short durations. The research underscores the need of hybrid systems and continuous innovation by demonstrating that no one storage solution can currently meet all demands for renewable energy integration. The paper emphasizes the need for integrated planning strategies, increased investment in research and development, and supportive regulatory frameworks to expedite the deployment of mature and scalable energy storage technologies, ensuring a future of consistent, reliable, and sustainable renewable energy.

Keywords- : renewable energy, integration, energy storage

INTRODUCTION

It is challenging to incorporate solar and wind power into the architecture of current power networks due to the fact that both forms of energy are inherently intermittent, despite the fact that they are renewable and abundant. It is likely that the unpredictability of various energy sources might result in problems with the stability of the grid, mismatches between supply and demand, and a decrease in the extent to which energy can be relied upon. The development and implementation of sophisticated energy storage systems (ESS) becomes an imperative necessity at this point in time in order to handle these difficulties. The possibility exists that ESS technologies will be able to supply renewable energy networks with the stability and flexibility that they require. The process of absorbing and releasing extra energy during times of low output is capable of accomplishing this goal. In addition to reducing dependency on fossil fuels and contributing to a more ecologically friendly and sustainable energy future, this capability not only assures a continuous and steady supply of energy by boosting the utilisation of renewable sources, but it also reduces the amount of consumption of fossil fuels [1-2]. "Thermal storage, pumped hydro storage (PHS), compressed air energy storage (CAES), and advanced battery systems are all examples of innovative energy storage systems (ESS)". Additional examples include improved battery systems. Each of these systems comes with its own individual set of benefits and drawbacks, particularly with regard to the efficiency, cost, and scalability of the system [3]. For the purpose of determining the role that these systems play in the incorporation of large-scale renewable energy sources, it is vital to have information of the technological preparation and scalability of these systems.

In spite of the remarkable progress that has been made with these technologies, there are still a number of challenges that prevent the widespread application of energy storage systems. The high capital expenditures, constraints on energy density, problems with the longevity of the system, and worries over its effect on the environment are some of the factors that contribute to these issues. The scalability of these technologies continues to be an issue, taking into mind the fact that the requirement for energy storage is expanding in line with the increase of renewable energy output. Furthermore, in order to properly integrate these storage systems with the grid infrastructure that is currently in place, it is vital to give considerable attention to grid stability, energy management approaches, and regulatory frameworks." The study will also explore the scalability of these technologies, especially looking at how they may be extended to meet the growing energy demands of markets that are based on renewable energy. In addition to this, the study will look at how these technologies could be expanded. The purpose of this study is to undertake a complete analysis of prior research in order to highlight the advantages, disadvantages, and potential future applications of energy storage systems (ESS) in facilitating the transition to a more environmentally friendly and robust electrical grid [5-6].

Impacts on ecosystems and wildlife

Wind turbines that are put on land have the capacity to terrify and drive away terrestrial creatures, but they also have the ability to have a substantial effect on bat and bird populations. [7] : It is common knowledge that the United States of America, which has 112 gigawatts of installed capacity, is alone responsible for the deaths of hundreds of thousands of birds per year as a result of turbine accidents. In spite of the fact that the exact number of bats and birds that are killed by wind turbines on a worldwide scale is unclear, this is the situation that has materialized. It is possible that animals that live for a long time and reproduce slowly may be particularly negatively affected by additional mortality caused by automobile accidents. Bats, raptors in flight, and migratory species are among the most vulnerable and susceptible to the impacts of increased mortality from the consequences of additional mortality. Wind turbines are responsible for a far smaller number of bird deaths as compared to other man-made structures, such as dwellings and power lines, which are also responsible for tragedies. Research, on the other hand, indicates that wind farms in the United States have not significantly impacted bird populations between the years 2000 and 2020. This is the conclusion that can be drawn from its findings. This is in spite of the fact that the construction of new wind farms may lead to the extinction or decreased population of some species [8]:

Very little is known about offshore wind farms and the consequences they have on ecosystems that are dominated by shrubs and forests, as well as the effects of underwater noise pollution, which is harmful to marine species such as seals, whales, and porpoises. It is difficult to predict the impact that offshore wind farms will have on the nature of the ecosystem as a whole, but it is possible that specific bird species would benefit from their presence. [9] Because it disrupts their breeding and migrating patterns, birds, bats, and marine species are especially susceptible to the population decline and displacement that is caused by wind turbine noise. This is because wind turbine noise interferes with their natural behaviors. It is possible for bats, in particular, to display avoidance tendencies in reaction to noises including construction, operating, and shadow flicker movements. Wind farms have the potential to transform landscapes in ways that disrupt ecosystems and the interconnection of the environment. This might potentially have an impact on the paths that animals use to get from one location to another. It is difficult to generalize the findings since there has been a lack of study that has been conducted over an extended period of time to investigate the influence that wind power has on animal populations. [10] Wind farms should be positioned appropriately to avoid any high-risk areas in order to mitigate the effects of these factors. Increases in the wind speed threshold for bat and bird activity are two more potential options. Another option is to establish temporary shutdowns.

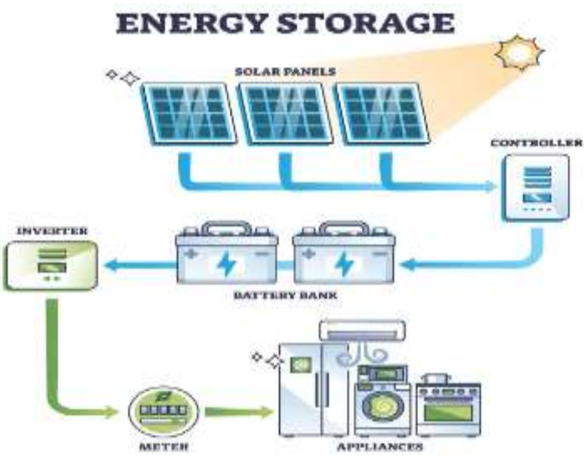

Figure 1: Impacts of Energy Storage Systems on Conservation of Wildlife and the Environment

Impacts on wind resources and weather

There is a degree of ambiguity regarding the extent to which the construction of large-scale wind farms will have an impact on the weather and climate patterns of particular locations. This occurs as a result of the fact that wind turbines are able to collect kinetic energy from the wind, which is then made available for use farther downstream. Large wind farms, particularly those that are situated offshore, have the ability to drastically diminish wind speeds in their immediate area. This may have an impact not only on the farms that are placed nearby, but also on the overall efficiency of the energy production system. In all, eleven out of The amount of energy that can be gathered from wind farms is greater than what was first predicted, and there is a chance that this impact might be minimized by the utilization of strategic design and wake steering. In spite of the fact that the variations in surface temperature or precipitation that are brought about by wind farms are frequently fairly little and restricted, they nonetheless have the ability to have an impact on conditions that are located in close proximity to them. It is possible that offshore wind farms will have an effect on the temperatures and currents of the ocean. This is something that should be considered. When compared to the global ramifications of climate change, the regional weather events that are currently occurring will not have much of an influence on the world. On the other hand, individuals have the ability to protect themselves from the consequences of climate change by taking precautions such as appropriately structuring their surroundings.[12]

OBJECTIVES

1. Evaluate the technological readiness of emerging energy storage systems for solar and wind integration.
2. Analyze the scalability of energy storage technologies for large-scale renewable energy deployment.

RESEARCH METHODOLOGY

The objective of this review research is to assess the technological readiness and scalability of new energy storage systems (ESS) for the aim of integrating them with wind and solar electricity. The method of research that is utilized in this investigation is a thorough examination of the existing body of literature. the same as in [13] For the aim of this systematic review, the objective is to study the performance, problems, and advances of various ESS technologies. This will be accomplished via the utilization of publications that have been subjected to peer review, case studies, and industry reports that have been published within the past five years. The sources will be evaluated based on their capacity to counterbalance the intermittent nature of renewable energy, as well as their effect on grid stability, efficiency, and scalability. This review will take place in the future. It is [14] For inclusion to occur, it is necessary to conduct a thorough analysis of a number of aspects, such as the level of technological maturity, compatibility with the existing power infrastructure, and practical application. A comprehensive knowledge of the existing status as well as the potential future trajectories of ESS in relation to the absorption of renewable energy sources may be attained via the utilization of this approach. [15]

Energy Storage Systems

In order to address the challenges associated with intermittent energy production, the incorporation of renewable energy sources (RES) such as wind and solar into power networks necessitates the utilization of energy storage systems (ESSs). [16] Because of their unpredictability and volatility, renewable energy sources pose a danger to the dependability of the grid, in contrast to traditional power plants. Through the process of storing energy at times of high output and releasing it during times of low generation or peak demand, energy storage systems (ESSs) improve supply-demand balance and grid congestion [17] They also decrease the utilization of fast-start thermal units and the inaccuracies that occur during prediction. ESSs have the potential to reduce curtailment by storing excess electricity during times of low demand in order to increase the utilization of renewable resources. Installations of ESS are anticipated to increase around the globe by the year 2030, hence strengthening their position within renewable energy networks. Demand-side management and grid operation both make use of a variety of different systems, including mechanical, electrical, electrochemical, thermal, and chemical systems. [18–19]

1. Energy Storage Methods Based on Mechanical Design

Because of its advanced stage of development and widespread use, gravitational potential energy storage (PHS) "accounts for more than 90 percent of the total storage capacity that is deployed around the world. When there is a low demand for energy, the system is designed to create electricity through the use of turbines by storing water in a reservoir and then releasing it when there is a high demand for energy". In comparison to batteries, which have a capacity to store 8 gigawatt hours of energy, pumped hydro storage (PHS) systems have the ability to store 9,000 gigawatt hours of information. The power ratings of these systems range from one megawatt to more than three thousand megawatts, and their lifespans sometimes surpass forty years. Prolonged installation times, high building costs, and limited geographic coverage are some of the downsides associated with public health surveillance (PHS) systems. Their operations are frequently scheduled to take place during specific times of the year, which limits their adaptability and necessitates the development of novel solutions in order to improve their operational flexibility. In order to overcome some of the shortcomings of pumped hydro storage (PHS), solid gravity energy storage (SGES) devices were created. Without regard to geographical limitations, SGES is able to provide similar energy storage capacity by utilizing either piston-based or tower-based devices. In addition to having a lifespan of more than 35 years and an efficiency rate of between 80 and 85 percent, SGES provides a scalable energy storage system.

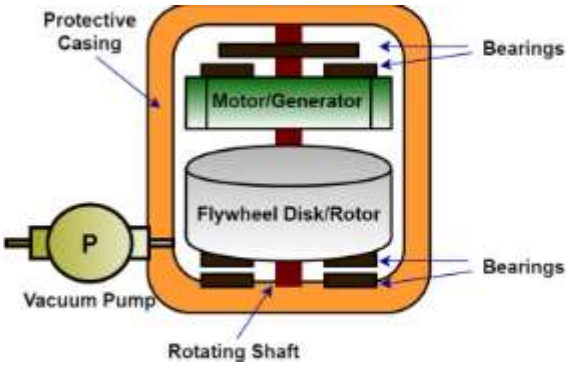

Fig 2: "Overview of Mechanical Energy Storage Technologies"

"Compressed air energy storage (CAES), which is an alternative to piped hydrogen storage (PHS), has recently emerged as a viable option due to its low impact on the environment, high economic feasibility, and dependability. CAES is an alternative to PHS. For the purpose of storing energy, systems known as compressed air energy storage (CAES) compress air and store it in subterranean cavities or other containers that are suitable". The electricity that these gadgets use comes from either the grid or from renewable energy sources. The discharge cycles cause the compressed air to be heated and then released, which in turn powers turbines that create energy so that the system can function properly. It is possible for CAES systems to be beneficial for both small-scale and large-scale applications in [20]. The efficiency range of these systems is between 48 and 54 percent, which is greater than the efficiency range of traditional gas turbines. The fact that they are dependent on natural gas and need particular geological formations is the reason why they are not utilised on a regular basis. "Flywheel energy storage (FES) is a one-of-a-kind system that use a rotating mass for the purpose of storing energy in the form of kinetic energy. This is accomplished through the utilisation of spinning mass. The use of flywheels is connected with a variety of benefits, some of which include a reduction in the amount of energy that is lost due to friction, a speedy reaction time, and a high energy and power density (with an efficiency of up to 95%)". Among the several types of FES, one kind is designed for applications that are supposed to run for a shorter amount of time, while the other type is suited for programs that are designed to run for a longer period of time [21] Although there have been several advancements made in rotor materials, power electronics, and system performance, FES continues to suffer with considerable self-discharge rates and high idle losses. This is despite the fact that there have been numerous breakthroughs.

2. Overview of Electrical Energy Storage Technologies

While operating at low temperatures, a superconducting coil has the potential to store electrical energy in a magnetic field that is produced by direct current. The energy storage utilised here is superconducting magnetic energy. Although superconductors are expensive, low-temperature operation is necessary, and self-discharge rates are substantial, SMES provides excellent power density, efficiency, power quality, and stability. However, superconductors are rather expensive. "Super capacitors, also known as electrochemical double-layer capacitors (EDLCs), are devices that store energy in the form of a static charge between the carbon electrodes and the electrolyte. They are capable of rapid charging and discharging, cycling in an effective manner, and providing high power for brief periods of time. Due to the fast pace at which they discharge themselves, they are only suitable for short-term storage". Electric vehicles (EVs) are causing a shift in the transportation and energy infrastructures by utilizing the technology known as vehicle-to-grid (V2G). Voltage control, frequency management, and peak shaving are all possible thanks to this technology, which enables electric vehicles to store and return excess renewable energy to the grid. Through the utilization of intelligent charging, electric vehicles have the potential to optimize energy flow, therefore stabilizing the grid and lowering the need for traditional power sources. The technology known as vehicle-to-home (V2H) enables electric vehicles to store renewable energy and deliver it during times of peak demand, therefore enhancing the energy independence of households. [22]

Performance Evaluation of Energy Storage Systems

The power rating, specific energy, energy and power density, round-trip efficiency, reaction time, discharge length, longevity, technological maturity, and daily self-discharge are some of the primary technical metrics that have been developed in order to evaluate the technical performance of an energy storage system (ESS) [23]. For the purpose of assessing the technical performance of an ESS, several metrics have been developed. For the purpose of providing the foundation for the information that is presented in Tables 1 through 3, a current literature review on energy storage was conducted. In terms of their practicability, cost, and performance on the market, these tables offer a solid platform for assessing and comparing the various ESS systems that are now available.

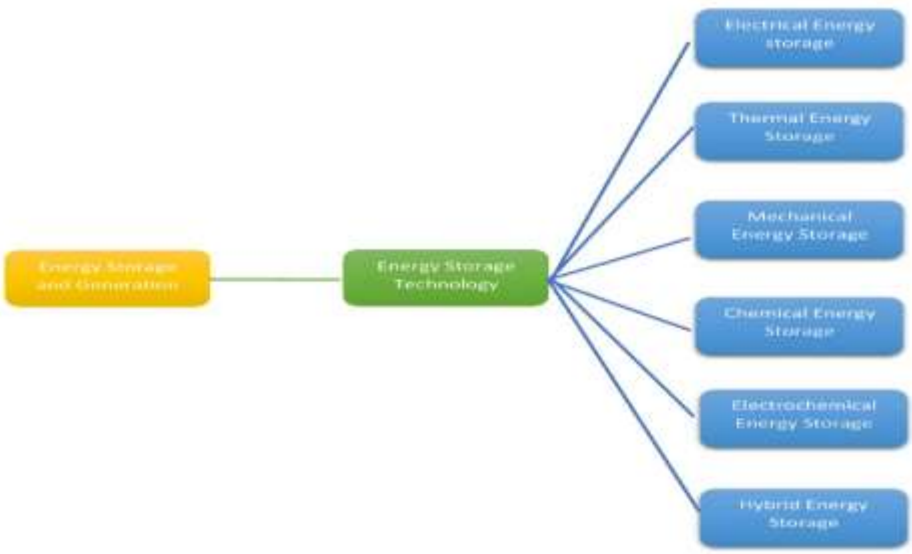

Figure 3: Considerations to Make When Assessing Energy Storage Systems

Table 1. ESS technologies' technical qualities and attributes [24]

Technology	Rating of Power (W)	Energy Specific (Wh/kg)	Particular Power (W/kg)	Lifespan (Years)	Ability to Cycle	Density of Energy (kWh/m³)	Density of Power (kW/m³)
PHS	40-60	(1-3) x 10^4	10-5000	30-60	12,000-30,000	0.5-1.5	0.5-1.5
CAES	20-30	5-300				0.4-20	0.5-2
FES	15-20	20,000	0.1-20	30-60	~5 low speed, ~100 high speed	0.5-1.5	0.5-2
Li-ion	6-20	up to 20,000	0.1-100	75-200	150-315	150-230	150-230
NaS	10-20	2500-4500	0-40	150-250	150-250	10-400	150-250
Pb-acid	5-15	500-1000	0-40	30-50	25-100	150-300	150-250
Ni-cd	13-20	2000-2500	0-40	50-75	60-150	2-3.5	150-250
VRFB	5-15	12,000+	0.3-3	10-20	20-70	1-34	150-250
PSB	10-15	-	8-12	20-29	20-30	150-250	80-120
ZnBr	8-10	2000+	0.1-6	30-50		150-250	100-200
SMES	20	2 x 10^4	0.1-10	10-75	90-110	500-2000	30-60
SCES	8-17	5 x 10^4	0.02-10	2.5-15	2000-5000	1000-5000	2000-5000
Hydrogen	500-3000	5-15	2 x 10^4	0.1-1000	100-150	500+	100-150
PCM	20-40	-	0.001-1				
STES	10-20	-	0.001-10	150-250	80-120	10-30	80-120

The chart presents a comparison of several energy storage technologies based on important performance metrics such as power rating, specific energy, specific power, longevity, cycling capability, energy density, and power density. The table also includes further information about the power density of each technology. As a result of their capacity for large-scale, long-duration energy storage, moderate power density, and high energy density, technologies like as PHS and CAES are ideally suited for grid balancing. As a result of their high specific power and cycle capabilities, lithium-ion and nickel-cadmium-cadmium batteries are better suited for applications that need rapid charging and portability. Because of its exceptionally high specific energy and power density, hydrogen storage stands out as a remarkable material. As a result, it is well-suited for applications that require huge amounts of energy storage in a relatively small space. Other systems, such as NaS and VRFB, have extended lifespans and moderate cycle capacities, which allows them to provide a compromise between long-term efficiency and consistent power supply.

Table 2. factors that are connected to costs [25-27]

Technology	Cost Power (USD/KW)	Cost Energy (USD/KWh)
PHS	850-2126	22-58
SGES	2252-3285	791-908
CAES	645-750	1-33
FES	250-350	1000-14,000
Li-ion	1200-4000	300-1300
NaS	1000-3000	300-500
Pb-acid	300-600	200-400
Ni-cd	500-1500	800-1500
VRFB	600-1500	150-1000
PSB		

ZnBr	800-2900	150-1000
SMES	800-2900	150-1000
SCES	200-489	1085-10,854
Hydrogen storage	100-450	300-2000
PCM	1500-3000	2-15 EUR/kWh
STES (Cryogenic)	200-300	13.65-68.26
STES (Hydrothermal)	3650	0.14-13.65

Through the use of cost power (USD/KW) and cost energy (USD/KWh), the table presents a comparison of various energy storage systems. "Because of the low cost of energy and the high cost of electricity, large-scale energy storage systems such as PHS (Pumped Hydro Storage) are beneficial to projects that are being carried out over several years". As a result of their enhanced capabilities and adaptability, Li-ion and Ni-cd batteries are utilized in applications that are highly demanded and portable. This justifies the higher power and energy prices that these batteries need. On account of its low power and energy expenditures, CAES For medium-sized applications, (Compressed Air Energy Storage) is a great pick. Sodium sulphide (NaS) and flywheel energy storage (FES) systems are more cost-effective for specialized applications that need fast charging and discharging. In the energy storage industry, these setups are referred to as hybrids. The higher price tag of more efficient battery types as SMES and VRFB (Vanadium Redox Flow Batteries) is a reflection of their improved performance. For projects on a tighter budget, lead-acid and zinc bromide might be good options because to their cheaper price, shorter lifespan, and lower efficiency values. The intricacy and variety of hydrogen storage applications cause its energy costs to fluctuate widely. This is so even though hydrogen storage has several uses and has cheap power prices. The size and purpose of thermal energy storage systems, such Phase Change Materials (PCM) and Seasonal Thermal Energy Storage (STES), might affect their final price tag. Hydrothermal storage is more expensive than cryogenic storage.

Table 3. Metrics of performance and stages of maturity of electrical systems technologies [28]

Technology	ESS Efficiency (%)	Round-Trip Efficiency (%)	Self-Discharge Rate (%/day)	Discharge Time	Response (ms to h)	Technological Maturity
PHS	65-85	65-90	Almost zero	6-24 h	Minutes	Mature
SGES	65-85	65-90	Almost zero	Minutes	Almost zero	Demo/early commercializing
CAES	70-80	70-80	Almost zero	<20 h	Minutes	Mature
FES	75-90	55-100	<1 h	ms-15 min	<10 ms	Mature/commercializing
Li-ion	90-97	90-97	0.1-0.3	20 ms-s	Proven/commercializing	
NaS	75-90	89-92	0.05-2	1-24 h	1-2 min	Proven/commercialized
Pb-acid	63-90	63-90	0.1-0.3	<4 h	ms	Mature/commercialized
Ni-cd	65-80	65-80	0.2-0.6	Sec-h	20 ms-s	Mature/commercializing
VRFB	65-85	65-85	0.2	<8 h	Sec	Mature/commercialized
PSB	72-83	72-83	Small	-	-	-
ZnBr	65-75	65-75	Small	-	-	-
SMES	80-95	90-98	10-15	1 min	<10 ms	Mature/commercialized
SCES	5-40	65-90	1 min	<10 ms	-	Developing
Hydrogen Storage	Secs, <1/4 cycle	20-66	Almost zero	Secs-24 h+	Secs	Commercialized
PCM	75-90	75-90	0.5-1	h-days	<10 min	Developing
STES	50-90	50-90	0.05-1	Days-months	≤10 min	Developing

In this table, a number of different approaches to energy storage are compared with regard to their level of technological maturity, discharge time, self-discharge rates, discharge efficiency, and reaction time. Because of their remarkable round-trip efficiencies (90-97% for Li-ion and 75-90% for FES) and very fast reaction times (milliseconds), Li-ion and FES are extremely well-suited for applications that need high performance and rapid response. Despite the fact that PHS, CAES, and NaS have a high round-trip efficiency, their discharge lengths can range anywhere from a few hours to several days, which makes them more ideal for storage with longer durations. When it comes to short bursts of electricity, technologies such as SMES shine and have reaction times that are less than 10 milliseconds. Their efficiency ranges from 80 to 95 percent. On the other hand, SCES may not be the best option for long-term energy storage (5–40%). Despite the fact that they are surpassed by more contemporary systems such as Li-ion and FES, Pb-acid and Ni-cd are well-established technologies that are accessible for commercial use and have respectable efficiency and self-discharge rates. Additional experimental technologies, such as hydrogen storage and STES, offer promise for long-duration storage; response times can range anywhere from seconds to months, depending on the kind of storage.

Table 4. Principal benefits and drawbacks associated with the use of ESS technologies [29-30]

Technology	**Storage Duration**	**Advantages**	**Disadvantages**
PHS	Mid-long	Extremely long lifespan, which allows for more flexibility in power regulation	Geographical restrictions, high installation prices, lengthy building times, and efficiency concerns (sealing friction) are some of the challenges experienced.
SGES	Mid-long	Adaptability to a wide range of geographical situations, rapid reaction capabilities, high scalability characteristics, and a low daily self-discharge rate (SD)	High installation costs, long construction time
CAES	Mid-long	enables flexibility in power control and has a low rate of self-discharge on a daily foundation	High idle loss, high installation costs, problems with efficiency, and a lack of modern adiabatic CAES to minimise natural gas use are all examples of problems.
FES	Seconds, short	Exceptionally quick charging, lightning-fast reaction, superior power quality, high energy density, and a reduced weight	Significantly high rates of self-discharge, increased production costs, a limited lifespan, and the requirement for overcharging protection
Li-ion	Short-mid	A very short charge and discharge time, a very long life period, a high cycle life, high efficiency, and high power rates are all notable characteristics.	Risks associated with flammability, high production costs, and relatively high prices
NaS	Long	An very high power and energy density, a low daily self-discharge rate, and a continuous decrease in manufacturing costs	a high initial cost, a short cycle life, and the requirement of an external heat system
Pb-acid	Short-mid	Costs of capital and maintenance are minimal, and the efficiency of round-trip travel is great.	The lifespan is restricted, the self-discharge rate is high, and the specific energy is poor.
Ni-Cd	Short-long	Extensive cycle life, a large capacity for deep discharge, and excellent efficiency	Ineffective performance at high charging rates, decreased efficiency over the whole round trip, and a high rate of self-discharge
VRFB	Long	Power rates that are high, cycle life that is high, design flexibility that is high, and prolonged life period	With a low specific energy, a danger of contamination, and no evidence that it is beneficial for utility-scale applications
PSB	Short-long	Exceptionally high power rates, a very short charge and discharge time, and a very long cycle life	A high rate of self-discharge and a decrease in energy density
ZnBr	Short-long	High power rates, a long cycle life, and the highest possible efficiency	Contamination risk, not demonstrated to be beneficial for utility-scale applications

SMES	Short	Extremely rapid charging and discharging times, as well as high power rates	The capital cost is expensive, the energy density is poor, and the daily self-discharge is high.
SCES	Short	Efficiency and power rates that are both high	Self-discharge rate that is high, capital cost that is high, and energy density that is low

The following table provides a summary of the various energy storage technologies, including the storage durations, benefits, and downsides associated with each system. A variety of technologies are available to meet a variety of requirements; some of these technologies, such as NaS and PHS, offer long-term storage, while others, such as FES and Li-ion, place an emphasis on rapid reaction and strong energy density. In many technologies, there are still issues that need to be addressed, such as the high cost of initial setup, the inability to scale, and concerns over the environment.

CONCLUSION

When it comes to the technological readiness and scalability of combining solar and wind energy, developing energy storage systems (ESS) create a scenario that is both diverse and promising. As a result, this situation is both promising and diversified. Battery technologies such as sodium-sulfur (NaS) and lithium-ion (Li-ion) are examples of leading technologies that exhibit amazing economic viability, extended cycle lifetimes, and the potential to have rapid reaction times. These technologies are utilised in the context of balancing the intermittent energy supplies that come from renewable sources. On the other hand, there are still questions that need to be answered concerning the affordability, energy density, and impact on the environment of specific materials.

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