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Review

Energy Storage Systems for Photovoltaic and Wind Systems: A Review

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Abstract: The study provides a study on energy storage technologies for photovoltaic and wind systems in response to the growing demand for low-carbon transportation. Energy storage systems (ESSs) have become an emerging area of renewed interest as a critical factor in renewable energy systems. The technology choice depends essentially on system requirements, cost, and performance characteristics. Common types of ESSs for renewable energy sources include electrochemical energy storage (batteries, fuel cells for hydrogen storage, and flow batteries), mechanical energy storage (including pumped hydroelectric energy storage (PHES), gravity energy storage (GES), compressed air energy storage (CAES), and flywheel energy storage), electrical energy storage (such as supercapacitor energy storage (SES), superconducting magnetic energy storage (SMES), and thermal energy storage (TES)), and hybrid or multi-storage systems that combine two or more technologies, such as integrating batteries with pumped hydroelectric storage or using supercapacitors and thermal energy storage. These different categories of ESS enable the storage and release of excess energy from renewable sources to ensure a reliable and stable supply of renewable energy. The optimal storage technology for a specific application in photovoltaic and wind systems will depend on the specific requirements of the system. It is important to carefully evaluate these needs and consider factors, such as power and energy requirements, efficiency, cost, scalability, and durability when selecting an ESS technology.

Keywords: storage; wind turbine; photovoltaic; energy storage; multi-energy storage

Citation: Rekioua, D. Energy Storage Systems for Photovoltaic and Wind Systems: A Review. *Energies* **2023**, *16*, 3893. https://doi.org/10.3390/en16093893

Academic Editor: Nicu Bizon

Received: 28 March 2023
Revised: 1 May 2023
Accepted: 3 May 2023
Published: 4 May 2023

1. Introduction

The significance of solar and wind energies has grown in importance recently as a result of the need to reduce gas emissions [1]. Energy storage systems (ESSs) store excess energy when demand is not sufficient and release it when demand is satisfied. Furthermore, the desire for transportation alternatives with reduced CO_2 emissions has led to an interest in energy storage [2]. Electrochemical, mechanical, electrical, and hybrid systems are commonly used as energy storage systems for renewable energy sources [3–16]. In [3], an overview of ESS technologies is provided with respect to their suitability for wind power plants. The authors in [4] conduct a review of advancements in ESSs from 1850 to 2022, with their evolution, classification, operating principles, and comparison. Reference [5] pays particular attention to energy storage systems and compares them. References [6–10] focus on storage in wind systems, while references [11–17] focus on storage in PV systems.

Electrochemical ESSs include batteries, fuel cells for hydrogen storage, and flow batteries. Mechanical storage includes pumped hydroelectric energy storage, compressed air energy storage (CAES), and flywheel energy storage. CAES stores compressed air in underground caverns and releases it to generate energy during periods of high demand. Flywheel energy storage (FES) stores kinetic energy in a rotating flywheel. The choice of mechanical energy storage system will depend on factors, such as the available technology, cost, efficiency, and environmental impact.

There are three types of electrical energy storage technologies: supercapacitor energy storage (SES), superconducting magnetic energy storage (SMES), and thermal energy storage (TES). SES uses electrostatic fields to store energy. It has a high power output and fast response times, making it applicable in regenerative braking in electrical vehicles and grid stabilization. TES uses a variety of storage media. It provides long-duration storage but typically has lower power output compared to other technologies.

A hybrid or multi-energy storage system uses different ESS technologies to enhance the overall system performance. By utilizing multiple storage technologies, a hybrid ESS can provide the advantages of each technology while minimizing the drawbacks to obtain a more effective and dependable ESS. The chosen ESS technology for PV and wind systems depends on a number of variables, such as the system's needs, expense, and performance characteristics. It is also worth noting that a combination of different ESS technologies may be the best option for some applications, as this can offer the benefits of multiple technologies and help to address their respective limitations. To effectively manage different ESS technologies in PV and wind systems, power management controls (PMCs) are applied [18–23]. PMCs ensure that the system operates efficiently and safely and maximizes the use of renewable energy. PMCs are typically implemented using algorithms and software that continuously monitor the system's energy production. In reference [18], the PMC system was applied to a wind turbine/battery system, while in reference [19], it was applied to PV installations with storage. In reference [20], PMCs were applied to multi-source systems, such as PV/wind turbine/batteries for electrification, and in reference [21], they were used for pumping water. Similarly, the authors in references [22,23] apply the same PMC system to supervise and control PV/fuel cells/batteries. Modeling and sizing of batteries in PV and wind energy systems, as well as PMCs in ESS technologies, are essential aspects of designing efficient renewable energy systems. They are detailed to help our understanding of the behavior of such systems.

In PV systems, ESS has a variety of uses, such as load balancing, backup power, time-of-use optimization, and grid stabilization. Additionally, in wind systems, ESS is used for various applications, including grid stabilization, remote power supply, industrial applications, peak shaving, and backup power supply.

In this work, different storage and multi-storage systems are examined by providing different advantages and drawbacks to help choose the optimal ESS technology for a specific application in photovoltaic and wind systems. The main objective of this paper is to enable researchers of renewable energy and researchers of modern power systems to quickly understand the different storage systems used in wind and solar plants. Further, it allows us to show the importance of an ESS in renewable energy systems (RESs) in the worldwide energy mix.

2. Energy Storage Overview

The main categories of ESS are [1]: electrochemical, mechanical, thermal, electrical storage, and hybrid systems or multi-storage (Figure 1).

2.1. Electrochemical Storage

Many types of electrochemical storage (ES) technologies are used, including batteries and fuel cells. ES has several advantages. It satisfies a variety of power and energy storage requirements and is scalable and modular. It is also highly efficient, with many electrochemical storage technologies offering high round-trip efficiency rates. However, ES also has some limitations, including the need for specialized infrastructure, limited life cycle, and high capital costs.

2.1.1. Batteries Energy Storage Systems (BESSs)

Batteries work by using a chemical reaction to create a flow of electrons, which can be harnessed to power electronic devices or other electrical loads. Numerous other battery types are used in energy storage devices. The following table summarizes some characteristics of these batteries based on cost, technology, life cycle, energy density, and efficiency (Table 1) [24–39]. These values vary depending on the specific battery chemistry, manufacturer, and application.

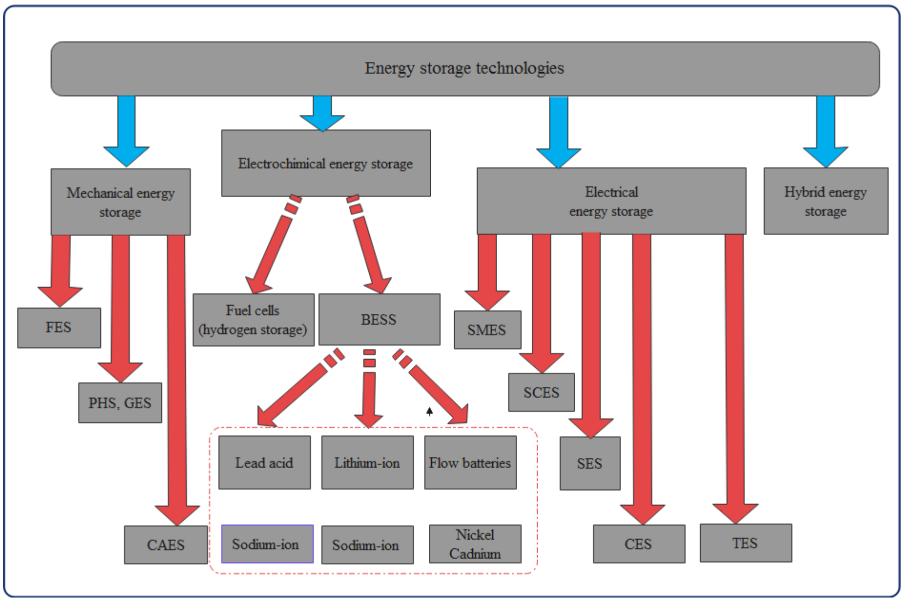

Figure 1. Energy storage system technologies.

Table 1. Some characteristics of the most used batteries.

Battery Type	Cost	Technology	Specific Power (W/kg)	Specific Energy (Wh/kg)	Efficiency (%)	References
Lead-acid	Low	Mature	75–300	30–50	70–80	[24–26]
Lithium-ion	High	Advanced	150–315	75–250	95–98	[27,28]
Sodium-sulfur	High	Advanced	150–230	150–240	80–90	[29–31]
Zinc-bromine	High	Advanced	100–166	60–70	65–90	[32,33]
Vanadium Redox	High	Advanced	100–166	10–35	65–85	[34]
Nickel-Cadmium	Moderate	Mature	150–300	70–75	70–80	[35,36]
Nickel-Metal Hydride	Moderate	Mature	200–300	70–100	60–70	[36,37]
Sodium-Nickel Chloride	High	Advanced	150–200	100–120	80–90	[37,39]

2.1.2. Fuel Cells for Hydrogen Energy Storage (HES)

The hydrogen generated by an electrolyzer is stored in a tank until it is needed. When the stored hydrogen is needed, it is fed into a fuel cell where it reacts with oxygen to generate electricity and water. HES has several advantages as an energy storage technology. It is an excellent option for ESS in off-the-grid or remote areas because it can be stored for a long time and can be produced using renewable energy sources. It is also a safe and versatile energy source. However, HES also has some limitations. One challenge is the cost of producing and storing hydrogen, which can be higher than other energy storage technologies. HES also requires specialized infrastructure, such as pipelines and fuel cells, which can be expensive to install and maintain. The hydrogen storage modes that are used in HES are given in Tables 2 and 3 [1].

Table 2. Advantages of hydrogen storage modes.

Storage Type	Maintenance	Safety	Storage Life
Compressed Hydrogen Storage	Minimal	No chemical reactions used	Long
Liquefied Hydrogen Storage	low	No chemical reactions used	Long
Metal Hydride Storage	Minimal	Safe and easy to handle	Long

Table 3. Weaknesses of hydrogen storage modes.

Storage Type		**Weaknesses**			
Compressed Hydrogen Storage	Requires high pressures	Heavy storage tanks	Compression requires energy	Gas compression can generate heat,	subject to leakage if tanks are damaged
Liquefied Hydrogen Storage	Requires cryogenic temperatures	Boil-off losses can be significant	Heavy storage tanks are required	Maintaining cryogenic temperatures can be difficult and expensive	subject to leakage if tanks are damaged
Metal Hydride Storage	Limited by the capacity of the metal hydride material	May require high temperatures or pressures	Can be slow to charge and discharge	Energy density is lower than compressed or liquefied hydrogen storage	Cost and availability of metal hydride materials can be a limiting factor

2.2. Mechanical Storage

2.2.1. Pumped Hydroelectric Energy Storage (PHES)

Pumped hydroelectric energy storage (PHES) is a type of energy storage system that utilizes two reservoirs at different elevations to store and generate electricity. During periods of excess power generation on the grid, typically during low-demand periods or when there is an excess of renewable energy generation, water is pumped, thereby storing the excess energy as gravitational potential energy. When there is a need for additional energy, such as during periods of high electricity demand or when renewable energy generation is low, the stored water in the higher reservoir is released and allowed to flow downhill through turbines. The flowing water drives the turbines, which are connected to generators, producing electricity that is fed back into the grid to meet the demand [1]. Particularly well suited for long-term storage, PHES systems are a good choice. However, PHES facilities usually require access to appropriate topography and water resources, and their installation costs can be high in comparison to those of other energy storage technologies.

2.2.2. Compressed Air Energy Storage (CAES)

It operates by compressing air, which it then stores in underground caverns or containers as energy. The compressed air is released and expanded through a turbine to produce energy. It is possible to use CAES to balance the output of wind and solar electricity by offering large-scale, long-duration energy storage. Contrary to other ESSs, CAES facilities can be more costly to build and need access to appropriate geological formations.

2.2.3. Flywheel Energy Storage (FES)

It is typically made of lightweight materials such as carbon fiber and spins at high speeds inside a vacuum-sealed enclosure, which reduces friction and energy loss. The flywheel is accelerated to store energy when it is available, and when energy is required, the flywheel's rotational energy is transformed back into energy via a generator. Flywheels are useful for applications, such as grid stabilization and uninterruptible power supplies. They have fast response times, as they can respond to changes in demand within seconds. They also have a relatively long lifespan compared to other energy storage technologies and can operate at high efficiencies. However, FES is typically not as suitable for long-duration energy storage as other technologies, such as pumped hydroelectric storage or battery storage, due to energy loss through friction and other factors over time.

2.2.4. Gravity Energy Storage (GES)

This stores potential energy by lifting weights to a certain height. The stored energy can be used at another moment by releasing the weights, which then fall and drive a generator to generate energy. When there is a surplus of energy being produced, water is pumped, where it is then released to continue generating electricity when there is a high demand [40–45].

2.3. Electrical Energy Storage

2.3.1. Super Capacitor Energy Storage (SES)

This uses electrostatic fields to store energy. SES systems are similar to traditional capacitors but have a much higher energy density, allowing them to store and release larger amounts of energy more quickly [46].

2.3.2. Superconducting Magnetic Energy Storage (SMES)

SMES systems consist of a superconducting coil, a power conditioning system, and a cryogenic cooling system. The superconducting coil is typically made of a superconducting material, such as niobium–titanium or niobium–tin, and is cooled to extremely low temperatures using a cryogenic cooling system. When a current is applied to the coil, it generates a magnetic field, which can be used to store energy [47].

2.3.3. Capacitor Energy Storage (CES)

Two conductive surfaces and an insulating substance known as a dielectric separate two capacitors. An electric field forms between the plates of the capacitor when a voltage is applied, making one plate positively charged and the other negatively charged. The capacitor's electromagnetic field stores the energy, which can be released when necessary [48].

2.3.4. Thermal Energy Storage (TES)

Applications for TES include electricity generation, industrial processes, and the heating and cooling of buildings. TES systems use a variety of storage media, including water, molten salt, and phase change materials. When energy is required, the heat that has been stored is released to create power, heat, or both [45].

2.4. Benefits and Drawbacks of the Different ESSs

Table 4 gives the benefits and drawbacks of the different ESSs.

Table 4. Benefits and drawbacks of some energy storage systems.

ESS Technology	Benefits	Drawbacks
	Mechanical Storage	
PHES	- High efficiency, - Large storage capacity and long cycle times,	- Requires specific geography, large amounts of water, - High capital costs,
CAES	- Large storage capacity - Low carbon footprint and minimal environmental impact,	- Limited efficiency, - Requires specific geology for underground storage,
FES	- High efficiency, - Fast response time for grid stabilization,	- Limited energy storage capacity, - High capital costs,
GES	- Used in a wide range of locations, - Long life cycle with minimal maintenance	- Limited efficiency, - Requires significant civil engineering

Table 4. *Cont.*

ESS Technology	Benefits	Drawbacks
Thermal Energy Storage (TES)		
	- Provide both heating and cooling,	- Limited energy storage capacity,
	- High energy density,	- Limited thermal conductivity of some materials,
	- Use a variety of storage media,	- Limited commercial availability of some technologies,
	- Integrated with existing heating and cooling systems,	- Thermal losses can occur during storage and use,
	- No harmful emissions or waste products,	- Efficiency can be reduced by thermal losses,
	- Long lifespan,	- Requires appropriate insulation and safety measures
	- Reduce peak energy demand and energy costs	- Can be sensitive to environmental conditions
Super Capacitor Energy Storage (SES)		
	- Fast charging and discharging,	- Limited energy density,
	- Long lifespan,	- Higher cost per unit of energy stored,
	- No toxic or hazardous materials	- Limited range of operating temperatures,
	- Low maintenance requirements,	- Voltage drop during discharge can be steep
	- High power output capability,	- Limited storage capacity,
	- Can operate in extreme temperatures,	- Can experience self-discharge over time,
	- Can reduce peak energy demand and energy costs	- Can be sensitive to environmental conditions
Superconducting Magnetic Energy Storage (SMES)		
	- Long lifespan,	- Higher cost per unit of energy stored,
	- No toxic or hazardous materials,	- Limited range of operating temperatures,
	- Low maintenance requirements,	- Voltage drop during discharge can be steep
	- High power output capability,	- Limited storage capacity,
	- Can operate in extreme temperatures,	- Can experience self-discharge over time,
	- High efficiency	- Limited commercial availability

2.5. Energy Storage Technology Efficiencies

Several variables, including but not limited to charging and discharging rates, temperature, state of charge, age, and operating conditions, can affect how effective an energy storage technology is. The state of charge (SoC) affects the lifespan or longevity of a battery. The SoC of a battery can impact its performance, efficiency, and overall health. The relationship between SoC and battery lifespan follows a general rule: operating a battery at extreme SoC levels, either very high or very low, can degrade its performance and reduce its lifespan. Most battery chemistries are sensitive to SoC levels and can experience accelerated degradation when operated outside of their optimal SoC range (Figure 2). The depth of discharge (DoD) of a battery indicates how much of its energy has been used up before it needs to be recharged.

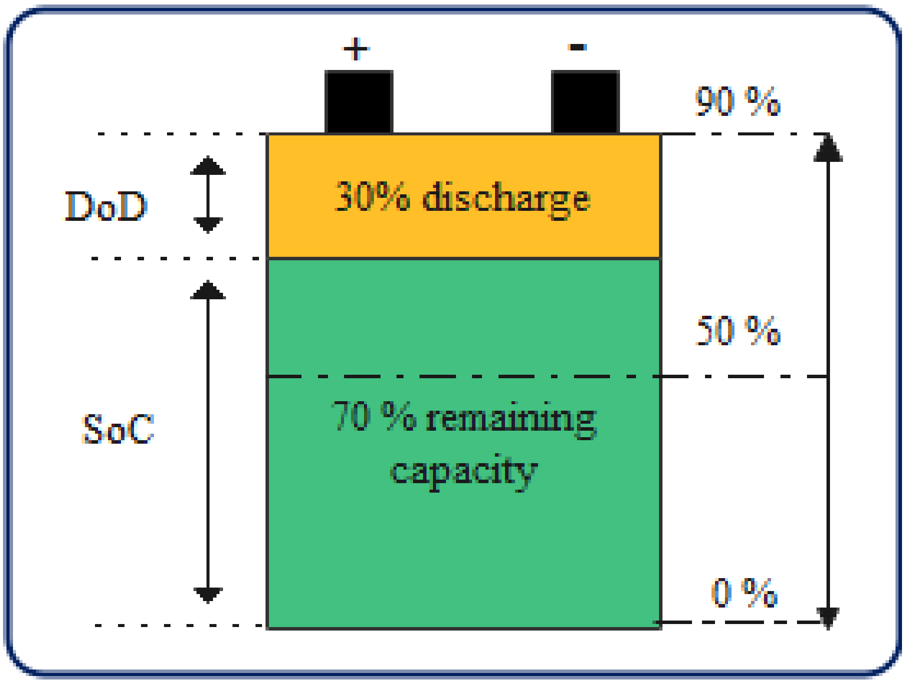

Figure 2. Diagram of a battery charge state.

The performance efficiency of the most popular ESS is summarized in Figure 3 [43–48]. Black color corresponds to the minimal value of efficiency, and red color corresponds to the maximum value of efficiency.

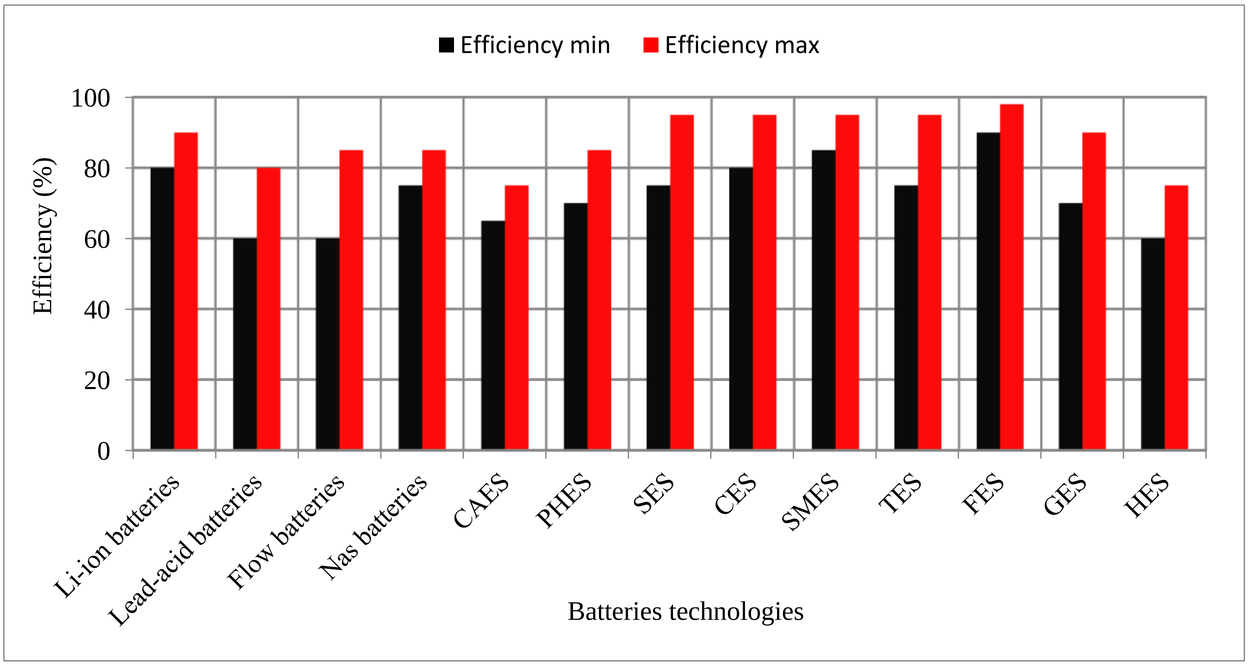

Figure 3. Efficiency of the most used energy storage technologies.

3. Energy Storage Systems Commonly Used for PV and Wind Power Systems

Modeling and sizing of batteries in PV and wind energy systems, as well as power management control of ESS technologies, are essential aspects of designing efficient and reliable renewable energy systems.

3.1. PV/Wind/Battery Energy Storage Systems

PV/wind/battery energy storage systems (BESSs) involve integrating PV or wind power generation with BESSs, along with appropriate control, monitoring, and grid interaction mechanisms to enhance the integration of renewable energy into the electrical grid, improve system stability, and support a more sustainable energy system by using technical basics. The most important factors are as follows:

- PV or Wind Power Generation: PV systems generate electricity by converting sunlight into electrical energy using photovoltaic panels, while wind power systems generate electricity using the kinetic energy of wind through wind turbines. These systems can vary in size and capacity, depending on the specific application and location.
- Battery Energy Storage Systems (BESSs): They are used to store excess electricity generated by PV or wind systems during periods of low demand or high generation. BESSs typically consist of batteries that can store and release electrical energy as needed. They can vary in size, capacity, and technology, and their performance characteristics can impact the overall system efficiency and effectiveness.
- Charge and Discharge Control: It is a crucial aspect of the PV/wind + BESS system. During times of high PV or wind generation and low demand, excess electricity is stored in the BESS. When demand exceeds generation, the BESS is discharged to supply additional electricity to the grid or the load. Sophisticated control algorithms are used to manage the charging and discharging of the BESS, ensuring optimal operation and performance.
- Inverter Systems: They are typically used in PV and wind systems to convert the DC energy generated by PV panels or wind turbines into AC energy that can be fed into the grid or used locally. Inverter systems also play a role in interfacing the PV/wind systems with the BESS, managing the charging and discharging process.
- Grid Interaction: PV/wind + BESS systems can interact with the electrical grid in different ways, depending on the specific application and grid requirements. They can supply surplus energy to the grid during periods of high generation, draw electricity from the grid during periods of low generation or high demand, and provide grid support services as frequency regulation and voltage control, depending on the capabilities of the BESS and the system configuration.
- Monitoring and Control: They are essential for the operation and performance optimization of PV/wind + BESS systems. They typically involve sensors, communication networks, and control algorithms that continuously monitor the performance of the PV/wind systems, the BESS, and the grid, and make decisions on charging, discharging, and grid interaction based on real-time data.
- System Integration and Design: They are critical for the effective operation of PV/wind + BESS systems. Factors, such as the sizing of the PV or wind system, the capacity and performance of the BESS, the control strategies, and the grid requirements, need to be carefully considered to ensure optimal performance, system efficiency, and grid stability.

3.2. Classification of PV Architectures

Solar PV systems come in various sizes and configurations depending on the application and power requirements. The choice of PV architecture depends on factors, such as the size of the PV system, site conditions, cost, and desired level of monitoring and control. Each type of inverter has its advantages and disadvantages, and careful consideration is required to select the appropriate PV architecture for a particular application. Based on the power handling capability, PV architectures are classified into different types (Table 5).

Table 5. Classification of PV architectures [11].

PV Inverters	Operation	Power Range	
Central PV inverter	Multiple PV modules are connected in series to form a string, and then multiple strings are connected in parallel to a central inverter. The central inverter converts the DC power generated by the PV modules into AC power that is fed into the grid or used locally.	Small utility-scale systems	500 kW–1 MW
		Medium utility-scale systems	1–5 MW
		Large utility-scale systems	5–20 MW
String PV inverter	Each string of PV modules is connected to a dedicated inverter. The DC power generated by each string is converted into AC power by the respective string inverter, and then the AC power is combined and fed into the grid or used locally	Residential	1–10 kW
		Commercial/Utility-scale	10–500 kW
Multi-string PV inverter	This configuration is similar to the string PV inverter, but with the ability to connect multiple strings to a single inverter. It allows for more flexibility in system design and is commonly used in larger PV installations	3–10 kW	
AC module PV inverter	In this configuration, the inverter is integrated directly into the PV module, and each module operates independently, generating AC power that can be fed into the grid or used locally. This type of PV inverter is commonly used in small-scale applications where individual modules need to be easily monitored or replaced.	50–500 W	
Hybrid Inverter (with energy storage)	Combines the functionalities of an inverter and a battery storage system. It is typically used in renewable energy systems. It offers efficient energy management, increased self-consumption of renewable energy, backup power, and potential cost savings.	3–10 kW	

3.3. Advantages and Disadvantages of RESs

Renewable energy systems (RESs), which harness energy from natural sources that are constantly replenished, have many advantages and disadvantages, which vary depending on the specific technology, location, and context in which they are deployed (Table 6).

Table 6. Advantages and disadvantages of renewable energy systems.

Advantages	Disadvantages
1. Environmentally friendly	1. Intermittency and variability
2. Sustainable and abundant	2. Initial costs
3. Diversification of energy sources	3. Land and resource requirements
4. Economic benefits	4. Transmission and infrastructure challenges
5. Improved public health	5. Energy storage limitations

3.4. Advantages and Disadvantages of BESSs

The advantages and disadvantages of battery energy storage systems (BESSs) can vary depending on the specific application, size, and technology of the battery storage system, as well as local regulations and market conditions. It is important to carefully consider the specific circumstances and requirements when evaluating the benefits and limitations of BESSs (Table 7).

Table 7. Advantages and disadvantages of battery energy storage.

Advantages	Disadvantages
1. Energy storage flexibility	1. High upfront costs
2. Enhanced renewable energy integration	2. Limited energy storage capacity
3. Grid stabilization and peak shaving	3. Environmental considerations
4. Backup power during outages	4. Battery degradation and lifespan
5. Demand management and load shifting	5. Safety and regulatory concerns

3.5. ESSs Commonly Used for Photovoltaic and Wind Power Systems

An energy storage system's suitability will be chosen based on the specific needs and limitations of the PV or wind power system in question, as well as factors, such as cost, dependability, and environmental impact. Table 8 summarizes the key features and characteristics of energy storage systems commonly used for photovoltaic and wind systems.

Table 8. Characteristics of ESSs commonly used for photovoltaic and wind power systems.

ESS	Key Features	Advantages	Disadvantages	References
Lead-acid Batteries	Low cost, widely available	Simple design, easy to maintain, Proven technology	Shorter lifespan, lower energy density, limited charging and discharging cycles	[39]
Lithium-ion Batteries	High energy density, longer lifespan	Efficient charging and discharging, low self-discharge rate	Higher cost, potential safety concerns, requires a battery management system	[40]
Flow Batteries	Scalable, longer lifespan	Can be discharged completely without damage	More complex design, lower energy density	[31]
Redox Flow Batteries	High scalability, Longer lifespan compared to some battery types	Good for applications requiring long-duration discharge	Requires regular maintenance, More expensive compared to lead-acid batteries and some lithium-ion batteries, Lower energy density compared to some battery types	[41]

Table 8. *Cont.*

ESS	Key Features	Advantages	Disadvantages	References
Sodium-Sulfur Batteries	High energy density	Long lifespan compared to some battery types	More expensive compared to lead-acid batteries- Limited availability due to current production constraint	[42]
Supercapacitors	High power density, fast charging	Long life cycle, low maintenance	Limited energy storage capacity, higher cost, Requires a control circuit to prevent overcharging and over discharging	[43]
Flywheel Systems	Fast response time, long lifespan	Highly efficient, no hazardous materials	Expensive, requires precise engineering	[44]
Hydrogen Fuel Cells	High energy density, long lifespan	Can operate continuously, no emissions	Higher cost, requires hydrogen fuel infrastructure	[45]
Compressed Air Energy Storage (CAES)	Low cost compared to some other technologies	High energy capacity	Requires underground storage caverns or tanks, Not suitable for small-scale applications	[46]
Pumped Hydro Energy Storage (PHES)	High energy capacity, Mature technology	Long lifespan	Large-scale installations only, High construction cost	[47]
Thermal Energy Storage (TES)	Mature technology, High energy density	Can be integrated with existing heating and cooling systems	High construction cost, Not suitable for small-scale applications	[48]
Capacitor Banks	Fast response time, High cycling capability	Low maintenance	Not suitable for long-duration energy storage	[49]
Gravity Storage	Low cost compared to some other technologies, High efficiency	No hazardous materials involved	Limited energy storage capacity compared to some other technologies	[50]

3.6. Battery Modeling

In the literature and in the field of electrochemical engineering, there are various models used to describe the behavior and characteristics of batteries, including their energy storage capacity, state of charge (SoC), discharge behavior, voltage and current waveforms, and other performance parameters. These models can help researchers and engineers understand the underlying electrochemical processes that occur within batteries, predict their performance under different operating conditions, and optimize their design and operation. It is important to note that the choice of each model depends on the specific application, desired level of accuracy, available data, and computational resources [49]. Table 9 summarizes the battery models used in PV and wind systems:

Table 9. Battery models used in PV and wind systems.

Battery Model	Advantages	Limitations
Equivalent Circuit Model (ECM)	- Simple and easy to implement - Provides accurate voltage and current predictions - Suitable for real-time simulations	- Limited accuracy for complex battery chemistries - May not capture all electrochemical processes - May require calibration
Two-Point Model	- Simpler than ECM - Suitable for real-time applications - Can be used for SoC estimation	- May not capture battery dynamics accurately - temperatures - May require calibration

Table 9. *Cont.*

Battery Model	Advantages	Limitations
Electrochemical Impedance Spectroscopy (EIS)	- Provides detailed information on battery electrochemical processes - Suitable for studying battery aging - Can be used for SoC estimation	- Requires specialized equipment and expertise - Time-consuming and complex data analysis - May have limited accuracy in dynamic conditions
Diffusion Model	- Captures lithium ion diffusion dynamics - Can predict battery behavior under various conditions - Suitable for studying thermal effects	- Complex and computationally intensive - Requires detailed battery parameter - May have limitations for extreme temperatures
Electro-Thermal Model	- Captures both electrical and thermal behavior of batteries - Suitable for studying battery thermal management - Can predict battery performance under varying load conditions	- Requires detailed thermal and electrical parameters - Complex and computationally intensive - May require extensive calibration

3.7. Battery Sizing

Battery sizing in PV and wind systems requires careful consideration of energy demand, energy production, battery capacity, battery depth of discharge, battery efficiency, autonomy, system voltage, and environmental factors. The proper sizing of batteries ensures optimal performance, reliability, and longevity of the ESS in conjunction with the PV or wind system [50]. Properly sizing the batteries ensures that the system can efficiently store and utilize excess energy generated by the PV or wind system and provides reliable power during periods of low or no energy production. There are several key factors to consider when sizing batteries for PV and wind systems [51,52]:

1. Energy Demand: The first step in battery sizing is to determine the energy demand of the system. This includes understanding the energy needs of the load that the PV or wind system will be powering, such as lighting, appliances, or other electrical devices. Energy demand is typically expressed in kilowatt-hours (kWh) and can be determined by analyzing historical energy usage data or through load profiling.
2. Energy Production: The next factor to consider is the energy production of the PV or wind system. This includes understanding the average daily energy production of the PV or wind system, as well as seasonal variations. Energy production is typically expressed in kilowatt-hours per day (kWh/day) or kilowatts (kW).
3. Battery Capacity: It is the amount of energy that a battery can store. It is important to select a battery with enough capacity to store excess energy generated by the PV or wind system during periods of high energy production and discharge the stored energy during periods of low energy production.
4. Battery Depth of Discharge (DoD): It is the percentage of the total battery capacity that can be discharged without damaging the battery. It is important to select a battery with an appropriate depth of discharge to ensure optimal battery performance and longevity. Generally, a higher depth of discharge allows for more usable energy from the battery but may reduce the overall lifespan of the battery.
5. Battery Efficiency: It is the percentage of energy that can be stored in the battery compared to the energy that is discharged. It is very important to consider the efficiency of the battery when sizing, as lower-efficiency batteries may require larger capacities to achieve the desired energy storage goals.
6. Autonomy: It is the number of days that the battery system can sustain the energy demand of the load without being recharged by the PV or wind system. Autonomy requirements depend on the specific application and the availability of renewable energy sources. Longer autonomy requirements may require larger battery capacities.
7. System Voltage: It is an important consideration for battery sizing, as it determines the compatibility of the battery with the system. The battery voltage should be compatible

with the PV or wind system voltage to ensure efficient charging and discharging of the battery.

8. Environmental Factors: Temperature, humidity, and altitude can also impact battery performance and should be considered when sizing batteries. Some batteries may have reduced capacity or efficiency at extreme temperatures or high altitudes, which may affect their suitability for the PV or wind system.

The battery capacity can be calculated as in [53–57]:

$$C_{\text{batt}} = \frac{E \cdot \text{Aut}}{V_{\text{bat}} \cdot \text{DoD} \cdot \text{Aut} \cdot \eta_{\text{bat}}}. \tag{1}$$

where V_{bat} is the battery voltage, DoD is the depth of discharge, Aut is autonomy days, η_{bat} is the efficiency of battery, and E is the load energy.

The number of batteries can be calculated from the capacity of a battery unit $C_{\text{batt,u}}$ [54]:

$$N_{\text{batt}} = \text{ENT}\left[\frac{C_{\text{batt,min}}}{C_{\text{batt,u}}}\right] \tag{2}$$

In reference [20], PMCs were applied to multi-source systems (Figure 4), such as PV/wind turbine/batteries for electrification, and in reference [21], they were used for pumping water. Similarly, the authors in references [22,23] applied the same PMC system to supervise and control PV/fuel cells/batteries. In a battery-SC hybrid storage system, the power management control algorithm can regulate the currents of the battery and SCs to maintain the desired SoC levels, optimize charging and discharging rates, and ensure safe and efficient operation (Figure 5). The algorithm may also consider factors, such as renewable energy availability, load demand, and system constraints, to determine the optimal operation mode of the system, such as charging from renewable energy sources during excess generation, discharging during peak demand periods, or providing power for critical loads during grid outages.

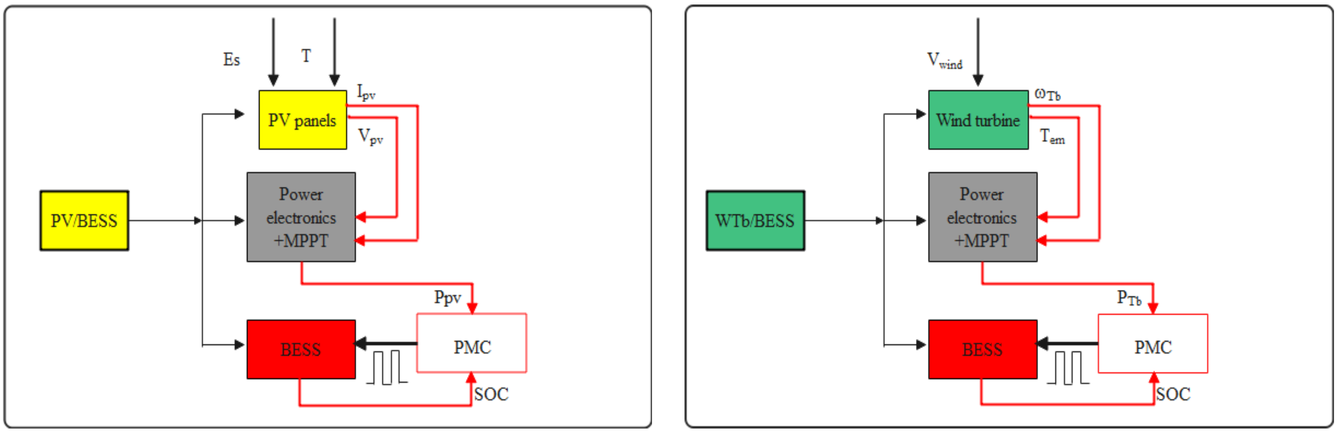

Figure 4. Power management control in PV/BESS and in WTb/BESS.

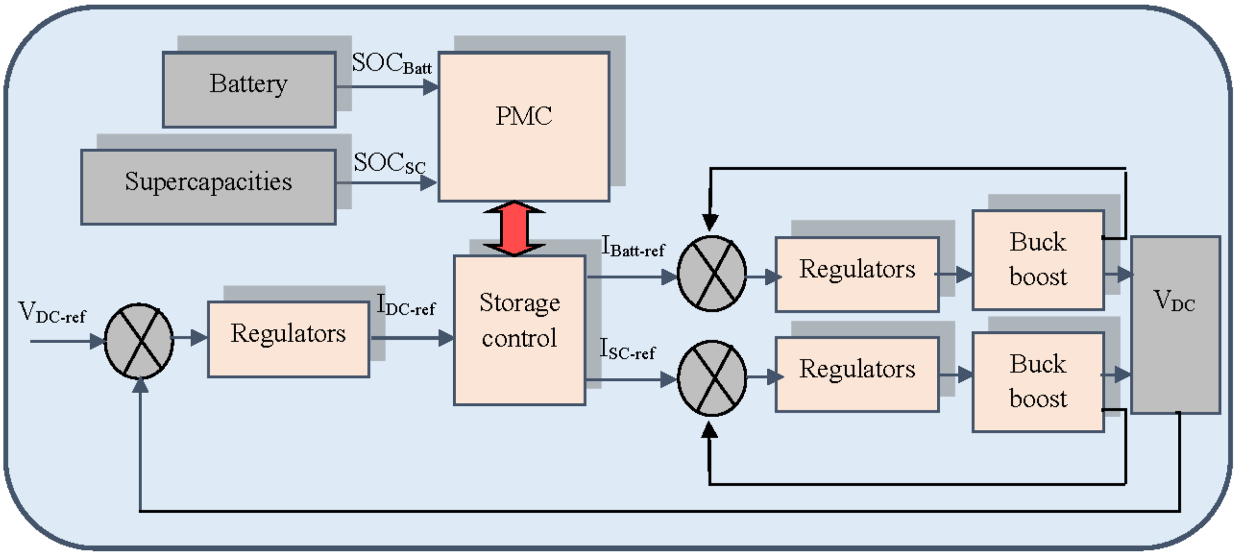

Figure 5. PMC of battery and supercapacities.

4. Hybrid or Multi-Energy Storage

Hybrid energy storage systems integrate multiple technologies to provide a more comprehensive and flexible solution for renewable energy systems. By combining different technologies, these hybrid systems can maximize each technology's benefits while minimizing their drawbacks. The system chosen will rely on factors, such as the specific energy storage requirements of the system, the renewable energy sources being used, and the available resources and infrastructure. Table 10 summarizes the different combinations of the ten most commonly used energy storage technologies, totaling 100 cases. This includes 74 possible real cases (cells in green color), with 10 cases that do not involve any combinations (cells in red color), as well as 16 cases that are recognized as innovative solutions and require expensive materials or are still in development (cells in blue color).

Table 10. Summary of different combinations of energy storage.

	BES	SES	FES	TES	SMES	PHES	HES	CAES	GES	CES
BES	🟥	🟩 x	🟩 x	🟩 x	🟩 x	🟩 x	🟩 x	🟩 x	🟩 x	🟩 x
SES	🟩 x	🟥	🟩 x	🟩 x	🟩 x	🟩 x	🟩 x	🟩 x	🟩 x	🟦 x
FES	🟩 x	🟩 x	🟥	🟩 x	🟦 x	🟩 x	🟩 x	🟩 x	🟩 x	🟩 x
TES	🟩 x	🟩 x	🟩 x	🟥	🟦 x	🟩 x	🟩 x	🟩 x	🟩 x	🟩 x
SMES	🟩 x	🟩 x	🟦 x	🟦 x	🟥	🟦 x	🟩 x	🟦 x	🟦 x	🟦 x
PHES	🟩 x	🟩 x	🟩 x	🟩 x	🟦 x	🟥	🟩 x	🟩 x	🟩 x	🟩 x
HES	🟩 x	🟩 x	🟩 x	🟩 x	🟩 x	🟩 x	🟥	🟩 x	🟩 x	🟩 x
CAES	🟩 x	🟩 x	🟩 x	🟩 x	🟦 x	🟩 x	🟩 x	🟥	🟦 x	🟦 x
GES	🟩 x	🟩 x	🟩 x	🟩 x	🟦 x	🟩 x	🟩 x	🟦 x	🟥	🟩 x
CES	🟩 x	🟦 x	🟩 x	🟩 x	🟩 x	🟩 x	🟩 x	🟩 x	🟩 x	🟥

There are various battery combinations that are commonly used for different applications. These combinations are often composed of battery energy storage systems (BESSs) combined with various technologies to achieve specific energy storage requirements. For instance, BESS/SES is often used in applications that require both long-term energy storage and fast discharge times, such as electric vehicle charging stations and rural electrification. This is mentioned in references [25,58–62]. On the other hand, BESS/FES is a reliable and flexible solution for the power needs of an island and is commonly used in residential microgrids. This combination is discussed in references [63–65]. BESS/TES is particularly useful for renewable energy systems that require both short-term and long-term energy storage capabilities, as cited in references [66–68]. BESS/SMES, as mentioned in references [69,70], is a suitable option for renewable energy systems that require high power output and high energy density. BESS/PHES is useful for grid-scale energy storage applications, as mentioned in references [71–74]. Furthermore, BESS/HES is designed to power remote off-grid locations, as cited in reference [66]. BESS/CAES is particularly useful for grid-scale energy storage applications, as mentioned in reference [66]. BESS/GES is designed for grid-scale energy storage and backup power for critical infrastructure, as noted in reference [75]. Lastly, BESS/CES is commonly used for smoothing out power fluctuations in renewable energy systems and providing backup power for critical infrastructure, as cited in reference [48].

Different combinations and the specific applications that each combination is best suited for can be used with SESs. To start with, SES/FES is used for mitigating power fluctuations in renewable energy systems and providing backup power for critical infrastructure, as noted in [76]. In addition, SES/TES is well suited for renewable energy systems that require both high power output and thermal energy management. Moreover, SES/SMES is a useful combination for applications, such as electric vehicles and renewable energy systems. SES/PHES, on the other hand, is a suitable option for renewable energy systems that require both high power output and long-term energy storage. Furthermore, SES/HES is an appropriate choice for renewable energy systems that require both high power output and long-term energy storage, as mentioned in references [77–79]. Lastly, SES/CAES and SES/GES are commonly used for renewable energy systems.

The different combinations that can be achieved with FES and the specific applications for each combination are as follows. To begin with, FES/PHES is useful for grid-scale energy storage applications. Furthermore, FES/HES is a suitable option for remote power generation or backup power systems, as referenced in [80]. FES/CAES is another combination that is well suited for renewable energy systems requiring both fast response times and long duration energy storage. In addition, FES/GES is useful for applications, such as remote power generation, grid stabilization, and backup power systems. Moreover, FES/CES is commonly used for mitigating power fluctuations in renewable energy systems and providing backup power for critical infrastructure. Lastly, FES/TES is a useful combination for smoothing power fluctuations in renewable energy systems and providing backup power for critical infrastructure.

TES is a versatile technology that can be combined with different systems to meet various energy storage needs in the renewable energy sector [81]. TES/PHES is ideal for renewable energy systems that generate excess energy during specific times of day, such as solar power systems. TES/HES is suitable for off-grid power generation. On the other hand, TES/CAES is useful for renewable energy systems that require long-term energy storage and high energy density. Additionally, TES/GES can be used for specific applications. Lastly, TES/CES is recommended for applications that require the smoothing out of power fluctuations in renewable energy systems and providing backup power for critical infrastructure. With SMES, there is only one hybridization with hydrogen energy storage SMES/HES. This hybrid system combines the high power output and fast response times of supercapacitors with the high energy density of hydrogen fuel cells.

PHES technology provides several possibilities to combine with different energy storage systems, providing flexible and sustainable solutions for the renewable energy sector. With the ten proposed technologies, only four possible combinations are possible, each with its unique benefits [82]. One way to combine PHES and hydrogen energy storage (HES) is to use excess renewable energy to produce hydrogen through electrolysis and then store the hydrogen in a tank. When energy is needed, the hydrogen can be converted back into electricity through fuel cells or other means. Alternatively, excess renewable energy can be used to pump water from a lower reservoir to a higher reservoir in a PHES system, and then the water can be released to generate electricity when energy is needed. PHES/CAES is another combination that brings together the long-duration energy storage capabilities of compressed air energy storage with the high power output of pumped hydroelectric storage. In this system, excess energy is stored in underground caverns using compressed air, which can be released to drive turbines and generate electricity. When the compressed air is depleted, the pumped hydroelectric system can provide additional energy as needed. Moreover, PHES/CES systems use capacitors to provide a quick response to changes in energy demand or renewable energy production. During times of high energy demand or sudden changes in renewable energy production, the capacitors can quickly discharge to provide additional power, while the PHES system ramps up to provide longer-term energy storage. For PHES/GES, combining these two technologies could offer the benefits of both, with PHES providing long-term energy storage and GES offering a quick burst of power for short-term energy demands. However, the feasibility and cost effectiveness of such a system would depend on various factors, such as specific site conditions, the availability of water resources, and the cost of materials and construction. Nevertheless, some existing systems, already combine these two technologies.

HES, or hydrogen energy storage, offers three potential combinations: HES/CAES, HES/GES, and HES/CES [83,84]. The HES/CES combination is especially well suited for renewable energy systems that require both high power output and long-term energy storage. This is due to the combination of the high power output and fast response times of supercapacitors with the high energy density of hydrogen fuel cells. In HES/GES, excess renewable energy can be utilized to both lift weights in the GES system and produce hydrogen through electrolysis. By storing hydrogen, it can then be used to generate electricity during periods of high energy demand but low renewable energy production. During times of low energy demand, excess renewable energy can be used to lift the weights again, creating potential energy for later use. HES/CAES operates in a similar fashion to HES/GES, but instead of lifting weights, excess renewable energy can be used to compress air in the CAES system. The hydrogen produced through electrolysis can then be stored and used to generate electricity during periods of high energy demand but low renewable energy production. And during times of low energy demand, excess renewable energy can be used to compress air again. Finally, GES can only be combined with capacitive energy storage (CES) to form GES/CES.

4.1. Multi-Storage Technologies Used in PV Systems

The development of multi-storage systems in wind and PV systems is a rapidly evolving field, with ongoing research and development aimed at improving the efficiency, cost effectiveness, and performance of these technologies. The development of efficient and reliable energy storage technologies will be essential in ensuring a sustainable and resilient energy future, as renewable energy sources continue to gain importance.

4.1.1. Different Multi-Storage Technologies in PV System

Table 11 summarizes some common multi-storage technologies used in photovoltaic systems [85–88].

Table 11. Advantages of common multi-storage technologies used in photovoltaic systems.

ESS	Short-Term Energy Storage	Long-Term Energy Storage	Energy Capacity	System Efficiency	Environmental Impact	Reliability
Lithium-ion/Lead-acid Battery	High	Low	Moderate	High	Moderate	High
Lithium-ion Battery/Supercapacitor	High	Low	Low	High	Low	High
Lithium-ion Battery/Flow Battery	High	High	High	High	Low	High
Lithium-ion Battery/Thermal Energy Storage	High	High	High	High	Low	High
Lithium-ion Battery/Compressed Air Energy Storage	High	High	High	High	Low	High
Lithium-ion Battery/Hydrogen Storage	High	High	High	High	Low	High
Lithium-ion Battery/Flywheel Energy Storage	High	Low	Low	High	Low	High
Lithium-ion Battery/Pumped Hydro Storage	High	High	High	High	Low	High
Lead-acid Battery/Flow Battery	High	High	High	High	Low	High
Lithium-ion/Lead-acid Batter/Supercapacitor	High	Low	Moderate	High	Moderate	High
Lithium-ion Battery and Lead-acid Battery and Flow Battery	High	High	High	High	Low	High

Moreover, these combinations have disadvantages, as summarized in Table 12.

Table 12. Disadvantages of some multi-storage systems used in PV systems.

Technology Combination	Cost	Complexity	Maintenance	Space Requirements	Compatibility
Lithium-ion battery and lead-acid battery	High	High	High	Low	Low
Lithium-ion battery and supercapacitor	High	Moderate	Low	Moderate	Low
Lithium-ion battery, lead-acid battery, and supercapacitor	High	High	High	Low	Low
Lithium-ion battery and flow battery	High	High	High	High	Low
Lithium-ion battery and thermal energy storage	High	High	High	High	Low
Lithium-ion battery and compressed air energy storage	High	High	High	High	Low
Lithium-ion battery and hydrogen storage	High	High	High	High	Moderate
Lead-acid battery and flow battery	High	High	High	High	Low
Lithium-ion battery and flywheel energy storage	High	High	High	High	Low
Lithium-ion battery and pumped hydro storage	High	High	High	High	Low

4.1.2. Applications of Multi-Storage in PV Systems

In PV systems, energy storage has a variety of uses, such as load balancing, backup power, time-of-use optimization, and grid stabilization. Table 13 summarizes some applications of PV systems used in storing energy [89–103].

Table 13. Some applications of PV systems used in storing energy.

Application of Storage in PV Systems	References
Residential photovoltaic systems with battery storage for peak shaving and load shifting	[89]
Community PV systems with BESS for demand response and grid support	[90]
PV systems with battery storage for self-consumption and backup power	[91]
Utility-scale PV systems with PHES for grid stabilization and load balancing	[92]
Remote area PV systems with BESS for off-grid power supply	[93]
PV systems with flow BESS for frequency regulation and grid support	[94]
PV systems with TES	[95]
PV systems with supercapacitor storage for fast response and power quality improvement	[96]
Microgrid PV systems with BESS for islanded operation and grid connection	[97]
Commercial and residential PV systems with lithium-ion battery storage for self-consumption and energy independence	[98]
PV systems with FES for fast response and frequency regulation	[99]
PV systems with CAES for energy arbitrage and peak shaving	[100]
Multi storage for Grid Integration	[101]
Multi storage for Microgrids	[102]
Multi storage for Large-Scale PV Systems	[103]

4.2. Multi-Storage Technologies Used in Wind Turbine Systems

Many factors influence the decision to choose a multi-storage system, such as the wind turbine system's capacity, energy storage requirements, and environmental conditions. A well-designed hybrid energy storage system can improve the energy efficiency, reliability, and stability of the wind turbine system.

4.2.1. Different Cases of Multi-Storage Used in Wind Turbines

The multi-storage systems used in wind turbine systems are summarized in Table 14 [104–123]. They offer a range of benefits in terms of energy storage capacity, efficiency, environmental impact, reliability, and flexibility. However, the suitability of each combination depends on the specific application and requirements of the wind system. Short-term energy storage refers to combinations suitable for short-term energy storage needs, while long-term energy storage refers to combinations suitable for long-term energy storage needs. Energy capacity denotes a high energy storage capacity, system efficiency refers to the high efficiency of the combination, environmental impact describes a low environmental impact, reliability relates to a high degree of reliability, and flexibility refers to the combination's ability to offer flexibility in terms of application and integration. These general advantages may vary depending on specific system configurations and operating conditions.

Table 14. Advantages of some multi-storage systems used in wind turbine systems.

Energy Storage Combination	Short-Term Energy Storage	Long-Term Energy Storage	Energy Capacity	System Efficiency	Environmental Impact	Reliability	Flexibility
FES/BESS	High	Moderate	High	Low	High	High	High
TES/FES	High	High	High	Moderate	High	Moderate	High
CAES/FES	High	High	High	Moderate	High	Low	High
Li-ion BESS/HES	High	High	High	Low	High	Low	High
TES/HES	High	High	High	Low	High	Low	High
SES/Flow BESS	Moderate	High	High	Low	High	High	Moderate
PHES/BESS	High	High	High	Low	High	High	High
FES/HES	High	High	High	Low	High	Moderate	High
CAES/TES	High	High	High	Moderate	High	Low	High
BESS/CAES	High	High	High	Moderate	High	High	High
BESS/TES/CAES	High	High	High	Low	High	High	High

High means significant advantage, moderate means moderate advantage, and low means minimal advantage.

They also offer a range of disadvantages (Table 15) in terms of cost, complexity, maintenance, space requirements, and compatibility. Cost denotes the increased overall cost of the system due to the need for multiple components when combining energy storage technologies. Complexity arises when different energy storage technologies are combined. Maintenance is a concern because the multiple components in a combined energy storage system may require additional maintenance and service. Space requirements increase when different energy storage technologies are combined, increasing the physical footprint of the system and requiring more space for installation and operation. Compatibility issues may arise when integrating different energy storage technologies, requiring additional hardware and software to ensure proper operation.

Table 15. Drawbacks of some multi-storage systems used in wind turbine systems.

Energy Storage Combination	Cost	Complexity	Maintenance	Space Requirements	Compatibility
FES/BESS	High	High	Moderate	High	Moderate
TES/FES	High	High	Low	High	Low
CAES/FES	High	High	Moderate	High	Moderate
Lithium-ion BESS/HES	High	High	Moderate	Moderate	Moderate
TES and HES	High	High	Moderate	High	Moderate
SES/flow BESS	High	Moderate	Low	Moderate	Low
PHES/BESS	High	High	High	High	Low
FES/HES	High	High	Moderate	High	Low
CAES/TES	High	High	Low	High	Low
BESS/CAES	High	High	Low	High	High
BESS/TES	High	High	Low	High	High
BESS/FES/CAES	High	High	High	High	High

The terms “High”, “Moderate”, and “Low” are relative to other combinations.

4.2.2. Some Applications of Wind Turbine Systems Used in Storage Energy

Table 16 summarizes some important applications of wind turbine systems that use energy storage. These applications demonstrate the versatility and potential of wind turbine systems with energy storage for various applications, including grid stabilization, remote power supply, industrial applications, and backup power supply.

Table 16. Some important applications of wind turbine systems using energy storage.

Application	Energy Storage Type
Offshore wind farm	Lithium-ion battery
Microgrid system	Redox-flow battery
Wind power plant	Flywheel
Hybrid power system	Supercapacitor
Wind-diesel hybrid system	Hydrogen fuel cell
Grid stabilization	Supercapacitor
Remote power supply	Lead-acid battery
Peak shaving	Thermal energy storage
Electric vehicle charging	Lithium-ion battery
Island grids	Redox-flow battery
Building power supply	Supercapacitor
Renewable integration	Sodium-sulfur battery

5. Recent Research on Storage in Photovoltaic and Wind Systems

The need for efficient energy storage devices is growing with the importance of renewable energy sources, such as solar and wind, in the world's energy supply. Energy storage enables excess energy generated during periods of high production to be stored and used later when production is lower or demand is higher, providing a more stable and reliable energy supply. Furthermore, energy storage systems can support grid balancing by offering flexibility and dependability that can help the grid incorporate intermittent green energy sources. This is crucial because it may reduce the effects of fluctuations in wind or solar power as the proportion of renewable energy in the system increases. There has been an increase in the study and development of new technologies as a result of the ambitious goals that have been set worldwide for the deployment of energy storage systems [124–126]. Recent years have seen an increase in the interest in energy storage for renewable photovoltaic (PV) and wind systems, supported by a number of variables. The following are the major factors that are driving energy storage's growing significance in renewable energy systems:

1. Integration of intermittent renewables: Both PV and wind energy are intermittent, meaning that their output can fluctuate based on weather conditions and other factors. Energy storage systems can help mitigate this variability by storing excess energy when generation is high and releasing it when generation is low.
2. Grid stability and reliability: By offering ancillary services, such as frequency regulation and voltage support, energy storage systems can help improve the stability and reliability of the electrical grid.
3. Cost reduction: Energy storage can also help reduce the cost of renewable energy systems by reducing the need for backup power and grid infrastructure.
4. Decentralization of energy systems: Energy storage can enable the decentralization of energy systems, allowing for greater local control and self-sufficiency.

Table 17 summarizes the progress and applications of different energy storage in photovoltaic and wind systems:

Table 17. Progress of some energy storage in PV and wind systems.

Energy Storage Technology	Progress
Battery technology	Improving energy density and life cycle, reducing cost, increasing efficiency
Pumped hydro storage	Improving efficiency, reducing cost, developing small-scale systems for remote areas
Compressed air energy storage	Improving efficiency, reducing cost, developing large-scale systems for grid-scale applications
Flywheel energy storage	Improving efficiency, reducing cost developing small-scale systems for residential and commercial use
Thermal energy storage	Developing new materials for thermal storage, improving efficiency and reducing cost

6. Conclusions

This paper presents a study on energy storage used in renewable systems, discussing their various technologies and their unique characteristics, such as lifetime, cost, density, and efficiency. Based on the study, it is concluded that different energy storage technologies can be used for photovoltaic and wind power applications. For short-term needs and power quality, flywheels, batteries, capacitors, and supercapacitors are the most appropriate options, while other applications may use batteries, flow batteries, fuel cells, or metal–air cells. The development of multi-storage systems in wind and photovoltaic systems is a crucial area of research that can help overcome the variability and intermittency of renewable energy sources, ensuring a more stable and reliable power supply. The main contributions and novelty of this study can be summarized as follows:

- ➢ An overview of energy storage systems (ESSs) with categorization based on advantages, drawbacks, efficiencies, and applications in photovoltaic (PV) and wind systems is presented.
- ➢ The hybrid energy storage combinations used in PV and wind systems are presented, detailing their advantages in terms of short-term and long-term energy storage, energy capacity, system efficiency, environmental impact, and reliability. The disadvantages, such as cost, complexity, maintenance space requirements, and compatibility, are also discussed.
- ➢ A discussion of the applications of multi-storage energy in PV and wind systems, including load balancing, backup power, time-of-use optimization, and grid stabilization, along with the type of energy storage used in each case is presented.
- ➢ A presentation of the theorem of PV/wind + battery energy storage systems (BESSs), highlighting how combining PV or wind power with BESSs can enhance renewable energy integration, along with key technical elements is given.
- ➢ Modeling and sizing of batteries in PV (photovoltaic) and wind energy systems, as well as power management control of ESS (Energy Storage System) technologies, which are essential aspects of designing efficient and reliable renewable energy systems, are examined. They are detailed to help our understanding of the behavior of such systems.
- ➢ An explanation of commonly used electrochemical battery models, their advantages and drawbacks, and the importance of choosing the appropriate model based on the specific application, accuracy requirements, available data, and computational resources is provided.
- ➢ A detailed consideration of design aspects for commonly used storage, including assessment of energy demand, energy production, battery capacity, depth of discharge, efficiency, autonomy, system voltage, and environmental factors, is given. The proper sizing of ESSs is crucial for optimal performance, reliability, and longevity of the energy storage system in conjunction with PV or wind systems.
- ➢ A presentation of the recent research on storage in PV and wind systems, along with the major factors driving the growing significance of energy storage in renewable energy systems, is provided.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Conflicts of Interest: The author declares no conflict of interest.

Abbreviations

Aut	Autonomy days
BESSs	Battery energy storage systems
ECM	Equivalent Circuit Model
EIS	Electrochemical Impedance Spectroscopy
ES	electrochemical storage
ESSs	Energy storage systems
CES	Capacitor energy storage
DoD	Depth of Discharge
GES	gravity energy storage
CAES	compressed air energy storage
FES	flywheel energy storage
HES	Hydrogen energy storage
PHES	pumped hydroelectric energy storage
RES	Renewable energy system
SES	supercapacitor energy storage
SMES	superconducting magnetic energy storage
SoC	State of Charge
TES	thermal energy storage
PV	photovoltaic
PMCs	power management controls
V_{bat}	battery voltage
η_{bat}	efficiency battery
E	load energy
N_{batt}	number of batterie
$C_{batt,u}$	capacity of a battery unit
$I_{Batt\text{-}ref}$	reference battery current
$I_{SC\text{-}ref}$	reference supercapacities current
$I_{DC\text{-}ref}$	reference DC bus current
V_{DC}	DC bus voltage
$V_{DC\text{-}ref}$	reference DC bus voltage

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