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# A Guide to the Integration and Utilization of Energy Storage Systems with a Focus on Demand Resource Management and Power Quality Enhancement

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**Abstract:** The increasing peak electricity demand and the growth of renewable energy sources with high variability underscore the need for effective electrical energy storage (EES). While conventional systems like hydropower storage remain crucial, innovative technologies such as lithium batteries are gaining traction due to falling costs. This paper examines the diverse applications of energy storage, spanning from grid connectivity to end-user solutions, and emphasizes large-scale energy recovery and system stability. The integration of EES with various energy infrastructures and consumer strategies is explored, highlighting the use of tariffs and peak pricing systems for energy cost savings. Country-specific priorities shape EES deployment, with the U.S focusing on grid stability, Japan on emergency power, and South Korea, still in the demonstration phase, prioritizing peak demand reduction. Our analysis of the UK, U.S., and South Korea reveals the pivotal role of energy storage in achieving flexible and efficient energy systems. The industry shows promising growth, with significant commercial expansion expected around 2035, presenting profound policy and deployment implications for the future.

**Keywords:** energy storage systems; grid connection; control; frequency variations

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## 1. Introduction

An Energy Storage System (ESS) refers to the collection of energy in a physical medium to reduce the imbalance between energy production and the end users' consumption. This also includes the transformation of difficult-to-store forms of energy into more convenient and economically viable forms. Major advanced countries are actively promoting the expansion of energy storage systems by supporting technological development, subsidizing demonstration projects, providing tax incentives, and mandating implementation through government budgets. Companies are also showing a keen interest in the ESS market, where tangible results are anticipated. Among energy sources, electricity is the most widely used in production activities and daily life due to its convenience. However, it has certain disadvantages, such as the need for rapid output adjustment to respond to constant changes due to the simultaneous balance of production and consumption and the requirement for expensive power sources and reserve capacities. Nevertheless, the demand for electricity is expected to steadily increase in the future due to its convenience, necessitating an inevitable expansion in generation capacity [1].

The necessity for large-scale energy storage is becoming more pronounced as industrial development leads to an increased demand for industrial electricity. As incomes rise, the use of electrical and electronic products grows, leading to a consistent increase in power consumption. However, there is a growing trend in the deviation of power usage depending

on the time of day and season, leading to challenges. To accommodate for the increase in peak power usage, additional power supply facilities are being built, but there is an issue with the drop in facility utilization due to fluctuations in power usage. Furthermore, restrictions on fossil energy usage are increasing as serious climate change effects from fossil fuel consumption become more evident [2].

With the enforcement of the Paris Climate Agreement on 4 November 2016, 197 parties agreed to strive to achieve greenhouse gas reduction targets by 2020 (to be achieved by 2030). For the UAE, the country must reduce 197 million tons of greenhouse gas emissions by 2030. The demand for renewable energy, which can suppress greenhouse gas emissions, is sharply increasing, and by 2050, the share of renewable energy in the UAE, for example, is expected to reach 44%. However, significant renewable energies like wind and solar power experience severe output fluctuations based on location, weather, and time, making continuous supply challenging and causing a time lag between energy production and demand. To overcome the challenges of idle power facility issues and renewable energy output fluctuations, large-scale energy storage technology is required. This can store excess energy and supply it at peak demand times, reducing power peaks, compensating for renewable energy output fluctuations, and securing power supply standby capacity. This technology can also be integrated with smart grids, allowing for real-time two-way power production and consumption information exchange, thereby playing a role in adjusting power demand and supply [3].

Energy storage systems (ESSs) can be installed throughout the entire electricity process, from power generation to transmission, substation, distribution, and to the consumer, serving various purposes. Notably, renewable energy generation is characterized by unpredictable outputs and high fluctuation rates, which, when integrated into the power grid, can result in voltage and frequency variations. ESSs can address these issues, promoting a broader utilization of renewable energy. To promote the widespread adoption of energy storage systems, Japan has been operating subsidy and support programs covering about one-third of the cost of ESS implementation by central and local governments to address unstable power issues after major earthquakes. The California legislature in the U.S. mandated the installation of energy storage systems responsible for 5% of peak power by 2020. The European Commission, through its Horizon 2020 program, allocated significant funding towards clean energy research, including energy storage. Horizon 2020 was the biggest EU Research and Innovation program ever, with nearly EUR 80 billion of funding available over seven years (2014 to 2020). In South Korea, according to the Renewable Energy 2030 Implementation Plan, the country plans to increase renewable its energy facility capacity to 48.7 GW by 2030, raising the proportion of renewable energy generation to 20%. Solar and wind power will account for 30.8 GW and 16.5 GW, respectively, making up over 95% of the total new facility capacity. Without energy storage devices, if renewable energy generation exceeds 10% of total generation, the entire power grid could become unstable, causing serious damage to power quality [4].

While energy storage technologies are rapidly evolving, not all meet the technical performance requirements demanded across various application domains. Most storage technologies are either under development or in their early application stages, meaning that they bear significant risks and uncertainties and require further validation. To promote the adoption of ESSs, it is essential to examine possible application areas and their respective technical requirements and to assess the current state and characteristics of storage technologies. If substantial potential benefits are anticipated at the national level, financial support and legal–systemic reinforcements might be required during the initial technology development or market emergence stages. Moreover, even if an ESS seems economically feasible or feasible for businesses from a national perspective, it will not penetrate the market if it is not economically viable for the consumers, who are the primary operators. Thus, ensuring economic feasibility from a consumer's standpoint is crucial. If ESSs, which are currently in their market infancy, do not spread quickly, the transition to mass production will be delayed, also affecting price reductions [5].

Energy storage types and their application areas vary significantly based on characteristics, efficiency, and cost-effectiveness. Recent research focuses on large-scale energy storage using sodium–sulfur (NaS) batteries and flow batteries. While NaS batteries have real-world applications, as seen in Japan's NGK, their requirement for high-temperature operation using sulfur is considered a downside. Flywheels, which convert electrical energy into rotational energy, have a long lifespan and high output, but they also carry high initial costs and explosion risks. While large-scale lithium-ion battery storage is gaining attention, its commercial application is still lacking. Other research focuses on pumped hydro storage and compressed air energy storage (CAES), each with its set of challenges, such as geographical limitations, low efficiency, and environmental concerns [6–9].

Energy storage can be used for various applications in distribution substations, including the following applications [10–12]:

- Large-scale load leveling.
- Area-specific load regulation.
- Emergency power supply during outages.
- Short-/long-term stabilization for renewable energy installations.
- Voltage regulation and line expansion cost reduction.

When integrated into the power grid, these storage solutions can improve power quality by addressing imbalances and maintaining voltage levels. They can also provide emergency power during outages and stabilize the system by adjusting frequency. Another essential function is load leveling, where excess energy is stored during periods of low demand and released during peak periods, enhancing efficiency. By addressing peak demands, storage can also reduce the intermittent nature of renewable sources like wind and solar power, reducing the need for fossil fuel backups [13].

For facilities at risk of fire or explosion due to sudden power outages, emergency power can be supplied. Regarding grid failures, these systems can also ensure the independent operation of power plants, potentially using batteries instead of traditional diesel generators to provide power more quickly. An application example in distribution substations involves considering the load characteristics of the main transformer and comparing it with the power system's load pattern to determine the optimal BESS functionality [14].

The focus of the paper is on various energy storage technologies and methods that are widely recognized and under development. This paper explores the process of using compressors to compress air for large-capacity storage, considering aspects like storage efficiency and waste heat. The paper also highlights the technique of storing electrical energy, emphasizing its energy storage density, and challenges like vibration control. Additionally, the article covers an innovative storage device that utilizes the elevation of heavy objects, discussing its capabilities, current development in Scotland, and the mechanical requirements needed for optimization. The overall emphasis of this paper is on the technical specifications, advantages, challenges, and potential applications of these energy storage technologies.

## 2. Concept and Components of Energy Storage Systems (ESS)

### *2.1. Concept of Energy Storage Systems*

Energy Storage Technology (EST) refers to the ability to store various forms of energy to be utilized when needed. With the commercialization of technologies capable of storing large quantities of energy, energy storage systems have become essential for building smart grids. The concept of energy storage systems is intuitively simple to understand. It refers to systems that store surplus produced energy as is or in a transformed state and supply it when needed. This encompasses not only electricity but also thermal energy storage devices or systems that can store energy when demand is low and use it when needed. Essentially, storage technology serves as a bridge that connects the temporal gap between energy supply and demand. Conventional energy resources like oil or gas have long been stored using technologies like tanks or reservoirs, and now, with technological advancements,

thermal and electrical energy storage technologies have reached the commercialization stage [15].

Various energy storage technologies are being utilized domestically and internationally, and active technology development is also ongoing. Demonstration projects for already developed technologies are being actively carried out both domestically and abroad. Energy storage technology development is currently mainly focused on electricity storage. The most mature energy storage technology today is pumped-storage hydroelectricity, which accounts for approximately 99% of the installed electrical storage capacity worldwide. The types and maturity levels of currently developed or commercialized energy storage technologies are as depicted in Figure 1 [16].

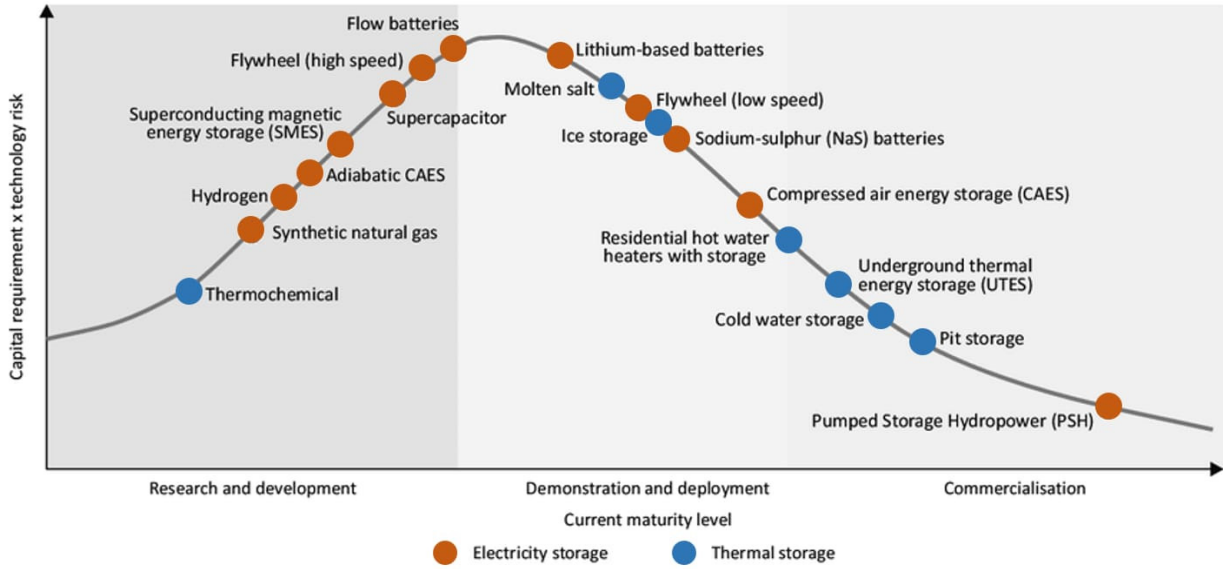



**Figure 1.** Energy storage technology types and technology maturity [16].

Lithium batteries, flywheels (low-speed), sodium–sulfur batteries, and compressed air energy storage technologies are in the demonstration and distribution phase. Superconducting energy storage, supercapacitors, flywheels (high-speed), and flow batteries are still in the research and development stage. The key factors that determine the performance of energy storage technology include storage capacity, energy density, charge–discharge efficiency, charge–discharge speed, and lifespan. Depending on these factors, the applicable fields may vary, and relative advantages and disadvantages may arise. Research and development to improve the performance of storage technology and reduce costs are actively being carried out both domestically and internationally [17].

### *2.2. Components of an Energy Storage System (ESS)*

An Energy Storage System consists of storage devices (such as reservoirs, compressed air storage, batteries), conversion devices (such as Power Conditioning Systems (PCSs), compressors/expansion engines, generators), and control devices. Figure 2 shows the basic components of an Energy Storage System using a battery (lithium-ion cell). A battery-based energy storage device essentially consists of a battery (cell) system and a Battery Management System (BMS) that manages and controls the battery's charging and discharging states. Additionally, it includes a PCS, which converts and manages the produced electricity's frequency and voltage according to grid and load characteristics, and an Energy Management System (EMS) or Power Management System (PMS) to monitor and control the energy storage system [18].

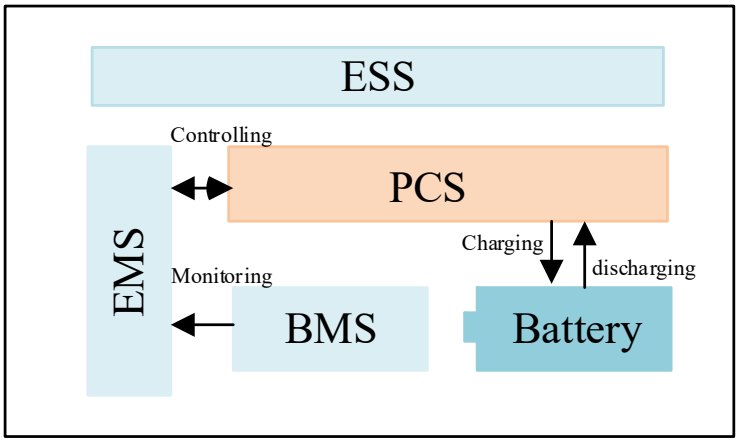



**Figure 2.** Components of an energy storage system.

The core device of the Energy Storage System, the battery device, is formed by battery cells (consisting of anodes, cathodes, electrolytes, and separators) grouped into modules. These modules form trays; the trays come together to form racks, and these racks come together to create the system. The battery system receives power through the PCS, converting and storing it in a specific form to discharge it when needed. Since each battery cell has different characteristics, a Battery Management System (BMS) is required to allow the battery to perform at its maximum efficiency. The BMS provides control management functions for efficient battery use, such as cell capacity protection, overcharging and over-discharging prevention, and lifespan prediction, and it communicates the battery's charging state through an external interface. Also, since the characteristics of power storage and usage vary, a power conversion device is needed to modify the characteristics for actual use. The PCS is a system that absorbs electricity produced by the generation source, stores or discharges it in the battery, and converts the electrical characteristics (AC/DC, voltage, frequency). The EMS performs the role of monitoring the battery and PCS state and controlling the PCS [19].

## 3. Types and Features of Energy Storage Systems

Energy storage technology can be classified in various ways based on specific criteria, as shown in Table 1. Generally, energy storage technology is categorized into electricity storage systems and thermal storage systems based on the type of energy produced. Depending on the storage form or method, it can also be divided into physical, chemical, and electromagnetic methods. Additionally, energy can be classified based on its discharge duration (short-term and long-term).

**Table 1.** Classification of energy storage technologies according to storage methods [20–22].

| Method | Type |
|---|---|
| Physical Storage (mechanical) | - Pumped Hydro Storage (PHS) |
| | - Compressed Air Energy Storage (CAES) |
| | - Flywheels |
| Chemical Storage (electrochemical) | - Lithium-Ion Battery (LiB) |
| | - Sodium–Sulfur Battery (NaS) |
| | - Lead Acid |
| | - Redox Flow Battery (RFB) |
| Electromagnetic Storage | - Super-capacitor or Ultra-capacitor |
| | - Superconducting Magnetic Energy Storage (SMES) |

The classification of energy storage devices can be based on various criteria (Table 2). Although various energy sources exist, this text focuses on electric energy and introduces energy storage devices by the form of stored energy, followed by a detailed introduction to candidates that can satisfy the system's requirements in terms of timing and functionality from the perspectives of renewable energy and system stabilization. Forms of energy in which electrical energy can be stored are broadly classified into mechanical energy, electric/electromagnetic energy, electrochemical energy, thermal energy, and chemical substances. Mechanical energy storage methods include pumped hydropower, compressed air storage, flywheels, and solid mass gravity storage. Electric/electromagnetic energy storage methods include supercapacitors and Superconducting Magnetic Energy Storage (SMES). Electrochemical energy storage is known as BESS (Battery Energy Storage System) and includes flow batteries, secondary cells (or rechargeable batteries), and ultrabatteries. Thermal energy storage methods include ice storage, liquefied air storage, and Carnot batteries [23]. The efficiency percentages of different energy storage technologies are shown in Figure 3.

**Table 2.** Classification of energy storage technologies based on produced energy and purpose [1].

| Storage Technology | Produced Energy | Purpose | Installation Location | Efficiency (%) | Initial Investment (USD/kW) |
|---|---|---|---|---|---|
| Pumped Hydro Storage | Electricity | Long-term | Supply | 50 | 85 |
| CAES | Electricity | Long-term | Supply | 20 | 70 |
| Battery | Electricity | Short-term | Supply/Demand | 75 | 95 |
| Hydrogen Storage | Electricity | Long-term | Supply/Demand | 22 | 50 |
| Flywheels | Electricity | Short-term | Transmission/Distribution | 90 | 95 |
| Super-capacitor | Electricity | Short-term | Transmission/Distribution | 90 | 95 |
| SMES | Electricity | Short-term | Transmission/Distribution | 90 | 95 |
| UTES | Heat | Long-term | Supply | 50 | 90 |
| Pit Storage | Heat | Medium Heat | Supply | 50 | 90 |
| Thermochemical Storage | Heat | Low to High | Supply/Demand | 80 | 90 |
| Molten Salts | Heat | High Heat | Supply | 40 | 93 |
| Solid Media | Heat | Medium Heat | Demand | 50 | 90 |
| Ice Storage | Heat | Low Heat | Demand | 75 | 90 |
| Hot Water Storage (Home) | Heat | Medium Heat | Demand | 50 | 90 |
| Cold Water Storage | Heat | Low Heat | Demand | 50 | 90 |

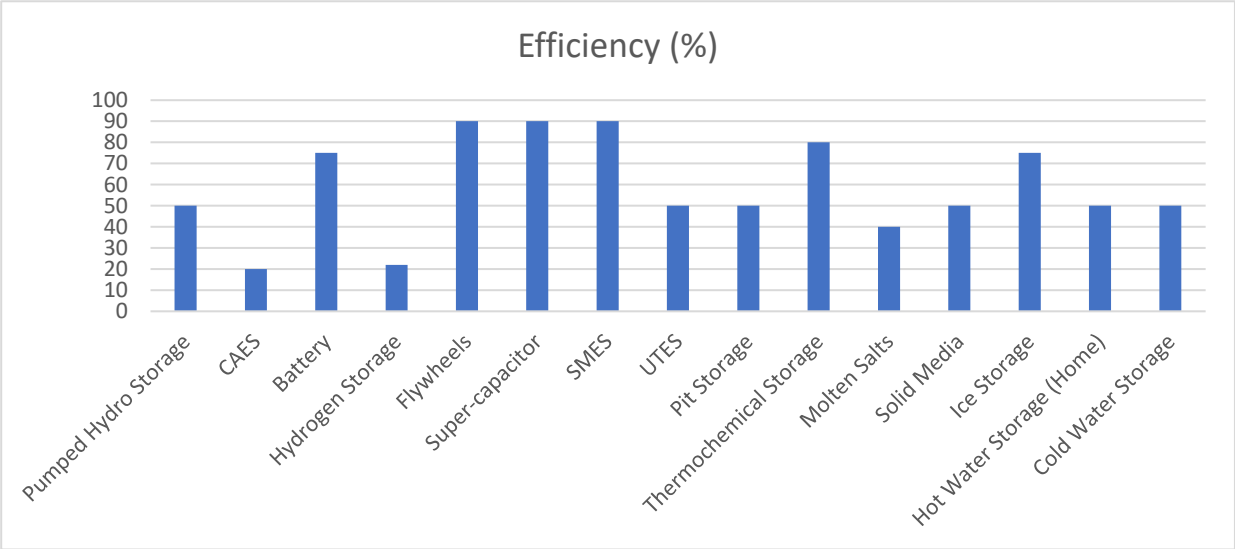



**Figure 3.** Efficiency percentages of different energy storage technologies.

## 4. Large-Capacity Energy Storage Systems

As a means of large-capacity energy storage, there are several methods that can store significant amounts of energy. These methods include pumped hydroelectric power, compressed air energy storage (CAES) systems, liquid air energy storage (LAES) systems, and lithium-ion batteries. Pumped hydroelectric power stores electrical energy as gravitational energy by pumping water when the demand for electricity is low and then releasing it to drive turbines when demand is high. The CAES system compresses air when electricity demand is low, storing electrical energy as pressure energy, and then expands the compressed air to generate electricity when demand is high. The LAES system, like compressed air, utilizes air as a medium but liquefies it to store energy at low temperatures when demand is low before pressurizing and vaporizing it to generate electricity when demand is high. Lithium-ion batteries charge and discharge electricity using a chemical method that involves the movement of lithium ions (Li+) between the anode and cathode [24].

Pumped hydro and CAES systems can store large amounts of energy (from several hundred MWh to a few GWh) relatively efficiently and have a long system life and high economic efficiency. However, they require a large installation area and have limitations regarding where they can be installed. Pumped hydro requires large dam construction, which can lead to deforestation, flooding, and compensation issues. CAES requires a large underground cavity to store compressed air at high pressure, raising concerns about the stability of the ground. Despite having superior specifications and economic storage methods, pumped hydro and CAES have some disadvantages.

Table 3 summarizes the characteristics of different energy storage methods.

**Table 3.** The characteristics of different energy storage methods [25].

| Method | Energy Storage Capacity (MWh) | Energy Density (Wh/L) | System Life (Years) | Installation Constraints | Charge–Discharge Efficiency (%) | Uniform Cost ($/MWh) |
|---|---|---|---|---|---|---|
| Pumped Hydro | 500–8000 | 0.5–1.5 | 40–60 | Large dam required | 70–85 | 150–200 |
| Compressed Air | −1000 | 3–6 | 20–40 | Large underground cavity required | 40–70 | 120–140 |
| Lithium-ion | −10 | 200–500 | 5–15 | None | 75–90 | 270–560 |
| Liquid Air | 25–1200 | 120–200 | +30 | None | +60 | 230–280 |

Despite their suitability, there are limitations in utilizing large-scale energy storage systems due to constraints related to installation locations. Lithium-ion batteries offer the highest energy density and charging and discharging efficiency. They have the advantage of a modular configuration, making the system installation simpler, meaning that it requires less space compared to other energy storage methods. However, they have a relatively shorter lifespan and are temperature-sensitive. In constructing large-scale systems, ensuring the stability of the batteries requires extra attention, particularly for heat management and control. Moreover, their recycling and regeneration mainly involve high-cost metals like cobalt, nickel, and lithium, leading to waste disposal issues for other components. Currently, the installation and maintenance costs are the most expensive costs among the different storage methods [26].

Liquid air energy storage systems, on the other hand, are capable of storing large-scale energy in the range of hundreds of MWh. From this perspective, liquid air energy storage systems can be seen as the most practical alternative for large-scale energy storage without installation constraints, being environmentally friendly and economical. They can also be used for additional applications. This system's low-temperature clean air output can be utilized for cooling in urban buildings, shopping malls, or for the refrigeration of food, meat, etc. It can also be harnessed as auxiliary power through the Dearman Engine, using liquid air as fuel, enhancing the system's economics. Liquid air energy storage systems were initially proposed by Newcastle University in the UK as an alternative to compressed air energy storage systems and were tested by Mitsubishi in 1998. The process and essential equipment for the current liquid air energy storage system were developed by the University of Leeds and Highview Power since 2005. A 350 kW/2.5 MWh pilot plant was constructed near London between 2011 and 2014 and tested with a nearby biomass power plant. In June 2018, a 5 MW/15 MWh demonstration plant was built near Manchester, linked with a nearby landfill gas power plant. In Germany, the KRYOLENS project started in 2016, aiming to increase the technology readiness level (TRL) of the liquid air energy storage system and assess its technical and economic feasibility [27].

The liquid air energy storage system is composed of three main processes. The first is the liquefaction process, where air in the atmosphere is compressed and liquefied. The second is the power generation process, in which the liquefied air is pressurized and vaporized before being expanded to produce electricity. The third process is the cold energy recycling process, which stores the cold energy produced during the vaporization of liquid air in the power generation process in a thermal storage device and utilizes it in the liquefaction process to enhance the system's efficiency. In the liquefaction process, air is drawn from the atmosphere, compressed to high pressure through a compressor, and then expanded through an expansion device to create liquid air. The boiling point of air is typically −195 °C, and to achieve such a low temperature, several stages of expansion and heat exchange are required. Particularly, two different expansion devices are used to attain this low temperature in the liquefaction of air: an expander and a Joule–Thomson valve. The former expands the air in an isentropic process, simultaneously producing useful work and a low temperature, and it has the advantage of high efficiency. In contrast, the Joule–Thomson valve has the advantage of being very simple in structure but expands the air in an isenthalpic process, resulting in lower efficiency with respect to achieving a low temperature. Utilizing expanders throughout can enhance the efficiency of the liquefaction process, but expanders that can be used in extreme low-temperature environments are expensive, and they may be damaged in the region where liquefaction occurs due to the impact of liquid. Therefore, in the liquefaction process, expanders are used in relatively higher temperature regions, while Joule–Thomson valves are used in the areas where actual air liquefaction occurs. This process of using both Joule–Thomson valves and expanders is referred to as the Claude cycle [28].

The air becomes cooler as it passes through the expansion devices, and several heat exchangers between expansion devices play a role in cooling the high-pressure air by heat exchanging it with low-pressure air that has been cooled by the expansion devices. By doing

this, a lower temperature can be achieved after passing through the expansion devices. By adding the aforementioned cold energy recycling process, the cold energy previously stored in the thermal storage device during the vaporization of liquid air in the power generation process can be additionally utilized to reduce the temperature of the high-pressure air during the liquefaction process, thus enhancing its efficiency. The liquefaction process can be described as a process that stores electrical energy in the form of low-temperature energy, while the power generation process is simply a process that generates electrical energy. When the demand for electricity is low, air is liquefied and stored as liquid air, and when electricity is needed, the liquid air is pressurized and vaporized to drive a power turbine to generate electricity. This power generation process is known as an open-Rankine cycle. The liquid air is pressurized and vaporized by an ultra-low temperature pump and supplied to the power turbine. The cold energy generated during the vaporization of liquid air is stored in the thermal storage device through the cold energy recycling process. Subsequently, the vaporized air undergoes additional heat exchange before expanding and being supplied to the multi-stage power turbine. Efforts to diversify the heat sources needed at this stage (e.g., compressed heat recycling, power plant waste heat, etc.) are also being made [29].

The liquefaction and power generation processes are directly and indirectly linked to the cold heat recycling process. The cold heat recycling process is a core process necessary for enhancing the efficiency of the liquid air energy storage system. It is structured to supply and recover cold heat through a thermal storage device. Due to the nature of the energy storage system, there is a time difference between when energy is stored and when it is utilized; thus, a regenerative heat exchange method must be applied rather than the recuperative heat exchange typically used in standard liquefaction or refrigeration processes. Simply put, when power supply is needed, the cold heat recycling process stores cold heat in a thermal storage device as liquid air is vaporized for power generation. Then, when power storage is necessary, the stored cold heat is utilized in the liquefaction process. Therefore, the development of technology for the material used to store cold heat, i.e., the thermal storage medium, is crucial [30].

A lot of research has been conducted on sensible heat storage devices that utilize the heat absorbed when the temperature of a specific substance changes, and this has been applied to pilot and demonstration plants in the UK. However, if a specific substance with high heat capacity at liquid air temperature and undergoing phase change can be developed and applied to the thermal storage device, an efficient thermal storage device that can utilize not only the sensible heat but also the latent heat of the material can be developed. Recent research on this subject is underway, and it is expected to greatly contribute to improving the efficiency of the liquid air energy storage system [31].

## 5. Energy Storage System Applications and Expected Effects

### *5.1. Energy Storage System Applications*

Electricity is widely used due to its convenience, and its most notable feature is that production and consumption must be balanced simultaneously. This makes storage difficult, and a rapid response is needed to match the constantly changing electricity demand. A downside is the high cost of running expensive power sources and maintaining reserve capacity. However, the rapidly advancing storage technology in the power sector has recently been noticed as a way to compensate for these disadvantages. Energy storage systems are used in the power grid to solve imbalances between electricity demand and supply. They can be used in various stages of the process, including power generation, transmission, transformation, distribution, and final consumption. In the context of power generation services, energy storage systems can be utilized in conjunction with existing generators as a resource for electricity sales and ancillary service provision in the power market. They also store electricity and supply it when needed, optimizing the operational efficiency of the power system by regulating the power load during peak demand times [32].

For transmission network services, energy storage systems can be linked to transmission and distribution networks to take on the roles of various power equipment needed for

stable operation. This can delay new equipment investments and enhance the reliability and stability of the power system. From the consumer's perspective, energy storage systems can prevent the degradation of quality and reliability in the power system due to changes in electricity production and consumption. Especially with the increased variability in electricity supply and demand due to renewable energy generation like solar and wind and electric vehicle charging, energy storage systems play a crucial role in controlling the volatile supply and demand and adjusting the frequently changing frequency, thereby enhancing the reliability of the power grid.

Furthermore, energy storage systems can provide stable power supply even during sudden blackouts. With the advancement of the information and communication environment, even a few seconds of power interruption can cause critical damage to data centers, manufacturing process equipment, and various communication devices. Therefore, energy storage systems provide emergency power quickly and even act as an independent power source during long-term power outages, preparing the power system for emergency situations. An energy storage system (ESS), while installed for specific purposes, can be used for other purposes as well, as seen in Table 4. In some cases, an ESS can generate sufficient revenue through single-use applications, but complex uses may be necessary for profitability. Therefore, the ESS can be used in a multifaceted way to maximize value. The various applications of ESSs across various fields (generation, transmission and distribution, and end-user stage) can maximize the benefits of their utilization as they could be applied as versatilely as possible. Of course, there may be constraints on the simultaneous use of an ESS for different purposes, so it is essential to operate within technically feasible categories without operational conflict [33].

Currently, ESSs are still in the experimental phase, and sufficient experience and knowledge to maximize benefits through various applications have not yet been accumulated. There remain several preconditions, such as the following:

1. Potential technical and operational conflicts.
2. Market entry barriers (regulations, required permissions, etc.).
3. Lack of engineering standards and tools.
4. Insufficient energy price signals and market absence.
5. The electricity industry's passive attitude towards new technology.

**Table 4.** Energy storage system multi-use metrics matrix (Matrix) [34]. E, Excellent; G, Good; F, Fair; P, Poor; I, Incompatible.

| | **Load Leveling (Arbitrage)** | **Supply Capacity** | **Load Following** | **Frequency Regulation** | **Reserve Capacity** | **Voltage Man-age-ment** | **Transmission Congestion Relief** | **Transmission and Distribution Investment Deferral** | **TOU (Time-of-Use) Charge Management** | **Peak Surcharge** | **Power Reliability** | **Power Quality** | **Renewable Integration** | **Renewable Grid Connection** | **Wind Power Grid Connection** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Load Leveling (Arbitrage) | | E | G | F | G | E | E | E | I | I | I | I | F | F | F |
| Supply Capacity | E | | G | F | G | E | G | E | I | I | I | I | F | F | I |
| Load Following | G | G | | F | G | G | F | G | F | F | I | I | F | I | I |
| Frequency Regulation | F | F | F | | F | I | F | I | I | I | I | I | P | P | I |
| Reserve Capacity | G | G | G | F | | E | F | F | F | F | I | I | F | F | |
| Voltage Management | E | E | G | I | E | | G | E | G | G | G | G | G | G | I |
| Transmission Congestion Relief | E | G | F | F | F | G | | G | G | G | P | I | F | F | I |
| Transmission and Distribution Investment Deferral | E | E | G | I | G | E | G | | G | G | P | G | G | G | I |
| TOU Charge Management | I | I | F | I | G | G | G | G | | E | E | E | G | G | I |
| Peak Surcharge | I | I | F | I | G | G | G | G | E | | E | E | F | E | I |
| Power Reliability | I | I | I | I | I | F | P | P | E | E | | E | F | F | I |

**Table 4.** *Cont.*

| | Load Leveling (Arbitrage) | Supply Capacity | Load Following | Frequency Regulation | Reserve Capacity | Voltage Man-age-ment | Transmission Congestion Relief | Transmission and Distribution Investment Deferral | TOU (Time-of-Use) Charge Management | Peak Surcharge | Power Reliability | Power Quality | Renewable Integration | Renewable Grid Connection | Wind Power Grid Connection |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Power Quality | I | I | I | I | I | F | I | I | E | E | E | | I | I | I |
| Renewable Integration | G | G | G | P | G | G | G | G | G | G | G | I | | E | |
| Renewable Grid Connection | G | F | I | P | G | G | G | G | G | E | G | I | E | | G |
| Wind Power Grid Connection | F | I | I | I | I | I | I | I | I | I | I | I | F | F | |

When energy storage systems are utilized for power applications in auxiliary services of the electrical grid, a high output power is typically needed for a short duration, ranging from a few seconds to a few minutes. In contrast, when used for energy applications, discharging is required for a relatively longer period, usually from a few minutes to several hours, necessitating a larger battery capacity. The battery capacity required for power applications with short-cycle high-output driving characteristics only needs to be sufficient to deliver the rated output power. Not all storage technologies meet the performance requirements of various applications. Although energy storage technology has rapidly evolved recently, most technologies are at the initial stages of application, with high risks and uncertainties, and further learning effects are needed. For quick-response auxiliary services in power applications, the most suitable storage technologies include supercapacitors, SMES, flywheels, etc. For long-duration, sustained output in energy applications, suitable technologies include pumped storage, CAES, and various batteries characterized by large capacity and long-cycle operation [35].

Depending on the application and purpose of energy storage systems, the requirements for response time, installed power capacity, discharge duration, and cycle vary. For relieving congestion in generation resources and transmission and distribution networks, as well as delaying investments in transmission and distribution networks, large long-duration outputs are needed. In contrast, energy storage systems for peak load reduction at the consumer level may require smaller capacities with a specific discharge duration. Discharge time is determined by the energy storage capacity, and the energy storage capacity is expressed as (kWh) = power (kW) $\times$ discharge time (h). Generally, considering each application area, energy storage systems for applications linked to generation sources and transmission and distribution networks must be large-scale facilities, with tens or hundreds of MWh, whereas small-capacity energy storage systems may be effective when linked to consumer demand, handling only the individual's load [36].

### *5.2. Expected Effects of Energy Storage Systems*

This section reclassifies the uses of energy storage systems, according to the specific circumstances of (KSA), into four major categories: utilization as a generation resource, linkage with transmission and distribution networks, linkage with renewable energy, and utilization as a demand resource. It then provides a detailed examination of each application method and the expected effects. Utilizing energy storage systems as power generation resources primarily involves the system taking over the electricity supply function that generators in existing power systems are typically responsible for. Energy storage systems can be used both for moving electric supply (differential trading) and as an electric supply capacity. Let us look at these aspects in detail [37]:

#### 5.2.1. Arbitrage (Electric Energy Time-Shift)

Power systems must supply electricity in real-time to meet fluctuating demand while enhancing both economic efficiency and reliability. To adapt to these real-time changes in demand, power systems are divided into base load generators and peak load generators. Stable base load demand is met by nuclear- and coal-powered plants, while the rapid increase in peak load demand is supplied by oil and LNG plants. Base load generators are relatively cheap, and peak load generators are more expensive but easily adaptable.

Peak demand can be responded to by shifting the load or storing electricity generated in base load times to use during peak load times. Examples include nighttime electricity systems and pumped-storage power. Energy storage systems can be used for both load shifting and supply shifting. By storing the electricity generated, it can be discharged and used when needed, allowing the system operator to move supply when desired. The power supply shift (time-shift) through discharge in peak load times with higher costs or trading prices from storage during lower-cost base load times can lead to economic gains through arbitrage. It is also expected to be economically beneficial by increasing the

utilization of base load generators and reducing the operation of peak load generators, thereby restraining or reducing the power supply cost [38,39].

#### 5.2.2. Electric Supply Capacity

Depending on the situation of the electricity supply system, energy storage systems can be utilized for electric supply capacity purposes, thus reducing the need for the additional procurement of new generation capacity in the electricity market. Electricity demand is rapidly increasing due to economic development and a demand for high-quality electricity to improve the quality of life. To meet this increasing demand, power system operators regularly establish and operate power supply plans, including the establishment of facility expansion plans based on predicted future electricity demand. Operating a power system with only base load generators is impossible, and preparation for various uncertainties such as unexpected load fluctuations is necessary.

To cope with these uncertainties, peak load generators with quick start-up characteristics and excellent load-following driving ability are needed. The problem is that, despite their short annual operating hours, peak load generators require substantial investment and expensive operating costs. In power planning, even a slight increase over the previous year's generation capacity can necessitate constructing large-scale power plants. However, if energy storage systems are used to discharge and utilize supply capacity during peak load hours, massive investments in peak load generators can be avoided [40].

Determining the operational time for utilizing an energy storage system (ESS) as a supply capacity is highly influenced by the electric market environment. Thus, it is very difficult to standardize the discharge time if the ESS is used as a supply capacity. The price for the supply capacity greatly influences the decision of the discharge time. For instance, if the supply capacity is determined on an hourly price, the ESS must supply power during the higher-priced hours, so the battery's discharge will be operated flexibly by the hour. If there is a price set for the supply capacity to enable the ESS to serve as a power supply capacity for a fixed duration, or if the system operator demands capacity for specific times, the discharge time of the ESS is operated according to those requirements.

Generally, although an ESS is greatly influenced by its installation location and electric market environment, when used as a power supply capacity, it can also be utilized for additional purposes like electric energy time-shift, electric supply reserve capacity, delaying Transmission and Distribution (T&D) system upgrades, voltage support, electric service reliability, and enhancing electric service power quality [41].

#### 5.2.3. Reserve Capacity

For stable power supply, the power system must have appropriate reserve capacity to cope with unexpected power plant failures, equipment accidents, supply reduction, and demand fluctuations. The minimum reserve capacity should at least be larger than the generation amount of the maximum output power plant. The definition of reserve capacity varies by country and the operational situation of the power system. In the United States, they keep a level of reserve capacity at 15–20% of normal supply capability.

Reserve capacity is divided into equipment reserve, supply reserve, and operational reserve. Equipment reserve refers to the facility capacity exceeding maximum demand. Supply reserve refers to the difference between the supply able capacity and maximum demand, excluding predictable output reduction like planned maintenance from the equipment reserve. Operational reserve refers to the capacity excluding temporary maintenance and power outage from the supply reserve. Operational reserves are further divided into spinning reserve, non-spinning reserve, and supplemental reserve based on the time available. Spinning reserve refers to the immediate increase in output (usually within 10 s) available from operating generators. Non-spinning reserve refers to the output (typically within 10 min) that can be quickly mobilized even though it is not currently operating. Supplemental reserve refers to the output available within (typically) one hour, even though

it is not currently operating. Supplemental reserve serves as a backup for spinning and non-spinning reserves [42–44].

Reserve capacity is defined as the generation power held in excess of electricity demand to maintain balance in the event of prediction errors, unexpected generator failures, etc. It is divided into supply reserve and operational reserve. The supply reserve refers to the operational reserve that must be secured first and the generation power that exceeds it and is under a power stoppage.

Operational reserve is composed of frequency adjustment reserve and standby replacement reserve. Frequency adjustment reserve refers to the reserve that can automatically respond instantaneously through automatic generation control (AGC) or the Governor-Free operation of generators connected to the system. Standby replacement reserve is the reserve that can be secured and utilized within 120 min (within 20 min during summer power supply measures) in preparation for unexpected stoppages of generation equipment, demand prediction errors, failures or stoppages of power plants, and transmission equipment. The standby replacement reserve is divided into operational status and stoppage status. Operational status standby replacement reserve refers to the reserve that can add the surplus output within 10 min after the power supply command from generators that are operating in the system and have excess generation power (beyond frequency adjustment reserve). Among frequency adjustment reserve and standby replacement reserve, those in the operational state are called operational reserves. Stoppage status standby replacement reserve refers to the reserve where standby generators (e.g., hydropower, pumped storage, gas turbine generators) that are not connected to the power system can be started at any time and connected to the power system to generate output within 120 min (or 20 min during summer measures) [45].

Energy storage systems are capable of being instantly deployed when reserve power is needed, allowing them to reach maximum output within a few seconds. To be used as reserve power, these systems must have a large enough battery capacity to supply sufficient energy for a specific period. Additionally, there must be high reliability in the energy storage system, as failure to supply the contracted capacity may result in penalties. Typically, the supply of reserve power should be able to provide electricity to the grid for 1–2 h and must respond to the grid operator's automatic generation control (AGC) signal. Most of the time, energy storage systems that are used for reserve power do not supply electricity. However, when not providing reserve power, energy storage systems can be sufficiently utilized for other purposes, such as electric energy time-shift, electric supply capacity, etc. For peak load reduction, energy storage systems that are on standby can be used to provide standby/alternative reserve power. They must have adequate capacity for the task [46].

#### 5.2.4. Frequency Regulation

Sudden changes in power grid frequency can adversely affect various equipment on the supply and demand sides and, in the worst case, may lead to power outages or supply disruptions. Frequency variations occur due to the difference between generation and load, and frequency regulation aims to minimize the constantly changing difference between power demand and supply, maintaining the power system's frequency at a consistent level. If the power supplied by the generators is either greater or lesser than the load at any given time, frequency regulation generators are used to mitigate the difference. Frequency regulation is typically performed by generators connected to the grid. The method involves either increasing or decreasing the power supply to regulate the frequency. If the power supply momentarily falls short, the generators responsible for the frequency will increase their output, and conversely, if there is a momentary oversupply of power, they will decrease their output [47].

Traditional fossil fuel generators are generally not suitable for frequency regulation as they are not designed to adjust output instantaneously to match momentary differences in power supply and demand. Specifically, fossil fuel generators are most efficient when

consistently delivering their rated output. Energy storage systems are suitable for frequency regulation for three main reasons: First, they have high charging and discharging efficiency (energy efficiency). Second, they can utilize up to twice their capacity for frequency regulation. Lastly, they can rapidly supply maximum output and allow for quick output adjustment [48].

Frequency-following operation is an auxiliary service provided for fine-tuning frequency control, and it is an area where the advantages of quick-responding energy storage systems can be best utilized. By responding to minor frequency fluctuations with energy storage systems, around the basic frequency, the base generators' GF area can be used as the main purpose of power supply, helping to save energy costs. AGC is intended to counter imbalances in supply and demand that cannot be addressed by GF and deals with load fluctuations in the time domain after GF operation. Short-term output maintenance, followed by a return when a new power source starts, allows for power supply through energy storage systems that can maintain output for 15 min to an hour [49].

#### 5.2.5. Black Start

Energy storage systems can be used as emergency power sources for a black start, supplying the necessary power to restart grid lines and power plants in the event of a massive blackout. Black start refers to the process of restoring a power plant to operation without relying on external power supplies. Typically, the power used in a power plant is supplied by its generators, so if all generators stop operating, power must be supplied from an external source through the electrical grid, see Table 5. If a wide-area blackout occurs and system power cannot be supplied, power plants without black start generators cannot restart their generators. To prepare for this, some power plants have small diesel generators for black start. These small diesel generators, known as Black Start Diesel Generators (BSDG), supply the necessary power to start large generators. Power for starting steam turbine generators is needed for things like boiler feed pumps, forced draft fans for boiler combustion air, and preparing fuel supplies [50].

**Table 5.** Black start and system recovery.

| Step | Description |
|---|---|
| Step 1 | A small diesel generator is installed in a hydropower plant (BSDG). |
| Step 2 | Utilize the power supply of the small diesel generator to start the hydropower generator. |
| Step 3 | Use the produced power of the hydropower plant to supply priority generators through designated transmission lines. |
| Step 4 | Utilize the hydropower's produced power to start priority supply generators (such as base load coal-fired generators). |
| Step 5 | Use the base load generator's power supply to start all other power plants (e.g., nuclear power plants) to recover the system. |

It is uneconomical for all power plants to have standby black start generators. Therefore, power is supplied from a black start power plant through a predetermined transmission system to start priority supply generators. Mainly, hydropower or pumped storage generation performs the role of the starting point for system recovery. They can start with a small supply and can provide power very quickly. Black start generators are generators that can start with their power source without the need for an external starting power supply, and they play an essential role in the restoration of the power system in severe situations like a total blackout. Since power generation must be possible without external power supplies, typically, hydropower or pumped storage generators or small diesel generators installed in gas turbine power plants operate as black start generators, playing the role of the starting point for power system recovery. If a power plant has energy storage systems of

sufficient size installed for starting power, it can quickly restore the power system through the charged power of the energy storage system [51].

It may be difficult to restore a large transmission and distribution network simultaneously during an extended blackout. For example, if there is a prolonged power outage during the winter, attempting to restore the system all at once could lead to a sudden spike in initial heating load, potentially exceeding the system's supply capacity. Therefore, the recovery of large transmission and distribution networks must be carried out gradually, in line with the restoration of supply capabilities.

## 6. Conclusions

In conclusion, the integration of energy storage systems (ESSs) into the energy spectrum is rapidly reshaping our perception of a dependable and adaptable power infrastructure. As global electricity demands surge and the unpredictable nature of renewable energy sources becomes more prevalent, ESSs emerge as essential tools, ensuring a more robust, flexible, and resilient power grid. Beyond merely serving large-scale transmission networks, these systems are revolutionizing the way individual consumers perceive and manage energy, offering them cost-saving solutions while enhancing power quality and reliability. This in-depth study of global practices, from the meticulous energy policies of the UK and U.S. to the forward-thinking strategies of South Korea, showcases a rich tapestry of strategies, each tailored to harness the maximal advantages of ESSs. However, to truly unlock the vast potential of energy storage systems, there remains a pressing need for tailored policy frameworks, enticing incentives, and relentless technological innovation. As we chart the future course of energy storage, emphasis must be placed on scalability, ensuring systems can meet ever-growing demands, interoperability, seamless communication between diverse systems, and the continued optimization of storage solutions. This trajectory will inevitably be laden with both technical and regulatory challenges that will only be resolved through collaborative efforts. The world is swiftly moving towards a decentralized, sustainable energy paradigm, and as we navigate this transition, ESSs stand out, not just as participants but as foundational pillars that are crucial to constructing an efficient, resilient, and sustainable energy future.

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## References

1. Merabet, A.; Al-Durra, A.; El-Saadany, E.F. Improved Feedback Control and Optimal Management for Battery Storage System in Microgrid Operating in Bi-directional Grid Power Transfer. *IEEE Trans. Sustain. Energy* **2022**, *13*, 2106–2118. [CrossRef]
2. Wang, Y.; Lin, X.; Pedram, M. A Near-Optimal Model-Based Control Algorithm for Households Equipped with Residential Photovoltaic Power Generation and Energy Storage Systems. *IEEE Trans. Sustain. Energy* **2016**, *7*, 77–86. [CrossRef]
3. Cao, Y.; Dhahad, H.A.; Mansir, I.B.; ABo-Khalil, A.G.; Alamri, S.; Rajhi, A.A.; Anqi, A.E.; Qasim, F. Development of a combined system based on a PEMFC and hydrogen storage under different conditions equipped with an ejector cooling system. *Int. J. Hydrog. Energy* **2022**, *47*, 26687–26700. [CrossRef]
4. Khani, H.; Zadeh, M.R.D. Real-time optimal dispatch and economic viability of cryogenic energy storage exploiting arbitrage opportunities in an electricity market. *IEEE Trans. Smart Grid* **2015**, *6*, 391–401. [CrossRef]
5. Mohsenian-Rad, H. Optimal bidding, scheduling, and deployment of battery systems in California day-ahead energy market. *IEEE Trans. Power Syst.* **2016**, *31*, 442–453. [CrossRef]

6. Ibrahim, H.; Ilinca, A. Perron Energy storage systems—Characteristics and comparisons. *Renew. Sust. Energy Rev.* **2008**, *12*, 1221–1250. [CrossRef]
7. Luo, X.; Wang, J.; Dooner, M.; Clarke, J. Overview of current development in electrical energy storage technologies and the application potential in power system operation. *Appl. Energy* **2015**, *137*, 511–536. [CrossRef]
8. Cohen, I.J.; Westenhover, C.S.; Wetz, D.A.; Heinzel, J.M.; Dong, Q. Evaluation of an actively controlled battery-capacitor hybrid energy storage module (HESM) for use in driving pulsed power applications. In Proceedings of the 2015 IEEE Pulsed Power Conference (PPC), Austin, TX, USA, 31 May–4 June 2015; pp. 1–5.
9. Chen, H.; Cong, T.N.; Yang, W.; Tan, C.; Li, Y.; Ding, Y. Progress in electrical energy storage system: A critical review. *Prog. Nat. Sci.* **2009**, *19*, 291–312. [CrossRef]
10. Whittingham, M.S. History Evolution and Future Status of Energy Storage. In *Proceedings of the IEEE 100*; No. Special Centennial Issue; IEEE: Piscataway, NJ, USA, 2012; pp. 1518–1534.
11. Zhang, H.; Mollet, F.; Saudemont, C.; Robyns, B. Experimental Validation of Energy Storage System Management Strategies for a Local DC Distribution System of More Electric Aircraft. *IEEE Trans. Ind. Electron.* **2010**, *57*, 3905–3916. [CrossRef]
12. Kalkhambkar, V.; Kumar, R.; Bhakar, R. Joint optimal allocation of battery storage and hybrid renewable distributed generation. In Proceedings of the 2016 IEEE 6th International Conference on Power Systems (ICPS), New Delhi, India, 4–6 March 2016; pp. 1–6.
13. Ashtiani, N.A.; Gholami, M.; Gharehpetian, G.B. Optimal allocation of energy storage systems in connected microgrid to minimize the energy cost. In Proceedings of the 2014 19th Conference on Electrical Power Distribution Networks (EPDC), Tehran, Iran, 6–7 May 2014; pp. 25–28.
14. Yaser, Q.; Kerdphol, T.; Mitani, Y. Different optimization schemes for community based energy storage systems. In Proceedings of the 2015 4th International Conference on Electric Power and Energy Conversion Systems (EPECS), Sharjah, United Arab Emirates, 24–26 November 2015; pp. 1–5.
15. Pathak, S.K.; Tazmeen, T.; Chopra, K.; Tyagi, V.V.; Anand, S.; Abdulateef, A.M.; Pandey, A.K. Sustainable Energy Progress via Integration of Thermal Energy Storage and Other Performance Enhancement Strategies in FPCs: A Synergistic Review. *Sustainability* **2023**, *15*, 13749. [CrossRef]
16. IEA. *Technology Roadmap—Energy Storage*; IEA: Paris, France, 2014.
17. Hossain, M.J.; Pota, H.R.; Mahmud, M.A.; Aldeen, M. Robust control for power sharing in microgrids with low-inertia wind and PV generators. *IEEE Trans. Sustain. Energy* **2015**, *6*, 1067–1077. [CrossRef]
18. Abokhalil, A.G.; Alobaid, M.; Makky, A.A. Innovative Approaches to Enhance the Performance and Durability of Proton Exchange Membrane Fuel Cells. *Energies* **2023**, *16*, 5572. [CrossRef]
19. Wang, S.; Tang, Y.; Shi, J.; Gong, K.; Liu, Y.; Ren, L.; Li, J. Design and advanced control strategies of a hybrid energy storage system for the grid integration of wind power generations. *IET Renew. Power Gener.* **2015**, *9*, 89–98. [CrossRef]
20. Tani, A.; Camara, M.B.; Dakyo, B. Energy management in the decentralized generation systems based on renewable energy—Ultracapacitors and battery to compensate the wind/load power fluctuations. *IEEE Trans. Ind. Appl.* **2015**, *51*, 1817–1827. [CrossRef]
21. IEA. *Energy Technology Perspectives 2014*; IEA: Paris, France, 2014.
22. Department of Energy (DOE). *Grid Energy Storage*; DOE: Washington, DC, USA, 2014.
23. Bae, S.; Kwasinski, A. Dynamic modeling and operation strategy for a microgrid with wind and photovoltaic resources. *IEEE Trans. Smart Grid* **2012**, *3*, 1867–1876. [CrossRef]
24. Luna, A.C.; Diaz, N.L.; Graells, M.; Vasquez, J.C.; Guerrero, J.M. Mixed-integer-linear-programming-based energy management system for hybrid PV-wind-battery microgrids: Modeling, design, and experimental verification. *IEEE Trans. Power Electron.* **2017**, *32*, 2769–2783. [CrossRef]
25. Olabi, A.; Abdelkareem, M.A.; Wilberforce, T.; Alkhalidi, A.; Salameh, T.; Abo-Khalil, A.G.; Hassan, M.M.; Sayed, E.T. Battery electric vehicles: Progress, power electronic converters, strength (S), weakness (W), opportunity (O), and threats (T). *Int. J. Thermofluids* **2022**, *16*, 100212. [CrossRef]
26. Teng, J.-H.; Luan, S.-W.; Lee, D.-J.; Huang, Y.-Q. Optimal charging/discharging scheduling of battery storage systems for distribution systems interconnected with sizeable PV generation systems. *IEEE Trans. Power Syst.* **2013**, *28*, 1425–1433. [CrossRef]
27. Mishra, S.; Pullaguram, D.; Buragappu, S.A.; Ramasubramanian, D. Single-phase synchronverter for a grid-connected roof top photovoltaic system. *IET Renew. Power Gener.* **2016**, *10*, 1187–1194. [CrossRef]
28. Kiehbadroudinezhad, M.; Merabet, A.; Abo-Khalil, A.G.; Salameh, T.; Ghenai, C. Intelligent and Optimized Microgrids for Future Supply Power from Renewable Energy Resources: A Review. *Energies* **2022**, *15*, 3359. [CrossRef]
29. Li, X.; Hui, D.; Lai, X. Battery Energy Storage Station (BESS)-Based Smoothing Control of Photovoltaic (PV) and Wind Power Generation Fluctuations. *IEEE Trans. Sustain. Energy* **2013**, *4*, 464–473. [CrossRef]
30. Almasalma, H.; Deconinck, G. Simultaneous Provision of Voltage and Frequency Control by PV-Battery Systems. *IEEE Access* **2020**, *8*, 152820–152836. [CrossRef]
31. Li, J.; You, H.; Qi, J.; Kong, M.; Zhang, S.; Zhang, H. Stratified Optimization Strategy Used for Restoration with Photovoltaic-Battery Energy Storage Systems as Black-Start Resources. *IEEE Access* **2019**, *7*, 127339–127352. [CrossRef]
32. Merabet, A.; Ahmed, K.T.; Ibrahim, H.; Beguenane, R.; Ghias, A.M.Y.M. Energy management and control system for laboratory scale microgrid based wind-PV-battery. *IEEE Trans. Sustain. Energy* **2017**, *8*, 145–154. [CrossRef]

33. Brenna, M.; Foiadelli, F.; Longo, M.; Zaninelli, D. Energy Storage Control for Dispatching Photovoltaic Power. *IEEE Trans. Smart Grid* **2018**, *9*, 2419–2428. [CrossRef]
34. SANDIA. *Market and Policy Barriers to Energy Storage Deployment*; Sandia National Labolatories: Albuquerque, NM, USA, 2013.
35. Sayed, K.; Abo-Khalil, A.G.; Alghamdi, A.S. Optimum Resilient Operation and Control DC Microgrid Based Electric Vehicles Charging Station Powered by Renewable Energy Sources. *Energies* **2019**, *12*, 4240. [CrossRef]
36. Arnaoutakis; Georgios, E.; Kocher-Oberlehner, G.; Katsaprakakis, D.A. Criteria-Based Model of Hybrid Photovoltaic–Wind Energy System with Micro-Compressed Air Energy Storage. *Mathematics* **2023**, *11*, 391. [CrossRef]
37. Olabi, A.; Wilberforce, T.; Sayed, E.T.; Abo-Khalil, A.G.; Maghrabie, H.M.; Elsaid, K.; Abdelkareem, M.A. Battery energy storage systems and SWOT (strengths, weakness, opportunities, and threats) analysis of batteries in power transmission. *Energy* **2022**, *254*, 123987. [CrossRef]
38. Sioshansi, R.; Denholm, P.; Jenkin, T.; Weiss, J. Estimating the value of electricity storage in PJM: Arbitrage and some welfare effects. *Energy Econ.* **2009**, *31*, 269–277. [CrossRef]
39. Connolly, D.; Lund, H.; Finn, P.; Mathiesen, B.; Leahy, M. Practical operation strategies for pumped hydroelectric energy storage (PHES) utilising electricity price arbitrage. *Energy Policy* **2011**, *39*, 4189–4196. [CrossRef]
40. Dongxia, Y.; Jianhua, Z.; Xiaoyan, W.; Yuan, G. Optimal capacity allocation of grid-connected wind-solar storage hybrid power generation system. *Proc. CSU-EPSA* **2019**, 59–65.
41. Cheng, L.; Xiu, Y.; Meixia, Z.; Haibo, W.; Jianhua, Y.; Jie, C. Optimal configuration scheme of hybrid energy storage of supercapacitor and battery based on cost analysis. *Autom. Electr. Power Syst.* **2013**, *37*, 20–24.
42. Pandžic, H.; Dvorkin, Y.; Carrion, M. Investments in merchant energy storage: Trading-off between energy and reserve markets. *Appl. Energy* **2018**, *230*, 277–286. [CrossRef]
43. Kazempour, S.J.; Hosseinpour, M.; Moghaddam, M.P. Self-scheduling of a joint hydro and pumped-storage plants in energy spinning reserve and regulation markets. In Proceedings of the 2009 IEEE Power & Energy Society General Meeting, Calgary, AB, Canada, 26–30 July 2009; pp. 1–8.
44. Nasrolahpour, E.; Kazempour, J.; Zareipour, H.; Rosehart, W.D. A bilevel model for participation of a storage system in energy and reserve markets. *IEEE Trans. Sustain. Energy* **2018**, *9*, 582–598. [CrossRef]
45. Akhavan-Hejazi, H.; Mohsenian-Rad, H. Optimal operation of independent storage systems in energy and reserve markets with high wind penetration. *IEEE Trans. Smart Grid* **2014**, *5*, 1088–1097. [CrossRef]
46. Bruninx, K.; Delarue, E. Endogenous probabilistic reserve sizing and allocation in unit commitment models: Cost-effective reliable and fast. *IEEE Trans. Power Syst.* **2017**, *32*, 2593–2603. [CrossRef]
47. Chen, S.; Zhang, T.; Gooi, H.B.; Masiello, R.D.; Katzenstein, W. Penetration rate and effectiveness studies of aggregated BESS for frequency regulation. *IEEE Trans. Smart Grid* **2016**, *7*, 167–177. [CrossRef]
48. Zhang, F.; Hu, Z.; Xie, X.; Zhang, J.; Song, Y. Assessment of the effectiveness of energy storage resources in the frequency regulation of a single-area power system. *IEEE Trans. Power Syst.* **2017**, *32*, 3373–3380. [CrossRef]
49. Yao, E.; Wong, V.W.S.; Schober, R. Robust frequency regulation capacity scheduling algorithm for electric vehicles. *IEEE Trans. on Smart Grid* **2017**, *8*, 984–997. [CrossRef]
50. Yao, F.; Chau, T.K.; Zhang, X.; Iu, H.H.-C.; Fernando, T. An Integrated Transmission Expansion and Sectionalizing-Based Black Start Allocation of BESS Planning Strategy for Enhanced Power Grid Resilience. *IEEE Access* **2020**, *8*, 148968–148979. [CrossRef]
51. Xu, Z.; Yang, P.; Zheng, Q.; Zeng, Z. Study on Black Start Strategy of Microgrid with PV and Multiple Energy Storage Systems. In Proceedings of the 18th International Conference on Electrical Machines and Systems (ICEMS), Pattaya, Thailand, 25–28 October 2015.


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