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Abstract: Smart grids are the ultimate goal of power system development. With access to a high proportion of renewable energy, energy storage systems, with their energy transfer capacity, have become a key part of the smart grid construction process. This paper first summarizes the challenges brought by the high proportion of new energy generation to smart grids and reviews the classification of existing energy storage technologies in the smart grid environment and the practical application functions of energy storage in smart grids. Secondly, optimization planning and the benefit evaluation methods of energy storage technologies in the three different main application scenarios, including the grid side, user side, and new energy side, are analyzed. The advantages and shortcomings of the current research are also pointed out. Furthermore, the paper sheds light on the pressing issues that demand further consideration in energy storage planning. Finally, the aspects that warrant attention in the future application and promotion processes are elucidated in detail, culminating in a comprehensive understanding of the energy storage technologies in smart grids.

Keywords: energy storage; smart grid; benefit evaluation; planning; renewable energy

1. Introduction

Currently, many studies have focused on renewable energy sources, HVDC transmission projects [1], and the coupling of multiple energy sources because of the energy crisis and environmental concerns. The pursuit of carbon neutrality in the energy sector has been advocated by many countries globally as a means to combat climate change. The power industry, which is a major carbon emitter, must build a new type of power system with renewable energy as the mainstay and promote the development of sources, such as wind power and photovoltaic energy, to accelerate the decarbonization process. As society and the economy continue to develop, and with an increasingly strained energy supply, the development of new energy sources has become a crucial aspect of future energy strategies.

While the adoption of renewable energy sources can bring many benefits in responding to climate change and addressing the energy crisis, high levels of renewable energy penetration in power grids can also cause significant impacts on the grid. For one, the output of renewable energy is unpredictable and intermittent due to uncontrollable external factors, such as weather and the environment, making it difficult to meet the voltage and waveform requirements of an ideal power supply system and resulting in power quality problems. Voltage fluctuations and flicker, voltage imbalance, frequency deviation, a low power factor, and harmonic pollution are among the main impacts of high renewable energy penetration on power quality in a distribution network [2]. In order to reduce the negative impact of the randomness of new energy sources on a power grid, a new control method for doubly-fed wind generators was proposed [3]. The use of power electronics to connect renewable energy sources to the grid also inevitably introduces harmonic components to the grid [4]. Furthermore, the integration of new energy generation into the grid can
exacerbate the problem of voltage imbalance in the grid, leading to additional power losses and reducing the capacity of transformers and lines [5]. The high proportion of renewable energy penetration can cause voltage fluctuations, which may interfere with sensitive electrical and electronic equipment and affect the safe and stable operation of the power system [6]. Additionally, due to the intermittent nature of renewable energy output and the uncertainty of load demand, the mismatch between power generation and load demand leads to deviations in grid frequency [7]. From a power dispatch perspective, generator sets can be categorized as controllable or uncontrollable, with controllable generator sets having less impact on traditional dispatching methods. Renewable energy units, as uncontrollable generator sets, often require power generation forecasts due to their dependence on weather and other unpredictable factors [8]. When uncontrollable renewable energy units are connected to the system, the power-dispatching process becomes more complicated [9]. These problems can be solved with the application of energy storage technology, which can effectively cope with access to new energy with high penetration rates. Thus, it is necessary to study energy storage capacity planning and economically analyze various types of energy storage technology.

With a smart grid scenario that combines centralized and distributed power generation, and a sizable portion of the total consumption supplied by decentralized generation, the role of decentralized generation becomes questionable in the absence of efficient and cost-effective energy storage system (ESS) technology. Nowadays, energy storage technology is widely used. For example, it has been applied in shipboard integrated power systems [10]. The widespread adoption of ESS technology enables the opportunity for demand-side management and peak load demand shaving, reducing the need for additional generation capacity to be deployed [11]. ESS technology can effectively realize demand-side management, eliminate the difference between peaks and valleys day and night, smooth the load, improve the utilization rate of power equipment, reduce power supply costs, and promote the use of renewable energy. It can also be used to improve the stability of the power system, adjust the frequency, and compensate for load fluctuations. Energy storage technology has become an important part of the development of smart grids. For integrating energy storage systems into a smart grid, the distributed control methods of ESS are also of vital importance. The study by [12] proposed a hierarchical approach for modeling and optimizing power loss in distributed energy storage systems in DC microgrids, aiming to reduce the losses in DC microgrids. In [13], a three-layer hierarchical control scheme was proposed to balance the state of charge (SoC) and state of health of distributed battery systems (DBS) in DC microgrids. The study by [14] proposed a unified loss model and a dual-ascent algorithm to optimize the current distribution coefficients in a DC microgrid with DESSs, achieving real-time loss minimization, adaptive current sharing, and robust performance in various scenarios.

This paper first summarizes the challenges brought by the high proportion of new energy generation to smart grids and reviews the classification of existing energy storage technologies in the smart grid environment and the practical application functions of energy storage in smart grids. Secondly, optimization planning and the benefit evaluation methods of energy storage technology in different application fields, including the power grid, users, and new energy, are analyzed. The advantages and shortcomings of the current research in the field are also pointed out. The algorithm of energy storage optimization planning is analyzed and summarized. Finally, the paper expounds on the problems that need to be further considered in energy storage planning and the aspects that should be paid attention to.

In summary, this paper makes a significant contribution by addressing the role of energy storage systems in the development of smart grids. It highlights the challenges associated with integrating a high proportion of renewable energy sources and provides an overview of the existing energy storage technologies and their practical applications in smart grids. We also analyze optimization planning and benefit evaluation methods for energy storage in three key application scenarios: the grid side, the user side, and
the new energy side. Additionally, we discuss algorithmic approaches to energy storage optimization planning and identify pressing issues that require further consideration. By offering insights into future applications and promotion processes, the paper provides a comprehensive understanding of energy storage technologies in the context of smart grids, benefiting researchers, practitioners, and policymakers alike.

2. Challenges for Smart Grid and Energy Storage Role Analysis

With the rapid development of power electronic conversion and new energy power generation technologies, such as wind and photovoltaic, the power system has undergone profound changes and gradually transitioned into a new power system stage characterized by a high proportion of new energy. The operating characteristics of the system are changing profoundly, and the power and energy balance at multiple time scales is facing new and significant challenges. Diversified energy storage technologies can control the input and output of power and energy at different time scales, which is expected to improve the stability and operation characteristics of smart grids. This section analyzes the main challenges faced by smart grids and the application requirements for energy storage.

Different from the traditional power system, the new power system takes new energy units and power electronic equipment as the main body. It has the characteristics of power electronic control, multiple time scales, low inertia, and weak immunity, and also combines the strong randomness and high volatility of primary energy, which brings new major challenges to the power–energy balance of the power system at multiple time scales.

In a short time scale, a high proportion of new energy connected to the power grid will not only affect all aspects of classical stability but will also cause new stability problems. The access to a large number of new energy units will change the power grid structure and power flow distribution, which will have a significant impact on the stability of the small disturbance/transient power angle, voltage stability, and frequency stability characterized by electromechanical dynamics. The degree of impact depends on the new energy penetration rate, unit type, access location, operating conditions, and control strategy.

In the medium and long time scales, the main challenges brought by the high proportion of new energy access to the smart grid are as follows: The increasing proportion of new energy sources, such as wind power and photovoltaic, with strong randomness and volatility, makes the adjustability and flexibility of the power grid decrease, resulting in the difficulty of achieving power and energy balance between the source and load and the deterioration of the economy. In the traditional power system, whether it is thermal power, hydropower, or nuclear power on the power supply side, its power and electricity can be efficiently adjusted in a large capacity and a wide time range to meet random but predictable load changes. In the new energy high penetration power system, primary energy sources, such as wind and photovoltaic, are random and uncontrollable and fluctuate greatly due to seasonal and diurnal changes, and some special meteorological factors can cause sharp changes in the output in a short period. The mismatch between new energy and the load, coupled with the decreasing proportion of flexible resources, makes it more difficult to achieve reliable and efficient operation of the power grid through traditional dispatching.

In summary, with access to a high proportion of new energy and power electronic equipment in the power system, the stability of a short time scale and the operational reliability of the medium and long time scales pose major challenges, and it is urgent to find technologies and equipment that can adjust the power and energy within a wide time scale to ensure the stability and economy of the operation of the new power system. With their energy transfer capacity, energy storage systems have become a key part of the future development of smart grids. Table 1 summarizes the challenges of smart grids regarding the power–energy balance and the role of energy storage systems.
### Table 1. Challenges for smart grids and energy storage role analysis.

<table>
<thead>
<tr>
<th>Challenges for Smart Grids</th>
<th>Role of Energy Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Short time scales</strong></td>
<td>Fast frequency adjustment</td>
</tr>
<tr>
<td>• The power grid structure and power flow distribution are changed.</td>
<td>Suppresses low-frequency oscillations</td>
</tr>
<tr>
<td>• High penetration of renewable energy power generation will have a significant impact on the stability of small disturbance/transient power angle, voltage stability, and frequency stability.</td>
<td>Automatic generation control (AGC)</td>
</tr>
<tr>
<td></td>
<td>Smooths the fluctuation of new energy output</td>
</tr>
<tr>
<td></td>
<td>Overvoltage suppression</td>
</tr>
<tr>
<td></td>
<td>Short-term voltage stability</td>
</tr>
<tr>
<td></td>
<td>Automatic voltage control (AVC)</td>
</tr>
<tr>
<td></td>
<td>Harmonics and resonance suppression</td>
</tr>
<tr>
<td></td>
<td>Sub-synchronous/super-synchronous resonance suppression</td>
</tr>
<tr>
<td></td>
<td>Electrical energy quality control</td>
</tr>
<tr>
<td></td>
<td>New energy output plan tracking</td>
</tr>
<tr>
<td><strong>Medium and long time scales</strong></td>
<td>New energy output climbing control</td>
</tr>
<tr>
<td>• The adjustability and flexibility of the grid decrease.</td>
<td>Alleviates transmission and distribution equipment congestion</td>
</tr>
<tr>
<td>• The difficulty of balancing power and energy between the source and load increases.</td>
<td>Peak shaving and valley filling</td>
</tr>
<tr>
<td>• It is increasingly difficult to achieve reliable and efficient operation of the power grid through traditional dispatching.</td>
<td>Participates in market regulation</td>
</tr>
<tr>
<td></td>
<td>Delays the expansion and upgrading of transmission and distribution</td>
</tr>
<tr>
<td></td>
<td>Works as a backup power source</td>
</tr>
</tbody>
</table>

### 3. Overview of Energy Storage Technologies and Their Practical Application Functions

The status quo of energy storage functions in smart grids is classified according to [15–66].

#### 3.1. Overview of Energy Storage Technologies

With an array of highly specialized and distinct electrical energy storage technologies available, the world of electrical energy storage can be split into six distinct categories based on their configurations and forms, including mechanical, chemical, electrochemical, electromagnetic, thermal, and hybrid energy storage systems [44–47]. Each energy storage system differs from the others based on various factors, such as discharge time, discharge loss, energy density, wattage rating, and life cycle [48]. Pumped hydro storage, compressed air storage, and battery energy storage are the current energy storage technologies with higher technical maturity and more applications. While pumped hydro storage and compressed air storage are more suited to peak adjustment of the power grid, battery storage energy is better suited for small- and medium-sized energy storage and new energy power generation. In contrast, superconducting electromagnetic energy storage and flywheel energy storage is more suitable for power grid frequency adjustment and electrical quality guarantee. Finally, supercapacitor energy storage are more suitable for electric vehicle energy storage and hybrid energy storage [49]. As seen in Figure 1, the specific classification of various types of energy storage is quite complex, but careful consideration of each system’s strengths and weaknesses can allow for the optimal selection and application of energy storage technology.
(1) Mechanical energy storage

The transformation of energy from mechanical to electrical forms is a complex process in mechanical energy storage systems. In this regard, three types of mechanical energy storage have been in use for a long time: compressed air energy storage, flywheel energy storage, and pumped energy storage. Among these, pumped energy storage is the most widely used and largest form of energy storage, where energy is converted into water potential energy for storage and then released through a turbine for conversion into electrical energy. This system boasts a large capacity, long life cycle, high efficiency, and cost-effectiveness, which makes it suitable for frequency regulation, peak shaving, emergency backup, and other scenarios. However, it also has high site environment requirements.

Compressed air energy storage, on the other hand, utilizes electric energy to compress air into a confined space, and then uses compressed air to push a steam turbine into electrical energy. It is further divided into traditional types, including those with heat storage devices, and liquid gas types. This system has the characteristics of a long storage period, large capacity, low cost, and high efficiency, with an efficiency rating of 70–89% and a rated power of 50–300 MW. However, it also has high site environment requirements.

Lastly, flywheel energy storage uses a flywheel’s angular momentum to store energy, where the motor drives the flywheel during charging, and the flywheel drives the generator to generate electricity during discharging. The stored energy is dependent on the flywheel’s size, mass, and speed, while the rated power is dependent on the motor and generator. Flywheel energy storage has low maintenance and long life, making it suitable for high-power, short-term scenarios, such as improving the power quality, providing reactive power support, and providing rotational backup.
(2) Electromagnetic energy storage

Electromagnetic energy storage has been a hot topic in the energy storage field, especially the two main forms of supercapacitors and superconducting magnetic energy storage (SMES). They have been identified as having high efficiency, high energy density, and high cost.

SMES is a promising energy storage solution that stores energy in the form of electromagnetic energy. The stored energy is converted through superconducting material coils, and its efficiency is more than 95%, thanks to the near-zero resistance of superconductors. SMES also boasts fast response times and a long life cycle, making it a popular option for improving transmission and system capacity, enhancing the power supply quality, and ensuring operational stability. However, the cost of SMES is still a limitation to its widespread adoption, as well as the superconducting critical temperature and potential environmental impact.

Supercapacitors have a simpler construction, consisting of two non-reactive porous electrode plates suspended in an electrolyte and charged on the plate. By electrochemically polarizing the electrolyte, it achieves energy storage without any electrochemical reactions occurring in the process, making it a reversible process. Supercapacitor energy storage has the advantages of a higher power density and long service life, making it ideal for high-power, short-term load smoothing, and high-peak power occasions, such as high-power DC motor starting support and dynamic voltage restorers.

(3) Electrochemical energy storage

Compared to other types of energy storage, the electrochemical energy storage technology represented by batteries has the widest diversity and the fastest development, and different kinds of chemical energy storage can meet various power system demands. Electrochemical energy storage uses the conversion between electrical energy and chemical energy for the storage and release of electrical energy. It has good environmental adaptability, a fast response ability, low standby loss, and high energy efficiency (60–95%). However, due to its characteristics of a small power capacity, high maintenance cost, short life cycle, and limited discharge capacity, the application scale is small. At present, the battery energy storage technologies that have been commercialized or demonstrated mainly include lead–acid batteries, lithium-ion batteries, sodium–sulfur batteries, and flow batteries [50].

Lead–acid batteries are super cheap and have a large energy storage capacity. However, they have some serious issues with self-discharge, a short life cycle, heavy metal contamination, and deep discharge.

Lithium-ion batteries can be combined in series or in parallel to provide high voltage or high capacity, but they are pretty expensive. However, they have a high energy density and great charge and discharge efficiency.

Sodium–sulfur batteries have a lot going for them, such as high energy density, excellent charge and discharge efficiency, cheap operating costs, modest space requirements, and simple maintenance. The depths of their discharge and life cycle, however, still need to be enhanced and preserved while in use. The utilization rate of their electric energy is 100% [51].

Flow batteries have the advantages of high power output, fast response, high energy conversion rate, simple maintenance, safety, and stability, and are currently the most popular batteries. However, their material costs are high. Nevertheless, they are a top pick for large-scale grid-connected power generation, energy storage, and regulation [52].

This paper provides the fundamental properties of various electrochemical energy storage methods in Table 2 to make comparisons among them.
Table 2. Characteristics of electrochemical energy storage technologies in smart grids [53].

<table>
<thead>
<tr>
<th>Technology</th>
<th>Name</th>
<th>Capacity (MWh)</th>
<th>Power (MW)</th>
<th>Response Time</th>
<th>Discharge Time</th>
<th>Lifetime (Years)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrochemical</td>
<td>Lead–acid</td>
<td>0.25–50</td>
<td>≤ 100</td>
<td>≤ 4 h</td>
<td>≤ 20</td>
<td>≤ 20</td>
<td>≤ 85</td>
</tr>
<tr>
<td></td>
<td>Lithium-ion</td>
<td>0.25–25</td>
<td>≤ 100</td>
<td>Millisecond</td>
<td>≤ 1 h</td>
<td>≤ 15</td>
<td>≤ 90</td>
</tr>
<tr>
<td></td>
<td>Sodium–sulfur</td>
<td>≤ 300</td>
<td>≤ 50</td>
<td>≤ 6 h</td>
<td>≤ 15</td>
<td>≤ 15</td>
<td>≤ 80</td>
</tr>
<tr>
<td></td>
<td>Flow batteries</td>
<td>≤ 250</td>
<td>≤ 50</td>
<td>≤ 10 min</td>
<td>≤ 8 h</td>
<td>≤ 10</td>
<td>≤ 80</td>
</tr>
</tbody>
</table>

(4) Chemical energy storage

Chemical energy storage is a highly sophisticated system that enables the storage and release of energy through chemical reactions, resulting in the formation of other compounds. This futuristic technology is characterized by zero emissions and an impressive storage capacity of over 100 GWh [54]. One of the prime examples of chemical storage is the fuel cell, which continually converts the chemical energy of fuel into electrical energy. Fuel cells, unlike batteries, produce energy by integrating fuel and oxidizers from the outside. The significant advantage of fuel cells is that they can generate electricity as long as they receive active substances. Fuel cells’ fuel efficiency generally ranges from 40 to 85%.

Fuel cell technology, being an excellent source that can reduce fossil fuel usage and CO₂ emissions, is composed of a liquid or gaseous fuel as the anode and oxidants, such as oxygen, air, or chlorine, as the cathode. The hydrogen fuel cell, in particular, is highly favored in the market. This type of fuel cell uses a combination of hydrogen and oxygen to generate electricity, which can be regenerated and reversed by water and electricity. The hydrogen storage tank’s size optimization enables the storage of large amounts of energy in fuel cells regardless of the rated power. These fuel cells are applied in distributed microgrid power generation scenarios and the automotive industry, where only water vapor is released into the environment.

(5) Thermal energy storage

Thermal energy storage is an innovative technology that can store energy from electric or solar heaters in a reservoir for later use in heating systems or power plants. The technology offers a wide range of options, including latent heat storage, sensible heat storage, and thermochemical adsorption storage systems. Latent heat storage systems utilize various materials, including organic (such as paraffin), inorganic (such as hydrochloride), and phase-change materials (PCMs), to store energy during the phase change of the storage medium [55]. Molten salt is the latest solid–liquid PCM, and it is being used in concentrated solar power plants [56]. Latent heat storage systems have a high energy density, high heat transfer efficiency, and constant temperature capacity [57]. Sensible thermal storage systems are the most common, and they utilize various media, including solids (such as ground, cast iron, or concrete) or liquids (such as water or thermal oil) to store energy. The storage capacity of sensible thermal storage systems depends on the heat capacity of the material used. The technology is versatile, reliable, and can be used in many heating applications, including district heating systems and industrial processes.

In addition, thermal energy storage may be considered to be extended to a more general type. Integrated energy systems go beyond traditional electrical energy storage and incorporate storage-like effects from other energy carriers, such as the heating network [58] and the gas network [59]. By integrating thermal energy storage, heating networks, and gas networks, an integrated energy system can exploit the storage-like effects of these interconnected networks to optimize energy utilization and enhance system flexibility. Further research and development are needed to explore the technical, economic, and regulatory aspects of expanding energy storage to include thermal energy storage and integrated energy systems. By leveraging the storage potentials from diverse energy carriers, we can unlock additional flexibility and enhance the overall performance and reliability of future energy systems.
(6) Hybrid energy storage

A hybrid energy storage system is the process of complementing the characteristics of two or more heterogeneous storage systems to create a super energy storage device. In the harsh operating environments of real-time applications, a single ESS system cannot meet all ideal specifications (such as energy density, power rating, operating temperature, discharge rate, life cycle, and cost). The main goal of hybrid systems is to combine high-energy-density (usually slow-response systems) with high-power-density (fast-response system) equipment to achieve high-energy and high-power rating characteristics for fast response [60].

Hybrid energy storage systems have been developed that electronically combine the output power of two or more energy storage systems with complementary characteristics. In hybrid energy storage systems, heterogeneous systems are organized in such a way that short-term high-power requirements will be provided by high-power devices, while long-term energy requirements will be met by high-energy devices [61]. Hybrid energy storage systems are divided into battery and battery hybrids, battery and supercapacitor hybrids, fuel cell and battery hybrids, battery and SMES hybrids, battery and flywheel hybrids, etc. The size and possible combinations of hybrid energy storage systems depend on factors such as environmental, economic, and type of use [62]. The use of multifunctional hybrid energy storage systems is the best choice for building smart grids and requires interdisciplinary collaboration and research to further develop and advance the field.

3.2. Temperature Regulation Technologies for Energy Storage Systems

Temperature regulation plays a crucial role in ensuring the optimal operation and longevity of ESS in smart grids [63]. Effective temperature management involves utilizing thermal models, implementing thermal regulations, and employing appropriate cooling technologies.

Thermal models are used to simulate and predict the temperature behavior of ESS components. These models consider factors such as the heat generation, heat transfer, and thermal capacitance of the storage system. Different types of thermal models, including lumped parameter models, distributed parameter models, and electro-thermal coupled models, can be utilized to understand the thermal characteristics of the ESS. These models enable accurate temperature predictions, aiding in the design and optimization of thermal management strategies.

Thermal regulation involves establishing temperature limits and implementing control strategies to maintain the ESS within a safe operating range. This includes defining the upper and lower temperature thresholds for various components and implementing control algorithms to regulate the temperature. Thermal regulation is essential for preventing excessive temperatures that can degrade the performance, capacity, and lifespan of the ESS. By carefully monitoring and controlling temperature levels, the system can operate efficiently and safely.

Cooling technologies are employed to manage and dissipate heat generated by the ESS components. Different cooling methods can be utilized based on the specific requirements and constraints of the system. Some commonly used cooling technologies include air cooling, liquid cooling, phase-change materials (PCMs, and heat pipes. Air cooling utilizes fans or natural convection to remove heat from the ESS components. Air cooling is cost-effective and suitable for low- to medium-power applications. Liquid cooling involves circulating a coolant, such as water or a specialized coolant fluid, through heat exchangers or directly in contact with the ESS components. Liquid cooling offers higher heat-transfer efficiency and is suitable for high-power or high-temperature applications. PCMs can absorb or release latent heat during phase transitions, making them ideal for passive cooling in the ESS. These materials store and release heat energy as they change from solid to liquid or vice versa, helping to stabilize temperatures within the system. Heat pipes are heat transfer devices that use the principles of evaporation and condensation to efficiently transport heat from the ESS components to cooler areas or heat sinks. They
offer high thermal conductivity and are particularly effective for removing heat from concentrated areas.

3.3. Practical Application Functions of Energy Storage

Energy storage equipment can realize the input and output regulation of electric energy at different time scales, which can effectively improve the operating characteristics of the system and meet the power and energy balance requirements of a smart grid. The application of different energy storage technologies in power systems is also different. As can be seen in Table 3, for the power type and application time scale of energy storage, the current application of energy storage in the power grid mainly focuses on power frequency active regulation, especially in rapid frequency regulation, peak shaving and valley filling, and new energy grid-connected operation. From the perspective of the application distribution of energy storage in the power grid, it mainly includes the following aspects:

(a) The functions of the power generation side mainly include fast frequency regulation, the suppression of low-frequency oscillation, automatic generation control, smoothing new energy output fluctuations, new energy output plan tracking, new energy output climbing control, etc.

(b) The functions of the transmission and distribution network side mainly include optimizing new energy integration, delaying transmission and distribution line blockage, delaying equipment upgrading, and optimizing power flow distribution.

(c) Load-side functions mainly include improving the power quality, providing distributed energy supply, participating in market regulation, etc.
### Table 3. The status quo of energy storage functions in smart grids.

<table>
<thead>
<tr>
<th>Function</th>
<th>ESS Type</th>
<th>Mechanical ESS</th>
<th>Electrochemical ESS</th>
<th>Chemical ESS</th>
<th>Electromagnetic ESS</th>
<th>Thermal ESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power frequency active regulation</td>
<td>Fast frequency adjustment</td>
<td>[15]</td>
<td>[16,17]</td>
<td>[18]</td>
<td>[16,17]</td>
<td>[16,19]</td>
</tr>
<tr>
<td>Short time scales</td>
<td>Suppresses low-frequency oscillations</td>
<td>[22]</td>
<td>[23,24]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Automatic generation control (AGC)</td>
<td>[25]</td>
<td>[26]</td>
<td>[27,28]</td>
<td>[19,29]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Smooths the fluctuation of new energy output</td>
<td>[30]</td>
<td>[31]</td>
<td>[17,32]</td>
<td>[34]</td>
<td>[35]</td>
</tr>
<tr>
<td></td>
<td>New energy output plan tracking</td>
<td>[29,31]</td>
<td>[29]</td>
<td>[29]</td>
<td>[29]</td>
<td></td>
</tr>
<tr>
<td>New energy output climbing control</td>
<td>[29]</td>
<td>[29]</td>
<td>[29]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium and long time scales</td>
<td>Alleviates transmission and distribution equipment congestion</td>
<td>[37]</td>
<td>[26,37]</td>
<td>[38]</td>
<td>[37]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Peak shaving and valley filling</td>
<td>[15]</td>
<td>[29]</td>
<td>[33]</td>
<td>[33]</td>
<td>[29]</td>
</tr>
<tr>
<td></td>
<td>Participates in market regulation</td>
<td>[40]</td>
<td>[41]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Delays the expansion and upgrading of transmission and distribution</td>
<td>[37,42]</td>
<td>[26,37]</td>
<td>[29]</td>
<td>[29,43]</td>
<td>[37]</td>
</tr>
<tr>
<td>Power frequency reactive power regulation</td>
<td>Overvoltage suppression</td>
<td>[29]</td>
<td>[31]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Short time scales</td>
<td>Short-term voltage stability</td>
<td>[31]</td>
<td>[29]</td>
<td>[31]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Automatic voltage control (AVC)</td>
<td>[17]</td>
<td>[28,35]</td>
<td>[29]</td>
<td>[29,41]</td>
<td></td>
</tr>
<tr>
<td>Non-power frequency regulation</td>
<td>Harmonic and resonance suppression</td>
<td>[29]</td>
<td>[17]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Short time scales</td>
<td>Sub-synchronous/super-synchronous resonance suppression</td>
<td>[29]</td>
<td>[31]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrical energy quality control</td>
<td>[29]</td>
<td>[26]</td>
<td>[29,41]</td>
<td>[17]</td>
<td>[29]</td>
<td>[34]</td>
</tr>
<tr>
<td>Integrated energy system</td>
<td>[58,59]</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>
4. Optimal Configuration of the Energy Storage System in Different Scenarios

Energy storage is one of the most important links in smart grids, and power systems face many challenges with future access to a high proportion of renewable energy. Energy storage technology is considered to be one of the key technologies to balance the intermittency of variable renewable energy to achieve high penetration. A connection structure diagram of an energy storage system and a public power grid is shown in Figure 2.

![Structural diagram of an energy storage system connected to a public power grid.](image)

Energy storage systems are applied in different scenarios, and their main role and the value of different investors are also different. Researchers have spent considerable time and effort devising optimal plans for deploying energy storage technology across diverse applications, and have even developed models to evaluate its economic impact. The different scenarios for energy storage can generally be categorized into three main categories: grid-side, user-side, and new energy-side applications, which include microgrids. The distinctive value proposition of energy storage in each scenario is highlighted in Figure 3, illustrating the multifaceted nature of energy storage applications.

![Value manifestation of energy storage in different scenarios.](image)

**Figure 3.** Value manifestation of energy storage in different scenarios.
4.1. Optimal Configuration of Energy Storage System on the Grid Side

Energy storage systems are a highly sophisticated technology that has revolutionized the power grid in more ways than one. By deferring the upgrading of the power grid, reducing transmission resistance, alleviating peak adjustment pressure, and providing auxiliary services, these systems have significantly improved the reliability of the power supply and the quality of power, bringing about numerous benefits to users. However, the complexity of energy systems has made it difficult to optimize their performance.

Different research studies have focused on various aspects of energy storage systems, resulting in different target functions. The existing research has predominantly aimed to maximize the return on investment by optimizing the allocation of energy storage. In [67], a maximum optimization model of the income was established, and then the genetic algorithm combining linear planning was used to solve it. This was carried out while considering the advantages of delaying the grid upgrade, decreasing the cost of blocking, and the high income and high arbitrage of the power grid. In [68], considering the aspects of energy storage systems in delaying grid upgrading, providing auxiliary services, improving transmission network equipment utilization, load, and power generation optimization management, etc., a multi-objective optimization model was established, with the largest net present value and the lowest cost. The genetic algorithm was used to solve the problem, and the optimal capacity and economy of the energy storage system were analyzed. Reference [69] improved the economic efficiency of planning by utilizing the particle swarm optimization algorithm and considering the profits of distributed generation operators and energy storage operators as the objective function. In [70], the objective was to minimize the overall annual cost of planning. They employed simulated annealing and the lion algorithm to achieve the coordinated optimization of energy storage and active distribution network planning. In [71], a coordinated planning method for the transformation of energy storage and thermal power units, taking into account the benefits of auxiliary service revenue, was proposed by analyzing the deep peak shaving of thermal power units and the peak–valley arbitrage of energy storage. In [72], in order to enhance the overall peak-shaving benefits and promote the enthusiasm for peak-shaving transactions in a multi-source system, proactive peak-shaving constraints were introduced to the energy storage-assisted thermal power unit peak-shaving model.

Some studies have planned with the goal of achieving the best social benefits brought by a specific purpose of the energy storage system, such as the goal of maximizing the emission reduction effect of the power grid after the construction of the energy storage system. In [73], aiming at superconducting magnetic energy storage features in a power grid, the characteristics of power operation were optimized, with minimalization of the total system’s total carbon dioxide emissions as the goal, and using the Lagrange multi-plication method to combine the K-T conditions for a solution. In [74], an optimization model was established for the combined dispatch of solar thermal power generation and thermal power generation, with the objective of minimizing the curtailed wind and solar power. In [75], they proposed a coordinated planning method for energy storage and thermal power unit flexibility transformation, focusing on deep peak-shaving compensation of the thermal power units and the peak–valley arbitrage of energy storage. In [76], to maximize the total life cycle benefit of battery energy storage systems in the distribution network, a hybrid optimization model was established by considering factors such as energy storage arbitrage income, government electricity price subsidy income, reducing electric energy conversion freight, delaying power grid upgrading, and life-cycle cost. In [77], taking the sodium–sulfur energy storage system as an example, the economy of transmission operation was evaluated based on the operation model of a wind storage and transmission dual system. The correlation between the operating cost of the energy storage system and the number of discharges was analyzed in depth, and the improved particle swarm algorithm was used to solve the established optimization model. In [78], considering the health state of energy storage batteries, a configuration model was established to maximize
the net return of the system, and the appropriate ratio of photovoltaic, energy storage, and load was obtained.

Energy storage systems are installed in power grids, and the benefits generated have many aspects. These benefits generally do not all belong to the investment subject but have real significance. However, when the unit cost of the energy storage system is too high, it is often concluded that it is not economical due to ignoring other hidden economic values, which is not conducive to the commercialization of this technology. How to comprehensively evaluate the value of the energy storage system and measure the social and economic benefits and beneficiary subjects attached to it so that investors to obtain the support of national policies needs to be studied.


As an important means to increase the consumption of new energy, energy storage will become the mainstream trend of new energy development against the background of “carbon peaking and carbon neutrality”, requiring the vigorous development of new energy, such as wind and solar. Energy storage systems play a major role in smoothing the fluctuation of new energy output power, improving new energy consumption, reducing the deviation of the power generation plan, and improving the safe operation stability of the power grid. Specific classification scenarios are shown in Figure 4. How to rationally allocate energy storage to meet the relevant needs in different application scenarios while improving the economy has become an urgent problem to be solved.

Figure 4. Classification of new energy storage application scenarios.

The configuration of energy storage on the new energy side needs to consider the randomness of new energy output and the indicators in single- or multiple-application scenarios. According to the uncertainty of new energy output and the different goals of energy storage optimal allocation, the uncertainty, economic benefits, environmental benefits, technical benefits, and multi-factor comprehensive evaluation indicators of new energy output were selected to establish an optimal energy storage allocation model, as shown in Figure 5.
The uncertainty and power prediction error of new energy output, such as wind power and photovoltaic sources, will affect the results of energy storage planning. By applying the uncertainty programming method to energy storage optimization configuration, the uncertainty optimization problem can be transformed into a deterministic optimization problem, thus simplifying the solving process of energy storage planning. The uncertainty planning method mainly includes random planning, fuzzy planning, robust optimization, and a scene analysis method.

Random planning is a traditional optimization method to respond to the uncertainty of modeling and establish the probability density function of wind power and photovoltaic. The Weibull probability distribution function is commonly used to model wind power, and the Beta probability distribution function is used to model photovoltaic [79,80]. The fuzzy programming method describes the uncertainty of wind power by constructing a fuzzy membership function in which the trapezoidal membership function is often used to deal with the uncertainty of wind power in the field of high-proportion wind power system optimization [81]. Robust optimization is a way to solve the problem of uncertain parameter optimization. In [82], the robust optimization programming method was used to construct a set of probability distribution functions of wind power output based on historical data, and the curtailment rate of the wind requirement was taken as the robust opportunity constraint to establish a robust opportunity constraint programming model, with the minimum energy storage investment cost as the goal and the curtailment rate of the wind as the constraint. In [83], the robust joint opportunity constraint model of probability distribution was used to describe the optimal configuration of energy storage in wind farm systems, and the robust opportunity constraint model was transformed into a deterministic linear matrix inequality problem. The scenario analysis method is a kind of probability distribution model with random variables in specific scenes and simulates the distribution of original random variables with as few scenarios as possible to transform the stochastic optimization problem into a deterministic optimization problem. The photovoltaic output was separated into five typical weather conditions according to the headroom model, and the probability density function was calculated by fitting the distribution parameters in [84].

According to the different energy storage optimal allocation goals, the existing literature has selected economic, environmental protection, technical, and multi-factor comprehensive evaluation indicators to construct an optimal allocation model for energy storage. In the optimal configuration of an energy storage system, the economic factor usually...
considers the minimum total cost and maximum total benefit. In [85], a planning model was established with the minimum total cost of the system as the optimization goal, and the power supply and energy storage capacity under the three cost scenarios of high, medium, and low were comprehensively optimized. In addition, economic analysis of energy storage instead of thermal power was proposed by new energy allocation. In [86], the impact of an energy storage system’s capacity on the economy of the whole life cycle of the system was studied to minimize the total cost of the system, including grid power supply costs, photovoltaic power generation costs, and battery charging and discharging depreciation costs. In [87], to minimize the total power generation cost of the system, a nonlinear optimization planning model of the combined wind-pumped storage system was established, and the benefits of the system in reducing carbon dioxide emissions were calculated. In [88], aiming at the optimal allocation of capacity of the photovoltaic energy storage system, a maximum intraday net income objective function model of the photovoltaic storage system was constructed. Environmental indicators usually include the emissions of CO$_2$ and other pollutants. In [89], the annual environmental cost was included in the objective function of the energy storage optimal allocation model, and the lower the annual environmental cost, the higher the utilization rate of new energy in the region. In [90], the establishment of a carbon emission cost calculation model fully considered the environmental factors of carbon emissions to achieve the minimum system operating cost, and at the same time, reduced the curtailment of wind, photovoltaic power generation, and load reduction. In the optimal configuration model of energy storage, the technical indicators mainly include voltage quality and system network loss. In [91], the voltage stability margin was used as the index to pre-select the site, and based on considering the charging and discharging state of the energy storage equipment, the active network loss was taken as the objective function to determine the installation location and capacity of the energy storage system. In [92], the voltage timing sensitivity was proposed to plan the installation location and capacity of the energy storage system from the perspective of improving the voltage distribution. In [93], by calculating the power loss sensitivity, the energy storage was selected in the position with the highest power loss sensitivity.

In the actual energy storage planning problem, it is difficult to achieve the best optimization configuration effect by considering a single optimization goal. Therefore, scholars have carried out a large number of studies on energy storage planning methods that take into account multiple factors based on single objectives. In [94], a phased capacity optimization allocation model was proposed. In the first stage, the maximum consumption of new energy was the target, and in the second stage, the minimum storage cost to meet the utilization rate of new energy was the optimization objective. In [95], the upper model aimed at the minimum annual comprehensive cost, and the lower model aimed at the minimum system network loss. In [96], the upper layer aimed to maximize the total capacity of the power station, and the lower layer aimed to minimize the investment cost to optimize the wind storage ratio. In [97], the upper layer aimed to select the site with the best improvement effect of voltage fluctuation, and the lower layer targeted the minimum investment cost for a volumetric setting. In [98], the upper layer aimed to minimize the total cost of the coordinated frequency regulation of the frequency modulation generator and energy storage, and the lower model considered the minimum cost of system network loss and voltage regulation penalty for energy storage site selection and capacity. In [99], the upper layer aimed to maximize the benefit, and the lower layer considered the capacity loss of the energy storage battery and optimized the allocation of energy storage with the goal of the largest on-site absorption rate of new energy.

Currently, with the penetration of a high proportion of new energy, the frequency and voltage of power grids have become unstable, causing a sharp increase in the operating pressure. As a result, in multiple application scenarios, it is particularly important to research the optimal allocation method of energy storage that considers the absorption and improvement of the capacity of a new energy storage power station to actively support
the power grid. Furthermore, it is necessary to comprehensively consider the influence of factors such as the selection of the energy storage technology type and control strategy on the optimization configuration results.

4.3. Optimal Configuration of Energy Storage System on the User Side

From the perspective of users, battery energy storage systems with swift adjustment performance are typically used for peak–valley spread arbitrage and demand response. Demand response refers to utilizing pricing or other incentive mechanisms to motivate power users to adjust their load characteristics to meet power system operation requirements. To alleviate grid load, enhance user load management capabilities, and increase power supply reliability, users employ energy storage to charge during low grid loads and supply electricity during high loads. Time-of-use arbitrage is the most commonly used scenario for user-side energy storage. In [100], the difference between the power cost and the equivalent electricity price throughout the energy storage system’s entire life cycle was compared, and economic criteria for user-side energy storage to participate in time-sharing arbitrage were given. In [101], the applications of sodium–sulfur batteries and flywheel energy storage systems in the New York market were studied, and feasible arbitrage schemes were proposed, highlighting the strong economic prospects for energy storage systems in energy arbitrage applications.

Several scholars have conducted relevant research on the value of energy storage systems in reducing users’ electricity costs. In [102], an energy storage system of industrial users with wind turbines was optimized using a multichannel iterative particle swarm optimization algorithm to minimize the users’ monthly electricity cost and obtain the optimal charging/discharging strategy and energy storage scale. In [103], a dynamic programming method was used to optimize the scale and operation strategy of energy storage to maximize the net income generated by the battery energy storage system used for load regulation.

In recent years, to maximize users’ investment income, multi-scenario joint operation optimization of user-side energy storage has gradually attracted widespread attention from academia and industry. Grouping energy storage systems so that different groups of energy storage undertake different functions is an effective means of realizing the simultaneous participation of energy storage systems in multiple profit models. Additionally, considering the decoupling of periods, operating energy storage at different times can assume different functions [104]. Most research chooses to build a unified comprehensive economic operation model of energy storage from the perspective of multi-scenario and multi-time coupling. In [105], a scheduling strategy for user-side energy storage to participate in frequency regulation and reduce the peak load of users at the same time was proposed, taking the cumulative maximum demand as the daily state variable and considering the impact of monthly demand electricity costs, using the German electricity market as an example. In [106], a nested model of energy storage operation based on dynamic programming was established, solving the problem of different time scales participating in frequency regulation and electricity price arbitrage through sub-models of different optimization time domains. In [107], a two-stage optimization model integrating time-sharing arbitrage, demand management, and grid frequency regulation was proposed, deciding the declared capacity, maximum demand threshold, and optimal SOC trajectory of energy storage on the target day in the pre-day stage, and dispatching energy storage output in real time in the intraday stage, while tracking the previous trajectory as much as possible to ensure that the peak load does not exceed the limit.

4.4. Energy Storage System Deployment Planning Approaches

In the world of energy storage application planning, the literature predominantly has employed mathematical modeling, which can vary greatly depending on the different value aspects considered, the varying constraints, and the number of periods divided. As a result, solution methods can differ vastly and mainly include conventional optimization al-
algorithms, heuristic algorithms, hybrid optimization algorithms, and AI-based technologies, as reviewed and classified in this paper. The classification is shown in Figure 6.

**Figure 6.** Types of energy storage system deployment planning approaches.

1. **Conventional optimization algorithm**

Conventional optimization algorithms theoretically guarantee optimal solutions, but they often require the strict expression of the objective function and constraints, limiting their adaptability. The most popular mathematical technique with an ideal theory and solution is linear programming, which boasts an ability to handle complex problems, straightforward calculations, and quick resolution times. However, modeling the actual problem through a linear description can introduce significant inaccuracies, which is why linear programming is only used in the literature [67]. Nonlinear programming methods have been widely used to more accurately describe the actual problem and establish an accurate model of the problem. A nonlinear constraint programming model associated with the K-T condition was solved using the traditional Lagrange multiplier method in [73], and researchers used GAMS software to solve a nonlinear programming model with constraints in a study [87]. Nonlinear programming methods are computationally intensive and take a long time to calculate, necessitating the decomposition of the problem when applying large-scale systems. Dynamic programming methods are an effective means to study the optimal solution of a multi-stage decision-making process, which considers discrete variables and random factors with no strict restrictions on the objective function and constraints. The solution steps are clear, and it is easy to find the global optimum. Hence, dynamic optimization methods are widely used in related research, as found in the literature [103,106]. However, one of the limitations of dynamic optimization methods is that when the number of state variables in the model increases, the number of dimensions also sharply increases.

2. **Heuristic optimization algorithm**

In the realm of energy storage application planning, the literature has mostly utilized mathematical modeling. However, due to the complexities and nuances involved in the energy storage problem, heuristic algorithms are becoming increasingly popular, as they do not require explicit mathematical formulas and are suitable for multi-objective optimization problems. These algorithms utilize artificial intelligence methods to determine the optimal size and location of energy storage systems. One such algorithm is the particle swarm optimization (PSO) and genetic algorithm (GA), which are effective for energy storage placement problems. For instance, multi-channel iterative PSO was used in [102] to determine the optimal charge/discharge strategy and energy storage scale. Additionally, a genetic algorithm was utilized in [68] to solve a multi-objective optimization model and examine the optimal efficiency and capacity of energy storage systems. It is important to note that while heuristic algorithms offer more flexibility than mathematical optimization methods, they come at the expense of solution accuracy, as they do not guarantee the global optimum and may instead fall into a local optimum.
(3) Hybrid optimization algorithm

As the complexity of power grids continues to increase, a single algorithm is often not enough to solve the problem of energy storage distribution. Hybrid algorithms combine the benefits of various optimization strategies while overcoming the limitations of a single approach. For instance, the GA has the opposite features of PSO, which has a quick search speed and high local search capability but weak global search capability. In [108], these two algorithms were merged to overcome these limitations and offer a quick and reliable worldwide search capability. The generalized Benders decomposition (GBD) approach was combined with second-order cone programming (SOCP) relaxation to prevent becoming stuck in the local optima and achieved great computation efficiency [109]. This resulted in the best solution for the ESS size, placement, number, and operation. Hence, compared to a single method, hybrid optimization algorithms can tackle more complicated problems with a faster convergence speed and better solution quality. Thus, as the complexity of the algorithm rises, some investigations have turned to hybrid optimization algorithms.

(4) The application of AI-based technologies in ESS planning and control

Evaluation indicators and the application of AI-based technologies are discussed in [101,110–129]. With the advancement of artificial intelligence (AI) technology, many AI techniques have been applied to ESS in smart grids, which are important for ESS in smart grids. In an energy storage-enabled smart grid, in the planning phase, AI can optimize energy storage configurations and develop appropriate selection schemes, thereby enhancing the system inertia and power quality and reducing construction costs. In terms of energy storage planning, the study [122] proposed the use of fuzzy logic algorithms to optimize the energy storage capacity, quantity, and charging/discharging time, effectively reducing the investment and operational costs of microgrids. Reference [123] utilized a multilayer perceptron to optimize the capacity and placement of energy storage, thereby improving the voltage/power distribution of the system and reducing the overall cost of the microgrid. Reference [124] applied lightweight neural networks and Q-learning methods to quantitatively evaluate the state of health (SOH) of energy storage batteries. Based on this evaluation, it optimized the energy storage capacity and charging/discharging rules, considering both the economic aspect and battery lifespan of the microgrid. This approach enhanced the operational performance of the microgrid. However, it did not consider the impact of renewable energy sources and load variations.

In recent years, the emerging deep reinforcement learning algorithms have provided new perspectives for handling complex microgrid control in terms of coordinated control and energy management of the energy storage. Reference [125] applied the deep Q-network (DQN) algorithm to implement energy storage scheduling strategies for microgrids. It also utilized deep convolutional neural networks to extract temporal information features for microgrid scheduling, aiming to maximize the operational benefits of the microgrid. Reference [126], in the context of microgrids with multiple heterogeneous battery types, employed the DQN to control the charging and discharging cycles of different battery systems, thus improving the operational efficiency of the microgrid. However, for a large number of batteries with significantly different characteristics, this method may require additional computation time. Reference [127] proposed an improved DQN model to guide the dynamic scheduling of energy storage in microgrids. It employed a Monte Carlo tree search to estimate the maximum action value expected by the DQN and embedded some scheduling rules within the DQN to guide the training process. Reference [128] utilized the DQN to develop optimal operational strategies for energy storage systems in microgrids under grid-connected and islanding modes. In the grid-connected mode, the objective is to maximize profits, while in islanding mode, the aim was to minimize the overall system’s unmet load. Apart from reinforcement learning, the existing research has demonstrated the applicability of various artificial intelligence methods for energy storage control in microgrids. Reference [129] proposed a fuzzy logic algorithm combined with an attention mechanism, which can quickly and accurately mitigate bus power fluctuations.
while protecting the energy storage system. This approach improved the economic and reliability aspects of the microgrid. Reference [130] introduced a deep belief network-based method for assessing the power quality of energy storage-enabled microgrids.

The breakthrough development of AI technology has brought transformative impacts on the development, operation, and modes of operation of energy storage in smart grids. It has also become one of the forward-looking research directions in the field of smart grids. The future prospects and research directions of AI in energy storage technology require further exploration.

5. Evaluation of the Benefits of Energy Storage System Applications

The evaluation of energy storage systems is a complex task that requires the consideration of various indicators and factors. Research in this field has focused on the electricity market and incentive policies, aiming to evaluate the economic benefits of energy storage. However, the evaluation process is far from straightforward, as it involves the analysis of numerous functions and parameters. This section mainly reviews the benefit evaluation of energy storage systems from the perspectives of evaluation indicators and evaluation methods.

5.1. Evaluation Indicators

In terms of evaluating indicators, the studies by [110–112] have identified several key functions of energy storage, such as low charge and high discharge, backup power supply, frequency regulation auxiliary services, and delayed power grid upgrading. These functions have been used to establish an economic benefit calculation method. Additionally, the study by [113] considered multiple aspects, including application demand, technology maturity, environmental protection, economy, installation location, and investment cost, when selecting evaluation indicators. The study by [114] proposed a multi-index comprehensive evaluation method that considered economy, reliability, and load smoothness. From a technical and economic perspective, the study by [115] established a numerical simulation model for the optimal operation of a wind–solar-storage independent power supply system, aiming to obtain the best power structure and energy storage capacity of the system. Moreover, some studies have compared the economics of different energy storage technologies. For instance, the study by [116] calculated the annual rate of return of vanadium battery and sodium–sulfur battery energy storage systems to maximize the revenue of spread arbitrage ancillary services. The study by [101] evaluated the economics of sodium–sulfur battery energy storage and flywheel energy storage under different operation schemes, considering low storage, high arbitrage, and frequency regulation income. In addition, the study by [117] studied the economic benefits of compressed air energy storage under different optimized dispatching operation modes and business models to maximize the benefits of the day-ahead market and the real-time balanced market.

5.2. Evaluation Methodology

When it comes to evaluation methods, there are various approaches, such as the multi-attribute decision-making method, the fuzzy evaluation method, and the gray association method. However, most of these methods are based on a single approach in practical application and are combined with other methods to achieve combined improvement. The differences among the applications of comprehensive evaluation methods in different fields are mainly reflected in three aspects: research parameters, empowerment methods, and evaluation methods. For instance, fuzzy comprehensive evaluation requires the selection of evaluation parameters and weight calculation methods, which include subjective calculation and objective calculation. The studies by [118–120] used expert subjective empowerment, but without testing the expert score. Among these, the studies by [119,120] respectively used the validity coefficient and multiplicative synthesis to achieve subjective and objective combination empowerment. However, this approach can lead to important indicators being ignored. Additionally, the selection of membership function is critical, and
common determination methods are the intuition method, fuzzy statistical method, and fuzzy distribution method [121].

6. Discussion and Conclusions

As renewable energy is being integrated into grids on a larger scale, it has become increasingly difficult to match generation, transmission, distribution, and use in space and time. This has made energy storage technology a focal point in current power grid development. In the quest for solutions, the existing literature has mostly adopted mathematical modeling, but some issues remain. When conducting smart grid energy storage planning, the following directions are worth considering in subsequent research:

(1) Urgent attention must be given to building a power-based and energy-based energy storage technology system. The characteristics of power, capacity, life, and cost of energy storage technology must be sorted out, and the complementarity and adaptability between energy storage technologies and renewable energy should be analyzed to form perfect technical standards. Different energy storage technologies have their strengths and weaknesses, and their advantages can be fully utilized to achieve hybrid energy storage.

(2) In the energy storage planning model, a bi-level planning model that combines planning and operation should be used to consider numerous factors such as new energy output uncertainty, economy, environmental protection, and technology. While this model considers the problem more comprehensively, it also makes the solution more complicated, so the focus should be on researching the bi-level planning model.

(3) Energy storage technology can be applied to the user side to achieve demand-side management, but when the scale of energy storage application in the power consumption link is large, it can have a significant impact on the peak and valley electricity prices. This can affect the economy of the energy storage device and even lead to investment recovery risks. Therefore, the overall planning and research of the scale of energy storage in the power grid should be strengthened.

(4) Intelligent energy storage management and control: Studying intelligent management and control strategies for energy storage, including optimizing the scheduling, energy flow management, and capacity planning of storage systems, should be carried out to achieve stable operation and optimal energy utilization in smart grids.

(5) Energy storage economics and policy research: Analyzing the economics of energy storage technologies, studying their cost-effectiveness, business models, and policy support mechanisms should be carried out. Additionally, the development of adaptive policies to promote the deployment and adoption of energy storage technologies and enhance the development of energy storage markets should be researched.

(6) To enhance the configuration efficiency of energy storage in smart grids, a software platform can be developed that integrates the simulation of new energy generation scenarios, energy storage system selection, the optimization of energy storage configuration, and the economic evaluation of energy storage systems. This platform will provide a theoretical foundation for practical engineering construction.


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