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# Optimization of Frequency Modulation Energy Storage Configuration in Power Grid Based on Equivalent Full Cycle Model

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**Abstract:** This paper aims to meet the challenges of large-scale access to renewable energy and increasingly complex power grid structure, and deeply discusses the application value of energy storage configuration optimization scheme in power grid frequency modulation. Based on the equivalent full cycle model and a large number of actual operation data, various energy storage technologies are technically analyzed, and the economic and environmental performance of different energy storage configuration schemes are comprehensively evaluated. On this basis, this paper puts forward a set of efficient and economical energy storage configuration optimization strategies to meet the demand of power grid frequency modulation and promote the wide application of energy storage technology. After an in-depth analysis, it is found that the optimized energy storage configuration scheme is excellent in technology, economy, and environmental protection. Specifically, in terms of technical performance, the optimization scheme has significantly improved key indicators such as energy storage efficiency, capacity and power, and response speed, which can better meet the requirements of power grid frequency modulation. Through the verification of actual operation data, it is found that the overall efficiency of the optimized energy storage configuration scheme is above 55%, which is helpful to the stability and efficiency of power grid frequency modulation. In terms of economic performance, although the initial investment cost of the optimization scheme may be high, it is found that it has good economy through the evaluation of long-term operation benefits. Considering that the energy storage system can reduce the operating cost of the power grid, improve the energy utilization rate, and achieve the optimization of cost-effectiveness in the long run, this scheme is economically feasible and attractive. In terms of environmental performance, the optimization scheme effectively reduces the negative impact on the environment by improving energy storage efficiency, reducing emissions, and optimizing resource utilization. This is not only conducive to the sustainable development of the power grid but also in line with the current global trend of promoting green and low-carbon transformation. To sum up, this paper not only provides an efficient and economical energy storage allocation optimization strategy for power grid frequency modulation but also provides a scientific basis for relevant decision-making departments. By promoting the practical application and development of energy storage technology, this paper is helpful to improve the frequency modulation ability of power grid, optimize energy structure, and reduce environmental pollution, and thus achieve the goal of sustainable energy development. The data results and in-depth analysis of this paper provide strong support for the practical application of energy storage configuration optimization scheme and also provide important reference for the further innovation and development of energy storage technology.

**Keywords:** renewable energy; power grid structure; power grid frequency modulation; energy storage configuration; equivalent total cycle

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## 1. Introduction

The power grid is facing an increasing number of issues as a result of the new energy power generation technology developing so quickly. In particular, the unpredictable and fluctuating nature of new energy power generation poses a major risk to the power grid's frequency stability [1]. Energy storage technology (EST) is becoming more increasingly significant in power grid frequency modulation (FM) in this regard. Through an ideal setup, the energy storage system (ESS) may not only reduce the variability in new energy generation and increase the power grid's reliability in terms of power supply, but it can also enhance the grid's economy and environmental protection [2]. As an effective analysis tool, the equivalent full cycle model (EFCM) can comprehensively consider various factors in the process of power grid operation, including load changes, fluctuations of new energy generation, constraints of transmission lines, etc. to accurately evaluate the performance of ESS in power grid FM [3]. The dynamic behavior and optimization approach of the ESS in the power grid FM may be thoroughly examined by the EFCM, offering theoretical support for real-world implementation [4]. Nonetheless, the optimization of ESS configuration is a multifaceted issue that encompasses the choice of energy storage apparatus type, capacity assessment, and operation plan development. The layout of ESSs is also influenced by the load characteristics of the power grid, the fluctuations in new energy generation, the restrictions of transmission lines, and the technical and financial characteristics of various energy storage devices [5]. As a result, it is essential to take all of these aspects into account and create a sensible energy storage configuration optimization strategy.

In an active distribution network, Naemi et al. (2022) investigated the best scheduling and allocation practices for mobile energy storage. In order to minimize power outage loss, this study proposed the ideal placement allocation model for mobile energy storage by analyzing its function and the grid-connected mode. Furthermore, the optimization of mobile energy storage charging and discharging was deliberated, with a focus on renewable energy consumption and enhancing power supply quality. This paper's primary contributions included a theoretical foundation and practical recommendations for the best possible scheduling and distribution of mobile energy storage [6]. Wang et al. (2022) concentrated on the complete life cycle economic assessment of energy storage. A cost–benefit model was developed based on the revenue source and energy storage cost composition. This model included options such as government electricity price subsidies, postponing investment in power grid infrastructure, and taking advantage of the arbitrage of "low storage and high production." The impact of important variables on the energy storage economy was also examined, including the price differential between peak and valley electricity, the cost of energy storage batteries, and the price of government-subsidized electricity. The primary contributions of this study include a quantitative assessment approach and an economic analysis framework for energy storage project investment decisions [7]. ALAhmad (2023) studied the optimal allocation of ESS capacity in a microgrid. A mathematical model of multi-objective optimal allocation of microgrid ESS capacity based on a Pareto-optimal solution set was proposed, which aimed at the optimal power balance, the minimum fluctuation of renewable energy, and the lowest investment cost. The main achievements of this paper provided theoretical support and practical guidance for the scientific and quantitative allocation of energy storage capacity of a microgrid [8]. Hjalmarsson et al. (2023) investigated the best configuration and scheduling for ESSs using deep learning technology. The training of the deep learning model allowed for the precise forecast of renewable energy output and power grid demand, which in turn allowed for the optimization of the ESS's charging and discharging strategy. The primary accomplishments of this paper were the development of fresh concepts and approaches for enhancing the economic advantages and operational effectiveness of ESSs through the use of artificial intelligence [9]. For the power grid FM, Chang et al.'s (2022) paper focused on the dynamic optimal allocation of EST. An ideal ESS setup approach based on real-time data was suggested, taking into account the fluctuating power grid load in real time as well as the unpredictability of renewable energy sources. The primary contributions of this study were the enhancement of the power grid

FM's response time and accuracy as well as the provision of technological support for real-time configuration strategy adjustments of ESSs [10]. Singh and Sharma (2022) discussed the best configuration for an ESS and its use in distributed energy systems. An analysis of the role that ESSs play in reducing the gap between supply and demand, increasing energy utilization rates, and enhancing dependability, was conducted, and the best energy storage allocation approach for distributed energy systems was proposed. The primary contributions of this study were to offer theoretical validation and useful recommendations for the use of EST in distributed energy systems [11]. To sum up, the research in the field of energy storage allocation optimization has made remarkable progress, involving economic evaluation, capacity optimization allocation, scheduling strategy, and other key aspects. These studies not only deepen the understanding of the role of energy storage systems in power grid frequency modulation but also put forward a series of optimization schemes with practical application value. However, despite these achievements, there are still some important challenges and problems to be solved. Firstly, the energy storage system in actual operation is restricted by many complex constraints, such as power grid structure, energy supply and demand, energy storage technology characteristics, etc. The influence of these factors on the optimization of energy storage configuration has not been fully studied. Therefore, it is necessary to further consider these practical constraints in order to propose a more accurate and practical optimization scheme. Secondly, the problem of energy storage configuration optimization often involves a lot of data and complex calculations, which need the support of efficient and real-time optimization algorithms. At present, although some algorithms have achieved good results in this field, their efficiency and real-time performance still need to be further improved to meet the needs of practical applications. In addition, with the continuous development of deep learning technology, its application in the field of energy storage configuration optimization has also received extensive attention. However, the stability and generalization ability of the deep learning model still need to be further verified and improved to ensure its stable and reliable operation in the complex and changeable actual environment. This shows that although important progress has been made in the field of energy storage configuration optimization, efforts are still needed to further study and solve the existing challenges and problems to promote the wider application of energy storage technology and further enhance the frequency modulation capability of power grid.

Thus, this paper investigates the optimization of FM energy storage arrangement in the power grid based on the EFCM. To identify the proper types and capacities of energy storage devices, the technical features and financial prices of various energy storage devices are first examined. The best course of action is then developed once the ESS's performance in the power grid FM is assessed using the EFCM. Lastly, the efficiency and applicability of the energy storage configuration optimization technique put forward in this paper are confirmed using a real-world scenario. This paper's research can lead to new concepts and strategies for optimizing the power grid FM energy storage configuration, encourage a broader use of EST in the power grid FM, and offer substantial backing for the advancement of new energy power generation and power grid construction.

## 2. Technical Characteristics and Economic Cost Analysis of ESS

### *2.1. Common Types of Energy Storage Equipment and Their Technical Characteristics*

ESSs are an indispensable part of the power system. By storing electric energy, they can cope with the fluctuation in power demand, balance power supply and demand, and improve the stability and reliability of the power system [12–14]. Common types of energy storage devices include battery energy storage, mechanical energy storage, thermal energy storage, etc. Each device has its own unique technical characteristics [15–18]. In Table 1, statistics of types and characteristics of energy storage equipment are displayed.

**Table 1.** Types of energy storage equipment and their digital technology and economic characteristics.

| Type of Energy Storage Equipment | Type | Digital Technical Characteristics | Economic Characteristics |
|---|---|---|---|
| Storage battery | Battery energy storage equipment | Intelligent management system to accurately control the charging and discharging process | Moderate cost, mature technology, and wide application |
| Lithium-ion batteries | Battery energy storage equipment | Efficient energy management system to optimize battery life | High energy density, but high cost |
| Lead-acid battery | Battery energy storage equipment | Simple charge and discharge control and low maintenance cost | Low cost, short service life, and environmental pollution risk |
| Super capacitor | Battery energy storage equipment | Fast charge and discharge technology and high power output | Long life, but relatively low energy density |
| Compressed air energy storage | Mechanical energy storage equipment | Efficient compression technology and intelligent energy management | Suitable for large-scale energy storage, but the construction cost is high |
| Gravity energy storage (such as pumped storage) | Mechanical energy storage equipment | Takes advantage of the terrain and is stable and reliable | Suitable for specific terrain and long construction period |
| Superconducting magnet energy storage | Other | Superconducting material application and lossless storage | Advanced technology, but high cost and complicated maintenance |
| Hydrogen energy storage | Other | Integration of hydrogen production, storage, and power generation | Clean and pollution-free, but the storage and transportation costs are high |
| Mobile energy storage equipment | Common use | Integrated design and light and easy to carry | Flexible application and adaptability to various scenarios |
| Thermal energy storage equipment (such as heat pump energy storage) | Thermal energy storage equipment | Efficient heat energy conversion and storage technology | Suitable for scenes with large heat demand and moderate cost |
| Distributed energy storage equipment | Common use | Modular design and easy to expand and integrate | It can operate independently and enhance the stability of the power grid |

Table 1 shows that the types of energy storage equipment are rich and diverse, and each type belongs to a broader category, which is helpful to systematically understand and compare their characteristics [19]. In terms of digital technology, modern energy storage equipment generally adopts intelligent management systems and efficient energy conversion technology, which significantly improves the performance and efficiency of energy storage equipment. Meanwhile, the modular design also makes the energy storage equipment more flexible and easier to integrate [20]. In terms of economic characteristics, there are significant differences in the cost, life, and market demand of different energy storage equipment. For example, although lithium-ion batteries have high energy density, their cost is relatively high. Lead-acid batteries, though low in cost, have a short service life and a risk of environmental pollution [21]. In addition, the application scenarios and policy support of energy storage equipment also affect its economic characteristics. Therefore, when selecting energy storage equipment, it is necessary to comprehensively consider its technical maturity, cost-effectiveness, and market prospects. To sum up, with the continuous progress of technology and market changes, the field of energy storage equipment will continue to develop, and more innovative technologies will emerge. People should pay close attention to the latest development of energy storage technology to provide more efficient, economical, and environmentally friendly energy storage solutions for practical applications. Meanwhile, policy makers and investors should also formulate appropriate policies and investment strategies according to market demand and technology development trends to promote the wide application and sustainable development of energy storage technology.

### 2.2. Economic Cost Analysis of Energy Storage Equipment

The economic cost analysis of energy storage equipment is an important link to determine its investment feasibility and economic benefits. Different types of energy storage equipment have different economic cost components and influencing factors [22].

(1) Battery energy storage:

The economic cost of battery energy storage mainly includes the purchase cost, installation cost, operation and maintenance cost, and the possible recycling cost of the battery itself. Among them, the battery purchase cost is the biggest part, which is influenced by many factors such as battery materials, production technology, scale effect, and market demand [23]. With the development of technology and the appearance of scale effect, the cost of battery is decreasing year by year. The installation cost depends on the scale and complexity of the energy storage power station. Operation and maintenance costs include regular maintenance, replacement of damaged parts, and operating costs of energy management systems [24]. Finally, although the cost of battery recycling is relatively small at present, with the improvement in environmental protection requirements, this cost may rise in the future [25].

(2) Mechanical energy storage:

The economic cost of mechanical energy storage mainly includes construction investment, operation and maintenance cost, and geographical environment cost. The construction cost of pumped storage power station is high, including reservoir construction, water delivery system, and generator set, but the operation and maintenance cost is relatively low [26]. The cost of compressed air ESS mainly depends on the purchase cost of gas storage tank, compressor, and expander. The cost of flywheel energy storage is related to flywheel material, manufacturing process, and the maintenance cost of high-speed rotation. In addition, the cost of mechanical energy storage equipment is also restricted by geographical environment, for example, pumped storage requires suitable hydrological and geological conditions [27].

(3) Thermal energy storage:

The economic cost of thermal energy storage equipment mainly includes equipment purchase cost, operation cost, and the potential loss caused by thermal energy conversion efficiency. The cost of the regenerative electric heater is affected by the electric heating conversion efficiency, heat storage materials, and cooling system. The cost of energy storage of phase change materials is related to the type of phase change materials, heat storage density, and production cost [28]. Because the energy storage density of thermal energy storage equipment is relatively low, its economic cost may be limited by the energy storage scale and energy conversion efficiency.

(4) Principles of frequency modulation:

The principle of frequency modulation is to make the carrier frequency change according to the law of modulation signal, that is, the instantaneous angular frequency of modulated signal changes with the change in baseband signal. Specifically, when the amplitude of the modulation signal becomes larger, the frequency of the carrier signal increases. However, when the amplitude of the modulation signal becomes smaller, the frequency of the carrier signal decreases. At the receiving end, the modulated signal is restored to the original signal by demodulation, which requires the use of a demodulation circuit, which can extract the frequency variation in the carrier signal, thus obtaining the original signal. The circuit to achieve frequency modulation is called frequency modulator, which is widely used in FM broadcasting, TV sound, microwave communication, phase-locked circuit, and frequency scanner. The basic requirements for frequency modulator are a large frequency shift, good frequency modulation characteristics, and a small parasitic amplitude modulation. The radio wave generated by the FM method is called the FM wave, and its basic feature is that the oscillation amplitude of the carrier remains unchanged, and the oscillation frequency changes with the modulation signal.

In the analysis of economic cost, it is also necessary to consider the whole life cycle cost of energy storage equipment, including initial investment, operation and maintenance cost, replacement cost, and decommissioning treatment cost. Meanwhile, it is necessary to comprehensively evaluate the performance parameters, service life, and the expected benefits of energy storage equipment [29].

### *2.3. Relationship Analysis between Capacity and Performance of ESS*

There is a close relationship between the capacity of ESS and its performance. This relationship is mainly reflected in the following aspects:

Firstly, energy storage capacity is an important index to measure the energy storage capacity of the system [30]. If an energy storage system has a larger capacity, it can store more electric energy. This means that it can provide power support for a longer time during the peak period of power demand or when high power output is needed. This enhancement of energy storage capacity makes the energy storage system perform better in meeting all kinds of demands of power system, whether it is for peak-valley regulation, maintaining frequency stability, or providing emergency power supply.

Secondly, the energy storage capacity also affects the charging and discharging rate of the ESS. Generally, ESSs with larger capacity have higher charge and discharge rates because they have more energy reserves to support the rapid charge and discharge process. This means that the large-capacity ESS can adjust its power output faster to meet the real-time demand of the power grid in the power scene that needs rapid response [31].

In addition, the capacity of ESS is closely related to its life cycle and energy efficiency. Generally speaking, large-capacity ESSs need to adopt more advanced battery technology and management strategies to ensure their stable performance during long-term operation. Meanwhile, these technologies and management strategies are also helpful to improve the energy efficiency of ESSs and reduce energy losses [32].

However, it is worth noting that it is not necessary to choose the ESS with the largest capacity in all cases. In fact, it is very important to choose the appropriate energy storage capacity according to the specific application scenarios and requirements. For example, in a microgrid or distributed energy system, only a small-capacity ESS may be needed to meet the demand. However, in large-scale power grid or renewable energy access scenarios, a larger capacity ESS is needed to cope with more complex power demand [33].

## 3. EFCM and Its Application in Power Grid FM

The basic principle of the EFCM is to simplify the complex power grid system into an equivalent cycle model to analyze and understand the dynamic behavior and performance of the power grid more intuitively. Based on the principle of energy conservation and constant conversion efficiency, the model abstracts all links in the power grid (such as power generation, transmission, distribution, and energy storage) into equivalent modules, and describes the operation state of the whole power grid through the energy flow and conversion relationship among these modules. When constructing the EFCM, it is necessary to make clear the main components of the power grid and the energy flow relationship among them. Then, according to the principle of energy conservation and constant conversion efficiency, each part is abstracted into equivalent modules, and the connection mode and parameters among modules are determined. These parameters usually include energy conversion efficiency, energy loss, and so on, which can be obtained through experimental data or theoretical calculation. In the process of model construction, it is also necessary to consider the FM demand of power grid. FM is an important means for the stable operation of power grid, which balances the fluctuation of supply and demand of power grid by adjusting the output of generators or the charging and discharging of energy storage equipment. Therefore, in the EFCM, it is necessary to pay special attention to the modules and parameters related to FM in order to simulate and analyze the FM performance of power grid more accurately.

According to the basic principle and construction method of EFCM, an EFCM is successfully constructed for the power grid FM analysis. The model abstracts all the links in the power grid equivalently, and considers the key parameters and variables related to the FM. Table 2 and Figure 1 shows the model construction results.

**Table 2.** Model construction results.

| Module Type | Parameter Name | Set Value |
| --- | --- | --- |
| Power generation module | Generator type | Wind power, solar energy, coal burning |
| | Maximum output | Wind power: 2 MW, solar energy: 1 MW, coal burning: 10 MW |
| | Minimum output | Wind power: 0.5 MW, solar energy: 0.2 MW, coal burning: 2 MW |
| | FM response speed | Wind power: 2 min, solar energy: 5 min, coal burning: 1 min |
| Transmission module | Transmission line impedance | 0.1 j + 0.05 Ω/km |
| | Transmission efficiency | 95% |
| Power distribution module | Load characteristic | Peak: 120%, flat peak: 100%, trough: 80% |
| | Distribution efficiency | 90% |
| Energy storage module | Energy storage type | Lithium-ion battery |
| | Energy storage capacity | 5 MWh |
| | Conversion efficiency | Charge: 92%, discharge: 90% |
| FM instruction module | FM strategy | Load forecasting and generator output forecasting based on auto regressive integrated moving average (ARIMA) |
| | FM command response time | 1 min |

```
# Model parameters
storage_capacity = 5.0  # MWh
charge_eff = 0.92
discharge_eff = 0.90
load_forecast = 12.0  # MW
generator_output = 10.0  # MW

# Calculate regulation requirement
regulation_req = load_forecast - generator_output

# Apply regulation using storage
if regulation_req > 0:
    discharge_amount = min(regulation_req, storage_capacity * discharge_eff)
    storage_capacity -= discharge_amount / discharge_eff
else:
    charge_amount = min(abs(regulation_req), storage_capacity * (1 - charge_eff))
    storage_capacity += charge_amount / (1 - charge_eff)

# Output updated storage capacity and regulation status
print(f"Storage capacity: {storage_capacity:.2f} MWh")
print(f"Regulation status: {regulation_req - discharge_amount + charge_amount:.2f} MW")
```

**Figure 1.** Model construction results.

In Table 2 and Figure 1, Table 2 shows the results of model construction in detail, including the types of each module, parameter names, and corresponding set values. In the table, the model covers many key links such as power generation module, transmission module, distribution module, energy storage module, and frequency modulation instruction module to comprehensively simulate and evaluate the operation of power system. In the power generation module, the model considers three different types of generators, i.e., wind power, solar power, and coal-fired power generation, and sets their respective maximum output, minimum output, and frequency modulation response speed. The setting of these parameters reflects the technical characteristics and operation limitations of different types of generators, which is helpful to simulate the power generation process more accurately. The transmission module pays attention to the impedance and efficiency of power in the transmission process. By setting the transmission line impedance and transmission efficiency, the model can simulate the power loss and efficiency change in the transmission process, thus more truly reflecting the actual situation of the power system. The distribution module focuses on load characteristics and distribution efficiency. By setting different load characteristics (such as peak, flat peak, and trough), the model can simulate the change in power demand in different time periods. Meanwhile, the setting of distribution efficiency also considers the energy loss in the process of distribution, which makes the model closer to reality. The energy storage module is an important link in the model. It uses lithium-ion battery as the energy storage type and sets the energy storage capacity and conversion efficiency. The existence of energy storage module enables the model to simulate the process of energy storage and release in power system, thus achieving the optimal dispatch of power system. Finally, the frequency modulation instruction module is responsible for formulating the frequency modulation strategy according to the load forecast and the generator output forecast. Here, a forecasting method based on autoregressive integral moving average is adopted, which can accurately predict the future power demand and generator output. Meanwhile, the setting of frequency modulation command response time also ensures that the model can respond to the changes in power system quickly and achieve real-time frequency modulation. Figure 1, as an intuitive display of the model construction results, contains the simulation algorithm of the model. Through this diagram, people can more intuitively understand the overall framework and running process of the model, as well as the interaction and relationship between various modules, thus helping this paper to better understand and evaluate the performance of the model.

In this paper, Matrix Laboratory (MATLAB) R2014a, a powerful software tool, is mainly used for power system modeling and simulation analysis. MATLAB, the short form of Matrix Lab, is a mathematical calculation software developed by MathWorks Company of the United States, which is widely used in calculation, algorithm development, and data analysis in various scientific and engineering fields. In the research of power systems, MATLAB has become an important tool for model construction and simulation with its excellent numerical calculation ability and rich toolbox support. Using Simulink module of MATLAB, the dynamic model of power system is built through graphical interface, including power generation module, transmission module, distribution module, and energy storage module. Simulink module library provides a wealth of predefined components, which can easily build complex power system models and set corresponding parameters for simulation. In the process of model construction, the corresponding control algorithm and simulation script are written using MATLAB programming language. These scripts can automatically execute the simulation process, collect simulation data, and carry out subsequent data processing and analysis. MATLAB's powerful mathematical calculation ability makes it possible to efficiently process a large number of simulation data, extract useful information, and further reveal the operating rules and characteristics of power system. In addition, MATLAB also provides a wealth of visualization tools to display the simulation results intuitively in the form of charts, curves, and so on. This enables this paper to better understand and analyze the behavior of power systems, find potential problems, and propose corresponding optimization measures.

## 4. Optimization Method of FM Energy Storage Configuration in Power Grid

The optimization of FM energy storage configuration in power grid is a comprehensive problem involving many aspects, aiming at improving the FM performance, economic benefits, and environmental benefits of the power grid through the rational configuration of ESS.

Firstly, the choice of energy storage type is very important. Different types of energy storage have different technical characteristics and economic performance, so it is necessary to make a reasonable choice according to the characteristics and needs of the power grid. For example, lithium-ion batteries have the advantages of high energy density, fast charge and discharge, and long life cycle and are suitable for application scenarios requiring fast response and high energy density. Pumped storage has the characteristics of large energy storage capacity and low operating cost and is suitable for large-scale energy storage and long-term dispatching scenarios.

Secondly, the determination of energy storage capacity is also a key step in the optimization process. Through the bi-level optimization model, the optimal energy storage capacity can be determined by comprehensively considering the annual operating cost of the system and the equivalent annual investment cost of energy storage. In this process, it is necessary to fully consider the load characteristics of power grid, FM demand and the technical and economic performance of ESS to achieve the reasonable allocation of energy storage capacity.

Economic evaluation and cost optimization are also an important part in the optimization of FM energy storage configuration in power grid. Through the economic analysis of the procurement, operation, and replacement of ESS, the whole life cycle cost can be reduced, and the economic benefit can be improved. In addition, people can increase the income of ESS and further improve its economy by participating in power market transactions and obtaining subsidies.

Finally, environmental benefit is also an important factor to be considered in the optimization of FM energy storage configuration of the power grid. By selecting low-carbon and environmentally friendly energy storage technologies and equipment, carbon emissions and environmental pollution can be reduced, and the green and low-carbon development of power grid can be promoted. This will not only help to meet the challenge of global climate change but also enhance the sustainable development capacity of power grid. In Table 3, the specific optimization scheme design is shown.

**Table 3.** Optimization scheme design.

| Optimization Content | Specific Optimization Design |
|---|---|
| Energy storage type | Lithium-ion battery is selected as the main energy storage type. |
| Energy storage capacity | It is determined to be 5 MWh to balance FM demand and cost-effectiveness. |
| Energy storage layout | The centralized energy storage power station is set at the key nodes and load centers of the power grid. |
| FM strategy | Based on real-time load and power generation forecasting, accurate FM strategy is formulated. |
| Economic optimization | 1. Purchase in bulk to reduce purchasing cost<br>2. Optimize operation and maintenance strategy and reduce operation and maintenance expenses<br>3. Extend the service life of the equipment and reduce the replacement cost<br>4. Explore participation in electricity market transactions to increase economic benefits |

**Table 3.** *Cont.*

| Optimization Content | Specific Optimization Design |
| --- | --- |
| Improvement in environmental benefits | Choose environmentally friendly materials and technologies to reduce carbon emissions |
| Intelligent technology application | 1. Use intelligent algorithm to solve optimization problems<br>2. Establish an intelligent monitoring system to monitor the running state of energy storage in real time |
| Risk and uncertainty management | 1. Formulate risk response strategies to deal with load changes and equipment failures<br>2. Establish a regular evaluation mechanism and dynamically adjust the optimization scheme |

## 5. Evaluation of Energy Storage Configuration Optimization Scheme

### *5.1. Technical Evaluation*

The technical evaluation of energy storage configuration optimization scheme is very important, which comprehensively examines the feasibility and performance of the scheme at the technical level. The evaluation process covers many dimensions, such as energy storage efficiency, capacity and power, response speed and flexibility, and life cycle and safety, to ensure that the optimized ESS is not only technically feasible but also has excellent performance, which can fully meet the power grid demand and achieve efficient and stable operation. The specific technical evaluation results are shown in Figure 2.

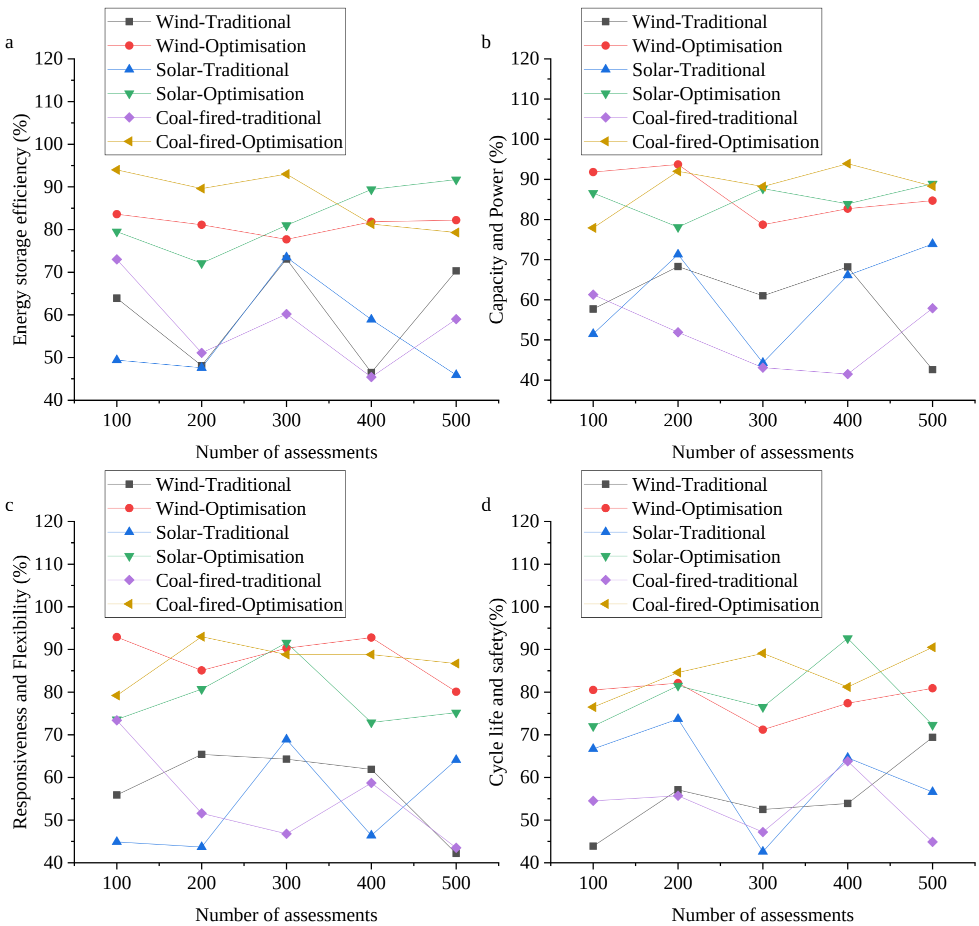


**Figure 2.** Technical evaluation results ((**a**) is energy storage efficiency, (**b**) is capacity and power, (**c**) is response speed and flexibility, and (**d**) is life cycle and safety).

In Figure 2, the equipment before and after the optimization of energy storage configuration under three energy storage modes is technically tested and evaluated. After evaluation, it shows that the optimized equipment has great advantages in energy storage efficiency, capacity and power, response speed and flexibility, and life cycle and safety, and its overall efficiency value is above 70%, while that of the traditional mode is below 72%. It shows that the configuration optimization strategy designed in this paper has achieved a great technical breakthrough.

### 5.2. Economic Evaluation

The economic evaluation of energy storage configuration optimization scheme mainly focuses on the investment cost efficiency, operation and maintenance, expected income, and comprehensive economic benefits of the scheme. In Figure 3, the evaluation results of the optimized configuration in this paper are shown.

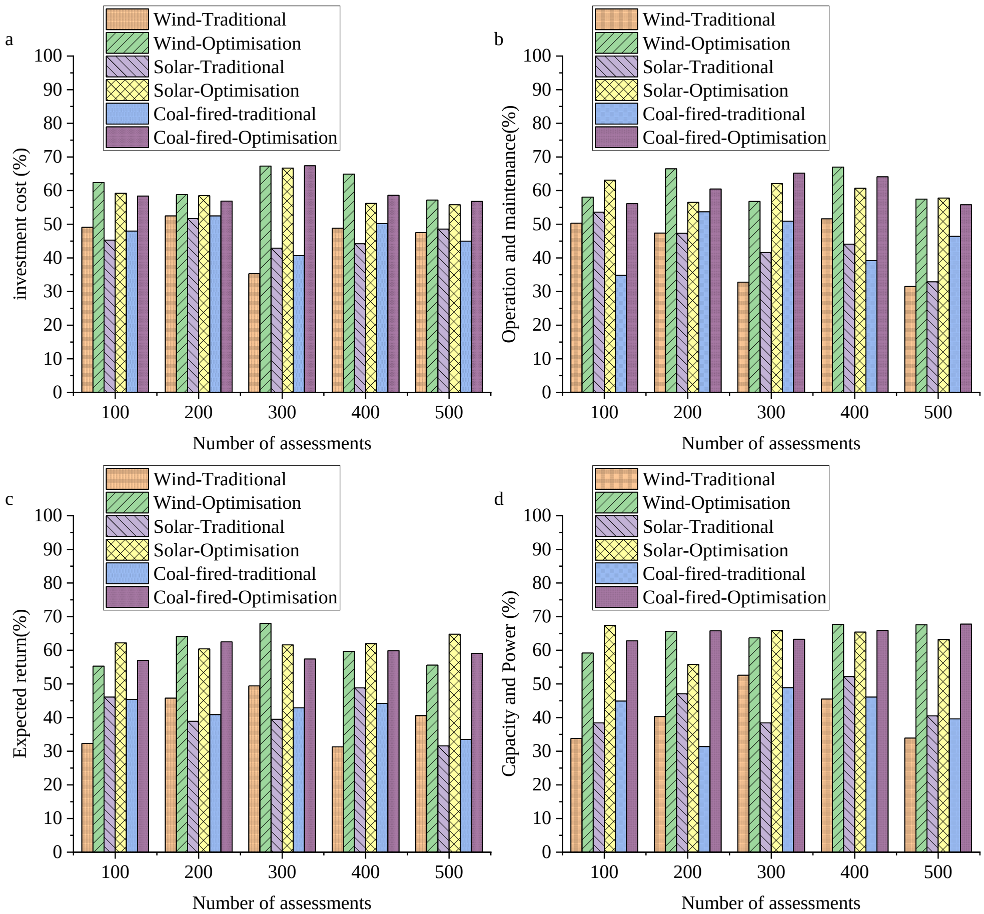


**Figure 3.** Economic evaluation ((**a**) is investment cost, (**b**) is operation and maintenance, (**c**) is expected income, and (**d**) is comprehensive economic benefit).

In Figure 3, this paper tests and evaluates the equipment before and after the optimization of energy storage configuration under three energy storage modes. Through the evaluation, it is found that the efficiency of the optimized configuration is above 55% in all aspects of economy, while the efficiency of the traditional configuration is below 45% in all aspects of economy, which shows that the optimized configuration has also achieved a great breakthrough effect in economy.

### 5.3. Environmental Protection Assessment

The environmental protection evaluation of energy storage configuration optimization scheme is very important, which deeply considers the potential impact of the scheme on the environment and resource consumption. The performance of each scheme in emission control, resource utilization efficiency, ecological impact, and sustainability is evaluated in detail, aiming at selecting an efficient and environmentally friendly energy storage configuration scheme to achieve a win–win situation of economic benefits and environmental protection. The results of the environmental protection assessment are shown in Figure 4.

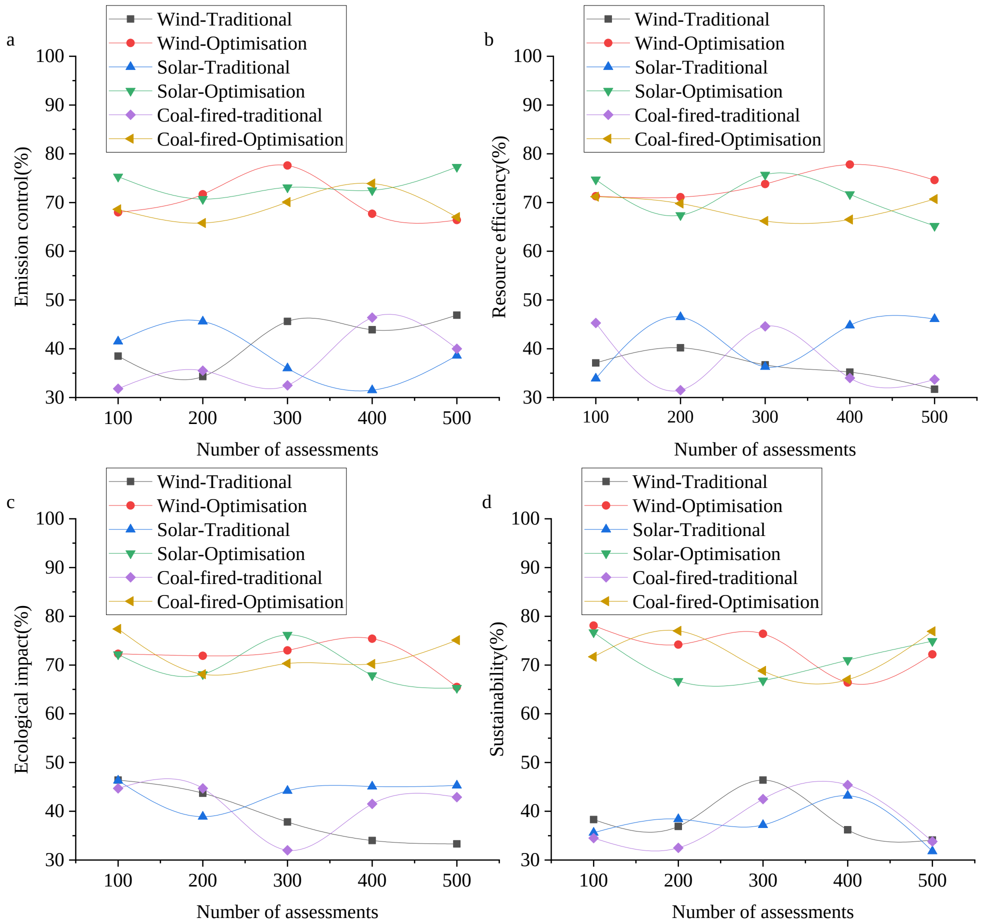


**Figure 4.** Environmental protection assessment ((**a**) is emission control, (**b**) is resource utilization efficiency, (**c**) is ecological impact, and (**d**) is sustainability).

In Figure 4, this paper tests and evaluates the environmental protection of the equipment before and after the optimization of energy storage configuration under three energy storage modes. Through the evaluation, it is found that the efficiency of the optimized configuration is above 65% in all aspects of environmental protection, while the efficiency of the traditional configuration is below 47% in all aspects of economy, which shows that the optimized configuration has also achieved a great breakthrough effect in economy.

Compared with the research of Tiwari and Kumar (2023) [34], this paper has unique contributions and importance in many aspects. Firstly, in terms of model construction, this paper adopts a more comprehensive and detailed power system model, including power generation, transmission, distribution, energy storage, and frequency modulation instructions to simulate and evaluate the operation of the power system more accurately. In contrast, this paper only focuses on a specific aspect of power system, such as energy storage system or transmission network, but fails to fully consider the complexity of the whole system. Secondly, in the aspects of simulation analysis and data processing, this paper adopts advanced algorithms and tools, such as Simulink module of MATLAB and powerful mathematical calculation ability to reveal the operating rules and characteristics of power system more deeply. This enables this paper to find some potential problems that have not been noticed before and put forward corresponding optimization measures. In contrast, the above research may be limited by tools or methods, and the information in the data cannot be fully mined and utilized. Finally, in terms of the application value of the research results, this paper not only pays attention to the theoretical analysis, but also pays attention to applying the results to practical engineering problems. Through cooperation and communication with experts in other fields, the research results are transformed into practical solutions, which provides strong support for the optimization and the upgradation of power systems.

## 6. Conclusions

With the vigorous development of renewable energy and the increasingly complex power grid structure, energy storage technology plays an increasingly important role in the power grid with its unique frequency modulation ability, which has aroused widespread concern in the industry. However, how to optimize the energy storage configuration scheme to achieve the comprehensive improvement in technical performance, economic benefit, and environmental protection is still a key problem to be solved urgently. This paper is devoted to providing a set of efficient and economical energy storage configuration optimization strategies for power grid frequency modulation through systematic and comprehensive analysis. In this paper, the equivalent full cycle model is adopted, and combined with practical cases, different energy storage configuration schemes are deeply discussed. Firstly, from the energy storage efficiency, capacity and power, response speed, and other dimensions, various energy storage technologies are analyzed technically, and their applicability and potential advantages in power grid frequency modulation are clarified. Secondly, the economic factors such as investment cost, operation and maintenance cost, and expected income are comprehensively considered, and the energy storage configuration scheme is comprehensively evaluated to find the most economical configuration scheme. Finally, the environmental protection performance of energy storage configuration scheme is also concerned, and it is evaluated from emission control, resource utilization efficiency, and sustainability. Through comparative analysis, it is found that the optimized energy storage configuration scheme has obvious advantages in many aspects. Specifically, it is superior to the traditional configuration in energy storage efficiency, capacity and power, response speed and flexibility, life cycle and safety, etc. The efficiency values of the traditional mode are generally lower than 72%, while the overall efficiency values of the optimized configuration in this paper remain above 70%. Meanwhile, the optimized configuration scheme also performs well in economy, and the efficiency values in all aspects are over 55%, while the efficiency values of traditional configuration are mostly lower than 45%. In addition, in terms of environmental performance, the optimized configuration scheme also shows obvious advantages, and the efficiency values of all aspects are over 65%, while the efficiency values of traditional configuration are mostly lower than 47%. Although some achievements have been made in this paper, people still need to recognize its limitations. For example, in the process of data collection and processing, it may be limited by the availability and accuracy of data, which may have a certain impact on the evaluation results. Future research can further expand data sources and adopt more advanced evaluation methods to improve the accuracy and reliability of evaluation results. Meanwhile, more factors, such as policy environment and market demand, can be considered to evaluate the optimization effect of energy storage configuration scheme more comprehensively.

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