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Research on Optimization Strategies of New Energy Storage Technology Based on Desert Environment

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Abstract. Chinese desert areas are rich in solar and wind energy resources, making them core areas for new energy development. However, extreme climate, geographical constraints, insufficient grid access and energy volatility pose higher demands on energy storage technology. Therefore, this paper will explore the optimization strategy of new energy storage technology in desert environment based on the actual situation. Based on national policy orientation, the current state of technology and the characteristics of the desert environment, this paper proposes an optimization strategy system covering technology paths, industrial chain coordination, policy mechanisms and ecological integration, and verifies its feasibility through case studies. This research results has shown that through material innovation, intelligent management and ecological synergy, the efficiency of new energy storage in deserts, the efficiency of energy utilization, and economic efficiency can be significantly improved. It is of great significance for promoting the coordinated development of ecological governance and regional economy, promoting the green transformation of energy, ensuring energy security, and facilitating the realization of the "dual carbon" goals.

Keywords: New energy generation, Energy storage technology, Application optimization, desert environment

1. Introduction

The development of new energy in desert areas is a key direction for China's energy transition. By the end of 2025, China plans to build large-scale wind and photovoltaic power bases in deserts, Gobi and wastelands, with the proportion of non-fossil energy generation in the country reaching about 39% and the demand for energy storage surging [1]. However, the high temperatures, sand and dust, and large temperature differences between day and night in the desert environment have led to a decline in the efficiency of energy storage systems and a shortened lifespan. This study aims to explore how technology optimization and model innovation can be combined with literature research and current situation analysis to solve the adaptability problem of energy storage technology in desert environments and provide a theoretical basis for its large - scale application.

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2. Current situation and challenges of energy storage technology in desert environments

2.1. Current situation analysis

The current mainstream energy storage technologies are mechanical energy storage and electrochemical energy storage.

Mechanical energy storage has improved adaptability, represented by pumped storage and compressed air energy storage [2]. Although pumped storage is a mature technology with a low cost (the lowest cost per kilowatt-hour), it is difficult to be applied in desert areas because of geographical limitations. Compressed air energy storage, which can store gas in salt caverns or abandoned mines, has high adaptability.For instance, the 1 million kilowatt project in Ordos and the 300MW project in Yingcheng, Hubei, have achieved an energy conversion efficiency of 70%, making it a preferred solution for large-scale energy storage in deserts [3].

Electrochemical energy storage dominates the market, with lithium-ion batteries taking the lead due to high energy density and mature technology, but the high-temperature environment in deserts is prone to thermal runaway risks and requires optimization of thermal management systems [4]; Driven by policy and market, the "14th Five-Year Plan Implementation Plan for the Development of New Energy Storage" of the state clearly states that new energy storage will enter the large-scale stage in 2025 [5], with a focus on supporting the construction of energy storage facilities for large-scale wind and solar bases in deserts and Gobi, developing long-duration energy storage technologies such as sodium-ion batteries and flow batteries, and promoting the "wind-solar-storage integration" model [6]. Local policies such as the mandatory energy storage requirement in Ningxia (15%-20%×4h) and differentiated subsidies in the three North regions (such as 0.3 yuan /kWh) have stimulated the implementation of desert energy storage projects.

2.2. Core challenges

The main challenges are in the following aspects: technology itself, cost chain, policy and ecology.

First, in terms of technology, there will be adaptation bottlenecks, specifically, insufficient environmental tolerance, high temperatures (> 40 ° C) causing a 30% reduction in the cycle life of lithium-ion batteries and an accelerated evaporation of the electrolyte; Dust covers the heat dissipation channels of photovoltaic panels and energy storage devices, reducing efficiency by 8%-12%. Long-duration energy storage technology is not economically viable, flow battery systems are still more expensive than lithium batteries, and electrolyte transportation and maintenance costs are high in desert areas [7].

Secondly, there is pressure in terms of the industrial chain and cost. The self-sufficiency rate of lithium resources is only 40%, and it relies on imports. The sodium-battery supply chain has not yet formed a closed loop, and the capacity of key materials (such as hard carbon anodes) is insufficient. Concerns about overcapacity, an energy storage capacity utilization rate of only 65% in 2024, some companies facing overstocked inventories, and the long payback period of desert projects (about 8 - 10 years) have exacerbated financial pressure.

In addition to the above two aspects, there are also deficiencies in policies and standards, unstable subsidy mechanisms, and frequent adjustments to energy storage subsidy policies in some provinces, such as Gansu's cancellation of some electricity price subsidies in 2024, which led to a 5%-8% decline in project returns. The lack of uniform technical standards and the absence of national standards for weather resistance tests and fire protection grades of energy storage equipment in desert environments restricts the replication of cross-regional projects.

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Finally, there is the problem of balancing ecology and safety, insufficient coordination in ecological restoration, and some projects neglect the restoration of vegetation under the slabs, resulting in local soil compaction; The recovery rate of silicon material from decommissioned energy storage facilities is less than 30 percent, which may cause secondary pollution. Fire prevention pressure, the dry desert environment increases the risk of lithium electric heating runaway, and the response time of existing fire protection systems (> 30 seconds) makes it difficult to meet the requirements of high-temperature scenarios.

3. Optimization strategy for energy storage technology in desert environments

The main optimization strategies include technological path innovation, cost control and industrial chain synergy, policy business model design, ecological integration and intelligent management.

First, in terms of technological path innovation, there is compressed air energy storage optimization: constructing gas storage facilities by using desert salt caverns or abandoned gas fields to cut down site-selection costs. For example, Ordos plans to consume green electricity through salt cavern compressed air projects, with a long-term plan of 1 million kilowatts. Improved compatibility of flow batteries: Development of high-temperature resistant electrolytes and modular designs, such as vanadium flow batteries maintaining efficiency of over 90% at 40 ° C. Hybrid energy storage systems: Combining lithium-ion batteries (fast response), flow batteries (long-term peak shaving) and supercapacitors (high power density) to achieve short-term frequency regulation and long-term peak shaving in desert microgrids.

Secondly, through cost optimization such as cost reduction on a large scale: by vertically integrating the supply chain (such as self-sufficiency in lithium resources) and automated production, and by domesticating sodium-ion anode materials (such as hard carbon), the cost of electrochemical energy storage can be reduced. It is expected that the cost of lithium batteries will be reduced to less than 0.5 yuan per watt - hour by 2025, or through industrial - chain synergy such as waste resource utilization: recycling silicon materials from decommissioned desert photovoltaic panels for the manufacturing of energy-storage equipment to form a “photovoltaic - storage - recycling” circular economy.

In addition, policy and business model design can also be an effective way to achieve this goal, such as the linkage of subsidies and carbon taxes: providing subsidies per kilowatt-hour (such as 0.3 yuan/kWh) for desert energy storage projects and converting the amount of sand fixation (1 ton/hectare) into carbon quotas to increase project revenue by 12%-15% [1]. Define the rules for energy storage to participate in the electricity spot market and ancillary services market, and ensure long-term benefits through capacity pricing mechanisms. EPC model promotion: Work with EPC vendors with photovoltaic experience to optimize the design and grid connection process of energy storage systems and shorten the construction period.

Finally, in line with the trend of the era of large models, the "photovoltaic + sand control" model was adopted: The Jiuduntan project in Wuwei, Gansu Province, increased the vegetation coverage rate from 3% to 22% by planting drought-resistant plants under the panels, and the annual sand fixation capacity was 1.2 million tons. With AI dynamic optimization: Applying digital twin technology to predict the cycle of dust coverage, optimizing the scheduling of cleaning robots, and reducing operation and maintenance costs by more than 30%. To achieve the purpose of optimization.

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4. Case study

4.1. Ordos wind-solar-hydrogen-storage integrated project

The project is planned to be equipped with 16 million kilowatts of renewable energy capacity and 400,000 tons of green hydrogen annually. Through the synergy of compressed air energy storage and electrochemical energy storage, the rate of wind and solar power curtailment has been reduced from 20% to less than 5%. Through the under-board drip irrigation system, the coverage rate of forage planting has reached 35%, and it has driven an average annual increase of 4,000 yuan for farmers and herdsmen, verifying the effectiveness of the multi-technology synergy.

4.2. Zhangjiakou 100-megawatt compressed air energy storage demonstration project

Using non-combustion technology, the system efficiency reached 70%, and the unit construction cost was reduced to 5,000 yuan/kW, approaching the level of pumped storage, providing a reference for large-scale application in desert areas.

5. Future development direction

New energy storage in desert environments needs to focus on technological adaptability as the core, combined with policy incentives and business model innovation, with the "technology-industry - policy-ecology" four-dimensional synergy as the core, and focus on breaking through the following directions.

5.1. Material innovation

China's desert energy storage material innovation is centered on "weather resistance, safety and economy", and through multi-technology path collaboration and industrial chain integration, gradually address the technical bottlenecks in extreme environments.

Research and development of high-temperature - resistant and anti - aging materials: Solid electrolytes and nano-coatings. In response to the issues of high temperatures (> 40 °C) and sand and dust coverage in the desert, CTS (cell to System) integration technology is adopted to reduce modular structures and increase energy density. Meanwhile, nano-hydrophobic coatings are used to enhance the resistance of battery surfaces to sand and dust. Develop thermal radiation reflective coating materials and windbreak protection materials in combination with a centralized cooling system to effectively reduce the impact of equipment temperature fluctuations on performance. Research on wide temperature range electrolytes, by improving the electrolyte formula to enable the vanadium REDOX flow battery to operate stably within the range of -30° C to 50° C, and solve the problem of efficiency degradation in both cold and hot environments.

Innovations in liquid cooling and thermal management materials: Optimized liquid cooling systems, integrated cold and heat storage materials, and efficient thermal management in environments with temperature differences > 20° C through external active balancing modules and multi-level pipeline valve designs, reducing maintenance time by 50%. Research on molten salt heat storage technology, taking advantage of the high heat storage density (> 750 MJ/m³) and wide temperature range characteristics of molten salt materials to achieve continuous power supply day and night and mitigate the negative ecological impact of evaporation recovery at night.

Developing high-temperature resistant solid electrolytes: Resolving the contradiction between ion conductivity and interface impedance, using mechanical ball milling + hot pressing sintering

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process, controlling the particle size of LPSCl and reducing grain boundary resistance; Develop a "positive electrode - electrolyte - negative electrode" gradient interface layer to reduce interface impedance; Develop a new type of thiophosphate or halide electrolyte with a target room-temperature conductivity > 20mS/cm and thermal stability > 500 ° C. To address the high cost of large-scale preparation, introduce dry coating technology to reduce the cost of preparing sulfide electrolyte membranes and increase production capacity; Recycling of waste materials, establishing waste recycling lines, and recovering metals such as La and Zr through acid leaching - precipitation to improve material utilization. To address the issue of insufficient high-temperature cycling stability, develop UV-cured prepolymers to form a solid electrolyte layer in situ inside the battery, and improve capacity retention after 1000 cycles; The use of phase change materials (paraffin/graphene composite) in conjunction with microchannel liquid cooling plates for heat dissipation enables the solid-state battery module to have a temperature rise of less than 5 ° C in desert environments.

5.2. Smart management

In response to the multi-source heterogeneous data, complex working condition fluctuations and multi-objective optimization requirements faced by desert energy storage systems, AI algorithms significantly improve system efficiency and reliability through a "predictive - decision-making - control" closed-loop mechanism [7].

Dynamic optimization core architecture: Multi-modal data fusion, integration of multi-source data such as weather stations (wind speed, irradiance), energy storage devices (SOC, temperature), and power grids (electricity price, load), and cross-system data privacy sharing through federated learning; Edge computing nodes deploy AI edge computing modules at desert base stations to process terabyte-level data streams in real time with latency < 10ms. Build predictive models to optimize decision-making, predict photovoltaic output (error < 5%) and load demand in the next 24 hours, simulate the impact of extreme weather (sandstorms, high temperatures) on energy storage systems, and generate enhanced training datasets; Deep reinforcement learning, constructing Markov decision processes, with the goal of minimizing cost per kilowatt-hour, dynamically adjusting charge and discharge strategies; Multi-objective particle swarm optimization, balancing economic, safety and ecological benefits, improves the efficiency of Pareto frontier solution by 40%. Establish a 1:1 virtual image of the energy storage system, implement strategy pre-validation through digital threads, and dynamically adjust control parameters in combination with fuzzy logic to maintain the battery temperature at 25±3 ° C in the high-temperature desert environment.

Breaking through technical challenges: solving data quality and computing power bottlenecks, lightweight model, using knowledge distillation technology to compress the BERT model to 1/10 scale, adapting to edge device computing power; Abnormal data repair, reconstructing missing or noisy data based on VAE (Variational Autoencoder). To solve the problem of insufficient model generalization ability, transfer learning is used to adapt the model trained in the eastern region to desert scenarios through Domain Adaptation, reducing the demand for labeled data by 80%; Physical information embedding, adding electrochemical equation constraints to the neural network loss function to improve prediction reliability under extreme conditions. To address the contradiction between security and real-time performance, federated learning + blockchain ensures secure sharing of multi-agent data; Hierarchical decision-making architecture, high-frequency control (MS-level) is executed by local rule bases, and low-frequency optimization (minute-level) is decided by cloud AI.

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5.3. Ecosystem synergy

In the development of new energy in desert areas, achieve ecological synergy optimization of the trinity of "energy production-ecological restoration-improvement of people's livelihood".

Establish a coupling mechanism for ecological restoration and energy production: Regulate the microenvironment of photovoltaic panels, reduce surface wind speed (30%-50%) and evaporation (20%-30%) through the physical shading effect of photovoltaic panels, create a microclimate conducive to vegetation growth, and achieve the dual goals of photovoltaic power generation and sand fixation. Vegetation restoration drive, project revenue feeds back to the direct restoration of ecological engineering, and a certain proportion of power generation revenue is used for the construction of drip irrigation facilities to increase the vegetation coverage under the panels. Promote biodiversity by using grass grid sand barriers (1×1 m) and plant sand fixation, and attract birds and insects to return after vegetation coverage, forming small ecological chains. Comprehensive management of soil erosion, reducing wind speed and surface runoff through photovoltaic arrays, reducing soil erosion, and improving soil organic matter with soil cover and microbial organic fertilizer.

To achieve economic benefits through industrial integration: Build a "photovoltaic + agriculture/animal husbandry" circular economy, interboard intercropping of high-value crops such as tomatoes and potatoes, complementary livestock and photovoltaic farming of poultry such as chickens, ducks and geese, and build high-end beef cattle breeding bases to boost the income of farmers and herdsmen.Carry out eco-tourism and science popularization education. Build facilities such as observation towers and peony gardens in the photovoltaic base in combination with the desert landscape, and construct ecological landscape areas to attract tourists, thus achieving the transformation from "sand, land and wilderness" to "green, beautiful and prosperous". Integrate carbon sink trading with green finance, and incorporate ecological benefits into the carbon trading market by converting sand fixation into carbon quotas (1 ton/hectare≈0.5 ton CO_2 equivalent) to increase revenue.

Through these strategies, desert energy storage technology is expected to reduce the cost per kilowatt-hour by 30 percent by 2030, supporting China in building the world's largest integrated wind-solar-storage energy base.

6. Conclusion

This paper focuses on the optimization strategy for new energy storage technology in the desert environment. Firstly, it analyzes the current situation and challenges of energy storage technology in desert areas.Mainstream energy storage technologies include the pros and cons of mechanical and electrochemical energy storage in desert environments. For example, pumped storage is low in cost but is greatly influenced by geographical conditions; Lithium-ion batteries are prone to thermal runaway in desert environments. The challenges include technical bottlenecks, cost pressures in the supply chain, and the lack of policy standards. Therefore, to address these issues, this paper presents optimization strategies covering technological path innovation, cost control and industrial chain synergy, ecological integration and intelligent management. The feasibility of the optimization strategy is confirmed through the analysis of existing cases.

However, this study has certain limitations. On the one hand, scarf studies have been based on sufficient empirical research, mostly theoretical and case studies. On the other hand, the limited number of references in the research process may result in an insufficiently comprehensive perspective.

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In view of the above limitations, future research may consider strengthening empirical studies, collecting more actual operation data in desert areas, and conducting in-depth analyses of the practical effects of different optimization strategies in various complex desert environments. At the same time, extensively review more relevant domestic and foreign literature, track the latest research progress of energy storage technology, and further improve the optimization strategy system of new energy storage technology.

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