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Original Research

Multi-Dimensional Exploration of Pumped Storage to Solve the Challenges in New Power System Transformation under the "Dual Carbon" Target

Cong Feng[1, 2, 3]*, Qi Guo[1, 4], Qian Liu[1, 4], Feihong Jian[1, 4]

[1]Hubei Key Laboratory of Construction and Management in Hydropower Engineering, China Three Gorges University, Yichang 443002, China
[2]College of Economics and Management, China Three Gorges University, Yichang 443002, China
[3]College of Civil Engineering, Henan Polytechnic Institute, Nanyang 473000, China
[4]College of Hydraulic and Environment Engineering, China Three Gorges University, Yichang 443002, China

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Abstract

Driven by the "dual carbon" target, the new power system transformation is facing challenges in system stability and economy brought by the new energy's multi-temporal and spatial uncertainties. Pumped storage is a good response to these challenges by providing multiple-time-scale energy storage to improve the grid security level and power energy quality and achieve economical and energy–saving operation of the power grid. Starting by analyzing the main challenges faced during the power system transformation process, this study summarizes the current research status of pumped storage in China in terms of functional application scenarios, technological innovations, economic benefits, and environmental benefits. Then, a multi-objective optimization model of the combined wind-photovoltaic-thermal-pumped storage system is developed to provide preliminary ideas for addressing the current challenges. Finally, we discuss the scientific issues that need to be focused on in order to maximize the benefits of pumped storage from the technical, economic, and environmental perspectives and propose future research directions based on international experience. The results show that the established model can effectively improve the economic return of the system and reduce the volatility of the power grid connection. At the same time, it can promote the efficient utilization of new energy, and the model has high feasibility. In the future, we should carry out in-depth research on the principles of pumped storage participation in multi-energy complementation across multi-temporal and spatial scales, vigorously promote technological innovation and upgrading, explore the market-oriented revenue return mechanisms reflecting the value contribution of pumped storage, and strengthen the energy and environmental management of pumped storage power stations. The research in this paper takes into account both macro and micro-level

*e-mail: fengcong@hnpi.edu.cn

scientific issues and provides ideas for efficiently addressing key challenges in the new power system transformation.

Keywords: New power system, pumped storage, multi-energy complementation, international comparison, multi-dimension analysis

Introduction

In 2021, the United Nations issued a "red alert" for the climate crisis in its published climate change assessment report. In order to achieve global carbon neutrality earlier, a profound transformation has taken place in the energy systems of countries around the world. As the biggest country in energy production and consumption, China plays a significant role in addressing the issue of global carbon emissions. In September 2020, China brought forth the "3060 dual carbon" target. In December of the same year, China restated that by 2030 non–fossil energy will have decreased its percentage in primary energy consumption to around 25%. Driven by the "3060 dual carbon" target, the power system has experienced and will continue to promote in–depth reform, gradually transitioning to the new power system dominated by new energy.

As new energy takes up an increasing percentage of the installed capacity and electricity generation, grid connection capacity from thermal power has been decreasing. New energy resources represented by wind and solar power are gradually emerging as major sources of electricity generation. However, because their energy density is lower than that of traditional power sources, they have the disadvantages of low tolerance to extreme weather conditions, inherent intermittency, and strong random fluctuations. Without corresponding regulating power sources, the power grid will face severe challenges in balancing electricity and integrating new energy resources. All these challenges have a deep impact on the integral security, stability, and economy of the power grid [1, 2]. To meet the demand for large–scale new energy grid connections, there is an urgent demand now for lots of regulating power to provide high-quality ancillary services. So pumped storage, as a representative regulating power source, has seen its scale expand continuously, rising to be a mainstay of flexible regulation. Nevertheless, with the transformation and upgrading of the power system, pumped storage will face higher requirements and challenges in terms of playing key functional characteristics with the grid-connected operation of new power sources, enhancing their absorption, and promoting the stability and reliability of the power grid. In addition, its own sustainability is also a key concern.

Previous studies have assessed the development of new energy units combined with pumped storage from different perspectives. These integrated systems can address the inherent volatility and unpredictability of new energy generation and optimize the overall system benefits. Tian et al. established a grid-connected wind-photovoltaic-battery-pumped storage combined generation system optimal scheduling model with the optimization objective of minimizing the total operating cost in response to user electricity demand and renewable energy generation. Then, three different forms of energy storage were simulated and compared to determine the optimal combination [3]. Wu et al. established a day-ahead optimal scheduling model of a wind-thermal-storage bundled transmission system aiming at the lowest operating cost. A variety of indicators were integrated to evaluate the flexibility of the day-ahead optimal dispatch of different types of pumped storage units [4]. With the objective of maximizing the monthly operating profit of the energy system, Naval et al. established an optimal hourly management model combining photovoltaic, wind power, and pumped storage units to ensure the safety and stability of the power system with a high proportion of renewable energy generation [5]. Zhang et al. constructed a multi-benefit economic evaluation model for a hybrid wind- photovoltaic-pumped storage power generation system under different installed capacity scenarios and considered the impact of carbon emissions in the social and environmental benefit indices [6]. Ma et al. conducted a techno-economic optimization of a multi-energy system with the objectives of maximizing power supply reliability and minimizing system life cycle costs and used genetic algorithms for simulation and optimization of the system [7].

The studies in the above literature have mainly explored the application of pumped storage in the joint operation of multi-energy systems, but they have mostly focused on a single or a few objectives, such as economic benefit optimization and power leveling, with a relative lack of environmental benefit analysis. Meanwhile, previous studies mainly focus on model optimization at the micro level, with limited research breadth and a lack of systematic analysis of the current situation and development of pumped storage in the industry macro environment. Based on the above situation, this paper uses a combination of quantitative and qualitative methods to analyze the new energy multi-temporal and spatial uncertainty challenges in the new power system transformation, summarize the current development of pumped storage in China, and propose a multi-objective optimization model of the combined wind-photovoltaic-thermal-pumped storage system as a preliminary solution to the challenges. Then, the scientific issues that need to be focused on for pumped storage to be effective in various benefits are discussed and analyzed in comparison with international cases in order to look forward to the future development direction of pumped storage in China. The research in this paper takes into account both macro and micro-level scientific issues and analyzes the development path of pumped storage from multiple perspectives of technology, economy, and environment, which increases the breadth of the research and provides support for efficiently solving the key challenges of the new power system.

Material and Methods

In order to provide a multi-dimensional direction reference for the future development of pumped storage in China, it is necessary to have a clear understanding of the challenges in the new power system transformation and the development status of pumped storage, as well as to carry out multi-objective optimization solutions of the joint system, and then systematically expand the discussion on the scientific issues faced in the future and the international experience to learn from. Based on this research purpose, this paper adopts a combination of quantitative and qualitative analysis methods as follows.

The Method of Data Statistical Analysis

Data statistical analysis is a research method used to analyze phenomena by collecting, organizing, and analyzing data systematically. In this study, in order to analyze the multi-temporal uncertainty characteristics of new energy sources such as wind and solar, we have collected hourly-level electric load, wind power, and photovoltaic output data from January to December 2022 in Belgium, as well as the distribution data of wind and solar resources in China. The multi-temporal scenarios are visualized and mapped in order to obtain their overall fluctuation trends and distribution characteristics. In addition, this study also collects the key technical parameters of eight common energy storage methods as well as the installed capacity, construction growth rate, and geographic distribution data of pumped storage power stations in China over the years in order to quantitatively demonstrate the technical advantages and scale status of pumped storage.

The Method of Comparative Analysis

Comparative analysis is a method used to find commonalities and differences by comparing the characteristics, modes, and effects of different things. In this study, some pumped storage power stations in operation and under construction in the United States, the United Kingdom, and Japan are selected as typical cases. By analyzing their construction technologies, operation modes, and environmental impacts, the advanced experiences are summarized in multiple dimensions. Finally, the study takes this as a reference for a more comprehensive outlook on the future development direction of pumped storage in China.

Multi-Objective Optimization Model

In order to more intuitively show the outstanding role of pumped storage in technology, economy, and environment and to provide solution ideas for the challenges faced in the new power system transformation, this study designs a coordinated optimal scheduling model for a wind-photovoltaic-thermal-pumped storage system with the optimization objectives of minimizing net load fluctuation, maximizing system economic benefit, and minimizing new energy power abandonment.

Objective Function

Minimizing Net Load Fluctuation

Net load is the remaining load actually borne by thermal power units after deducting the combined output of wind, solar, and storage in the system. In order to fully utilize the pumped storage system capacity to compensate for the volatility of renewable energy output, the net load volatility borne by thermal power units is minimized as much as possible, and large and frequent adjustments of output by thermal power units are avoided. The minimum objective function of net load fluctuation is shown as follows:

$$\min F_1 = \frac{1}{T}\sum_{t=1}^{T}\left|P_{nl,t} - P_{anl,t}\right| \tag{1}$$

$$P_{nl,t} = P_{l,t} - \sum_{w=1}^{N_w} P_{w,t}^{wind} - \sum_{v=1}^{N_v} P_{v,t}^{pv} - \sum_{s=1}^{N_s} P_{s,t}^{ps} \tag{2}$$

$$P_{anl,t} = \frac{1}{T}\sum_{t=1}^{T} P_{nl,t} \tag{3}$$

Where, $P_{nl,t}$ is the net load value at time t; $P_{l,t}$ is the grid load value at time t; $P_{w,t}^{wind}$ is the actual grid-connected power of the wind unit w at time t; $P_{v,t}^{pv}$ is the actual grid-connected power of the photovoltaic unit v at time t; $P_{s,t}^{ps}$ is the output power of the pumped storage unit s at time t; $P_{s,t}^{ps}>0$ denotes power generation, $P_{s,t}^{ps}<0$ denotes pumping; $P_{anl,t}$ is the average value of the net load in a scheduling cycle; N_w is the total number of wind units; N_v is the total number of photovoltaic units; N_s is the total number of pumped storage units.

Maximizing System Economic Benefit

The resulting objective function, which mainly takes into account the electricity revenue of the system as well as the operating cost of the thermal power unit, is as follows:

$$\max F_2 = \sum_{t=1}^{T}(C_t^{f-peak}\cdot\sum_{f=1}^{N_f}P_t^{f-peak}+C_t^{w}\cdot\sum_{w=1}^{N_w}P_{w,t}^{wind}+C_t^{v}\cdot\sum_{v=1}^{N_v}P_{v,t}^{pv}+C_{g,t}^{ps}\cdot\sum_{s=1}^{N_s}P_{g,s,t}^{ps})-C_{p,t}^{ps}\cdot\sum_{s=1}^{N_s}P_{p,s,t}^{ps}-\sum_{t=1}^{T}\sum_{f=1}^{N_f}(a_f\cdot P_{f,t}^2+b_f\cdot P_{f,t}+c_f)-\sum_{t=1}^{T}\sum_{f=1}^{N_f}C_t^{f-start}\cdot u_{f,t}\cdot(1-u_{f,(t-1)}) \tag{4}$$

Where, $C_t^{f\text{-}peak}$ is the thermal power peak compensation cost; $P_t^{f\text{-}peak}$ is the thermal power paid peak power at time t; N_f is the total number of thermal power units; C_t^w, C_t^v and $C_{g,t}^{ps}$ respectively denote the wind power, photovoltaic and pumped storage feed-in tariffs; $P_{g,s,t}^{ps}$ is the generated power of pumped storage at time t; $C_{p,t}^{ps}$ is the pumping tariff; $P_{p,s,t}^{ps}$ is the pumping power of pumped storage at time t; a_f, b_f and c_f, respectively denote the coal consumption coefficients of the thermal power unit f; $C_t^{f\text{-}start}$ is the starting cost of the thermal power; $u_{f,t}$ denote the start-stop state of the thermal power.

Minimizing New Energy Power Abandonment

The new energy absorption capacity is expressed by the sum of wind and photovoltaic power abandonment during the dispatch cycle. The specific objective function is as follows:

$$\min F_3 = \sum_{t=1}^{T}\sum_{w=1}^{N_w}P_{curt,w,t}^{wind}\cdot\Delta t+\sum_{t=1}^{T}\sum_{v=1}^{N_v}P_{curt,v,t}^{pv}\cdot\Delta t \tag{5}$$

Where, $P_{curt,w,t}^{wind}$ is the abandoned power of wind unit w at time t; $P_{curt,v,t}^{pv}$ is the abandoned power of photovoltaic unit v at time t; the value of duration Δt in each period is 1 h.

Constraint Conditions

Power Balance Constraints

$$\sum_{f=1}^{N_f}P_{f,t}^{fire}+\sum_{w=1}^{N_w}P_{w,t}^{wind}+\sum_{v=1}^{N_v}P_{v,t}^{pv}+\sum_{s=1}^{N_s}P_{s,t}^{ps}=P_{l,t} \tag{6}$$

Where, $P_{f,t}^{fire}$ is the active power output of the thermal power unit f at time t; $P_{w,t}^{wind}$ is the actual grid-connected power of wind unit w at time t; $P_{v,t}^{pv}$ is the actual grid-connected power of photovoltaic unit v at time t; $P_{s,t}^{ps}$ is the output power of pumped storage unit s at time t; $P_{l,t}$ is the grid load value at time t.

Thermal Power Output Constraint

Output power constraint:

$$u_{ft}\cdot P_{f,\min}^{fire}\le P_{f,t}^{fire}\le u_{ft}\cdot P_{f,\max}^{fire} \tag{7}$$

Unit climbing constraint:

$$-r_{f,down}\le P_{f,t}^{fire}-P_{f,(t-1)}^{fire}\le r_{f,up} \tag{8}$$

Where, $r_{f,down}$ and $r_{f,up}$ are respectively the maximum upward climbing rate and maximum downward climbing rate of the thermal power unit.

Wind Power Output Constraint

$$0<P_{w,t}^{wind}\le P_{w,t,\max}^{wind} \tag{9}$$

Where, $P_{w,t,\max}^{wind}$ is the maximum output of the wind unit at time t.

Photovoltaic Power Output Constraint

$$0<P_{v,t}^{pv}\le P_{v,t,\max}^{pv} \tag{10}$$

Where, $P_{v,t,\max}^{pv}$ is the maximum output of the photovoltaic unit at time t.

Output Power Constraint of Pumped Storage

$$P_{s,t,\min}^{ps}\le P_{s,t}^{ps}\le P_{s,t,\max}^{ps} \tag{11}$$

Where, $P_{s,t,\max}^{ps}$ and $P_{s,t,\min}^{ps}$ respectively denote the maximum and minimum output power of pumped storage at time t.

Capacity Constraint of Pumped Storage Reservoir

$$\begin{cases} S_{\min}^{u}\le S_t^{u}\le S_{\max}^{u} \\ S_{\min}^{d}\le S_t^{d}\le S_{\max}^{d} \end{cases} \tag{12}$$

$$\begin{cases} S_{t+1}^{u}=S_t^{u}+(\Delta t\cdot P_{p,s,t}^{ps}\cdot\eta_p-\dfrac{\Delta t\cdot P_{g,s,t}^{ps}}{\eta_g}) \\ S_{t+1}^{d}=S_t^{d}+(\dfrac{\Delta t\cdot P_{g,s,t}^{ps}}{\eta_g}-\Delta t\cdot P_{p,s,t}^{ps}\cdot\eta_p) \end{cases} \tag{13}$$

Where, η_p and η_g respectively denote the pumping efficiency and power generation efficiency of pumped storage units; $S^u_{\max}$ and $S^u_{\min}$ are the maximum and minimum values of the upper reservoir capacity; S^d_{max} and S^d_{min} are the maximum and minimum values of the lower reservoir capacity.

Solution Method

A multivariate programming model is mainly established by introducing the YALMIP toolbox of MATLAB software based on optimization modeling and constraint solving. The model takes the operation optimization of thermal power, wind power, photovoltaic, and pumped storage units as the core, and comprehensively considers the objectives of system load fluctuation, economic efficiency and power abandonment. The constraints are refined as upper and lower limit constraints of wind and solar power output, thermal power unit output range constraints, and pumped storage pumping and generating power and capacity change constraints, etc., to ensure the feasibility and power balance of system operation. The decision variables and binary variables are defined using sdpvar by invoking the CPLEX solver to solve the optimization problem efficiently with objective function and constraints.

Parameter Setting

The capacity of the units in the combined system is 400 MW for wind power, 300 MW for photovoltaic, 100 MW for pumped storage, and 400 MW for thermal power. The maximum climbing rate of the thermal power unit up and down is set to be ±30% of the maximum output, respectively. The maximum pumping and generating power of the pumped storage unit is 100MW, and the integrated efficiency is 0.9. The feed-in tariff of pumped storage is 372 Yuan/MWh according to the benchmark price of coal-fired power generation, and the pumping tariff is valued at 75% of the benchmark price of coal-fired power generation. The penalty tariff for abandoned wind and light is 600 Yuan/MWh. Based on the CO_2 emission factor data for fossil energy power published by China's Ministry of Ecology and Environment in 2021, the emission factor for thermal power is taken as 0.8426 tCO_2/MWh. Taking full account of the difference in electricity prices between peak and valley hours in the electricity market, the 24-hour electricity price for one day is formulated as shown in Table 1.

Results

According to the method described in the previous section, the multi-temporal and spatial uncertainty distribution of wind and solar resources, the application status of pumped storage, and the multi-objective optimization results of the combined wind-photovoltaic-thermal-pumped storage system can be obtained as follows.

Table 1. The time-of-use electricity price information.

Time	Electricity price/ (Yuan·MW^{-1}·h^{-1})	Time periods
10:00-14:00	1350	Peak
18:00-22:00		
7:00-9:00	820	Flat
15:00-17:00		
23:00-6:00	380	Valley

Uncertainty Distribution of Wind and Solar Resources

Time Scale

In the short–term time scale (intra–day, day–ahead), as shown in Fig. 1, the daily output fluctuations of new energy are considerable, with complex boundaries and strong randomness. Under the extreme scenario, prediction biases can easily appear to aggravate the pressure of system frequency modulation.

According to the day–ahead fluctuations of new energy in Fig. 2, there is a "dislocation" phenomenon between new energy power generation and peak demand for electricity. The previously existing nighttime trough in net load has transformed into dual troughs during periods of high photovoltaic power generation at noon and high wind power generation at night. During the trough period, coal power needs to reduce its output in time, but at the evening peak, photovoltaic power output drops sharply, and coal power needs to climb rapidly to increase its output. So this reliance solely on the complex and time–consuming start–stop processes of coal power units and limited load–side adjustment ability is insufficient to meet the grid's peak adjustment challenges.

In the medium–term time scale (weekly, monthly), the daytime output of new energy still exhibits significant fluctuations and intermittency. As shown in Fig. 3, the weekly output is highly uncertain and difficult to predict, and the periodic regulation pressure of the power system continues to increase, which seriously influences the system power supply efficiency and absorption capacity.

In the long–term time scale (seasonal, annual), the monthly average of photovoltaic seasonal output is also uneven, roughly higher in summer and lower in winter, which is complementary to wind power. As shown in Fig. 4, the new energy output and the load demand are seasonally mismatched to some extent. As a result, power grid cross–seasonal balance adjustment and new energy seasonal absorption have been increasingly contradictory, resulting in economic deterioration.

Spatial Scale

On the spatial scale, new energy resources are significantly varied in different regions of China. Wind and solar are concentrated in western, northern, and other remote regions, while areas with high electricity demand are mainly in the central and eastern regions. This spatial misalignment presents significant

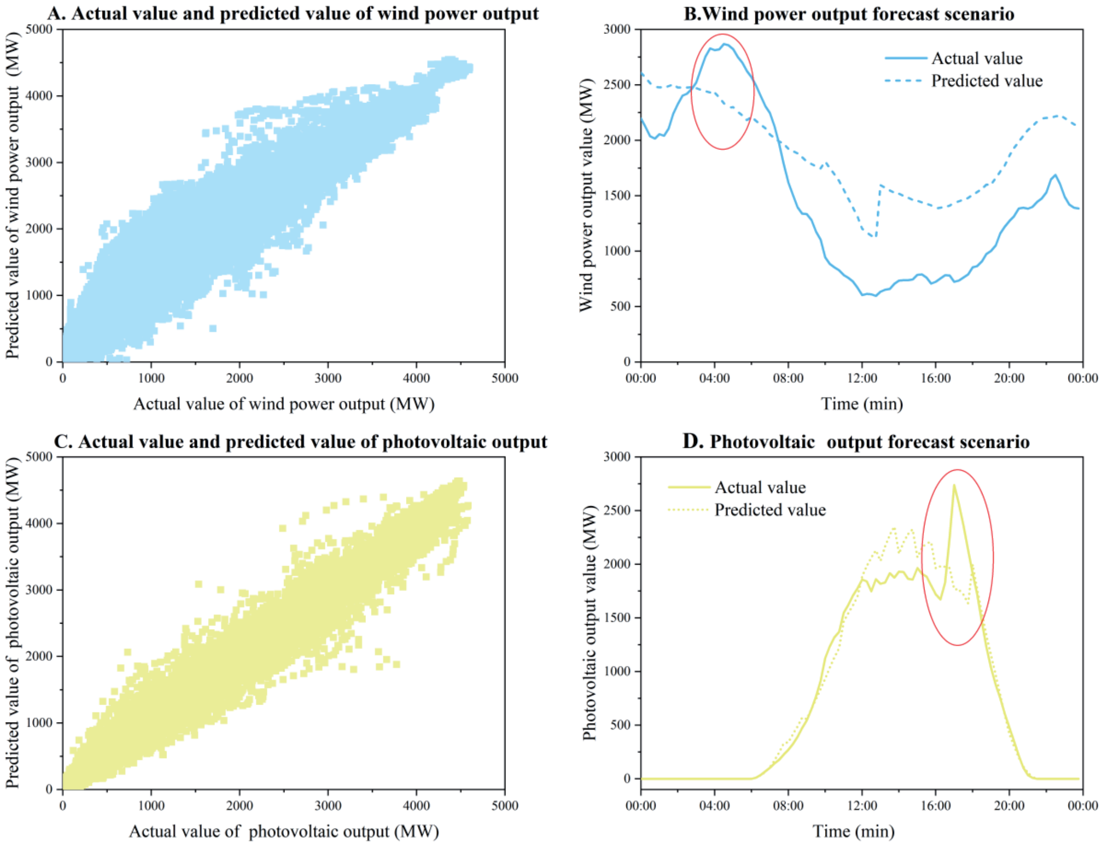

Fig. 1. New energy intra–day output scenario.

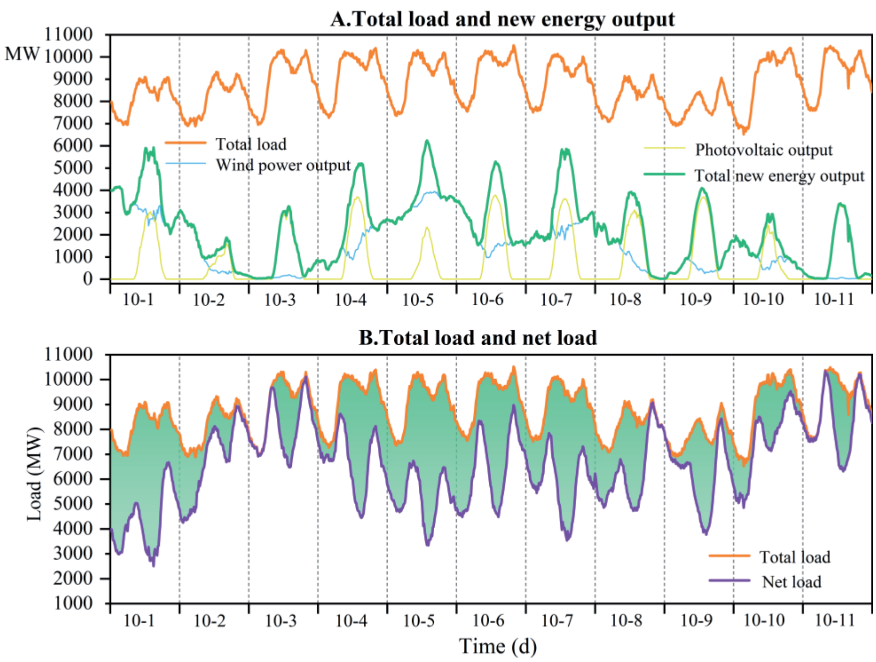

Fig. 2. New energy day–ahead output scenario.

challenges in long–distance grid transmission scheduling and absorption of new energy. The distribution of wind and solar resources in China is illustrated in Fig. 5.

Summary of Pumped Storage Applications

Energy Storage Modes and Key Technical Features

By the end of 2022, China's new–type energy storage cumulative installed capacity had reached 8.7 GW, and the total installed scale of the pumped storage was 45.79 GW. As predicted, the new–type energy storage installed scale will reach more than 30 GW, and the pumped storage installed scale will reach more than 62 GW in total. In Table 2, eight kinds of commonly–seen energy storage modes and their key technical features are summarized.

A comparison of critical technical features in Table 2 suggests that PS and CAES are two energy storage technologies capable of long–duration discharge, large–scale storage, and low LCOS. FES and electrochemical energy storage are faster in response, but they come with higher technical costs, smaller deployment scales, and the risk of fire hazards associated with electrochemical technology. Next is HES, which is a clean, efficient, and sustainable storage technology with long storage time and strong environmental compatibility. However, it is confronted with challenges like low energy conversion efficiency and high investment costs. SMES has fast response speeds and high energy cycle efficiency but limited capacity, short discharge duration, and higher costs. In summary, pumped storage is still the most economical and technologically mature type of storage in the near future.

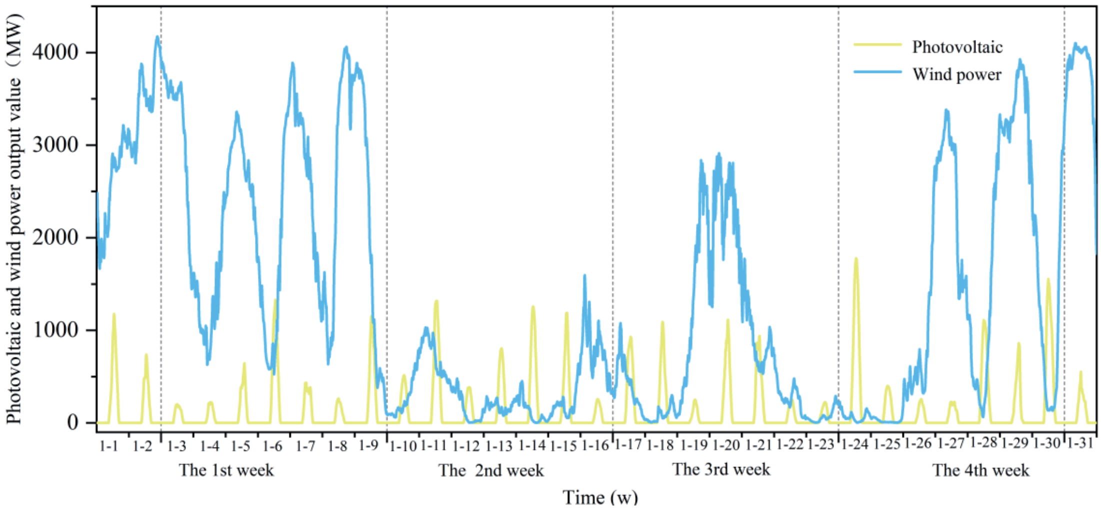

Fig. 3. New energy daytime output scenario.

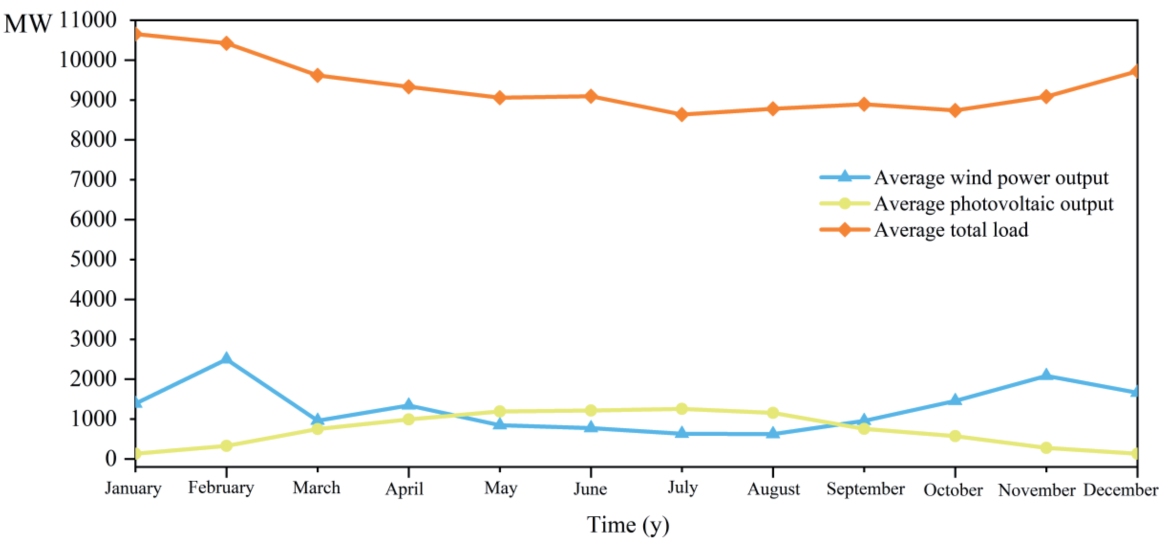

Fig. 4. New energy seasonal output scenario.

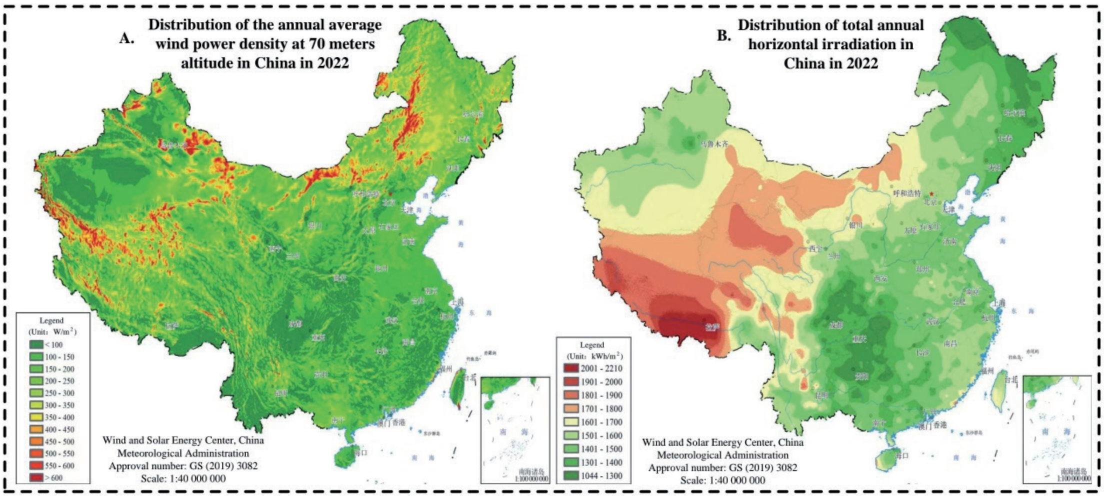

Fig. 5. Distribution of wind and solar resources in China (*Source:* [8]).

Table 2. Comparison of key technical parameters between pumped storage and new–type energy storage.

Types of energy storage technology		Response time	Discharge duration time	Power range/MW	Capacity range/ MW·h	Energy exchange efficiency /%	Lifetime /y	Security	LCOS	Energy storage mode
PS		min [9]	1~24h [10, 11]	10-5000 [11, 12]	200-500 [10, 11]	70-85 [10, 11, 13]	30-60 [9, 13]	High [14]	Lower [9, 14, 15]	Mechanical energy storage
New–type energy storage	CAES	min [16]	1-24h [16]	5-300 [12, 16]	200-1000 [16]	41-75 [12, 17, 18]	20-40 [9]	High [19]	Low [9]	
	FES	s [13]	s-15min [13]	0.1-1 [12, 17]	0.025-5 [20, 21]	80-95 [22]	15-20 [23]	Medium [9, 19]	Higher [17, 18]	
	Li-ion	ms [9, 24]	min-1h [9, 24]	0.05-100 [25]	0.25-25 [22]	85-95 [26, 27]	20-25 [28]	Medium [9, 19]	Low [14, 15, 29]	Electrochemical energy storage
	Pb-A	ms [9, 24]	s-5h [24]	<100 [14]	18-100 [30]	70-90 [14, 27]	5-15 [9]	High [9, 14, 19]	High [14, 29]	
	VFB	ms [27, 31]	5-12h [27, 31]	0.01-10 [32]	4-40 [32]	60-75 [27, 33]	10-20 [34]	High [14, 19]	Low [14, 15, 27]	
	HES	s [31]	s-24h [13]	0.001-1000 [19, 35]	<200 [36]	20-50 [27, 37]	5-15 [37]	Low [19]	Higher [31]	Chemical energy storage
	SMES	ms [11]	ms-s [38]	0.01-10 [12]	0.015-0.1 [9]	90-98 [11, 38]	20-30 [11, 38]	Medium [19]	Higher [38]	Electromagnetic energy storage

* LCOS – Levelized cost of storage, PS – Pumped storage, CAES – Compressed air energy storage, FES – Flywheel energy storage, Li-ion – Lithium-ion battery, Pb-A – Lead-acid battery, VFB – Vanadium flow battery, HES – Hydrogen energy storage, SMES – Superconducting magnetic energy storage.

Application Scale of Pumped Storage

Statistics showed that by the end of 2022, the cumulative installed capacity of the global pumped storage had reached 175.06 GW, of which 26.2% was contributed by China, ranking No. 1 on the list. China's pumped storage cumulative installed capacity had reached 45.79GW, and the total installed capacity under construction was 121 GW [39]. Relevant national departments in China claimed that by 2025, the national pumped storage total installed capacity will have exceeded 62GW, by 2027, by more than 80GW, and by 2030, by around 120GW. By reviewing the development and planning of pumped storage in China from 2011 to 2030 (see Fig. 6) [40], the installed capacity of pumped storage power stations has witnessed dramatic growth. The current development scale and construction pace have been accelerated, but the development cannot yet satisfy the planned demand.

As can be seen from Fig. 7, pumped storage power stations that have been put into production and under construction are mainly distributed in economically–developed regions with concentrated electrical loads, such as Guangdong, Zhejiang, Anhui, and Hebei. In contrast, northwestern regions like Inner Mongolia, Ningxia, Gansu, Qinghai, and Xinjiang, which

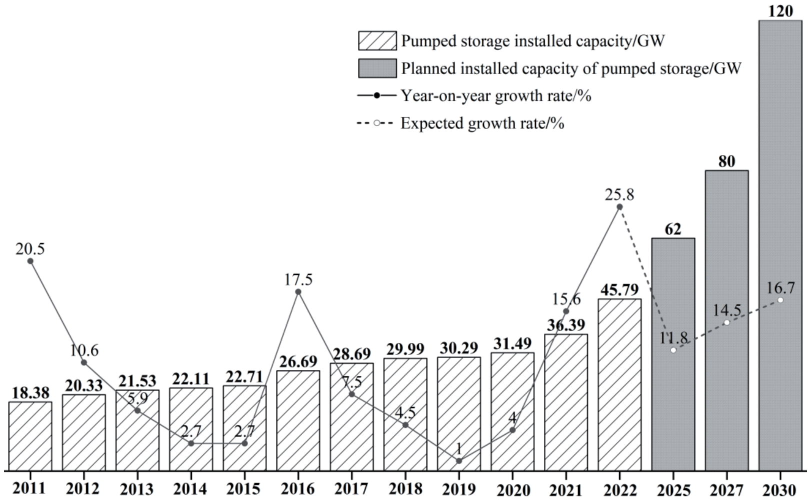

Fig. 6. Development and planned scale of pumped storage in China from 2011 to 2030.

Fig. 7. Distribution of pumped storage power stations in China.

boast abundant wind and solar resources, almost have no units commissioned due to insufficient local power consumption capacity. This situation leads to a significant demand for long–distance power transmission.

Application Function of Pumped Storage

As a mature energy storage technology, pumped storage can provide energy storage on multiple time scales (See Fig. 8). On the source side, it can be used for short-term frequency modulation, voltage support, spinning reserve, and smoothing out new energy fluctuations. It can also be used as a medium- and short-term peak shaving and black-start power source; some power stations also have seasonal peak load balancing functions. On the grid side, pumped storage power plants can relieve transmission line congestion and delay grid expansion and upgrading. On the load side, it can bear the role of quick recovery and backup power.

Multi-Objective Optimization Results for Wind-Photovoltaic-Thermal-Pumped Storage System

Comparison Results of Model Objective Function Values Before and After Pumped Storage Addition

After the pumped-storage unit participates in the combined system, the variance results of economic

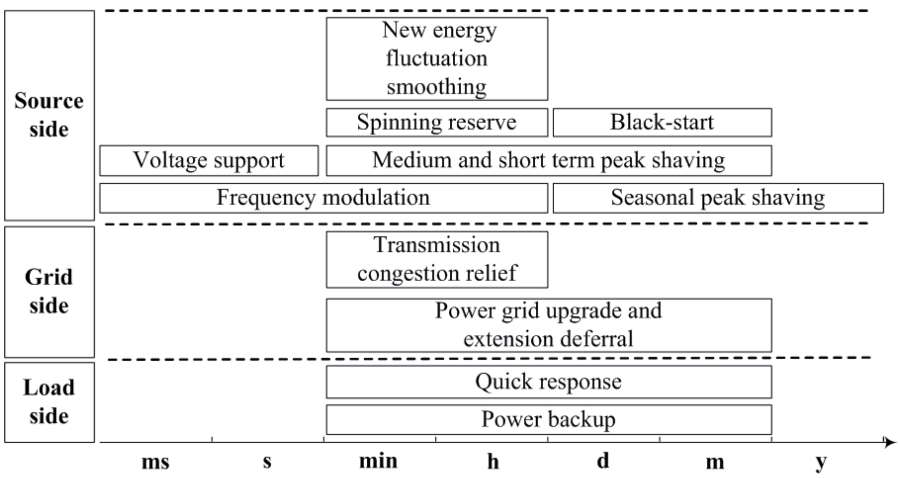

Fig. 8. Functional applications of pumped storage on multiple time scales.

benefits, new energy abandonment, and net load fluctuation are summarized as shown in Table 3.

It can be seen from Table 3 that the economic benefits, new energy power abandonment, and load fluctuation of the combined system have been improved. Specifically, the economic benefit of the system is increased by 1.5 million Yuan, the amount of abandoned wind and light is reduced by 411.45MW, and the power abandonment rate is reduced from 12.4% to 5.2%. In addition, the fluctuation variance of the system load has improved slightly, from 21005 to 20995. According to China's punishment measures for wind and light abandonment, the system's abandonment power is reduced by 411.45MW after the addition of pumped storage, and the abandonment penalty is also reduced by 246,870 Yuan.

Optimization Results of Combined System Operation

After the addition of pumped storage, the working status of the combined wind-photovoltaic-thermal-pumped storage system in each time period is shown in Fig. 9.

In Fig. 9, when the total output power of each unit is less than the power system load, the pumped storage will be in the power generation state. When the total output power is greater than the power system load, pumped storage converts to a pumping state to store electricity. After observing the output of thermal power units, the output power of thermal power units is reduced in each time period after adding pumped storage, totaling 587.4 MW. Combined with the data on thermal power emission factors, the system can reduce CO_2 emissions by 495 t. If the system enters into the carbon market and trades, according to the average price of China's current national carbon emission right trading of 66 Yuan/t, the reduction of carbon emissions can increase income by 33,000 Yuan for the system.

Table 3. Comparison of the objective function values of the combined system before and after pumped storage addition.

Objective function value	Before	After
System economic benefit / (Yuan·d^{-1})	1.71×10^7	1.86×10^7
New energy power abandonment / MW	708.60	297.15
Load fluctuation variance	21005	20995

Discussion

Discussion on Current Applications of Pumped Storage

As can be seen from the first two parts of the results section, it has been imperative to explore technical equipment capable of involving in regulating services of the new power system in source, grid, load, and storage in response to the challenges posed by new energy uncertainties in power system transformation and upgrading. This equipment should also support the high penetration of new energy absorption and enable power and energy balance adjustments across multi–temporal and spatial scales to ensure the stability and economy of the new power system. As a power system flexible regulation power supply, although there is a certain degree of geographical and geological conditions of constraints and limited resource sites, it has a diverse range of application scenarios and significant technical advantages. Therefore, it is evident that, in the process of achieving the "dual carbon" target, China still has a large demand for the construction of pumped storage power stations. Moreover, these pumped storage power stations will continue to develop and play an increasingly important role. Next, this study will discuss the current status of pumped storage applications in terms of functional, technological, economic, and environmental aspects.

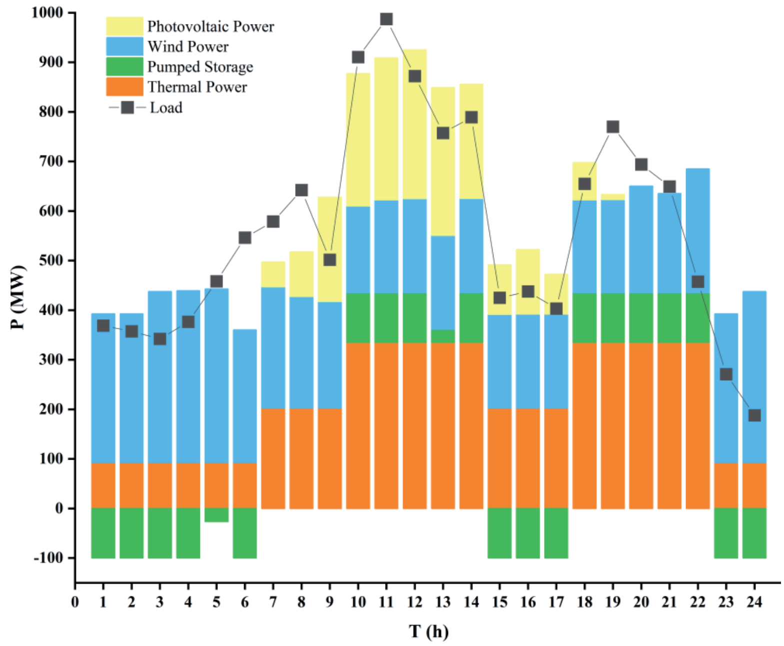

Fig. 9. Operational status diagram of the combined wind-photovoltaic-thermal-pumped storage system.

Function Application Scenario

Alleviating Peak–Valley Disparity and Promoting the Absorption of Renewable Energy Sources

Pumped storage technology has been playing a critical role in peak shaving and valley filling in the power system, which can easily meet the needs of large-scale power regulation. With the transformation and upgrading of the new power system, power sources with different characteristics are connected to the power grid on a large scale, and the energy time-shift characteristics of pumped storage are gradually highlighted. This technology can improve new energy absorption by adjusting the fluctuation of their output power in the spatiotemporal perspective [41].

Improving Power Grid Frequency Characteristics and Bettering System Stability

When the power grid breaks down, the pumped storage unit can effectively prevent the expansion of accidents in one to two minutes from electricity generation upon startup to full load under the idle state. The frequency modulation of pumped storage has become increasingly obvious in power systems with a high proportion of wind and solar power penetration. The unit application has gradually shifted from the planned on-and-off regulation to the flexible on-and-off regulation according to the system frequency modulation actual multi–scale needs [42]. This conversion can better inhibit the fluctuations of new energy and accelerate the stable operation of the power system.

Upgrading the Quality of Electric Energy and the Reliability of System Power Supply

When the power system is faced with the short–term problems of electric energy, pumped storage can quickly respond to system dynamic changes by working in phase modulation mode and realize reactive voltage regulation at the cost of small active power loss to reduce the voltage fluctuations and flickers. This can help ensure the quality of power supply for users. When emergencies or power grid collapses happen, the pumped storage unit is capable of dynamic services, such as black start, and also serves as emergency power to earn precious time for the recovery of the power grid. This can also prevent the power cutoff to avoid further losses and reinforce the system's capability to withstand accident impact.

Optimizing Transmission and Distribution Lines and Enhancing Integration of Renewable Energy

Pumped storage, as an energy storage technology integrated into high–penetration new energy grids, can reduce or delay grid upgrade investments, alleviate grid transmission capacity constraints, and increase the transmission capacity of key power transmission channels and sections.

Specific Technological Innovation

As mentioned above, the scale of China's pumped storage has ushered in a leapfrog development by 2022, and in order to support its multi-scenario application functions, various technological research and digital intelligence exploration practices have been carried out in depth.

Specifically, with the increasing number of areas with complex geological conditions in the selection of pumped storage power station sites in China, such as alpine, high-altitude, fragile ecological environments and water-scarce areas, the preliminary geological exploration, engineering design, and construction management are facing new situations. Technical means such as flat hole exploration, small section TBM digging technology, deep hole drilling, and geophysical exploration technology have begun to be explored and applied. Long-inclined shafts and vertical shaft construction technology have also made great progress. In the overall design of pumped storage power station units, manufacturing complexity has reached world-leading standards, achieving hydraulic development for pump turbines operating at an 800-meter head and with a single-unit capacity of 400MW or more.

In addition, the current development of the digital economy promotes the application of digital technology [43], which also provides a broad basis for the technological innovation of pumped storage. China's power grid companies actively study the layout of digital intelligent power station construction. Pumped storage power stations such as Ninghai, Jinyun, and Tiantai have established infrastructure intelligent control centers and intelligent site management systems to realize intelligent management during the construction period. Guangzhou, Huizhou, Qingyuan, and other pumped storage power stations are connected to the China Southern Power Grid energy storage platform in order to realize real-time monitoring of unit status, intelligent early warning and fault diagnosis, and improve daily work efficiency.

However, technological innovation and challenges are coexisting. Realistic problems that still need to be addressed include special engineering geological treatment, slope stability assessment for constructing pumped storage power stations in repurposed mine pits, design of large-scale variable-speed pumped storage units and their supporting control and protection equipment, the development of digital and intelligent technology framework, and securing the necessary funding for these initiatives.

Current Situation of Economic Benefit

Technological innovations have facilitated the functional benefits of pumped storage while also influencing its economic performance. The balance between technological investment and economic returns is a key consideration for all projects. Therefore, in addition to considering functionality and technology, it is essential to delve deeper into the current economic status of pumped storage.

Currently, China is transitioning from a planned electricity system to a market-based system, with most pumped storage power stations fully controlled by subsidiaries of the State Grid and China Southern Power Grid or jointly owned by other power generation companies [44]. In terms of the pricing mechanism for pumped storage, a two-part tariff system is implemented. The capacity price mainly reflects the value of providing peak shaving, valley filling, energy storage, as well as frequency modulation, reactive power support, standby, and black-start services, determined according to the principle of covering fixed costs and ensuring a reasonable return. The electricity price primarily covers pumping costs and revenue from electricity generation, compensating for variable costs such as pumping and power generation losses. However, as pumped storage units are still considered non-marketized, the capacity price is mainly approved by government departments based on the industry's advanced standards.

In terms of taxation, China had previously implemented a policy before 2017 that refunded the portion of VAT exceeding 12% for pumped storage enterprises. However, at present, the VAT rate for wind and solar power is approximately 3%, for hydropower, it is around 8%, while pumped storage faces a VAT rate of about 15%. Nevertheless, the latest green development tax and fee preferential policies stipulate that water resources taxes are exempt for pumped storage plants using water for power generation.

In this context, China's pumped storage power stations face certain challenges in terms of survival and development, such as weak social investment willingness and difficulty in recovering operational costs.

Current Situation of Environmental Benefit

With the continued advancement of the "dual carbon" target, environmental problems are receiving increasing attention in energy projects. The development of pumped storage not only requires strong technical and economic support but also needs to coordinate and balance environmental benefits.

As a green and low-carbon clean energy storage method, pumped storage can reduce carbon emissions by facilitating the integration of renewable energy, reducing energy curtailment, and replacing traditional power sources for peak shaving. China's carbon emission trading market is primarily divided into cap-and-trade based on total emission control and project-based voluntary emission reduction trading [45]. The former involves the trading of carbon emission quotas allocated to various regulated industries by the government, based on overall carbon emission control targets. The latter involves the trading of nationally certified voluntary emission reductions, which are achieved by industries through voluntary carbon reduction projects that are quantified and verified by relevant authorities. However, neither of these ways has accounted for pumped storage, and its green benefits have not been reasonably reflected in the carbon trading market.

In addition to its carbon reduction benefits, pumped storage also implements environmental protection measures during its construction and operation, such as the discharge of ecological flow to protect the ecosystem, with its effects monitored using ultrasonic measurement. Moreover, vegetation restoration is conducted during and after construction to mitigate the impact of soil erosion. However, for pumped storage power stations located in ecologically sensitive areas or built using abandoned mines as upper and lower reservoirs, ecological restoration remains a significant challenge.

In summary, China has made significant progress in the technical, economic, and environmental aspects of pumped storage. However, there is still room for improvement. The following section will analyze the main scientific issues facing the development of pumped storage, based on the results of the multi-objective optimization model and the current application discussion of this section.

Analysis of Scientific Issues

From the multi-objective optimization results of the combined system, it can be seen that a reasonable pumped storage power station for the multi-energy system can increase the economic and environmental benefits of the system, and at the same time, it can also reduce the harm of the new energy fluctuation to the power grid to a certain extent. Pumped storage can provide a huge boost to China's "double carbon" target while promoting the development of new energy. However, the new power system is a more complex and large system, and further expansion is needed based on the methodological scenarios proposed in this paper. In view of the foregoing, a multi-energy synergistic regulation system (shown in Fig. 10) is demonstrated to discuss the scientific issues that need to be focused on for pumped storage to be effective in various benefits in the new power system.

In addition to the type of units involved in this study, the new power system can be regarded as a more comprehensive large-scale multi-energy complementary system integrating wind power generation, photovoltaic generation, hydroelectric generation, thermal power generation, and pumped storage. Meanwhile, the combined dispatching and centralized control center is set up for operation management. The centralized control center cooperates with the power grid externally, taking into account the changes in load demand and the uncertainties of external climate and other factors so as to flexibly operate the output power. When the power grid gives the integrated dispatching command, the operation management system of the centralized control center calculates the optimal operation mode by combining the wind and solar power prediction data and pumped storage status information and optimizes the dispatching commands of each subsystem in the wind-solar-hydro-thermal-pumped large-scale multi-energy complementary system. In the system, the output of wind and photovoltaic generation lacks stability, so they belong to the non-controllable power source. Hydropower and thermal power are highly controllable. Pumped storage is implemented according to the actual

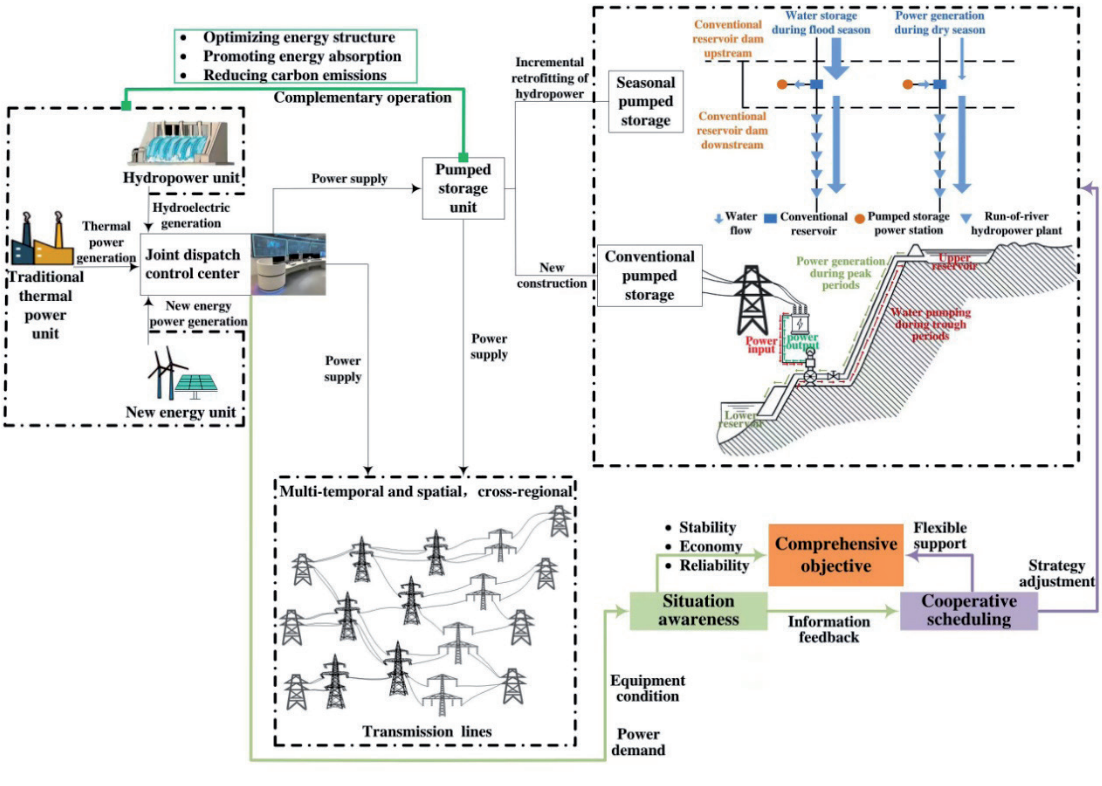

Fig. 10. Schematic diagram of multi-energy synergistic regulation system.

output and load demand of each power source in the whole system. In the aforesaid system, the following critical scientific issues require immediate solutions.

Technical Path Planning Issues for Pumped Storage to Support Large-Scale New Energy Development

Under the new situation of green and sustainable development, the speed and scale of clean energy development in China are constantly increasing. In order to ensure that there will not be a large amount of energy abandonment after the completion of water, wind, and solar projects, comprehensive strategic planning is necessary for future large-scale wind and solar development. This means that we need to deeply study the complementary issues of wind-solar-hydro-thermal-pumped across regions from multiple aspects, such as sources, grids, and loads. This is essentially an optimization problem for a multi-energy complementary system. Particularly, with the inclusion of multi-temporal and spatial regulation requirements, pumped storage plants face higher demands, even requiring the addition of seasonal or periodic pumped storage power stations within cascade hydropower plant clusters to meet the flexible needs of the power grid. As a result, based on the existing optimization models, the constraints and variables of the power source, grid, load, and storage at all ends become significantly more complex, and the expansion of temporal and spatial dimensions poses challenges in modeling and solving. Therefore, there is an urgent need to develop optimization control theories and methods for multi-energy systems, incorporating multi-time scales and cross-regional coordination.

Economic Benefit Issues of Pumped Storage Participation in Diversified Electricity Markets

From the multi-objective optimization model proposed in the previous section, it can be seen that the economic efficiency of the combined system is closely related to the feed-in tariff of each unit. Currently, China is accelerating the entry of new energy into the market. After the full participation of new energy in the market transactions, if energy storage entities such as pumped storage cannot be included in the unified optimization of the electricity spot market, their operation mode arrangements will significantly impact the time-of-use electricity price in the market. However, the operational and cost models of pumped storage are different from the existing market entities represented by thermal power. As the electricity market undergoes different developmental stages in achieving the "dual carbon" target, it will be challenging to ensure its economic viability through market competition similar to traditional thermal power. Therefore, in the future, pumped storage will need to carefully balance its priorities when participating in various markets, using historical data and forecasting models to analyze market prices and risk trends and address the issue of benefit compensation in multi-market convergence and nesting.

Issues in Assessing the Environmental Benefit of Pumped Storage

The addition of pumped storage to the multi-energy system is a way to reduce the output of thermal power by increasing the absorption of new energy, thus achieving carbon emission reduction. However, as discussed earlier on the current status of environmental benefits, there is no scientific consensus on the quantitative evaluation of the carbon reduction benefits of pumped storage. Different research methods and accounting standards may lead to estimation biases, making it difficult to reach a unified assessment of the actual contribution of pumped storage to carbon reduction. Moreover, due to the lack of a systematic carbon reduction accounting framework and industry standards, the green benefits of pumped storage have not been reasonably reflected in the carbon trading market, which affects its market competitiveness in low-carbon development and indicates a lack of economic compensation for its environmental benefits. In addition, the impact of pumped storage on the ecological environment also carries some uncertainty, particularly regarding the long-term effects of large-scale projects on water resource utilization, habitat changes, and environmental load, which require further investigation.

International Comparative Analysis

Pumped storage, as the largest and most technologically mature form of energy storage worldwide, has become increasingly important in ensuring the safe operation of global power systems and promoting large-scale development of renewable energy, especially as thermal power development faces limitations and gas supply security remains a challenge. Internationally, Japan and the United States (U.S.) rank second and third in installed pumped storage capacity, respectively, with pumped storage playing a vital role in their power systems. Although the installed capacity of pumped storage in the United Kingdom (UK) is relatively small, following electricity market reforms, a mature market system and pricing mechanism have been developed. In this section, the U.S., the UK, and Japan will be selected as representatives to analyze the construction and operation of typical pumped storage power stations, which will provide a reference for future research on pumped storage in China.

Typical Cases of International Pumped Storage Projects

The United States

In the U.S., as federal and state governments implement climate change policies, there has been a continuous increase in stringent requirements for clean energy generation, driving the demand for ancillary services and the exploration of stable energy storage methods. Due to different approaches to electricity market reforms across states, the operation and profitability models of pumped storage power stations vary. The main models include grid unified operation, independent operation, and leasing model.

The Ludington Pumped Storage Plant, located in Michigan, has a capacity of 2,172 MW and primarily supports load balancing for the Michigan grid. It operates under a grid unified model, managed through the MISO market dispatch system. The revenue model of the plant typically relies on price fluctuations, obtaining economic returns through price differentials. The Summit Pumped Storage Plant in Ohio is located within the PJM electricity market area. Despite the highly developed PJM market, the plant operates under a leasing model with the grid. Its revenue mainly comes from capacity leasing, resulting in relatively lower returns.

It is noteworthy that California has established an ancillary services market based on bidding outside the traditional electricity market, which plays an important role in compensating for the ancillary service benefits of pumped storage. For example, the Helms Pumped Storage Plant in California, with a capacity of 1,200 MW, primarily supports the integration of the state's solar power grid. Revenue from ancillary services accounts for 60% of its total income, and the number of times the plant is utilized has significantly increased with the establishment of the ancillary services market [46]. Additionally, California is currently constructing the Eagle Mountain Pumped Storage project, with a capacity of 1,300 MW. Utilizing the infrastructure left by an abandoned mine, it can provide over 18 GWh of emissions-free energy storage. The project is led by a private development company, with approval from the California government after over a decade of environmental reviews and scientific studies. It follows a public-private partnership model and is progressing steadily.

However, in the current U.S. electricity market policy, many grid services provided by pumped storage still face insufficient compensation. Furthermore, the federal tax policy currently provides a 30% investment tax credit for energy storage technologies but excludes pumped storage from this incentive.

The United Kingdom

The development of pumped storage in the UK is closely tied to the evolution of its electricity market. Currently, the UK has established a comprehensive electricity market system that includes the energy market, ancillary service market, and capacity market across various time scales. Pumped storage power stations are operated independently by their owners and participate in market competition alongside other power plants, primarily generating revenue by engaging in the energy market and ancillary service markets.

In the specific construction of pumped storage power stations, the Dinorwig Pumped Storage Plant, with a power capacity of 1,728 MW and an energy storage capacity of 9,100 MWh, has a stable income mainly derived from its permanent on-demand capability for emergency frequency modulation. In 2016, this revenue was approximately £10.8 million [47]. Notably, Dinorwig's design was optimized to minimize environmental impact by using underground cables instead of overhead transmission towers, preserving the natural landscape of the area. The Cruachan Pumped Storage Plant in the UK is one of the world's first underground pumped storage facilities, with its core power generation and storage facilities built inside a mountain. Although its initial capacity was only 440 MW, this underground design not only reduced the environmental impact on the surface but also allowed the plant to coexist harmoniously with the surrounding natural landscape. The expansion of the Cruachan Pumped Storage Plant is currently progressing steadily, with the peak construction period expected to support around 900 jobs nationwide and provide approximately 300 GW of renewable energy to the grid annually. By 2050, the expansion is expected to save consumers over £350 million in energy costs.

Within the UK's capacity market, the 15-year contract structure provides stable funding for new or refurbished projects. This contract model allows project developers to win long-term contracts through a bidding process, ensuring future market revenue to offset construction and operational costs, thereby incentivizing more social investment.

Japan

In Japan, pumped storage power stations are generally divided into two categories based on the investment entities: one type is developed and managed by independent power developers, while the other is owned by electric power companies. The corresponding operational and revenue models are also divided into leasing and internal grid settlement.

In practice, Japan's Okinawa Yambaru Station is the world's first seawater pumped storage power plant. When it was completed in 1999, it was a pilot project with a capacity of 30 kW. This plant uses seawater as the upper reservoir, aiming to address the energy-balancing needs of areas with scarce water resources. It employs corrosion-resistant materials and advanced water quality management technologies to mitigate the corrosive effects of seawater on the equipment. The plant also prioritizes environmental impact, implementing biodiversity assessments and water quality monitoring measures to minimize damage to the ecosystem. The establishment of this plant marked an innovative application of seawater resources for pumped storage, providing valuable lessons for other coastal regions.

However, it was later decommissioned due to cost and demand issues.

The Kazunogawa Pumped Storage Plant is one of Japan's key underground pumped storage projects, with an installed capacity of 1,648 MW. It adopts a deep underground engineering design, placing some of its facilities deep underground. The plant's underground powerhouse design emphasizes seismic resistance and spatial optimization, making it particularly suitable for areas with complex geological conditions and higher natural disaster risks [48].

Summary and Enlightenment

Overall, the 1970s and 1980s were the golden development periods for pumped storage worldwide, with many economically developed countries beginning to build pumped storage power stations on a large scale. After entering the 21st century, with the slowing economic growth in Western countries such as the U.S. and Europe, the scale of pumped storage power station construction has been limited, primarily focusing on upgrades and retrofits. In contrast, the economic growth in Asian countries has accelerated, driving a strong demand for electricity and a rapid increase in the need for pumped storage power stations. As a result, the focus of pumped storage development has shifted from the West to Asia. The international experience is summarized below from the perspectives of technology, economy, and environment.

In terms of technology, China is currently making significant investments in the construction of pumped storage power stations and will also face the challenge of upgrading and retrofitting these power stations in the future. In Europe and the U.S., upgrades to turbines, main intake valves, and control systems of pumped storage power stations have not only extended their operational life spans but also enhanced their ability to stabilize the grid. China can draw on the unique technological innovations in underground pumped storage in the UK and Japan when constructing pumped storage power stations in mountainous or ecologically sensitive areas. These innovations help optimize plant layout by reducing land usage and minimizing ecological disturbance. Additionally, China is exploring the feasibility of seawater pumped storage. In 2017, China released a survey report on seawater pumped storage, which identified 238 seawater pumped storage sites across 8 provinces, with a total capacity of about 42 million kW. Among these, 14 sites are suitable for immediate experimental demonstration projects. Japan's use of corrosion-resistant materials, monitoring of water quality, marine life impact, and equipment corrosion in similar projects can also provide useful insights.

In terms of the economy, as discussed earlier in the section on the current economic benefits, China's subsidies for auxiliary services in pumped storage are more likely to be provided through government subsidies or added to electricity prices. In contrast, flexible electricity market mechanisms abroad provide diversified revenue sources for pumped storage power stations, which can serve as a model for China's new power system reform. By adopting time-of-use pricing and auxiliary service markets, more profit opportunities can be created for these power stations. The U.S. has developed some pumped storage power stations through public-private partnership models, while the UK's capacity market offers 15-year contracts for newly constructed or refurbished pumped storage power stations. Similar implementation experiences can be promoted in China's medium and long-term electricity market transactions to attract social capital investment in pumped storage projects, improve project financing efficiency, and stabilize economic expectations. Additionally, the economic feasibility challenges faced by seawater pumped storage projects in Japan, such as the high costs of corrosion-resistant equipment and extensive maintenance needs, should be fully considered by China in the future development of pumped storage, with comprehensive economic model evaluations.

In terms of the environment**,** strict environmental monitoring systems are implemented internationally in pumped storage projects, covering both the construction and operational phases. Measures such as ecological management, noise control, and the use of underground cables and powerhouse designs to reduce surface disruption and protect natural landscapes can help China establish higher environmental standards, especially for power stations located in scenic areas or ecologically sensitive regions. These practices are crucial for ensuring the sustainable development of China's pumped storage projects.

Research Prospect

In response to the urgent needs of pumped storage power station development under the new situation and the major scientific issues restricting the utilization of pumped storage benefits in the power system dominated by renewable energy sources, combined with the summary of international experiences, future research should focus on the following four aspects to better display the strategic role of pumped storage in low-carbon energy transformation.

In-Depth Research on the Principles of Pumped Storage Participation in Multi-Energy Complementation Across Multi-Temporal and Spatial Scales

In the future, new pumped storage projects in China will mainly serve the large-scale development of new energy and the need for power export, promoting the integrated construction of wind-solar-hydro-thermal-pumped multi-energy complementation. As an overall operational mode, in order to timely allocate power resources effectively and solve the problems of clean energy absorption and grid fluctuations caused by excessive proportions, it is necessary to combine Internet big data and extend the traditional operation simulation based on typical daily scenarios or the annual 8760 hours to higher temporal resolutions such as multiple years. Thus, it reflects the long-term temporal variations of new energy generation and accurately matches supply and demand information on the power source and load sides to improve the overall efficiency of the power system.

In the planning model, full consideration is given to the compensatory adjustment ability of traditional power sources and pumped storage for new energy. By simultaneously incorporating constraints on long, medium, and short-term flexibility requirements, as well as complex nonlinear operational constraints of power stations with adjustment ability such as pumped storage, and combining the previously obtained temporal data of new energy output, the accuracy of simulation results can be improved.

To address the difficulties in model solving arising from the increased complexity of constraints and variables during the process of improving the reliability of simulation results, a variable scale method can be utilized. This method can be used to decompose large models into several levels and modules based on different temporal and spatial scales and solve the sub-problems step by step. What's more, combined with advanced mathematical methods and intelligent optimization algorithms such as the relaxation technique, dual decomposition, and meta-heuristic algorithm, the solving efficiency of models can be significantly improved.

Vigorously Promoting Innovation and Upgrade of Pumped Storage Technology

In the new power system architecture, innovation and upgrade of pumped storage technology are essential for improving system efficiency, stability, and sustainability. Enhancing the design of pumps and turbines to increase the energy conversion efficiency of pumped storage units can reduce energy losses and the demand for fossil fuels, leading to lower carbon emissions. Utilizing variable-speed drive technology, self-starting can be achieved through AC excitation, replacing external inverters, and back-to-back starting methods. The speed can automatically adjust based on the head width, ensuring optimal operation of the pumped storage units at all times and enhancing operational stability and efficiency. At the same time, it can improve the compatibility with intermittent energy sources such as wind and solar power, better balance the impact of large-scale integration of new energy sources on grid stability, and reduce energy waste and carbon footprint.

The development of underground pumped storage is an attempt to solve the problem of the shortage of conventional pumped storage sites. At the same time, it is necessary to break through the large-scale deep underground geological exploration technology to meet the accuracy of geological exploration. And develop key technologies to ensure the safety and reliability of underground space.

Exploring Market-Oriented Revenue Return Mechanisms That Reflect the Value Contribution of Pumped Storage

Considering the sustainable development of pumped storage in the future electricity market, it is necessary to explore revenue return mechanisms and benefit evaluation systems that reflect the value contribution of pumped storage. Through the establishment of a flexible climbing market and a frequency modulation market with differentiated frequency modulation signals, price competition mechanisms such as on-grid peak-valley electricity prices and ancillary service electricity prices can be perfected. By clarifying the investment return methods, the revenue return for the value of its regulation speed can be realized, further enhancing the economic benefits and operational efficiency of pumped storage power stations.

It is necessary to give pumped storage enterprises the same level of value-added tax preferential policies as hydropower, wind power, photovoltaic power, and nuclear power to enhance the accumulation of pumped storage's own funds and accelerate the speed of industrial development. In the future, power systems dominated by new energy and pumped storage are expected to participate in market competition equally with new energy, traditional generation resources, and load-side resources. With economic efficiency as the goal and safety as the constraint, optimizing the operation of various resources through the electricity market will be an indispensable way to achieve a sustainable low-carbon energy transition in China.

Strengthening Energy and Environmental Management During the Construction and Operation of Pumped Storage Power Stations

While actively promoting renewable energy development, it is essential to accurately quantify the carbon reduction benefits of pumped storage and establish a scientific carbon reduction accounting system and standardized protocols. This will effectively reflect the carbon reduction value of pumped storage. Artificial intelligence and big data analysis techniques should be employed for precise power demand forecasting and intelligent scheduling, optimizing energy storage and release, as well as enabling accurate carbon emission calculations and predictions [49].

Additionally, the development of real-time monitoring systems based on the Internet of Things and artificial intelligence should be prioritized to track the long-term impact of pumped storage power stations on surrounding ecosystems. Water storage facilities with ecological restoration capabilities should be designed, particularly in ecologically sensitive areas or regions with high biodiversity. Furthermore, research into appropriate environmental compensation mechanisms for pumped storage should be conducted to incentivize the implementation of environmental protection measures.

Conclusions

Driven by the "dual carbon" target, the construction of the new power system dominated by new energy faces great challenges in the aspects of grid stability control and the high level of energy absorption brought about by the multi-temporal and spatial uncertainties of new energy. By giving full play to the regulatory function of pumped storage technology in the multi-energy complementary system, it is expected to improve the stability and operation characteristics of the power system and provide strong support for energy transition and sustainable development. This paper provides an in-depth analysis of the challenges posed by multi-temporal and spatial uncertainties in new energy within the evolution of the power system and examines the key technical parameters of various energy storage technologies. Based on the development scale of pumped storage, the study discusses its current research status in China from the perspectives of functional application scenarios, specific technological innovations, economic benefits, and environmental impacts. Subsequently, a multi-objective optimization model is proposed, considering the minimization of net load fluctuations, maximization of economic benefits, and minimization of new energy power abandonment in wind-solar-thermal-pumped storage systems, offering preliminary strategies to address these challenges. Finally, based on the development status and optimization results, this paper explores critical scientific issues necessary for maximizing the benefits of pumped storage across technical, economic, and environmental dimensions. Drawing on international experiences, it outlines key research directions for the future development of pumped storage in China.

The main findings of this study are as follows:

(1) The optimized scheduling model of the wind-solar-thermal-pumped storage combined system proposed in this paper comprehensively considers the three objectives of net load fluctuation, economic benefit, and new energy abandonment. After optimization, the combined system can increase its annual revenue by about 550 million Yuan, and it can additionally reduce carbon emissions by about 180,000 t. This low-carbon and high-efficiency system operation provides a useful reference for the transformation and development of new power systems.

(2) To ensure that pumped storage achieves its full potential in new power systems, critical scientific issues in technical, economic, and environmental dimensions must be addressed. These include: technical path planning issues for pumped storage to support large-scale new energy development, economic benefit issues of pumped storage participation in diversified electricity markets, and issues in assessing the environmental benefit of pumped storage.

(3) To enhance the strategic role of pumped storage in the transition to low-carbon energy systems, future research should focus on four key areas: conducting in-depth research on the principles of pumped storage participation in multi-energy complementation across multi-temporal and spatial scales, promoting innovation and upgrade of pumped storage technology, exploring market-oriented revenue return mechanisms that reflect the value contribution of pumped storage, and strengthening energy and environmental management during the construction and operation of pumped storage power stations.

While this study comprehensively explores strategies for addressing the challenges of new power system transformation and outlines future development directions for pumped storage from both macro and micro perspectives, certain limitations exist in the proposed model. The data coverage primarily considers 24 hourly time intervals within a single day, lacking multi-temporal scale comparisons. The economic benefits of pumped storage are calculated based on the benchmark price of coal-fired power generation, without accounting for startup and shutdown costs of units. As China advances toward its "dual carbon" target, the electricity pricing mechanism for pumped storage will evolve alongside market development, necessitating continuous adjustment of model parameters. Future research will address these issues in greater depth.

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Conflict of Interest

The authors declare no conflict of interest.

References

1. NOTTON G., NIVET M.L., VOYANT C., PAOLI C., DARRAS C., MOTTE F., FOUILLOY A. Intermittent and stochastic character of renewable energy sources: Consequences, cost of intermittence and benefit of forecasting. Renewable Sustainable Energy Reviews, **87**, 96, **2018**.

2. SHI X., QIAN Y., YANG S. Fluctuation analysis of a complementary wind-solar energy system and integration for large scale hydrogen production. ACS Sustainable Chemistry & Engineering, **8** (18), 7097, **2020**.
3. TIAN S., YAO J., YANG Z., XU C., LIU X. Optimal dispatching strategy and evaluation of wind-solar-storage combined power generation system based on hybrid energy storage. Thermal Power Generation, **53** (10), 21, **2024**.
4. WU Z., WANG J., PENG S., ZHANG Y., PAN W., TANG J. Flexibility assessment of ternary pumped storage in day-ahead optimization scheduling of power systems. Applied Sciences, **14** (19), **2024**.
5. NAVAL N., YUSTA J.M., SÁNCHEZ R., SEBASTI F. Optimal scheduling and management of pumped hydro storage integrated with grid-connected renewable power plants. Journal of Energy Storage, **73**, **2023**.
6. ZHANG S., YANG W., LI X., ZHAO Z., WANG R., LI Y. Economic evaluation of Wind-PV-Pumped storage hybrid system considering carbon emissions. Energy Reports, **8**, 1249, **2022**.
7. MA T., YANG H., LU L., PENG J. Pumped storage-based standalone photovoltaic power generation system: Modeling and techno-economic optimization. Applied Energy, **137**, 649, **2015**.
8. 2022 China wind and solar energy resources annual outlook report. Available online: https://www.cma.gov.cn/zfxxgk/gknr/qxbg/202304/t20230421_5454513.html (Accessed on 10 April 2024).
9. NADEEM F., HUSSAIN S.M.S., TIWARI P.K., GOSWAMI A.K., USTUN T.S. Comparative review of energy storage systems, their roles, and impacts on future power systems. IEEE Access, **7**, 4555, **2019**.
10. BOICEA V.A. Energy storage technologies: The past and the present. Proceedings of the IEEE, **102** (11), 1777, **2014**.
11. BEAUDIN M., ZAREIPOUR H., SCHELLENBERGLABE A., ROSEHART W. Energy storage for mitigating the variability of renewable electricity sources: An updated review. Energy for Sustainable Development, **14** (4), 302, **2010**.
12. ROGALEV N., ROGALEV A., KINDRA V., NAUMOV V., MAKSIMOV I. Comparative analysis of energy storage methods for energy systems and complexes. Energies, **15** (24), 17, **2022**.
13. ANEKE M., WANG M.H. Energy storage technologies and real life applications - A state of the art review. Applied Energy, **179**, 350, **2016**.
14. LIU F., CHE Y., TIAN X., XU D., ZHOU H., LI Z. Cost sharing mechanisms of pumped storage stations in the new-type power system: Review and prospect. Journal of Shanghai Jiaotong University, **57** (7), 757, **2023**.
15. HE Y., CHEN Y., LIU Y., LIU H., LIU D., SUN C. Analysis of cost per kilowatt-hour and cost per mileage for energy storage technologies. Advanced Technology of Electrical Engineering and Energy, **38** (9), 1, **2019**.
16. CHATZIVASILEIADI A., AMPATZI E., KNIGHT I. Characteristics of electrical energy storage technologies and their applications in buildings. Renewable and Sustainable Energy Reviews, **25**, 814, **2013**.
17. CHEN H., CONG T.N., YANG W., LI Y., DING Y. Progress in electrical energy storage system: A critical review. Progress in Natural Science, **19** (3), 291, **2009**.
18. LUO X., WANG J., DOONER M., CLARKE J. Overview of current development in electrical energy storage technologies and the application potential in power system operation. Applied Energy, **137**, 511, **2015**.
19. LU H., Research on energy storage plan optimization and comprehensive value measurement in the new power system. Ph.D. dissertation, North China Electric Power University, **2021.**
20. SEBASTIÁN R., ALZOLA R.P. Flywheel energy storage systems: Review and simulation for an isolated wind power system. Renewable and Sustainable Energy Reviews, **16** (9), 6803, **2012**.
21. DÍAZ-GONZÁLEZ F., SUMPER A., GOMIS-BELLMUNT O., VILLAFÁFILA-ROBLES R. A review of energy storage technologies for wind power applications. Renewable and Sustainable Energy Reviews, **16** (4), 2154, **2012**.
22. ZAKERI B., SYRI S. Electrical energy storage systems: A comparative life cycle cost analysis. Renewable and Sustainable Energy Reviews, **53**, 1634, **2016**.
23. AMIRYAR M.E., PULLEN K.R. A review of flywheel energy storage system technologies and their applications. Applied Sciences, **7** (3), 21, **2017**.
24. CHAU K.T., WONG Y.S., CHAN C.C. An overview of energy sources for electric vehicles. Energy Conversion and Management, **40** (10), 1021, **1999**.
25. HU X., ZOU C., ZHANG C., LI Y. TTechnological Developments in Batteries: A Survey of Principal Roles, Types, and Management Needs. IEEE Power and Energy Magazine, **15** (5), 20, **2017**.
26. FAISAL M., HANNAN M.A., KER P.J., HUSSAIN A., BIN MANSOR M., BLAABJERG F. Review of energy storage system technologies in microgrid applications: Issues and challenges. IEEE Access, **6**, 35143, **2018**.
27. GUARNIERI M., MATTAVELLI P., PETRONE G., SPAGNUOLO G. Vanadium redox flow batteries. IEEE Industrial Electronics Magazine, **10** (4), 20, **2016**.
28. TIE S.F., TAN C.W. A review of energy sources and energy management system in electric vehicles. Renewable and Sustainable Energy Reviews, **20**, 82, **2013**.
29. JARNUT M., WERMINSKI S., WASKOWICZ B. Comparative analysis of selected energy storage technologies for prosumer-owned microgrids. Renewable and Sustainable Energy Reviews, **74**, 925, **2017**.
30. LAM L.T., HAIGH N.P., PHYLAND C.G., URBAN A.J. Failure mode of valve-regulated lead-acid batteries under high-rate partial-state-of-charge operation. Journal of Power Sources, **133** (1), 126, **2004**.
31. KYRIAKOPOULOS G.L., ARABATZIS G. Electrical energy storage systems in electricity generation: Energy policies, innovative technologies, and regulatory regimes. Renewable and Sustainable Energy Reviews, **56**, 1044, **2016**.
32. CHO J., JEONG S., KIM Y. Commercial and research battery technologies for electrical energy storage applications. Progress in Energy and Combustion Science, **48**, 84, **2015**.
33. LEUNG P., LI X., PONCE DE LEÓN C., BERLOUIS L., LOW C.T.J., WALSH F.C. Progress in redox flow batteries, remaining challenges and their applications in energy storage. RSC Advances, **2** (27), 10125, **2012**.
34. WEBER A.Z., MENCH M.M., MEYERS J.P., ROSS P.N., GOSTICK J.T., LIU Q. Redox flow batteries: A review. Journal of Applied Electrochemistry, **41** (10), 1137, **2011**.
35. XIE X., MA N., LIU W., ZHAO W., XU P., LI H. Functions of energy storage in renewable energy dominated power systems: Review and prospect. Proceedings of the CSEE, **43** (1), 158, **2023**.

36. MEKHILEF S., SAIDUR R., SAFARI A. Comparative study of different fuel cell technologies. Renewable and Sustainable Energy Reviews, **16** (1), 981, **2012**.
37. GÜR T.M. Review of electrical energy storage technologies, materials and systems: Challenges and prospects for large-scale grid storage. Energy & Environmental Science, **11** (10), 2696, **2018**.
38. ALI M.H., WU B., DOUGAL R.A. An overview of SMES applications in power and energy systems.IEEE Transactions on Sustainable Energy, **1** (1), 38, **2010**.
39. ZHAO Z., ZHAO Q., ZHU F., YU X., HAN D. Pumped Storage Industry Development Report 2022. China Water&Power Press: Beijing, **2023**.
40. SUI X. Global Hydropower Industry Annual Development Report 2021. China Water&Power Press: Beijing, **2021**.
41. CUI Y., HUANG S., MA M., WEI Z., ZHANG S., ZHAO C. Optimal scheduling of renewable energy system considering the regulation characteristics of concentrating solar power station. Renewable Energy Resources, **40** (12), 1636, **2022**.
42. COBAN H.H., REHMAN A., MOUSA M. Load frequency control of microgrid system by battery and pumped-hydro energy storage. Water, **14** (11), 22, **2022**.
43. HU J. Synergistic effect of pollution reduction and carbon emission mitigation in the digital economy. Journal of Environmental Management, **337**, 117755, **2023**.
44. HE Y., LIU Y., LI M., ZHANG Y. Benefit evaluation and mechanism design of pumped storage plants under the background of power market reform - A case study of China. Renewable Energy, **191**, 796, **2022**.
45. XU S., ZHANG G., WANG F., PU L. Study on carbon emission reduction calculation method for pumped storage based on CCER rules. Electric Power, **57** (01), 175, **2024**.
46. DEANE J.P., GALLACHOIR B.P.O., MCKEOGH E.J. Techno-economic review of existing and new pumped hydro energy storage plant. Renewable and Sustainable Energy Reviews, **14** (4), 1293, **2010**.
47. BARBOUR E., WILSON I.A.G., RADCLIFFE J., DING Y., LI Y. A review of pumped hydro energy storage development in significant international electricity markets. Renewable and Sustainable Energy Reviews, **61**, 421, **2016**.
48. NIE Z., XIAO L., QIU Q., ZHANG J. Overview of the development of underground pumped hydro storage. Energy Storage Science and Technology, **13** (05), 1606, **2024**.
49. HU J., ZHANG H., IRFAN M. How does digital infrastructure construction affect low-carbon development? A multidimensional interpretation of evidence from China Journal of Cleaner Production, **396**, 136467, **2023**.