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Pumped Storage Hydropower in Abandoned Mine Shafts: Key Concerns and Research Directions

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Abstract: The quest for carbon neutrality raises challenges in most sectors. In coal mining, overcapacity cutting is the major concern at this time, and the increase in the number of abandoned mine shafts is a pervasive issue. Pumped storage hydropower (PSH) plants built in abandoned mine shafts can convert intermittent electricity into useful energy. However, studies on basic theories and key technologies are a pressing issue. Six key scientific problems have been identified in PSH development in abandoned mine shafts that are relevant to China's national conditions, current resource structure, and relative status of energy storage technologies in China and other countries. It is proposed that the research on pumped storage should move closer to the direction of intelligence, stabilization, and greening, and the construction and development should gradually realize integration, completion, and coordination. The goal is to realize integrated, complete, and coordinated development of PSH in abandoned mine shafts, streamline national policies concerning PSH, drive the co-development of industry, education and research, and achieve the carbon neutrality targets set by China.

Keywords: abandoned mine shafts; pumped storage hydropower; underground reservoir; carbon neutrality targets; energy storage technology

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1. Introduction

China is currently undergoing a transition from a fossil-dominated energy structure to one dominated by clean, low-carbon, new energy technologies. China has committed to peak carbon dioxide emissions by 2030 and achieve carbon neutralization by 2060, which are both fast-approaching deadlines [1–3]. According to the predictions by the International Energy Agency, China needs to cut the proportion of fossil fuel to approximately 20% while raising the proportion of renewable energy to approximately 70% [4–6].

By the end of 2021, China's total energy consumption reached up to 5240 million tons of standard coal equivalent [7–9]. The consumption of non-fossil energies, including natural gas, hydropower, and wind power, accounted for 25.5% this year, which represents an increase of 1.2% compared with the previous year [10,11]. Besides, China's exploitable land-based wind energy is estimated to be 7.2 billion kW [12]. The total annual insolation in regions that are extremely abundant and abundant in solar energy, such as Qinghai-Tibet Plateau, Gansu, Xinjiang, and Inner Mongolia, is equivalent to about 4 thousand trillion kW·h. The installed capacity of exploitable hydropower reaches 540 million kW. The environmental protection requirements for the energy sector are expected to become stricter in the future, accompanied by a sharp decrease in coal consumption and a growing number of abandoned mine shafts.

In the 12th Five-Year Period alone, China had 7100 abandoned coal mines [13–15]. According to the key consulting project of the Chinese Academy of Engineering, titled

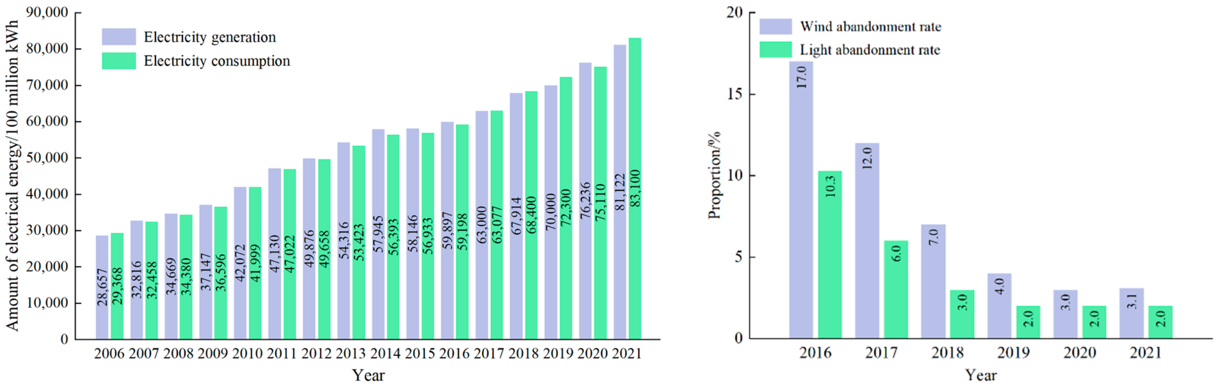
Strategies of High-Efficiency Recovery and Energy Saving for Coal Resources in China, it is estimated that by 2030, China will have about 15,000 abandoned mine shafts [16].

However, a one-size-fits-all strategy is usually adopted for handling abandoned mine shafts [17]. This is contrary to the guiding principles specified in the *Implementation Scheme for Promoting the High-Quality Development of New Energy in the New Era*, namely, the general principles of construction before destruction and the prioritization of overall planning. Considerable resources can be tapped from abandoned mine shafts to reap economic benefits. They offer new pathways for innovation in energy exploitation and utilization and developing new types of power systems. In a word, abandoned mine shafts can be used to solve the "construction" problem as opposed to the "destruction" problem mentioned above. Besides, exploiting these "abandoned" resources may help overcome the drawbacks of existing power systems, such as poor adaptability to connecting large-scale, high-proportion new energy to the grid, consumption of new energy, and limited land resources [18]. Based on this, research on the construction of pumped storage power stations in abandoned mines is carried out, the existing policies are analyzed, the existing problems are determined, and the direction of follow-up research and development are proposed. Provide a theoretical basis for the implementation of the project.

2. Current Development of Energy Storage Technologies

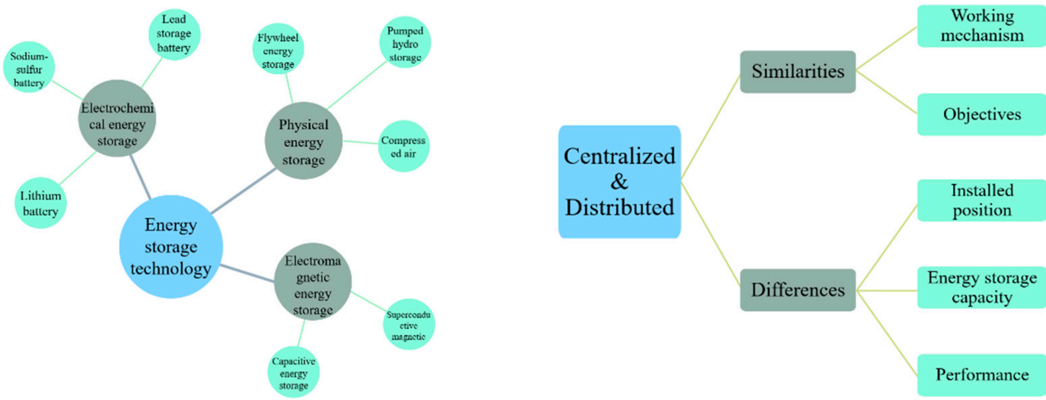
In the context of carbon neutrality, the amount of electricity produced by wind and solar energy will increase from 210 GW and 205 GW, respectively, in 2019 to 480 GW and 570 GW in 2030, and further to 1440 GW and 2160 GW in 2050. In the meantime, by 2035, the peak-valley load difference in China will exceed 1 billion kW [19]. The power system must also cope with the intermittence and fluctuation of electricity generated from new energy sources [20]. Energy storage technologies are regarded as important means to redress the changeability of new energy sources. They also lie at the core of achieving the carbon neutrality commitments by China. However, current electrochemical energy storage technologies are limited either geographically or in terms of scale, economical efficiency, and safety. Little breakthrough has been made in new technologies or techniques in this respect. The cross-regional, large-scale, centralized consumption of new energy can hardly be realized in the present or the foreseeable future. From 2007 to 2017, China's total full-caliber power generation had already exceeded the power consumption [21] (Figure 1a). After 2018, the adjustment of the energy structure has led to an increase in the installed capacity of new energy power generation. However, electricity cannot be efficiently stored during the off-peak period during the low period, and the wastage rates of wind and solar energy are surprisingly high (Figure 1b). The increasing peak-valley load difference indicates the contradictions between electricity demand and allocation. In this context, energy storage systems offer an efficient method for new energy development and grid connection [22].

At present, energy storage technologies can be roughly divided into three categories depending on the storage method (Figure 2a). Electrochemical energy storage is the most widely used, though its short service life is a defect that cannot be overlooked. Energy storage can be divided into two types based on scale (Figure 2b). Centralized energy storage has a scale that varies between several megawatts and hundreds of megawatts, with a longer discharge time [23]. By contrast, the scale of distributed energy storage is much smaller than that of centralized energy storage and varies between a few kilowatts to several megawatts.



(**a**) (**b**)

Figure 1. Electrical energy wastage. (**a**) Full-caliber total power generation and power consumption; (**b**) Average wind and light wastage rate in China.



(**a**) (**b**)

Figure 2. Energy storage technologies. (**a**) Energy storage methods; (**b**) Scale of energy storage.

In 2019, the total global energy storage capacity was 184.6 GW, with PSH capacity reaching 170.9 GW and accounting for 92.6% [24]. The electrochemical energy storage capacity was 9.6 GW, accounting for 5.2%. According to the statistics of China Energy Storage Alliance (CNESA) in 2021, PSH accounted for 86.3% of China's total energy storage capacity, new energy storage capacity accounted for 12.5%, and the rest accounted for 1.2% (Figure 3). Different types of energy storage are different in response speed, energy density, efficiency, life, and economic cost (Table 1). However, in the actual selection process, the environment required for construction and the scale of power storage that can be achieved is often considered. Although the new energy storage method has the advantages of fast response and high efficiency, its scale is limited, and the environmental requirements are high. PSH is the dominant energy storage technology globally. Technically mature large-scale PSH is the most practicable and reliable new energy source for large-scale, concentrated consumption in the present and the future. At the same time, the underground space contained in abandoned mines can save the initial investment in the construction of PSH, and the deep space is more conducive to the preservation of water sources.

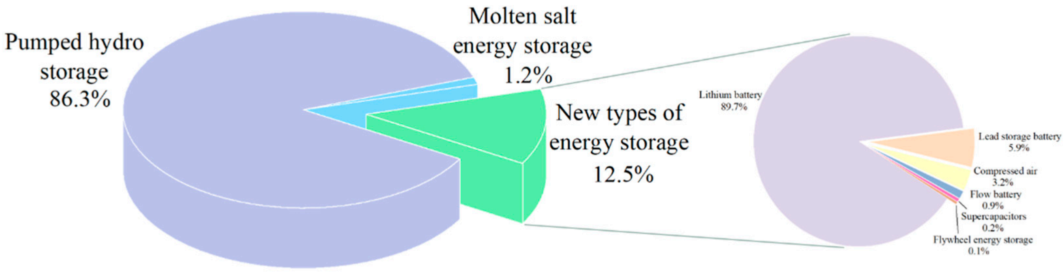


Figure 3. Proportions of installed capacity of different energy storage methods in China in 2021.

Table 1. Comparison of different energy storage technologies.

Energy Storage Technology	Response Rate	Efficiency/%	Cycle Life/Times	Cost/(Yuan·kW^{-1})	Intended Use
PSH	Second to minute scale	75–85	>10,000	1000–6000	Large-scale energy restoration to improve the reliability of power supply
Electrochemical energy storage	Millisecond scale	60–95	2500–3000	2000–3000	As a backup and for frequency modulation to improve the reliability of power supply
Compressed-air energy storage	Second to minute scale	80	>10,000	3000–4000	Using the peak load shifting strategy to improve the reliability of power supply
Thermal energy storage	Second to minute scale	50–90	>10,000	500–4000	Consuming the renewable energy and using the peak load shifting strategy
Hydrogen energy storage	Second scale	25–85	1000	2000–50,000	Consuming the renewable energy and achieving seasonal energy storage

3. Development of Pumped Hydro Energy Storage at Home and Abroad

3.1. Advantages of a PSH Plant

PSH plant is a special type of hydropower plant that can store electric energy. It is composed of an upper water reservoir, water transport system, generator set, water pump, and lower water reservoir. There are three types of reservoirs depending on the position, namely, entirely above the ground, semi-underground, and entirely underground [25].

The PSH plant uses water for energy conversion between the turbine and the pump. The water is pumped using surplus electric energy so that the water in the lower reservoir gains potential energy during the off-peak period by being transported and stored in the upper reservoir. When the load demand increases sharply, water will be released from the upper reservoir to the lower reservoir and flows down through a turbine that generates electricity (Figure 4). Thus, the peaks and valleys are reduced, and the power consumption profile is flattened, while the water can be used repeatedly in the PSH plant [26].

The National Energy Administration has explicitly pointed out in the *Pumped Storage Medium and Long-Term Development Plan 2021–2035* that "PSH plants fulfill multiple functions, including peak regulation, valley filling, frequency regulation, phase regulation, energy storage, backup for accidents, and black start. PSH plants are an integral part of the power system that is clean, low-carbon, safe, reliable, smart, flexible, economical, and highly efficient" [27].

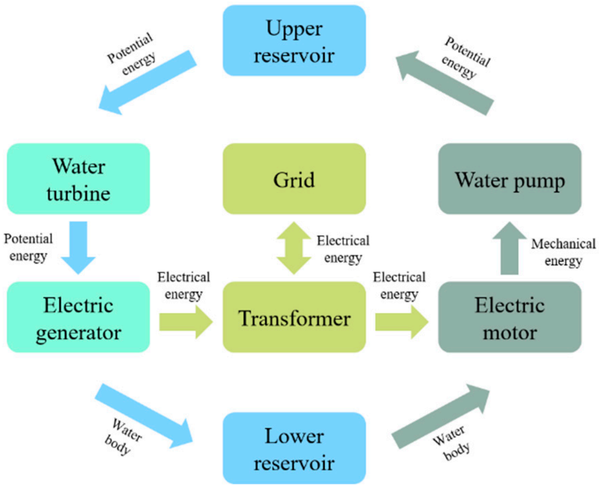


Figure 4. Schematic diagram of energy conversion.

The PSH plant reallocates the electric generation capacity of the power system temporally and reconciles the contradictions between power generation and power consumption. However, energy loss seems inevitable during the energy conversion process. The power generation efficiency of a PSH plant can reach 75–80% [28,29]. Relative economic efficiency is the practical consideration when the entire PSH system is concerned. Considering this, a PSH plant can be built in the abandoned mine shaft to dramatically reduce the construction and investment and simplify the water pipeline layout.

A PSH plant in an abandoned mine shaft utilizes the difference in elevation between the upper and lower reservoirs (Figure 5) to store and convert energy. It operates basically as a conventional PSH plant, except that the water storage facilities and the reservoir lie underground. The abandoned mine shaft provides the space required for water storage, and there is no need to do the rebuilding. Moreover, building a PSH plant in an abandoned mine shaft does not require surface land resources or damage the surface environment. It is estimated that the total installed capacity of conventional PSH plants in China will be 110 GW in 2030. Meanwhile, there will be about 15,000 sites suitable for building mineshaft-based PSH plants, with an installed capacity of approximately 1800 GW. These statistics suggest a huge market potential [30–32].

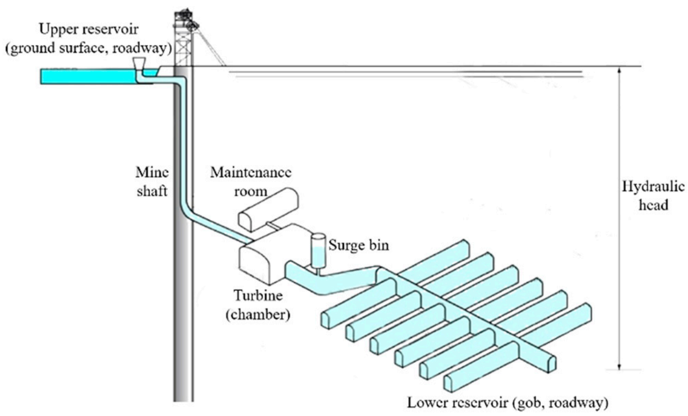


Figure 5. Schematic diagram of PSH in an abandoned mine shaft.

3.2. *Current Status of PSH in Abandoned Mine Shafts at Home and Abroad*

The world's first PSH plant that utilizes an abandoned mine shaft was built in the Prosper-Haniel hard coal mine in Germany [33]. This coal mine has a horizontal underground roadway that extends for approximately 25 km. The roadway depth is 1.2 km, and the water storage capacity reaches 1 million m^3. Germany also plans to build a fully underground PSH plant in Upper Harz, where an abandoned metal mine with a roadway with a diameter of 3.5 m and depth of 760 m is used as an underground reservoir. The reservoir capacity is estimated to be 250,000 m^3, and the installed capacity is 100 MW.

In New Jersey, US, a semi-underground PSH plant of 1000-MW capacity has been built in an abandoned iron-ore mine 760 m deep. The Eagle Mountain PSH project in California has been built by utilizing two abandoned mine pits, one upper and one lower, with an installed capacity of 1300 MW. The mine water inrush in the Asturian coal mine in Spain is exploited as the water source to build a semi-underground PSH plant. South Africa has converted an abandoned gold mine into a cascade PSH plant (Table 2).

Table 2. Design parameters of PSH plants constructed in abandoned mine shafts in the world.

Name	Type	Hydraulic Head/m	Capacity of Water Reservoir/km^3	Power/MW	Reservoir Capacity/MWh
Asturian coal mine in Spain	Semi-underground	300–600	170	23.52	141
FWR in South Africa	Fully underground	1200–1500	1000	1000	6800
Prosper-Haniel coal mine in Germany	Semi-underground	560	600	200	820
Grund ore mine in Germany	Semi-underground	700	260	100	400

In China, a demonstration project commenced in the Shenhua Daliuta coal mine in 2010. Thirty-two underground reservoirs have been completed so far, with a total capacity reaching 31 million m^3, making it the only underground reservoir group built in coal mines. In 2022, Shandong Province plans to invest a total of 3.3 billion RMB in building a 0.3 million-kW agro-optical complementary power station and a 0.2-million-kW PSH plant in the abandoned mine pits in Zichuan [34,35].

At present, the design of a PSH plant in coal mines is influenced by several factors, including geological conditions and mine structure. However, the PSH plant may adapt poorly to varying mine conditions, and the technical bottleneck for the large-scale application of PSH plants in coal mines still exists.

3.3. Domestic Policies for the Development of PSH

Several favorable policies have been issued by governments and relative authorities at various levels as the importance of energy storage technologies, especially PSH has been growing (Table 3). *The 14th Five-Year Plan for Scientific and Technological Innovation in the Energy Sector* lists PSH technology as the primary field of innovation in energy storage technologies. It also points out that by 2025, these energy storage technologies will enter the stage of large-scale commercialization.

In the meantime, reforms of the grid market are also underway. The National Development and Reform Commission has released a *Notice on Intensifying the Action Plan for Tariff Mechanism Reform During the 14th Five-Year Period* to accelerate the implementation of the tariff mechanism for PSH. The document titled *Opinions on Further Improving the Price Formation Mechanism of Pumped Storage* proposes competition-oriented electricity price formation and specifies the electricity price allocation mechanism for PSH.

So far, 23 provinces in China have released policies that urge the construction of energy storage facilities suitable for new energy generation. There is also a mandate for distributed energy distribution and storage. Building PSH plants in abandoned mine shafts are high on the agenda [36].

Table 3. Summary of policies related to PSH.

Time	Institution	Policy	Contents
31 May 2022	State Council	*A package of policy measures to stabilize the economy*	To construct a series of PSH plants that will considerably promote power system security and large-scale development of new energies
10 Aug 2021	State Development and Reform Commission, National Energy Administration	*Notice on encouraging renewable electricity generation enterprises to self-build or purchase peak shaving capacity to increase the grid-connected scale*	To encourage electricity generation enterprises to self-build or purchase peak shaving capacity
23 Jul 2021	State Development and Reform Commission	*Notice on tasks for coping with the summer peak season of energy consumption in 2021*	To greatly boost the accelerated PSH development and new types of energy storage
11 Jul 2021	National Energy Administration	*Notice on the development and construction of wind and PV power in 2021*	To connect to grid the flexible regulation capacity for the newly generated PSH, new types of stored energy, and adjustable load
13 Mar 2021	State Council	*Outline of the 14th Five-Year Plan for National Economic and Social Development and Vision 2035 of the People's Republic of China*	To speed up the construction of PSH plants and the large-scale application of new energy storage technologies
28 Jul 2020	State Council	*Outline of the Integrated Regional Development of the Yangtze River Delta*	To study and establish the cost allocation mechanism for the market-oriented operation of PSH in East China Power Grid
18 Jun 2020	State Development and Reform Commission, National Energy Administration	*Guiding opinions on guaranteeing energy security in 2020*	To proactively promote the construction of power sources with peak-shaving capacity, such as PSH plants and leading hydropower stations
23 Mar 2018	State Development and Reform Commission, National Energy Administration	*Guiding opinions on upgrading the regulation capacity of the electric power system*	To speed up the construction of the PSH plants that have been approved and for which the sites have been planned and recommended and conduct a new round of site-selection planning
30 Jun 2017	State Development and Reform Commission, Ministry of Commerce	*Negative List for Foreign Investment Access*	To continue encouraging the construction of large-scale PSH generators with a rated power of 350 MW and above

4. Key Scientific Issues in PSH Development in Abandoned Mine Shafts

To achieve carbon neutrality targets, China needs to speed up infrastructure construction for PSH exploitation in abandoned mine shafts. Concerted efforts will be made to initiate supply-side energy reformation, with a prioritization of energy regulation and a shift of focus from cutting down emissions alone to popularizing clean energy. The above measures are not only conducive to solving the existing ills in China's energy sector but will also revolutionize China's energy structure, energy planning, grid operation, and clean energy consumption. Several scientific problems need to be tackled during the implementation of PSH projects in abandoned mine shafts.

4.1. Evaluation Model for Site Selection of PSH Plants in Abandoned Mine Shafts

There is considerable variability in the construction of abandoned mine shafts across the mining areas due to historical reasons. We need to study the factors specific to abandoned mine shafts and summarize the conditions for PSH exploitation in abandoned mine shafts that have distinct geographical, sectoral, and technical features. It is necessary to build a mature evaluation system for PSH exploitation and utilization and propose a set of criteria for site selection in such PSH projects.

4.2. Purifying Minewater That Has Complex Components

The hydrodynamic and chemical profiles in the region change dramatically after the mines are closed. This will cause pollution of reservoir water sources, threatening normal operation and shortening the service life of the equipment. Purification technologies for water sources in abandoned mine shafts should be developed extensively; samples from mine water sources in the five major regions should be collected and analyzed for the chemical composition of mine water; the key purification parameters for each ingredient should be determined, and the influence of these components on PSH facilities should be analyzed. It is necessary to investigate the impact of mine water on the environment and soil in the upper reservoir and to determine the changes in composition during the cycle of the upper and lower reservoirs. New types of purification reagents must be developed to improve the water quality and timeliness of purification while decreasing the operating cost.

4.3. Clarifying the Evolutionary Mechanism of Groundwater Storage Coefficient for Transparent Mines

Data-driven health status evaluation and prewarning technology and suitable platforms should be proposed for the mining group, along with key equipment for the specific working environment (deep water and deep land, water-air alternation, and difficulty in manual operation) based on the precise detection and smart monitoring technology for underground spaces. We should analyze the structure and characteristics of underground water reservoirs to determine the spatial variation pattern of underground water reservoirs in abandoned mine shafts as space and time evolve and achieve dynamic feedback and regulation of the operation of PSH plants in abandoned mine shafts.

4.4. Assessing the Stability of Water Reservoirs under the Action of Long-Term Infiltration and Surging

Underground water reservoirs of PSH plants in abandoned mine shafts should satisfy the dual requirements of impermeability and stability. PSH plant reservoirs are subjected to long-term infiltration and cycling. It is necessary to reveal the mechanism of corrosion-induced weakening of the coal pillar dam body during water-rock ion exchange, analyze the influence of hydraulic shock on the mechanical parameters of the reservoir dam body, investigate the mechanism of fissure development under high surrounding rock stress, and build the multi-field coupled mechanical model for the reservoir dam body in abandoned mine shafts.

4.5. Proposing the Dispatching and Operating Model for PSH Plant Group in the Abandoned Mine Shaft

Although the total underground spaces of abandoned mine shafts are massive, the spaces in roadways and chambers are limited, which entails the use of distributed mode at both the planning and operational stages. We should study grid operation in both the peak and off-peak periods corresponding to varying availability of wind and solar energies, specifically, the conditions for electricity generation and consumption based on one day, ten days, and three months. The coupled factors that influence the operating environment of distributed underground water reservoirs should be considered, and the dispatching and operating mode for the PSH plant group in abandoned coal mines should be established.

4.6. Establishing Grid-Level Energy Transmission Mode for PSH Plant in Abandoned Mine Shafts

When the PSH plant is connected to the grid, the diesel generators and gas turbine generator set will be used as the backup power. PSH can be used to lower the peak and raise the valley to smooth out the fluctuations in power production by the photovoltaic system. Therefore, the entire renewable energy system will become more stable and efficient. When the PSH plant is disconnected from the grid, the PSH and light energy will complement each other, balance the electricity demand and supply and guarantee the maximum consumption of electricity generated by the photovoltaic system. The above-described design is crucial to sustaining the stable operation and development of the microgrid. We should also push ahead with the grid access management system for PSH in abandoned mine shafts and carry out the demonstration project for cluster PSH plants in abandoned mineshafts. The grid-level construction of PSH plants in abandoned mine shafts should be optimized based on the grid constraint conditions, real-time electricity pricing strategy, and instructions from dispatching institutions.

5. Potential Research Fields and Development Directions of PSH in Abandoned Mine Shafts

In order to realize carbon neutrality targets and resource reuse in abandoned mine shafts, studies on PSH development should be oriented toward intelligence, stabilization, and greening. Moreover, PSH development in abandoned mine shafts should also be aimed at integration, completion, and coordination (Figure 6).

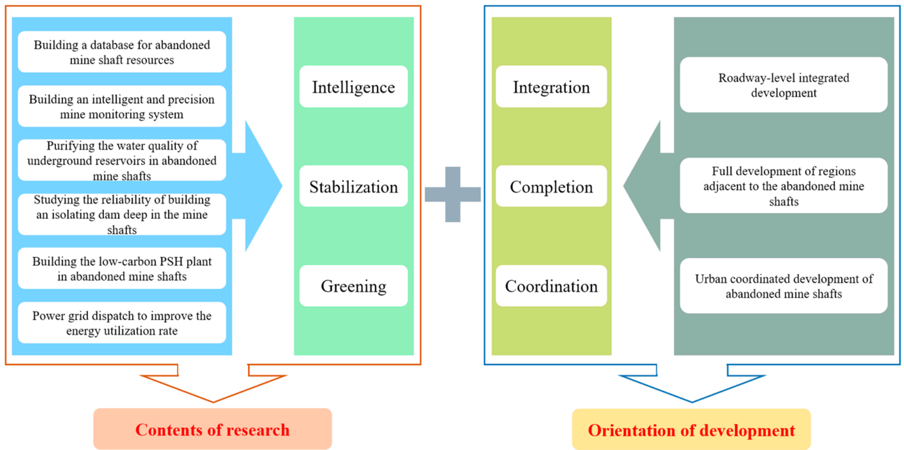


Figure 6. Framework of the contents of research and orientation of the development of PSH in abandoned mine shafts.

5.1. Thrust Areas of Research

5.1.1. Building a Database of Abandoned Mine Shaft Resources

Government authorities should take the lead, and industry should offer assistance for exhaustive research into the distribution, residual resources, and historical development of abandoned mine shafts in China. Enterprises in this industry should cooperate with government authorities and relevant parties in the above study. A database should be built regarding China's abandoned mine shafts to facilitate easy availability and exchange of information, which can lay a solid foundation for the regional, diversified planning and development of energy storage technologies and facilities.

5.1.2. Building an Intelligent and Precision Mine Monitoring System

Five major regions will be considered in the research. A survey will be conducted underground after the mine shafts stop operation, with full consideration of the regional geological features and the differences in the mining system. Real-time prospecting will be combined with numerical simulation to build a 3D visualization model for the abandoned mine shaft.

IOT-based monitoring equipment specific for underground water reservoirs in abandoned mine shafts should be developed for real-time capture-feedback-response. A health status evaluation method for PSH electromechanical equipment will be needed to provide data support for the maintenance and operation of the PSH plant in the abandoned mine shaft.

5.1.3. Improving the Water Quality of Underground Reservoirs in Abandoned Mine Shafts

We should analyze the water quality of typical water sources in mine shafts and determine the influence of underground water reservoirs on water sources. Deep purification technology for mine water with complex compositions must be investigated, and a comparative analysis of the influence of chemical reagents on the reservoirs and power generation equipment must also be carried out. The variation law of key purification parameters of underground water reservoirs in abandoned mine shafts must be determined.

We should push forward the research and development of water purification products to address water quality-related problems discovered on site; study the mechanism of ionic corrosion in mine water; establish grading indicators for mine water in abandoned mine shafts; summarize the advantages and disadvantages of each purification technology; analyze the key influence factors of the timeliness of water purification, and propose a composite influence model for mine water purification.

5.1.4. Improving the Reliability of Dam Construction Deep in the Mine Shafts

In underground dam construction, we should fully consider the effects of the underground stress environment, long-term water infiltration, and periodic shock. It is also necessary to analyze the mechanism of the hinged joint between the coal pillar and artificial dam body and optimize the reservoir dam body structure; investigate the mechanism of periodic water infiltration to induce the weakening of the reservoir dam body and develop an anti-seepage construction process for the dam body; determine the mechanical performance of underground coal pillar-artificial dam body, and build a mathematical model for underground reservoir stability.

We can perform indoor laboratory tests, theoretical analyses, and numerical simulations to reveal the damage mechanism of the dam body under different hydraulic pressures, classify the working conditions of the PSH plant, consider the impact caused by a surge to underground reservoirs, and determine the reliability indicators of the coal pillar dam body.

5.1.5. Building a Low-Carbon PSH Plant in Abandoned Mine Shafts

The construction of PSH plants in abandoned mine shafts can improve the comprehensive utilization rate of resources and promote social and economic development. During the construction process, we should give full consideration to the following aspects: regional water and soil loss, water quality degradation, balancing the contraindications of social development and ecological protection, constructing demonstration low-carbon projects, and adhering to the operating principles of precise management and sufficient implementation; practicing the water liability system, with the local government as the main actor to construct a management system that clearly defines the responsibility of each party and facilitates coordination and supervision. Such a liability system is highly important for the orderly construction of PSH plants in abandoned mine shafts.

5.1.6. Improving the Utilization Rate of Energy Generated by the Cluster Generator Set

Stand-alone medium- to small-sized power stations will serve as basic units in abandoned mine shafts. A clustered layout will be used if necessary. The PSH generator sets should be coordinated efficiently to fully utilize small reservoirs, such as distributed loads and ease of monitoring. The regulation ability of reservoir capacity can be increased through clustered reservoirs.

We should optimize the regional grid, prevent the wastage of solar energy and wind, improve load dispatch of regional grids, enhance information collection for electricity generated from new energy sources, optimize dispatch efficiency, build and improve multi-energy coordination optimization control technology, and reasonably allocate the power generation from wind, solar, and hydraulic energies across time periods in the grid and determine the proportion of energy storage and amount of energy transmission for each renewable energy source.

5.2. Main Orientations of Development

5.2.1. Roadway-Level Integrated Development of Abandoned Mine Shafts

Based on existing shafts and roadway spaces in abandoned mine shafts, we should estimate the underground water capacity and choose the mode of construction for the upper and lower reservoirs, depending on the geological and hydrological conditions of the mine shafts, take measures to ensure the stability and impermeability of the reservoirs, overcome problems associated with basic science in PSH exploitation in abandoned mine shafts, accomplish the PSH demonstration projects in several abandoned mine shafts, and release supportive regulations on PSH development in abandoned mine shafts. Form a pumped storage power station as the core, and build an integrated base for diesel power generation, gas power generation, and photovoltaic power generation in abandoned mines to provide power protection for production and life (Figure 7).

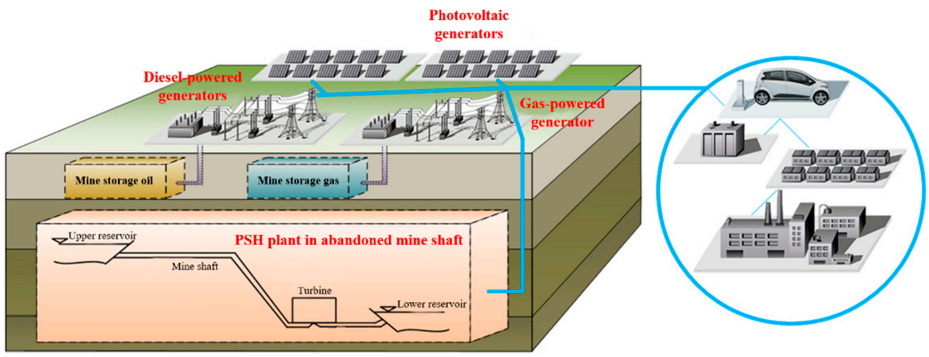


Figure 7. Integrated development.

5.2.2. Full Development of Regions Adjacent to Abandoned Mine Shafts

PSH plant trial projects can be launched in several abandoned mine shafts with stable geological conditions and favorable downhole transformation conditions (Figure 8). The transformation projects for PSH development in abandoned mine shafts lie at the core, while ecological restoration, new energy construction, and grid service facilities may be built near the abandoned mine shafts. One goal is to complete a series of engineering projects for large-scale energy storage to create a profitability system centered around the mining area. The main aim is to peak carbon dioxide emissions by 2030.

Figure 8. Full development.

5.2.3. City-Level Coordinated Development of Abandoned Mine Shafts

Based on abandoned mine shaft groups around China's resource-depleted cities, a series of underground energy storage projects will be built. Thus, several regionally distributed smart energy systems where renewable (light, hydraulic, wind, gas) and conventional energy sources and thermal energy that complement each other will be formed (Figure 9). Resource-depleted cities may thus be transformed, driven by the regional industrial chain and accompanied by the resettlement of mining-related populations. A national-level underground energy storage cloud based on PSH plants in abandoned mine shafts will be built, thereby laying the foundation for large-scale energy storage to meet China's carbon neutrality targets in 2060.

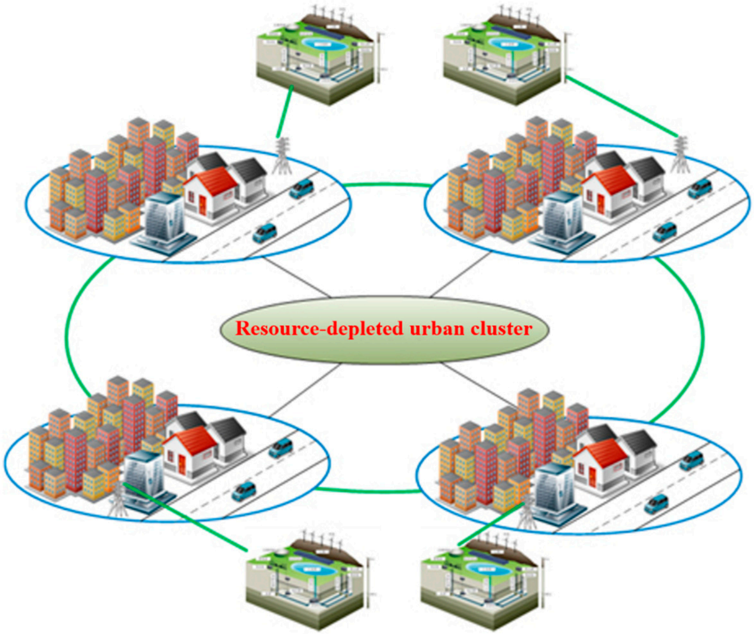


Figure 9. Coordinated development.

6. Outlook

China is riding a new wave of scientific and technological innovation and industrial transformation. The coal sector is facing the greatest period of change in a hundred years. To achieve carbon peaking and carbon neutrality targets, China needs to establish the full life cycle of coal mines and formulate and implement technological strategies for the transformational development of abandoned mine shafts. In the meantime, China should fully encourage new energy development, plan and construct a series of demonstration PSH plants, and push forward studies in relevant fields.

China should also step up efforts in the following aspects as resource development in abandoned mine shafts proceed: carry out a census of abandoned mine shafts; develop standards for resource development and utilization in abandoned mine shafts; enhance top-level design and policy guidance; promote safe, low-carbon development and utilization of PSH resources in abandoned mine shafts and the innovation of relevant technologies to upgrade the scientific and technological support capabilities; prioritize energy exploitation and utilization in abandoned mine shafts; focus on constructing abandoned mine shaft exploitation and utilization platform and talent cultivation; and achieve international leadership in relevant technologies through research, thereby making China a strong presence in cutting-edge energy science.

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