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Smart microgrid construction in abandoned mines based on gravity energy storage

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ABSTRACT

The share of new energy in China's energy consumption structure is expanding, posing serious challenges to the national grid's stability and reliability.As a result, it is critical to construct large-scale reliable energy storage infrastructure and smart microgrids. Based on the spatial resource endowment of abandoned mines' upper and lower wells and the principle characteristics of the gravity energy storage system, an intelligent microgrid system model for abandoned mines based on gravity energy storage is proposed, and the system's feasibility and key influencing factors are discussed and analyzed from the standpoint of economic benefits. The gravity energy storage system principle, system structure, subsurface powerhouse, underground storage, and transit system are all examined and analyzed.The viability of establishing intelligent microgrid systems in abandoned mines is proved using the resource conditions, technical conditions, economic advantages, and social benefits of Panyidong Mine in Huainan Coal Mine.The findings indicate that the project concept has good economic and social benefits as well as practical viability.Next, from the perspectives of technology, policy, and the ecological environment, several recommendations for the development of a smart microgrid system based on gravity energy storage power station are made. This study presents a novel concept for the advancement of energy storage technology and the reuse of abandoned mine resources, which is critical to the long-term development of abandoned mine resources and the advancement of energy storage technology.

1. Introduction

To combat global warming, China is actively optimizing the energy supply and consumption structure and promoting the implementation of the "double carbon" strategy [1], and the share of renewable energy generation in total power generation will reach 29.8 % by the end of 2021 [2], There is an urgent need to develop large-scale and high-stability energy storage technologies. The existing energy storage technology is affected by various factors such as site, environment, abrasion, and corrosion [3].

With the depletion of coal resources and the technological advancement of the coal industry, thousands of coal mines have been abandoned [4] but they are still endowed with adequate space, water, geothermal, and other resources [5], providing an important foundation for the reuse of abandoned mines. At the same time, the massive drop between the shaft and the abundant space resources [6] provide new development space for energy storage technology [7], and researchershave paid close attention to study on the reuse

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of abandoned mines.The Leyden abandoned coal mine in the United States was the first to construct the world's first abandoned mine gas storage facility in the nineteenth century [8]. Germany [9] and Spain [10] have both conducted design studies on the reuse of abandoned mines.Given the physical dimensions of an abandoned mine in the Midlands, UK, Thomas [11] investigated the relationship between the size of the suspended object's weight and the power stored before maximizing the stored energy.Jean-François et al. [12] built a mathematical model for an abandoned mine in Belgiumto study the feasibility of gravity energy storage in abandoned mines in terms of cost effectiveness. The study of abandoned mines in China beganlate.GuDazhao [13] proposed and successfully implemented a design concept for underground water reservoirs in coal mines based on the Shendong mining area. Huai'an Jintan area [14] converts abandoned salt cavities into underground gas storage with a capacity of 50 million m3; Xuzhou Pan'an Lake constructs a minepark [15], Datong [16] and Huainan [17] construct water photovoltaic power plants, thereby launching the treatment of abandoned mine collapse areas; Mostafa [18] establishes a theoretical model of gravity energy storage design parameters based on MATLAB SIMULINK , the energy storage rate optimization study was carried out by Taguchi and ANOVA technology. Julian David Hunt [19] proposes a new storage concept called Mountain Gravity Energy Storage (MGES) that could fill this gap in storage services; GezhoubaZhongke Energy Storage Technology Company [20] proposes a new type of energy storage To summarize, it is critical to conduct research and development of energy storage technology for abandoned mines due to China's massive demand for energy storage and abundant abandoned mine resources.

Pumped storage is now recognized as the most mature, dependable, cleanest, and cost-effective method of energy storage [21] However, in the process of retrofitting abandoned mines as pumped storage, site selection [22] impermeability [23] and construction scale [24] are still constrained to varying degrees. Based on this, this paper proposes an abandoned mine smart microgrid system based on gravity energy storage technology's technical advantages and combining it with abandoned mines [25].Using the Huainan Pan Yidong Mine as an example, a method of using abandoned mines to build gravity energy storage power plants is proposed based on the principle of gravity energy storage technology, and on which the concept of smart microgrid system is proposed, and an economic optimization model is constructed.

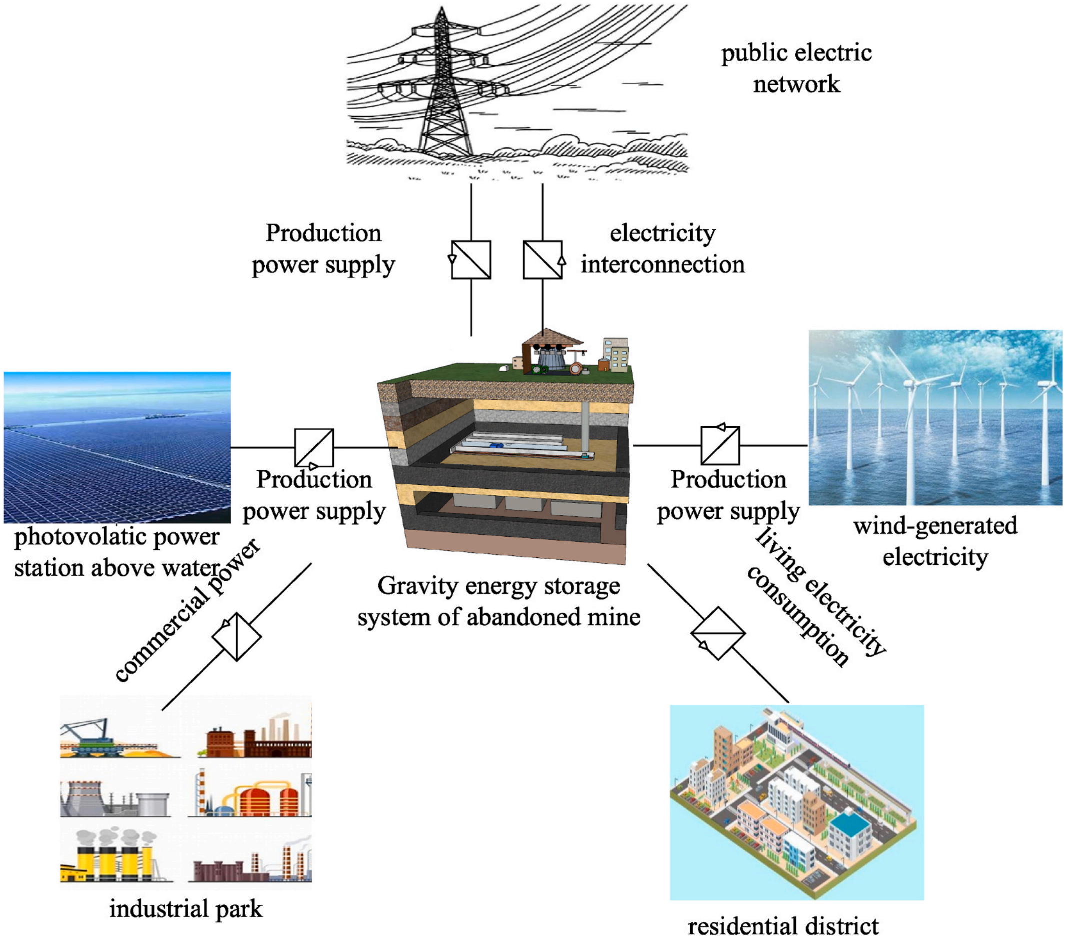

Fig. 1. Abandoned mine smart microgrid system.

2. Smart microgrid system for abandoned mines

The abandoned mine smart microgrid system is presented, which has the functions of peak shaving and valley filling, frequency regulation, and voltage regulation, based on the resource conditions of abandoned mines and the technical principle of new gravity energy storage.

2.1. Overview of smart microgrid system

Renewable energy has grown considerably in recent years. It exhibits volatility and intermittency, which has a significant impact on the stability of the national grid [26].As a result, a smart microgrid with safety, stability, and strong regulating capability is urgently required. The smart microgrid system is primarily deployed by the national grid and provides energy storage with the nearby new energy power plants in order to meet the goal of delivering production and living electricity while also stabilizing the national grid.An intelligent microgrid system for abandoned mines is presented in order to make logical use of the abundant resources left after mine closure (Fig. 1).

2.2. Overview of abandoned mine gravity energy storage power station

A new sort of large-scale energy storage plant is the abandoned mine gravity energy storage power station. It features a simple concept, a low technical threshold, good reliability, efficiency, and a huge capacity [27]. The abandoned mine gravity energy storage power station lifts the weight through a specific transportation system to drive the generator set to meet the purpose of mutual conversion of gravitational potential energy and electric energy [28] (Fig. 2) .Gravity energy storage in abandoned mines works on

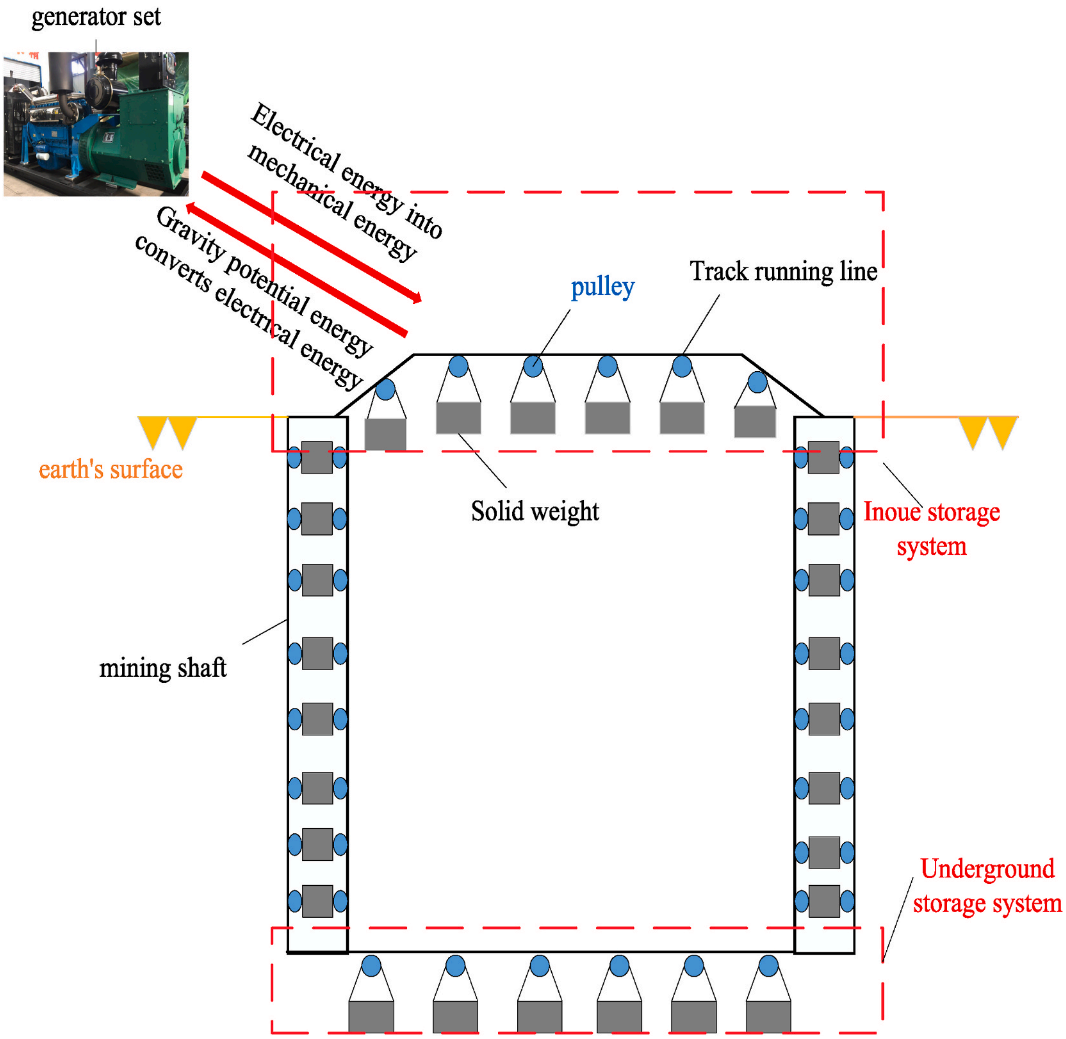

Fig. 2. Working principle diagram of suspended gravity energy storage.

the same principles as pumped storage power stations. Several issues should be considered during the construction process, including the above-ground plant's construction area and the number of gravity blocks, the installed capacity of the power station and the underground utilization space, the quality of the storage block, and the rail transportation's bearing capacity.

2.3. Intelligent microgrid system of abandoned mine based on gravity energy storage power station

A model of intelligent microgrid system in abandoned mines (Fig. 3) is presented to realize the new energy storage use of abandoned mines and the development of intelligent microgrid system in mining areas, in order to fulfill the goal of multi-energy complementary transformation [29].Fig. 4 depicts the essential design contents and characteristics. Abandoned mines offer a lot of space resources, and surface subsidence areas, industrial plants, coal bunkers, and other things have a lot of potential for transformation [30]. The key parameters of the intelligent microgrid system in abandoned mines mainly involve the construction and operation design of gravity energy storage power station, photovoltaic power station and wind power station, including the site selection, installed capacity, coordinated operation and operation monitoring of the three power stations. Among them, the gravity energy storage power station is the coordination center of the entire microgrid. It consumes the electric energy generated by the photovoltaic power station and the wind power station, and uses the difference between day and night electricity prices to generate surplus electric energy, which is in parallel with the power grid to provide production and living electricity. Photovoltaic power station and wind power station provide production electricity for gravity energy storage power station, and consume their own energy. They are used to construct gravity energy storage power plants, solar power plants, and wind power plants. In existing mines, solid gravity blocks are manufactured by combining coal gangue carried from coal mining, other metal solid wastes, and concrete. Using the ground workshop and the generator set as the well storage system, the gravity block is placed in the ground workshop. Using the ground workshop and the generator set as the well storage system, the gravity block is placed in the ground workshop. The abandoned coal mine's underground goaf and highway chamber have a wide space and a stable structure. To build the subterranean storage system, the track transportation system is installed in the subsurface space. The special track is installed in the abandoned mine's main and auxiliary shafts, and is supplemented by an intelligent monitoring and control system to form a reliable transportation system, allowing the gravity block to be lowered or lifted, and cooperating with the circulating track transportation on the well and the underground monorail crane transportation to allow for circulating transportation on the well and underground.

3. Systematic economic assessment models

Economic analysis is a critical component of determining the viabilityof the abandoned mine smart microgrid system.The potential

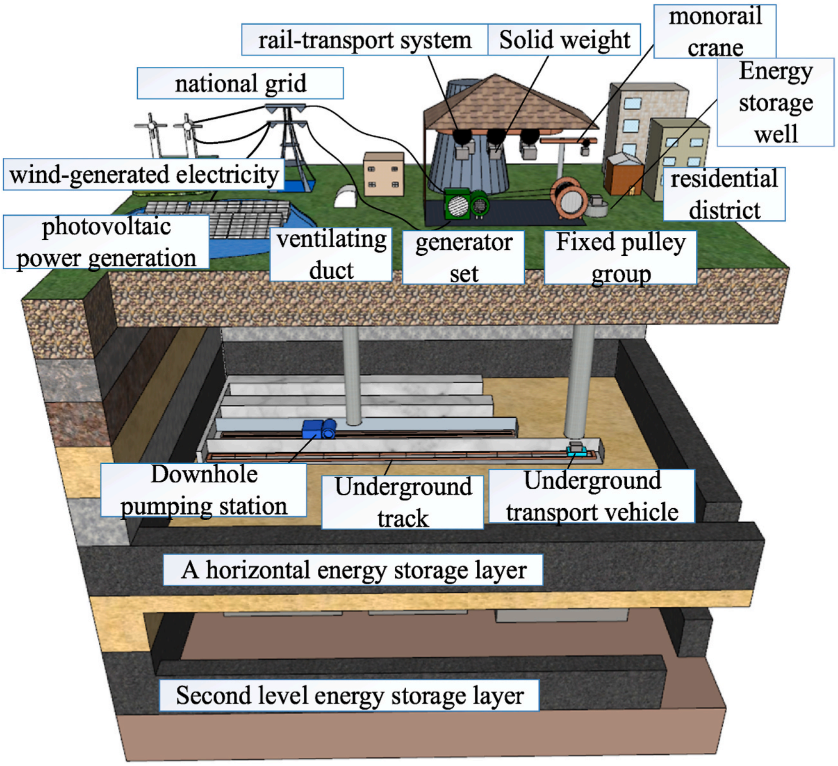

Fig. 3. Abandoned mine smart microgrid system model.

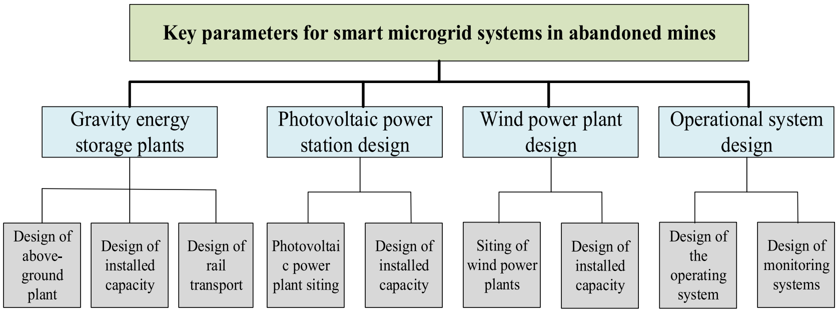

Fig. 4. Key parameters of the smart microgrid system in abandoned mine.

utilization value of the abandoned mine smart microgrid system can be fully explored by incorporating gravity energy storage, wind power generation, and photovoltaic power generation into an overall economic calculation model, providing a theoretical basis for project development decisions.

3.1. Smart microgrid economic assessment model

The smart microgrid's overall economic benefits include the overall benefits of each power station as well as the carbon reduction benefits, with the total benefits of each power station computed as follows (1) :

$$C_i = \left(C_{runi}\text{-}C_{capi}\text{-}C_{maci}\right) \tag{1}$$

where C_i is the total economic benefit of different types of power stations, Yuan; C_{runi} is the operating efficiency of different types of power stations, Yuan; C_{capi} is the construction cost of different types of power stations, Yuan; C_{maci} is the maintenance cost of different types of power stations, Yuan.

The resulting carbon reduction benefits are as follows (2):

$$C_{ci} = \sum_{t=1}^{T_i}\sum_{k=1}^{M} C_k r_k P_i(t) + C_c\frac{P_i(t)}{\varepsilon} \tag{2}$$

where , C_{ci} is the carbon reduction benefit of smart microgrid, Yuan; T_i is the power generation operation time of each power station,h; $P_i(t)$ is the installed capacity of each system , kwh; M is the type of carbon emission; C_k is the unit price of different types of carbon emission treatment , Yuan/m^3; r_k is the carbon emission of equivalent thermal power station,m^3; C_c is the unit price of standard coal, Yuan/t; and ε is the coefficient of one ton of coal generation,kwh/t。

3.2. Gravity energy storage

The gravity energy storage plant construction cost is divided into the manufacturing of gravity blocks, the construction of an above-ground storage center and transport system, the construction of an underground storage center and transport system, the construction of a shaft transport system, and the purchase of equipment. The operation cost is separated into two parts: energy storage and operation management.

Construction cost model for a gravity storage plant in an abandoned mine as follows (3) :

$$C_{cap} = \left(C_{gb}V_{gb} + C_{gp}A_{gp} + C_{orb}l_{orb} + C_{gen}\right) \tag{3}$$

where , C_{cap} is the total construction cost of the gravity storage plant, yuan; C_{gb} is the unit cost of manufacturing gravity blocks, yuan/m^3; V_{gb} is the volume of gravity blocks, m^3; C_{gp} is the unit cost of construction of the above-ground plant, yuan/m^2; A_{gb} is the floor space of the above-ground plant, m^2; C_{orb} is the construction cost of a single track, yuan/m; l_{orb} is the length of a single track,m; C_{gen} is the purchase cost of the generator set, yuan.

The total operating benefit model for an abandoned mine gravity storage plant is expressed as follows (4)、 (5):

$$C_{run} = C_{ge}\text{-}C_{st} \tag{4}$$

$$\begin{cases} C_{ge} = 9.81C_{t1}n_1\rho_{gb}V_{gb1}H_1T_2\eta_1 \\ C_{st} = C_{t2}\dfrac{9.81n_1\rho_{gb}V_{gb1}H_2T_3}{\eta_2} \end{cases} \tag{5}$$

where, C_{run} is the total operating benefit of the gravity storage power plant, Yuan; C_{ge} is the total generation benefit of the gravity storage power plant, Yuan; C_{t1} is the electricity price for integration into the grid at the moment of generation, Yuan/kwh; ρ_{gb} is the density of the gravity block, kg/m^3; H_1 is the drop height of the gravity block, m; T_2 is the generation time of the gravity storage power plant, h; η_1 is the generation efficiency; C_{st} is the gravity storage is the total cost of energy storage in the power station, C_{t2} is the grid electricity price at the time of storage, Yuan/kwh; H_2 is the lifting height of the gravity block, m; T_3 is the storage time, h; and η_2 is the power transmission efficiency.

The maintenance cost of the abandoned mine gravity storage power station is calculated as Eq. (6):

$$C_{mac} = C_{mac1}\sum_{t=1}^{T} P_g(t) \tag{6}$$

where , C_{mac} is the total maintenance cost of the gravity storage plant, yuan; C_{mac1} is the maintenance cost parameter at time t, yuan/kwh; P_g is the operating power of the gravity storage generator set, kw; T is the total operating period.

The carbon reduction benefits generated by gravity storage power plants are calculated as follows (7) [31]:

$$C_{cg} = \sum_{t=1}^{T_2}\sum_{k=1}^{M} C_k r_k P_g(t) + C_c\frac{P_g(t)}{\varepsilon} \tag{7}$$

where, C_{cg} is the gravimetric energy storage carbon reduction benefit, yuan。

3.3. Model optimization for smart microgrid systems

The overall economic benefit is an important metric to quantify the system's feasibility based on gravity energy storage, solar power generation, and wind power generation supplying electricity to the abandoned mine smart microgrid system.The goal of this optimization is to maximize the overall operational economy while minimizing construction and operating expenses, and it provides a joint system model for the abandoned mine smart microgrid.

The first objective function is to maximize the economic efficiency function as follows (8)

$$C_t = max\sum_{t=1}^{T_i} t\left(C_g + C_w + C_p\right) + C_{ci} \tag{8}$$

The minimum construction operational cost function is the second objective function as follows (9)

$$F_r(t) = min\ \left\{C_{capi} + \sum_{t=1}^{T_i} tC_{maci} + C_{st}\right\} \tag{9}$$

where , C_t is the overall economic benefit of smart microgrid, Yuan; C_g is the economic benefit generated by gravity energy storage per year, Yuan/year; C_w is the economic benefit generated by wind power per year, Yuan/year; C_p is the economic benefit generated by photovoltaic power per year, Yuan/year; t is the operating life, years; $F_r(t)$ is the overall construction and operation cost, Yuan.

3.4. Analysis of key model factors

The abandoned mine smart microgrid system is influenced by two major factors: first, the underground space of the abandoned mine has a significant impact on the installed capacity, which directly affects the size of the system's energy storage capacity; second, the depth of energy storage in the abandoned mine has a greater impact on the overall system's power generation efficiency and the determination of the working time.As a result, this article examines the overall economic optimization model's rationality in terms of the number of gravity blocks and the depth of energy storage in the abandoned mine.

Table 1
Summary of model calculation parameters.

	Projects	Unit price
Gravity storage power plants	Gravity Block Construction Costs	365 Yuan/m^3
	Above-ground plant construction costs	750-1000 Yuan/m^2
	Rail transport construction costs	670 Yuan/m
	Generator set acquisition costs	1.0 Yuan/w
	Maintenance costs for gravity storage plants	0.07 Yuan/kwh
Wind power plants	Wind power plant construction costs	4.5 billion
	Wind power plant maintenance costs	0.11 Yuan/MW
Photovoltaic power plants	Photovoltaic power plant construction costs	6750 million
	PV power plant maintenance costs	0.05 Yuan/MW
Electricity prices	Low Valley	0.32 Yuan/kwh
	Flat Valley	0.52 Yuan/kwh
Cost of carbon emissions	Carbon monoxide	493.03 Yuan/kwh
	Carbon dioxide	152,040 Yuan/kwh

(1) Impact of underground space capacity on overall economic efficiency

The installed capacity is determined by the available underground space capacity.Under the assumption that the installed capacity of photovoltaic and wind power plants is fixed at 65 MW and 50 MW, respectively, and that the complete power generation time is 10 h per day, the following table is used to generate and analyze this model [32].

The economic benefits were computed using the calculation model based on the above parameters (Table 1), and the results are displayed in Fig. 5 below.When the installed capacity of the photovoltaic and wind power plants, as well as the depth of the mine, are known, the overall economic function tends to be linear.The economic benefits are negative when the capacity is 0–20,000 m^3, but as the capacity of the underground space increases, the installed capacity gradually increases, the construction and operation costs rise slightly, but the overall economic benefits continue to increase as the system's electricity generation increases.As a result, the more the underground space's capacity, the greater the total benefits of the smart microgrid system.

(2) The impact of the depth of energy storage on the overall economic benefits

This calculation is based on the actual conditions of the experimental mine, which has a gravity block size of 2m2m2m, a gravity block quantity of 9,000, an underground available space of 72,000m3, a gravity energy storage power station installed capacity of 65 MW, a fixed installed capacity of 60 MW and 50 MW for the photovoltaic power station and wind power station, and a full power generation time of 10h per day.The remaining parameters are the same as in the previous calculation, and by adjusting the mine The energy storage depth is computed so that a graph showing the link between energy storage depth and economic benefits is obtained (Fig. 6). As the depth of energy storage increases, its overall economic benefit increases linearly while its construction and operation costs increaseslowly.The graph shows that when the critical energy storage depth is 450 m, the overall economic benefit is negative when the storage depth is less than 450 m and positive when the storage depth is greater than 450 m (see Fig. 7).

Based on the analysis of the above two instability factors, it is possible to conclude that the overall economic benefits of the system are positive when the capacity of the underground space exceeds 20000 m^3 and the depth of energy storage exceeds 450 m, and the economic benefits increase approximately linearly as the number of gravity blocks and the depth of energy storage increase.

4. Design solutions for gravity energy storage in abandoned mines

4.1. Determination of installed capacity

An abandoned mine's subterranean space is made up of the mining area, shaft, and highway chambers [33], which is useful for calculating the installed capacity of an abandoned mine gravity energy storage power plant.The design of the underground double-cycle track was adopted based on the hydrogeological conditions of the abandoned mine, as well as the complex underground environment, and taking into account the way the gravity storage power station works underground, with concrete cubes used for the solid weights, the main shaft and the wind shaft transformed into gravity storage power station energy storage shafts, and the Fuk shaft transformed into gravity storage power station energy storage shafts [31].The physical energy storage principle can be used to calculate the installed capacity of the gravity energy storage plant, taking into account the stability of the mine's underground space and the specifications of the underground tunnel:

$$P=\frac{\alpha\rho gHV}{T} \tag{10}$$

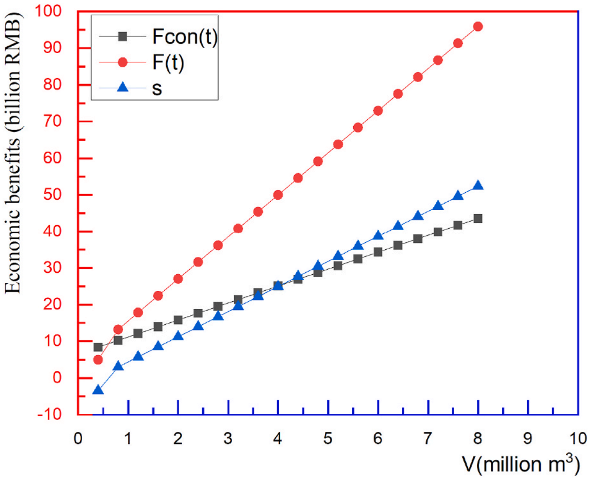

Fig. 5. Relationship between gravity block and economic benefits.

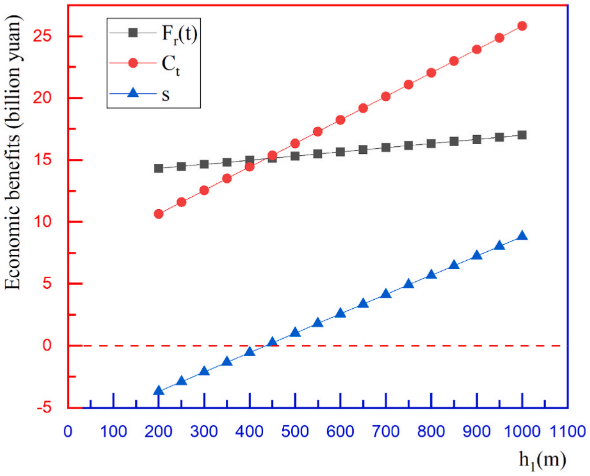

Fig. 6. Relationship between burial depth and economic benefits.

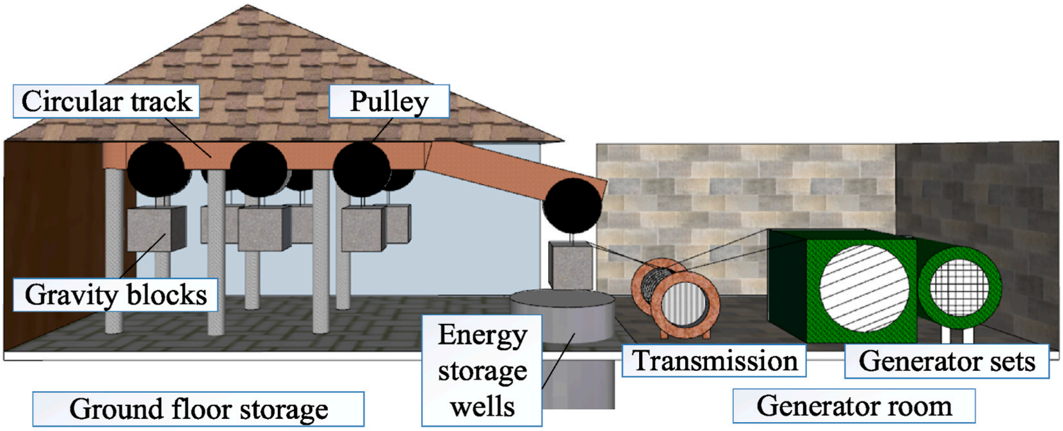

Fig. 7. Above-ground plant design scheme schematic.

where, P is the installed capacity of the gravity storage generator set; α is the integrated efficiency of the generator set, taken as 90 %; ρ is the concrete gravity block density，kg/m^3; g is the acceleration of gravity, taken as 9.81 g/s^2;H is the depth of the main shaft of the abandoned mine, m; V is the volume of the gravity block, m^3;T is the water transfer time, h.

4.2. Above-ground plant layout

The design of the abandoned mine gravity storage power station includes an above-ground plant configuration. The design of the above-ground plant primarily consists of the above-ground storage center and the generator room, with the above-ground storage center taking into account the following issues: (1) the number of gravity blocks and plant area size determination; (2) the balance between the quality of gravity blocks and the above-ground and underground load-bearing capacity; and (3) the design of the transport system between the above-ground plant and the energizing system.

The above-ground storage center uses a top-suspended storage method to facilitate continuous transportation up and down the mine, and the above-ground plant layout takes into account the large size of the gravity blocks, and to ensure safe operation, the gravity blocks should be suspended more than 1 m apart to prevent accidents due to the fast running speed of the track and the swaying of the gravity blocks; to ensure the convenience of the gravity blocks.To ensure that the gravity block in the track runs smoothly, connected two parallel tracks should be more than 2 m apart; gravity block suspension height in the ground plant should not be too high, to prevent heavy objects from falling off. The generator room is designed to be as close to the storage center and the energy storage shaft as possible while requiring the least amount of installation work.

4.3. *Underground storage and transport system design*

The underground storage and transportation system's design ensures that the gravity storage power station in the abandoned mine can generate electricity in a cyclic fashion, and it necessitates the full utilization of the subterranean highway area.A two-way monorail crane for the underground is proposed based on the dimensions of the subterranean tunnel group in the abandoned mine and the underground geological conditions. The two-way monorail crane must not have a gap between the crane and the roadway's roof, the hanging anchors are exposed by 100–150 mm, and steel rails with a spacing of more than 2 m are erected in the middle, the gravity block is suspended in the roadway by a lifting beam, and the gravity block is made to run at a uniform speed on the track by a driving device. The two-way monorail crane's design length is determined by the amount of space available in the shaft (See Fig. 8).

5. Case study

5.1. *Overview of the mine site*

The Huainan Mining Group's Pan Yidong Coal Mine is located in Panji District, Huainan City, Anhui Province, about 23 km from the center of Huainan, with the Huai River to the south and convenient transit. The climate is warm temperate monsoon, with 937 mm of annual rainfall, 2279.2h of yearly sunshine, and an average annual wind speed of 2.78 m/s. The mine offers excellent conditions for photovoltaic and wind power generation, and it is close to the Pingxu power plant, which has excellent grid connectivity. The design is centered on the development and utilization of the highway group surrounding Pan Yidong Mine's main shaft, secondary shaft, and central wind shaft (Table 2), which has a total possible roadway length of 13939.87 m.

5.2. *Design parameters of the abandoned mine smart microgrid system*

According to the characteristics of the tunnel group around the main shaft of Pan Yidong Mine, the first planned number of gravity blocks is 9000 blocks, with its ground layout formed as 100 blocks east-west and 90 blocks north-south.The ground plant is 360m360m5m in size based on the preceding ground plant layout ideas.The Pan Yidong Mine's main shaft is 871 m deep, and the gravity storage power station's total installed capacity is calculated to be 65 MW.The location of the gravity storage power station generator set is intended to be 30 m × 30 m × 5 m of open area. The total design length of the two-way monorail crane is 27,000 m, with two tracks in one lane, the required lane length is approximately 13,500 m, which primarily consists of the main shaft2# general joint lane, track lane and −848 m west wing of the track lane, 1# return air lane, 2# return air lane, return air lane and the west two13-1 pan area track lane, bottom plate return air joint lane, etc. The two-way monorail crane is set up.

5.3. *Analysis of economic benefits*

Based on the above design parameters and calculated parameters, we can obtain: the manufacturing cost of the gravity block is approximately RMB16.56 million; the design and manufacturing cost of the above-ground plant is approximately RMB129.6 million; a total of 54,000 m of track is used for the above-ground plant and the underground monorail crane, with a total cost of RMB36 million; a 65 MW generator is used for the generator set, with a total cost of RMB36million; In summary, the overall cost of building the gravity storage power station for the abandoned mine at Pan Yidong Mine is RMB 248 million.

The plan introduced limit of the Dish PanYidong Mine gravity stockpiling power station is 65 MW, considering the genuine productivity loss of the generator set, determined at 80 % of the real proficiency, the day to day power age is around about 6 h, and the gravity stockpiling power station can generate1.14×10^8kwh a year [34]; The configuration introduced limit of the Huainan PV power station is 150 MW, the genuine productivity is 75 %, the normal yearly daylight hours is 2272 h, which could provide2.56×10^8 kwh; Heihe at any point wind ranch has an introduced limit of 50 MW, with a genuine proficiency of 70 % and a normal yearly viable season of 3650 h, it can generate1.28×10^8 kwh per year; the activity cost of the Skillet PanYidong mine gravity stockpiling power station is determined at 13 h of the day, and the yearly utilization is 2.61×10^8 kwh; inoutline it can generate 2.37×10^8 kwh of all out power, in light of the modern power cost in Anhui Territory, for instance, the all out yearly monetary return is 285 million yuan. The 65 MW

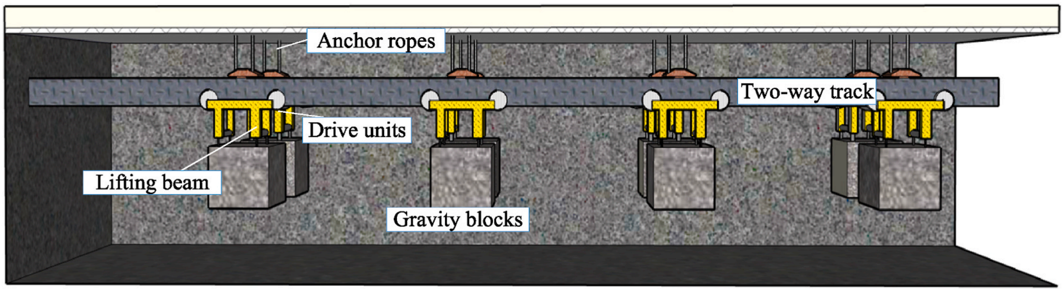

Fig. 8. Single track layout of part of the underground roadway.

Table 2
Parameters of some underground tunnels in Pan Yidong Mine.

Alleyways	Length of alleyway/m	Lane width/m
West II 13-1 Track Lane	550.03	5.6
−842 m West Wing 1# Return Air Lane	367.91	5
−842 m East Wing 1#Return wind tunnel	586.60	5
West two 13-1 pan area bottom return wind joint alley	122.44	5.06
West two 11-2 mining area trackway	1458.54	5.2
−842 m West wing 2# return wind tunnel	1898.9	5.14
−848 m West Wing Main Tape Machine Alley	3321.79	4.95
−848 m East Wing Track Lane	348.55	4.87
West II 11-2 mining area 2# general joint road	126.74	5.14

installed capacity generates approximately 49.275 million kilowatt-hours per year, resulting in a 78.9 thousand t reduction in standard coal consumption and a 204.9 thousand t reduction in carbon dioxide emissions. If the price of anthracite coal in 2022 is 1842 RMB per t, which is1842RMB/t , the annual cost of coal cost can be reduced by RMB 145 million.

5.4. *Social social advantages*

The abandoned mine smart microgrid system meets the coal industry's urgent need for the reuse of abandoned mine resources, and provides new ideas for the consumption of new energy, technology development, and the transformation and upgrading of abandoned coal mines by adapting to national demand for the development of new energy storage technology. Simultaneously, during the building and operation of the total system, a big number of unemployed coal miners will be able to change jobs, so resolving the re-employment problem. The development of a smart micro-grid system for abandoned mines efficiently encourages the rehabilitation of the ecological environment surrounding the mines and strengthens the development of ecological civilisation.

In the construction process of the gravity energy storage power station, the land resources left over from the abandoned mine are greatly utilized, such as the construction of industrial workshops, the layout of the system location of the coordinated transportation above and below the well, etc., which can be transformed by using the land and buildings left over from the mine, so as to avoid the waste of land resources after the mine is abandoned. At the same time, compared with the traditional thermal power plant, the gravity energy storage power station uses the gravitational potential energy to generate electricity, which almost does not produce toxic and harmful gases and dust pollution, and promotes the restoration of the mining environment.

6. Suggestions for the construction of smart microgrids in abandoned mines

The smart micro-grid system using abandoned mines to build gravity energy storage power stations is technically and economically feasible, but it must still consider the core technical difficulties of system construction, policy support for urban power grids, and coordinated development of mining area ecology to promote the joint progress of abandoned mine resource reuse and energy storage technology, and propose the following corresponding methods.

6.1. *Overcoming core technical problems and optimizing the construction of smart microgrid systems in abandoned mines*

During the construction of the abandoned mine smart microgrid system, the following core issues must be addressed: 1) the identification and design of the available space above and below the abandoned mine; 2) the transport regulation and intelligent control technology of "abandoned mine gravity energy storage"; 3) the design, manufacture, and installation of the "abandoned mine gravity energy storage" cycle transport track and generator set; and 4) the key theory and technology.Provide policy support to hasten the transformation of resource-based cities.

6.2. *Promote policy support to accelerate the transformation of resource-based cities*

The reuse of abandoned mine materials is the final link in a mine's "full life cycle. It is recommended that corresponding policies for abandoned mines be implemented, in conjunction with the development of new energy storage technologies, in order to accelerate the development of abandoned mine resources, strengthen cooperation with government, enterprises, universities, and other departments, investigate new energy storage technologies that combine abandoned mines with renewable energy, build demonstration projects, and promote the transformation of resource-based cities.

6.3. *Coordinating mining resources and accelerating ecological restoration*

Creating a smart microgrid system for abandoned mines requires knowledge of the surrounding light, wind, and space resources, as well as how to coordinate those resources to achieve maximum resource utilization.As a result, it is recommended that the government take the lead and that enterprises, universities, and research institutions work together to promote research on the reuse of abandoned mine resources, explore new energy storage technologies with abandoned mines as the mainstay, and carry out simultaneous restoration of the ecological environment of mining areas in order to promote the implementation of the new national energy security strategy.

7. Conclusion

(1) In a comprehensive analysis of energy storage technology solutions, construction feasibility, social and economic benefits, etc., as a response to the problem of a large number of remaining closed or abandoned mines and the increasing proportion of new energy in China, The purpose of the abandoned mine smart microgrid system is to use the gravity storage power station as its foundation, consume new energy, encourage the reuse of resources from abandoned mines, and carry out research into new energy storage technology.It also aims to fully address the legacy of abandoned mines and encourage the growth of the coal industry throughout its entire life cycle.
(2) The overall economic calculation model of the abandoned mine smart microgrid is designed, and it is concluded that the larger the available underground space and the deeper the energy storage depth of the mine, the greater the overall economic benefits.
(3) Based on the key specifications of the Pan Yidong Mine, the overall system design scheme is introduced, beginning with the design of the installed capacity and progressing to the design of the above-ground plant and the design of the underground rail transportation, highlighting the advantages of the smart microgrid system for abandoned mines over pumped storage power stations, analyzing the economic benefits and key issues to be studied later, The results show that Panyi East Mine has good construction conditions and the feasibility of building a smart microgrid system for abandoned mines.

Data availability

The data related to my research are not stored in the publicly available repository. The data used for conducting classifications are available from the corresponding author authors upon request.

CRediT authorship contribution statement

Qinggan Yang: Writing – review & editing, Writing – original draft, Funding acquisition, Conceptualization. **Qinjie Liu:** Funding acquisition, Formal analysis, Data curation. **Qiang Fu:** Resources, Methodology, Investigation. **Ke Yang:** Validation, Supervision, Project administration, Funding acquisition. **Man Zhang:** Writing – review & editing. **Qiang Chen:** Visualization, Validation, Software.

Declaration of competing interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and publication of this article.

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References

[1] Jianchao Hou, Mengchao Cao, Pingkuo Liu, Development and Utilization of Geothermal Energy in China: Current Practices and Future Strategies vol. 125, Renewable Energy, 2018, pp. 401–412, 09.
[2] Xiaoxin Zhou, Shuyong Chen, Zongsang Lu, et al., Technical characteristics of China's new generation power system in energy transition, Chinese Journal of Electrical Engineering 38 (2018) 1893–1904+2205, 07.
[3] X. Luo, J. Wang, M. Dooner, et al., Overview of current development in electrical energy storage technologies and the application potential in power system operation, Appl. Energy 137 (2015) 511–536.
[4] LyuXin, Ke Yang, Juejing Fang, et al., Simulation of the uniaxial mechanical properties and crack evolution of coal pillar-artificial dam in abandoned mines, Adv. Mater. Sci. Eng. (2022), 2022.
[5] Mifeng Cai, Minghui Ma, Jiliang Pan, et al., Current status and prospect of research on co-production model of mineral and geothermal resources[J/OL], J. Eng. Sci. (2022) 1–14, 09-20].
[6] L. Yuan, Y.D. Jiang, K. Wang, et al., Scientific thinking on the precise exploitation of resources of closed/abandoned mines in China, Journal of Coal 43 (1) (2018) 14–20.
[7] Yunliang Chen, Min Liu, Jiayi Fan, et al., Current status, technical concept and key issues of gravity energy storage power generation, Engineering Science and Technology 54 (2022) 97–105, 01.
[8] S.W. Tam, C.A. Blomquist, G.T. Kartsounes, Underground pumped hydro storage an overview [J]. Energy sources, Part A: recovery, utilization, and Environmental Effects 4 (4) (1979) 329–352.

[9] A.N.D.R.E. Niemann, Proposed underground pumped hydro storage power plant at prosper-haniel colliery in bottrop-state of play and prospects[J], Mining Report Gluckauf 154 (3) (2018) 214–223.

[10] JAVIER Menendez, J.O.R.G.E. Loredo, Use of coal mines facilities in northem Spain for the production of sustainable energy, J] . International Journal of Environmental Science 2 (2017) 324–328.

[11] Thomas Morstyn, Martin Chilcott, D. Malcolm, McCulloch, Gravity Energy Storage with Suspended Weights for Abandoned Mine shafts[J], Applied Energy, 2019, p. 239.

[12] Jean-François Toubeau, Chloé Ponsart, Christophe Stevens, Zacharie De Grève, François Vallée, Sizing of underwater gravity storage with solid weights participating in electricity markets, International Transactions on Electrical Energy Systems 30 (10) (2020).

[13] Dazhao Gu, Jingfeng Li, Zhiguo Cao, et al., Development strategy and engineering science and technology of coal mine water conservation and utilization in China, Journal of Coal 46 (10) (2021) 3079–3089.

[14] J. Hu, Deformation Law of Surrounding Rock under the Action of Gas Injection Cycle in Abandoned Mine Storage [D], China University of Mining and Technology, 2019.

[15] Qinjie Liu, Yun Han, Ke Yang, et al., Study on the design of underground tourism resources development scheme of abandoned mine in Baijiazhuang, Shanxi, Shanxi Coal 41 (2021) 122–128, 04.

[16] Yun Han, Qinjie Liu, Benniu Wu, et al., Study on the development and utilization model of underground space tourism resources in abandoned mines, Coalfield Geology and Exploration 49 (2021) 79–85, 04.

[17] Qinjie Liu, Jinjiang Wang, Ke Yang, et al., Study on the precise exploitation model of underground space resources in closed/abandoned mines, Coalfield Geology and Exploration 49 (2021) 71–78, 04.

[18] M.E.A. Elsayed, S. Abdo, A.A.A. Attia, et al., Parametric optimisation for the design of gravity energy storage system using Taguchi method, Sci. Rep. 12 (2022), 19648.

[19] Julian David Hunt, Behnam Zakeri, Giacomo Falchetta, et al., Mountain Gravity Energy Storage: a new solution for closing the gap between existing short- and long-term storage technologies, Energy 190 (2020), 116419.

[20] Su Wang, Liye Xiao, Wenbing Tang, et al., A review of new gravity energy storage research, Energy Storage Science and Technology 11 (5) (2022) 1575–1582.

[21] S. Rehman, L.M. Al-Hadhrami, M.M. Alam, Pumped hydro energy storage system: a technological review, Renew. Sustain. Energy Rev. 44 (2015) 586–598.

[22] M. Gimeno-Gutiérrez, R. Lacal-Arántegui, Assessment of the European potential for pumped hydropower energy storage: a GIS-based assessment of pumped hydropower storage potential, Eur Commission JCR Sci Policy Rep 1–74 (2013).

[23] Dazhao Gu, Theoretical framework and technical system of underground water reservoir in coal mines, Journal of Coal 40 (2) (2015) 239–246.

[24] Heping Xie, Zhengmeng Hou, Feng Gao, et al., New technology of underground pumped storage power generation in coal mines:principle, status and outlook, Journal of Coal 40 (2015) 965–972, 05.

[25] M. Franklin, P. Fraenkel, Gravity-based Energy Storage System, 2020-12-30 [P]: WO2020260596A1.

[26] K. Du, J. Xie, M. Khandelwal, et al., Utilization methods and practice of abandoned mines and related rock mechanics under the ecological and double carbon strategy in China—a comprehensive review, Minerals 12 (9) (2022) 1065.

[27] M.W. Ahmad, R. Raushan, Energy storage system in microgrid, Smart Grids and Microgrids: Technology Evolution (2022) 27–58.

[28] A. Fyke, The fall and rise of gravity storage technologies, Joule 3 (3) (2019) 625–630.

[29] Emrani Anisa, et al., Assessment of the round-trip efficiency of gravity energy storage system: analytical and numerical analysis of energy loss mechanisms, J. Energy Storage 55 (PA) (2022).

[30] N. Lior, Energy resources and use: the present situation and possible paths to the future, Energy 33 (6) (2008) 842–857.

[31] Renbo Gao, Fei Wu, Quanle Zou, Jie Chen, Optimal dispatching of wind-PV-mine pumped storage power station: a case study in Lingxin Coal Mine in Ningxia Province, China, Energy (2022) 243.

[32] Hui Hou, Tao Xu, Zhenfeng Xiao, et al., Optimal capacity planning and evaluation of a wind-photovoltaic-storage hybrid power system based on gravity energy storage, Power System Protection and Control 49 (17) (2021) 74–84, https://doi.org/10.19783/j.cnki.pspc.201449.

[33] Liang Yuan, Tong Zhang, Qinghe Zhang, et al., Considerations on the construction of green and low-carbon multi-energy complementary system in abandoned mines under double carbon target, Journal of Coal 47 (2022) 2131–2139, 06.

[34] Dexian Xu, Research on the Method of Tariff Setting and Economic Operation of Pumped Storage Power Plants [D], Hefei University of Technology, 2015.