Article

A Two-Step Site Selection Concept for Underground Pumped Hydroelectric Energy Storage and Potential Estimation of Coal Mines in Henan Province

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Abstract: In the context of carbon neutrality, the phase-out of coal from the energy structure has resulted in numerous old coal mines that possess abundant underground space resources suitable for underground pumped hydroelectric energy storage (UPHES). Site selection and estimation of potential are critical to the planning and implementation of UPHES in old coal mines. This paper introduces a two-step site selection concept, including a screening assessment followed by a comprehensive assessment, to determine suitable locations for UPHES. The screening indicators in the screening assessment comprise geological features, mine water disasters, and minimum installed capacity, while the analytic hierarchy process (AHP) is applied in the comprehensive assessment. Additionally, coal mines in Henan Province are preliminarily screened through the screening assessment and the potential for UPHES is thoroughly investigated. The estimated volume of the drifts and shafts in old coal mines is approximately 1.35×10^7 m^3, while in producing coal mines, it is around 2.96×10^7 m^3. Furthermore, the corresponding annual potential for UPHES is 1468.9 GWh and 3226.3 GWh, respectively. By consuming surplus wind and solar power, UPHES is able to reduce 4.68×10^5 tonnes of carbon dioxide (CO_2) emissions. The study provides preliminary guidance for policy-makers in developing UPHES in old coal mines.

Keywords: coal mines; underground pumped hydroelectric energy storage; site selection; the potential for UPHES

1. Introduction

Carbon neutrality through negative carbon technology and carbon emission reduction has become a global consensus to reduce atmospheric CO_2 concentrations and mitigate the impacts of climate change [1–6]. On account of coal's high emission intensity, early and substantial reductions in coal-related emissions are critical in all strategies that aim at carbon neutrality. According to the International Energy Agency (IEA), coal remains the largest global emitter of energy-related CO_2, amounting to approximately 15 billion tonnes in 2021 [7]. China, the largest consumer of coal to date, consumed 2934.4 million tonnes of standard coal equivalent (SCE), which comprised 53% of global coal consumption, and brought about 7.96 billion tonnes of CO_2 emissions in 2021 (Figure 1) [7,8]. Such immense consumption (accounting for nearly 56% of its primary energy consumption [9]) and production indicate that coal remains the cornerstone of the current energy structure in

China. The tremendous CO_2 emissions, constituting roughly 80% of total carbon emissions in China [6], reflect that the Chinese coal industry is subject to enormous pressure to reduce carbon emissions. The coal industry, therefore, urgently requires various approaches and means to realize its transition toward low-carbon development.
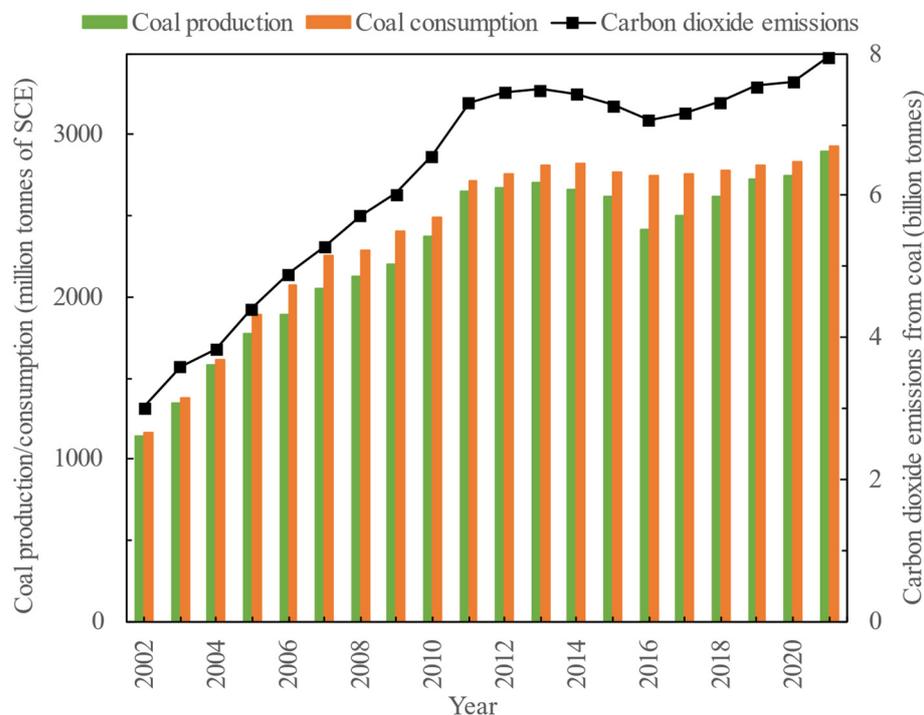

Figure 1. Annual coal production, consumption, and CO_2 emissions from coal in China. (Data source: Our World in Data [8] and China Statistical Yearbook 2022 [9]).

Low-carbon pathways for the coal industry encompass the entire life cycle of coal mines. Apart from safe, green, and intelligent mining [10–12], as well as ecological restoration of mining areas [13], sustainable planning for abandoned and closed mines is of identical importance [14–16]. After decades of exploitation, many coal mines in China have been closed because of resource exhaustion. Meanwhile, the coal industry has undergone structural adjustment, transformation and upgrading, leading to numerous coal mines being phased out [15]. Therefore, the number of abandoned and closed coal mines has been increasing year by year, making their treatment or redevelopment an imperative requirement. Some of those mines that have not initiated the closure process, hereafter referred to as old coal mines, possess abundant underground space resources which are applicable to redevelopment. UPHES in old mines is a highly promising alternative [17,18], and it can facilitate the achievement of carbon neutrality by ensuring the integration of renewable energy into the power grid.

Currently, there are some studies on UPHES, with a main focus on technical feasibility [19–22], environmental impact [23,24], and economic analysis [25,26]. However, limited attention has been paid to site selection [27,28], which is vital to the implementation of UPHES in old mines. Unlike conventional pumped storage projects, site selection for UPHES projects in old mines requires additional consideration of the geological and hydrogeological conditions of the mining area, which may even be decisive or restrictive. Tao et al. [27] proposed a hybrid multi-criteria decision-making framework to select suitable sites for UPHES in abandoned coal mines. However, the proposed framework is a traditional one-step assessment that may weaken the impacts of geological and hydrogeological conditions. In comparison, Yong et al. [28] introduced a two-stage fuzzy evaluation model for site selection, which included an initial veto assessment that excludes candidate sites failing to meet the requirements of restrictive indicators. Permeability coefficient and

horizontal distance were determined as two restrictive indicators, which only related to the properties of coal mine goaves. However, the drifts and shafts of old coal mines are more suitable for retrofitting into reservoirs, in which case, these restrictive indicators are of little significance. Therefore, developing reliable and effective evaluation models for site selection is still necessary for the implementation of UPHES in the drifts and shafts of old coal mines.

Additionally, UPHES is expected to play an important role in energy systems in that it presents the possibility of large-scale energy storage in flat terrain and the ability to be coupled with solar and wind power to achieve multi-energy complementarity [20,29]. Therefore, accurately estimating the UPHES potential and its capacity for carbon emission reduction is essential for policy-makers to plan energy systems and determine the required installed capacity. Ge et al. [30] studied the impact of UPHES on carbon emissions by the structural path analysis method from the perspective of the whole industrial chain; however, the carbon emission reduction capacity of UPHES itself remains unclear.

The objectives of this paper are to establish a reliable and effective evaluation model to identify suitable coal mines for the implementation of UPHES and to estimate the overall UPHES potential of coal mines in Henan Province. Therefore, this study introduces a two-step site selection concept, including a screening assessment followed by a comprehensive assessment. The screening assessment adopts restrictive indicators relevant to the geological and hydrogeological conditions of the mining area, while the AHP is applied in the comprehensive assessment. A case study is carried out to validate the proposed site selection concept. Additionally, preliminary screening of coal mines in Henan Province is performed based on the screening assessment. Subsequently, the underground space volume of the qualified coal mines is evaluated, and then the potential for UPHES is estimated thoroughly. Furthermore, this study quantitatively evaluates the contribution of UPHES to reducing CO_2 emissions through consuming surplus wind and solar power. The findings of this research provide preliminary guidance for policy-makers in developing UPHES in old coal mines.

2. Trends and Opportunities in the Coal Industry towards Carbon Neutrality

2.1. Trends in the Coal Industry

To achieve carbon neutrality, it is fundamental to restrain coal consumption and production constantly and firmly. Since China is the largest global coal consumer and emitter, energy conservation and CO_2 emission reduction in the coal industry are crucial in the present and will be in the future for a long time [31]. As shown in Figure 1, annual coal consumption in China experienced rapid growth before 2011, followed by fluctuations during the last decade. By contrast, for most countries that have already reached the carbon emission peak, their coal consumption has generally declined. For example, as reported by British Petroleum, the annual growth rates of coal consumption for the United States, Germany, and Russia from 2011 to 2021 were -6.0%, -4.3% and -1.4%, respectively. Many studies [7,32–34] have predicted that China's coal consumption in both the power and the industry sectors will peak before 2030, then gradually decrease and become concentrated in limited specific areas, including peak regulation of the power grid, carbonaceous reducing agents, and ensuring energy security [32]. In 2021, the Chinese government announced an action program for reaching the national carbon peak. The program emphasizes strict and reasonable restrictions on the growth of coal consumption in the near future and proposes a reduction be gradually achieved by 2030. Given the action program and the relevant predictions, the conclusion can be drawn that coal consumption in China will plateau at around the current level by 2030 and further decrease after reaching the national carbon peak.

The energy structure in China still heavily relies on coal, which necessitates a profound and systemic transformation. China's coal-dominated resource endowment implies that its energy transition would entail a direct change from coal to renewable energy instead of changing from coal to oil and gas and then to renewable energy, which is the common pathway adopted by Western countries [35]. Over the last decades, the rapid development

of renewable energy has led to a significant increase in its share of primary energy consumption in China (Figure 2a). Meanwhile, the ratio of coal consumption has shown a continuing downward trend since 2011. It indicates that renewable energy is progressively replacing coal in the energy structure. In Figure 2b, a comparison of energy structures of different countries is made, showing that the percentage of coal in China (54.5%) far exceeds that in the US and Germany, which are 11.4% and 16.7%, respectively. In the short term, completely replacing coal in the energy structure may be unattainable and introducing low-carbon technology into the coal industry appears more practical and crucial [6]. On the contrary, in the long term, renewable energy provides the main driving force of carbon emission reduction and energy transition [36]. The Chinese government has formulated the 14th 5 Year Plan (FYP) to promote the development of renewable energy, with a target of reaching a total consumption of around 1000 million tonnes of SCE by 2025. Furthermore, to achieve carbon neutrality, the proportion of renewable energy consumption to total primary energy consumption is anticipated to reach 75.3–78.6%, whereas the proportion of coal consumption needs to decrease to 4.3–4.8% by 2060 [37]. In the long term, as renewable energy consumption increases and substitutes for coal, coal consumption in the energy structure will decline significantly.
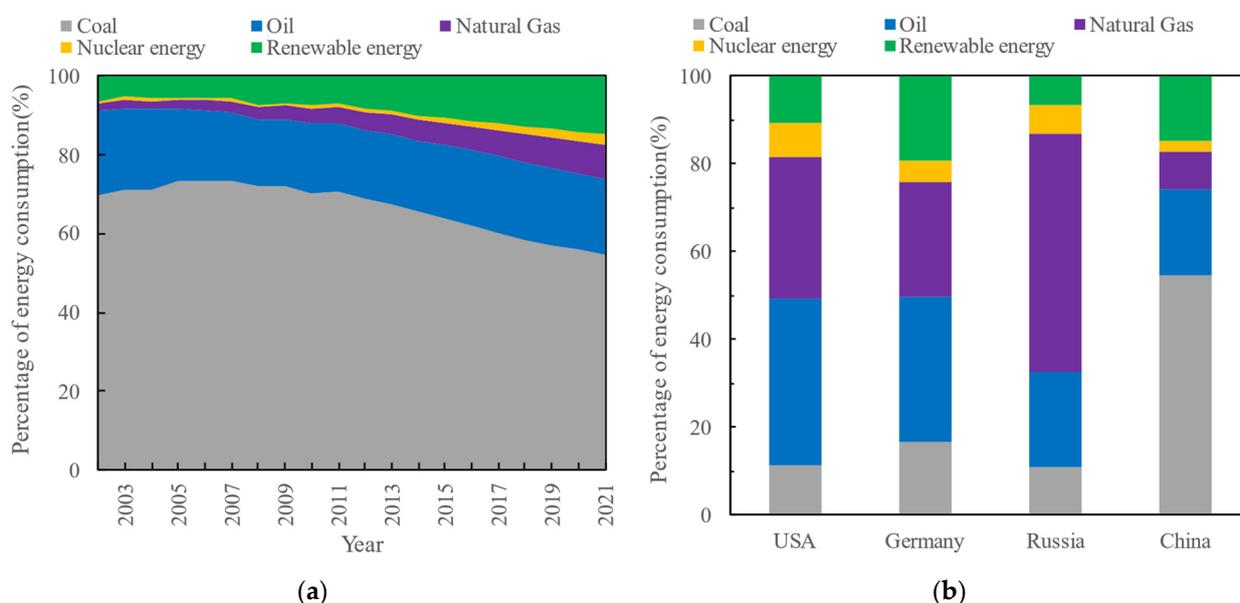

(**a**)   (**b**)

Figure 2. (**a**) Primary energy consumption in China by fuel type. (**b**) Primary energy consumption of several countries in 2021. (Data source: BP Statistical Review of World Energy).

In summary, coal consumption in China will show an inevitable downward trend in the medium to long term due to the restrictions on carbon emissions and the development of renewable energy. This trend in coal consumption will lead to a corresponding change in coal production, which is expected to remain steady in the near term but decline in the long run.

2.2. Development Opportunities Derived from Mined Underground Space

Against the background of carbon neutrality, China's coal industry has entered a new stage, and many coal mines have been abandoned or closed due to safety, efficiency, and economic concerns [38]. Additionally, some coal mines have reached the end of their lifespan after decades of exploitation [15]. As mentioned above, both coal production and consumption in China are anticipated to continue to decrease after 2030, resulting in the further phase-out of coal mines. Notably, during the 13th FYP period, approximately 5500 coal mines in China have already been abandoned or closed. Furthermore, projections suggest that this number will escalate to 15,000 by 2030 [39]. Many of those mines have

not yet initiated the closure process and are awaiting treatment. Meanwhile, these old coal mines contain a significant amount of underground space that is still available and accessible, such as hundreds of meters deep shafts, extensive drift networks, and ample goaves. Utilizing the underground space resources in old coal mines not only addresses the problem of treatment but also recreates economic values [40].

Generally, the utilization modes of underground space in old mines can be categorized into four aspects: energy storage, waste disposal, ecological restoration, and CO_2 sequestration [40] (Figure 3). Redeveloping old mines for underground energy storage not only offers a second life to otherwise unused assets but also can support the promotion of local renewable energy projects [41]. Solar and wind power are intermittent and subject to seasonal and weather-dependent variation. Therefore, the power grid needs to be equipped with energy storage facilities to balance supply and demand. The growing integration of renewable energy into the power grid would increase the demand for energy storage facilities, especially large-scale energy storage. The abundant underground space contained in the old mines can provide a guarantee for large-scale underground energy storage.
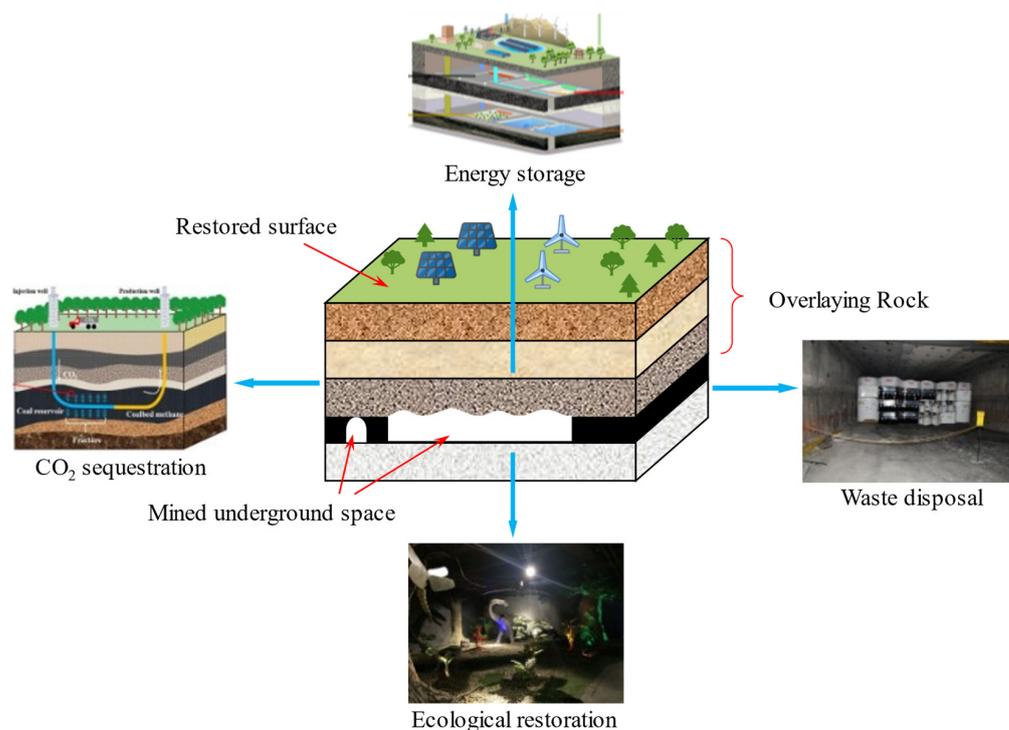

Figure 3. The four utilization modes of mined underground space in old mines [40,42].

Pumped storage is widely regarded as one of the most reliable, cost-effective, and mature technologies for large-scale energy storage, and it holds great promise for implementation in old coal mines. The process of coal mining naturally forms large quantities of underground caverns, which can serve as ready-made reservoirs with significant elevation differences, making them ideally suited for pumped storage. Moreover, the restored surface areas of old coal mines can be effectively repurposed as sites for wind and solar farms, ensuring a sustainable and renewable power supply for UPHES. This integration of renewable energy generation and energy storage unlocks new opportunities for the coal industry. Most UPHES projects are designed as closed-loop systems, operating independently from naturally flowing water bodies. This design allows the direct utilization of mine water as a supplement, mitigating the risk of water contamination and preserving water resources.

In Austria, the first practical implementation of UPHES was carried out, known as the intra-day pumped storage power plant Nassfeld. To meet the growing electricity demand, the power plant required an expansion of its storage capacity in 2006. In light of technical

and landscape-related constraints, expanding the lower reservoir above ground was not feasible [26]. Therefore, an underground cavern system was excavated, consisting of four main caverns measuring about 300 m in length and three connecting caverns, as shown in Figure 4. The caverns were largely unlined due to excellent sedimentary conditions. The lower reservoir is now composed of a surface reservoir and the underground cavern system, with a total volume of 230,000 m^3. The power plant now has an installed capacity of 31.5 MW and an estimated annual power generation of 50 GWh. In addition, several planned UPHES projects have carried out feasibility studies in Australia, China, Germany, Spain, and the USA [5,40].
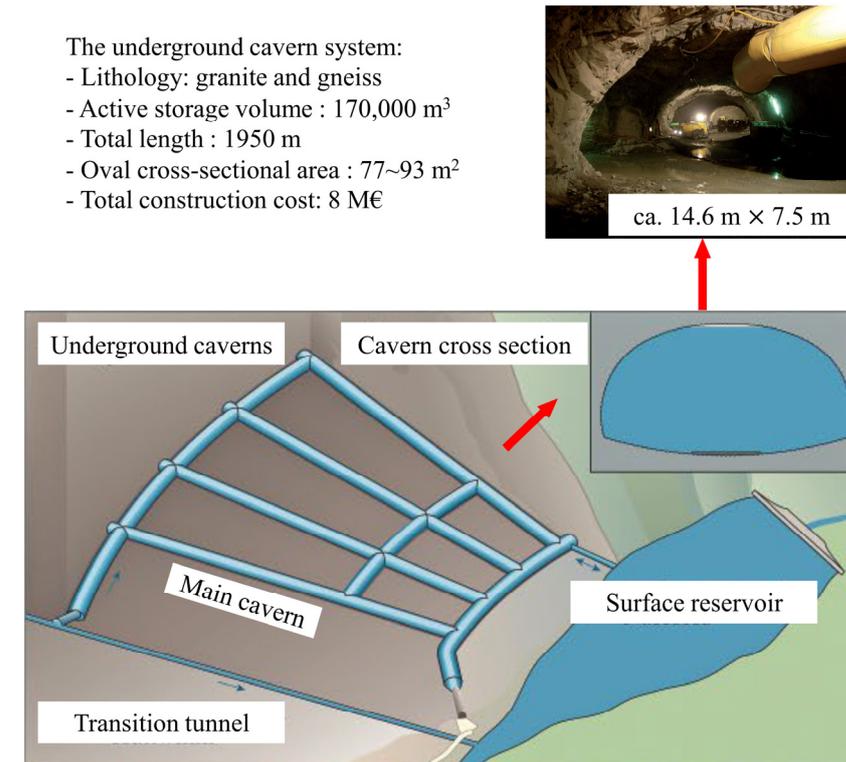
The underground cavern system:
- Lithology: granite and gneiss
- Active storage volume : 170,000 m^3
- Total length : 1950 m
- Oval cross-sectional area : 77~93 m^2
- Total construction cost: 8 M€

ca. 14.6 m × 7.5 m

Underground caverns

Cavern cross section

Main cavern

Surface reservoir

Transition tunnel

Figure 4. The lower reservoir of the power plant Nassfeld consisting of an underground cavern system and a surface reservoir [43].

3. Two-Step Site Selection Concept for UPHES in Old Mines

A viable old mine for UPHES should fundamentally possess certain advantages, such as a large-scale energy storage capacity and economic feasibility, as well as favorable geological and hydrological conditions to ensure stable operation and minimize environmental impact. Therefore, site selection plays a crucial role in identifying suitable locations for the implementation of UPHES projects.

The study of UPHES in old mines is an emerging research field, and presently, there are scarce studies [27,28,44,45] on site selection due to the complexity of the technical scheme and the uncertainty of the decision environment. Typically, site selection for conventional pumped storage projects considers techno-economic, social and environmental factors [46]. However, for UPHES projects in old mines, the geological and hydrogeological conditions of the mines themselves are also imperative considerations. Furthermore, with the rapid development of solar and wind power, a wind-PV-coal mine pumped storage hybrid system shows promise for efficient energy allocation in the time dimension [47]. Hence, when conducting site selection for UPHES projects in old mines, it is essential to consider the distribution and utilization of solar and wind power around the candidate mines.

Moreover, some restrictive indicators, such as adverse geological conditions of old mines, may pose challenges to the construction of UPHES projects. The traditional one-step

assessment method will weaken the significance of these restrictive indicators, resulting in unrealistic decision-making results. Therefore, to address the challenge of site selection effectively and reliably for UPHES projects in old mines, this study introduces a two-step site selection concept.

3.1. Step I: Screening Assessment

The screening assessment is a process in which several critical indicators are specified as screening criteria, and mines that satisfy the given conditions are immediately eliminated from the list of candidate sites for UPHES projects. By establishing screening criteria through restrictive indicators, the screening assessment not only enhances the efficiency of the entire site selection process but also emphasizes the decisive role of these indicators. In the case of conventional pumped storage projects, the screening indicators frequently involve the gross head, head-distance ratio, and water source. In this study, those indicators are combined with the geological and hydrological conditions of old mines themselves to determine the restrictive indicators for UPHES projects. Finally, geological features, mine water disasters, and minimum installed capacity have been identified as the three screening indicators.

- Geological features: an old mine is situated in karst topography or where underground rivers are known to exist in nearby areas. Karst topography is susceptible to water dissolution and erosion, which can damage the integrity of underground reservoirs and the stability of surrounding rocks, ultimately posing a risk of underground reservoir collapse;
- Mine water disasters: an old mine has experienced repeated water inrush accidents throughout its mining history or has a large mine water inflow, e.g., exceeding 600 m^3/h. Repeated water inrush accidents indicate that the mine is under complex hydrogeological conditions, threatening the safety and stability of underground reservoirs. Additionally, a substantial mine water inflow during the storage phase would occupy the lower reservoir, reducing actual power generation capacity and resulting in pumping costs surpassing revenue over the long term;
- Minimum installed capacity: the installed capacity of a UPHES power plant designed in an old mine is less than 20 MW. For a candidate mine, the installed capacity of a UPHES plant can be evaluated by [29]:

$$P = \rho g Q H \eta \tag{1}$$

where ρ is the density of water; g is the acceleration of gravity; Q is the planned water discharge through the turbine; H is the planned elevation difference between the upper and lower reservoirs, i.e., head height; η is the overall mechanical efficiency of the generation system, which is usually around 90%. The Nassfeld power plant, featuring a nominal flow rate of 11.6 m^3/s and a head height of 317 m, has an installed capacity of 31.5 MW and an annual power generation of 50 GWh, which can supply around 14,000 households with clean electricity. Based on these specifications, a minimum installed capacity of 20 MW is determined for UPHES power plants in old mines.

According to the three screening indicators, if an old mine fails to meet any of the above screening criteria, it is deemed to have passed the screening assessment. As a result, it can proceed with the second step of the site selection concept.

3.2. Step II: Comprehensive Assessment

An evaluation indicator system is formulated in this study to comprehensively assess the remaining candidate sites, with evaluation indicators identified through consultation with five experts who possess expertise in UPHES and redeveloping old mines.

This system places more emphasis on the distribution and utilization of renewable energy surrounding candidate mines than similar systems proposed in existing studies. UPHES power plants in old mines can effectively provide "peak shaving and trough filling" and surplus energy consumption services for highly volatile solar and wind power. On

the other hand, solar and wind power can provide electricity for pumping. Therefore, it is necessary to consider local distribution and utilization conditions of renewable energy to be evaluation indicators. Furthermore, this system introduces a novel economic evaluation indicator, i.e., local peak-to-valley tariff differential. For UPHES power plants, peak regulation for the power grid is a primary objective in daily operations and a key revenue generation method. A higher peak-to-valley tariff differential enhances the economic viability of the UPHES power plant.

3.2.1. Evaluation Indicators

The expert committee reached a consensus on the evaluation indicator system, including eighteen indicators that cover four aspects: geological and natural condition (C1), society (C2), resource (C3) and economy (C4). These indicators possess a tree-like structure in Figure 5 and are further elaborated below.
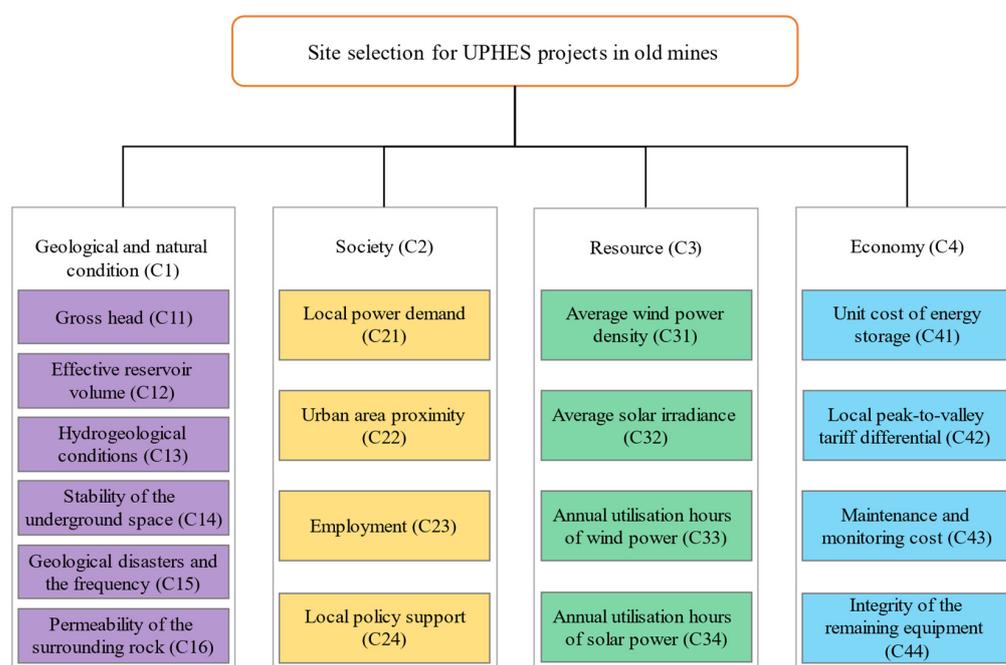

Figure 5. Tree structure of the evaluation indicator system for UPHES site selection in old mines.

Geological and natural condition (C1):

- Gross head (C11): this is the elevation difference between the lowest water level in the upper reservoir and the highest level in the lower one [46]. It is one of the dominant indicators of energy storage capacity;
- Effective reservoir volume (C12): this refers to the amount of water that can be stored in both the upper and lower reservoirs. In general, a larger reservoir volume enables the plant to store more electricity [28];
- Hydrogeological conditions (C13): there is a high possibility of underground water exchange occurring between the surrounding geological medium and the reservoirs, impacting the quality of nearby water bodies [48]. Thus, it is essential to consider hydrogeological properties, groundwater characteristics, and circulation behaviors.
- Stability of the underground space (C14) refers to the nature of maintaining the stability of geological conditions during the transformation and utilization of UPHES power plants [49];
- Geological disasters and the frequency (C15): the underground reservoirs are susceptible to geological disasters, so site selection should prioritize old mines with a lower occurrence of such disasters.

- Permeability of the surrounding rock (C16) signifies the hydraulic conductivity of the surrounding rock, which influences groundwater exchanges [48]. A high hydraulic conductivity and a high groundwater head result in the occupation of the lower reservoir by mine water, reducing the available volume for discharge and thus decreasing the efficiency of the power plant.

Society (C2):

- Local power demand (C21): UPHES power plants should contribute to the peak regulation and frequency modulation of the power grid [50]. The peak-to-valley ratio in power load [27] and the share of renewable energy in the local power grid should be considered to describe the local power demand;
- Urban area proximity (C22): to maximize the peak regulation effect of UPHES power plants, proximity to the high-load side, typically clustered around urban areas, is crucial. It also facilitates the delivery of materials and the mobility of personnel during construction, as well as the decrease in transmission losses during operation;
- Employment (C23): this evaluates the effectiveness of UPHES power plants in fostering employment in pertinent regional industries, such as manufacturing and transportation [28]. Additionally, it also involves the re-employment of former coal miners;
- Local policy support (C24): a stable and supportive local policy environment is important to promote UPHES projects.

Resource (C3):

- Average wind power density (C31): this refers to the average wind power potential at a particular position. As mentioned above, coupling UPHES power plants with nearby wind or solar farms is quite necessary, and this indicator represents the distribution of wind resources around the candidate site;
- Average solar irradiance (C32): this refers to the average solar radiation received at a specific location. Similarly, it stands for the distribution of solar resources around the candidate site;
- Annual utilization hours of wind power (C33): this relates to the number of hours in a year that a wind turbine or wind farm works at its rated capacity. This indicator reflects the utilization of wind resources around the candidate site;
- Annual utilization hours of solar power (C34): this relates to the number of hours in a year that a solar power system, such as photovoltaic panels, works at its rated capacity. This indicator denotes the utilization of solar resources around the candidate site.

Economy (C4):

- The unit cost of energy storage (C41): this is determined based on the construction cost and design storage capacity of UPHES power plants [28]. The cost includes expenses for equipment procurement, installation, civil engineering, operation, etc.;
- Local peak-to-valley tariff differential (C42): it refers to the difference between electricity prices during periods of high demand (peak hours) and low demand (off-peak hours) in a time-of-use pricing structure. A large difference is beneficial to the economics of the power plant;
- Maintenance and monitoring costs (C43): the chemical properties of mine water are complex and might induce corrosion of the pumping and generating equipment. The expenditure is necessary for regular mine water quality monitoring and equipment maintenance;
- The integrity of the remaining equipment (C44): this represents the infrastructure in an old mine that can be used sustainably. The remaining infrastructure, including transportation and communication systems, as well as substations, can be used to maximize the utilization of old mine resources and reduce construction costs.

3.2.2. Weight Calculation

For weight calculation, the AHP is a widely accepted subjective evaluation method [50–53]. It compares indicators in pairs and analyses their relative importance to determine their

weights. The AHP has good applicability for both qualitative and quantitative indicators. Given the presence of qualitative indicators in the evaluation indicator system, this study adopted the AHP for weight calculation. The AHP typically involves the following steps:

1. Create a hierarchy: Construct a hierarchical structure by organizing the goal, criteria, sub-criteria, and alternatives in a tree-like diagram. This has been accomplished in the last section, depicted as the tree structure (Figure 5);

2. Construct comparison matrixes: Evaluate the relative importance of indicators by pairwise comparisons. It involves comparing each indicator within a hierarchy level with all others at the same level and assigning numerical values representing their relative importance. The five experts evaluated the relative importance of each indicator using Saaty's nine-point scale [53];

3. Calculate priority: Pairwise comparison generates a matrix of the relative rankings for each level of the hierarchy. After all the matrices have been created, the vector of relative weight and maximum eigenvalue (λ_{max}) for each matrix is calculated.

4. Check for consistency: Verify the consistency of pairwise comparisons to ensure that they are reliable and do not contain logical contradictions. Inconsistencies require revisiting and refining the pairwise comparison. To validate the consistency, a consistency index (*CI*) is first calculated by $CI = (\lambda_{max} - n)/(n-1)$. The value λ_{max} is the maximum eigenvalue of the matrix, and *n* is the matrix dimension. Then, the consistency ratio (*CI*) is defined as $CR = CI/RI$. Value *RI* is the random consistency index, and it has corresponding values for different matrix dimensions. The acceptable value of *CR* depends on the dimension of the matrix (0.1 for matrixes $n \geq 5$). When the value *CR* is less than the specified value, it indicates that the consistency is adequate; otherwise, the consistency is inadequate.

According to comparison matrixes provided by the five experts, the final weight of each evaluation indicator is presented in Figure 6.
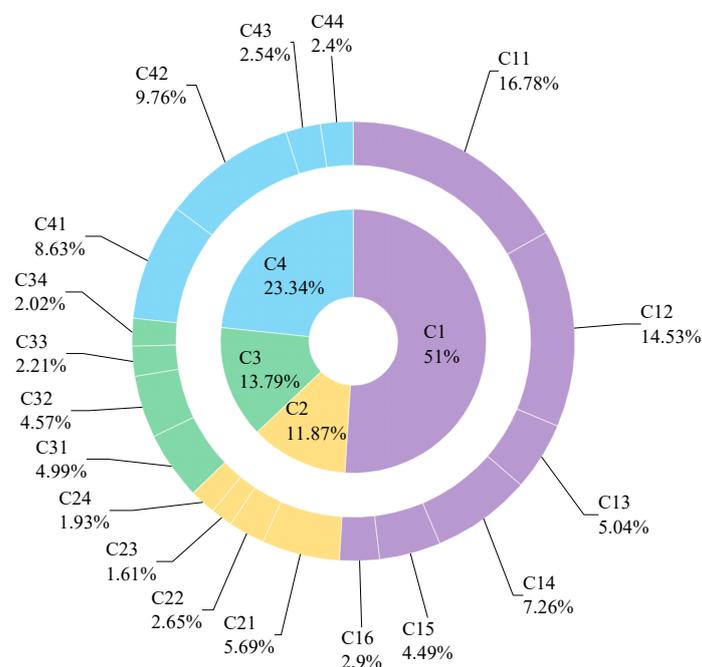

Figure 6. Weight results of evaluation indicators for the comprehensive assessment.

By weight calculation, indicators that have significant influences over site selection are identified, including the gross head (C11), the effective reservoir volume (C12), the local peak-to-valley tariff differential (C42), the unit cost of energy storage (C41), the stability of the underground space (C14), and the local power demand (C21). These indicators

play crucial roles in determining the technical feasibility, safety, and economic viability of UPHES projects in old mines.

3.3. Case Study

Three coal mines located in Yima (M1), Jiaozuo (M2), and Hebi (M3), as depicted in Figure 7, are chosen as potential sites for UPHES in Henan Province. To verify the practicality of the proposed site selection concept, this study applies the method to indicate which candidate site should be prioritized.

Figure 7. The location of three potential coal mines for UPHES in Henan Province.

3.3.1. The Screening Assessment

First, the basic data of the three coal mines are collected and presented in Table 1. In this stage, geological features, mine water disasters, and the minimum installed capacity of the three potential sites are assessed according to the screening criteria.

Table 1. The basic information of the three alternatives.

	M1	**M2**	**M3**
Mine water inflow (m^3/h)	300	2100	228
Planned head height (m)	800	500	400
Effective reservoir volume (10^4 m^3)	45	26	10
Urban areas' proximity (km)	5	15	40
Average wind power density (W/m^2)	160	170	190
Average solar irradiance (kWh/m^2)	1400	1200	1300

Mine M2, with a large mine water inflow, meets the screening criteria and is consequently eliminated from the list of candidate sites. On the other hand, both M1 and M3 fail to meet any of the screening criteria, indicating that they have passed the screening assessment and will be comprehensively assessed in the next step.

3.3.2. The Comprehensive Assessment

In this stage, the evaluation indicator system is utilized to assess the remaining two alternatives. The expert committee is invited to assign scores to each indicator for each mine. The weighted arithmetic mean of all indicator scores is calculated and deemed the final score for the candidate mine. A 10-point scale is employed in the assessment, and

a score of nine to 10 represents a site in excellent condition, seven to nine represents a suitable condition, five to seven represents a fair condition, and below five represents an unsuitable condition. The average scores for all indicators for both mines are provided in Table 2, alongside the final scores. Consequently, mine M1 obtained a score above seven, more than mine M3, indicating that it is a suitable site and should be prioritized for the UPHES project.

Table 2. Average scores for each indicator for the two candidate mines.

	C11	C12	C13	C14	C15	C16	C21	C22	C23	
M1	8.4	7.8	6.2	5.8	5.8	6.6	7.6	9.2	7.2	
M3	6.4	5.6	7.8	7.4	6.8	7.2	8.2	8.2	7.2	
	C24	**C31**	**C32**	**C33**	**C34**	**C41**	**C42**	**C43**	**C44**	**Final Score**
M1	8.0	6.4	5.8	7.2	5.6	7.4	7.6	6.4	5.6	7.21
M3	8.0	7.8	5.2	7.6	5.4	6.8	7.6	7.6	6.6	6.87

4. UPHES Potential of Coal Mines in Henan Province

Henan Province is representative of a coal-dominated energy structure and is one of the major provinces for coal production and consumption in China. With the advancement of its energy structure transition and the implementation of supply-side structural reform policies, there has been a decreasing trend in coal demand and production over the last few years. As reported by the Henan Province Bureau of Statistics, coal production has progressively decreased from 110 million tonnes of SCE in 2012 to 71.4 million tonnes of SCE in 2021, as illustrated in Figure 8. Since 2016, Henan Province has started to address the issue of over-capacity in the coal mining industry. In the meantime, the number of closed and abandoned coal mines has continued to increase; consequently, 242 coal mines were shut down during the 13th FYP period. In addition, numerous mines have been closed or abandoned for different reasons, such as resource exhaustion and frequent geological hazards. Due to the abundance of old coal mines, Henan Province confronts a massive burden of treating them. Utilizing the underground space in these mines to construct UPHES power plants not only addresses this issue but also enables large-scale underground energy storage, which contributes significantly to the energy structure transition and achieving carbon neutrality.

An accurate understanding of the volume of underground space is a prerequisite for planning and utilizing these resources. Currently, there is a lack of precise data on the volume of underground space in old coal mines in Henan Province, particularly considering the rapid increase in their number. Therefore, the total volume of underground space in coal mines has been estimated in this study, and on that basis, the potential for UPHES is further assessed. Generally, recently closed mines have better supporting conditions, preserve more intact underground space, and possess up-to-date geological and hydrogeological data, making them more appropriate for redevelopment [29]. On the other hand, mines that have been closed or abandoned for a longer period have already undergone treatment and are not suitable for further exploitation. Therefore, this study exclusively estimates the volume of underground space in old coal mines that have been closed or abandoned since 2016.

From 2016 to 2021, a total of 256 coal mines in Henan Province have been closed or abandoned. However, it is noteworthy that not all these old mines are suitable for UPHES. The proposed screening indicators are employed for a preliminary evaluation, resulting in the exclusion of 52 mines with a projected installed capacity below 20 MW and 21 mines due to mine water disasters. Among the 165 producing coal mines, 12 were excluded due to their small projected installed capacity, while 18 were eliminated because of mine water disasters.

4.1. Estimation of Underground Space Volume in Coal Mines

The underground space in coal mines consists mainly of drifts, shafts, chambers, and goaves. The drift, shaft, and chamber are more stable and reliable than the goaf because

they possess favorable supporting and ventilation conditions and maintenance. Therefore, they are considered readily available underground space for utilization, whereas goaves are deemed potentially available [54]. Nevertheless, in this study, the volumes of underground space are calculated separately for both categories.
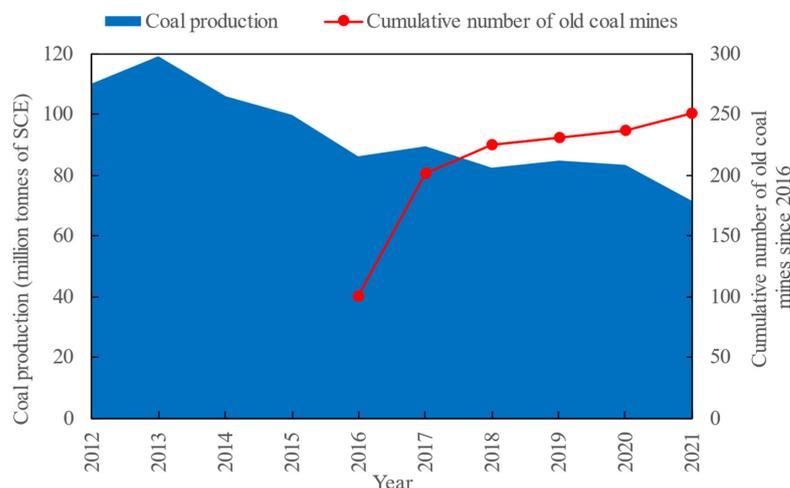

Figure 8. Coal production over the last decade and the cumulative number of old coal mines in Henan Province.

4.1.1. Volume of Coal Mine Drifts and Shafts

According to a previous investigation, an empirical coefficient α, related to the scale of coal mines, is introduced to calculate the underground space volume of coal mine drifts and shafts [55]. The corresponding values of the coefficient for coal mines of different scales in Henan Province are listed in Table 3. The volume of coal mine drifts and shafts V_d is given by,

$$V_d = C \times \alpha \tag{2}$$

where C is the coal mine production capacity, and α is the corresponding coefficient. The production capacity data of coal mines and the estimated volume of drifts and shafts are presented in Table 3. Since 2016, the total volume of drifts and shafts in old coal mines in Henan Province amounts to approximately 1.35×10^7 m^3, while the producing coal mines had a total volume of approximately 2.96×10^7 m^3 by the end of 2021.

Table 3. Estimation of underground space volume of coal mine drifts and shafts.

Coal Mine Production Capacity (Mt/a)	Coefficient α [55]	Old Coal Mines from 2016 to 2021			Producing Coal Mines		
		Total Number of Coal Mines	Total Capacity (Mt/a)	Volume (10^6 m^3)	Total Number of Coal Mines	Total Capacity (Mt/a)	Volume (10^6 m^3)
(0, 0.3]	0.28	153	29.88	8.37	54	14.19	3.97
(0.3, 1.2]	0.26	27	14.47	3.76	58	36.77	9.56
(1.2, 5.0]	0.25	3	5.40	1.35	23	64.28	16.07

4.1.2. Volume of Coal Mine Goaves

Based on the degree of damage and distance to the mined coal seam, the overlaying rock strata above the goaf can be categorized into three distinct zones, namely the caving zone, the fissure zone, and the displacement zone [20]. The caving and fissure zones contain the majority of the remaining underground space in coal mine goaves. Based on the three-zone theory, there exists a relationship among extracted coal volume V, surface subsidence volume V_1, rock expansion volume after pressure relief V_2, and goaf volume of the working face V_3. That is defined by [54],

$$V = V_1 + V_2 + V_3 \tag{3}$$

The extracted coal volume V can be calculated by dividing total crude coal production by an average coal density of 1.35 t/m^3. The surface subsidence volume V_1 can be estimated by multiplying the extracted coal volume V by a sinking coefficient η_s, which is set to 0.7 for coal mines in Henan Province. The rock expansion volume V_2 can be evaluated by multiplying the goaf volume V_3 by an expansion coefficient K that is equal to 0.1. Hence, the volume of coal mine goaves can be expressed by,

$$V_3 = V \cdot (1 - \eta_s)/(1 + K) \tag{4}$$

Crude coal production data in Henan Province from 2016 to 2021 were collected from the National Bureau of Statistics. According to Equation (4), the volume of underground space formed in coal mine goaves has been estimated, and the results are presented in Figure 9. The total crude coal production in Henan Province reached about 656.59 million tonnes from 2016 to 2021, resulting in a substantial volume of approximately 1.30×10^8 m^3 formed underground in coal mine goaves.
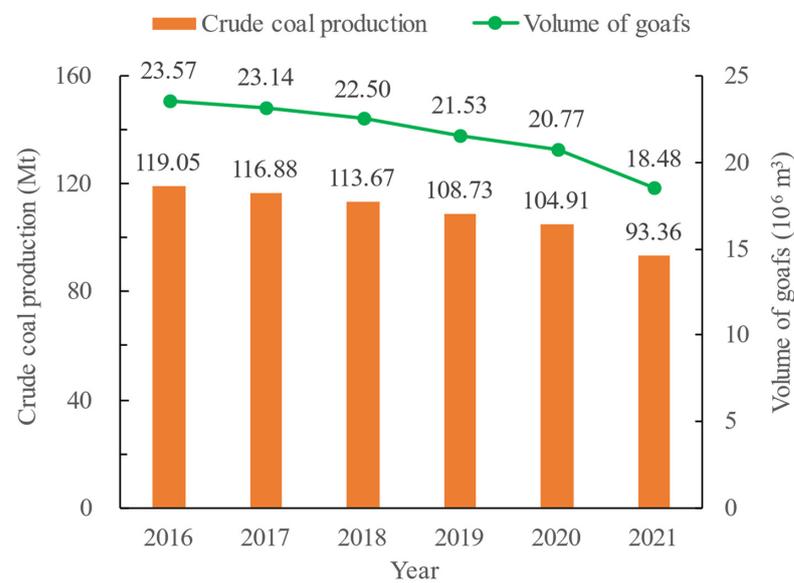
Figure 9. Estimated volume of coal mine goaves in Henan Province from 2016 to 2021.

4.2. Estimation of UPHES Potential

The effective reservoir volume and the elevation difference between the upper and lower reservoirs are two crucial factors in determining the installed capacity, power generation and economic profitability of a pumped storage power plant. The effective reservoir volume relates to the amount of water actively involved in the energy storage circulation. When constructing underground reservoirs in coal mine drifts, there are many determinants of the effective reservoir volume, including the arrangement and the spatial topological relationship of the drift network, hydrogeological conditions as well as the operating water level of the reservoir [56]. Typically, there is a distinct possibility of ineffective space and reverse slopes in underground reservoirs due to the undulation and deformation of drifts, resulting in stagnant zones where water does not contribute to the circulation. In addition, the constant inflow of groundwater in most coal mines occupies specific space in the lower reservoir, reducing the actual amount of water available for discharge. To obtain a reasonable estimation of UPHES potential, it is essential to accurately identify the effective reservoir volume of coal mine drifts. However, given the complexity of the spatial topological relationship of the drift network, there is currently no scientifically sound method for calculating the effective reservoir volume. Therefore, based on previous research [54,55,57], this study adopts an empirical reduction coefficient of 0.5 to estimate the effective reservoir volume of coal mine drifts, while 0.3 is used for coal mine goaves.

The effective reservoir volume of old and producing coal mine drifts total 6.74×10^6 m^3 and 1.48×10^7 m^3, respectively, whereas the effective reservoir volume of coal mine goaves is approximately 3.90×10^7 m^3.

The elevation difference between the upper and lower reservoirs, i.e., head height, depends on the mining depth. In Henan Province, coal mines currently have mining depths ranging from 300 m to 1200 m, with an average depth exceeding 600 m, providing readily available and ample head height for UPHES. However, not all old coal mines have suitable head heights for building pumped storage power plants. Existing studies [44,57] have indicated that the optimal head height is between 200 m and 800 m. When the head height is less than 200 m, both the efficiency and economic benefits of the power plant significantly decrease. On the other hand, when the head height exceeds 800 m, the current Francis turbine is unable to meet the high-pressure requirements [26]. Thus, multi-stage pumped storage power plants with intermediate storage reservoirs are regarded as an alternative.

For mines with only one mined coal seam, the mining depth exactly approximates the head height, and in that case, semi-UPHES power plants are adequate. Conversely, for mines with two or more mined coal seams, the most favorable elevation difference between the coal seams determines the head height, and full-UPHES power plants are preferable. Figure 10 depicts schematic diagrams for the two different power plant modes. Based on the head height categorized at 200 m intervals, five different scenarios for power plant construction have been proposed. The distribution of some old coal mines in Henan Province within those scenarios has been statistically analyzed and indicated in Table 4.

Table 4. Scenarios for UPHES power plants construction in Henan Province and the proportion [57].

	Mode of the Power Plant	Head Height (m)	Proportion (%)
Scenario 1		[200, 400)	47.6
Scenario 2	Semi-underground	[400, 600)	33.3
Scenario 3		[600, 800)	9.5
Scenario 4	Full-underground	[200, 400)	4.8
Scenario 5		[400, 600)	4.8

The formula for one-off power generation of all possible power plants is as follows [57]:

$$W = \sum_{k=1}^{3} \eta \rho g V_{sk} H_{sk} + \sum_{k=1}^{2} \frac{1}{2} \eta \rho g V_{fk} H_{fk} \tag{5}$$

where η is the overall mechanical efficiency of the generation system (90%); ρ is the water density (1000 kg/m^3); g is the acceleration of gravity (9.81 m/s^2); V_{sk} and V_{fk} are the effective reservoir volume of the semi- and full-UPHES power plant, respectively; H_{sk} and H_{fk} are the head height of the semi- and full-UPHES power plant, respectively; k represents different scenarios.

The ratios provided in Table 4 are utilized to calculate the individual effective reservoir volume for different scenarios, with the median employed as the head height. Conventional above-ground pumped storage plants commonly operate around 300 times per year. However, given the specificity of UPHES plants, such as groundwater contamination that reduces equipment lifespan [58], the assumed annual operation times are reduced to 75%. The estimated UPHES potential of coal mine drifts is listed in Table 5. Similarly, the estimation of UPHES potential in coal mine goaves has been conducted (Table 6).

4.3. Contribution to Reducing CO$_2$ Emissions

The power grid will benefit from the introduction of pumped storage, which stimulates the growth of power generation from renewable energy sources [30]. Renewable energy power is conducive to promoting the low-carbon power grid. Additionally, in a hybrid energy system comprising a wind farm, a photovoltaic (PV) power plant, a general

hydropower plant, a thermal power plant and a pumped storage plant, priority regulation of pumped storage can reduce annual carbon emissions and enhance the low-carbon economic performance [59]. Therefore, pumped storage can contribute to the goal of carbon neutrality as renewable energy increasingly penetrates the power grid.
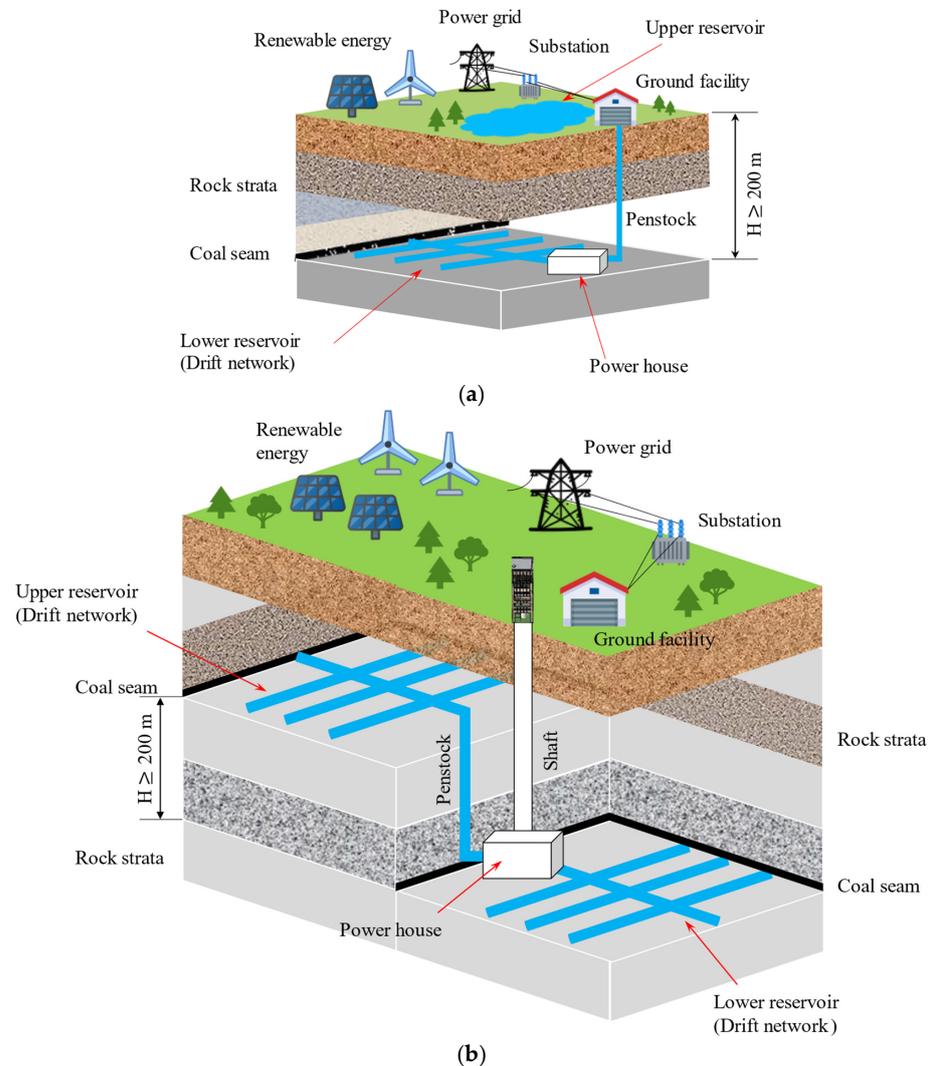

Figure 10. Schematic diagrams of UPHES power plants in coal mine drifts: (**a**) semi-underground UPHES power plant; (**b**) full-underground UPHES power plant.

UPHES, as an alternative to conventional pumped storage, can also consume surplus wind and solar power. According to the Henan Energy Regulation Office, the total installed capacity of power generation in Henan Province is 119.47 GW until December 2022. Among them, the installed capacity of wind power is 19.03 GW, accounting for 15.9%, and that of solar power is 23.33 GW, accounting for 19.5%. Figure 11 reflects wind and solar power generation in Henan Province during the last five years, along with the curtailment rates. As depicted, prior to 2020, all generated wind and solar power could be effectively consumed. However, with the increase in installed capacity and generation of wind and solar power, a noticeable consumption problem has emerged. It implies that existing energy storage methods and storage capacity are no longer sufficient to match the amount of electricity generated by wind and PV. In addition, Henan Province has insufficient power generation capacity, with a cumulative electricity generation of 3.33×10^5 GWh compared to a cumulative electricity consumption of 3.91×10^5 GWh in 2022. The complete utilization of renewable energy power can reduce external electricity dependence or the working hours of thermal power plants.

Table 5. Estimation of UPHES potential for redeveloping coal mine drifts.

	Head Height (m)	Old Coal Mine Drifts		Producing Coal Mine Drifts	
		Effective Reservoir Volume (10^6 m^3)	Power Generation (MWh)	Effective Reservoir Volume (10^6 m^3)	Power Generation (MWh)
Scenario 1	300	3.21	2360.2	7.05	5183.8
Scenario 2	500	2.24	2751.9	4.93	6044.1
Scenario 3	700	0.64	1099.1	1.41	2414.0
Scenario 4	300	0.32	119.0	0.71	261.4
Scenario 5	500	0.32	198.3	0.71	435.6
Potential annual energy storage (GWh)		1468.9		3226.3	

Table 6. Estimation of UPHES potential for further redeveloping coal mine goaves.

	Head Height (m)	Coal Mine Goaves	
		Effective Reservoir Volume (10^6 m^3)	Power Generation (MWh)
Scenario 1	300	16.89	12,428.4
Scenario 2	500	11.82	14,491.2
Scenario 3	700	3.37	5787.8
Scenario 4	300	1.70	626.6
Scenario 5	500	1.70	1044.4
Potential annual energy storage (GWh)		7735.1	

In 2022, wind and solar power curtailment rates in Henan Province were 1.8% and 0.5%, respectively. Accordingly, the abandoned wind and solar power during the year amounted to 686.7 GWh and 102.9 GWh, respectively. The surplus power can be consumed by UPHES power plants, with about 631.7 GWh of energy successfully stored (assuming the plant efficiency of 80%). There is enough UPHES potential in existing old coal mine drifts to handle this surplus power, as mentioned above. Based on the method from the literature [60], to generate the same amount of electricity, a conventional thermal power plant would consume 1.93×10^5 tonnes of SCE and produce 4.68×10^5 tonnes of CO_2 emissions. This value can be regarded as the potential carbon emission reduction capacity of UPHES by consuming the current surplus of renewable energy. Henan Province has set a target of generating 100 billion kWh of renewable energy power in 2025. Based on the current curtailment rates of wind and solar power, the surplus power is forecast to reach 1200 GWh in 2025. Similarly, by consuming surplus renewable energy, UPHES can reduce about 7.11×10^5 tonnes of CO_2 emissions in 2025.
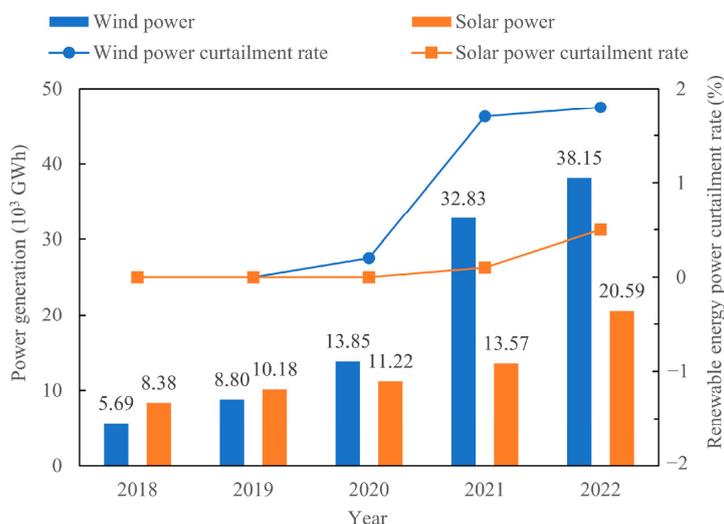

Figure 11. Statistics of wind and solar power generation and curtailment rates in Henan Province (Data source: the Henan Energy Regulation Office and China Renewable Energy Monitoring Platform).

5. Discussion

The two-step site selection concept proposed in this study for UPHES in old mines demonstrates improved reliability and effectiveness compared to existing methods. Firstly, unlike the traditional one-step method, which only employs a comprehensive assessment, the proposed approach incorporates a screening assessment. This addition improves the reliability of the evaluation results by separately considering restrictive indicators. Secondly, the screening indicators adopted in this study are more rational. The three screening indicators, namely geological features, mine water disasters and minimum installed capacity, effectively characterize geological and hydrogeological conditions, effective reservoir volume, and head height of the alternative sites. These indicators are more suitable for site selection when implementing UPHES in old mines. Lastly, the evaluation indicators used in the comprehensive assessment possess better relevance. For example, the indicator, local peak-to-valley tariff differential, represents the possibility of UPHES to generate revenue through peak regulation during operation, thereby better reflecting the economics of the alternative sites. By employing these more reasonable indicators, the effectiveness of the evaluation results is ensured. However, it is important to acknowledge the limitations of the proposed approach. The AHP applied in the comprehensive assessment is a method for calculating subjective weights. To further enhance the reliability, future research may consider incorporating objective weights and combined weights.

Additionally, this study focuses on all coal mines in Henan Province for potential estimation, which has pertinence and policy significance. Henan Province faces two major issues: the vigorous development of new energy sources and the treatment of abandoned coal mines. The estimation provides policy-makers with the overall potential of coal mines under their jurisdiction for UPHES, serving as a reference for energy system planning. Therefore, approximate values are used for the effective reservoir volume and head height in the estimation, while precise values can be obtained in specific cases by utilizing actual mine data and conducting on-site measurements. Subsequently, the exact energy storage potential can be determined based on Equation (5). The estimation results reveal that coal mine goaves have a significantly larger volume and energy storage potential compared to drifts and shafts. However, as mentioned above, goaves with mediocre supporting conditions are regarded as potentially available for utilization. Moreover, further detailed research is essential to develop these underground space resources [20].

6. Conclusions

The paper summarises the trend of China's coal industry in the medium to long term within the context of carbon neutrality. As the number of abandoned and closed coal mines continues increasing, the utilization of their underground space for UPHES offers new development opportunities to the coal industry. The objectives of this study are to propose a reliable and effective evaluation model for selecting suitable coal mines for the implementation of UPHES and to estimate the overall UPHES potential of coal mines in Henan Province. Thus, a two-step site selection concept is introduced, which consists of a screening assessment and a comprehensive assessment. Additionally, UPHES's potential for redeveloping coal mines in Henan Province and its ability to reduce CO_2 emissions are also estimated. The main conclusions are as follows:

1. The screening assessment incorporates three screening indicators: geological features, mine water disasters, and minimum installed capacity. The comprehensive assessment employs 18 indicators that cover four aspects: geological and natural conditions, society, resources, and economy, to formulate the evaluation indicator system. By weight calculation, indicators that have significant influences are identified, including gross head, the effective reservoir volume, the local peak-to-valley tariff differential, the unit cost of energy storage, and the stability of the underground space;
2. The screening assessment is applied to preliminarily evaluate the suitability of coal mines in Henan Province for UPHES. Consequently, 183 old coal mines and 135 producing coal mines are deemed suitable, and the volume of their drifts and

shafts are approximately 1.35×10^7 m^3 and 2.96×10^7 m^3, respectively. Additionally, it is estimated that a total volume of roughly 1.30×10^8 m^3 has formed in coal mine goaves since 2016;

3. The estimated annual potential for UPHES in old coal mine drifts and shafts in Henan Province is approximately 1468.9 GWh, while for producing coal mines, it is about 3226.3 GWh;

4. By consuming surplus solar and wind power, the potential carbon emission reduction capacity of UPHES is currently 4.68×10^5 tonnes of CO_2 emissions. It is forecast that UPHES can reduce about 7.11×10^5 tonnes of CO_2 emissions in 2025.

References

1. Luo, J.; Xie, Y.; Hou, M.Z.; Xiong, Y.; Wu, X.; Lüddeke, C.T.; Huang, L. Advances in Subsea Carbon Dioxide Utilization and Storage. *Energy Rev.* **2023**, *2*, 100016. [CrossRef]
2. Wu, L.; Hou, Z.; Xie, Y.; Luo, Z.; Xiong, Y.; Cheng, L.; Wu, X.; Chen, Q.; Huang, L. Fracture Initiation and Propagation of Supercritical Carbon Dioxide Fracturing in Calcite-Rich Shale: A Coupled Thermal-Hydraulic-Mechanical-Chemical Simulation. *Int. J. Rock Mech. Min. Sci.* **2023**, *167*, 105389. [CrossRef]
3. Wu, L.; Hou, Z.; Luo, Z.; Xiong, Y.; Zhang, N.; Luo, J.; Fang, Y.; Chen, Q.; Wu, X. Numerical Simulations of Supercritical Carbon Dioxide Fracturing: A Review. *J. Rock Mech. Geotech. Eng.* **2022**, *in press*. [CrossRef]
4. Cao, C.; Liao, J.; Hou, Z.; Xu, H.; Mehmood, F.; Wu, X. Utilization of CO_2 as Cushion Gas for Depleted Gas Reservoir Transformed Gas Storage Reservoir. *Energies* **2020**, *13*, 576. [CrossRef]
5. Xie, Y.; Wu, X.; Hou, Z.; Li, Z.; Luo, J.; Lüddeke, C.T.; Huang, L.; Wu, L.; Liao, J. Gleaning Insights from German Energy Transition and Large-Scale Underground Energy Storage for China's Carbon Neutrality. *Int. J. Min. Sci. Technol.* **2023**, *33*, 529–553. [CrossRef]
6. Hou, Z.-M.; Xiong, Y.; Luo, J.-S.; Fang, Y.-L.; Haris, M.; Chen, Q.-J.; Yue, Y.; Wu, L.; Wang, Q.-C.; Huang, L.-C.; et al. International Experience of Carbon Neutrality and Prospects of Key Technologies: Lessons for China. *Pet. Sci.* **2023**, *20*, 893–909. [CrossRef]
7. OECD. *International Energy Agency Coal in Net Zero Transitions: Strategies for Rapid, Secure and People-Centred Change*; OECD: Paris, France, 2022; ISBN 978-92-64-90003-5.
8. Ritchie, H.; Roser, M.; Rosado, P. *CO_2 and Greenhouse Gas Emissions*; Our World in Data: Oxford, UK, 2020.
9. China Statistical Yearbook 2022. Available online: http://www.stats.gov.cn/sj/ndsj/2022/indexeh.htm (accessed on 26 April 2023).
10. Ju, Y.; Zhu, Y.; Xie, H.; Nie, X.; Zhang, Y.; Lu, C.; Gao, F. Fluidized Mining and In-Situ Transformation of Deep Underground Coal Resources: A Novel Approach to Ensuring Safe, Environmentally Friendly, Low-Carbon, and Clean Utilisation. *Int. J. Coal Sci. Technol.* **2019**, *6*, 184–196. [CrossRef]
11. Wang, G.; Xu, Y.; Ren, H. Intelligent and Ecological Coal Mining as Well as Clean Utilization Technology in China: Review and Prospects. *Int. J. Min. Sci. Technol.* **2019**, *29*, 161–169. [CrossRef]
12. Martirosyan, A.V.; Kukharova, T.V.; Fedorov, M.S. Research of the Hydrogeological Objects' Connection Peculiarities. In Proceedings of the 2021 IV International Conference on Control in Technical Systems (CTS), Saint Petersburg, Russia, 21 September 2021; IEEE: Piscataway, NJ, USA; pp. 34–38.
13. Liu, Y.; Lei, S.; Gong, C. Comparison of Plant and Microbial Communities between an Artificial Restoration and a Natural Restoration Topsoil in Coal Mining Subsidence Area. *Environ. Earth Sci.* **2019**, *78*, 204. [CrossRef]
14. Wang, B.; Cui, C.-Q.; Zhao, Y.-X.; Chen, M.; Yuan, X.-C. Climate Change Mitigation in the Coal Mining Industry: Low-Carbon Pathways and Mine Safety Indicators. *Nat. Hazards* **2019**, *95*, 25–38. [CrossRef]

15. Lyu, X.; Yang, K.; Fang, J. Utilization of Resources in Abandoned Coal Mines for Carbon Neutrality. *Sci. Total Environ.* **2022**, *822*, 153646. [CrossRef]

16. Pershin, I.M.; Kukharova, T.V.; Tsapleva, V.V. Designing of Distributed Systems of Hydrolithosphere Processes Parameters Control for the Efficient Extraction of Hydromineral Raw Materials. *J. Phys. Conf. Ser.* **2021**, *1728*, 012017. [CrossRef]

17. Matos, C.R.; Carneiro, J.F.; Silva, P.P. Overview of Large-Scale Underground Energy Storage Technologies for Integration of Renewable Energies and Criteria for Reservoir Identification. *J. Energy Storage* **2019**, *21*, 241–258. [CrossRef]

18. Kitsikoudis, V.; Archambeau, P.; Dewals, B.; Pujades, E.; Orban, P.; Dassargues, A.; Pirotton, M.; Erpicum, S. Underground Pumped-Storage Hydropower (UPSH) at the Martelange Mine (Belgium): Underground Reservoir Hydraulics. *Energies* **2020**, *13*, 3512. [CrossRef]

19. Menéndez, J.; Schmidt, F.; Konietzky, H.; Fernández-Oro, J.M.; Galdo, M.; Loredo, J.; Díaz-Aguado, M.B. Stability Analysis of the Underground Infrastructure for Pumped Storage Hydropower Plants in Closed Coal Mines. *Tunn. Undergr. Space Technol.* **2019**, *94*, 103117. [CrossRef]

20. Fan, J.; Xie, H.; Chen, J.; Jiang, D.; Li, C.; Ngaha Tiedeu, W.; Ambre, J. Preliminary Feasibility Analysis of a Hybrid Pumped-Hydro Energy Storage System Using Abandoned Coal Mine Goafs. *Appl. Energy* **2020**, *258*, 114007. [CrossRef]

21. Jiang, D.; Chen, S.; Liu, W.; Ren, Y.; Guo, P.; Li, Z. Underground Hydro-Pumped Energy Storage Using Coal Mine Goafs: System Performance Analysis and a Case Study for China. *Front. Earth Sci.* **2021**, *9*, 760464. [CrossRef]

22. Martirosyan, A.V.; Ilyushin, Y.V. The Development of the Toxic and Flammable Gases Concentration Monitoring System for Coalmines. *Energies* **2022**, *15*, 8917. [CrossRef]

23. Pujades, E.; Jurado, A.; Orban, P.; Dassargues, A. Parametric Assessment of Hydrochemical Changes Associated to Underground Pumped Hydropower Storage. *Sci. Total Environ.* **2019**, *659*, 599–611. [CrossRef]

24. Bodeux, S.; Pujades, E.; Orban, P.; Brouyère, S.; Dassargues, A. Interactions between Groundwater and the Cavity of an Old Slate Mine Used as Lower Reservoir of an UPSH (Underground Pumped Storage Hydroelectricity): A Modelling Approach. *Eng. Geol.* **2017**, *217*, 71–80. [CrossRef]

25. Shang, D.; Pei, P.; Zuo, Y. Techno-Economic Feasibility Analysis of Pumped Storage Hydroelectricity in Abandoned Underground Coal Mines. *J. Energy Resour. Technol.* **2020**, *142*, 122001. [CrossRef]

26. Madlener, R.; Specht, J.M. An Exploratory Economic Analysis of Underground Pumped-Storage Hydro Power Plants in Abandoned Deep Coal Mines. *Energies* **2020**, *13*, 5634. [CrossRef]

27. Tao, Y.; Luo, X.; Zhou, J.; Wu, Y.; Zhang, L.; Liu, Y. Site Selection for Underground Pumped Storage Plant Using Abandoned Coal Mine through a Hybrid Multi-Criteria Decision-Making Framework under the Fuzzy Environment: A Case in China. *J. Energy Storage* **2022**, *56*, 105957. [CrossRef]

28. Yong, X.; Chen, W.; Wu, Y.; Tao, Y.; Zhou, J.; He, J. A Two-Stage Framework for Site Selection of Underground Pumped Storage Power Stations Using Abandoned Coal Mines Based on Multi-Criteria Decision-Making Method: An Empirical Study in China. *Energy Convers. Manag.* **2022**, *260*, 115608. [CrossRef]

29. Menéndez, J.; Ordóñez, A.; Álvarez, R.; Loredo, J. Energy from Closed Mines: Underground Energy Storage and Geothermal Applications. *Renew. Sustain. Energy Rev.* **2019**, *108*, 498–512. [CrossRef]

30. Ge, S.; Gao, Y.; Yao, X.; Liu, J. Can Pumped-Storage Power in Underground Coal Mine Reduce Carbon Emissions? *J. Clean. Prod.* **2020**, *255*, 120344. [CrossRef]

31. Zhou, A.; Hu, J.; Wang, K. Carbon Emission Assessment and Control Measures for Coal Mining in China. *Environ. Earth Sci.* **2020**, *79*, 461. [CrossRef]

32. Xie, H.; Ren, S.; Xie, Y.; Jiao, X. Development opportunities of the coal industry towards the goal of carbon neutrality. *J. China Coal Soc.* **2021**, *46*, 2197–2211. (In Chinese) [CrossRef]

33. Mengshu, S.; Yuansheng, H.; Xiaofeng, X.; Dunnan, L. China's Coal Consumption Forecasting Using Adaptive Differential Evolution Algorithm and Support Vector Machine. *Resour. Policy* **2021**, *74*, 102287. [CrossRef]

34. Wang, W.; Kao, X.; Lin, Z.; Zhang, Y. Has China's Coal Consumption Really Peaked?—Prediction and Scenario Analysis of China's Coal Consumption Peak under the Double-Carbon Target. *Front. Environ. Sci.* **2022**, *10*, 974763. [CrossRef]

35. Wang, Y.; Mao, J.; Chen, F.; Wang, D. Uncovering the Dynamics and Uncertainties of Substituting Coal Power with Renewable Energy Resources. *Renew. Energy* **2022**, *193*, 669–686. [CrossRef]

36. Jia, Z.; Lin, B. How to Achieve the First Step of the Carbon-Neutrality 2060 Target in China: The Coal Substitution Perspective. *Energy* **2021**, *233*, 121179. [CrossRef]

37. Ma, Y.; Li, Y.P.; Huang, G.H. Planning China's Non-Deterministic Energy System (2021–2060) to Achieve Carbon Neutrality. *Appl. Energy* **2023**, *334*, 120673. [CrossRef]

38. Zhong, C.; Dong, F.; Geng, Y.; Dong, Q. Toward Carbon Neutrality: The Transition of the Coal Industrial Chain in China. *Front. Environ. Sci.* **2022**, *10*, 962257. [CrossRef]

39. Lyu, X.; Yang, K.; Fang, J.; Tang, J.; Wang, Y. Feasibility Study of Construction of Pumped Storage Power Station Using Abandoned Mines: A Case Study of the Shitai Mine. *Energies* **2022**, *16*, 314. [CrossRef]

40. Du, K.; Xie, J.; Khandelwal, M.; Zhou, J. Utilization Methods and Practice of Abandoned Mines and Related Rock Mechanics under the Ecological and Double Carbon Strategy in China—A Comprehensive Review. *Minerals* **2022**, *12*, 1065. [CrossRef]

41. Morstyn, T.; Chilcott, M.; McCulloch, M.D. Gravity Energy Storage with Suspended Weights for Abandoned Mine Shafts. *Appl. Energy* **2019**, *239*, 201–206. [CrossRef]

42. Li, R.; Ge, Z.; Wang, Z.; Zhou, Z.; Zhou, J.; Li, C. Effect of Supercritical Carbon Dioxide (ScCO$_2$) on the Microstructure of Bituminous Coal with Different Moisture Contents in the Process of ScCO$_2$ Enhanced Coalbed Methane and CO$_2$ Geological Sequestration. *Energy Fuels* **2022**, *36*, 3680–3694. [CrossRef]
43. Pikl, F.G.; Richter, W.; Zenz, G. Large-scale, Economic and Efficient Underground Energy Storage. *Geomech. Tunn.* **2019**, *12*, 251–269. [CrossRef]
44. Shang, D.; Pei, P. Analysis of Influencing Factors of Modification Potential of Abandoned Coal Mine Into Pumped Storage Power Station. *J. Energy Resour. Technol.* **2021**, *143*, 112003. [CrossRef]
45. Wang, B.; Liu, P.; Deng, K. Site selection of pumped storage power station in abandoned mines: Results from fuzzy-based multi criteria decision model. *J. Min. Sci. Technol.* **2021**, *6*, 667–677. (In Chinese)
46. Nzotcha, U.; Kenfack, J.; Blanche Manjia, M. Integrated Multi-Criteria Decision Making Methodology for Pumped Hydro-Energy Storage Plant Site Selection from a Sustainable Development Perspective with an Application. *Renew. Sustain. Energy Rev.* **2019**, *112*, 930–947. [CrossRef]
47. Gao, R.; Wu, F.; Zou, Q.; Chen, J. Optimal Dispatching of Wind-PV-Mine Pumped Storage Power Station: A Case Study in Lingxin Coal Mine in Ningxia Province, China. *Energy* **2022**, *243*, 123061. [CrossRef]
48. Pujades, E.; Poulain, A.; Orban, P.; Goderniaux, P.; Dassargues, A. The Impact of Hydrogeological Features on the Performance of Underground Pumped-Storage Hydropower (UPSH). *Appl. Sci.* **2021**, *11*, 1760. [CrossRef]
49. Özarslan, A.; Aydıner, H.; Köken, E.; Alber, M. Stability Analysis of Deep Coal Mine Main Roadways for Pumped Hydropower Lower Reservoir Storage. In *Rock Mechanics for Resources, Energy and Environment*; Kwaśniewski, M., Łydżba, D., Eds.; CRC Press: Boca Raton, FL, USA, 2013; pp. 587–592. ISBN 978-1-138-00080-3.
50. Wu, Y.; Zhang, T.; Xu, C.; Zhang, X.; Ke, Y.; Chu, H.; Xu, R. Location Selection of Seawater Pumped Hydro Storage Station in China Based on Multi-Attribute Decision Making. *Renew. Energy* **2019**, *139*, 410–425. [CrossRef]
51. Jovanović, B.; Filipović, J.; Bakić, V. Prioritization of Manufacturing Sectors in Serbia for Energy Management Improvement–AHP Method. *Energy Convers. Manag.* **2015**, *98*, 225–235. [CrossRef]
52. Ji, L.; Li, X.; Huang, W.; Dong, J.; Bai, M.; Li, C. Study on Site Selection Combination Evaluation of Pumped-Storage Power Station Based on Cycle Elimination—Based on the Empirical Analysis of North China. *J. Energy Storage* **2022**, *52*, 104824. [CrossRef]
53. Saaty, R.W. The Analytic Hierarchy Process—What It Is and How It Is Used. *Math. Model.* **1987**, *9*, 161–176. [CrossRef]
54. Xie, H.; Zhao, J.W.; Zhou, H.W.; Ren, S.H.; Zhang, R.X. Secondary Utilizations and Perspectives of Mined Underground Space. *Tunn. Undergr. Space Technol.* **2020**, *96*, 103129. [CrossRef]
55. Xie, H.; Gao, M.; Liu, J.; Zhou, H.; Zhang, R.; Chen, P.; Liu, Z.; Zhang, A. Research on exploitation and volume estimation of underground space in coal mines. *J. China Coal Soc.* **2018**, *43*, 1487–1503. (In Chinese) [CrossRef]
56. Bian, Z.; Zhou, Y.; Zeng, C.; Huang, J.; Pu, H.; AXEL Preusse; Zhang, B.; HABIL Christoph Bruecker; Bai, H.; Meng, Q.; et al. Discussion of the basic problems for the construction of underground pumped storage reservoir in abandoned coal mines. *J. China Coal Soc.* **2021**, *46*, 3308–3318. (In Chinese)
57. Bian, Z.; Zhu, C.; Zhou, Y.; Xu, Y. Evaluation on potential of using abandoned mines for pumped storage in nine provinces of Yellow River Basin. *Coal Geol. Explor.* **2022**, *50*, 51–64. (In Chinese)
58. Lyu, X.; Zhang, T.; Yuan, L.; Yang, K.; Fang, J.; Li, S.; Liu, S. Pumped Storage Hydropower in Abandoned Mine Shafts: Key Concerns and Research Directions. *Sustainability* **2022**, *14*, 16012. [CrossRef]
59. Li, X.; Yang, W.; Zhao, Z.; Wang, R.; Yin, X. Advantage of Priority Regulation of Pumped Storage for Carbon-Emission-Oriented Co-Scheduling of Hybrid Energy System. *J. Energy Storage* **2023**, *58*, 106400. [CrossRef]
60. 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 Rep.* **2022**, *8*, 1249–1258. [CrossRef]