

Review

# Utilization Methods and Practice of Abandoned Mines and Related Rock Mechanics under the Ecological and Double Carbon Strategy in China—A Comprehensive Review

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**Abstract:** Governance of abandoned mines has become a pressing issue for China. The utilization of abandoned mines is a technology that can solve the problem of governance and recreate the value of mines, which is in line with the current strategic goals of ecological protection and double carbon in China. In this paper, the various utilization models and the advances in rock mechanics of abandoned mines across the globe are summarized and reviewed. The utilization models of abandoned mines can be categorized into four aspects: Energy storage, Waste treatment, Ecological restoration, and carbon dioxide (CO<sub>2</sub>) sequestration. There are a number of applications and uses of abandoned mines, such as pumped storage, compressed air storage, salt cavern gas/oil storage construction, carbon dioxide storage and utilization, radioactive waste disposal and treatment, and tourism development. Various progress practices of abandoned mines are discussed in detail with emphasis on the national conditions of China. The basic rock mechanics problems and advances involved in the construction of the facilities related to the utilization of abandoned mines are discussed and evaluated. The establishment of relevant research and experimental platforms will contribute to the sustainable development of China's mining industry and the improvement of clean technologies.

**Keywords:** double carbon; abandoned mines; resource development and utilization; rock mechanics



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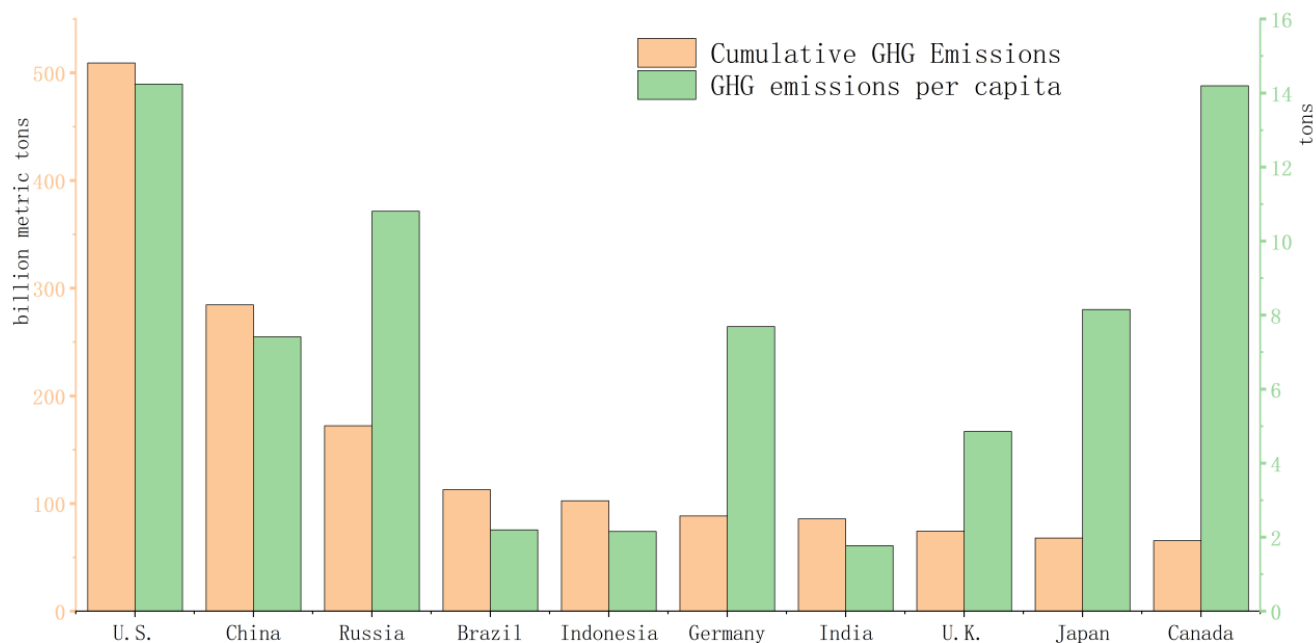
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## 1. Introduction

Environmental problems, such as melting glaciers, sea-level rise, and increased climate extremes caused by the greenhouse effect and animal extinction due to ecological destructions are becoming increasingly serious day by day. Many countries have pledged to do their part to combat climate change. It would be an impressive display of global solidarity if global greenhouse gas emissions fall sharply over the next decade. As one of the signatories of the 2016 Paris Agreement, China has put forward the double carbon goal strategy, i.e., reaching the carbon peak in 2030 and carbon neutrality in 2060. In addition, China has formulated its strictest ecological policy in history and fulfilled “the green mountains and waters being the golden and silver mountains” strategy. The construction, development, and progression of greener mines have become an important component of ecological and environmental protection in China. As one of the developing countries and a major consumer of energy, China's demand for energy has been continuously growing, and the country has surpassed the United States in terms of total annual greenhouse gas emissions and currently ranks first in the world. Figure 1 shows cumulative GHG emissions and per capita GHG emissions of the top 10 countries (data from [1,2]).

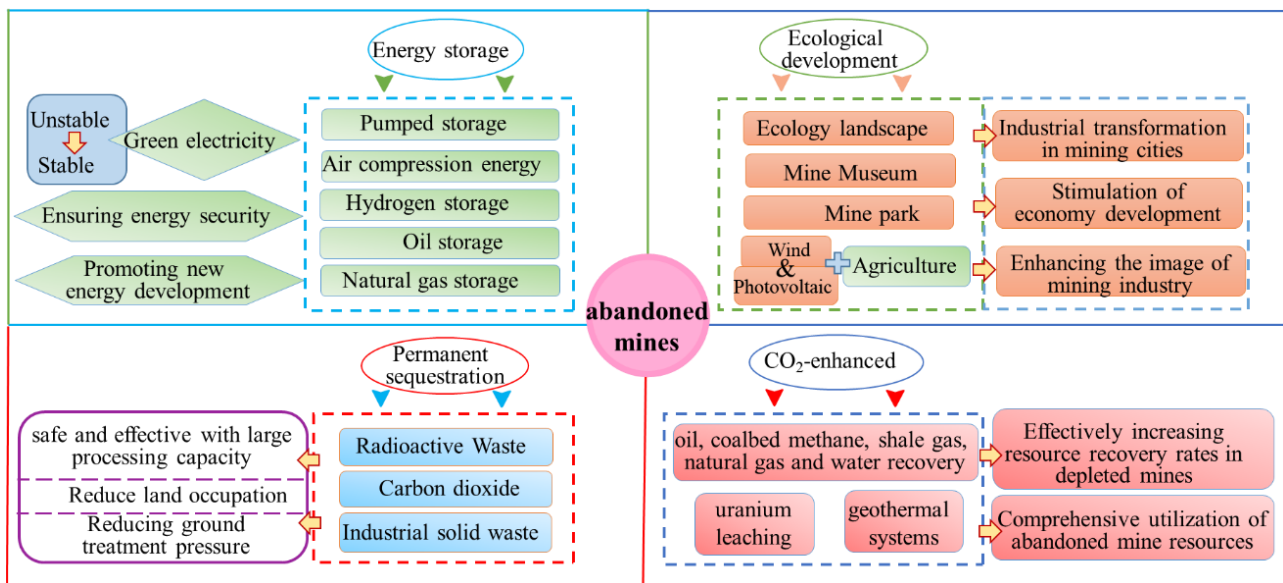
To reduce carbon emissions, China's “14th Five-Year Plan” and “Vision 2035” propose to vigorously develop renewable energy and resource-saving technologies. In recent years, China has seen rapid development of renewable energy, led by wind power and photovoltaic, with a growing share of power generation. It is planned to reach a total

installed capacity of over 1.2 billion kilowatts of wind and solar power in 2030, with the proportion of non-fossil energy consumption reaching around 25% [3]. However, there are many constraints in the development of renewable energy, for example, the difficulty and costs of hydropower construction are increasing, wind power and photovoltaics cannot supply electricity constantly, and nuclear power produces a large amount of radioactive waste every year [4–7].



**Figure 1.** Top 10 countries with cumulative GHG emissions from fossil fuels, land use, and forestry from 1850 to 2021 and GHG emissions (CO<sub>2</sub> emissions from the burning of fossil fuels for energy and cement production) per capita in these countries in 2020.

In the mining industry, mining companies around the world are aiming to minimize carbon emissions over the next 10 to 15 years, with the goal of reaching net-zero emissions by 2050. At the same time, China has continuously increased mine supervision and eliminated outdated production capacity. The number of mines has decreased by 80% in the past 20 years, and there are at least 20,000 abandoned mines [8]. However, abandoned mines do not indicate that they are really ‘abandoned’. On the contrary, the resources they contain, such as space, tourism, mine water, and coal bed methane, have a significant value-in-use. The research into the use of abandoned mines around the world today focuses on four main areas: Energy storage, ecological development, permanent sequestration, and CO<sub>2</sub> utilization (Figure 2). In addition, abandoned mines can be used to build special places, such as deep ground laboratories, confidential centers, medical clinics, and arsenals, etc. A 1500-m deep abandoned gold mine in the United States was developed to establish a deep ground laboratory for the study of particle physics. Ukraine used an abandoned rock salt mine to open a hospital specializing in the treatment of asthma patients [9].



**Figure 2.** Abandoned mine utilization mode.

China's ecological civilization cannot be separated from the remediation of abandoned mines. The rational use of abandoned mines from the perspective of resource reuse can create economic values, improve the energy structure, and help in achieving the "double carbon" goal. Therefore, in this paper, utilization of abandoned mines in China and abroad has been discussed incorporating the basic rock mechanics challenges and issues.

This paper summarizes and reviews the various utilization models of abandoned mines and the progress of rock engineering around the world. Section 2 describes specific abandoned mine utilization methods and the strengths and weaknesses of China in terms of resource potential, current development status, and the extent of development in other countries. Section 3 describes the basic rock mechanics involved in abandoned mine utilization and emphasizes the importance of coupling studies for the long-term stability of rock masses. Section 4 provides a conclusion and prospect of abandoned mine utilization technology and development in China. Notably, the review not only includes mines that have been abandoned due to safety, backward technology, poor management, etc., but also includes resource-exhausted mines and hard-to-use resource storage areas, such as unmineable coal seams.

## 2. Utilization Model of Abandoned Mines

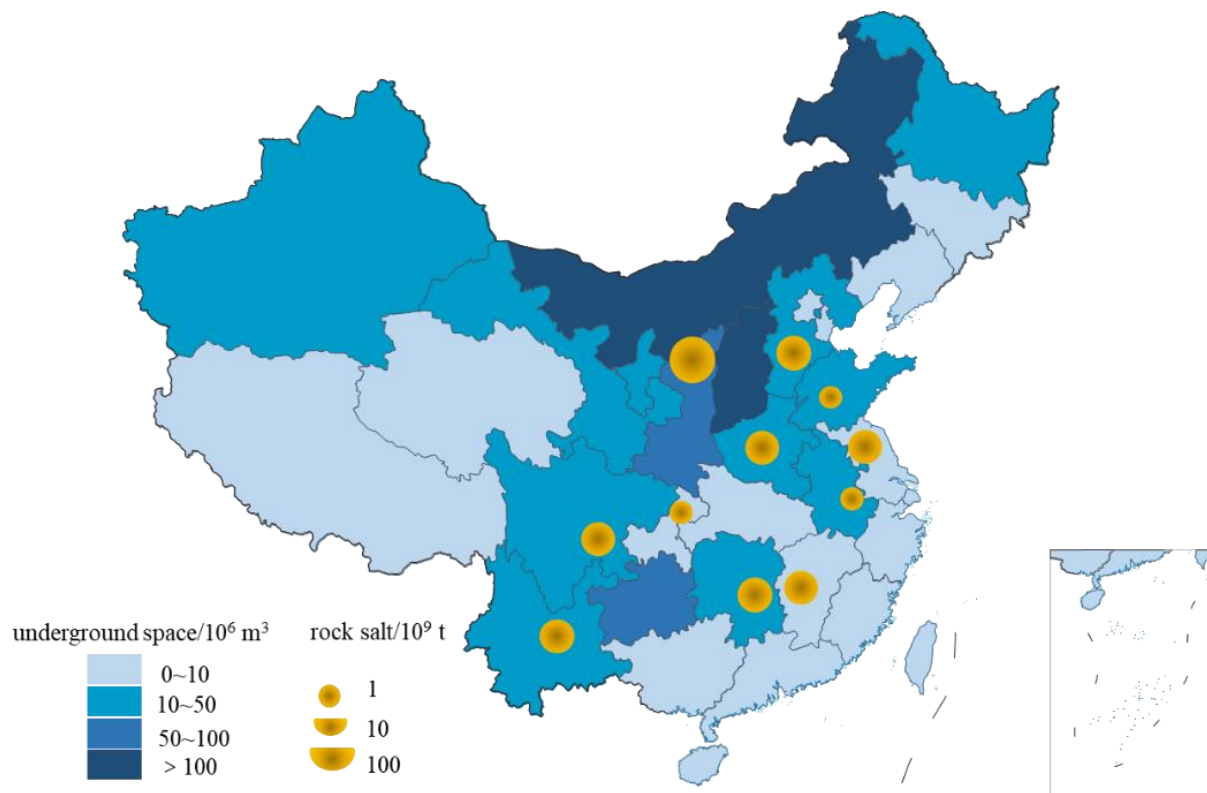
This section discusses the underground energy storage, radioactive waste storage, CO<sub>2</sub> sequestration, and ecological development of abandoned mines in the context of China.

### 2.1. Using Abandoned Mines to Build Underground Energy Storage

Large-scale energy storage is a solution to cope with the unstable power supply of renewable energy sources, such as photovoltaic and wind power and to guarantee the strategic needs of the country. The huge space contained in the abandoned mines can provide a guarantee for large-scale underground energy storage. Underground energy storage can be categorized into underground water storage, gas storage, and oil storage according to the energy medium.

Abandoned underground mines with huge space are the best places to build energy storage reservoirs. China is fortunate to have a large number of underground mines. The total amount of underground space available in China's coal mines is about  $4 \times 10^8$  m<sup>3</sup>, and the existing salt cavern space is  $1.3 \times 10^8$  m<sup>3</sup>. The available underground space has a good growth momentum and great potential for utilization with the elimination of backward mines and the continuous exploitation of rock salt mines [10,11]. Figure 3

shows the characteristics of subsurface space and rock salt distribution in China (the data of underground space from [10] and rock salt data comes from the official websites of Chinese county and city governments).



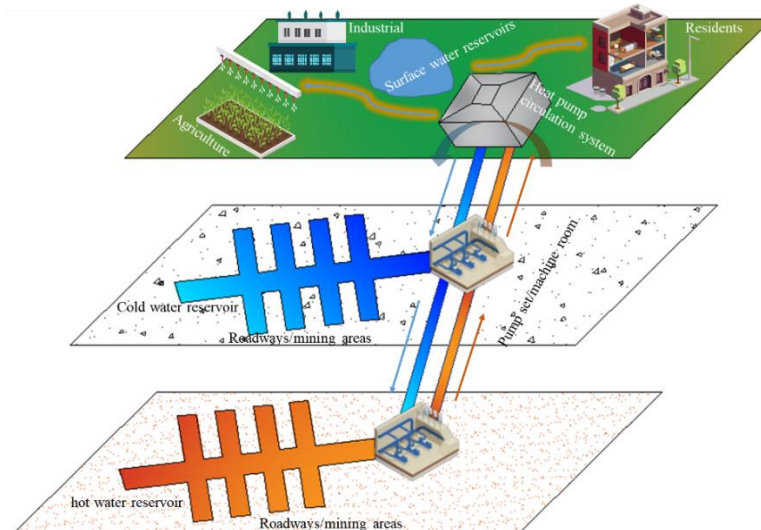
**Figure 3.** Estimates of underground space as of 2020 and distribution of proven rock salt reserves.

### 2.1.1. Underground Water Reservoir

The construction of underground water reservoirs in abandoned mines can be summarized in three models, such as storage and filtration of mine water, geothermal utilization model, and pumped hydroelectric storage (PHS) plants system. It has been found that high-intensity mining of coal causes serious damage to water reservoirs and resources. A study performed by Gu Dazhao et al. [12], showed that currently, China produces about  $6.88 \times 10^9 \text{ m}^3$  of coal mine water per year, with an average utilization rate of about 35% with a huge potential for upgrading this in the near future. Considering the climatic conditions in northwestern China, the mine water storage filters are capable of providing water for industrial and mining use and agricultural irrigation in the vicinity. By the end of 2020, China had more than 17 underground coal mine filter storage reservoirs built or under construction in Shaanxi, Shanxi and Inner Mongolia provinces alone, with a total storage capacity of  $26,486,000 \text{ m}^3$  [13].

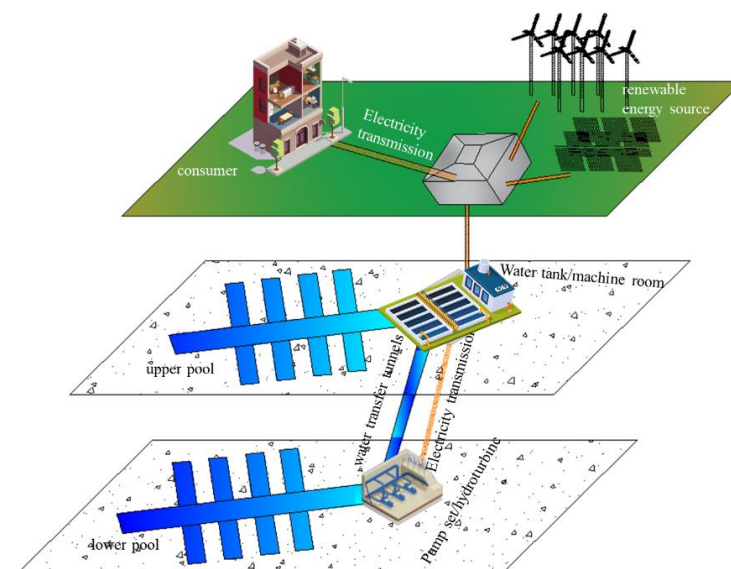
Low- and medium-temperature geothermal energy is widely distributed in China. The geothermal resources shallower than 200 m are equivalent to 9.5 billion tons of standard coal, and the geothermal energy from 200 to 3000 m is 12.5 billion tons of standard coal [14]. The geothermal utilization model of abandoned mines is usually a closed-loop or open-loop structure formed by injection wells (cold water injection), upper reservoirs (cold water), lower reservoirs (hot water), production wells (hot water extraction), and energy conversion plants. Figure 4 shows the geothermal energy utilization model of abandoned mines. Underground reservoirs act as water and energy storage in this model. As mining gradually moves deeper, geothermal resources will be more abundant in abandoned mines in the future, and the use of geothermal power generation will be better than the other renewable energy sources in terms of utilization factor, power generation cost,

and stability [15]. At present, the construction of underground water reservoirs in the geothermal mode of abandoned mines in China is still in the planning stage. In addition, it is proposed to use Functional Backfill to store heat/energy, while filling the goaf according to the characteristics of high-temperature in deep mining of metal mines. Moreover, as reported by Liu et al. [16,17], it is suggested to establish a unique mine backfill coupled heat exchange system that can realize geothermal energy recovery.



**Figure 4.** Geothermal energy utilization model of abandoned mines.

The development of PHS plants has a history of more than 100 years. It is the power storage system with the most mature technology and the highest actual energy conversion rate (about 80%) among all large-scale energy storage methods [18]. China's north and northwest plains lack natural high drop terrain conditions suitable for the establishment of surface pumped storage power plants, thus the use of abandoned mines is an ideal choice for construction [19]. Figure 5 shows the PHS plants system using an abandoned mine.



**Figure 5.** PHS plants system using abandoned mines.

In 1992, the State of New Jersey agreed to use abandoned iron ore mines to build the Mt. Hope PHS plant project, with a total capacity of 2000 MW, second only to the Bath County PHS plant (2100 MW) in the United States. The Mt. Hope PHS plant adopts a

closed-circulation water system power generation mode, relying only on lake water, mine water, and natural precipitation to meet all water needs [20–22]. Most of the coal mines in Spain were phased out in 2018, and the transformation of the tunnel system in the northern Asturias coal mining area into the lower reservoir of the underground pumped storage project was planned, with a storage capacity of about 200,000 m<sup>3</sup> at a depth of 300–600 m [23]. In 2015, the Czech Republic launched a research project on the operation of a pumped-storage power plant at the closed Jeremenko hard coal mine (near the Ostrava River), using the existing mine drainage system after nearly 4.5 years of preparation, which was expected to reach a power of 732 kW, actually about 680 kW (400 V), with a storage capacity of 3000 m<sup>3</sup> [24]. Germany is carrying out the project “Using Abandoned Mines to Store Wind Power”. A team of scientists from the Technical University of Clausthal and industry representatives have designated 104 abandoned underground mines suitable for the construction of pumped storage power plants and gradually worked on these mines between 2015 and 2018 [25,26]. At the same time, the project team selected the abandoned metal mine Wiemannsbucht in the Harz area for a pilot simulation study for the construction of an underground pumped-storage power plant [27]. Abandoned metal mines have a deeper mining depth compared to coal mines, which can provide greater hydraulic fall and better lithology and more stable underground space. In 2016, Germany carried out a feasibility study on the construction of an underground PHS plant in the Prosper-Haniel coal mine and provided a conceptual model of the plant. The plant is a closed system with a maximum output of 200 MW and a storage cycle of about 4 h (800 MWh), with the lower storage reservoir being the original shaft at a depth of 600–1000 m with a capacity of 600,000 m<sup>3</sup> [28,29]. After completion, it will be the world’s first abandoned coal mine to be used as an energy storage facility.

The use of abandoned mines to construct PHS plants in China is in the research stage as a whole, and there are no examples yet. Table 1 shows the projects of using mines to construct a PHS plant in China.

**Table 1.** The projects of using mines to construct pumped storage in China.

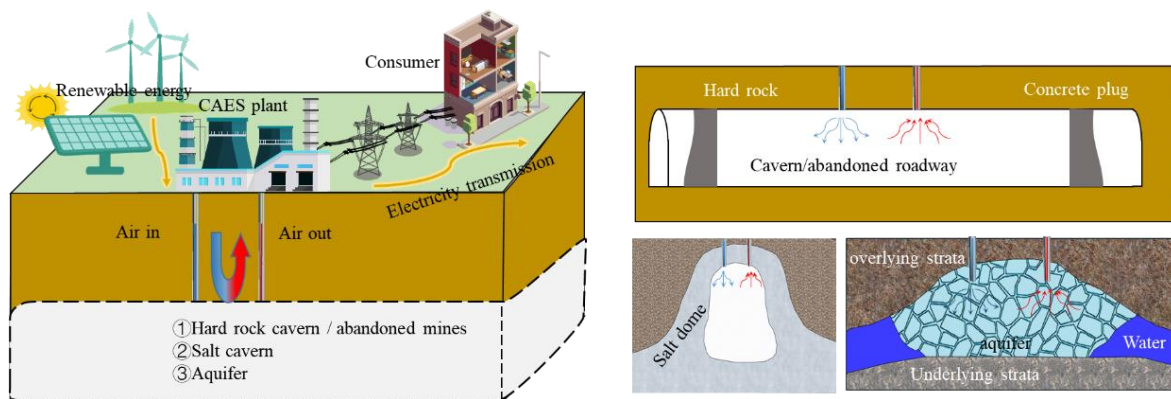
Location	Project Name	Status	Mine Type	Capacity
Jurong, Jiangsu Province	Shi Dangshan PHS plant Project [30]	Feasibility Study	Upper reservoir: Open-pit quarry Lower reservoir: Underground copper mine	1 billion kWh/year
Fuxin, Liaoning Province	Fuxin Haizhou Mine PHS plant Project [31,32]	Feasibility Study	350 m deep open-pit coal mine	3.6 million kW
Zibo Shandong Province	Huadian Zichuan Kunlun Town Multi-energy Complementary Energy Complex Project [33]	Under construction	Underground coal mines	22 million kW

### 2.1.2. Salt Cavern Gas Storage (SCGS)

Salt rocks are commonly used to build oil and gas storage reservoirs due to their excellent physicochemical properties. The United States completed the geological survey of known salt mines in the country as early as the last century (before 1978) [34]. It also has built hundreds of salt cavern oil and gas storages and attaches great importance to the development of hydrogen storage. SCGSs in operation in the world is mainly distributed in North America and Europe, with Germany and the United States in the majority [35].

Latest development of salt cavern storage in China is summarized as follows. In 2007, the first SCGS—Jintan gas storage was officially put into operation for gas injection [36]. The number of existing oil storage facilities in China are not able to meet the strategic needs, but the proportion is significantly increasing every year. Moreover, there is no hydrogen storage examples in China at present [35]. The first batch of compressed air energy storage (CAES) projects had been connected to the grid in 2021. There is a huge gap in China in terms of salt cavern energy storage compared to Germany, the United States, and other developed countries. However, China is pushing salt cavern storage technology, with a number of CAES and natural gas storage projects coming on stream [37,38].

1. CAES is considered to be the second most suitable technology for GW-scale large-scale power storage after pumped hydro storage. The types of gas storage caves for CAES can be mostly divided into salt caverns, hard rock caves, abandoned mines, and aquifers. Figure 6 shows the use of underground caves to build a CAES plant. To date, there are only two large-scale compressed air energy storage plants in commercial operation in the world, namely the Huntorf power plant in Germany built in 1978 and the McIntosh power plant in the United States built in 1991 [39]. Both were built in salt caverns and are functioning well today.



**Figure 6.** Construction of CAES plant using underground caves.

When discussing the feasibility of developing CAES, low-cost, large-scale available storage is critical. With the fact that it takes several years to dissolve a usable salt cavern, the use of existing salt caverns is an economically viable option. From China's Jintan salt cavern CAES construction experience, salt cavern gas storage has a number of advantages, such as low construction cost, small footprints, good sealing, safety, and stability [11].

2. Underground hydrogen storage has many advantages over surface storage, including safer storage, smaller footprints, larger storage capacity, and lower cost. Taylor et al. [40] pointed out that large-scale underground storage is only one-tenth or even less than the cost of surface storage facility. Zivar [41] and Tarkowski [42] discussed that among the three types (depleted reservoirs, aquifers, and salt caverns) of subsurface hydrogen storage, salt cavern hydrogen storage is the best option from various perspectives, including gas tightness of the reservoir, gas volume, extraction efficiency, biochemical reactions, and practical experience. According to CEDIGAZ (International Gas Information Association) 2019 data, salt cavern storage of natural gas now accounts for 26% of global deliverables [43].

The United Kingdom, the United States, Germany, and other countries have already built salt cavern hydrogen storage pilots [44–46]; however, to date, China has no underground hydrogen storage practice. It has been found that there is no essential difference between hydrogen storage in salt caverns and natural gas storage [41,42]. China has more than 10 years of experience in natural gas storage in salt caverns, and there is great potential for developing hydrogen storage in salt caverns. The results of a study performed by

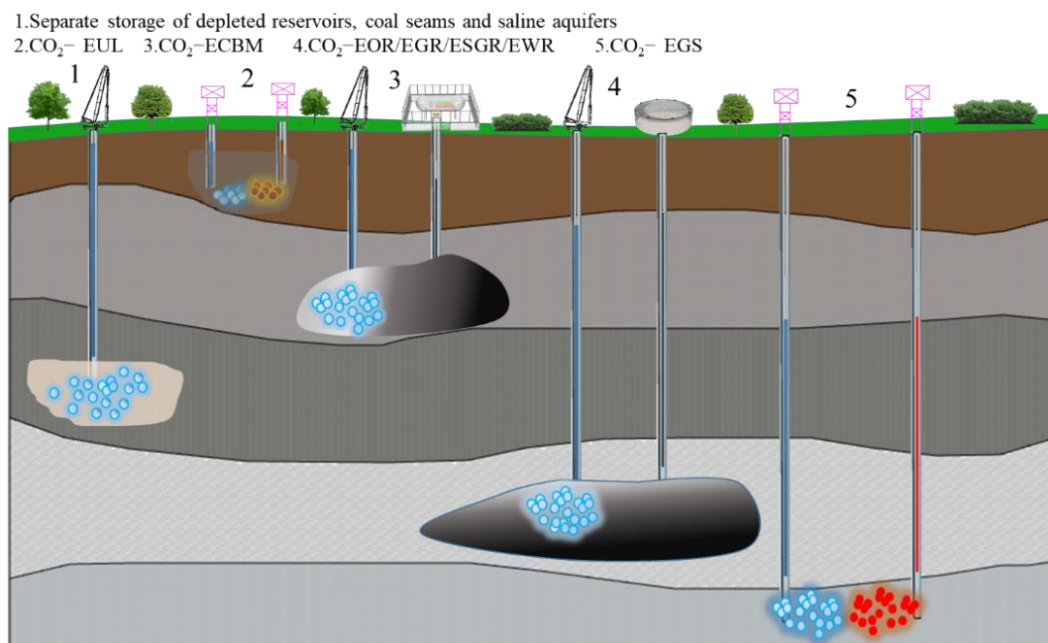
Yang Chunhe (Year, Ref), showed that the hollowed salt caverns of abandoned salt mines in Jintan have long-term storability values [47]. In September 2021, the Institute of Rock and Soil Mechanics, Chinese Academy of Sciences established a joint research center for hydrogen and helium storage technology in salt caverns with China National Salt Industry Group Company Limited. In combination with the trends of hydrogen development in China, a “production-storage-use” integrated hydrogen chain was proposed. Fang et al. [48] proposed an integrated hydrogen energy “production-storage-use” chain for three development scenarios from salt cavern hydrogen storage reservoirs in the context of China.

## 2.2. CO<sub>2</sub> and Radioactive Waste Sequestration

Deep sequestration of CO<sub>2</sub> and radioactive waste is a key technology that countries all over the world have reached a consensus on. Using abandoned mine shafts for storage can save costs and increase throughput.

### 2.2.1. CO<sub>2</sub> Geological Storage and Utilization

CO<sub>2</sub> storage technology is a key method to achieve the double carbon goal, which mainly includes separate storage in depleted oil and gas reservoirs, coal seams, and salt-water layers, and CO<sub>2</sub>-enhanced uranium leaching/enhanced coal bed methane recovery/enhanced oil recovery/enhanced natural gas recovery/enhanced shale gas recovery/enhanced water recovery/enhanced geothermal systems (CO<sub>2</sub>-EUL/ECBM/EOR/EGR/ESGR/EWR/EGS) [49]. Figure 7 shows CO<sub>2</sub> geological storage and utilization technology. Considering the storage volume and technical level, this section discusses the application of CO<sub>2</sub> in depleted oil and gas reservoirs and coal mines. When filling abandoned mines, it can imitate the natural CO<sub>2</sub> mineral absorption process, and use solid waste containing alkaline or alkaline earth metal oxides to form CO<sub>2</sub>-solid waste composite materials through carbonation reaction, thereby filling the mines and stabilizing CO<sub>2</sub> for a long period of time.



**Figure 7.** CO<sub>2</sub> geological storage and utilization technology.

1. Approximately 84 million tons of CO<sub>2</sub> are piped to depleted oil fields each year in the US to sequester and effectively increase oil production, and the US government is strongly encouraging this method [50]. In 2002, Australia used the Otway Basin



depleted gas field for carbon sequestration, which is the largest demonstration project of CO<sub>2</sub> geological storage in Australia [51]. Chinese gas reservoirs are mainly located in the Ordos, Sichuan, Bohai Bay and Tarim Basins. About 15.3 billion tons of CO<sub>2</sub> can be sequestered using depleted gas reservoirs, and about 9 billion tons of CO<sub>2</sub> can be sequestered by CO<sub>2</sub>-EGR technology [52]. However, China's natural gas industry started late and will not see large-scale depleted gas fields for a long period of time [53]. Therefore, China's carbon sequestration demonstration projects are primarily depleted fields. China's oil fields are mainly concentrated in the Songliao, Bohai Bay, Ordos and Junggar Basins, and about 5.1 billion tons of CO<sub>2</sub> can be sequestered through CO<sub>2</sub>-EOR [52]. CO<sub>2</sub>-EOR in China started in the early years. In 1963, CO<sub>2</sub>-EOR experiments were carried out in Daqing Oilfield, and it was proved that it could increase the production by 10% [54]. In 2010, Shenhua Group (now CHN ENERGY) launched the first demonstration project of the whole process of CO<sub>2</sub> capture and geological storage in China [55]. By 2020, more than 15 CO<sub>2</sub>-EOR demonstration projects have already been conducted in China in several provinces, including Jilin, Heilongjiang, Shaanxi, Shandong, Henan, and Jiangsu [50].

Compared with the United States and other countries, the disadvantageous conditions are that China's oilfields have complex strata structure, strong heterogeneity, low or ultra-low permeability, low porosity, and poor oiliness. CO<sub>2</sub>-EOR technology will be challenged by high miscible phase pressures, severe gas fouling, heavy solid phase deposition, and complex reservoir development [56]. Moreover, the CO<sub>2</sub> infused in China is mainly gaseous and liquid and is transported by road, while the US has a mature pipeline transportation system, and all the CO<sub>2</sub> used for infusion is supercritical CO<sub>2</sub>.

2. Geological caprocks that are not affected by mining disturbances and coal seams with good air tightness can achieve CO<sub>2</sub> storage. Coal seams are one of the most ideal sites for geological storage in China due to their huge open space and highly stable adsorption of CO<sub>2</sub>, especially the ability to displace coalbed methane [57–59]. According to the estimation performed by Yu et al. [60], the CO<sub>2</sub> storage capacity of Chinese coal seams is nearly  $142.67 \times 10^9$  t. In addition, Liu et al. [59] estimated the storage capacity of coal seams with a depth of 300–1500 m in China to be  $12.078 \times 10^9$  t. Coal mine goafs and non-minable coal seams contain a large amount of coalbed methane resources, and the permeability of coal reservoirs in China is generally low. CO<sub>2</sub>-ECBM is one of the potential methods to increase the production in low permeable coal seams. The main component of coalbed methane is methane, similar to natural gas. Using coalbed methane can prevent it from escaping into the air and increase the greenhouse effect. China is rich in coal-bed methane resources. Among the 30 major onshore coal-bearing basins in China, the amount of coal-bed methane resources are  $29.82 \times 10^{12}$  m<sup>3</sup> at a burial depth of 2000 m or less, and the recoverable resources are  $12.51 \times 10^{12}$  m<sup>3</sup>. Among them, the gas content of the Qinshui Basin in Shanxi reaches 21.85 m<sup>3</sup>/t, with a high recoverability factor [61]. According to statistics, the residual coalbed methane with a development value in Shanxi Province alone reached  $72.6 \times 10^9$  m<sup>3</sup> [62].

The CO<sub>2</sub>-ECBM field trial was first conducted by the United States in 2001 with a 95% coalbed methane recovery rate. Field trials of different scales have been conducted accordingly in Japan, the EU, and Canada [63]. Since the 1990s, China has been studying the feasibility of this technology [64], which is still in the pilot test phase. In 2004, China United Coal Bed Methane Co. Ltd. conducted a series of pilot injection and monitoring studies in Liulin and Shizhuang in the Qinshui-Linfen Basin.

### 2.2.2. Radioactive Waste Sequestration

The disposal of radioactive waste is considered to be one of the greatest problems in the world. Improper disposal may bring serious consequences. For example, in 2021, Japan discharged the Fukushima nuclear wastewater into the sea, which caused serious

environmental pollution and aroused strong condemnation from all over the world. Using the unique underground space created by abandoned mines to dispose of radioactive waste is one of the most effective methods. Table 2 shows underground disposal facilities of low-and-intermediate-level radioactive wastes constructed using abandoned mines in Germany and the Czech Republic.

**Table 2.** Abandoned mine shafts as disposal facilities of low-and-intermediate-level radioactive wastes.

Country	Name	Mine Type	Introduction [65]
	Asse	Rock Salt	Up to 765 m deep, 125,000 barrels of low-level radioactive waste and 1300 barrels of intermediate-level radioactive waste were stored during 1967–1968, and were later suspended due to salt water infiltration.
Germany	Morsleben	Rock Salt	The mining depth is 300–500 m. In 1971, the goaf was directly used as a disposal area. By 2014, before the disposal site was closed, a total of 36,752 m <sup>3</sup> of waste had been disposed of.
	Konrad	Iron	Storage of low-calorie radioactive waste, which accounts for about 90% of all radioactive waste in Germany, with a disposal scheme similar to that of the Asse disposal facility.
Czech Republic	Richard	Limestone	Operating in 1964, it is scheduled to close in 2070. In the existing roadway of the reinforcement part, the waste is disposed of in the roadway of 70~90 m underground.
	Bratrství	Uranium	One roadway and five chambers have been transformed and reinforced for the disposal of radioactive waste. It started in 1974 and is still in operation.

Research on the permanent disposal of high-level radioactive waste began in the United States in 1955 [66], and after extensive research, deep rock-salt reservoirs were set as the preferred target. The Waste Isolation Pilot Plant (WIPP) has been using the Salado salt mine to receive radioactive waste left over from nuclear weapons research and production since 1999 [34]. The Chinese scholars Ding and Xie [67] both also proposed the use of underground salt caverns for nuclear waste disposal.

In China, granite with high strength and excellent mechanical properties [68,69] is selected as the carrier of the disposal. At present, the geological disposal of high-level radioactive waste in China has entered the preparation stage of the underground laboratory. The main structure scheme of spiral slope + three shafts + two-story level road is adopted, and test platforms are constructed at 280 and 560 m under the Beishan Mountains of Gansu [70]. Figure 8 shows China's underground radioactive waste disposal repository.

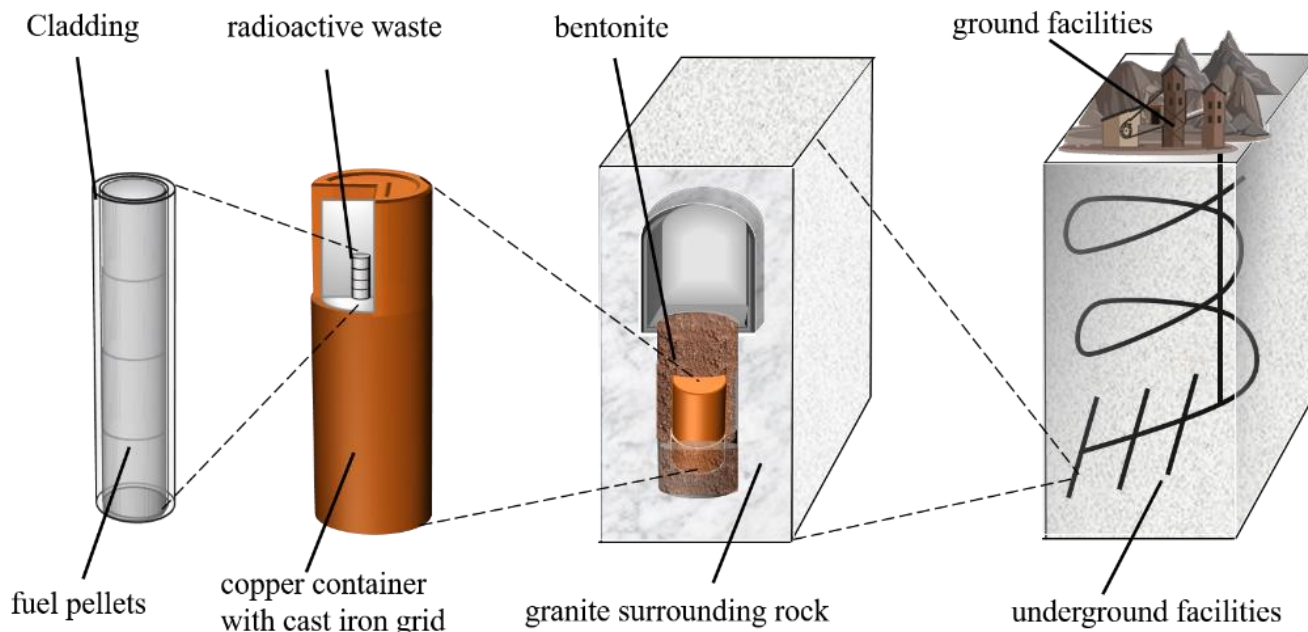


Figure 8. Model of underground radioactive waste disposal repository in China.

### 2.3. Abandoned Mine Ecological Resource Development

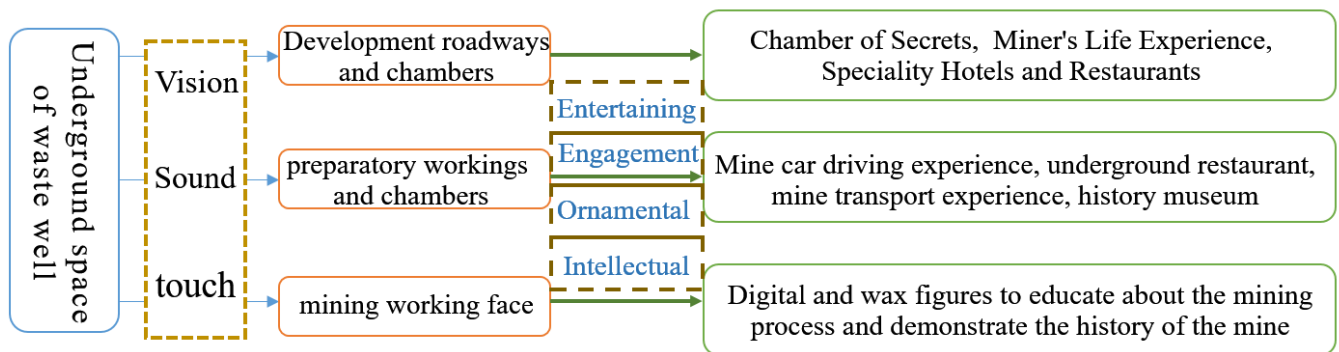
The ecological development of abandoned mines is mainly expressed in the form of tourism. As shown in Figure 9, the more common forms of tourism in abandoned mines can be roughly divided into the close-to-nature model of building parks and gardens with the abundant light and water storage capacity characteristics of open-pit mines; and the humanistic exploration model of building underground exploration tours and experiences with the interactive long-walled spaces of underground mines and the chambers along the tunnel.



Figure 9. Ecological development model of abandoned mines.

In China, there is a rich experience in tourism development of abandoned open-pit mines. The more famous ones are Inter Continental Shanghai Wonderland Hotel and Hubei Huangshi National Mine Park. In addition, China is actively exploring the use of flat land formed by abandoned open-pit mines to develop a new agro-tourism model of “renewable energy generation + agriculture + tourism”.

China is still in the exploration stage of tourism development of abandoned underground mines. Figure 10 shows the form of tourism development for the underground space (figure elements from [71]).



**Figure 10.** Abandoned underground mine tourism project development.

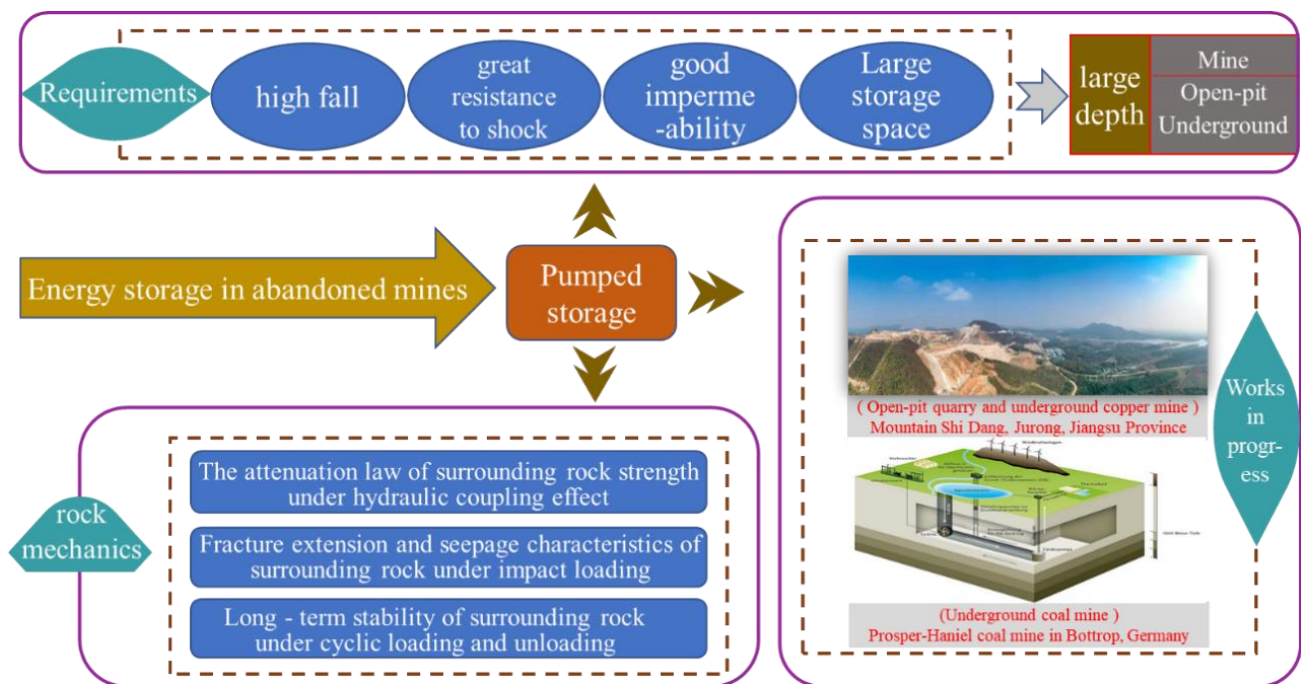
The development of mine tourism resources is constrained by many aspects, such as minerals, government, economy, and natural conditions. Taking the construction of China’s national mine parks as an example, there are four batches of 88 national mine parks, most of which are concentrated in the eastern and central provinces, and less in the western provinces. The spatial distribution is clearly coupled with China’s four major economic zones, and the richer the history and heritage of mining development, the more likely it will be a National Mine Park [72]. It can be inferred that the tourism resources of abandoned mines are concentrated in the surrounding areas with good economic development and mining history.

### 3. Basic Rock Mechanics of Using Abandoned Mines

The rock mechanics challenges of using abandoned mines to construct underground projects can be summarized in two aspects: 1. The geological characteristics of abandoned mines, such as rock mass lithology, hydrology and earthquake, as well as the mining characteristics of internal rock mass spatial structure. For example, cylindrical columns are more reliable than prismatic isolated pillars [73] and height to width ratios and width to thickness ratios have a great influence on the bearing ability of rocks [74]. 2. Requirements of underground engineering operation on the surrounding rock. For example, the surrounding rock of abandoned mine used for underground water reservoir construction must be impacted by water flow in different degrees for a long period of time, which requires high mechanical properties of surrounding rock.

#### 3.1. PHS Plants/Underground Water Reservoir

Figure 11 shows construction requirements and rock mechanics of abandoned mine PHS plants. The engineering and stress environment of the underground water reservoir of the abandoned mine PHS plant is as follows:



**Figure 11.** Construction requirements and rock mechanics of abandoned mine PHS plants.

The surrounding rock of the underground water reservoir and the artificial dam are in a high crustal stress environment;

The collapsed rock mass and the overlying rock in the goaf are in a state of movement for a long period of time, which produce lateral pressure on the surrounding rock of the reservoirs;

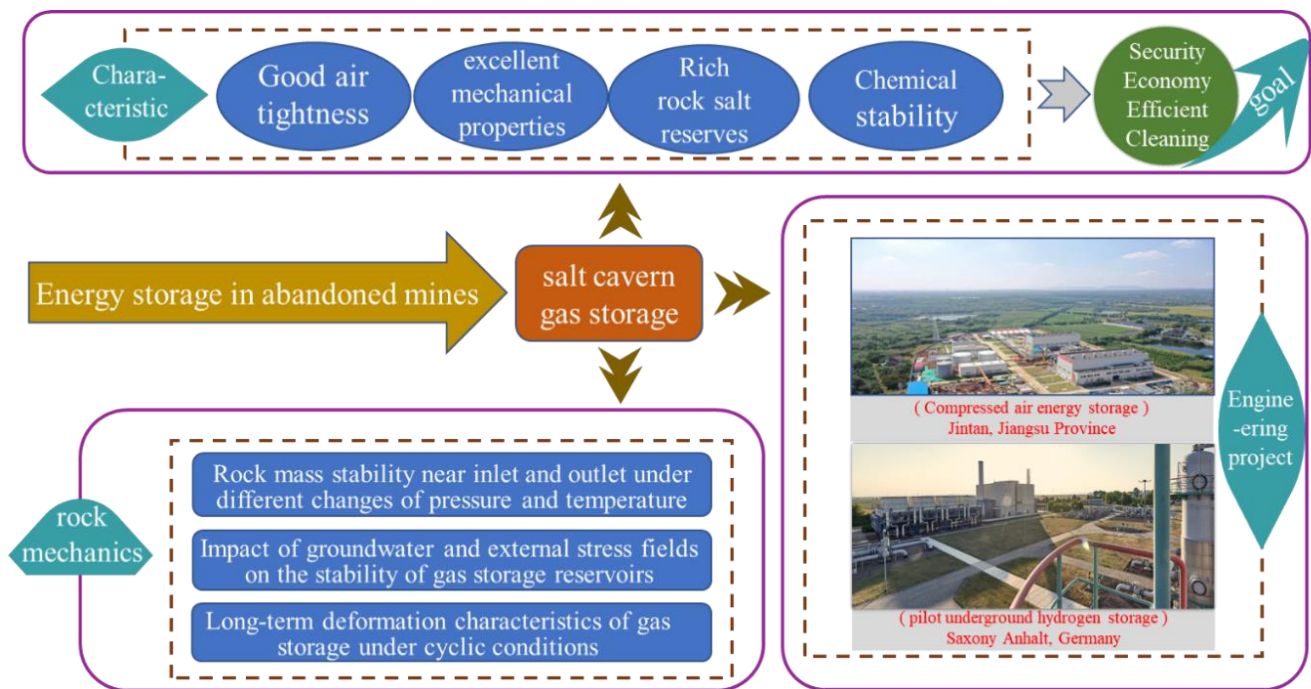
Long-term frequent pumping and filling of water in the reservoir produce strong cyclic fatigue load on the surrounding rock;

Effect of strong dynamic impact on surrounding rock of reservoir, such as high drop and large flow impact, wave and its reflection in tunnel and mine quake.

### 3.2. Underground Energy Storage

In China, large-scale oil reserves are carried out by sealing caverns with underground water, and most of the existing operating and large-scale underground gas storage are salt caverns. Therefore, only the rock mechanics of the construction of salt cavern gas storage are introduced here.

Depending on the frequency of gas used in the gas storage, stress cyclic loads of different time frequencies will be formed and an inhomogeneous thermal field will be generated near the inlet and outlet of the salt cavern. Li et al. [75] proposed a coupled thermodynamic model of wellbore-salt cavern that can be used for the thermal state analysis of salt caverns considering the cyclic conditions of natural gas storage reservoirs. Contrary to Europe and other western countries, where salt rocks are mostly salt domes, salt deposits in China generally have the characteristics of many layers and a thin single layer. Complex geological conditions increase the possibility of underground energy storage risks [47,76,77]. Therefore, many scholars have studied the influence of the interlayer on the shape and stability of gas storage reservoirs. [78–81]. In addition, salt is easily soluble in water, and gas storage in salt caverns is in the form of gas storage clusters. Therefore, extra attention should also be paid to the groundwater distribution and the influence of stress distribution in adjacent salt caverns when selecting the site for gas storage. Figure 12 illustrates the general framework of salt cave gas storage.



**Figure 12.** General framework of salt cave gas storage.

### 3.3. CO<sub>2</sub> and Radioactive Waste Sequestration

CO<sub>2</sub> geological sequestration mechanisms can be divided as physical and chemical sequestration mechanisms. Among them, physical sequestration mechanisms include tectonic stratigraphic sequestration, bounded sequestration, and hydrodynamic sequestration; whereas chemical sequestration mechanisms include dissolution sequestration and mineralization sequestration, etc. With current estimates, CO<sub>2</sub>-EOR and CO<sub>2</sub>-ECBM have the greatest potential for CO<sub>2</sub> storage in China, thus only the related rock mechanics issues with these two are presented here. The CO<sub>2</sub> sequestration depth is generally below 800 m, where the temperature and pressure conditions maintain the CO<sub>2</sub> in a liquid or supercritical state. Supercritical carbon dioxide can dissolve organic matter in sequestered rocks, such as coal matrix, forming voids, and reducing the strength of the surrounding rock. Carbon dioxide reacts chemically with water and acid roots and metal ions in the formation, corroding the rock, promoting crack expansion, and further reducing strength. In CO<sub>2</sub>-ECBM, supercritical CO<sub>2</sub> is adsorbed in the formation of expansion stress and shear deformation, reducing the formation strength, seriously affecting the integrity and possibly leading to CO<sub>2</sub> leakage. In actual engineering, the injection of carbon dioxide is periodic, and the change of rock mass strength under the condition of cyclic injection of CO<sub>2</sub> is different [82].

For the disposal of radioactive waste, the difficulty for China and the world lies in the high-level waste (HLW). The HLW deep-buried point is in a state of high in situ stress. To safely bury it for a long period of time, three development stages of fatigue failure of rock mass under microseismic conditions should be considered [83]. Due to the continuous decay of nuclides, a large amount of heat is released, and the temperature at the deep burial point is high and subject to fluctuating changes. HLW has the nature of nuclide migration, and it is necessary to ensure the tightness of the repository, especially since there should be no water connected to the biosphere nearby. To achieve biosphere isolation in ten thousand years or even tens of thousands of years, the near-field and far-field thermal-hydraulic-mechanical coupling process and long-term behavior estimation was performed during the geological disposal (excavation, operation, and later closure) of high-level nuclear waste. In summary, HLW deep burial requires the following rock mechanics studies:

1. The evolution law of temperature and pressure of the surrounding rock.
2. The rock rupture process and fracture expansion law.
3. The long-term stability and shape change law of the facility.
4. The influence of possible earthquakes and water flows on the stability of the facility.

Figure 13 illustrates the use of abandoned mines for permanent sequestration of carbon dioxide and radioactive waste.

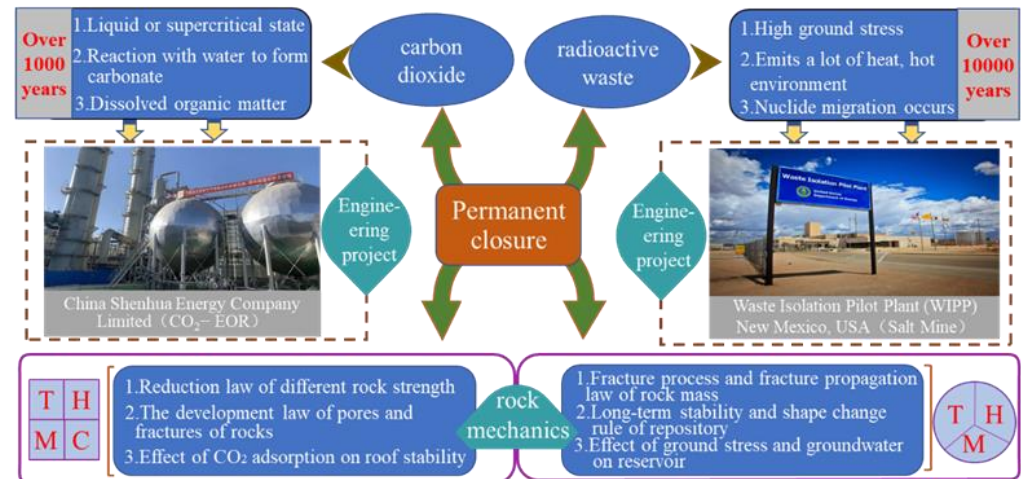


Figure 13. Use of abandoned mines for permanent CO<sub>2</sub> and radioactive waste sequestration.

#### 4. Conclusions and Prospects

The reuse of abandoned mines is a low-carbon environmental technology that saves resources and brings a series of socio-economic benefits, which is important for China to realize the construction of ecological civilization and achieve the double carbon goal. To date, most of the utilization models of abandoned mines remain a world problem. Developed countries, such as the United States, Germany, and the United Kingdom were the first to start research on the use of abandoned mines and have established a series of industrial projects with a considerable degree of experience that can be used as a reference for China.

China has a large number of abandoned mines with high potential for utilization. However, most of the utilization technologies are still in the pioneering research stage and only a few have entered the industrial demonstration stage. Moreover, compared with European and American countries, abandoned mines in China have more complex geological conditions, and significant rock mechanics challenges, issues, and problems, which need to be solved. Existing engineering research should learn from foreign experience and combine it with China's own engineering geological conditions to explore the utilization mode of abandoned mines that conforms to China's national conditions. Investment in research on key utilization models, such as energy storage and CO<sub>2</sub> sequestration in abandoned mines should be increased. Furthermore, an increasing number of industrial demonstration projects should be established, and key rock mechanics issues should be tackled in a proper manner. Finally, exploring a mature business model from mining to the reuse of abandoned mines will achieve sustainable development of the mining industry.

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