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The Great Role of Geological Storage-Based Carbon Capture and Storage in Mining Site Regeneration

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Abstract. To promote the application of carbon sequestration technology in mine reclamation and to fill the research gap regarding the long-term development direction of carbon sequestration areas, this study focuses on the feasibility of the coordinated development of underground and the surface systems in mining areas. By systematically analyzing historical restoration pathways of mining areas and current mainstream mine renovation paradigms, three critical bottlenecks are identified: uncertainties related to geological safety, inadequate governance structures, and the need to enhance social acceptance. Subsequently, the research focuses on examining two major case studies: the park renovation initiative in Germany's Ruhr region and the conflict scenarios at Chile's Chuquicamata Mine. This paper proposes a multi-dimensional promotion framework, covering technical standards, economic incentives, legal and regulatory mechanisms, as well as social governance strategies. Finally, from the perspective of long-term development, a comprehensive evaluation index system will be established for the future positioning of mining areas.

Keywords: Carbon capture and storage, ecological synergy, social acceptance, integrated framework, mining areas.

1. Introduction

Carbon Capture and Storage (CCS) is an emerging solution to global climate change. As defined by the United Nations Intergovernmental Panel on Climate Change (IPCC), it involves capturing CO_2 from some large fixed sources, transporting it via pipelines, and injecting it into deep geological structures that are suitable for permanent sequestration [1]. In addition to typical storage carriers, such as some gas fields and salt formations, mining areas have unique storage potential due to their geology and spatial characteristics. At the same time, as global carbon emission issues receive increasing attention, their ecological restoration is gradually moving towards a comprehensive model [2]. However, existing studies focus on ecological restoration or underground storage in isolation, lacking systemic subsurface-surface integration, with technical barriers and low public acceptance limiting research.

From the perspective of the historical evolution of mining areas, the concept of ecological restoration in mining regions has undergone significant updates and transformations [3]. Recovery planning often lacks a systematic perspective. It is mainly characterized by two isolated methods:

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one focuses on the ecological engineering of surface reclamation, the other focuses on the protection of industrial traces, and finally evolved into a part of the cultural tourism industry, which has become particularly popular in recent years [4,5]. Although these two methods have successfully realized the basic ecological restoration and development transformation of the mining area, from the perspective of integrated transformation and space utilization, they have not fully considered the methods and economic value of underground space utilization in these areas [6]. The underground space in the mining area has a large capacity and rich rock structure, but its storage and utilization value are often ignored due to unstable geological structure and a lack of professional technical support. At present, the recovery and development of mining areas are mainly faced with problems such as poor ecological stability, high cost of pollution control, no targeted scheme, large initial investment, long return cycle, and difficult marketization, and a lack of a sustainable collaborative development mode. At the same time, there is also a certain gap in the positioning evaluation of the later development of the mining area. In addition, the research focusing on the transformation and utilization of the underground part of the mining area is not the mainstream direction, and the lack of data and cost problems are more prominent.

In order to solve the core contradiction of the isolation between ecological restoration and carbon sequestration applications in mining areas, and the lack of collaborative governance between underground and surface systems, this paper centers on mining area collaboration, and from the integrated perspective of 'technology-space-management trinity’, constructs a four-dimensional system to promote the implementation of this technology, including technical standards, economic incentives, laws and regulations, and social governance. A set of evaluation systems also be provided for determining its long-term development orientation.

2. Current situation review

2.1. Problems review and system construction

CCS refers a process, which capturing CO_2 from large fixed sources, transporting it through pipelines to target areas, and finally injecting it into deep geological structures to achieve permanent storage. In terms of CCS technology, the techniques for capturing CO_2 from point sources and transporting it via pipelines are relatively mature. In the final storage link, the main problem is mine leakage. In traditional storage research models, most geological bodies are uniform and intact. While in mining areas, especially those with frequent mining activities, most geological bodies are affected by the mechanical effects of mining, resulting in irregular fractures and prominent risks of gas leakage and migration. Storage safety and effectiveness cannot be guaranteed. Because of the complexity and variability of geological conditions, relevant solutions are still under development, with only pilot attempts and no promotion [7]. Therefore, the current research direction first needs to determine the key indicators that determine the safety of mining areas and attempt to establish risk assessment standards for mining areas. Secondly, it is expected that the above-ground ecological restoration and underground storage management in the mining area can be seamlessly coordinated in multiple aspects, which directly affects the practical feasibility of technology and solutions.

2.2. Existing perspective of mine underground space

There are three mainstream perspectives on the utilization of underground space in mining areas. It is necessary to introduce a method that is solution-oriented through technology and energy. This method utilizes resources through technologies such as physical energy storage and geothermal

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exploitation. It still primarily focuses on energy development and utilization, without changing its core essence. Examples include the gravity energy storage at Baijiazhuang Mine in Shanxi and geothermal development at Zhangji Mine in Xuzhou [8]. The advantage of this approach is that energy technologies are relatively mature and the returns are more stable compared to other methods, but the initial investment is high and needs careful consideration. Next is a economy-oriented approach that concentrates on transforming mines for cultural tourism and commercial use, revitalizing industrial heritage to create underground museums and tourist attractions. Typical cases include the Dahecun Ruins Museum in China and the Prosper-Haniel coal mine cultural tourism project in Germany [9,10]. This method has strong cultural value and the potential to promote employment, but as a tertiary industry, it has a high demand for innovation and is easily affected by fluctuations in the tourism market, resulting in weak stability. The system integration approach emphasizes full life-cycle management, coordinating multiple goals in energy, ecology, and society, such as the ecological restoration in Datong from China. It can deliver the optimal overall benefits among the three approaches, yet significant challenges remain in coordinating technology and policy formulation.

3. Technical concepts and problem assessment

3.1. Multidimensional integration framework

Based on this, reviewing the core viewpoint of this article, the aim is to promote the practical application of carbon dioxide sequestration in ecological restoration of mining areas by constructing a new risk assessment system, and to evaluate its long-term development positioning, to ultimately achieve a comprehensive development model of above-ground and underground collaboration. This paragraph will be guided by a risk assessment system and systematically organized and promoted from three levels: technology, spatial planning, and governance, to ensure the safety, feasibility, and sustainability of carbon dioxide storage in mining areas. At the technical level, the specific implementation pathway involves establishing a geo-ecological information system capable of integrating geological analysis, simulation of CO_2 migration pathways, and surface ecological data. Technologies such as gel-cement composite sealing can be employed to address fracture-related geological sealing challenges, where the fracture permeability decreased from 10^{-12} m^2 to 10^{-18} m^2 after plugging [8]. And a comprehensive 'geology-engineering-ecology' approach can help reveal the mechanisms of CO_2 storage and reduce uncertainties associated with geological changes. In terms of spatial planning, functional zoning of mining areas can be carried out based on quantitative risk assessment, designating regions of different levels to ensure storage safety. This strategy has been applied to the Sanhe enclosed coal mine in China, where zoning was conducted based on nine main factors to identify favorable, moderate, and unfavorable storage areas. The approach was validated for two target coal seams using the fuzzy comprehensive evaluation method, resulting in a total CO2 storage potential of 288.5 million tons [11]. At the governance level, it is necessary to establish a cross-departmental coordination mechanism, which is a comprehensive governance framework with clearly defined responsibilities and authority [12]. This mechanism will integrate multiple fields such as engineering, ecology, landscape, and social governance, forming a professional management model. In addition, it is also necessary to draw on some relevant international experiences. For example, the European Union's 'Directive on the Geological Storage of Carbon Dioxide' is a regulation that can be referenced.

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3.2. Social acceptance

In addition to hardware conditions, soft measures are equally important. Social acceptance is one of the soft measures that need special attention. Due to the high professionalism of CCS technology, coupled with the fact that it has not been widely promoted, the public has questioned its maturity and security mechanism. In addition, the establishment of a carbon dioxide storage area needs to occupy a certain amount of land. It is closely related to the active cooperation of local governments and residents. So that it is vital to make a clear and actionable plan to reduce doubts and improve cooperation.

This promotion plan can be carried out simultaneously online and offline. The online part mainly involves verifying basic information, leaving electronic records and widely disseminating relevant popular science content in the community, explaining carbon sequestration technology and its benefits to the environment and human beings to residents in an easy-to-understand way. Offline work should focus on strengthening communication with government departments to ensure information synchronization and monitor compliance. And the innovative landscape design can transform technological facilities into perceptible public education platforms, thereby enhancing project transparency [13]. At the same time, appropriately disclosing project development progress to the public is also a way to safeguard their right to be informed.

Additionally, this paper proposes the introduction of a new credit allocation system. The system is designed according to the principles of a circular economy and is integrated with carbon-related economic benefits. Carbon credit revenues are distributed not only to local applications but also to a broader range of relevant beneficiaries. To ensure the legality of transactions, its operation will be certified and supervised by designated national authorities. Through this mechanism, communities can participate in decision-making as fully as possible and receive certain economic returns, which can be used for public welfare such as education and healthcare. The specific distribution ratio of carbon credit revenue is shown in Figure 1.

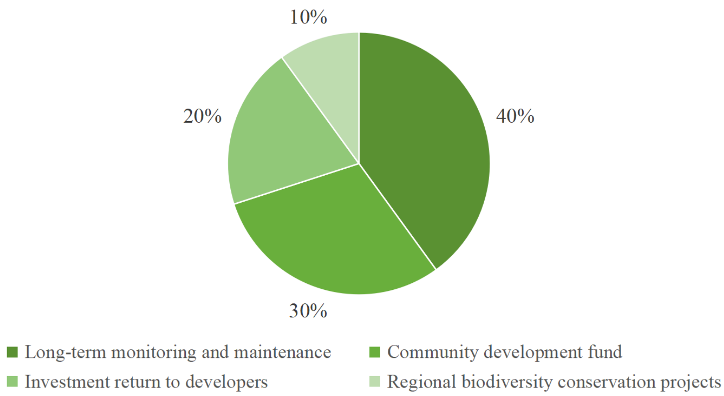

Figure 1. Specific allocation proportions of income from the carbon credit system (picture credit: original)

4. Case analysis

4.1. The Emscher Park project in Germany’s Ruhr

The Emscher Park project in Germany’s Ruhr region can be regarded as a significant turning point. Its implementation process can be summarized as follows: crisis identification → macro-planning

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→ core project launch → spatial construction → specific project implementation → long-term mechanism establishment. Launched in 1989 and led by the state government, the project first addressed issues stemming from local traditional industries by rehabilitating the underground section of the Emscher River into a clean ecosystem as foundational engineering. On this basis, a blue-green landscape park network covering approximately 800 square kilometers and connecting 17 cities was constructed to spatially integrate urban areas. The project has delivered over 120 specific renovation projects, including the conversion of a former gasometer into an art exhibition hall and a steel plant into a climbing park. Through professional management institutions such as the Emscher Cooperative, which cooperates across cities, multiple participants are included in it to discuss and formulate strategies to ensure the unified planning and long-term maintenance of the region, and finally transform this area. It has been in industrial decline, into a multifunctional and livable area. This project in the Ruhr area is a successful practice, and a reference case for the transformation of many post-industrial areas around the world. This case is highly relevant to the three key issues mentioned above, and combines industrial protection with ecosystem restoration, which is a very appropriate case [14].

4.2. The Codelco Chuquicamata copper mine in chile

The reconstruction project of the Codelco Chuquicamata copper mine in Chile is a good example of the importance of social acceptance. The copper mine project ignored the acceptance of local residents in the early stage and put the engineering planning above the resettlement of residents, which eventually led to serious conflicts [15]. In order to resolve the conflict, the solution proposed by the project team is to strengthen communication with residents and update the management mode after providing basic compensation configuration. They introduced the concept of community co-garnance, strengthened the participation of local people, and gave them a more equal right to participate. This case is a historical example of the past, and it is also a key point that needs to be paid attention to in the design of transformation projects for the local masses today. At the same time, the need for collaborative governance to be included in the risk assessment framework is also obvious. In a word, in the promotion of industrial zone projects, mass conflicts are not a rare thing, but it is necessary to make predictions in advance and put forward a handling plan in advance. The mechanism of community joint governance (for example, organizing a joint design group in advance) is an significant solution to this problem, which is a relatively easy-to-implement and quick-effective method at present [16].

5. Conclusion

Continuously promoting and expanding the application fields and ways of carbon sequestration technology is a win-win event for mankind and the environment. The introduction of carbon sequestration technology into the recovery and development of mining areas is a vivid practice to realize it. Through cooperation and efforts in technology, spatial planning, governance and acceptance, the development of this technology will make a qualitative leap. The development of this technology is a process to achieve comprehensive goals, including environmental protection and economic development. It is also a new way of comprehensive restructuring.

In the process of introducing technology, need to pay attention to the following aspects: first of all, pay attention to technical standards. Technology is the top priority in this project and the prerequisite for the next steps. The project needs to clarify the monitoring norms in the operation of the follow-up mechanism. For example, the industry and management institutions need to discuss

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and formulate implementation standards for advanced methods such as distributed optical fiber sensing. Secondly, the formulation of relevant laws is also a big part of the project. The formulation of local policies should pay attention to local conditions, and cannot be generalized. In terms of social governance, the interests of the community need to be paid more attention. The distribution of community interests should be carefully negotiated and formulated, and carbon income should be rationally distributed and utilized as much as possible. At the same time, it should be stipulated that some high-emission enterprises should submit carbon life cycle plans in the production process to ensure the transparent development and production of carbon emissions. After the implementation of the lockdown, the relevant departments should establish a long-term development assessment system to provide clear goals for the future development of the mining area. This system will divide the minerals used as sealing carriers into permanent protection closed areas, restricted open areas and comprehensive development zones through the scoring system of indicators (geological stability, ecological recovery, economy, and culture). In addition, there are still many gaps that need to be supplemented in the future research and practical development related to this topic. Two aspects will be mentioned here. One is to evaluate technology. The assessment of risk and early warning is a key factor in the success of the project. Therefore, the evaluation of technology should continue to increase research. You can try to integrate artificial intelligence (AI) and unmanned aerial vehicle (UAV) remote sensing data, and use long ahort-term memory (LSTM) neural networks to predict the trajectory of carbon dioxide movement, so as to achieve prediction. The second is to guide the public's participation, give the facilities an educational nature, and balance their development and humanistic value.

References

[1] The United Nations Intergovernmental Panel on Climate Change (IPCC). (2005). Special report on carbon dioxide capture and storage. IPCC.

[2] Jiang, C., Liu, T. C., & Feng, S. S. (2017). Research on landscape reconstruction model of mining wastelands in China. Journal of Landscape Architecture.

[3] Xu, H. L., Waheed, A., Kuerban, A., Muhammad, M., & Aili, A. (2025). Dynamic approaches to ecological restoration in China's mining regions: A scientific review. Ecological Engineering, 214, 107577.

[4] Bian, Z. F., Lei, S. G., & Wang, N. (2023). Mine ecological restoration models under the background of ecological civilization. China Land, (11), 4–8.

[5] Hunan Provincial Department of Natural Resources. (2025). Transforming "industrial scars" into "joyful miracles": A case study of ecological restoration and ecological product value realization at Changsha Xiangjiang Happy City mine pit.

[6] Tibbett, M. (2024). Post-mining ecosystem reconstruction. Current Biology, 34(9), R387–R393.

[7] Rutqvist, J. (2012). The geomechanics of CO_2 storage in deep sedimentary formations. Geotechnical and Geological Engineering, 30(3).

[8] Zhang, F. W., Zhao, M., Li, S. T., Tan, X. F., Yao, H. C., & Cui, J. Y. (2024). Development and utilization of geothermal resources in abandoned coal mines. Geology in China, 51(6), 1883–1894.

[9] Wang, J. M., Feng, Y., Ye, T. T., et al. (2025). Theoretical framework and technical pathway for the integrated ecological restoration throughout the overall life cycle of mining based on NbS. Coal Science and Technology, 53(1), 377–391.

[10] Henan Provincial Bureau of Cultural Heritage. (2025, June 11). The new building of Dahecun Ruins Museum: Digital technology empowering the interpretation of Yangshao culture [Cultural heritage protection technical report].

[11] Qian, J., Yi, G. F., Zhou, Q. Z., Tang, Z. G., Peng, Y. X., Wang, Y., & Chen, S. B. (2024). CO_2 storage potential of coal seam in Sanhejian closed coal mine. Coal Science and Technology, 52(3), 258–268.

[12] European Commission. (2009). Directive 2009/31/EC on the geological storage of carbon dioxide.

[13] Hodge, S., & Shearer, A. (2024). From engineering infrastructure to educational landscape: A case study of Sidwell Friends Middle School, USA. Landscape Performance Series, 24(5), 1–12.

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[14] Eiringhaus, P. (2020). Inventing the Green Metropolis Ruhr, Germany: Postindustrial greening narratives and critical history culture. In A. Campbell, M. Duffy, & B. Edmondson (Eds.), Located research. Palgrave Macmillan.
[15] Minuchin, L. (2022). The discarded city of extractivism: The case of the Chuquicamata copper mine, Chile [PhD dissertation, University of Manchester].
[16] Wang, G. H. (2024). The construction of a community with shared view on community governance based on the theory of co-production: A case study of Community D in Shenzhen City. Journal of Xihua University (Philosophy & Social Sciences), 43(5), 77–88.