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Analysis of Economic Benefits of Using Deep Geological Storage Technology to Treat High-Salinity Brine in Coal Mines

Song Du [1,*], Chao Zhang [2], Jianguo Liu [3], Chunhui Zhang [4], Yinlin Fan [1], Qiaohui Che [1], Sitong Song [1] and Sheng Tao [3]

[1] General Prospecting and Research Institute of China National Administration of Coal Geology, Beijing 100039, China; cheqiaohui@126.com (Q.C.)
[2] China Construction Environmental Energy (Shandong) Environmental Technology Co., Ltd., Taian 271000, China
[3] Institute of Environmental Science and Technology, Inner Mongolia University of Technology, Hohhot 010051, China; jgliu_yxc@163.com (J.L.)
[4] Institute of Environmental Science and Technology, China University of Mining and Technology (Beijing), Beijing 100083, China; truemanjung@163.com
* Correspondence: du@cct.org.cn

Abstract: Some provinces in China require zero discharge of coal mine wastewater, with a focus on the disposal of high-salt water, because evaporation ponds have been completely banned. Deep geological storage (DGS) technology is a novel geological environment solution that uses rock pores and microfissures within deep strata for safely storing liquid or gas to avoid its environmental impact on the biosphere. The author and his research team were the first to put forward the research idea of using DGS technology to dispose of high-salinity brine in coal mines in China and performed related research. Taking a coal mine in the south of Ordos Basin as an example, this study designed a conventional, mine-specific, zero-discharge water treatment process route based on a evaporation–crystallization process. This strategy was tailored to the unique water inflow conditions of the mine. Furthermore, the technical and economic efficiencies were assessed for the generation and treatment scenarios of a four-stage highly concentrated brine solution. In addition, the comparative analysis of the economic prospects of using DGS technology to treat high-salinity brine revealed that combining DGS with post-conventional treatment in secondary reverse osmosis, whose flow quality is 481 m^3/h and TDS is 24,532.66 mg/L, can maximize the economic benefits. This integration heightened water resource utilization while maintaining a cost-effective, comprehensive water treatment approach. These results provide a valuable reference value for the future zero-discharge treatment of coal mine water.

Keywords: DGS; high-salinity brine in coal mines; zero discharge; economic

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1. Introduction

The whole process of coal mine water treatment, which is structured around hierarchical processing and quality-based utilization, can be generally divided into three stages [1]. The first stage is pretreatment, which mainly deals with pollutants such as suspended particles in mine water. Pollutants within mine water, such as coal dust, rock slag, sand and soil, and other inorganic suspended particles, mainly originate from coal mining activities. Among these, organic pollutants, such as hydraulic oil and other organic substances, are present in low concentrations. Therefore, pretreatment, that is, the removal of suspended solids, is the professional characteristic of mine water treatment.

Pretreatment enables a substantial portion of mine water to meet the "Coal Industry Pollutant Emission Standard (GB20426-2006)" [2] and "Coal Mine Underground Firefighting, Sprinkler Design Code (GB50383-2006) [3]," thereby achieving production reuse. The second stage involves in-depth treatment, mainly using membrane separation technology, to achieve the highest quality drinking water standard; however, it produces a certain amount of concentrated high-salinity brine. With the increased water resource utilization rate, simple underground firefighting and sprinkler reuse falls short of the demands of modern society. Moreover, the rapid advancements in the current water treatment technologies and advanced membrane separation equipment considerably improve the recuperation rate of industrial wastewater. In particular, when the quality of pretreated mine wastewater is good, subsequent in-depth treatment can help realize the standard of "industrial and recycled water norms (GB50050-2007) [4]" and can be used for general industrial purposes. The quality of mine water from certain sources can even reach that of drinking water via reverse osmosis membrane treatment. The third stage of mine water treatment involves the zero-discharge link, which is based on improving environmental protection requisites, augmenting water resource reuse targets, and managing high-salinity water discharge [5].

Currently, the zero-discharge method for treating high-salinity brine in coal mine water mostly adopts a combination of multiple concentrations, desalination, evaporation, and crystallization to extend the deep treatment of reverse osmosis-concentrated water and the extraction of water resources. After the third treatment stage, mine water can attain >90% overall water resource reuse, with organic pollutants being largely eliminated and minerals being crystallized into salt. However, the operation cost of this type of technology is considerably high, thus limiting its industry-wide adoption. The zero-discharge project of mine water in the Shenhuaning Coal Mine in 2017 was the first zero-discharge project of mine water in China. Since then, the Yankuang Group, the China National Coal Group, and other large central enterprises have successively built zero-discharge demonstration projects for mine water based on the evaporation–crystallization process. However, the development of this technology is impeded by elevated energy consumption, leading to high operational costs [6].

2. Cost Analysis of the Zero-Discharge Treatment Based on the Evaporation–Crystallization Process

2.1. Process Route Design and Description

Based on the actual water quality and quantity of mine water at H coal mine, a shaft coal mine located in the southern Ordos Basin, alongside the established successful methodologies, this study designed a conventional zero-discharge technical route for mine water treatment based on evaporation and crystallization (Figure 1) [7].

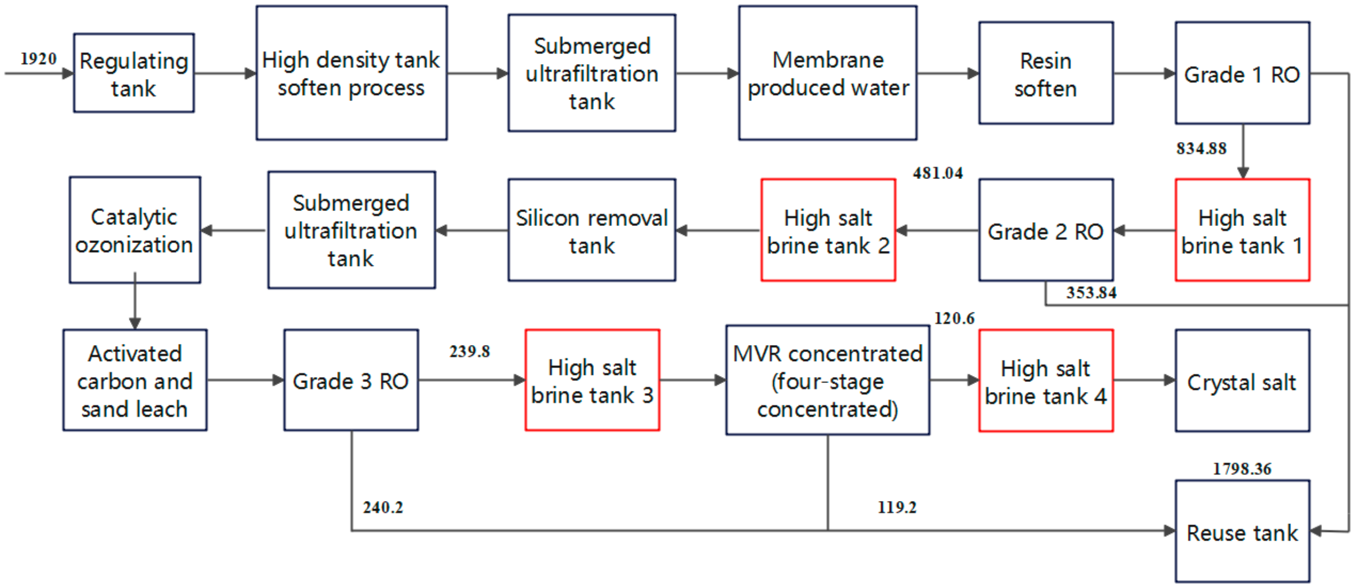

Figure 1. Process flow chart of the zero-discharge treatment of H coal mine drainage (m^3/h).

The incoming water first enters a regulating tank, followed by submerged ultrafiltration after softening treatment in the high-density tank. The average pore size of the ultrafiltration membrane filaments is 0.03–0.05 microns, which can effectively capture colloids and suspended impurities in the water. The water produced by the submerged ultrafiltration membrane is pumped into a resin-softening bed, following which the softened water enters a softening tank. Then, the water from the softening tank enters a reverse osmosis device, followed by passage through a security filter to remove the 5 μm particulate impurities. The output water from the reverse osmosis device 1 enters the reuse tank, while the concentrated water enters the concentrated tank 1 before entering the reverse osmosis device 2. The output water from the reverse osmosis device 2 enters the reuse tank, and the concentrated water enters the concentrated tank 2. The recovery rates of the reverse osmosis devices 1 and 2 are 70% and 60%, respectively [8,9].

Due to reconcentration, the concentrated water from the reverse osmosis device 2 contains a high concentration of SiO_2, causing membrane fouling and thus necessitating treatment. Therefore, this concentrated water is sent to a high-density tank for silicon removal. Furthermore, flocculants, coagulant aids, and sodium meta-aluminates are added into the silicon removal tank to remove the soluble silicon from the water. The effluent from the silicon removal tank flows into the submerged ultrafiltration membrane tank 2 to remove the suspended colloids in the water. While conventional mine water treatment seldom requires advanced oxidation for organic matter, certain mine water zero-discharge projects have utilized an ozone catalytic oxidation device to reduce the membrane material load for treating highly concentrated influent water. After the aforementioned influent water pretreatment attains the requisite water quality for membrane treatment, it progresses to the reverse osmosis device 3. The output water from reverse osmosis device 3 enters the reuse tank, whereas the concentrated water enters the mechanical vapor recompression (MVR) evaporator for reconcentration. The condensate enters the reuse tank, while the concentrated liquid with a total dissolved solid (TDS) of $\geq$100,000 enters the evaporation–crystallization salt-separation device [10].

Figure 1 depicts the outcomes of three-stage reverse osmosis concentrations and MVR concentrations, producing stage 4 high-salinity brine. The corresponding water volumes and TDS concentrations after the simulation calculations are shown in Table 1.

Table 1. Water quantity of four Stages of high-salinity brine in H coal mine.

	Units	**Stage 1 RO Concentrated Water/High Salt Brine to Be Stored 1**	**Stage 2 RO Concentrated Water/High Salt Brine to Be Stored 2**	**Stage 3 RO Concentrated Water/High Salt Brine to Be Stored 3**	**Stage 4 Concentrated Water/High Salt Brine to Be Stored 4**
water intake	m^3/h	834.88	481.04	239.8	120.6
TDS	mg/L	14,248.44	24,532.66	49,027.64	88,249.752

2.2. Comparison and Rationality Analysis of Key Processes in Conventional Design

The key sections of the evaporation–crystallization-based zero-discharge process for mine water are membrane concentration and evaporation–crystallization, complemented by auxiliary sections and equipment for safeguarding the process. The ultimate product water should contain TDS levels below 1000 mg/L, necessitating the elevation of nearly all the salts in the water. This results in the formation of mixed salts, preferably yielding industrially viable raw salts adhering to certain technical criteria [11].

(1) Selection of membrane concentration process

The membrane concentration process specifically refers to the secondary and tertiary membrane concentration stages after the primary reverse osmosis. These secondary and tertiary stages address the concentrated water produced after the primary concentration. The suspended solids (SS) in the influent water and turbidity generally remain at low levels, complying with the prerequisites for the concentration treatment. However, insoluble salts, such as Ca^{2+}, Mg^{2+}, Ba^{2+}, Sr^{2+}, HCO_3^-, SO_4^{2-}, and SiO_2, approach saturation or might have already reached the upper dispersion agent limit. The TDS is generally between 10,000 and 40,000 mg/L, necessitating special pretreatment measures before concentration. Coordinating the secondary and tertiary membrane concentrations is crucial and challenging in zero-discharge technology. The main technical difficulties are the economical and efficient anti-fouling pretreatment technology and high-concentration strategies [12].

The TDS of the product water varies greatly across different concentration treatment processes. The effluent TDS for the brackish water reverse osmosis (BWRO) and seawater reverse osmosis (SWRO) membranes remains below 1000 mg/L, while for nanofiltration (NF), the disc tube reverse osmosis membrane system (DTRO), and STRO, the TDS generally falls within 1000–2000 mg/L. Based on different process conditions, electrodialysis (ED) yields an effluent TDS below 20,000 mg/L, mostly around 15,000 mg/L. The more established concentration treatment options are the BWRO + SWRO and BWRO/SWRO + DTRO/STRO processes. The former is suitable for treating a TDS below 20,000 mg/L, achieving a final TDS of highly concentrated brine of over 50,000 mg/L, with the highest osmotic pressure reaching 8 MPa. The latter suits a TDS below 30,000 mg/L, with a final TDS of highly concentrated brine exceeding 80,000 mg/L and the highest osmotic pressure up to 12 MPa. The BWRO/SWRO + ED process combines the high desalting rate of BWRO/SWRO with the suitability of ED to high-salt content. The circulating desalination and concentration of the product and concentrated water enable high desalination and concentration rates, respectively, with a final effluent TDS below 1000 mg/L. The TDS of highly concentrated brine can reach 100,000–140,000 mg/L. Additional approaches involve a NF + SWRO/DTRO process and positive osmosis. The former is mostly used for material separation, while the latter involves complex considerations such as driving fluid or drawing fluid selection, contamination, huge investment, and high operation costs [13].

For the simulation design, before the secondary membrane concentration, water hardness reduction and tubular microfiltration (TMF) are used. TMF, ion exchange, and carbon removal are used before the tertiary membrane concentration. BWRO is used for the secondary membrane concentration, while DTRO is used for the tertiary membrane concentration [14]. This process has been employed in mine water zero-discharge projects, showcasing its practical application.

(2) Selection of Evaporation–Crystallization Process

Evaporation and crystallization are the pivotal and final methods for treating concentrated salt water in the zero-discharge process. This encompasses the evaporation pond (drying pond) process, multi-effect evaporation (MED), and MVR [15]. The evaporation pond approach has been discontinued owing to policy factors. MED uses vapor to heat the material and then uses the secondary vapor produced in the process to heat the material in a cyclic manner. Generally, a three-effect evaporation configuration exhibits cost-effectiveness while offering temperature control for each effect, conducive to salt-separation operations. MVR involves compressing the secondary vapor produced by the first-effect evaporator, increasing the pressure, saturation temperature, and enthalpy. This compressed vapor is then sent to the evaporator as a heat source, replacing raw steam recycling and achieving energy savings. In terms of energy costs, industry experts debate between MED and MVR. Generally, MVR is deemed cost-effective in places with high vapor prices, while MED holds pronounced advantages in places with low vapor prices [16].

2.3. Complete Analysis of Water Quality

After sampling and analyzing the mine water of the H coal mine, the study utilized the reverse osmosis simulation software of the LG Chem Chemical Company to simulate the high-salinity brine water quality generated by the four-stage concentration process. This involved comprehensive index considerations and ion balance corrections. The results from both the detection analysis and simulation analysis are shown in the following table.

Table 2 reveals that, except for total salt content, the pollutant levels in raw mine water are minimal, complying with standards. Throughout the concentration process, fluoride and chemical oxygen demand and other characteristic pollutants in water are increased, but they remain within the low environmental risk range [17]. In the table, stage 4, highly concentrated salt water, denotes the four target substances for storage.

Table 2. Water quality and the simulation data.

	Units	**Raw Water**	**Stage 1 RO Concentrated Water**	**Stage 2 RO Concentrated Water**	**Stage 3 RO Concentrated Water**	**Stage 4 Concentrated Water**
Water intake	m^3/h	1920	834.88	481.04	239.8	120.6
NH_4^+	mg/L	0.5	0.94	1.42	2.72	4.896
Na^+	mg/L	1693.43	3865.93	6647.45	13,279.53	23,903.154
K^+	mg/L	12.7	28.64	48.52	96.7	174.06
Mg^{2+}	mg/L	184	421.16	726.73	1454.73	2618.514
Ca^{2+}	mg/L	154	353.71	612.92	1226.21	2207.178
Sr^{2+}	mg/L	9.2	21.13	36.62	72.02	129.636
Ba^{2+}	mg/L	0.02	0.05	0.08	0.16	0.288
F^-	mg/L	0.7	1.58	2.68	5.34	9.612
CI^-	mg/L	1540.00	3502.90	5998.60	11,976.87	21,558.366
SO_4^{2-}	mg/L	2450.00	5621.89	9730.69	19,468.34	35,043.012
NO_3^-	mg/L	2.05	4.18	6.25	0	0
CO_3^{2-}	mg/L	1.87	4.29	7.43	25.56	46.008
HCO_3^-	mg/L	150.06	335.85	563.86	1121.57	2018.826
B^{3+}	mg/L	0	0	0	0	0
Br^-	mg/L	0	0	0	0	0
SiO_2	mg/L	37.5	86.16	149.39	297.88	536.184
CO_2	mg/L	1.9	1.9	1.9	6.14	11.052
TDS	mg/L	6236.03	14,248.44	24,532.66	49,027.64	88,249.752
pH	-	8	8.35	8.57	8.3	14.94
Water temperature	°C	23.50	23.50	23.50	23.50	23.5
DOC	mg/L	5.40	5.80	5.10	4.40	4.3
NH_3-N	mg/L	0.11	0.10	0.12	0.42	0.45
TP	mg/L	0.03	0.09	0.15	0.26	0.44
TN	mg/L	1.07	1.36	2.50	4.60	10.22
As^{3+}	µg/L	36.7	ND	ND	ND	ND
Hg^+	µg/L	0.04	ND	ND	ND	ND
Cu^{2+}	µg/L	12.9	20.30	40.20	50.80	80.92
Zn^+	µg/L	2.05	13.00	24.00	33.00	63.34
Cr^{2+}	µg/L	0.25	0.11	0.08	0.08	0.1
Cd^{2+}	µg/L	1.09	2.21	3.88	5.12	10.8
Cr^{6+}	mg/L	ND	ND	ND	ND	ND

Table 2. *Cont.*

	Units	Raw Water	Stage 1 RO Concentrated Water	Stage 2 RO Concentrated Water	Stage 3 RO Concentrated Water	Stage 4 Concentrated Water
COD	mg/L	13	12.00	10.00	25.14	60.14
BOD_5	mg/L	ND	ND	ND	ND	ND
CODMn	mg/L	1.84	2.38	2.18	2.18	2.19

2.4. Construction Investment for Evaporation–Crystallization-Based Zero-Discharge Processes

According to the process outlined in Figure 1, the mine water zero-discharge project at the H coal mine entails a construction investment of ~CNY 234 million. This encompasses an equipment investment of ~CNY 119 million and a civil construction investment of ~CNY 68 million. The detailed breakdown is shown in Table 3.

Table 3. Estimation of construction investment for traditional mine water zero-discharge treatment process at H coal mine (CNY 10^4 = CNY 10 thousand).

Serial Number	Work Section (Equipment)	Size (m^3/h)	Single Set Size (m^3/h)	Quantities	Single Investment (CNY 10^4)	Investors (CNY 10^4)
1	High-density tank	2200	550	4	550	2200
2	High-strength film	2240	160	14	80	1120
3	Soften	2240	160	14	48	672
4	Reverse osmosis 1	2000	200	10	155	1550
5	Reverse osmosis 2	600	150	4	135	540
6	High-density tank	300	300	1	320	320
7	High-strength film	320	160	2	80	160
8	Ozone	260	65	4	120	480
9	Raw materials	325	65	5	28	140
10	Sand filtration	325	65	5	25	125
11	Reverse osmosis 3	240	120	2	130	260
12	MVR concentration	120	60	2	2200	4400
Total	(1) Equipment	11,967.00 (CNY 10^4)				
	(2) Civil construction	6775.00 (CNY 10^4)				
	(3) Design fees	562.26 (CNY 10^4)				
	(4) Electro-mechanical	2752.41 (CNY 10^4)				
	(5) Installation	957.36 (CNY 10^4)				
	(6) Commissioning technical services	418.845 (CNY 10^4)				
In total		**23,432.875** (CNY 10^4)				

According to the generation of four-stage concentrated brine, the process is divided into four work sections, with the equipment investment for each section detailed in Table 4.

Table 4. Section construction investment analysis.

Work Section	Water Production (m^3/h)	Concentrate Brine (m^3/h)	Water Yield (m^3/h)	Investment in Equipment (CNY)	Investment per Tons of Produced Water (CNY/ton)	Investment Ratio
Grade 1	1085.12	834.88	56.52%	5542	5.11	46.31%
Grade 2	1438.96	481.04	74.95%	6082	4.23	50.82%
Grade 3	1680.2	239.8	87.51%	7567	4.50	63.23%
Grade 4	1799.4	120.6	93.72%	11,967	6.65	100.00%

Upon completing the second stage (reverse osmosis) of construction, 74.95% of the water is obtainable with only 50% of the total investment, rendering it the most cost-effective, as shown in Figure 2.

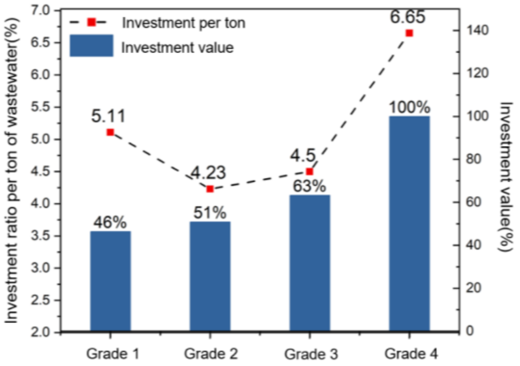

Figure 2. Investment value and investment ratio per ton of water produced (h).

Figure 2 illustrates that grade 2 incurs an investment of CNY 42,300 per ton of produced water (hourly), showcasing the best cost-effectiveness compared to other sections. The grade 3 section ranks second in cost-effectiveness at CNY 51,100, exceeding the grade 1 section. Meanwhile, the Stage 4 section has the highest investment, with a 55.56% increase in investment per ton of water production compared to grade 2.

2.5. *Operating Cost Analysis for Evaporation–Crystallization-Based Zero-Discharge Process*

The project operating costs encompass electricity, vapor (in the evaporation and crystallization section), pharmaceuticals, other consumables, labor, membrane equipment depreciation, maintenance, and testing [18]. Calculated based on the four-stage design, the raw water volume, water intake of each section, and operating costs are detailed in Table 5.

Table 5. Summary of operating cost analysis.

Sports Event	Unit (of Measure)	Reverse Osmosis 1	Reverse Osmosis 2	Reverse Osmosis 3	MVR Concentration
Water treatment capacity	m^3/h	834.88	481.04	239.8	120.6
Annual running time	h	8000	8000	8000	8000
Discounted direct costs based on raw water					
Electricity	CNY/m^3	1.05	1.15	1.88	2.95
Vapor	CNY/m^3	0.05	0.05	0.08	0.52
Chemicals	CNY/m^3	3.47	3.55	4.05	4.09
Disposables	CNY/m^3	0.06	0.09	0.14	0.19
Labor cost	CNY/m^3	0.19	0.21	0.26	0.31

Table 5. *Cont.*

Sports Event	Unit (of Measure)	Reverse Osmosis 1	Reverse Osmosis 2	Reverse Osmosis 3	MVR Concentration
membrane depreciation	CNY/m^3	0.54	0.68	0.73	0.73
Inspection and maintenance	CNY/m^3	0.11	0.15	0.19	0.25
(Grand) Total		**5.47**	**5.88**	**7.33**	**9.04**
Discounted direct costs by segment					
Electricity	CNY per ton of water	2.41	4.59	15.05	46.97
Vapor	CNY per ton of water	0.11	0.20	0.64	8.28
Pharmaceutical products	CNY per ton of water	7.98	14.17	32.43	65.11
Disposables	CNY per ton of water	0.14	0.36	1.12	3.02
Labor cost	CNY per ton of water	0.44	0.84	2.08	4.94
Membrane depreciation	CNY per ton of water	1.24	2.71	5.84	11.62
Inspection and maintenance	CNY per ton of water	0.25	0.60	1.52	3.98
(Grand) Total	CNY per ton of water	**12.58**	**23.47**	**58.69**	**143.92**

As shown in Figure 3, extending the work section leads to a pronounced rise in mine water treatment operating costs. In the fourth work section, operating costs reach CNY 143 per ton, equivalent CNY 9.04 per ton based on raw water volume (total hourly mine water volume as the denominator).

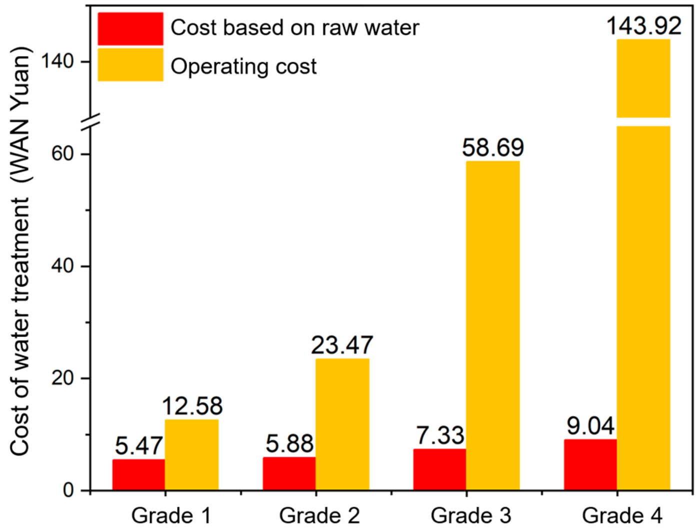

Figure 3. Water treatment cost chart of Walnut Yu Mine.

Based on the cost breakdown analysis and calculations, the total annual operating costs of the H coal mine water treatment project are shown in Table 6.

The total annual theoretical income for the mine water zero-discharge project is as follows:

$$V_{\text{sum}} = \sum_{n=1}^{4} \left(V_{\text{water-n}} - C_{\text{n}}\right) + V_{salt} \tag{1}$$

This involves deducting the total operating costs from the combined value of water resources generated by the four-stage process and adding the total value of the produced salt resources.

Table 6. Analysis of operating costs and benefits.

Work Shift	Water Production (m^3/h)	Annual Running Costs (CNY 10^4)	Theoretical Gains in Water Production (CNY 10^4)	Real Gains from Water Production (m^3/h)	Doctrinal Revenue from Salt Production (CNY 10^4)
Grade 1	1085.12	8401.92	6944.77	836.12	0.00
Grade 2	1438.96	9031.68	9209.34	836.12	0.00
Grade 3	1680.2	11,258.88	10,753.28	836.12	0.00
Grade 4	1799.4	13,885.44	11,516.16	836.12	15.05

The calculations are based on the water volume produced at all the treatment stages, according to the "Management Measures of Water Abstraction License and Water Resource Fee Collection" in the province where the H coal mine is located, considering the highest water price of the local industry (8 CNY/m^3). Additionally, the evaporation–crystallization treatment project will produce 250 tons/year of industrial secondary sodium chloride and 350 tons/year of industrial secondary sodium sulfate. Based on market prices (70 CNY/ton for sodium chloride and 380 CNY/ton for sodium sulfate), the total annual theoretical value of industrial salt from mine water production is CNY 150,500.

In reality, the value of water production is only related to the water consumption of the coal mine itself. When cross-enterprise water resource allocation cannot be realized, the high-quality intermediate water from the treatment adheres to discharge standards but lacks actual value. According to the "H Coal Mine Design-Water Supply and Drainage", the maximum daily water consumption is estimated at 5280.75 m^3/d. This encompasses the water consumption of the main shaft industrial site of 2606.44 m^3/d, covering domestic (185.72 m^3/d), production (162.48 m^3/d), and underground production (2258.23 m^3/d) water, along with primary firefighting consumption (671.76 m^3). The water consumption of the auxiliary shaft industrial site is 2674.32 m^3/d, involving domestic (1146.90 m^3/d), production (1009.42 m^3/d), and yellow mud grouting water usage (518.00 m^3/d), as well as primary firefighting water consumption (396 m^3). Calculated at 4.75 CNY/m^3 for tons of water, the actual water production income remains notably lower than the theoretical value owing to low mining area water demand. However, selling the produced water to nearby industries could yield more revenue, but it would need policy support.

In addition, selling regenerated industrial salt becomes challenging without a salt-alkali chemical industry in the surrounding area. Storing this salt requires constructing a preservation warehouse, involving construction investment, land acquisition, and handling solid waste (or hazardous waste) in temporary storage [19]. Eventually, the actual economic value of the 1920 m^3/h gushing water from the H coal mine, after multistage treatment, equates to the current value of the amount of water needed for industrial and domestic water reuse—amounting to CNY 8,361,200. The excess treated water will be discharged in accordance with the discharge standards.

2.6. Calculations of Energy Consumption and Carbon Emission for Evaporative Crystallization Zero-Discharge Process

Water treatment projects require energy sources such as coal, electricity, and boiler steam. According to the 1986 Energy Statistical Reporting System for Key Industrial and Transportation Enterprises of the former State Economic Commission and the National Bureau of Statistics, the China Energy Statistical Yearbook 2005, and the standard coal consumption calculation for thermal power generation in China, the consumption of electricity and steam is converted into standard coal units. Subsequently, the standard coal usage is converted into carbon dioxide emissions [20] using the method outlined in the "Verification Guidelines for Greenhouse Gas Emission Reporting by Enterprises (for Trial Implementation)."

The provided statistical table (Table 7) reveals that by implementing the evaporation–crystallization zero-discharge process for mine water treatment at the H coal mine, the annual carbon dioxide emissions across the four treatment stages amount to 23,100, 25,300, 41,200, and 164,300 tons, respectively.

Table 7. Carbon emission calculations for zero-discharge treatment of mine water in H coal mine.

Sports Event	Unit (of Measure)	Reverse Osmosis 1	Reverse Osmosis 2	Reverse Osmosis 3	MVR Concentration
Water treatment capacity	m^3/h	834.88	481.04	239.8	120.6
Annual running time	h	8000	8000	8000	8000
Electricity	CNY per ton of water	2.41	4.59	15.05	46.97
Corresponding carbon consumption	kg CO_2	3.22	6.12	20.08	62.67
Vapor	CNY per ton of water	0.11	0.20	0.64	8.28
Corresponding carbon consumption	kg CO_2	0.2382	0.4420	1.3780	107.6400
Total annual aggregate carbon emissions	t	23,067	25,268	41,164	164,313

In 2020, China contributed nearly 10 billion tons to global carbon emissions, accounting for ~30% of the world's total. The annual per capita carbon dioxide emissions reached 6.8 tons, while the carbon dioxide emissions per unit of GDP stood at ~0.95 tons per CNY 10,000 [21]. The total carbon emissions of the "H Coal Mine Zero Discharge of Mine Water Project" reached 164,300 tons, while the theoretical value of its output was CNY 115,161,600. This translates to ~14.27 tons of carbon emissions per CNY 10,000 of GDP, greatly surpassing the national average. Calculating based on an actual income of CNY 8,361,200 exacerbates the carbon emissions per unit of production value.

Therefore, it can be concluded that evaporative crystallization-based zero-discharge mine water treatment comes with high energy consumption and carbon emissions.

3. Economic Analysis of Mine Water Treatment Process Using Deep Geological Storage of High-Salinity Brine

Deep geological storage (DGS) technology involves injecting liquids or gases through deep wells into deep strata below 1500 m below the earth's surface, far from drinking water aquifers and without resource attributes. This utilizes the pore space or microfissures of porous rock formations for secure storage and disposal. It is not a simple underground discharge but a safe means of environmental disposal of substances outside the biosphere, leveraging the unique properties of the fourth type of environmental medium (the deep geological environment) to store, solidify, and even degrade the substances. The Institute of Geological Deep Well Injection and Storage of General Prospecting Institute of China National Administration of Coal Geology introduced adopting DGS technology to dispose of high-salinity brine in coal mines. They pioneered research examining stratigraphic selection conditions, deep geological transport monitoring methods, solute transport, mineralization transformation laws, and environmental risk impacts. The DGA project has low investment and operation costs, offering evident environmental and carbon reduction benefits (Figure 4).

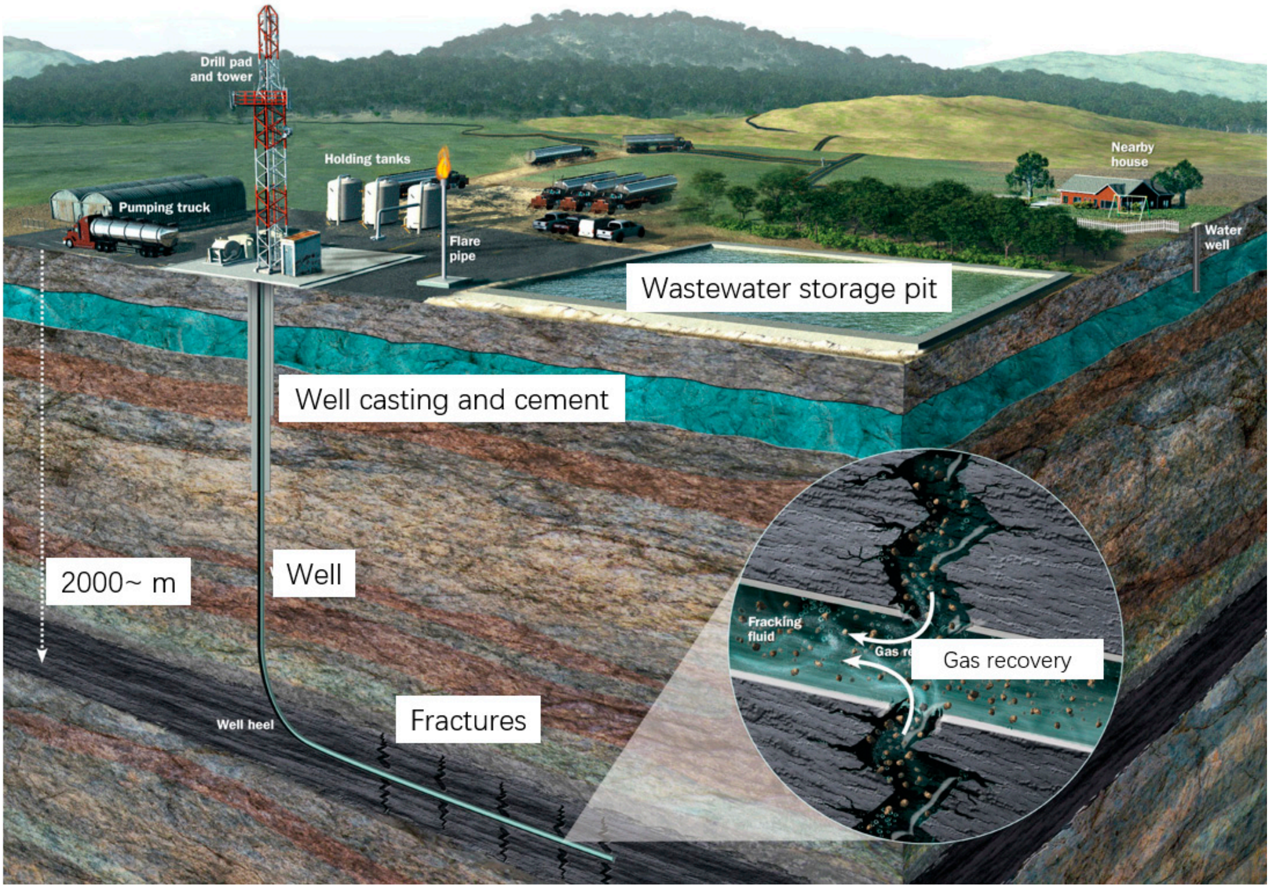

Figure 4. Schematic of the deep geological storage technology.

3.1. Engineering and Equipment Inputs

3.1.1. Storage Well Drilling Engineering

According to the actual engineering experience, a single storage well in the H coal mine requires a construction investment of ~CNY 12 million, including the cost of drilling engineering, casing consumables, logging, cementing, and relevant pressure water tests, along with coring analysis tests.

3.1.2. Major Equipment for Deep Geological Storage

The DGS of highly saline water projects employs compact equipment with minimal spatial requirements [22]. The total cost for each infilled storage well, encompassing equipment and civil works, is ~CNY 5 million, including the storage of piezoelectric equipment, high-salinity brine tanks, wellhead pressure control devices, storage control systems, and pipeline laying and installation.

3.1.3. Monitoring Systems

Currently, the DGS of the high-salinity brine project in China is still in the stage of technological development and demonstration. Owing to the absolute importance of the regional ecological environment and shallow groundwater system, accurate monitoring of high-salinity brine transformation and transportation in deep strata and long-term monitoring of shallow groundwater environmental indicators are vital [23]. The Institute of Geological Deep Well Injection and Storage spearheads the use of various geophysical means for effective hypersaline water deep transportation monitoring. They have also constructed a regional multidimensional groundwater monitoring system to assess the impact of DGS on shallow groundwater systems. Based on practical experience, the one-time investment for the whole monitoring system is ~CNY 8 million.

In the early research and exploration stage, constructing monitoring wells at the same depth as storage wells is imperative for effective high-salinity brine transformation and transportation monitoring in deep strata [24]. Four monitoring wells encircling each storage well direction necessitate an additional investment of CNY 40 million.

The above calculation shows that the total investment is ~CNY 65 million.

3.2. Analysis of Operating Costs Based on Deep Geological Storage Technology for High-Salinity Brine

According to previous operating testing, the operating costs, detailed in the table below (Table 8) (the unit price of electricity is 0.75 CNY/kWh), have been converted into water ton costs.

Table 8. Operation cost analysis of high-salinity brine deep storage project.

Sports Event	Quantities	Prices	Corresponding to CO_2 Emissions
Electricity	1.8 kWh/m^3	1.3 CNY/m^3	1.73 kg CO_2
Maintenance of equipment	maintenance	0.1 CNY/m^3	-
Labor cost	3 persons in 2 shifts	0.3 CNY/m^3	-
Total other miscellaneous	-	0.2 CNY/m^3	-
Add up the total		1.9 CNY/m^3	1.73 kg CO_2/m^3

The operating cost of high-salinity brine storage remains unaffected by the TDS content of the stored liquid. This underscores the superiority of coal mine high-salinity brine storage technology over evaporation–crystallization-based zero-discharge technology in construction, investment, and the overall operational economy.

4. Conclusions

(1) Adopting DGS technology for high-salinity brine disposal in coal mine water treatment projects offers great economic advantages. The total investment is ~1/2 of that required for a conventional zero-discharge process. Moreover, the operational energy consumption and costs are very low, and the project requires less space and less personnel allocation compared to the evaporation–crystallization-based zero-discharge project. With potential policy support, this technology resolves the low-cost disposal challenge of high-salinity brine.

(2) In this study, centered on the H coal mine, the optimal process involves secondary reverse osmosis and the DGS of high-salinity brine. The secondary reverse osmosis yields ~1438 ton/h of water, with a water yield of 75%. Simultaneously, deep underground, DGS technology stores ~480 ton/h of concentrated salt water, with a TDS of ~24,000 mg/L. The total operating cost is 6.36 ~CNY/ton, calculated as $5.88 + 1.93 \times 480/1920$. This mine water zero-discharge project based on high-salinity brine DGS demonstrates much lower operating costs compared to the evaporation–crystallization-based approach. It also realizes water resource recovery and utilization while permanently addressing the safe disposal of high-salinity brine. The carbon emission analysis reveals a total annual carbon dioxide emission of 32,425 ton for this optimal combination process, reducing it by 131,888 ton compared to evaporation–crystallization-based zero-discharge treatment systems, which is equivalent to the total carbon dioxide absorbed by ~150,000 mu of carbon sink forest annually.

(3) The application of DGS technology requires long-term monitoring of solute transportation and diffusion in the deep geology, shallow groundwater quality indexes, and corresponding emergency measures and protection plans. Additionally, comprehensive research on ion transformation and metallogenic laws in the deep strata is

essential. While this series of supporting research may require greater investment compared to the storage technology itself, it has greater significance.

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