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Deep Mine Geothermal Resource Collaborative Exploitation Technology Research

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Abstract: Deep mines must remove heat to keep working faces habitable, while the same rock mass and mine water form a large low-grade geothermal resource. This study examines how heat hazard control and geothermal recovery can be operated collaboratively, using a parameterized energy-balance model of a deep mine district at 1,200 m depth. Three scenarios were compared: an independent baseline with a capacity-limited chiller and a gas boiler (S0), a mine water source heat pump that supplies heat only (S1), and a collaborative cascade in which mine water first feeds the heat pump evaporator and is then used as the cold source of airway coolers (S2). Seventeen runs covering mine water inflow of 100–300 m^3/h with S1 at 0.60 and S2 at three effectiveness levels were evaluated with relations for air temperature, water-side heat extraction, heat pump performance, primary energy and operating cost. For the typical scenario of 250 m^3/h, the model estimates working-face air temperatures of 31.2, 31.2 and 28.0 °C, recovered heat supplies of 0, 6.34 and 8.19 MW, and primary energy reductions of 0, 29.1% and 39.8% for S0, S1 and S2, respectively. The cascade requires an inflow of about 192 m^3/h to reach the 28 °C design target. The results indicate that sharing one water loop between cooling and heat recovery improves both thermal safety and energy performance, provided that inflow and exchanger effectiveness are adequate. The conclusions apply to the stated parameter ranges and require field calibration before engineering use.

Keywords: Deep Mining; Geothermal Energy; Mine Heat Hazard; Mine Water; Heat Pump; Collaborative Exploitation; Energy Balance.

1. Introduction

As a result of the depletion of near-surface resources, mining has been declining. The temperature of the virgin rock increases with depth, so ventilation alone can no longer keep the air temperature at the working face in the range of what is permitted. Research on thermal management in deep mines has moved from independent cooling methods to combined, multi-objective ones, but most studies have focused only on reducing operational energy consumption and have not carried out all-round sustainability assessments[1]. At the same time, there is a relatively large amount of low-grade heat in the rock mass and water of deep mines. Mine water has been used for geothermal heating and cooling in many countries, and a way to assess the feasibility of such projects has been put forward[2],and regional mapping can show where flooded coal mine workings can provide heat networks[3].

Most of the research on recovery is concentrated in closed or abandoned mines. Technical lessons and economic scenarios for the supply of heat from geothermal mine water have been reported[4,5]; geothermal development models have been explored for the underground roadways of abandoned mines[6]; and the heat extraction performance of closed-loop coaxial horizontal well systems has been examined. In an active deep mine, the situation is different because the heat that needs to be removed for safety and the heat that can be recovered for use are the same energy stream viewed from two sides. Therefore, in recent years, some studies have combined the two tasks and developed a similarity criterion for synergistic mining cooling [7], constructed a multi-level, multi-branch geothermal well system for synergistic exploitation and heat hazard prevention [8], created an integrated extraction and cooling system based on the holistic use of mine space [9], built a thermal-hydraulic-mechanical-ventilation coupling model [10], designed heat-pump-coupled backfill heat exchangers [11], and applied a mine-water-source heat pump to drive a deep mine cooling system [12].

Most of the above studies are particular cases or system-based studies of a single technology. The Design Team should draw a short energy balance diagram to show how the flow of water, the efficiency of heat exchangers and the lift work of heat pumps are combined to determine whether both cooling and heat supply can be achieved. Build the model of the deep mine district in this paper and compare the three parametrized scenarios. The contributions of this paper are as follows: An open-minded framework has been established to study the connections among air temperature, water-side heat extraction, heat pump performance, primary energy and cost; quantitative comparisons have been made of independent, heat-only and collaborative cascade operations; and sensitivity results have been obtained to determine the minimum inflow and effectiveness required for the collaborative mode. All the results are model estimates over the given range of parameters.

2. Methods

2.1. System Configuration

The collaborative configuration is shown in Fig. 1. Mine water at the inlet temperature $T_{w,in}$ is collected in the sump, filtered and passed through the heat pump evaporator, where its temperature falls to $T_{w,out}$. Because this cooled water is below the airway air temperature, it is routed to the airway coolers as the cold source; the return water is then discharged.

The heat pump lifts the recovered heat to the condensing temperature T_{cond} and delivers it to surface heat users; a gas boiler tops up any shortfall. A single water loop thus serves heat hazard control and geothermal recovery in sequence, which is the sense of collaborative exploitation used here.

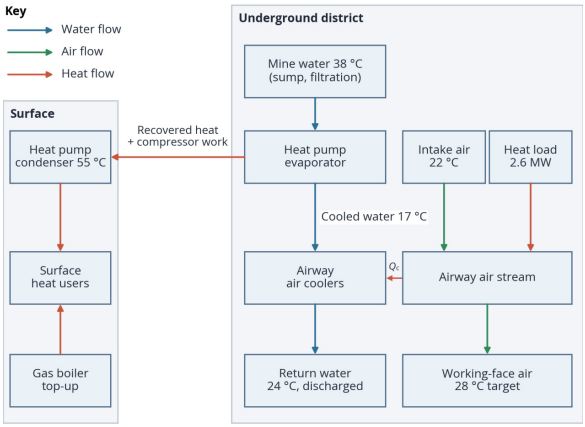


Fig 1. Collaborative exploitation configuration of the deep mine district (scenario S2); arrows show the direction of water, air and heat flow.

2.2. Governing Relations

The district is treated as a steady-state lumped system with sensible heat only, so the dry-bulb temperature of working-face air, T_f, is the thermal safety indicator:

$$T_f = T_{in} + \frac{Q_{load} - Q_c}{\dot{m}_a\, c_{p,a}} \tag{1}$$

where T_{in} is the intake air temperature, Q_{load} the district heat load, Q_c the cooling duty delivered, $\dot{m}_a$ the air mass flow and $c_{p,a}$ the specific heat of air. Mine water with inflow $\dot{V}_w$ enters the evaporator at $T_{w,in}$. The exchanger effectiveness ε is the fraction of the available drop $T_{w,in} - T_{min}$ that is realized, where T_{min} is the lowest practical outlet temperature:

$$T_{w,out} = T_{w,in} - \varepsilon\,(T_{w,in} - T_{min}) \tag{2}$$

$$Q_w = \rho_w c_w\, \dot{V}_w\,(T_{w,in} - T_{w,out}) \tag{3}$$

where $\rho_w c_w$ is the volumetric heat capacity of water; with 4.18 MJ/(m³·K), an inflow of 1 m³/h corresponds to 1.161 kW/K. In S2 the cooled water absorbs heat in the air coolers until it leaves at T_{ret}, which gives the available cascade duty Q_{cool}, while the duty needed to hold the design target T_{tar} is Q_{req}:

$$Q_{cool} = \rho_w c_w\, \dot{V}_w\,(T_{ret} - T_{w,out}) \tag{4}$$

$$Q_{req} = Q_{load} - \dot{m}_a\, c_{p,a}\,(T_{tar} - T_{in}) \tag{5}$$

The delivered duty is $Q_c = \min(Q_{cool}, Q_{req})$ in S2 and equals the chiller duty Q_{ch} in S0 and S1. The heat pump evaporates at T_{evap} and condenses at T_{cond} (both in kelvin in Eq. (6)), with Carnot fraction η_C and evaporator approach ΔT_{ap}, giving the heat pump coefficient of performance ($\mathrm{COP_h}$):

$$\mathrm{COP_h} = \eta_C\, \frac{T_{cond}}{T_{cond} - T_{evap}}, \qquad T_{evap} = T_{w,out} - \Delta T_{ap} \tag{6}$$

The condenser heat obtainable from the water and the heat supplied against the demand D_h are

$$Q_{cond} = Q_w\, \frac{\mathrm{COP_h}}{\mathrm{COP_h} - 1}, \qquad Q_h = \min(Q_{cond}, D_h) \tag{7}$$

so the compressor power is $W_{hp} = Q_h / \mathrm{COP_h}$ and the source heat drawn is $Q_{src} = Q_h - W_{hp}$. Total electric power and boiler fuel are

$$W_{tot} = W_{hp} + \kappa\,(Q_{src} + Q_{cas}) + \frac{Q_{ch}}{\mathrm{COP}_c}, \qquad F = \frac{D_h - Q_h}{\eta_b} \tag{8}$$

where κ is the auxiliary power coefficient for pumps and fans, Q_{cas} the cascade cooling duty ($Q_{cas} = Q_c$ in S2 and zero otherwise), COP_c the chiller coefficient of performance and η_b the boiler efficiency. Over H equivalent full-load hours, with η_g the efficiency from primary energy to delivered electricity, the primary energy PE, the saving ratio ψ relative to S0, the annual operating cost C and the simple payback t_{pb} are

$$PE = H\left(\frac{W_{tot}}{\eta_g} + F\right), \qquad \psi = \frac{PE_0 - PE}{PE_0} \tag{9}$$

$$C = H\,(c_e W_{tot} + c_g F), \qquad t_{pb} = \frac{I}{C_0 - C}, \qquad I = u_I Q_h + I_{int} \tag{10}$$

where the subscript 0 denotes S0, c_e and c_g are the electricity and gas prices, I is the investment, u_I the installed cost per kilowatt of recovered heat and I_{int} the cascade integration cost (S2 only).

2.3. Calculation Sequence

The calculation sequence is given in Fig. 2. In S0 and S1 the cooling duty is the chiller capacity, so the cascade branch applies to S2 only.

3. Simulation Scenarios and Parameters

The model area is at a depth of 1,200 m; the surface mean temperature is 15 ° C, the gradient is 3.0 ° C per 100 m, and therefore the virgin rock temperature is about 51 ° C. The ventilation airflow is 150 m³/s and the combined heat load of rock, machinery and oxidation is 2600 kW. Three Scenarios were set. In S0 (baseline), a 1,000kW chiller is used to lower the temperature of the air, mine water is drained without heat recovery, and a gas boiler provides all the heat. S1 (heat-only recovery): A mine water source heat pump with $\varepsilon = 0.60$ is employed to supply heat; the chiller is not changed, and the water is discharged directly after the evaporator. In S2 (collaborative cascade), a high-efficiency exchanger with $\varepsilon = 0.75$ is used to provide heat for the heat pump, the cooled water is employed by the airway coolers, and the chiller is taken out of service. The boiler tops up S1 and S2. The main parameters (inlet temperature, COPs, costs and prices) are in line with those of other deep mines and mine water heat projects.1,2,4 Table 1 shows these parameters.

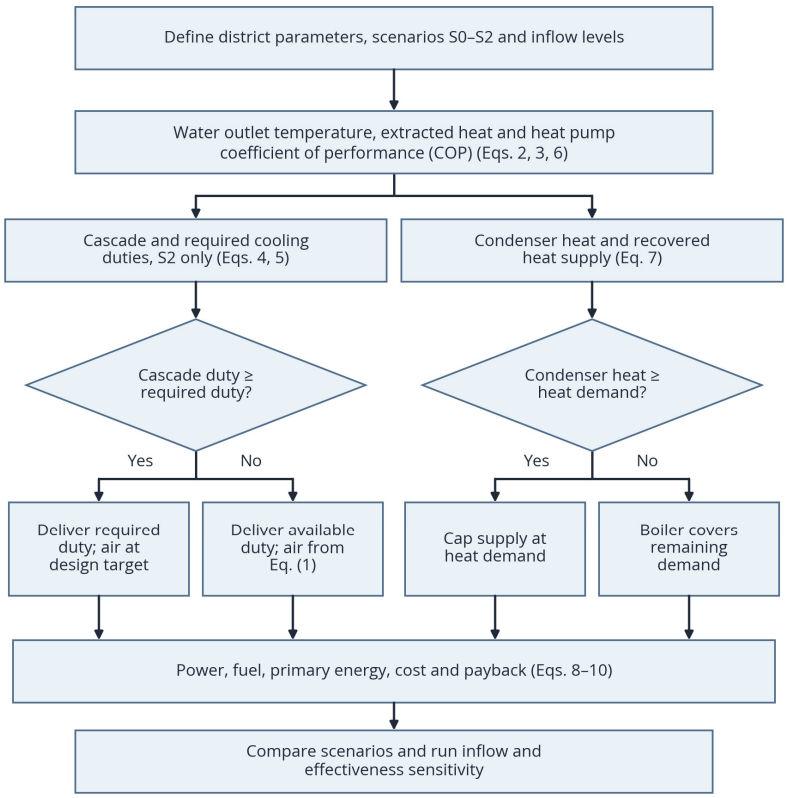


Fig 2. Calculation workflow of the deep mine geothermal collaborative exploitation model.

Table 1. Parameter list of the deep mine district model (typical values and ranges)

Parameter	Symbol	Value	Unit
Air mass flow	$\dot{m}_a$	172.5	kg/s
Air specific heat	$c_{p,a}$	1.005	kJ/(kg·K)
Intake air temperature	T_{in}	22	°C
District heat load	Q_{load}	2,600	kW
Design target air temperature	T_{tar}	28	°C
Mine water inflow	$\dot{V}_w$	100–300 (typical 250)	m^3/h
Inlet water temperature	$T_{w,in}$	38	°C
Minimum outlet temperature	T_{min}	10	°C
Volumetric heat capacity	$\rho_w c_w$	4.18	MJ/(m^3·K)
Exchanger effectiveness	ε	0.60 (S1); 0.75 (S2); 0.65–0.85	—
Cascade return temperature	T_{ret}	24	°C
Condensing temperature	T_{cond}	55	°C
Carnot fraction	η_C	0.50	—
Evaporator approach	ΔT_{ap}	4	K
Auxiliary power coefficient	κ	0.02	—
Heat demand	D_h	9,000	kW
Chiller duty (S0, S1)	Q_{ch}	1,000	kW
Chiller coefficient of performance (COP)	COP_c	3.0	—
Boiler efficiency	η_b	0.90	—
Primary-to-electricity efficiency	η_g	0.40	—
Equivalent full-load hours	H	6,000	h/yr
Electricity price	c_e	0.08	USD/kWh
Gas price (fuel basis)	c_g	0.05	USD/kWh
Installed cost of recovery plant	u_I	900	USD/kW
Cascade integration cost (S2)	I_{int}	1.5	MUSD

Each scenario was evaluated at five inflow levels (100, 150, 200, 250 and 300 m^3/h), giving 15 runs, with 250 m^3/h as the typical scenario. Two further S2 runs at 250 m^3/h used ε=0.65 and ε=0.85. The model is deterministic, so repeated runs reproduce identical values.

4. Results

4.1. Typical Scenario

Table 2 summarizes the model estimates for the typical inflow of 250 m³/h.

Table 2. Model estimates for the three scenarios at a mine water inflow of 250 m³/h

Indicator	Unit	S0	S1	S2
Working-face air temperature T_f	°C	31.2	31.2	28.0
Cooling duty delivered Q_c	kW	1,000	1,000	1,560
Heat extracted from mine water Q_w	kW	0	4,877	6,096
Heat pump coefficient of performance (COP), COP_h	—	—	4.34	3.91
Recovered heat supplied Q_h	kW	0	6,336	8,193
Share of D_h covered	%	0	70.4	91.0
Total electric power W_{tot}	kW	333	1,891	2,250
Boiler fuel F	kW	10,000	2,959	897
Primary energy PE	GWh/yr	65.0	46.1	39.1
Primary energy saving ψ	%	0	29.1	39.8
Annual operating cost C	MUSD/yr	3.160	1.795	1.349
Annual cost saving	MUSD/yr	—	1.365	1.811
Investment I	MUSD	—	5.70	8.87
Simple payback t_{pb}	yr	—	4.2	4.9

In S0 and S1 the 1,000 kW chiller leaves 1,600 kW of the load unremoved, so T_f reaches 31.2 °C, 3.2 K above the design target, and S1 adds no cooling. In S2, Eq. (2) lowers the water to 17.0 °C, and Eq. (4) gives a cascade duty of 2,032 kW, above the 1,560 kW required by Eq. (5). The coolers are therefore throttled to the required duty and T_f holds at 28.0 °C without routine chiller operation. The cold water is a by-product of heat extraction rather than an additional energy input, which is the source of the synergy.

Heat supply follows the same pattern. S1 supplies 6,336 kW (70.4% of D_h) at COP_h=4.34, and S2 supplies 8,193 kW (91.0%) at 3.91. The higher effectiveness lowers the evaporating temperature and therefore the COP, but the 29.3% larger heat output outweighs the efficiency loss. Electric power rises from 333 kW in S0 to 1,891 and 2,250 kW, while boiler fuel falls from 10,000 kW to 2,959 and 897 kW. Primary energy decreases from 65.0 to 46.1 and 39.1 GWh/yr, savings of 29.1% and 39.8%. Operating cost falls from 3.160 to 1.795 and 1.349 MUSD/yr, with simple paybacks of 4.2 and 4.9 years. Relative to S1, S2 needs 3.17 MUSD of additional investment for an additional saving of 0.446 MUSD/yr, an incremental payback of 7.1 years, and in return lowers the working-face air temperature by 3.2 K.

4.2. Sensitivity to Inflow and Effectiveness

Recovered heat and air temperature respond to mine water inflow as Fig. 3 shows.

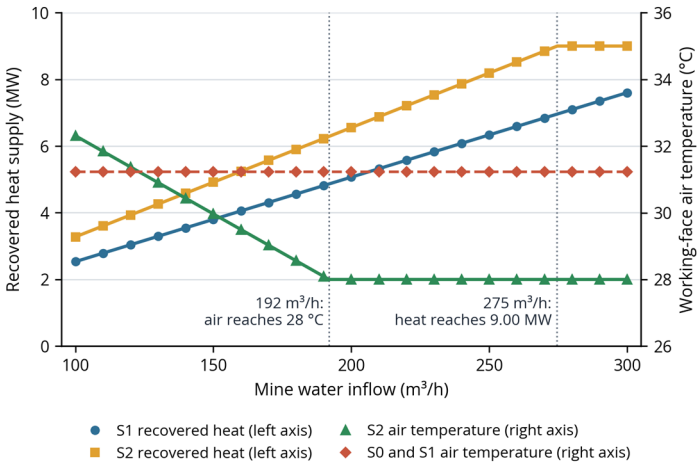


Fig 3. Recovered heat supply and working-face air temperature as functions of mine water inflow (model estimates; S1 effectiveness 0.60, S2 effectiveness 0.75).

Recovered heat in S1 rises linearly from 2.53 to 7.60 MW. In S2 it rises from 3.28 MW at 100 m³/h to 8.19 MW at 250 m³/h and reaches the 9.00 MW demand limit at about 275 m³/h, beyond which additional inflow adds no heat. The air temperature in S2 is 32.3 °C at 100 m³/h and 30.0 °C at 150 m³/h, and it holds at the 28.0 °C target from 200 m³/h. Setting $Q_{cool}=Q_{req}$ gives a minimum inflow of 1,560/(1.161×7)≈192 m³/h for the target. Below about 123 m³/h the cascade delivers less cooling than the 1,000 kW chiller.

Higher effectiveness increases recovered heat and lowers air temperature but reduces the heat pump COP. At 250 m³/h, ε=0.65, 0.75 and 0.85 give recovered heat of 6.94, 8.19 and

9.00 MW, the last being limited by demand (9.50 MW without the limit). The corresponding COP values are 4.19, 3.91 and 3.66, and the air temperatures are 30.0, 28.0 and 28.0 °C. Effectiveness of 0.65 therefore fails the temperature target, while 0.75 meets it (the minimum is about 0.69) and 0.85 covers the full demand (+0.81 MW over 0.75) but adds no further cooling benefit and lowers the COP from 3.91 to 3.66.

5. Discussion

According to the above calculations, the benefit of joint operation comes from sequencing. A large temperature drop is required in the mine water for the heat pump, and the air coolers need cold water; thus, cold water is produced by extracting heat. The same way it raises the heat output will also reduce the temperature of the water, so S2 has good thermal safety and energy-saving characteristics. The direction of this result is in line with the trend of integrated, multi-objective deep-mine thermal management mentioned in a recent review, 1 and with system concepts that combine geothermal energy utilisation and cooling [9,12].

Three Design Directions are as follows. First, the size of the water flow should be based on the cooling demand, not the heat load; the minimum is set at 192 m³/h according to the target for the air side, and a margin should be added because the air temperature will gradually rise below this value. Secondly, the range of the effect in this area is about 0.70 - 0.80; if the lower limit is not reached, it will not meet the objective, and if it is too high, it will only increase the remaining demand at a high COP without further cooling benefits. Third, operation should adjust coolers and water flow according to the demand, and the chiller should be in standby mode when the inflow is less than about 123 m³/h. Economically, heat from a heat pump costs about 0.018-0.020 US dollars per kWh of heat in electricity; for comparison, boiler heat costs about 0.056 US dollars per kWh, so whether it is more economical depends on the price ratio of gas and electricity and on the continuous heat demand. The longer the incremental payback of S2, the more justifiable it is for the cascade to meet the thermal safety requirements in this way.

The model is a steady-state and lumped model, so it does not consider spatial temperature fields, thermal drawdown of the rock and mine water, or the coupled hydraulic and mechanical processes in detail [8, 10]; these models can provide *Qload* and *Tw,in* as input. Only dry-bulb air temperature is used; as heat stress is also related to humidity, the wet-bulb criterion will need to be adopted in the final design. It is assumed that the equivalent full-load hours represent continuous heat demand, and seasonality and storage are not taken into account. Pumping energy to the surface, water quality, scaling and corrosion are not included, and the economic parameters are all the same. Therefore, the results are only applicable to districts with an inflow of 100-300 m³/h at about 38 °C, airflow near 150 m³/s and a heat load of about 2.6 MW; other conditions need to be recalibrated.

6. Conclusion

A Parameterised Energy-Balance Model for the Joint Development of Deep Mine Geothermal Resources and Three Scenarios were built in this paper. The main conclusions are as follows.

(1) At the typical scenario of 250 m³/h, the independent baseline and the heat-only scheme leave the air at the working face at 31.2 °C, and the collaborative cascade is able to keep it at the target of 28.0 °C.

(2) The collaborative cascade can provide 8.19 MW of recovered heat, which is 91.0 per cent of the assumed demand, and reduce the primary energy consumption by 39.8 per cent from 29.1 per cent in the case of heat-only recovery.

(3) The cascade needs an inflow of about 192 m³/h at an effectiveness of 0.75, and at 250 m³/h, the exchanger effectiveness should be at least 0.7; higher effectiveness will reduce the heat pump COP but will not increase the useful heat once demand is met.

(4) The collaborative scheme will have an additional investment of 3.17 million US dollars compared with that of heat-only recovery, but the extra payback period will be only 7.1 years; thus, it is only suitable for cases that need air temperature regulation.

The upper and lower bounds of the parameters are as follows. In the future, we will use the measured water and air data to calibrate the model, add humidity, seasonal storage and thermal drawdown, and couple it with spatially resolved models.

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