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Mine Water Geothermal Systems: Assessing Heat Recovery and Seasonal Thermal Storage

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ABSTRACT

Mine water geothermal technology is a developing renewable energy approach that utilizes the consistent thermal properties of mine water for both heating and cooling purposes. Although the mining sector is vital for supplying key minerals, closed mines are often left unused. These abandoned sites offer a new opportunity as potential sources for thermal energy storage and geothermal energy. This paper explores both the potential and challenges of using water-filled, abandoned mine workings for thermal energy storage, with a particular focus on Australia, given its extensive mining history. Considering the Bendigo-Ballarat fields in Victoria as a representative case study, the study evaluates their technical viability under Australia's distinct geological and climatic conditions. Additionally, the study introduces a coupled fluid-flow and heat transfer model aiming to assess the impact of operational and geological parameters and seasonal temperature changes on energy storage and heat extraction. The results indicate that while optimized flow rates enhance heat recovery, overly high circulation can lead to efficiency losses due to temperature equalization. Over 30 years simulations considering parameters such as operation mode, scheduling, idle-band range, and solar-assisted recharge showed that adaptive operation strategies improved mine-water thermal balance by 28–37%. The study also highlights the critical role of geological and hydrological conditions in influencing the mine's energy storage capabilities, especially for managing seasonal energy demands.

1 BACKGROUND

Thermal energy storage using subsurface resources represents a promising complement to conventional electrochemical storage technologies, particularly for meeting heating and cooling requirements with lower system losses (Fleuchaus et al., 2018). Flooded abandoned mines are of particular interest because they offer extensive subsurface void spaces that can be readily utilized for mine-water based geothermal energy systems (Hall et al., 2011; Walls et al., 2021). Water-filled galleries provide a convenient heat transfer medium, while the surrounding rock mass acts as a large thermal reservoir capable of seasonal storage. Heat transfer occurs through conduction between the mine water and rock walls, and by convective mixing and advection within interconnected galleries (Todd et al., 2024). The overall performance of such systems depends on hydrogeological and operational factors including mine geometry, volume, hydraulic connectivity, host-rock thermal properties, and flow rate management (Monaghan et al., 2026). When properly designed, mine water thermal energy storage can support seasonal balancing of energy systems and facilitate deeper integration of variable renewables into the grid (Raymond and Therrien, 2014).

Mine water geothermal systems have been piloted and demonstrated at numerous sites across Europe and North America, providing clear evidence of their technical feasibility for both heating and cooling applications (Hall et al., 2011; Raymond and Therrien, 2014; Todd et al., 2024). These systems typically exploit flooded coal mines at depths of 50–300 m and deliver thermal powers in the range of several hundred kilowatts to multiple megawatts, depending on mine geometry and system configuration (Farr and Busby, 2020; Monaghan et al., 2026; Walls et al., 2021). Long-term monitoring has shown that mine water temperatures remain stable, with seasonal fluctuations typically within ±1–2 °C at depth, owing to the large thermal mass of the host rock and its buffering capacity (Hall et al., 2011; Walls et al., 2021). One of the most advanced examples is the Heerlen Minewater Project in the Netherlands, which operates a distributed production–injection well network that maintains warm (≈ 28 °C) and cold (≈ 16 °C) storage zones in different parts of the flooded mine system. Seasonal injection and abstraction cycles are actively managed to provide low-temperature district heating and cooling to urban buildings, illustrating how mine water systems can function as large-scale seasonal thermal energy storage infrastructure (Schmidt et al., 2021; Verhoeven et al., 2014). Smaller-scale installations in Spain, notably in the Asturias region, also utilize warm mine water for district and greenhouse heating (Schmidt et al., 2021), highlighting the adaptability of the approach across different geological and operational contexts.

2 MINE WATER THERMAL ENERGY UTILIZATION POTENTIAL IN AUSTRALIA

Australia hosts thousands of abandoned mine workings, particularly concentrated in historically important gold and coal mining districts (Australia Minerals, 2025; Werner et al., 2020). Many of these legacy sites are now partially or fully flooded, representing a substantial, largely untapped subsurface resource for thermal energy storage and recovery. Figure 1 illustrates a conceptual map of Australia showing the distribution of major active and abandoned mine sites reflecting opportunities for integrating mine-based thermal energy storage within existing energy systems.

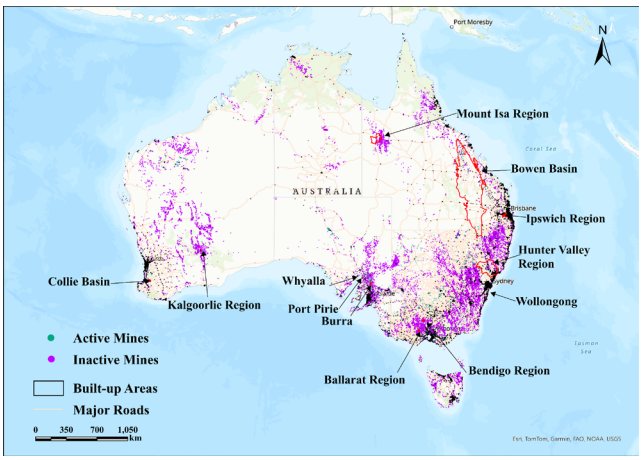


Figure 1: Distribution of mines in Australia, overlaid with major roads and built-up areas

Several prominent mining clusters stand out as suitable candidates for seasonal mine-water thermal storage. In Victoria, the Bendigo goldfield, Ballarat, and surrounding districts host deep, extensive underground networks beneath temperate-climate urban areas (Giri et al., 2025). In New South Wales, the Hunter Valley coalfields and Wollongong region contain large, water-filled mine workings located close to major population centers and grid infrastructure. In Queensland, the Bowen Basin and Ipswich coalfields provide opportunities for large-volume seasonal storage and potential cooling-dominated applications. The Mount Isa region offers deeper, hotter geological conditions, making it suitable for higher-temperature storage concepts. In Western Australia, Kalgoorlie hosts some of the deepest mines in the country, with elevated rock temperatures and good connectivity to existing transmission corridors (Roche and Mudd, 2014). Additional opportunities exist in Collie and in South Australia's copper–lead–zinc belts, including Whyalla, Port Pirie, and Burra, as well as in Tasmania's historical mining districts, which combine cool climates with extensive flooded workings (Nascimento et al., 2023). These clusters collectively demonstrate that mine thermal energy storage potential is geographically widespread, spanning a variety of geological settings and climatic zones across Australia.

In the context of Australia's energy transition and commitment to net-zero targets, the repurposing of abandoned mine workings for thermal energy storage represents a promising opportunity. Australia's diverse climate imposes distinct challenges for matching energy supply and demand. The country spans multiple climate classification zones, ranging from the hot, arid interior to temperate southern regions and the tropical north. Seasonal variations are especially pronounced in the temperate and Mediterranean-type climates of southeastern Australia, where cold winters drive heating demand and hot summers require substantial cooling. The rapid growth of renewable electricity generation, particularly from wind and solar has amplified the mismatch between seasonal demand and generation profiles, highlighting the increasing need for long-duration and seasonal energy storage (Helwig and Bell, 2024).

While several pilot projects in Europe and North America have successfully demonstrated the use of mine water for geothermal heating and seasonal storage, equivalent assessments for Australian geological, climatic, and infrastructural conditions remain scarce. By applying transient heat conduction and advection–dispersion modelling to the Bendigo–Ballarat fields in Victoria, this study provides the first high-level assessment of mine thermal energy storage in Australia under realistic local geological and climatic conditions. The analysis provides insight into the dominant parameters controlling heat exchange between injected water, mine voids, and the surrounding rock mass, and examines their influence on seasonal storage performance. The framework provides a scalable and computationally efficient pathway for early-stage screening and feasibility assessment of mine thermal energy storage projects.

3 REGIONAL CASE STUDY: BENDIGO AND BALLARAT, VICTORIA

3.1 Mining History, Mine Workings and Flooding Conditions

The Bendigo and Ballarat goldfields are located approximately 100–150 km northwest of Melbourne, in central Victoria, Australia. These fields were among the most productive gold mining regions globally during the late 19th century. Gold was discovered at Bendigo in 1851 and at Ballarat shortly after, initiating rapid settlement and extensive underground mining operations. By the late 19th century, both goldfields featured dense networks of shafts, drives, and crosscuts (Bristow, 2007). Bendigo's quartz reef systems were exploited to depths exceeding 1,200 m, while Ballarat mines typically extended to 500–800 m (Edwards, 2001).

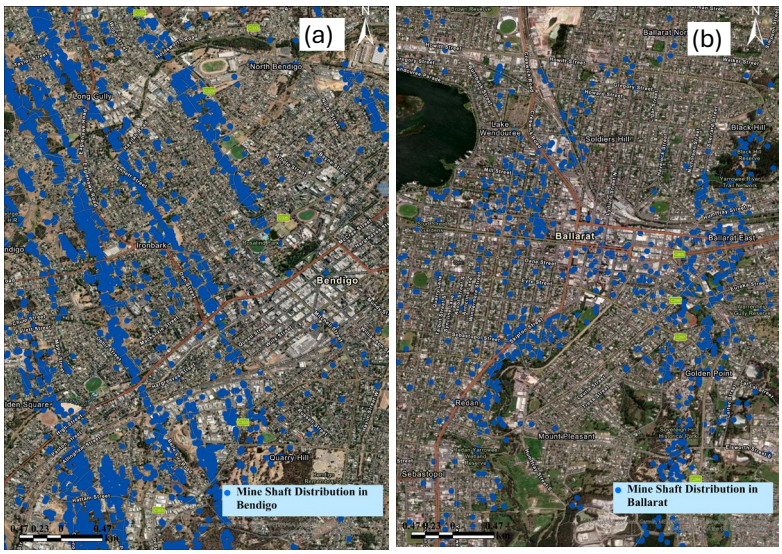


Figure 2: Distribution of mine shafts in (a) Bendigo, (b) Ballarat

Figure 2 illustrates the distribution of major historical mine shafts and underground workings in the Bendigo–Ballarat region, overlaid with urban centers. This spatial overlap between legacy mining districts and population centers highlights the practical potential of mine-water geothermal and thermal energy storage systems. The Bendigo field alone contains more than 5,000 registered mine sites, with total tunnel lengths estimated to span several hundred kilometers, though exact figures remain uncertain due to incomplete historical records (DEECA, 2025a). Following the cessation of mining around the 1990s, dewatering operations were halted, allowing groundwater levels to rebound and progressively flood the mine voids. Current water tables are typically 20-40 m below ground surface in many parts of Bendigo. Shaft collars and boreholes remain as access points to the underground network, and monitoring bores are maintained by the Victorian Government for water quality and groundwater level observations (DEECA, 2025b, WMIS, 2025)

3.2 Subsurface Thermal and Hydrogeological Setting

Regional geothermal gradients in central Victoria typically range between 25 and 35 °C km^{-1}, leading to estimated subsurface temperatures of 35–40 °C at around 1,000 m depth (Gerner and Holgate, 2010)). As shown in Figure 3(a), shallow groundwater temperature–depth profiles indicate that, at depths of less than 50 m, in the Bendigo–Ballarat region maintains stable temperatures of approximately 16–19 °C throughout the year. Figure 3(b) presents the interpolated groundwater temperature map derived from monitoring bore data (DEECA, 2025).

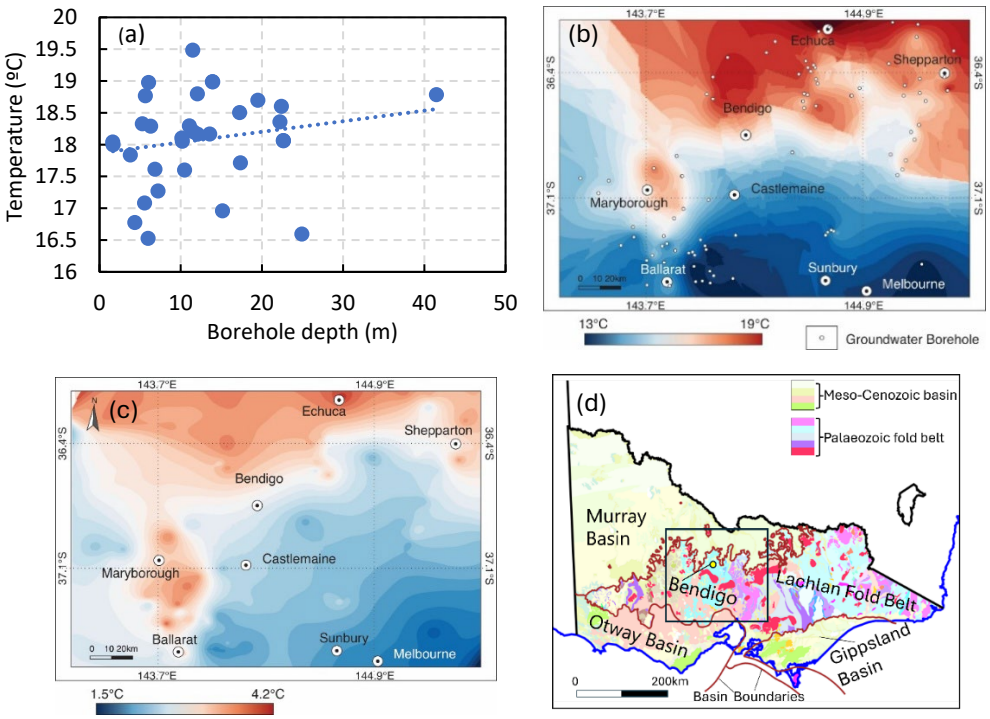


Figure 3: (a) groundwater temperature vs borehole depth profiles at Bendigo-Ballarat region, (b) the interpolated groundwater temperature map (< 50 m depth), (c) map of shallow groundwater temperature (T_w) - average long-term air temperature ($T_{air,\,avg}$), and (d) the regional basin boundary

Figure 3(c) shows the map of difference of shallow groundwater temperature and average long-term air temperature (T_w -$T_{air,\ avg}$). Taking average air temperature as a climatic baseline reveals a clear temperature difference in the subsurface, particularly in the northern part of the map near Echuca. This area coincides with the margin of the Murray Basin, a broad sedimentary basin that extends across northern Victoria as shown in Figure 3(d) (Edwards, 2001). The Murray Basin is characterised by thick sequences of low-thermal-conductivity sediments, including clays, sands, and limestones, which act as an insulating cover over the basement rocks (Tickell and Humphries, 1985). These sediments reduce heat loss to the surface and contribute to slightly elevated shallow groundwater temperatures. The long residence time of groundwater within the basin further stabilises subsurface temperatures. In contrast, Bendigo and Ballarat are underlain by Ordovician sandstones, siltstones and shales of the Lachlan Fold Belt, intersected by a network of faults and fractures that provide secondary permeability. In Bendigo, temperature profiles show gradual warming with depth, consistent with conductive geothermal gradients, but also localised cooling near shafts and open workings where groundwater recharge promotes vertical mixing. In Ballarat, shallow groundwater is slightly cooler (13–15 °C), most likely due to recharge through permeable basalt layers associated with the Newer Volcanics Province, which introduces cooler seasonal rainfall into the subsurface (Gill et al., 2011) . Mine workings intersect and enhance natural flow paths, increasing connectivity between previously isolated compartments and creating large, flooded volumes with relatively stable thermal conditions.

3.3 Climate Characteristics and Energy Demand

According to long-term meteorological records from the Bureau of Meteorology, Australia, the Bendigo–Ballarat region has a temperate climate, with a mean annual air temperature of 14.5 °C. Typical maximum daytime temperatures reach about 30 °C in summer (January–February), while minimum night-time temperatures fall to around 4 °C in winter (July). Based on the data of average hourly air temperature values of a 5-day climatological period from 2015 to 2023 (Gill et al., 2011), heating degree days (HDD) are substantially higher than cooling degree days (CDD), indicating dominant winter heating needs. For instance, taking 18ºC as the base temperature 1820 HDDs and 491 CDDs were obtained. Regional utility data further show pronounced winter peaks in natural gas consumption for space heating, while summer peaks in electricity demand are driven mainly by air conditioning.

Groundwater at around 16-19 °C can serve as a heat source during winter extraction accompanied with heat pump systems. Particularly deeper flooded mine sections (>300 m) are naturally warmer remain more thermally stable conditions. Conversely, during summer, mine water at stable temperatures can provide efficient cooling. Furthermore, the seasonal asymmetry creates opportunities to use mine water reservoirs as inter-seasonal thermal energy storage systems. Surplus solar energy generated during summer months, supported by Victoria's high rooftop PV penetration, can be stored as heat within the mine voids and recovered during winter through heat pumps for district or building-level heating.

However, it is essential to highlight that the large-scale district heating and cooling networks are uncommon in Australia due to its low urban density and suburban development patterns. Despite that, stable mine water temperatures offer strong potential for decentralized thermal applications. For example, in industrial sites, mine water at approximately 16 °C can be upgraded by heat pumps to 50–70 °C and supplied directly to hot water loops, wash systems, or process preheating, displacing natural gas (Raymond and Therrien, 2014). Agricultural enterprises, particularly in peri-urban areas around Bendigo and Ballarat where many legacy mine sites are located, could benefit from low-enthalpy geothermal systems for greenhouse heating, frost protection, or controlled-environment agriculture. Mine water can also enhance data center and commercial building cooling, base-load cooling increasing chiller efficiency and lowering peak electricity demand during summer. This site-specific and modular approach may align closely with Australian context and energy use, offering a realistic pathway for integrating geothermal resources into industrial, agricultural, and commercial energy systems.

4 PREDICTION OF MINE WATER HEAT EXTRACTION AND THERMAL STORAGE

The interaction between geological structure, aquifer properties, and mine void geometry is central to understanding and predicting the thermal behavior of the mine-water geothermal system. When warm or cold water is circulated through abandoned mine galleries, heat is transferred to the surrounding rock mass and can later be recovered seasonally or for short-term thermal buffering. This principle has been widely explored in the context of mine-water geothermal systems and underground thermal energy storage technologies (Monaghan et al., 2026, Todd et al., 2024). Understanding how injected heat propagates from mine water into the surrounding rock is crucial for evaluating both the efficiency and longevity of thermal storage.

4.1 Mathematical framework for heat exchange in flooded mines

Once heated or cold injected water enters a flooded gallery, the adjacent rock does not equilibrate instantaneously with the far-field temperature. Instead, heat gradually penetrates the rock, forming a near-wall thermally active zone, often referred to as the rock skin, that exchanges heat with the mine water while slowly conducting energy into the deeper undisturbed rock mass. The rock skin is represented as a finite thermal capacity node that grows over time, allowing thermal penetration depth to evolve dynamically. Similar energy balance formulations have been used in analytical and semi-analytical models for heat exchange in subsurface cavities and tunnels (Claesson and Hellström, 1992, Raymond and Therrien, 2014).

The coupled energy exchange between mine water, rock skin, and far-field rock can be described by two ordinary differential equations:

$$\frac{dT_m}{dt} = \frac{Q}{V}\left(T_{sup} - T_m\right) - \frac{h_{eff}A}{\rho c_p V}\left(T_m - T_s\right) \quad (1)$$

$$\frac{dT_s}{dt} = \frac{h_{eff}A}{C_{s\,(t)}}\left(T_m - T_s\right) - \frac{G_{rf}}{C_{s\,(t)}}\left(T_s - T_{r,\infty}\right) \quad (2)$$

where, $T_m(t)$ is the mine-water bulk temperature, $T_{sup}(t)$ the injection temperature, $T_s(t)$ the temperature of the near-wall rock skin, and $T_{r,\infty}$ the far-field rock temperature.

The volumetric flow rate and mine water volume are denoted by Q [$m^3\ s^{-1}$] and V [m^3], respectively, with ρc_p the volumetric heat capacity of water [J m^{-3} K^{-1}]. The wetted wall area A [m^2] and effective interface coefficient h_{eff} [W m^{-2} K^{-1}] define the water–rock conductance. The rock skin has a thickness δ(t), yielding a skin heat capacity:

$$C_{s\,(t)} = \rho_r c_{p,r} A\ \delta(t) \quad (3)$$

where $\rho_r c_{p,r}$ is the rock volumetric heat capacity [J m^{-3} K^{-1}].

Thermal leakage to the far field is represented by conductance [W K^{-1}]:

$$G_{rf} = \frac{k_r A}{L_{eff}} \quad (4)$$

where k_r is the rock thermal conductivity [J m^{-3} K^{-1}] and L_{eff} the effective distance to the far field [m].

The thermal penetration depth (skin thickness) is modeled as:

$$\delta(t) = \delta_0 + c_\delta\sqrt{(\alpha_t t)} \quad (5)$$

Here δ_0 seeds a pre-warmed/roughness skin [m] and c_δ controls the growth following classical conduction solutions for semi-infinite media (Carslaw and Jaeger, 1959). Furthermore δ_{max} caps month-scale participation.

This representation allows progressive attenuation of the heat exchange rate between mine water and surrounding rock as the skin thickens. Equivalent formulations are common in underground thermal storage modeling ((Raymond and Therrien, 2014, Monaghan et al., 2026, Todd et al., 2024). Key assumptions in this approach are mine water is perfectly mixed; rock adjacent to water is represented by a finite-capacity skin node of temperature Ts(t) and heat capacity $C_{s\,(t)} = \rho_r c_{p,r} A\ \delta(t)$ that grows with time as thermal penetration deepens. The skin couples to the far-field rock (fixed at $T_{r,\infty}$) via conductance $G_{rf} = k_r A/L_{eff}$. The rock thermal diffusivity $\alpha_r = k_r\ /\ \rho_r c_{p,r})$ controls the growth of δ(t) and, consequently, the transient strength of the wall sinks through $(T_m - T_s)$.

4.2 Parameter selection

The flooded mine workings of the Bendigo goldfield in Victoria, Australia were uses as an illustrative case in this study. Table 1 summarises typical parameters employed in the simulation. The underground voids are surrounded by fractured sedimentary rock with moderate thermal conductivity (~2–3 W m^{-1} K^{-1}) and relatively stable geothermal gradients (Preene & Younger, 2014; Banks et al., 2019). Thermal diffusivity and effective L_{eff} depend strongly on hydrogeological conditions. In competent rock with low groundwater flow, L_{eff} can extend tens of meters, enabling seasonal storage (Todd et al., 2024). In contrast, fractured or high-permeability zones result in rapid thermal leakage to the far field (Monaghan et al., 2026). For Bendigo's moderate depths and rock diffusivities, δ_{max} (month-scale thermal penetration) of 4–10 m are realistic, consistent with analytical

conduction estimates (Carslaw and Jaeger, 1959, Raymond and Therrien, 2014). When L_{eff} significantly exceeds this depth, stored heat can be retained through summer into winter, which is advantageous for heating-dominated systems such as district heating or integrated heat pumps (Walls et al., 2021).

Table 1: Parameter values considered in the simulation

Quantity	Typical Range	Notes
Q	10-200 L/s	Based on typical mine-water geothermal applications, base case 50 L/s
V	50,000 to 1 million m^3	Exact mine volume yet to be determined, base case 200,000 m^3
A/V	1–10 m^{-1}	Depends on geometry of mine voids; base case A/V=3m^{-1}
h_{eff}	5-75 $W{\cdot}m^{-2}{\cdot}K^{-1}$	Depends on low regime, roughness; base case 25 $W{\cdot}m^{-2}{\cdot}K^{-}$
k_r	2.5 $W{\cdot}m^{-1}{\cdot}K^{-1}$	Depends on rock type
$\rho_r c_{p,r}$	$2.26{\times}10^6$ $J{\cdot}m^{-3}{\cdot}K^{-1}$	Depends on rock type
L_{eff}	10-100 m	Higher → better seasonal retention; base case 40m
δ_0	0–1 m	Depends on pre-warmed condition or skin roughness; base case 0.2m
c_δ	2	Penetration scaling factor (Carslaw and Jaeger, 1959)
δ_{max}	8 m	Cap for month-scale depth
$T_{r,\infty}$	16 °C	Far-field rock temperature depends on geothermal gradient and depth

4.3 Year 1 operation considering the base-case parameters

Figure 4 summarises the results on the year 1 operation of the mine-water extraction using the base-case parameters in Table 1. The hourly air temperature, the instantaneous thermal power at the mine interface and mine water temperature has been superposed. The active pumping term is:

$$\mathrm{P}_{active}(\mathrm{t}) = \rho \mathrm{c}_p Q \left[T_{sup}(t) - T_m\,(t)\right] \tag{6}$$

The initial mine-water and the far-field rock was considered 16 °C. Operation is event-driven by ambient air. Once the local air temperature drops below 15 °C, the system discharges for space heating and when it exceeds 26 °C, it charges by rejecting heat.

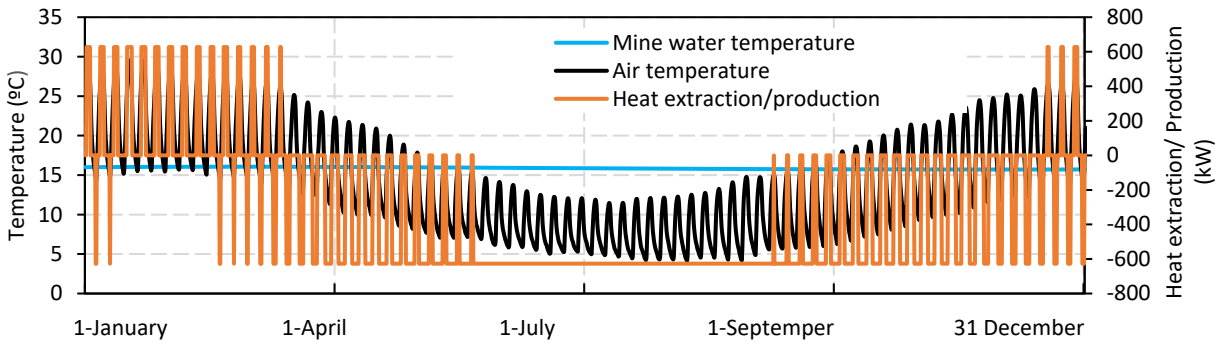


Figure 4: Bendigo average hourly air temperature data based on a 5-day climatological period from 2015 to 2023 (Gill et al., 2011) along with simulated ground water temperature and heat extraction/ production for Year 1

Results demonstrate an operating band of ±627 kW (positive for heat injection and negative for extraction) for the design flow of 50 L s−1 and a supply–return lift of ~3 K. If a 5 K lift were imposed at the same flow, the band would be ~1.05 MW. A ±627 kW thermal module sits in the range of a mid-size commercial building or small campus when coupled to heat pumps. Contemporary office buildings in Australia typically deliver operational energy intensities that, with efficient HVAC, are compatible with electrified heating via heat pumps (Ries et al., 2009). Heat pumps routinely deliver 3–5 times the useful heat per unit electricity versus combustion heat at the point of use, implying large operational savings relative to gas boilers at similar supply temperatures (Vanwormer and Grassl, 2018). For example, a water-source heat pump with a seasonal COP of 3.5 would draw ~180 MWh of electricity to deliver that heat. The same thermal service from a 92% condensing gas boiler would require ~681 MWh of gas energy. Figure 4 further demonstrates the mine-water temperature $T_m(t)$ which appears nearly constant, however zoomed views show a slight summer rise during charging followed by a non-linear winter decrease as extraction dominates. Using the base-case geometry and properties (Table 1), the net Year-1

drawdown is modest (~0.3 °C). This outcome is sensitive to operational and site parameters including flow rate, flooded volume, *A/V* ratio, interface conductive and convective thermal coefficient and the skin growth. Following section provides systematic exploration of those parameters.

4.4 Mine-water temperature response and parameter sensitivity after Year 1 operation

Following the baseline simulation, the influence of key hydraulic and thermal parameters on mine-water temperature variation was evaluated over a one-year operational cycle. Figure 5 summarises these sensitivities for (a) flow rate, (b) mine volume, (c) area-to-volume ratio (*A/V*), and (d) effective heat transfer coefficient (h_{eff}).

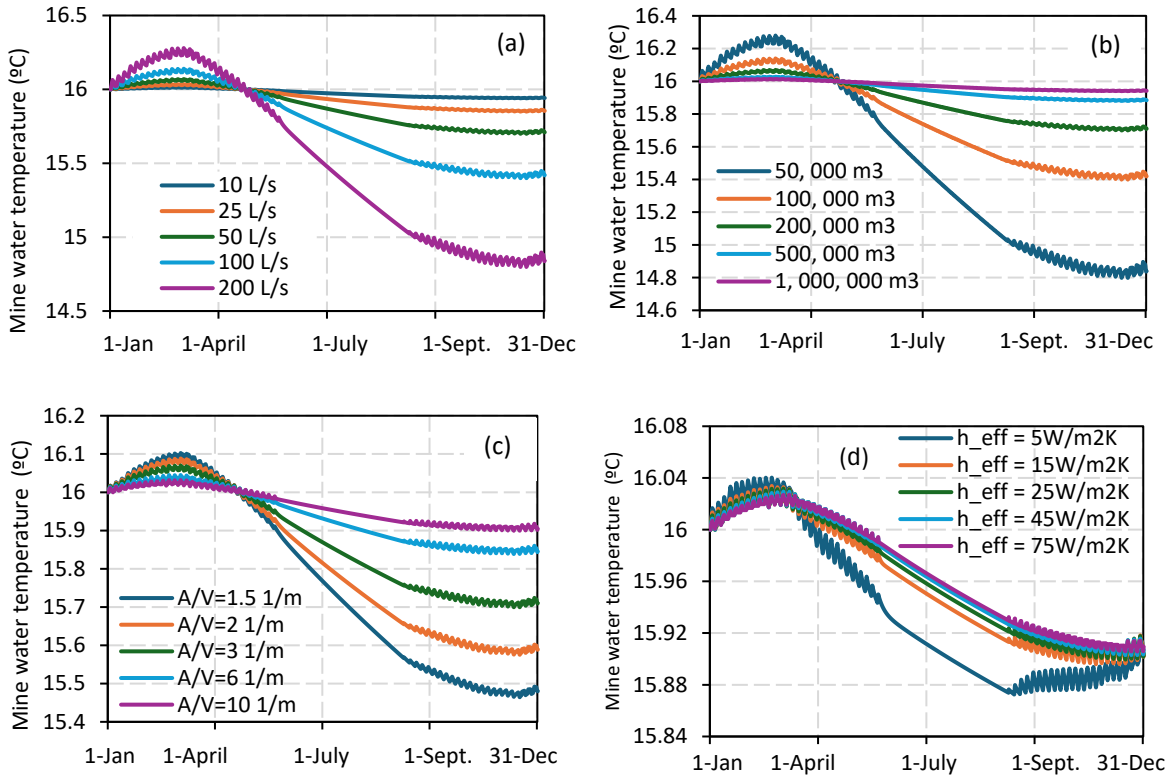


Figure 5: Effect of (a) flow rate, (b) mine volume, (c) area-to-volume ratio (A/V), and (d) effective heat transfer coefficient for mine water temperature (T_m) after heat extraction/ production in Year 1

4.4.1 Effect of flow rate

Figure 5(a) illustrates how increasing the pumping flow rate (10–200 L s^{-1}) enhances instantaneous thermal power, consistent with Eq. 6, but simultaneously intensifies thermal drawdown. Larger flows rate increases the volumetric turnover of mine water and the rate of heat extraction, reducing the residence time for conductive heat recovery from the surrounding rock. Under the base-case parameters, the 200 L s^{-1} case produces roughly four times higher instantaneous power than 50 L s^{-1}, but the average mine-water temperature drops by about 1.16 °C after one year, compared with only 0.06 °C for the 50 L s^{-1} scenario. While higher flow rates appear favourable for short-term energy delivery, they can compromise long-term sustainability by accelerating cooling and reducing the available temperature lift for heat pumps in subsequent years [4]. In practice, pump capacity, hydraulic head, and energy consumption impose further limits. Most operational mine-water schemes internationally operate within 30–100 L s^{-1} per well, delivering 0.3–3 MW_{th} depending on site temperature and depth (Raymond and Therrien, 2014; Todd et al., 2024; Walls et al., 2021).

4.4.2 Effect of mine volume

Mine-water volume governs the thermal mass of the storage system. Figure 5(b) shows results for volumes between 50 000 m^3 and 1 000 000 m^3, representing typical uncertainties for Victorian legacy mines where exact flooded geometries are poorly constrained (DEECA, 2025). Larger volumes act as thermal buffers, absorbing or supplying heat with smaller temperature excursions due to their greater $\rho c_p V$ capacity (Todd et al., 2024). Accordingly, the annual temperature drop reduces markedly as volume increases, highlighting the need for robust hydrogeological characterisation and sensitivity analysis to account for large uncertainties in void mapping and connectivity (Raymond and Therrien, 2014).

4.4.3 Effect of surface-to-volume ratio

The ratio *A/V* quantifies the heat exchange interface area per unit water volume, strongly influenced by mining geometry such as drive spacing, stope width, pillar stability, and post-collapse void fraction (Monaghan et al., 2026). *A/V* values between 1.5 m^{-1} and 10 m^{-1} were tested, encompassing likely conditions from deep, widely spaced tunnels (low *A/V*) to extensively fractured or collapsed shallow workings (high *A/V*). In physical terms, a higher *A/V* enhances the available surface area for conduction and convection between mine water and surrounding rock, thus promoting better thermal coupling and smaller drawdown. In the simulations, increasing *A/V* systematically reduces the amplitude of temperature fluctuations, confirming that geometries with greater exposed rock surfaces (e.g., collapsed stopes or open voids) behave as more effective thermal stores. For thermal extraction design, this implies that zones with extensive gallery networks or void collapses that are often viewed as structural liabilities, can actually be advantageous for heat exchange and seasonal storage potential.

4.4.4 Effect of effective heat transfer coefficient

The parameter h_{eff} represents the combined convective and conductive heat transfer across the mine-water/rock interface, integrating fluid mixing, boundary-layer turbulence, and rock roughness [1, 4]. It is analogous to an overall heat transfer coefficient in heat-exchanger analysis. In quiescent flooded workings, values near 5–15 W m^{-2} K^{-1} are typical, while well-circulated or turbulent zones can reach 30–60 W m^{-2} K^{-1} [1]. For Bendigo-type conditions, narrow, rough drives with some internal flow, the midrange 20–30 W m^{-2} K^{-1} may be realistic (Todd et al., 2024; Verhoeven et al., 2014). Simulations show that higher h_{eff} reduces winter drawdown by improving the rate of conductive recharge from the rock. Conversely, at low h_{eff} (≈5 W m^{-2} K^{-1}), there is a sharp temperature drop after winter heat extraction, but the temperature recovers rapidly in summer when the system charges. Over a full year, the net difference remains small. Hence, while h_{eff} influences short-term dynamics, its long-term average impact is moderate for the parameter set considered. The effect of L_{eff} which characterises the distance over which the rock skin conducts heat to the far field were further considered. Physically, it corresponds to the approximate depth beyond which temperature perturbations become negligible. Within the first operational year, variation in L_{eff} (10–100 m) produces negligible differences (<0.01 °C) in mine-water temperature. Long-term simulations (≥10 years) are needed to assess its cumulative impact and the eventual equilibration with the far-field rock temperature. These findings further reinforce that site characterisation and adaptive operation, including intermittent or seasonal scheduling, are crucial for sustainable mine-water energy (Monaghan et al., 2026, Todd et al., 2024).

4.5 Long-term thermal evolution and operational strategies

To assess the sustainability of mine-water energy use over extended operation, the one-year model was repeated for a 30-year period under different operational scenarios. Figure 6 illustrates the evolution of average mine-water temperature (T_m) for four representative configurations: (i) a continuous 15–26 °C deadband operation (base case in Fig. 3); (ii) a narrower 15–20 °C deadband operation; (iii) night-only operation with 15–20 °C thresholds, and (iv) a solar-assisted hybrid system combining daytime thermal charging and night-time heat extraction.

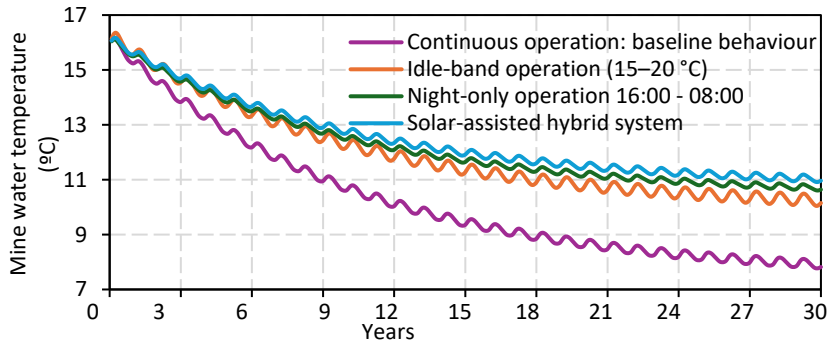


Figure 6: Evolution of mine-water temperature (T_m) for different operational configurations

Under continuous operation between 15 °C (heating threshold) and 26 °C (cooling threshold), the system extracts heat during cold periods and injects heat in summer. After 30 years, the mean mine-water temperature decreased by approximately 8.3 °C, with the most rapid decline occurring during the first 5–7 years before gradually stabilising. The result is an initially steep decline followed by asymptotic stabilisation consistent with analytical and field observations from long-running mine-water systems in Europe (Walls et al., 2021).

Following, a narrower operational band was then introduced, in which the system remains idle when air temperature lies between 15 °C and 20 °C, operating only during colder or hotter periods. Compared to the 15–26 °C baseline, the 15–20 °C band achieved approximately 5.4 °C thermal drawdown after 30 years. This

improvement arises because Bendigo's climate is heating-dominant, with prolonged winter heating loads and relatively short, moderate cooling seasons. In the broader 15–26 °C scenario, the system operates extensively for heating but only briefly for cooling, leading to a long-term net extraction of heat from the mine-water reservoir and progressive cooling. From a comfort perspective, the 15–20 °C range also corresponds well to the typical indoor HVAC neutral zone in Australian climates, where heating demand dominates below 18 °C and cooling systems are generally activated above 22–24 °C (Ries et al., 2009). This idle-band strategy therefore provides both energy efficiency and improved long-term thermal sustainability, without compromising occupant comfort.

Given the strong solar potential in central Victoria, a third configuration considered night-only operation, recognising that daytime loads could be supplemented by solar-driven systems while the mine operates primarily for night-time heating or cooling. Operational window of 16:00–08:00 was tested using the improved 15–20 °C thresholds. Compared to the continuous 15–26 °C base case, night-only operation reduced thermal drawdown by approximately 38% over 30 years because daily idle periods allow partial thermal recovery (passive recharge), moderating long-term cooling.

Finally, a solar-assisted hybrid configuration was simulated using the 15–20 °C thresholds and the 16:00–08:00 operational window. In this scheme, surplus solar thermal or photovoltaic-driven heat pump energy during the daytime is injected into the mine-water system. The injected power was parameterised as a daytime heat input scaled to typical solar availability in Bendigo considering solar radiation 5.25 kWh m^{-2} day^{-1}. A 1 000 m^2 photovoltaic–heat pump array ($\eta \approx 0.18$, COP ≈ 3.5) provided around 3.3 MWh_{th} day^{-1} of recoverable heat during summer, distributed over a 10:00–16:00 local window using a Gaussian diurnal profile. This configuration represents a medium-scale installation capable of partially offsetting winter extraction losses and reducing the long-term thermal drawdown to 6 °C after 30 years. Further reduction can be achieved by modestly increasing the collector area. In practice, such integration could be achieved via roof-mounted solar collectors, water-to-water heat pumps, or waste-heat recovery from nearby industrial sources. Beyond sustaining the mine's thermal balance, hybrid systems align well with Australia's high solar penetration and peak-demand structure, offering opportunities for load shifting and renewable integration consistent with national decarbonisation targets.

5 CONCLUSIONS

- In the Australian context, mine-water geothermal systems represent a technically viable and environmentally aligned opportunity to decarbonize space heating. With over 500 abandoned or flooded mines in Victoria alone, these reservoirs offer stable, low-carbon thermal storage resources.
- In heating-dominant regions like Bendigo adaptive control including integration of abundant solar resources can deliver reliable thermal energy.
- Parametric analysis of flow rate, mine volume, surface-area-to-volume ratio (A/V), and heat-transfer parameters revealed that system sustainability depends strongly on geometric and hydraulic configuration. Proper balancing of these parameters is essential for sustainable operation.
- Thirty-year simulations showed that continuous operation causes substantial cumulative cooling due to heating-dominated energy extraction. Introducing a 15–20 °C idle-band improved thermal balance by engaging more frequent summer cooling and limiting winter operation. Night-only scheduling further reduced drawdown by allowing daily passive recovery, while a solar-assisted hybrid configuration achieved near-thermal equilibrium by actively recharging the reservoir during daytime.
- This study provides a high-level simulation assessing geological and operational parameters relevant to Bendigo, Australia. Future research should develop site-specific 3D models incorporating actual mine geometries to capture detailed thermal–hydraulic interactions more accurately.

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