



Ventilation, Thermal Comfort, and Energy Strategies for Underground Shelters

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ABSTRACT

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The compilation of findings in this literature review addresses ventilation performance, thermal comfort, humidity control, and energy-efficient heating, ventilation, and air conditioning (HVAC) design in underground shelter-type environments. This helps develop a comprehensive approach to passive, hybrid, and mechanical ventilation systems, as well as integrating renewable energy into low-carbon operation. Passive ventilation strategies utilize buoyancy and natural pressure differences to maintain acceptable air exchange rates. The application of hybrid systems, which involve integrated photovoltaic/thermal collectors and ground-source heat pumps (PVT-GSHPs), results in reduced energy consumption while maintaining temperature stability. Studies on thermal comfort in earth-sheltered buildings show that indoor temperatures are relatively stable; however, high humidity levels—often exceeding 80%—are common. As a result, mechanical dehumidification is typically required to maintain comfort. Both computational and experimental approaches, including Computational Fluid Dynamics (CFD) and Response Surface Methodology (RSM), are increasingly employed to optimize air distribution and enhance system efficiency. Overall, the reviewed studies highlight the importance of an integrated HVAC strategy that combines passive ventilation, renewable energy systems, and intelligent humidity control to achieve thermal comfort, occupant safety, and long-term sustainability in underground shelters.

1. INTRODUCTION

Underground shelters and fortifications are increasingly considered in both civil defense and sustainable urban planning contexts. Such spaces, while offering protection and temperature stability, pose unique heating, ventilation, and air conditioning (HVAC) challenges due to limited air exchange, interactions with the surrounding soil, and persistent humidity. Therefore, HVAC system design in such environments will require a balanced methodology. It has to be safe, comfortable, and energy efficient.

In this review, the term “underground shelters” refers primarily to enclosed, human-occupied underground spaces.

Intended for protection and refuge under abnormal or emergency conditions (e.g., civil-defense shelters, refuge chambers, hardened bunkers, and protected underground rooms). These shelters are typically characterized by high occupancy density, limited or no direct openings to the outside, and the need for autonomous operation over extended durations with constrained power and resources.

This distinguishes them from conventional underground buildings such as basements, car parks, subway stations, and commercial underground spaces, which generally have larger openings, shorter occupancy times, easier access to outdoor air, and are served by standard grid-connected HVAC systems under normal operating conditions. The present work focuses on small- to medium-scale shelters (from single-room refuge

chambers to multi-room civil-defense shelters), where resilience, occupant life safety, and long-duration habitability impose stricter HVAC and ventilation requirements than in typical underground constructions.

Traditional mechanical ventilation systems normally require high power input and continuous operation, making them less suitable for long-duration emergencies or autonomous shelters. Recent research has therefore focused on passive and hybrid ventilation systems that utilize natural airflow dynamics and renewable energy sources for sustainable conditioning.

This review aims to synthesize recent findings related to HVAC and ventilation in underground and shelter environments. Topics discussed include passive ventilation optimization, hybrid system integration, thermal comfort assessment, humidity control, and low-carbon HVAC pathways. The results are used to inform design guidelines and identify knowledge gaps for future research and practical implementation.

A systematic literature review was conducted based on relevant studies, peer-reviewed journal articles, conference proceedings, and technical reports published within the last five years (2020–2024).

The selected studies were grouped into four integrated thematic clusters that reflect the main dimensions of HVAC design in underground shelters: natural and hybrid ventilation strategies, thermal and moisture control, emergency and

refuge-specific systems, and system-level optimization and low-carbon pathways.

Within these clusters, the literature was further organized into the following 11 thematic categories:

1. Passive and hybrid systems ventilation

Passive ventilation - buoyancy and wind-driven airflow.

Hybrid systems - combined passive and renewable-based HVAC configurations.

2. System-level optimization and low-carbon pathways

Mechanical and CFD-GA Design Optimization for Environmental Comfort.

Low-carbon HVAC technologies — system-level optimization and energy efficiency.

Optimization of PCM-Integrated Thermal Energy Storage (TES) for Emergency Cooling in Underground Shelters.

3. Thermal and Moisture Control in underground environments

Thermal Comfort in underground dwellings - human comfort and temperature stability.

Ground Thermal Stability and Its Implications for Energy Utilization in Underground Environments – GSHPs.

Humidity control and evaporative cooling — environmental control strategies.

Heat-Moisture Coupling and Ventilation Systems in Underground Structures.

4. Emergency and refuge-specific HVAC systems

Refuge chambers and tunnel ventilation — emergency operation and airflow management.

Modeling Heat Transfer and Improving Indoor Air Quality in Underground Shelters.

Each selected study was analyzed based on research objectives, methodology, and quantitative results regarding airflow velocity, temperature range, humidity, and energy consumption. The findings were summarized in tabular form to enable comparative discussion and cross-referencing using numerical citations.

2. RESULTS AND THEMATIC REVIEW

2.1 Passive ventilation systems

A comprehensive field and data-driven study has been conducted on naturally ventilated underground spaces in Fuzhou, China, that uses environmental monitoring and machine learning analysis. Their results showed that underground areas maintained lower and more stable air temperatures ($\approx 30.9\text{ }^\circ\text{C}$) compared with aboveground levels due to high thermal mass and shading; however, these spaces also exhibited high humidity ($\approx 80\%$) and nearly stagnant air ($V \approx 0\text{ m/s}$), leading to strong heat stress conditions with a mean Physiologically Equivalent Temperature (PET) of approximately $35\text{ }^\circ\text{C}$. Global sensitivity analysis identified metabolic rate and air temperature as the key factors influencing thermal comfort, highlighting the need for effective ventilation and humidity control [1].

Passive ventilation is a fundamental principle in the design of underground HVAC systems. Wen et al. [2] analyzed airflow in sustainable underground buildings using natural pressure differences. It was found that vertical shafts and cross-ventilation corridors can maintain sufficient airflow without the use of mechanical fans if they are appropriately located with respect to the prevailing wind direction [3].

Ji et al. [4] and Jin et al. [5] applied CFD and RSM

techniques to optimize ventilation performance at the tunnel-type civil-defense shelters at Yunlong Mountain, Xuzhou. Their results demonstrated that negative-pressure shafts.

Enhanced airflow uniformity and reduced mean air age. Multi-shaft configurations with optimized spacing achieved up to 18% improvement in air velocity compared to single-shaft systems. Shaft natural ventilation is a passive strategy in which air is supplied to and exhausted from an underground shelter through two vertical shafts. One shaft introduces outdoor air driven by pressure differences between the indoor and outdoor environments—arising from both wind and thermal buoyancy—while the other serves as an exhaust outlet. Both shafts extend above ground level, with the exhaust shaft positioned higher than the supply shaft to enhance the pressure differential. The system’s performance improves as the temperature difference between the indoor and outdoor air increases; hence, it operates more effectively in winter, when outdoor temperatures are typically lower than those inside the shelter [6].

This method also influences indoor humidity: when ambient humidity is high, similar conditions can develop inside the shelter, making the approach more suitable for cold and dry climates than for hot and humid ones. Field studies indicate that, under specific conditions, shaft ventilation can provide adequate airflow. However, hybrid configurations—combining natural and mechanical ventilation—often achieve superior performance, for example by adding fans to enhance air exchange rates. Table 1 summarizes the suitability of natural ventilation in underground shelters according to the climate zone and season of each city.

The cited study validated a numerical model against an actual underground shelter in China and then subjected the system parameters to changes to analyze the ventilation behavior. A multizone airflow model was combined with dynamic heat transfer computations to predict natural ventilation rates. CFD was not employed due to its complex coupling with other numerical models and the significant computational time required [6].

Table 1. Schedule for natural ventilation of underground shelters using vertical shafts [6]

Cities	Climate Zone	Suitable Ventilation Times
Urumqi	SCZ, dry region	Throughout the year, but ventilation rate < 0.1 each in winter
Lanzhou	CZ, dry region	Throughout the year, but ventilation rate < 0.1 each in winter
Harbin	SCZ, humid region	Except summer, and ventilation rate < 0.1 each in winter
Beijing	CZ, humid region	Except summer, and ventilation rate < 0.1 each in winter
Shanghai	HSCWZ, humid region	Except summer, May, and September
Guangzhou	HSWWZ, humid region	Only in winter
Kunming	TZ, humid region	Except summer, May, and September

These findings confirm that confined space airflow distribution is highly dependent on shaft number, size, and position—all important considerations for the design of the HVAC system within an underground shelter where passive airflow may represent the first tier of ventilation defense.

2.2 Hybrid ventilation and renewable energy integration

Hybrid systems integrate natural and mechanical ventilation to dynamically respond to changing environmental conditions.

Li et al. [7] extended this framework for nuclear HVAC systems by proposing hybrid low-carbon pathways that combine waste-heat recovery and ground-source cooling. Although focused on nuclear facilities, these insights are clearly applicable to underground shelters, where resilience and continuity of operation become essential.

Both studies emphasize system coupling, control logic, and the possibility of shifting energy loads between renewable and conventional sources in achieving stable comfort with minimal energy consumption.

The enclosed and hidden nature of underground buildings makes proper ventilation a vital element in maintaining air quality indoors. In all buildings, natural ventilation is driven either by buoyancy forces, wind pressure differences, or both in hybrid systems. Among buoyancy-driven mechanisms, SCs are widely used to enhance indoor-outdoor temperature differences, thereby increasing airflow rates. They involve the incorporation of solar-absorbing plates within the SC. The orientation and tilt angle of the SC are also optimized to maximize efficiency. Their performance depends strongly on the local solar intensity. Figure 1 illustrates natural ventilation systems utilizing solar chimneys [8].

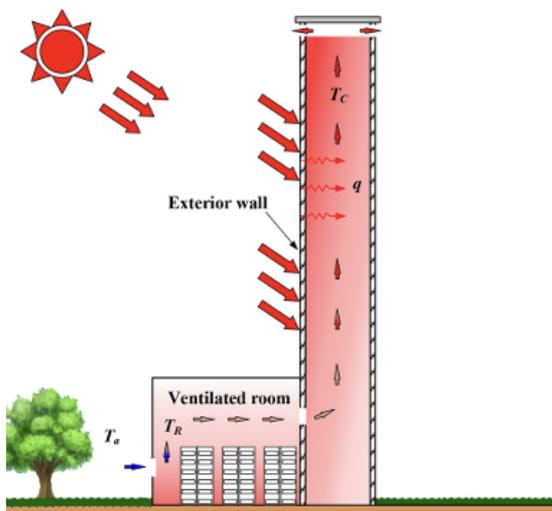


Figure 1. The natural ventilation systems using solar chimneys [8]

Khaksar et al. [9] demonstrated that integrating PVT panels with ground-source heat pump systems reduces HVAC energy use by 23%, with solar input used for preheating and geothermal storage stabilizing cooling. Photovoltaic systems are widely integrated with buildings, but their electrical

efficiency declines as temperatures rise. To address this limitation, photovoltaic/thermal (PVT) systems were developed to recover heat generated by PV panels for use in applications such as desalination, food drying, and domestic heating. Recent studies have examined the coupling of PV/T units with ventilation systems, for example, using them as a heat source in a solar chimney to cool PV modules while enhancing indoor ventilation efficiency. Figure 2 illustrates a ventilation system combining the solar chimney effect with PV/T technology. This approach can also be integrated with vertical shaft ventilation systems, extending its applicability to underground buildings where direct solar exposure is limited [8].

High outdoor temperatures significantly reduce the efficiency of natural ventilation, creating a major challenge in cooling underground shelters. The integration of chimney ventilation with auxiliary cooling systems has shown promise in addressing the issue by lowering the supply air temperature. Various methods have been proposed that combine solar chimneys with radiative or evaporative cooling, metal-foam absorbers, or geothermal systems, demonstrating significant temperature reductions and improved airflow performance [8].

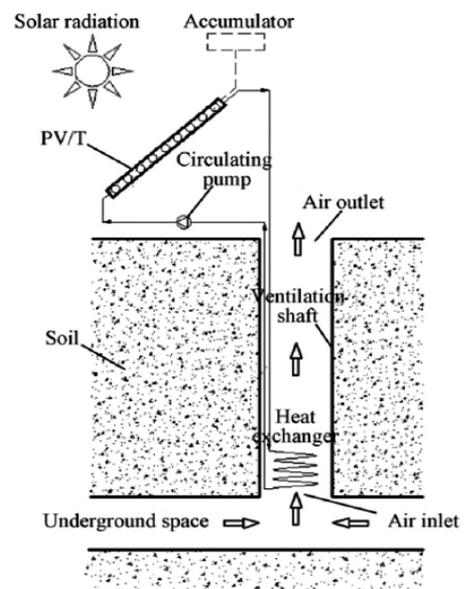


Figure 2. Ventilation system combining solar chimney effect and PV/T [10]

Integrated passive and hybrid ventilation systems show strong potential for maintaining comfortable indoor environments. These solutions could benefit underground shelters, but further validation under actual subterranean conditions is necessary.

Table 2. Cooling and heating capacity of the air intake tunnel [9]

Tunnel	Air Volume (kg/s)	Summer		Winter		
		Cooling Quantity (kW)	Enthalpy Difference (kJ/kg)	Air Volume (kg/s)	Heating Quantity (kW)	Enthalpy Difference (kJ/kg)
Jiangxi (1500 m)	35	988	28.1	36	292	8.3
Sichuan (2800 m)	175	2169	12.4	257	663	3.8
Hainan (1400 m)	53	606	11.4	64	–	–

The underground air-intake tunnel functions as a natural heat exchanger, preheating or precooling the air entering the underground plant, thereby reducing the energy consumption of the mechanical HVAC system. As air flows through the tunnel, its temperature decreases due to heat exchange with the surrounding soil, resulting in condensation of water vapor on the tunnel walls and a reduction in the air's absolute humidity. The authors concluded from their experiment that a specific length of a tunnel is not a decisive factor in the heat transfer performance. Indicating that at some point, the extra length wouldn't be of significant effect due to the relatively low temperature difference. On the other hand, because the air temperature has dropped, the relative humidity correspondingly rises to 95% or higher at the outlet of the tunnel. The authors recommend explicitly accounting for air intake tunnel conditions—such as temperature and humidity changes—when designing the plant's HVAC system. Table 2 presents data on the cooling and heating capacities of air intake tunnels during summer and winter seasons at three different locations [11].

2.3 Computational fluid dynamics and mechanical design optimization

A highly occupied underground shelter with narrow sleeping spaces was numerically investigated using CFD-GA (genetic algorithm). First, the researchers validated the numerical model using experimental or published data. They then used the model to study how key design parameters—including inlet air velocity, temperature, air supply angle, and airflow pattern—affect the indoor environment and energy consumption [12].

Six scenarios have been built: the first one was to validate the CFD model, then the second was used as a base for the upcoming scenarios, and the third used to investigate the temperature parameter by conducting CFD simulations on a range of temperatures while fixing other parameters, while the fourth scenario investigates the velocity parameter, and the fifth investigates the effect of air supply angle.

These scenarios gave an idea about the range within which the values of the parameters should be investigated in the CFD-GA optimization model. The following needed to be achieved:

According to ASHRAE Standard 55-2017, the PMV values fall within the range from 0.5 to +0.5, while the PPD values fall within the range from 0 to 10%. The standard identified that for PD, the percentage of dissatisfaction with draft sensation is lower than 15%, and the CO₂ concentrations are lower than 1000 ppm. The last objective was low energy consumption. Therefore, for Scenario-6, the CFD-GA method was used to optimize the key design parameters of the environment control system to achieve the objectives.

The results showed that increased flow speed increases PD and power consumption while decreasing PMV, PPD, and CO₂ concentrations. Increasing the temperature decreases power consumption and PD, but increases PMV and PPD, while having a negligible effect on CO₂ concentrations. Increasing the inlet angle decreases PMV, PPD, and CO₂ concentrations, but increases PD.

The displacement pattern was also investigated: Up-supply and Down-return, and Down-supply and Up-return. The results indicated that PPD values in the bed area were approximately the same for both airflow patterns; however, the Down-supply and Up-return pattern produced higher PD

values, resulting in a stronger draft sensation in the bed area. The "Up-supply and Down-return pattern had higher PPD and PD in the corridor area.

The mouths of the occupants were the primary source of CO₂; however, exhaled air also contains aerosols, which can transmit infectious diseases. The potential impact of aerosols was not addressed in this study. Additionally, the effects of air inlet and outlet placement in the ceiling and floor were not investigated.

Figure 3 presents a flowchart of the modified genetic algorithm (GA), illustrating the iterative optimization process using genetic operations such as selection, crossover, and mutation [12].

2.4 Thermal comfort in earth-sheltered structures

Thermal comfort studies [4] provide important information on occupant perception in underground spaces. Monitoring of 22 earth-sheltered buildings in Meymand, Iran, revealed that interior temperatures typically ranged from 21 to 27 °C, while outdoor temperatures varied from 5 to 38 °C. Although soil has some thermal inertia that buffers diurnal variation, relative humidity levels were above 70% for significant periods, which creates discomfort according to ASHRAE Standard 55.

Occupant surveys revealed that, while most people were satisfied with temperature levels, many frequently reported dampness and condensation on surfaces, which diminished overall comfort. This suggests that thermal comfort in these spaces depends not just on temperature, but also on the interplay of humidity and airflow. In warm, humid conditions, high moisture levels reduce the body's ability to evaporate sweat, causing even moderate temperatures to feel stuffy or oppressive, especially when airspeed is low. In contrast, during cooler conditions, high humidity can intensify the sensation of chill, particularly near cold surfaces.

These results highlight that, in humid regions, passive thermal regulation alone cannot ensure comfort indoors. Effective HVAC design for earth-sheltered structures must fully integrate humidity management, temperature control, and adequate airflow to maintain conditions within the ASHRAE 55 comfort zone. To maintain acceptable indoor environmental quality, it is essential to balance temperature, humidity, and airflow. Strategies to achieve this include mechanical ventilation with dehumidification, controlled air distribution, and surface temperature management to prevent condensation.

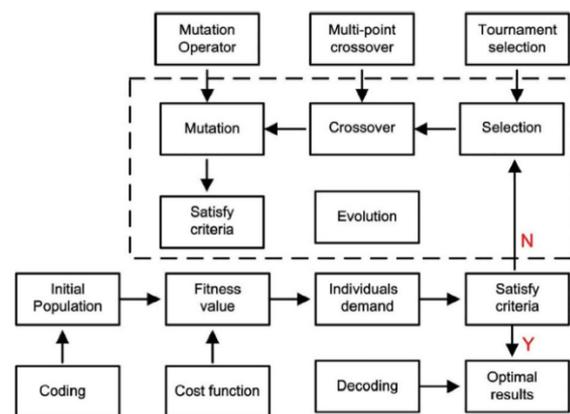


Figure 3. Flowchart of the modified genetic algorithm [12]

2.5 Ground thermal stability and GSHP systems

Due to the high heat storage capacity and insulation of the soil, temperature variations within the ground layer are minimal in both seasonal and diurnal cycles. The ground layer thus acts as a reliable heat source, and GSHP systems can reduce electrical energy use up to two-thirds compared with electric boiler systems. Yet, average ground temperatures increase about 1 °C for every 30 m depth, offering opportunities and challenges for deeper underground developments. The higher geothermal gradient increases the potential for energy extraction and heating applications. However, generating electricity would require drilling several kilometers to reach suitable temperatures, which would significantly increase cooling and ventilation demands, as well as the complexity of deep underground construction [13].

2.6 Modeling heat transfer and improving indoor air quality in underground shelters

Therefore, a thorough analysis of the indoor environment in underground shelters must include the study of heat transfer between the surrounding soil and the building structure. In recent decades, several analytical, numerical, and simplified methods have been developed. Analytical and semi-analytical methods were first applied owing to their simplicity and low computational costs; however, their applicability is rather limited to simple geometries and boundary conditions. To overcome these limitations, researchers introduced numerical approaches such as finite difference, finite element, and finite volume methods. These techniques offer higher accuracy and allow for modeling of complex configurations, but they require greater computational resources [10].

To improve computational efficiency, response factor and transfer function methods were proposed. These techniques use pre-calculated response factors that characterize how the system reacts to temperature variations over time, enabling faster simulations. Nevertheless, their accuracy decreases for systems with high thermal inertia, such as soil, or for complex geometries, where finite element methods remain more robust for transient analyses. More recently, the element-free Galerkin (EFG) method has been employed to achieve high accuracy and flexibility without requiring a fixed mesh. Unlike FEM, which divides the domain into discrete elements, the EFG method distributes nodes throughout the domain and constructs shape functions using a moving least-squares approximation. However, this approach is computationally expensive.

Simplified manual methods have also been developed to provide practical estimates of heat transfer using parameters derived from analytical or numerical results. Mitalas's method used 2D and 3D FEM results that were corrected with experimental data to account for corner effects. Krarti and Choi presented a simplified approach based on the ITPE method, which exhibited less than 10% deviation from detailed simulations. Similarly, Shi et al. [6] proposed a validated method with average temperature errors less than 10% for both walls and floors. Dynamic dimensioning approaches were also developed to estimate air and wall temperature variations and heat flow more efficiently. More recently, regression-based and machine learning techniques have appeared that can provide fast and accurate predictions but are strongly dependent on the quality and scope of the training dataset. Numerical methods remain the most reliable,

with response factor and regression-based techniques efficient alternatives for large-scale or long-term simulations.

In addition to heat transfer, indoor air quality is a major concern in underground environments due to the presence of pollutants such as radon, total volatile organic compounds (TVOCs), formaldehyde, and CO₂. Light plasma purification technology has been applied in central air-conditioning systems because it is effective against a broad range of contaminants. Artificial anion generation has also been explored to enhance occupant satisfaction and reduce the prevalence of Sick Building Syndrome. The main source of radon in underground buildings is the surrounding soil, which poses health risks due to its radioactivity. Mitigation strategies include selecting construction sites with low natural radon concentrations and installing advanced electrostatic filtration systems. These systems use electrostatic fields to remove radon and its radioactive progeny, thereby improving indoor air quality [10].

2.7 Refuge chamber and tunnel ventilation studies

Jin et al. [5] conducted experimental studies on underground refuge chambers under natural convection and ventilation conditions. Their results indicated that rock temperature, occupant density, and airflow rate are dominant factors in determining indoor heat buildup.

A 10 °C rise in surrounding-rock temperature reduced the cooling potential of the chamber by 15%, indicating that ventilation systems need to be adaptable to geological conditions.

Complementary evidence is drawn from tunnel ventilation research. Figure 4 shows a typical secondary ventilation system in an underground hard rock mine. Energy-efficient underground fortification systems using multi-zone air flow control were presented by Namgay and Nwokeji [14]. Compiled global practices in ventilation, describing the development from longitudinal jet fans to semi-transverse systems, which could maintain safe CO and temperature levels. A recent review [15] of modern tunnel ventilation control highlighted that integrating smart sensors and predictive modeling into fan operation can significantly reduce power consumption.

Various studies of underground metro stations have presented ventilation strategies that can also improve the air quality and comfort of underground shelters by increasing air exchange rates with outdoor air, reducing the recirculation of stale air, applying ASHRAE-recommended ventilation rates, and adopting high-efficiency filtration systems such as H10 or HEPA.



Figure 4. A typical secondary ventilation system in an underground hard rock mine [14]

Automated sensor-based ventilation control and periodic HVAC maintenance are crucial to maintaining safe indoor air quality. Using low-emission construction materials and adsorption-based filtration systems can further minimize indoor pollutants [16].

The research examined the performance of auxiliary ventilation systems used in tunnel and mining excavations, with a focus on how duct diameter, length, and leakage influence airflow, pressure distribution, and fan power. Their analysis showed that reduced diameter or higher leakage greatly increases the pressure losses and energy demand, while larger ducts increase efficiency but lead to higher excavation costs. These findings relate to HVAC system design in underground shelters, where adequate air circulation, pressure balance, and energy-efficient mechanical ventilation are major factors affecting occupant safety and comfort in confined spaces [17].

Together, these findings support hybrid tunnel ventilation systems that combine passive shafts and active jets to ensure redundancy and safety. This approach is directly applicable to civil defense shelters.

2.8 Humidity control and evaporative cooling

The most difficult parameter to control in underground environments remains the humidity. Ma et al. [11] pointed out that insufficient humidity management in underground utility tunnels results in condensation, corrosion, and biological growth, which is harmful to both structure and health. They recommend that ventilation design explicitly include dewpoint and moisture control calculations.

In practice, humidity control in underground spaces requires a combination of architectural, passive, and mechanical strategies. For the building envelope, apply continuous vapor barriers and capillary breaks to walls and floors in contact with soil, along with external waterproofing and perimeter drainage systems to minimize groundwater moisture ingress. Internally, sloped floor finishes should direct water toward drainage channels and collection sumps. These measures help remove condensate and leakage water, thereby limiting the accumulation of standing moisture and preventing surface wetting [18].

From a mechanical perspective, supply air conditions must be selected based on indoor humidity ratio and dew point, not just dry-bulb temperature. Dedicated outdoor air systems (DOAS) with cooling coils sized for latent load, followed by reheat, can dehumidify ventilation air before it enters the occupied zone. In high-load or critical areas, standalone dehumidifiers or desiccant wheel systems can be integrated to handle peak latent loads and maintain relative humidity within the recommended range of 40–60% RH. Humidity sensors should be distributed in representative locations and connected to the building management system (BMS), enabling modulating control of airflow, coil leaving temperature, and dehumidification capacity [19].

Evaporative cooling was investigated in hot-arid climates [20], where coupling underground structures with evaporative systems reduced indoor temperature by 4–7 °C while maintaining energy efficiency. However, excessive humidity (>80% RH) could result if not properly regulated.

Therefore, the evaporative-cooling systems should be accompanied by vapor barriers, drainage layers, and integrated dehumidification to sustain comfort and durability.

2.9 Heat–moisture coupling and ventilation systems in underground structures

The moisture transfer in the underground space increases not only the surface humidity but also affects the whole heat load. Heat transfer in underground spaces primarily depends on conduction and the distribution of moisture within the building envelope. Conversely, mass transport depends on moisture and thermal diffusion processes. The coupled transient heat and moisture transfer in the underground ducts depends on time, spatial, and inlet conditions. Therefore, to achieve an understanding of interactions, numerical models were developed that simulate the simultaneous heat exchange between air and tunnel surfaces, taking into account the condensation effects that occur inside the tunnel [20].

The process of underground heat exchange between airflow and tunnel surface is complicated and unsteady, being influenced by heat sources, humidity, and soil properties. A numerical model was developed to predict thermal performance and cooling capacity for underground soil-to-air systems. Later, the soil inhomogeneities were revealed. Several tools exist that can help estimate temperature and airflow, but their one-dimensional approach limits their accuracy. Some specific formalism was proposed to meet the demand of the underground tunnel unsteady heat transfer problem. However, further research is needed to establish the efficacy of this method. Therefore, advanced models should incorporate transient effects and heterogeneous soil conditions to improve the reliability of thermal analysis in underground environments.

Energy tunnels have recently emerged as an effective approach to reduce fossil fuel consumption and greenhouse gas emissions by using the surrounding soil for heat exchange. The key benefit of energy tunnels is their high heat transfer capability, which results from several influencing factors such as tunnel geometry, airflow rate, inlet air temperature, and wall roughness. Studies demonstrate that airflow conditions and tunnel shape significantly influence thermal boundary layer development and overall heat transfer efficiency.

Most energy tunnel systems use large-diameter pipes inside the tunnel lining, which can be expensive and difficult to install. As an alternative, capillary heat exchange networks have been proposed. Numerical and experimental studies demonstrate that capillary systems can achieve effective heat exchange, with intermittent operation outperforming continuous operation in terms of efficiency. Although capillary tunnels show significant potential for energy savings, few studies have examined these systems, and further validation through large-scale applications is needed.

Mechanical ventilation systems include three main types: forcing systems, which use fans or blowers to introduce fresh air into a space; exhausting systems, which use exhaust fans to remove stale or contaminated air from the space; and air curtain systems, which create an invisible barrier of high-velocity air across a doorway or opening to separate two different environments. Air curtains are used in situations where it is necessary to prevent outdoor air—such as when it is contaminated due to pollution, hazardous events, or security concerns—from entering the indoor space [20].

They explored the temperature and humidity couplings of the underground ventilation systems. They performed data-driven system identification and obtained transfer-function models for both the temperature and humidity channels. They then designed feed-forward decoupling, bat-algorithm-

optimized PID, and RBF-neural-network-based adaptive decoupling controllers to cope with the coupled temperature-humidity control system [15].

Heat and moisture transport in an underground collection building in Northwest China were investigated to optimize HVAC system design and reduce energy consumption. In contrast to above-ground buildings, the thermal and moisture behaviors are quite different because underground buildings are in contact with soil and never exposed to sunlight. Therefore, dehumidification and moisture-proof functions are essential for achieving indoor comfort and preventing system inefficiency [21].

This study creates a 1:1 physical model of the underground building using Design Builder software, whose computational core is EnergyPlus, in which envelope materials are detailed with specific boundary conditions. Annual hourly heat, cooling, and humidity loads have been incorporated into the simulation for the quantitative analysis of dynamic energy behavior. Mathematical models were developed for heat and moisture transfer—including conduction, convection, radiation, and moisture dissipation—to calculate the corresponding loads in the underground environment.

Based on this, five different air-conditioning design temperature conditions were simulated to analyze their impact on energy consumption. Seasonal temperature control—setting 16 °C in winter and 22 °C in summer—results in approximately 59% total energy savings compared to maintaining a constant 18 °C throughout the year. Based on this observation, the underground buildings have lower thermal loads compared to surface buildings and exhibit "warm in winter and cool in summer" performance. Figure 5 illustrates energy consumption under different design conditions.

Humidity analysis indicated that while winter humidity can be effectively controlled, transition and summer seasons often exceed the desired 45–60% range, highlighting the need for specialized dehumidification systems. The simulation estimated a dehumidification requirement of approximately 45 kg/h for 1500 m², highlighting dehumidification as a key challenge in underground HVAC design.

In response, this study outlines a quantitative framework for assessing heat and humidity loads in underground buildings, offering guidance for the selection, operation, and optimization of HVAC systems in similar environments.

Although this case study focused on a storage facility, its quantitative analysis of heat and moisture transfer offers a scientific basis for optimizing HVAC systems in underground spaces intended for human occupancy [21].

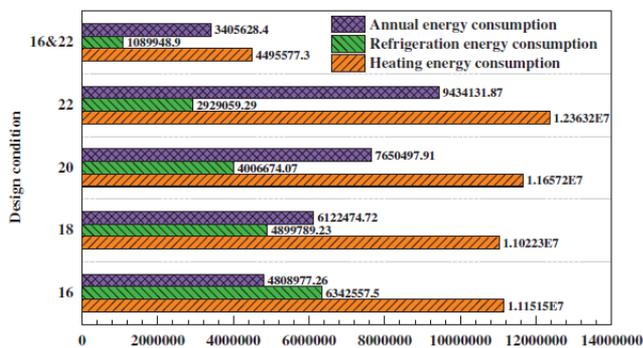


Figure 5. Energy consumption (kWh) [21]

2.10 Low-carbon HVAC and environmental control

The comprehensive review in Energies [7] summarized global advancements in underground ventilation and environmental control, emphasizing that hybridization, automation, and adaptive control are essential for low-carbon operation in these systems.

Emerging strategies include heat recovery ventilators, real-time CO₂ and RH sensors, and variable-speed fan systems that respond to occupancy and temperature fluctuations.

These ideas align with larger sustainability objectives and demonstrate that smart control integrations can maintain safety while reducing energy consumption in sealed or semi-sealed underground spaces.

2.11 Optimal PCM-integrated TES for emergency cooling in underground shelters

Due to the frequency of natural and artificial disasters, underground shelters and related facilities have become integral parts of modern city architecture. Such high-temperature, confined spaces are prone to sudden power cuts; therefore, emergency cooling systems must be highly reliable. Since thermal loads in these situations are both sudden and infrequent, effective, low-maintenance, and quickly deployable cooling systems are needed [22].

The very first systems employed sensible thermal storage, such as water or ice tanks, for emergency cooling regulations. Later, LHTES using PCM became popular due to their higher energy density, extended cooling duration, and compactness. Integrating the PCM modules into water tanks increases storage capacity and reduces tank volume, while enhancing energy efficiency with reduced carbon emissions. When integrated with air-conditioning or heat pump systems, the PCM-based heat exchanger can provide both heating and cooling, achieving energy savings of up to 67%, which makes it suitable for confined underground environments.

Combining this resource with TES further improves the efficiency and sustainability of the resource. For instance, using TES tanks based on PCMs coupled with a ground source heat pump system maintains cooling water temperature under peak loads better than conventional ground exchangers do. However, while single water-PCMs tanks are limited in their capacity and geometry, the multi-modular water-PCM tank (MMWPT) systems overcome some of these problems due to the possibility of using modules connected in different configurations. Figure 6 illustrates a schematic diagram of a hybrid system integrating Water-Loop Heat Pumps (WLHPs), a Ground Heat Exchanger (GHE), and Modular Water-Phase Change Material Tanks (MWPTs).

A recent study examined the effect of MMWPT configurations on the cooling performance of a GSHP system for underground shelters during emergency conditions, using a validated MATLAB-based model. Results showed that modular configurations improve cooling stability compared to single-tank systems. Series connections extended effective discharge duration (EDD), and higher PCM phase change temperatures further increased EDD while shortening solidification time. Optimal setups were found in 3 × 4 and 3 × 5 matrices using PCMs with phase change temperatures of 19.41 °C and 22.41 °C. Although the system effectively managed intermittent peak loads, performance depended on geological and thermal conditions. Future work should validate the approach across different climates and address

uneven heat distribution by employing cascaded PCMs with varied phase change temperatures [22].

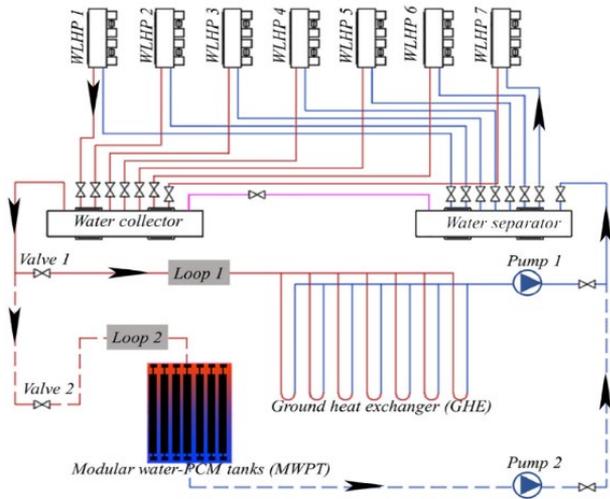


Figure 6. Schematic diagram of the hybrid system [22]

3. DISCUSSION

3.1 Integrating passive and hybrid systems

The reviewed studies reveal a clear trend toward combining passive and hybrid systems. While passive ventilation provides low-cost and resilient air exchange, it lacks precision control under fluctuating environmental or occupancy conditions. In an integrated system context, passive ventilation defines the baseline airflow condition upon which active environmental control strategies are layered. Hybrid systems [7, 9] address these limitations by integrating mechanical assistance with renewable energy sources.

For underground shelters, such dual-mode systems enable coordination with humidity regulation, energy supply strategies, and safety mechanisms discussed in subsequent subsections.

3.2 Importance of humidity and thermal balance

Humidity management emerges as the critical constraint in all underground HVAC applications. Even with stable thermal conditions, discomfort and material degradation occur when RH exceeds 70–80%. Because humidity transport is governed by airflow patterns, moisture control performance is directly dependent on the ventilation strategies described in Section 3.1.

Studies [4, 16, 11] agree that dedicated dehumidification, desiccant materials, or vapor barriers are necessary.

CFD and experimental data demonstrate that air stratification frequently occurs in long tunnels and chambers, leading to localized moisture zones. HVAC design must therefore integrate airflow distribution and humidity sensing into a unified control strategy.

3.3 Optimization and modeling tools

Advanced numerical techniques—CFD and RSM—are now standard tools for underground ventilation design [4, 5]. CFD models enable visualization of air trajectories, velocity fields, and temperature gradients, guiding optimal shaft placement prior to construction. RSM provides statistical correlations

between input variables (shaft size, temperature difference, airflow rate) and outputs (air velocity and air age).

These tools provide the quantitative linkage between airflow generation, humidity control, energy consumption, and safety performance, enabling coordinated system optimization rather than isolated component tuning.

3.4 Energy efficiency and sustainability

Renewable energy coupling through PVT, GSHP [9], and hybrid recovery systems [7] helps achieve both reduced power demand and carbon neutrality. The soil surrounding underground structures offers stable thermal conditions ideal for ground-coupled heat exchange.

Such systems can operate in a “free-cooling” mode during moderate seasons, switching to GSHP during peak thermal loads. Automation and sensor feedback further ensure that energy is used only when necessary, aligning with low-carbon design principles outlined in the study of Li et al. [7].

3.5 Safety and resilience

Refuge and fortification structures prioritize life safety during emergencies. Findings emphasize redundancy—ensuring that if one ventilation system fails, another maintains safe CO₂ and temperature limits. For instance, longitudinal jet systems can supplement passive shafts during overpressure events, while negative-pressure zones prevent the smoke propagation.

These principles are directly applicable to civil-defense shelters, where HVAC must sustain breathable air and temperature limits during extended periods of isolation.

3.5.1 Ventilation fan configurations and airflow management

Ventilation fan design plays a critical role in maintaining air quality and pressure balance in underground shelters and mining-type environments. The choice between axial, centrifugal, and mixed-flow fans depends on operational constraints, space availability, and desired airflow direction. Fan configuration selection must therefore be consistent with the overall airflow strategy, energy system capacity, and safety redundancy requirements of the integrated ventilation system. Most underground facilities position their primary fans in exhaust airways, as this configuration simplifies pressure control and minimizes contamination risks within occupied areas.



Figure 7. A mine axial fan [14]

Three primary fan configurations are typically employed:

1. Axial Fans — These units move air parallel to the fan shaft, allowing direct discharge toward the exhaust side

(Figure 7). They are efficient for large airflow volumes at relatively low pressure.

2. Centrifugal Fans — Air enters the fan center and is expelled radially by centrifugal force through a collecting scroll or volute, generating higher pressure suitable for longer duct systems (Figure 8).



Figure 8. A mine centrifugal fan [14]

3. Mixed-Flow Fans — These combine axial and centrifugal characteristics, delivering intermediate pressure and stable flow. They are useful in compact or multi-branch ventilation systems.

Such configurations ensure redundancy and adaptability in shelter HVAC systems, allowing airflow control during both normal operation and emergency isolation. Integrating mixed-flow or variable-speed fans within hybrid ventilation frameworks enhances safety by maintaining minimum oxygen levels and removing contaminants even under partial power conditions.

3.6 Oxygen generation and consumption considerations

In underground shelters, ventilation design controls airflow and humidity, but ensuring a continuous, sustainable supply of oxygen (O_2) is just as vital for occupant survival during extended periods of isolation. In fully sealed or only intermittently ventilated shelters, the HVAC system must therefore go beyond standard air exchange and incorporate active oxygen supply and CO_2 removal, effectively functioning as an integrated life support system.

Human metabolic oxygen demand has been well established in physiology literature, with resting consumption rates typically between 200- and 350- $mL\ O_2 \cdot min^{-1}$, or approximately 0.5 $kg\ day^{-1}$ per adult [23, 24]. Activity level, body mass, and age influence this value; however, the average range serves as a reliable baseline for emergency shelter design. Prolonged occupancy without adequate air exchange leads to oxygen depletion and CO_2 accumulation, necessitating the use of either stored oxygen systems or on-site generation technologies.

Recent studies in electrochemical energy systems highlight water electrolysis as a viable method for producing breathable oxygen within sealed environments. The overall reaction is well characterized, and the mass ratio of 1.125 $kg\ H_2O$ per 1 $kg\ O_2$ is consistent across electrolysis models [25, 26]. Modern proton-exchange-membrane (PEM) and alkaline electrolyzers achieve system-level efficiencies of 50–55 $kWh\ kg^{-1}\ H_2$, corresponding to approximately 6 $kWh\ kg^{-1}\ O_2$. These figures enable designers to estimate the required water and electrical energy inputs when sizing life-support systems for underground or confined shelters. Incorporating electrolysis into hybrid HVAC systems can therefore ensure breathable air continuity while simultaneously generating hydrogen for

auxiliary power or heat recovery.

The integration of oxygen generation within HVAC design complements passive and hybrid ventilation approaches by providing redundancy during periods of external air isolation. Electrolytic O_2 production, coupled with automated CO_2 scrubbing and humidity control, forms a closed-loop environmental management system suitable for civil-defense or long-duration refuge applications [27, 28]. As renewable-powered electrolyzers become more efficient, their application in underground environments presents a promising pathway toward energy-autonomous and low-carbon life-support infrastructure.

If no ventilation from outside air can be provided, the air within the space must be treated to maintain a breathable atmosphere. This can be achieved using a series of processes and technologies known as air revitalization, similar to those used in spacecraft, which include the removal of carbon dioxide and trace contaminants, as well as the provision of oxygen [29].

To reduce CO_2 there are several methods. Levels were controlled using lithium hydroxide (LiOH), which happens via the following chemical reaction:



While this method is effective in removing CO_2 , it has a significant limitation since it can't be reused. This method was used in space for only 2 weeks, but as longer durations were required, regenerative systems were proposed. Zeolites, aluminum silicate-based materials, were utilized to absorb. Zeolites can be regenerated via a two-stage process, which increases the temperature released from the zeolite, and connecting it to a vacuum facilitates the transfer of CO_2 out of the space. In the space, connecting it to the space vacuum was an option, but for underground space, a vacuum pump will be needed. This system was further enhanced to reduce humidity by incorporating a regenerable desiccant system to capture water vapor before venting.

Amine chemistry is another regenerative method used for both CO_2 and H_2O removal and can be regenerated using heating or vacuum. Table 3 provides a summary of control options.

There are methods used to reduce CO_2 and recycle O_2 for breathable air; some of these methods are Sabatier, Sabatier with additional methane processing, Bosch, and co-electrolysis.

The Sabatier process passes CO_2 over a heated catalyst in the presence of hydrogen. However, this system recovers only half the oxygen from CO_2 , so it's a partially closed loop.

The Bosch process uses hydrogen in the presence of high temperatures and a catalyst to fully reduce:

This process can lead to the complete recovery of O_2 from CO_2 through water electrolysis.

Co-electrolysis is the electrolysis of CO_2 in the presence of steam. This process recovers a larger amount of O_2 in CO_2 compared to the Sabatier process. Figure 9 shows the 3 systems in order of higher loop closure.

Oxygen can be supplied from high-pressure tanks or cryogenic storage, but for a regenerative (closed loop) life support system, the Oxygen Generation Assembly (OGA) is employed. The OGA produces oxygen by electrolyzing water, providing oxygen for breathing and hydrogen for the Sabatier process. The water produced in the Sabatier process is recovered and recycled back to the electrolysis unit; however, because some hydrogen is lost as methane, water makeup is required.

Table 3. CO₂ control options [29]

Mission Duration	Hours	< 10 Days	10–30 Days	>6 Months	>2 Years
Critical attributes	Simple, reliable	Small, simple, and reliable	Very small or reusable, reliable	Recover CO ₂ for loop closure, extremely reliable	Control CO ₂ to low levels, reliable and repairable, recover CO ₂ for loop closure
Method of operation	Irreversible, single use, chemical reaction	Irreversible, single use, chemical reaction	Reversibly adsorb at cabin pressure, vent to vacuum	Reversibly adsorb at ambient temperature, regenerate at 200 °C	TBD
Biggest problems	Single use, non-regenerable, caustic material that is prone to dusting	Requires crew change-out and substantial space in crew cabin area	Mechanically more complex, no CO ₂ recycling with mixed CO ₂ and H ₂ O venting	Requires power for thermal regeneration, prone to dusting	TBD
System name	LIOH	LIOH	Solid amine	Four-bed molecular sieve	TBD
Flight system	EMU portable life support system	Apollo and Shuttle	Shuttle and Orion	International Space Station	Exploration

Activated carbon is used to remove trace contaminants such as VOCs, and it is typically paired with acid-treated carbon for ammonia removal. A catalytic oxidizer can be used to remove CO. In closed environments, particulate matter such as dust, fibers, and microbes can be removed using high-efficiency filters, typically HEPA filters [29].

The optimized design placed three ventilation shafts at 54.76 m, 51.45 m, and 79.85 m along the tunnel, achieving:

- Average air velocity: 0.222 m/s
- Indoor temperature: 26 °C
- Relative humidity: 85.5%
- Average air age: 10.57 s

This case demonstrates how passive ventilation can be engineered for a real underground civil defense shelter, using CFD simulation and RSM to optimize shaft location and airflow performance.

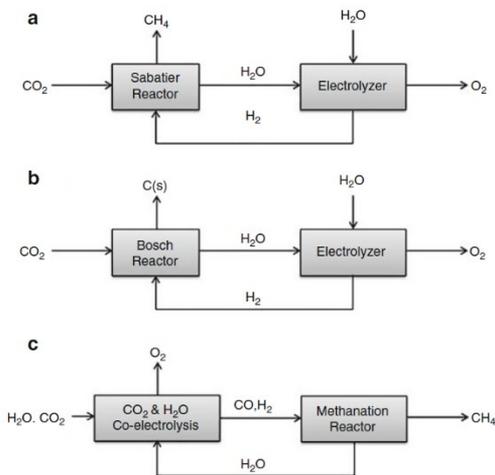


Figure 9. CO₂ reduction technologies in order of higher loop closure: Sabatier (a), Bosch (b), and co-electrolysis (c) [29]

4. ENGINEERING CASE STUDIES OF UNDERGROUND SHELTERS WITH IMPLEMENTED HVAC DESIGNS

A tunnel-type civil defense shelter is located at Yunlong Mountain, Xuzhou [11].

The Yunlong Mountain civil defense project in Xuzhou, China, is a tunnel-type underground shelter designed for wartime protection and peacetime public use. The shelter is approximately 180 m long, 72 m wide, and 3.6 m high, with a surrounding rock cover of approximately 40 m. It experiences poor natural ventilation and high humidity in summer.

To improve indoor air quality and thermal comfort, a passive ventilation system using vertical shafts was designed and optimized using CFD and Response Surface Methodology (RSM). The study evaluated single-shaft vs. multi-shaft configurations under positive and negative pressure and found that a multi-shaft negative-pressure system performed best.

5. TECHNICAL LIMITATIONS IN EXISTING RESEARCH

The sources identify several critical limitations in current methodologies and systems for underground environmental control.

5.1 Simulation and modeling tools

o Standard commercial software (such as CONTAMW or TAS EDSL) is primarily designed for above-ground structures and often fails to account for the unique heat exchange properties of soil without significant "workarounds," such as using extremely thick virtual walls [6, 30].

o While CFD modeling provides high accuracy, it is extremely time-consuming and computationally expensive, making it difficult to use for long-term (annual) dynamic simulations [6, 30].

5.2 Architectural factors

o Much of the existing research focused on thermal insulation while largely ignoring architectural layouts, such as length-to-width proportions and building orientation, which significantly impact annual thermal comfort.

o Standard "static" thermal comfort models (like Fanger's PMV) are often inaccurate underground; occupants frequently report feeling colder than predicted by these models [10].

5.3 Passive ventilation effectiveness

o Natural ventilation is insufficient for deep tunnel-type spaces, where air flow is too weak to form effective paths

[11].

o In humid regions, natural ventilation during summer can actually worsen the indoor environment by introducing moisture-laden air that leads to severe condensation on cool underground surfaces [6].

5.4 Deep underground challenges

o Standard pressurized air systems are only suitable for shallow layers; deep underground environments require supplemental joint temperature control, such as ice storage or Phase Change Materials (PCM) [5].

o In auxiliary systems, flexible ducts often experience significant air leakage, and selecting small duct diameters results in a substantial, non-linear increase in fan power consumption [31].

5.5 Occupant-specific dynamics

Current optimization models for narrow sleeping spaces often overlook air-borne infection risks (droplets/aerosols) and do not account for the optimal size and location of outlets in multi-occupant scenarios [12].

6. CONCLUSIONS

This literature review provides a comprehensive overview of current research trends and design strategies for HVAC systems in underground shelters. Key conclusions include:

1. Passive ventilation—When designed using CFD and RSM optimization, passive shafts and buoyancy-driven systems can sustain adequate air exchange with minimal energy demand.

2. Hybrid HVAC systems—Integrating renewable technologies such as PVT systems and GSHP can achieve energy savings of up to 23%. These solutions also enhance thermal stability, making them well-suited for self-sustaining shelters.

3. Thermal comfort and humidity control—Stable underground temperatures are advantageous, but high humidity remains a critical challenge requiring mechanical or material-based dehumidification.

4. Energy and environmental performance—Hybrid low-carbon systems supported by intelligent controls can drastically reduce emissions and operational costs.

5. Safety and resilience—Redundant ventilation pathways and smart monitoring systems are essential for emergency operation and long-term reliability.

6. Research gaps—Future investigations should focus on long-term humidity regulation, field validation of hybrid configurations, life-cycle energy analyses, and integration of real-time control technologies.

The following guide provides specific design parameters for underground shelter environments

1. Ventilation Strategy

• Airflow Pattern: In narrow sleeping or living quarters, utilize an "Up-supply and Down-return" pattern. This avoids draft sensation in sleeping areas while maintaining air quality.

• Pressure Management: For long tunnels or hallways, negative pressure ventilation using multiple shafts acts as a

"relay" and is more efficient than positive pressure systems at maintaining air freshness.

• Winter Conservation: In cold climates, reduce ventilation rates to less than 0.1 air changes per hour (ach) during winter to prevent rapid heat loss and protect equipment.

2. Passive and Hybrid Cooling

• Geothermal Pre-cooling: Route intake air through an underground pipe gallery (at least 23 m long) before it enters the shelter. The soil can pre-cool summer air by as much as 13.1 °C.

• Evaporative Cooling: In hot, dry regions, utilize on-site built evaporative cooling units. These systems can drop indoor temperatures by up to 12 °C during peak summer hours.

• Thermal Storage (PCM): For emergency modes (e.g., power failure), integrate MMWPTs. These can provide a minimum of 6 hours of passive cooling by absorbing excess heat.

3. Moisture and Radon Control

• Vapor Barriers: Install vapor retarders directly under concrete slabs and seal all exterior joints to prevent groundwater moisture and radon gas from infiltrating the space.

• Dehumidification: since underground surfaces are naturally cool, specialized dehumidification equipment is mandatory in summer to prevent relative humidity from exceeding the 60–70% threshold, which triggers mold growth.

Designing an underground shelter is like building a giant earthen thermos. The soil provides excellent insulation (thermal mass), but without a "straw" (a properly organized ventilation path), the air inside becomes stale and damp. If the straw is used to suck in hot, humid air in the summer, the indoor environment will quickly lose its cool. The secret to a perfect thermos is a controlled, pre-cooled intake and an airtight seal against the surrounding ground moisture.

7. NOVELTY

This review offers a distinctive, quantitative, and system-level synthesis of HVAC strategies for underground shelters, moving beyond descriptive summaries to provide actionable, data-driven insights and integrated design frameworks. Its novel contributions are:

• Integrated Multi-System Framework with Performance Metrics: This work synthesizes disparate research into a quantifiable, tiered design framework. It demonstrates how integrating passive shafts (optimized with CFD/RSM to improve air velocity by up to 18%) with hybrid photovoltaic/thermal collectors and ground-source heat pump (PVT-GSHP) systems (reducing HVAC energy use by ~23%) can meet baseline needs. Crucially, it layers this with mechanical dehumidification for humidity greater than 80% RH and emergency life-support (e.g., electrolysis at ~6 kWh/kg O₂) to create a resilient, multi-mode system for normal and extended isolation scenarios.

• Climate-Adaptive Design with Quantitative Thresholds: The review provides a climate-adaptive, quantitative analysis of passive ventilation performance, applying real-world climatic data to assess system effectiveness. It highlights that while shaft ventilation can maintain adequate air exchange (e.g., 0.1–0.3 m/s) in temperature differentials >5 °C, it fails in hot-humid climates where ambient RH exceeds 70%, directly linking external dew point to the necessity for mechanical or desiccant

dehumidification. This provides clear, numerical thresholds for technology selection based on location.

- **Resilience and Emergency Life-Support Synthesis:** A novel synthesis of refuge chamber, mining, and aerospace ECLS data is presented. It quantifies safety margins by recommending redundant ventilation—such as combining axial and centrifugal fans—to maintain CO₂ concentrations below 1000 ppm. The analysis also evaluates regenerative CO₂ removal methods (e.g., Sabatier and Bosch processes) in conjunction with Oxygen Generation Assemblies (OGAs) for closed-loop operation. By comparing the oxygen recovery efficiency of co-electrolysis (~75–85%) to that of the Sabatier process (~50%), the review offers a technical foundation for selecting life-support systems in long-duration confinement.

- **Advanced Optimization and Control Strategy Transfer:** The paper details the cross-disciplinary application of advanced tools, showing how CFD-GA optimization can reduce Predicted Percentage of Dissatisfied (PPD) to <10% while minimizing energy, and how RSM can model the non-linear interaction between shaft diameter, spacing, and airflow rate. It further explores the transfer of adaptive decoupling controllers (e.g., RBF neural networks) from industrial processes to manage the tightly coupled temperature-humidity dynamics in underground spaces.

- **Quantification of the Humidity-Energy Trade-off:** A key novel insight is the detailed analysis of the humidity challenge. The review consolidates data showing that earth-sheltered structures often maintain stable temperatures (21–27 °C) but suffer from persistent RH >70%, which not only causes discomfort but also increases latent loads. It quantifies the consequent dehumidification demand (e.g., ~45 kg/h for a 1500 m² facility), framing it as a primary driver of shelter HVAC energy consumption and a critical design focus.

- **Identification of Underexplored, Data-Rich Gaps:** By intersecting building science, geotechnics, and energy engineering, the review pinpoints specific, quantifiable research gaps:

- o **Transient Heat-Moisture Coupling:** The need for validated models of simultaneous heat and moisture (HAM) transfer in heterogeneous soils over diurnal and seasonal cycles.

- o **Scalable Emergency Thermal Storage:** Optimizing Modular Water-PCM Tank (MWPT) configurations (e.g., 3 × 4 matrix with PCM phase change at 19.41 °C) to extend EDD for emergency cooling during power loss.

- o **System-Level Integration and Control:** Field validation of smart hybrid systems using real-time sensors (CO₂, RH) with variable-speed drives to achieve energy savings of 30–50% while maintaining safety limits.

In summary, the novelty of this work lies in its quantitative, integrative approach. It transforms scattered research into a coherent design manual with performance benchmarks, climatic thresholds, and system interdependencies, specifically tailored to optimize the energy efficiency, occupant safety, and long-term resilience of underground shelter environments.

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NOMENCLATURE

OGA	Oxygen Generation Assembly
PEM	proton-exchange membrane (electrolyzer type)
LiOH	lithium hydroxide (CO ₂ scrubber)
VOCs	volatile organic compounds
MET	Metabolic Equivalent of Task (physiological unit)
PET	Physiologically Equivalent Temperature (thermal comfort index)
RH	relative humidity
EED	effective discharge duration (PCM system performance metric)
FEM	finite element method (numerical modeling)
EFG	element-free Galerkin (numerical modeling)
ITPE	integrated thermal performance evaluation (simplified modeling method)
Mitalas's method	simplified heat transfer estimation method
Kararti and Choi method	simplified heat transfer estimation method
Wang et al. Method	simplified heat transfer estimation method
BAT	Bat Algorithm (optimization technique)
GSHP	ground source heat pump
PID	Proportional-Integral-Derivative (control system)
RBF	Radial Basis Function (neural network)
H10	Filtration standard (high-efficiency filter)
HEPA	High-Efficiency Particulate Air (filtration standard)
Sabatier	chemical process for CO ₂ reduction
Bosch	chemical process for CO ₂ reduction
co-electrolysis	electrochemical process for CO ₂ reduction