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An efficient and sustainable approach for cooling underground substations

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ABSTRACT

With rapid rates of urbanisation and significant improvements in construction technologies, the number of subsurface infrastructure projects has drastically increased in recent years. In addition to their primary functions, these structures have shown great potential as energy geo-structures, exchanging heat with the ground to heat and cool spaces. Given their large contact area with the ground, energy tunnels are proving to be a sustainable source of thermal energy for effectively heating under- and above-ground spaces. However, their efficiency in cooling-dominated conditions has not yet been adequately studied. This paper tackles one of the key challenges regarding transport tunnels: sustainable cooling of underground substations, by introducing an efficient and cost-effective cooling method. The method takes advantage of airflow in the tunnels and relatively stable ground temperatures and involves heat exchangers in the form of water-filled high-density polyethylene (HDPE) pipes being integrated into the tunnel space. The efficiency of the proposed system is numerically assessed by analysing the spatio-temporal variations of temperature in the ground, substation, tunnel air, tunnel structure and heat exchangers caused by continuous heat rejection from the substations. A detailed 3D finite element heat and mass transport model is used, and alternative placements of heat exchangers are investigated. Results show that heat exchangers placed on the tunnel lining, and hence exposed to the tunnel airflow, could efficiently supply a substation's cooling demand, without significantly increasing the temperature of the tunnel air or the ground. The substantial economic benefits of this cooling system compared to a conventional cooling system is also demonstrated.

1. Introduction

Increased use of underground space and energy resources in combination with the pursuit of renewable sources of energy has resulted in the newly established concept of energy geo-structures, gaining significant attention in recent years. Any structures that are in contact with the ground, such as piles, retaining walls and tunnels, can be converted with relative ease and affordability into energy geo-structures, by incorporating heat exchange elements (Makasis et al., 2020, Barla et al., 2019, Cousin et al., 2018, Batini et al., 2015, Adam and Markiewicz, 2009, Brandl, 2006, Bidarmaghz et al., 2017, Makasis et al., 2018). Then, in addition to their primary functions, these geo-structures act as heat exchangers, transferring heat between the ground and under- or above-ground spaces, for heating and cooling purposes.

Along with various other types of energy geo-structures, transport tunnels have demonstrated great potential as sustainable heat sources for heating under- and above-ground spaces, due to the large area in contact with the ground (Bidarmaghz and Narsilio, 2018, Bidarmaghz et al., 2017, Buhmann et al., 2016, Epting et al., 2020). Geothermal energy in the ground, as well as heat generated in the tunnels and platforms by vehicles (e.g. engines and braking) and passengers, can be harvested via heat exchangers incorporated into the tunnel structures (Barla et al., 2016, Bidarmaghz and Narsilio, 2018) and transferred elsewhere. Even though the efficiency of energy tunnels in the long-term heating of under- and above-ground spaces has been demonstrated in recent research (Laloui and Di Donna, 2013, Laloui and Loria, 2019, Buhmann et al., 2016), their thermal performance in cooling-dominated conditions seems not to reach the same level of efficiency. This is attributed to the consequent temperature increases in the ground and the tunnel air due to heat rejection from the cooling processes and the heat generated by train and tunnel operation (Bidarmaghz et al., 2019, Bidarmaghz et al., 2020). Cousin et al. (2019) investigated the energy

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performance and economic feasibility of energy tunnels using a 3D thermo-hydraulic finite element analyses of a real case study. However, in that work, energy segmental lining for cooling purposes was not considered due to the high temperature levels during the cooling season. In another study, Insana and Barla (2020) assessed the energy performance of a thermo-active tunnel lining via numerical analysis and experimental data obtained from a full-scale energy tunnel prototype in Turin, Italy. Intermittent heating and cooling cycles, lasting approximately two to 13 days, simulated winter and summer conditions. Similar studies on the thermal performance of energy tunnels in heating-only or heating–cooling conditions are available in the literature (Tinti et al., 2017, Nicholson et al., 2014). Even though Akrouch et al. (2013) have reported the overall inefficiency of energy geo-structures in cooling-dominated conditions, the efficiency of energy tunnels in such conditions and the feasibility of tunnel utilisation in cooling under- or above-ground spaces has not yet been widely investigated.

Therefore, efficient and sustainable cooling systems remain one of the main challenges for road and rail tunnels and the associated underground spaces, with substantial economic, social and environmental implications. For example, the report by Ampofo et al. (2004) recorded temperatures of more than 37 °C within the London Underground network when the ambient surface temperature was approximately 30 °C in summer. Cockram and Birnie (1976) showed a 4–5 °C temperature increase in the ground surrounding the Victoria Line in London, less than ten years after it opened.

For deep underground tunnel substations that do not have easy or substantial access to the surface due to highly urbanised environments or other constraints, traditional chillers with cooling tower systems are not an option. Moreover, conventional direct expansion (DX) air-conditioning units are frequently integrated into transport tunnels despite their high economic cost. Therefore, innovative solutions for cooling tunnels have been introduced in recent studies, as reviewed by Mortada (2019). For example, in the system proposed by Thompson et al. (2006), groundwater was pumped through ground heat exchangers in the tunnel to cool the tunnel air, and fans circulated the cooled air to the station platform. However, the environmental implications of increased groundwater temperatures hindered the wide applicability of this solution. In another trial study, regenerative braking systems were introduced to the New York Subway trains to reduce the amount of heat being released, with some of the heat released by the brakes being captured and fed as electrical energy into the grid (Gilbey et al., 2011, Jaffe, 2012). However, these systems resulted in a negligible reduction in tunnel and platform temperatures.

In general, most transport tunnels are longitudinally ventilated in normal traffic operation. In such conditions, at traffic speeds above 60 km/h, vehicle movement drives the air through the tunnel, fulfilling air quality requirements. Note that jet fans operate to complement the vehicle movement in drawing fresh air into the tunnel when traffic is slow or stopped or in the extreme case of fire and smoke in the tunnel (Ridley, 2019). The tunnel's ventilation system - primarily responsible for the air quality and temperature of the tunnel and platform - receives its power supply from underground substations, which are specified rooms containing various essential electrical equipment (e.g., transformers). The operation of other utilities such as lighting and sump pumps, are also served by facilities located in these rooms. Underground substations require an efficient cooling system to maintain temperatures within the operational range for the equipment. Despite some preliminary research into increasing the efficiency of substations' cooling systems (Feng et al., 2012, Longardner and Visnesky Jr, 2005), DX units are currently the most common cooling method utilised in these spaces. However, the economic and environmental costs of these systems due to their significant power consumption and CO_2 emissions (depending on the nature of the electricity source) hinders the efficient utilisation of DX units in underground substation cooling.

This paper addresses a crucial gap in the literature by introducing a novel approach for cooling tunnel substations using heat exchangers integrated into a tunnel's structure. Even though the concept of using energy tunnels for heating spaces follows a similar methodology, the potential of energy tunnels for cooling underground spaces has not yet been adequately investigated. This lack of research is mostly attributed to the computational complexity of modelling the thermodynamics of airflow in ventilated tunnels coupled with heat transport in the ground, and tunnel structure and heat and mass transport in the heat exchangers – which is tackled in this study. The lack of research can also be attributed to the cost associated with full-scale trials. The typical approach in energy tunnel modelling is to assume (i) a constant temperature at the lining-air boundary (i.e., the tunnel lining), and (ii) that the convective heat transfer coefficient is representative of the airflow in tunnels. As such, the temperature variability of tunnel air, and hence the efficiency of the cooling systems, are not captured. While these simplified assumptions are not critical where energy tunnels are being used for heating purposes, they have resulted in thermal inefficiency in energy tunnels utilised for cooling, as the capacity of tunnel air as a long-term heat sink has been neglected.

Therefore, the main novelty of this work lies in the conceptualisation and detailed modelling of an alternative method – the application of energy tunnels for cooling-only conditions – to continuously remove heat from deep underground substations. The substantial economic benefit of the proposed system compared to a conventional cooling system is demonstrated herein.

High temperatures in the underground substations, and hence the significant cooling demand of these spaces, require the tunnel air and surrounding ground to act as long-term heat sinks. Heat from the substations is exchanged with large volumes of tunnel air and the ground, using heat exchangers coupled with heat pumps. This approach is expected to (i) increase the cooling efficiency in the substations, with substantial savings in power consumption, and (ii) lead to a lower concentration of hot air in the tunnel compared to when using DX units to cool the substations, therefore reducing the impact on the tunnel's air temperature, and hence the tunnel's ventilation system.

Fig. 1 presents a schematic of the proposed system, depicting the tunnel, the substation (accommodating the heat pump) and the absorber pipes integrated into the tunnel structure. The absorber pipes and the carrier fluid circulating within them are referred to as heat exchangers in this study. The heat pump located in the substation transfers the heat from the substation to the heat exchangers, to be released to the tunnel air and the ground. With the large longitudinal scale of the heat exchangers, this system aims to effectively cool the substation without a substantial temperature increase in the tunnel or the ground. To fulfil this aim, it is crucial to investigate the heat exchange mechanism between the ground, the tunnel and the heat exchangers in the long term. To achieve this, heat and mass transport in the ground, tunnel structure, tunnel air and heat exchangers are modelled by coupling and solving energy, momentum and continuity equations within the COMSOL Multiphysics finite element package. A 250 m long section of the tunnel and the ground is modelled and six 200 m long U-loop heat exchangers are integrated into the tunnel structure to fulfil 45 kW of the substation's constant cooling demand. Only three U-loops are shown in Fig. 1. Note that only three of the six HDPE U-loop heat exchangers are displayed in this figure, exploiting the symmetry along the tunnel axis. The heat pump is not explicitly modelled in this work. The cooling load, however, is applied at the inlet pipe (entering the tunnel), for which the carrier fluid temperature is adjusted based on the outlet temperature and the given thermal load. Tunnel ventilation is modelled, accounting for typical airflow velocity in transport tunnels (as a result of vehicle movement in normal traffic conditions), while the substation's cooling demand is represented by a thermal load implemented at the heat exchanger's inlet. The efficiency of this system is studied herein by investigating the long-term temperature change in the ground, the tunnel air and the carrier fluid within the heat exchangers as a response to the substation's cooling process.

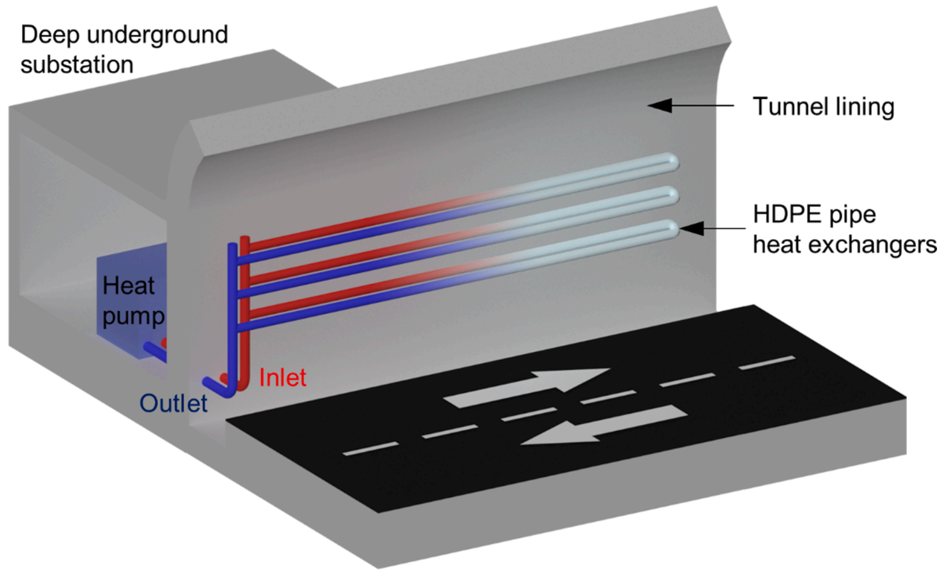

Fig. 1. Schematic concept design for cooling substations.

2. Underground substation cooling system

A new methodology for cooling underground substations is presented in this section, in which the heat generated in the substations is gradually dissipated within a relatively long length of the tunnel via water-filled HDPE pipe heat exchangers. This approach enables a large volume of the tunnel air and the ground to act as long-term heat sinks, considering the positive impact of the tunnel airflow on the dissiption of heat.

To test the feasibility of the proposed method, a 3D finite element model was built and solved to numerically model heat and mass transport in the ground, the tunnel and the heat exchangers. Note that the numerical methodology, governing equations and coupling techniques for energy tunnels and energy retaining wall simulations have been tested and validated against full-scale field data in the works of Makasis et al. (2020) and Bidarmaghz et al. (2017). Even though the 3D finite element model used in this study has not been validated against measured data, the previous studies provide confidence in its use.

2.1. Numerical model: Governing equations and key assumptions

The governing equations that define the system regard heat transfer in fluid and solid media, turbulent fluid flow through the pipes and turbulent fluid (air) flow in the tunnel. The heat transfer modes consist of: (i) conduction, mainly in the solid elements such as the ground, pipe walls and concrete, and partially in the circulating carrier fluid and air, and (ii) convection, primarily in the circulating carrier fluid and the flowing air. The flow in the pipes is considered to be fully developed, and therefore 1D elements are used for the pipes, coupled to the 3D heat transfer in the remaining domains. To model the 1D fluid flow, the continuity and momentum equations for an incompressible fluid are used, as seen in Eqs. (1) and (2) (Barnard et al., 1966). The energy equation for the convective-conductive heat transfer in the carrier fluid flow can be seen in Eqs. (3) and (4) (Lurie, 2008). The convective-conductive heat transfer between the pipes and the surrounding elements (pipe walls, concrete elements, ground, tunnel air) is modelled by Eq. (5), in which the second term is only applicable for the air flowing through the tunnel. The equations are numerically solved for the pressure, the velocity field and the temperature field. Utilising these equations, the heat transfer occurring throughout the 3D elements and 1D pipe elements and the fluid flow in the 1D pipe elements are coupled using the temperature of the pipe wall, $T_{m,pipewall}$:

$$\nabla(A\rho_w\mathbf{v}) = 0 \tag{1}$$

$$\rho_w\left(\frac{\partial\mathbf{v}}{\partial t}\right) = -\nabla p - f_D\frac{\rho_w}{2d_h}|\mathbf{v}|\mathbf{v} \tag{2}$$

$$\rho_w AC_{p,w}\frac{\partial T}{\partial t} + \rho_w AC_{p,w}\mathbf{v}\nabla T = \nabla(A\lambda_w\nabla T) + f_D\frac{\rho_w A}{2d_h}|\mathbf{v}|\mathbf{v}^2 + Q_{wall} \tag{3}$$

$$Q_{wall} = f\left(T_{m,pipewall}, T\right) \tag{4}$$

$$\rho_m C_{p,m}\frac{\partial T_m}{\partial t} + \rho_m C_{p,m}\mathbf{u_a}\cdot\nabla\mathrm{T_m} = \nabla.(\lambda_m\nabla T_m) \tag{5}$$

where A is the inner cross-section of the HDPE pipe $[m^2]$, ρ_w is the density of the carrier fluid $[kg/m^3]$, $\mathbf{v}$ is the fluid velocity field within the pipes $[m/s]$, t is time $[s]$, p is pressure $[Pa]$, f_D represents the Darcy friction factor [-], d_h is the hydraulic diameter of the pipe $[m]$, $C_{p,w}$ is the specific heat capacity of the fluid $[J/kgK]$, λ_w is the thermal conductivity of the fluid $[W/mK]$, Q_{wall} is the external heat exchange rate through the pipe wall $[W/m]$ and a function of the temperature of the pipe outer wall, $T_{m,pipewall}$ $[K]$, and the temperature of the carrier fluid, T $[K]$, ρ_m is the material density $[kg/m^3]$,$C_{p,m}$ is the specific heat capacity of a material $[J/kgK]$, $\mathbf{u_a}$ is the velocity field relating to the material (in this case for the air in the tunnels) and λ_m is the thermal conductivity of a material $[W/mK]$. Groundwater flow is not incorporated in the presented work; however, details of how this can be included, by incorporating Darcy's law, which in general can improve the GSHP system performance, are presented by Bidarmaghz et al. (2017).

The air flowing through the tunnel is modelled as a single-phase compressible flow (Wilcox, 1998). The Reynolds-averaged Navier-Stokes (RANS) equations are implemented for conservation of momentum, as well as the continuity equation for conservation of mass, as seen in Eqs. (6) and (7), respectively. Eqs. (8) and (9) present the transport equations for the turbulent kinetic energy, k, and the turbulent dissipation rate, ϵ, respectively. Lastly, Eqs. (10) and (11) further define factors of the previous equations. These equations are coupled with the heat transfer using the air velocity field, $\mathbf{u_a}$, and Eq. (5).

$$\rho_a\left(\frac{\partial \mathbf{u_a}}{\partial t}\right) + \rho_a(\mathbf{u_a}\cdot\nabla)\mathbf{u_a} = \nabla\cdot\left[-p_a I + (\mu+\mu_T)\left(\nabla\mathbf{u_a} + (\nabla\mathbf{u_a})^T\right) - \frac{2}{3}(\mu + \mu_T)(\nabla\cdot\mathbf{u_a})I - \frac{2}{3}\rho_a k \mathrm{I}\right] + F \tag{6}$$

$$\frac{\partial \rho_a}{\partial t} + \nabla\cdot(\rho_a \mathbf{u_a}) = 0 \tag{7}$$

$$\rho\frac{\partial k}{\partial t} + \rho(\mathbf{u_a}\cdot\nabla)\mathrm{k} = \nabla\cdot\left[\left(\mu + \frac{\mu_T}{\sigma_k}\right)\nabla_k\right] + P_k - \rho_a \epsilon \tag{8}$$

$$\rho_a\frac{\partial \epsilon}{\partial t} + \rho_a(\mathbf{u_a}\cdot\nabla)\epsilon = \nabla\cdot\left[\left(\mu + \frac{\mu_T}{\sigma_\epsilon}\right)\nabla_\epsilon\right] + \frac{C_{\epsilon 1}\epsilon}{k}P_k - \frac{C_{\epsilon 2}\rho_a \epsilon^2}{k} \tag{9}$$

$$\mu_T = \frac{\rho_a C_\mu k^2}{\epsilon} \tag{10}$$

$$P_k = \mu_T\left[\nabla\mathbf{u_a} : \left(\nabla\mathbf{u_a} + (\nabla\mathbf{u_a})^T\right) - \frac{2}{3}(\nabla\cdot\mathbf{u_a})^2\right] - \frac{2}{3}\rho_a k \nabla\cdot\mathbf{u_a} \tag{11}$$

where ρ_a is the density of air $[kg/m^3]$, $\mathbf{u_a}$ is the velocity vector for the air $[m/s]$, p_a is the air pressure $[Pa]$, I is the identity matrix [-], μ is the dynamic viscosity of air $[Pa.s]$, μ_T is the eddy or turbulent viscosity $[m^2/s]$, k is the turbulent kinetic energy $[m^2/s^2]$, F is the volume force vector $[N/m^3]$, ϵ is the turbulent dissipation rate $[m^2/s^3]$ and the empirically calculated coefficients σ_k, σ_ϵ, $C_{\epsilon 1}$, $C_{\epsilon 2}$ and C_μ have values of: 1, 1.3, 1.44, 1.92 and 0.09, respectively (as per (Wilcox, 1998)).

2.2. Numerical model: Geometry, material properties and boundary conditions

This study utilises numerical modelling of a representative 250 m long tunnel section to demonstrate the feasibility of incorporating heat exchangers for removing heat from underground substations. A schematic of the modelled tunnel geometry and the incorporated pipes is shown in Fig. 1. In the numerical model, typical dimensions for a multi-lane vehicular tunnel are adopted, and the conditions and material properties used are representative of Sydney, Australia. The values used for the material properties are summarised in Table 1, noting that when modelling the water and air, the values are temperature-dependent, utilising empirical distributions incorporated in the material library for COMSOL Multiphysics. A constant 45 kW cooling capacity is representative of such substations.

Fig. 2 summarises the geometry and initial boundary conditions of the model. The symmetry heat transfer boundary condition is applied on both ends of the tunnel along the XZ plane, simulating the case where multiple heat exchangers (HDPE U-loops) would be placed along the tunnel. Symmetry is also placed on the YZ plane, allowing only half the tunnel to be modelled since the other half is identical in configuration. There are a total of six U-loops in the proposed system; however, due to symmetry, it is only necessary for half of these to be modelled. Thermal insulation, has been applied to the ground surface (top XY surface), assuming the tunnel is located underneath densely constructed urban area. For the remaining surfaces within the model, a constant temperature equal to the farfield value, 20.1 °C (Geodata Koda Australia, 2019), has been prescribed. A constant air velocity value of 0.5 m/s (minimum air velocity in transport tunnels induced by vehicle movements) and the transient air temperature distribution (Gilbey et al., 2011) presented as an inset in Fig. 2 are set at the tunnel portal (entry XZ surface to the tunnel) to represent the airflow into the tunnel. The outflow/outlet (open boundary) condition is set at the exit surface. The constant airflow velocity at the tunnel portal resembles the normal traffic operation in the tunnel, in which vehicle movement draws fresh air through the tunnel (natural ventilation). Jet fans are not explicitly modelled in this study as their operation is limited to extreme conditions such as emergency fire and high concentration of smoke in the tunnel (Ridley, 2019).

A zero-airflow velocity and undisturbed ground temperature (farfield temperature) are incorporated into the model as initial values (prior to operation of the system). The heat exchangers are modelled using HDPE pipes of 32 mm outside diameter (25.6 mm inner diameter), carrying fluid at a velocity of 0.5 m/s (fully turbulent flow) to transfer the 45 kW total cooling load (constant load shared equally between the six loops) from the substation to the tunnel area and the ground. The pipe loops are connected to the heat pump, which is located in the substation (shown in Fig. 1).

In this study, three different placements of pipe heat exchangers in the tunnel are proposed, as presented in Fig. 3. The heat exchangers are placed: (i) on the tunnel lining (Case 1), (ii) inside the tunnel lining (Case 2), and (iii) in the ground adjacent to the tunnel (Case 3). These distinct cases enable different media and thus heat transfer modes (conduction or convection) to have more or less prominent roles in the heat transfer process, which leads to different thermal performance and efficiency for each case. Three U-loops (six pipe legs in total) connected in parallel are used on each side of the tunnel with a vertical spacing of 0.5 m in all cases, and the loops are placed mid-height of the tunnel lining.

Table 1
Material properties.

Parameter	Value (s)	Unit	Description
λ_{ground}	2.2	W/(mK)	Thermal conductivity of ground
ρ_{ground}	2000	kg/m^3	Density of ground
$C_{p\ ground}$	850	J/(kgK)	Specific heat capacity of ground
$\lambda_{concrete}$	2.1	W/(mK)	Thermal conductivity of concrete
$\rho_{concrete}$	2200	kg/m^3	Density of concrete
$C_{p\ concrete}$	900	J/(kgK)	Specific heat capacity of concrete
λ_{water}	0.58*	W/(mK)	Thermal conductivity of water
ρ_{water}	998*	kg/m^3	Density of water
$C_{p\ water}$	4186*	J/(kgK)	Specific heat capacity of water
λ_{airr}	0.026*	W/(mK)	Thermal conductivity of air
ρ_{air}	1.225*	kg/m^3	Density of air
$C_{p\ air}$	1005*	J/(kgK)	Specific heat capacity of air

* The material properties of water and air are implemented using the material libraries of COMSOL Multiphysics, which use temperature-dependent distributions to obtain the values. The values shown here are representative.

3. Results and discussions

This work presents a novel methodology to improve the efficiency of underground substations' cooling systems and to overcome the environmental and economic implications of conventional air-conditioning systems (DX units) currently being utilised in these spaces. As illustrated in Fig. 3, three different heat exchanger placements are considered in this study (Cases 1, 2 and 3). The efficiency of each case is assessed by quantifying the temperature variations in the surrounding ground, tunnel air, tunnel structure and carrier fluid circulating within the heat exchangers, resulting from the heat removed from the substations.

3.1. Investigating the cooling system efficiency

To ensure the efficiency of these systems, the temperature increase is investigated since this must be within acceptable ranges for each of the various media in the system (e.g., fluid, soil, tunnel structure, air).

3.1.1. Heat exchangers

Fig. 4 presents the resulting transient fluid temperature at the inlets and outlets of the pipes for different heat exchanger placements (Cases 1, 2 and 3). Even though the temperature difference between the inlets and the outlets at the end of 20 years is similar for the three cases (~7°C), the heat exchangers placed on the tunnel lining (Case 1)

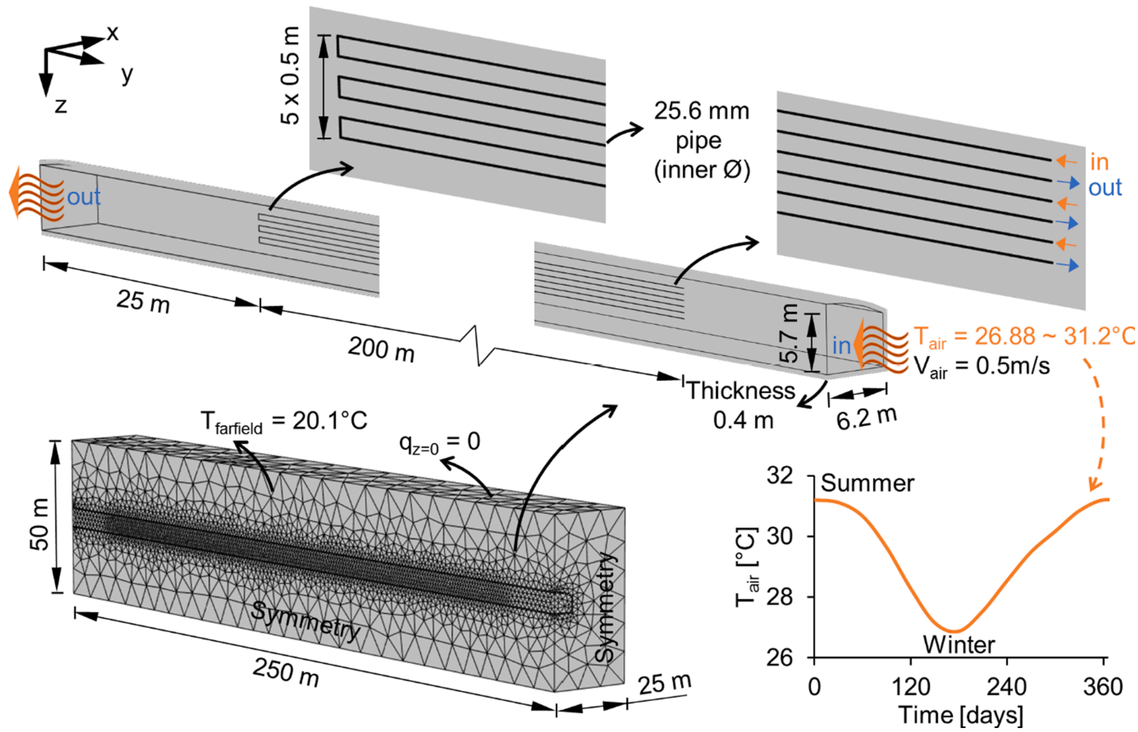

Fig. 2. Geometry, pipe configuration and boundary conditions of the modelled tunnel section.

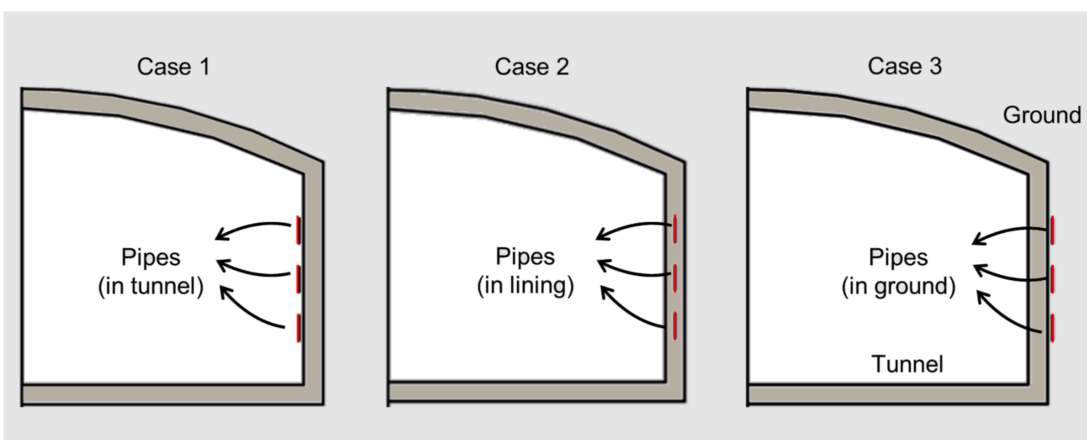

Fig. 3. Schematic of the three different cases based on the pipe placement.

demonstrate a significantly lower temperature range in 20 years in order to fulfil the required cooling load. To supply the 45 kW cooling demand in Case 1, the fluid temperature at the inlet of the heat exchangers reaches a maximum of 36.9 °C by absorbing heat from the substation via the heat pump, and decreases to 30.1 °C at the heat exchangers' outlets by rejecting the heat to the tunnel air and the ground. However, for heat exchangers inside the tunnel lining (i.e., Case 2, which is the most common configuration of heat exchangers in energy tunnels (Barla and Di Donna, 2018), or in the surrounding soil (Case 3), the carrier fluid undergoes a more substantial temperature increase in order to fulfil the same cooling demand. The inlet fluid temperature increases to a maximum of 46.7 °C in Case 2 and 47.4 °C in Case 3, while removing heat from the substations. Rejecting the heat to the tunnel air and the ground via heat exchangers results in the outlets' fluid temperature decreasing to a maximum of 39.8 °C in Case 2 and 40.7 °C in Case 3 in 20 years. The fluid temperatures in these two cases reach approximately 40 °C soon after operation starts. Heat pump manufacturers (e.g., WaterFurnace^{TM}, Envision series) generally advise that operating fluid temperatures do not exceed 40–45 °C. Note that the pipe outlet temperature corresponds to the water entering the heat pump.

It is noteworthy to mention that the fluid temperatures at the inlet of each of the six loops are the same for each configuration, as the inlet temperature is defined by the cooling demand, which is constant in all loops and in all cases. There are, however, slight variations in the fluid temperature at the outlets of the loops in each case. This is likely attributed to the spatial distribution of the loops, which imposes slightly different heat exchange rates.

From these results, it is clear that placing the HDPE pipe heat exchangers in contact with the tunnel air (Case 1), renders overall lower mean fluid temperatures and thus better system cooling efficiencies than when placed within the lining of the tunnel (Case 2) or in contact with the ground (Case 3). From a constructability point of view, Case 1 may also be simpler than Cases 2 and 3.

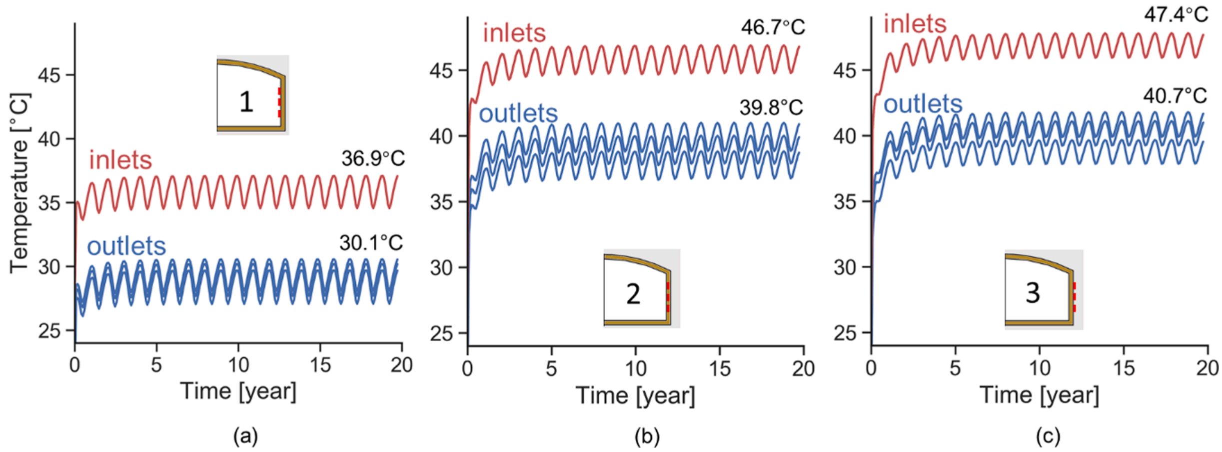

Fig. 4. Transient carrier fluid temperature variations for different heat exchanger cases.

3.1.2. Tunnel air and ground

The proposed cooling system works based on the gradual dissipation of the heat removed from the substations to the tunnel air and the surrounding ground. This makes the temperature variations within the tunnel air and the ground a key parameter (in addition to the carrier fluid temperature in the heat exchangers) for the long-term sustainability and efficiency of these systems. Fig. 5 shows the maximum temperature of the air volume in the tunnel and demonstrates the transient temperature in the tunnel air and the ground for all three cases. It is observed that when heat exchangers are placed on the tunnel lining (Fig. 5a), despite the continuous heat rejection from the heat exchangers to the tunnel air, the airflow in the tunnel – mostly generated from vehicle movement – has a significant impact on improving the efficiency of the cooling system. In this case, the volumetric tunnel air temperature (maximum temperature of the air volume in the tunnel) does not exceed 32.2 °C in 20 years despite the significant heat rejection from substations to the tunnel air. The tunnel air temperatures in the other two cases (Fig. 5b and c) seem to be minimally impacted by the substation cooling processes, showing a slight increase in temperature, yielding a maximum of 32.1 °C. Conversely, the maximum volumetric soil temperature is profoundly different between the cases, resulting from the placement of the heat exchangers. Case 1 yields the lowest maximum soil temperature (29.8 °C), while in Case 3, the volumetric soil temperature reaches a maximum of 44.2 °C. These observations indicate that the air inside the tunnel is acting as an efficient heat sink, absorbing the heat from the heat exchangers without undergoing a significant temperature increase. In contrast to Cases 2 and 3, in which the significantly high ground temperature hinders the efficient operation of the cooling system, Case 1 seems to be an efficient system set-up for sustainable cooling of substations.

Fig. 6 presents air temperature adjacent to the tunnel lining along the tunnel length for the three cases. This figure clearly illustrates that even though the ventilation airflow continuously dissipates the heat accumulated in the tunnel from the operation of the heat exchangers, a significant increase in air temperature could still occur if the heat exchangers reach high enough temperatures. In other words, Cases 2 and 3 will minimally benefit from the tunnel ventilation system, which is shown by the relatively high air temperature profile for these cases (Fig. 6), while the air temperature profile for Case 1 indicates an efficient operation for the system, supplying the cooling demand of the substation without a significant temperature increase in the tunnel air. In this case, the air temperature increases slightly in the proximity of the heat exchanger inlets, which is attributed to the temperature increase in the carrier fluid due to heat removal from the substations. A continuous decrease is then observed in the air temperature along the length of the tunnel, approaching an undisturbed temperature (relative to prior to the operation of the heat exchangers).

In order to understand the thermal interaction between different media within the system in the long term, the spatial temperature variations in the tunnel and the ground in the 20th year of the system operation are investigated for the three cases and presented in Fig. 7. It is observed that the movement of air inside the tunnel has a significant

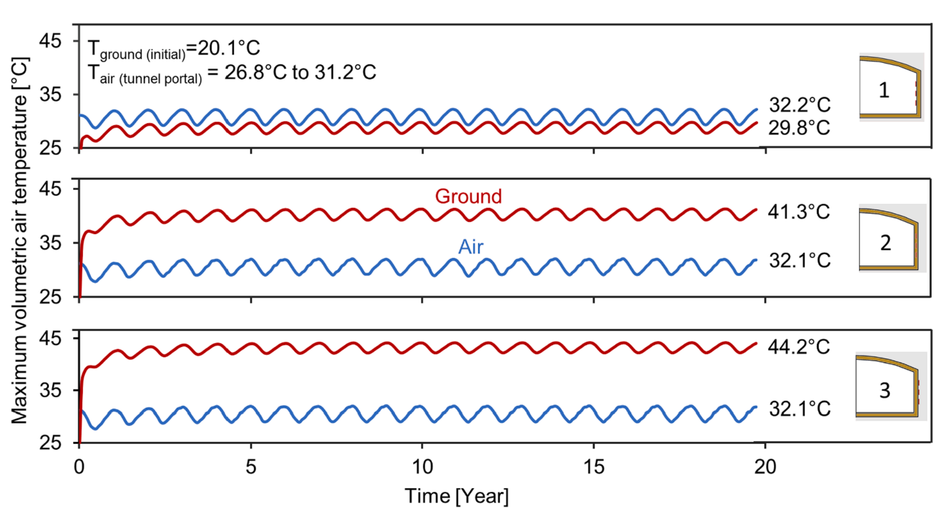

Fig. 5. The maximum volumetric temperature of the ground and tunnel air for (a) Case 1, (b) Case 2 and (c) Case 3 in 20 years.

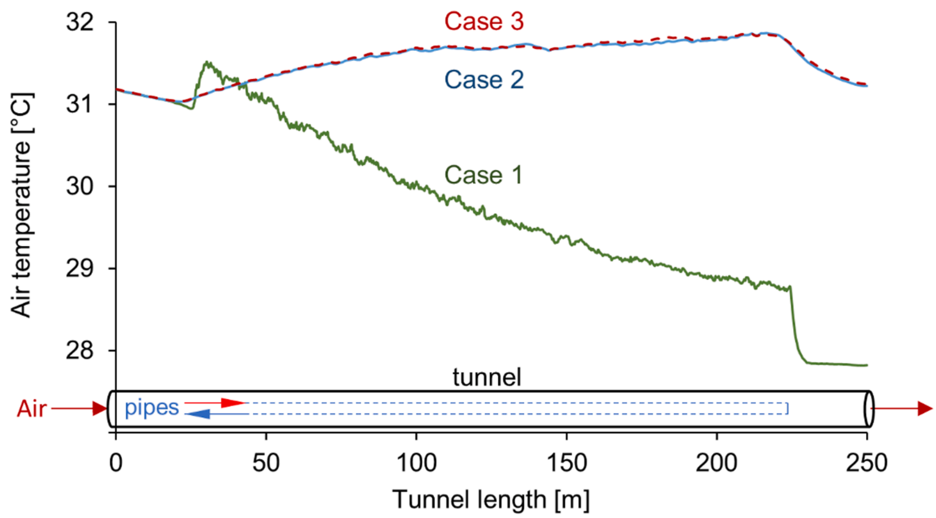

Fig. 6. Air temperature parallel to the tunnel lining along the tunnel length (only one heat exchanger loop shown).

impact on improving the efficiency of the substation's cooling system by facilitating convective heat transfer between the air and the heat exchangers. This effect can be considered analogous to the effect of groundwater flow on the efficiency of energy geo-structures (Bidarmaghz and Narsilio, 2018, Bidarmaghz et al., 2017). This is clearly illustrated in the temperature distribution in Case 2 (Fig. 7b), in which the heat exchangers are neither in contact with the soil nor with the tunnel air (they are placed inside the tunnel lining). The soil temperature increases in Case 2 is significantly higher than the air temperature increase, which shows the higher efficiency of convective heat transfer within the tunnel air in such systems. Even though the maximum temperatures reached in various media in Case 1 are lower than in the other two cases, it should be noted that the thermally impacted area of the ground surrounding the tunnel is significantly larger in Case 1. This is associated with the multi-dimensional heat exchange between the tunnel air and the ground (from the tunnel lining, slab and ceiling) due to the uniform temperature increase within the tunnel. By contrast, in Cases 2 and 3, the greatest temperature increase occurs in the proximity of the heat exchangers, thus thermal disturbance remains local and within the tunnel lining in these cases. Overall, the importance of heat accumulation is evident throughout the results: the rejected heat tends to accumulate in the structural elements and/or ground, the temperatures increase faster than heat is transferred to the tunnel air to be dissipated, causing significant inefficiencies in the system, or in extreme cases, a system that may shut off if the maximum operating temperature of the heat pumps is exceeded.

These results highlight the necessity of detailed simulation of air in the modelling of energy geo-structures for cooling purposes, to fully capture the thermal interactions between various elements of the system and the resultant temperature distribution. The simplified assumptions of thermal insulation, fixed temperature and the application of a convective heat transfer coefficient, commonly used in energy tunnel modelling, will result in inefficient systems for cooling purposes in the long term and hence hinder their sustainable application.

3.2. Economic analysis and financial feasibility

The financial feasibility of the substation cooling system options presented in this paper are evaluated through a life cycle cost analysis for (i) a conventionally used DX air-conditioning unit, (ii) the cooling system where pipes are exposed to the tunnel air (Case 1), and (iii) the cooling system where pipes are embedded either in the tunnel lining or the ground (Cases 2 and 3), as the two lead to similar capital and operational costs. Note that Cases 2 and 3 are not optimised for performance but are keeping the same heat exchange length as Case 1, for comparison. A 60-year design life is considered for all systems, approximately the same as the HDPE warranty period. The lifespans of the GSHP and a DX unit are assumed to be 20 and 10 years, respectively, following the literature (Aditya et al., 2020, Aditya and Narsilio, 2020, Lu and Narsilio, 2019, Lu et al., 2017). This implies incurring additional capital costs every 10 years when a new DX unit is installed, to replace the previous unit, or every 20 years for a GSHP unit. The net present cost (NPC) of each cooling system is estimated for comparison as:

$$NPC = \sum_{t=1}^{n} \frac{C_t}{(1+r)^t} \tag{12}$$

where n is the design life in years, C_t is the net cash outflow during a single period, t, in years (either capital cost or operating cost) and r is the discount rate taken as constant for the present cost at time, t, over a 60-year design life of the system for simplicity.

Capital costs are often the deciding factor between system options; however, many operators of the infrastructure will also consider and weight operating and maintenance costs in their decisions. Here is where system efficiency becomes important. The resulting operating fluid temperatures and ranges for Case 1, Case 2 and Case 3 influence the GSHP efficiency, measured as the Coefficient of Performance (COP), and thus the operating costs. Capital and operating costs are the key components for calculating the cash outflow in Eq. (12). Table 2 summarises key unit costs, to estimate capital costs. These are based on the literature, the current costing structures in Australia and the authors' experiences with system installations. The three cooling systems presented here involve 2,400 m of HDPE pipes as heat exchangers for the design thermal load for typical substations (45 kW of cooling in this study). The cost of a 45 kW (cooling) capacity heat pump is AUD $23,800 for the stand-alone Cases 1, 2 and 3 system designs (based on the 2019 price of a heat pump model NKW045 with HydroLink). Material and installation cost for pipes and circulation pumps are also included. Installation of pipes in the lining or in the ground are assumed to incur extra labour days relative to the design of Case 1, as construction may be undertaken in stages around other works. All works are possible to be scheduled outside the critical path for tunnel completion.

For the estimation of annual running costs, the COP of each system used for comparison is summarised in Table 3. The average annual COP values for Cases 1, 2 and 3 were computed based on the water temperatures entering the heat pump along with the technical specifications provided by WaterFurnace™ (NKW045 with HydroLink) and the COP of the DX unit was obtained from Qi et al. (2019).

For well-designed pipe reticulations, pumping costs represent a

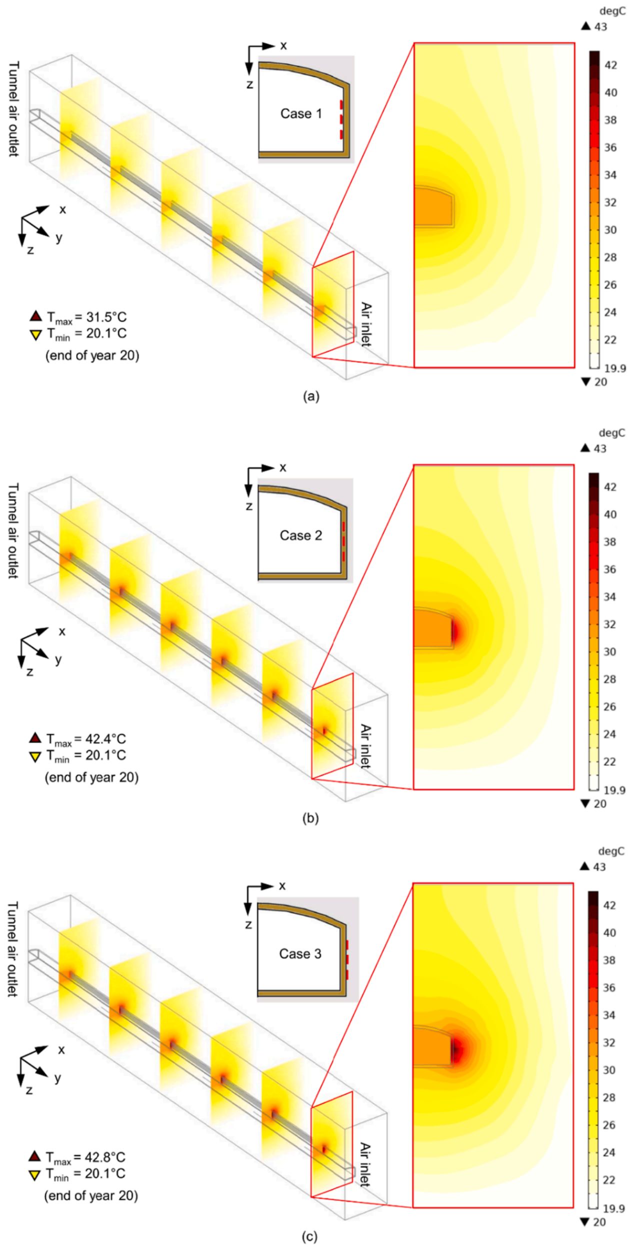

Fig. 7. Spatial temperature variations of the tunnel air, structure and the ground for (a) Case 1, (b) Case 2 and (c) Case 3 after 20 years of cooling system operation.

minor component of the running costs. This is particularly the case for such simple piping introduced here, and thus pumping costs are considered negligible in this analysis. However, it must be noted that poor designs or complex piping configurations may render higher pumping costs that may need to be accounted for in similar financial feasibility studies. Fig. 8 shows the net present cost (NPC) over a 60-year life span for the various cooling systems. The total NPC of the designed cooling system comprising a GSHP with heat exchangers exposed to the tunnel air (Case 1) resulted in AUD $293,799. This is found to be the most cost-effective compared to the systems with pipes embedded in the tunnel lining or the ground (Cases 2 and 3), or the conventionally used DX unit systems (Fig. 8-a). The Case 1 system shows the lowest capital and operational costs over 60-years. The design life of a DX unit is only 10 years, which results in an additional replacement (capital) cost every ten years of design life period. Thus, the DX unit system is the most capital intensive and requires more than twice (2.3 times) the capital cost of the piping systems. Moreover, unlike the innovative cooling system presented herein, the conventional DX unit system relies on ambient air as the exchange medium, which has a much smaller surface area, compared to the area over which water in the heat exchangers dissipates heat to the tunnel air. The cooling system presented in this study avoids heat concentration and enhances convective dissipation of the rejected heat, rendering more stable source-sink temperatures, thus ultimately providing more cost-effective space cooling. The same NPC trend is observed regardless of the cost of electricity (Fig. 8-b); however, it is not linearly proportional. The overall life cycle cost reduces by approximately 40% when the cost of electricity decreases by 50%. When comparing the NPC for Case 1 and the DX unit systems, an 80% difference can be seen when the electricity cost is 10 cents per kilowatt-hour, while these savings are close to 88% for a 5c/kWh electricity cost and 74% for a 20c/kWh electricity cost. In other words, for deep underground substations, the lower the electricity costs to run the cooling systems, the higher the return on investment on utilising HDPE pipes in the tunnel rather than conventionally used DX units.

4. Conclusions

This paper presents a sustainable and efficient approach for cooling underground substations by integrating heat exchangers into a tunnel's lining. Heat is removed from the substations and exchanged with the tunnel and the ground. This system takes advantage of the tunnel air and the ground potential as sustainable heat sinks, through which heat rejected from the substations can dissipate without imposing significant increases in their temperatures. This work evaluates the efficiency of the proposed cooling system for three different configurations of heat exchangers, located i) on the tunnel lining (Case 1), ii) within the tunnel lining (Case 2) and iii) embedded in the ground (Case 3). The efficiency is evaluated by numerically investigating the temperature changes in the ground, tunnel air, tunnel structure and carrier fluid circulating within the heat exchangers. Moreover, the cost-effectiveness of the proposed systems is investigated in this work by comparing their operational and

Table 2
Key assumptions for economic analysis (monetary values in Australian dollars).

Item	Value	Notes
Cost of 45 kW GSHP [AUD]	23,800	Heat pump costs for Cases 1, 2 & 3
Pipe cost [AUD/m]	5	Pipe material and installation cost
Pipe fitting cost [AUD/fitting]	20	Minimum spacing without using fittings is 800 mm
GSHP and pipe/pump installation costs	1000	Per day (5 days for Case 1, 7 days for Cases 2 & 3)
DX unit cost [AUD/kW]	1000	Equipment and installation of the system
Electricity cost [c/kWh]	5, 10, 20	Three electricity costs for sensitivity analysis
Lifespan of GSHP system [years]	20	
Lifespan of RCAC [years]	10	
Discount rate [%]	3.5	
Design life [years]	60	

Table 3
Efficiency of the different cooling systems under comparison.

System	COP (Heating)* [kW/kW]	COP (Cooling)* [kW/kW]	Design length [m]	Notes
GSHP Case 1	6.1	4.2	2400	HDPE pipe length
GSHP Cases 2 & 3	5.8	3.1	2400	HDPE pipe length
DX unit	–	2.5	–	

* Averaged heating/cooling coefficient of performance. No heating provided by these systems in the substations.

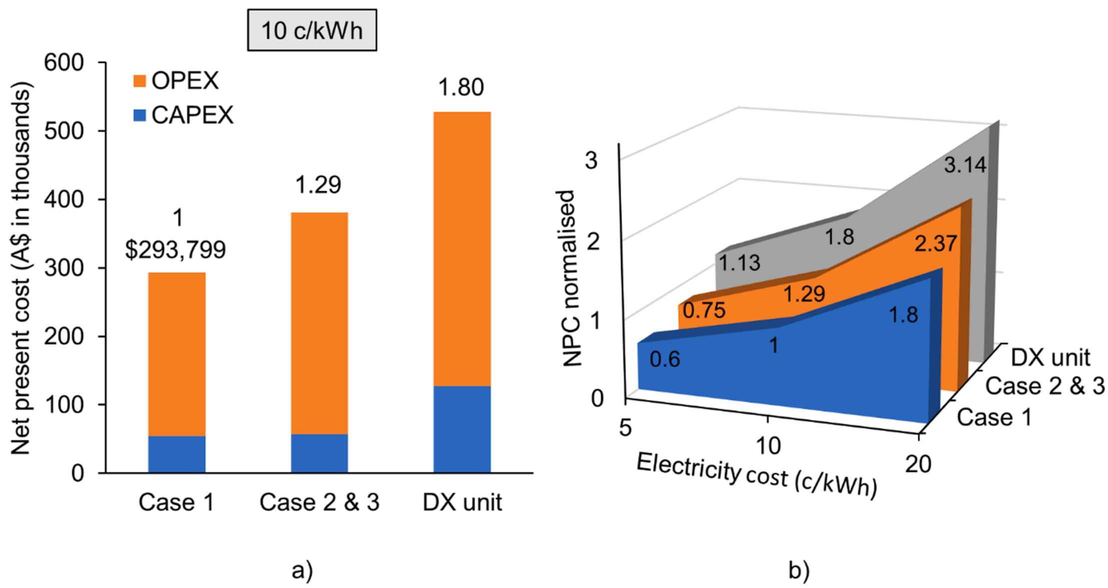

Fig. 8. Net present cost over a 60-year life span for various cooling systems: (a) total, capital cost (CAPEX) and operational cost (OPEX) for 10cents/kWh electricity cost, and (b) sensitivity to electricity costs, normalised to the Case 1 at 10c/kWh.

capital costs with those of the conventional and commonly used DX systems.

Overall, the results show that the system in which heat exchangers are exposed to the tunnel air (Case 1), could efficiently cool down the substations with the support of a water-coupled heat pump. This is demonstrated by the temperature distribution of the system (including the ground, tunnel air and carrier fluid) being maintained within an acceptable range while the total cooling demand of the substations is supplied by the heat exchangers. Significant temperature increases observed in the ground and tunnel air for Cases 2 and 3 indicate the lower efficiency of these systems in cooling the underground substations. These results highlight the importance of the movement of air inside the tunnel and its significant impact on improving the thermal efficiency of a substation's cooling system, by facilitating convective heat transfer between the air and the heat exchangers. It is concluded that detailed simulation of air in energy geo-structures modelling is crucial to fully capture the thermal interactions between various elements of the system – a necessity which is mostly overlooked in the literature and replaced by multiple simplified assumptions.

The total net present cost, or NPC, of the designed cooling system with heat exchangers exposed to the tunnel air (Case 1) is found to be the most cost-effective compared to the systems with pipes embedded in the tunnel lining or the ground (Cases 2 and 3) or the conventionally used DX unit systems. Moreover, the economic analysis has shown that the lower the electricity costs to run this cooling system for deep underground substations, the higher the return on investment on utilising heat exchangers in the tunnel.

The outcomes of the numerical models, as well as the economic analysis, show that the proposed cooling system can effectively improve the efficiency of cooling underground substations, by yielding a higher COP and lower NPC than for conventional DX systems, without imposing unsustainable practices on the ground, tunnel structure or tunnel air.

CRediT authorship contribution statement

Asal Bidarmaghz: Conceptualization, Writing - original draft, Validation, Methodology. **Nikolas Makasis:** Conceptualization, Visualization, Writing - review & editing. **Wenbin Fei:** Investigation, Visualization, Writing - review & editing. **Guillermo A. Narsilio:** Conceptualization, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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