Energy tunnels for a sustainable future in rock engineering

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Abstract

The use of geothermal energy for heating and cooling purposes is an environmentally friendly and cost-effective alternative with the potential to replace fossil fuels and help mitigate global warming as well. In the boost of innovation of the tunnelling industry, to face the challenges posed by climate change and the need for sustainable growth of cities and territories, it is of interest to embody the innovative use of the tunnel linings to also produce thermal energy for conditioning of buildings, cooling of tunnel air or de-icing of infrastructures. Relevant examples from the Author's recent experience, related to deep and shallow thermally activated underground excavations, will be revealed to highlight the methodological steps to be adopted for the geothermal potential evaluation and achieve a successful design of the integrated technology. These include specific rock mass thermal and hydraulic characterisation, GIS procedures and coupled numerical modelling. Applications under the Alps will show how energy tunnels may help unlock new opportunities for sustainability in rock engineering.

Keywords

Tunnels, sustainability, energy geostructures, geothermal energy

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1 Introduction

The growing energy demand has been increasingly leading to the spread of renewable sources-based systems. In the next years, it will be crucial to enhance the use of such systems, especially in urban areas, to cut down on carbon dioxide emissions and to meet the goals agreed in the European context (Directive 2009; European Commission 2016).

Among renewable resources, low-enthalpy geothermal plants are today common practice in many countries to supply heating and cooling through a clean and locally accessible form of thermal energy (Lund et al. 2011). Shallow geothermal energy, up to 400 m depth, takes advantage of the underground as a heat tank that can be tapped into for heating in winter and where buildings' excess heat can be stored in summer. At a depth of around 8-10 m, the soil temperature is essentially stable and is marginally affected by seasonal air temperature fluctuations. In mild climates soil temperature at these depths ranges from 8 to 16°C, being generally warmer than the external air in winter and colder in summer. In these contexts, heat transfer, by means of a geothermal heat pump system, can be advantageous. Geothermal energy resources are renewable in the long term because they would fully recover to their pre-exploitation state after an extended shut-down period. The geothermal reservoir itself is a thermal energy storage system as the thermal energy is continuously available 24 hours a day. Therefore, unlike solar thermal energy, geothermal energy sources can be utilized any time of the day on a need basis.

Beyond conventional closed-loop GSHP (Ground Source Heat Pump) systems, where heat exchange occurs between the ground and a heat carrier fluid flowing in the circuit installed in vertical or horizontal loops, or open-loop GWHP (Groundwater heat pump) systems, where heat exchange takes place with the groundwater itself through extraction and reinjection wells, today, shallow geothermal energy also includes the so-called energy geostructures. The latter are geotechnical structures, e.g. deep and shallow foundations, diaphragm walls and tunnel linings that are suitably equipped to exchange heat with the ground (Brandl 2006; Laloui and Di Donna 2013; Barla and Di Donna 2016).

Fitting reinforced concrete structural elements out with heat exchangers instead of traditional geothermal plants not only is particularly convenient from the economic perspective, since structural and energy needs are condensed into one single element, but it is also optimal from the physical standpoint because concrete is a material characterized by a good thermal conductivity and heat capacity. Thermal activation of structural elements is done through the arrangement of a high-density polyethylene pipe closed loop where the heat carrier fluid circulates.

The interest in the application of this technology to tunnel linings is driven by the fact that the ground-contact surface is far greater compared to piles and base slabs. The heat exchanged by the lining with the surrounding ground can have multiple purposes. From heating and cooling subway stations and substations (Barla et al., 2019a; Bidarmaghz et al., 2023) or buildings near the tunnel (Nicholson et al. 2014; Barla et al. 2016), to deicing of bridge decks, rails and routes strengthening both safety and durability (Baralis et al. 2021).

After the pioneering experiences in Austria and Germany (Unterberger et al. 2004; Adam and Markiewicz 2009; Schneider and Moormann 2010; Frodl et al. 2010; Franzius and Pralle 2011; Moormann et al. 2016), followed by those in South Korea and China (Lee at al. 2012; Lee et al. 2016; Zhang et al. 2013; Zhang et al. 2014), in 2016, an innovative, optimized energy segment (Enertun) was designed at the Politecnico di Torino. Next, a full-scale experimental prototype of an energy tunnel was installed in the Turin Metro Line 1 South Extension which still represents the most documented available database of real implementation of energy tunnels so far (Barla et al. 2019b). Data collected between 2017 and 2018 enabled the assessment of the technology performance in the city underground (Insana and Barla 2020). The research with its promising outcomes was preparatory for launching the feasibility study of the future Turin Metro Line 2 geostructures' thermal activation and other projects.

With the focus on the implementation of energy tunnels to rock masses, it is of interest here to illustrate the possible applications, which increased in typologies in the last few years. To provide a comprehensive picture, some general indications for the design of energy tunnels will be discussed, followed by the exemplification of different technological solutions that can be adopted in rock engineering. Relevant examples, related to deep and shallow thermally activated underground excavations, will be revealed to highlight the methodological steps to be adopted for the geothermal potential evaluation and achieve a successful design of the integrated technology. These include specific rock mass thermal and hydraulic characterisation, GIS procedures and coupled numerical modelling. The examples will also show how energy tunnels may help unlock new opportunities for sustainability in rock engineering.

2 Energy geostructures

2.1 The concept

An energy geo-structure is a type of infrastructure that integrates conventional geotechnical systems, such as foundations, retaining walls, or tunnels, with heat exchange capabilities to harness geothermal energy (Brandl 2006; Barla and Perino 2014). These structures are equipped with embedded heat exchanger pipes, typically connected to ground source heat pump systems, to provide sustainable heating and cooling for buildings or other facilities (Fig. 1). By combining structural support with renewable energy functionality, energy geo-structures offer a dual-purpose solution that reduces carbon emissions and improves energy efficiency.

a) b)

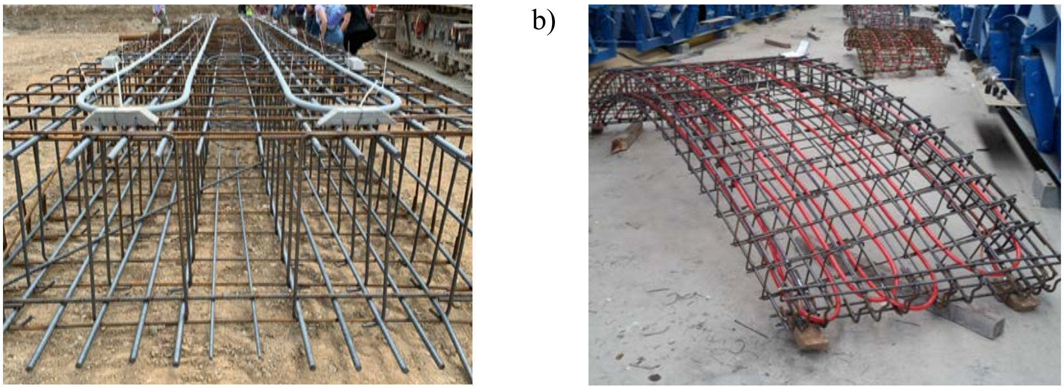


Fig. 1 Example of thermal activation of a diaphragm wall a) and a tunnel lining segment b) where exchanger pipes are fixed to the steel cage before installation or casting.

The main advantage of heat exchanger loops embedded into geotechnical structures lies in the reduction of geothermal plant building costs as the concrete elements are already required for structural reasons and do not need bespoke excavations or drillings. Conversely, the main drawback is the almost exclusive viability for newly constructed buildings, although some recent studies highlighted that there could be broad possibilities of application in buildings and infrastructure during retrofitting too (Ronchi et al. 2018; De Feudis et al. 2024b).

It is generally recognised that the use of energy geostructures began in the 80s, with the first examples related to applications to base slab foundations. Later, the use widened to other geostructural assets, such as piles and walls. Many case studies can be found in the literature, mainly from Austria, Germany, the UK and Switzerland (Brandl 2006; Amis et al. 2010; Adam and Markiewicz 2009; Di Donna et al. 2017; Bourne Webb and da Costa Goncalves 2016).

Among the applications worldwide, thermal activation of tunnel linings is probably the less common one. Nevertheless, this application could play a relevant role in coping with the growing energy demand. The ground-contact exchange surface is much more extensive compared to foundations. Moreover, when resorting to mechanized tunnelling, the lining ring consists of precast segments that are mounted on-site by the TBM (Tunnel Boring Machine). Therefore, segments can be equipped with heat exchangers in the manufacturing plant itself with low extra costs and limited influence on the tunnel construction phases. Other technological solutions have been proposed for conventional tunnels with shotcrete or cast-in-place concrete support that may also include the realisation of geothermal loops in the rock mass surrounding the tunnel. The geothermal plant, once completed, can also find an application for hot tunnels cooling, where trains and cars transit might represent in some cases an additional heat source. This last is particularly attractive for deep transportation tunnels excavated in rock masses where high temperatures are expected due to the natural ground conditions.

2.2 Specific features of energy tunnels

In recent years, there has been increasing interest in extracting energy from tunnel linings. Technologies that leverage the geothermal potential of water within the rock mass are well-established, particularly in Switzerland (Rybach 1995; Wilhelm and Rybach 2003) and more broadly in alpine regions. In this case, water inflows are collected with the purpose of heating nearby buildings, as in traditional heat exchange systems. Conversely, the idea behind energy tunnels is to exchange heat with the surrounding ground through the lining. A schematic view of the operation principle is presented in Fig. 2, where the geothermal loops within the tunnel lining can displace heat from the ground. The heat can then be diverted to external uses, including heating and cooling of buildings, de-icing of infrastructures, etc. Application to rock engineering is particularly intriguing considering the typically higher thermal conductivity than loose soils, that in case of, e.g., metamorphic rocks can reach values up to 5 W/mK.

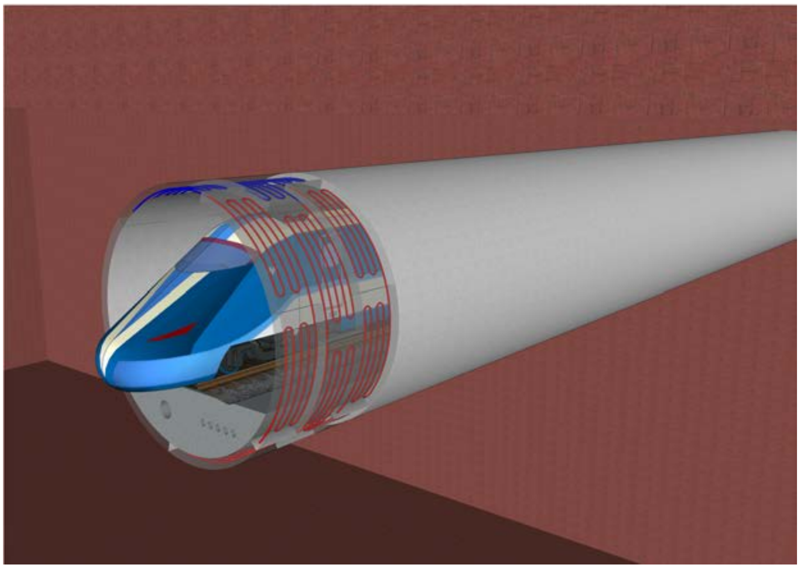


Fig. 2 Schematic view of the technological system used to exploit heat from the surrounding rock mass through the thermally activated concrete lining.

The first documented real-scale example of this innovative application is related to the Lainzer tunnel in Vienna (Adam and Markiewicz 2009). During tunnel excavation by conventional NATM (New Austrian Tunnelling Method) tunnelling technique, a thermal activation trial was performed in lot LT22 in 2003. In particular, pipes were fixed to geosynthetics off-site and then placed between the primary and the secondary lining. Hence, pipe laying can occur during the geotextile production process to streamline the installation phase on site. It consists of a full-fledged energy geotextile that was developed at Technische Universität in Vienna.

Another experience followed in Germany, where two 10 m-long sections of the Stuttgart-Fasanenhof urban railway link were equipped with an experimental geothermal plant (Schneider and Moormann 2010). The monitoring results on a 4-year span are described in the works by Moormann et al. (2016) and Buhmann et al. (2016). The experimental campaign assessed the heat exchange potential, the impact of thermal loads on the subsoil and the influence of tunnel climate.

More recently, in China, some investigations (Zhang et al. 2013, 2014) focused on energy tunnels implementation. Indeed, in some regions of China such as Mongolia, average yearly temperatures are below zero degrees. To preserve the serviceability of infrastructures such as tunnels, lining and drainage, heating systems have to be installed so that absorber pipes withdraw heat from the inner tunnel sections and heating pipes deliver this heat at the tunnel portals. In this case, energy tunnels could replace traditional electricity-driven or coal-driven systems and thus reduce the high management costs on one side and decrease the carbon footprint. A full-scale example is the Linchang tunnel, excavated in a weathered sandstone rock mass in the town of Yakeshi, an autonomous region of Mongolia. Here the primary circuit is placed between the primary and the secondary lining 600 m away from the tunnel portal. The secondary circuit is close to the tunnel entrance between the secondary lining and an insulation layer, as well as in a ditch running parallel to the tunnel axis.

When it comes to cut and cover tunnels, thermal activation can be achieved by equipping the diaphragm walls supporting the excavation and, possibly, the base slab with heat exchangers. Basically, the technology is the same as the one used for energy walls for urban excavations and/or foundations and support systems, for which many studies or real cases already exist in the literature (Amis et al. 2010; Bourne Webb et al. 2016; Di Donna et al. 2016; Sterpi et al. 2018; Makasis and Narsilio 2020; Zannin et al. 2020; Barla et al. 2023).

For tunnels built by mechanized tunnelling, the final lining is generally made of precast concrete segments mounted by the TBM within the shield protection. Precast segments are assembled to shape a ring, 1-2 m long. Typically every ring is made of 6-7 segments. In 2009 the first energy segments ring was tested in Katzenbergtunnel, driven mostly through tertiary sedimentary rocks such as clay, marl and limestone, sometimes also sandstone. Before tunnel opening, 5 segments were thermally activated for a total surface of 60 m^2 and a heat flux of around 10-20 W/m^2 (Franzius and Pralle 2011; Moormann et al. 2016). Later, in light of this experience, the technology was applied to the Jenbach railway tunnel in Austria, where 27 energy rings were conceived and built to cover the heat demand of the nearby city council (Frodl et al. 2010).

Other documented case studies can be found in Lee et al. (2012), who describes a testbed in Seocheon tunnel in Korea, or in Nicholson et al. (2014), for a potential application to Crossrail project's tunnels, Barla et al. (2016), Di Donna and Barla (2016), Bidarmaghz and Narsilio (2018) and Insana and Barla (2020), who studied the effect of soil thermal properties and hydraulic flow on heat exchange, Cousin et al. (2019), who studied the application to Grand Paris tunnels, Tinti et al. (2017), with reference to the Mules Access Tunnel of the Brenner Base Tunnel (BBT) system, Makasis and Narsilio (2020) for the M4-M5 Link project in New South Wales in Australia, and Alvi et al. (2022) for the Lyon-Turin base tunnel. Peltier et al. (2019) and Dornberger et al. (2020) focused on the relevant role played in energy tunnels by the internal airflow characteristics (airflow temperature and velocity and heat transfer coefficient). Also Ma et al. (2021) analyzed the tunnel environment's impact on energy tunnels' performance, finding that the temperature difference between tunnel air and heat carrier fluid is a key quantity, but attention should also be paid to the lining thermal properties. Recently, the thermo-mechanical behaviour was investigated by Insana et al. (2020), Rotta Loria et al. (2022) and Ma et al. (2022) for the case of coarse-grained soil.

The arrangement of the tunnel for heat exchange takes place by equipping the lining with geothermal loops and by creating a connection plant with the collection and distribution network to the users, whether they are the stations themselves or the buildings at the surface. Nicholson et al. (2014) show a simplified conceptual framework of an exchange and distribution network to ground surface buildings devised for the Crossrail project, then never turned into reality. In their example, every building is provided with a heat pump. The overall system should include appropriate hydraulic pumps for heat carrier fluid circulation to and from the geothermal probes. Another solution could see a unique, centralized heat pump and a low-temperature secondary distribution network towards the buildings. Both these options were studied for application to the city of Turin (Barla and Insana 2023).

The research carried out at Politecnico di Torino from 2013 onwards is particularly relevant for illustrating the milestones achieved, among which is the development of a precast energy segment patent called Enertun (Italian patent number: 102016000020821, European patent number: 16834047.9) and the experimental campaign carried out in South Extension Line 1 Turin Metro tunnel (Barla et al., 2019b). The latter represents the first application of this technology in Italy and by far one of the most well-researched, especially by reference to the lining thermo-mechanical behaviour (Insana et al., 2020; Insana, 2020).

Thanks to an innovative layout of the geothermal probes, the Enertun energy segment reduces head losses by 20-30% in each ring and increases its energy efficiency by up to 10%. The same segment can be used to cool down the tunnel environment. There are three different configurations of the segment, according to the pipes mesh positioning, that is close to the extrados (Ground, Fig. 3), close to the intrados (Air, Fig. 3) or can include two circuits, one per each of the previous locations (Ground&Air). In the first case, the heat exchange with the ground is predominating, while it mainly involves air in the second case. In the third case, heat exchange can occur in both directions.

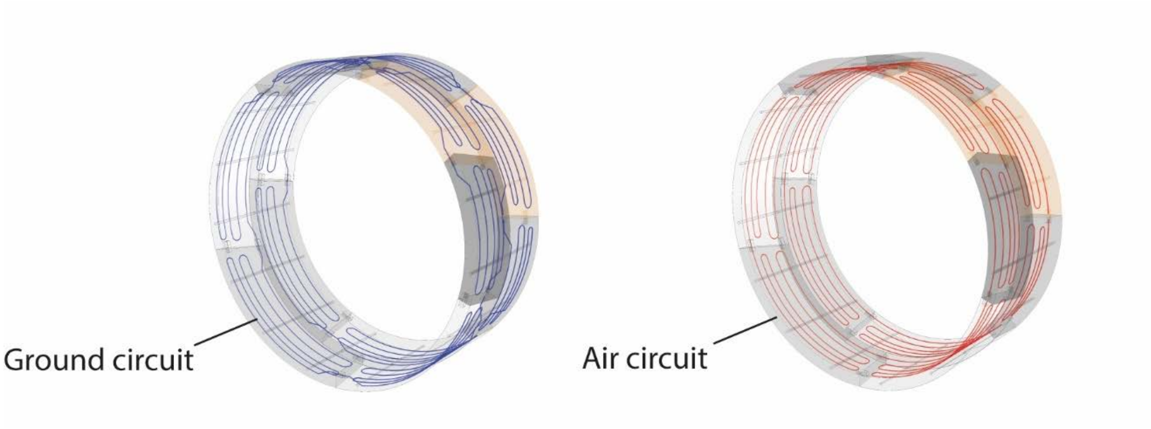


Fig. 3 Ground and air Enertun configurations.

Other than the lining, Brandl (2006) has suggested the possibility of thermally activating the rock bolts used for preliminary support in tunnels, while Mimouni et al. (2014) studied the application to anchors. Thermal activation can be achieved using coaxial heat exchanger pipes installed within the bolt/anchor. The fluid flows through a central pipe and then comes out around the perimeter, following extended paths to maximize thermal exchange efficiency. An example of thermally activated anchors is found in a portion of the Lainzer tunnel in Vienna, Austria (Adam and Markiewicz 2009).

In the above, the interest was mainly posed on new tunnels, designed to be thermally activated from the early design stage. However, recent activities have investigated the application to existing tunnels which potentially opens a new and large business sector considering the age of many tunnels in Europe. Depending on the typology of the existing lining as well as the ground conditions, different technological solutions were proposed by De Feudis et al. (2024b). The main rationale is to implement the thermal activation of the tunnel by taking advantage of planned refurbishment works.

3 Design aspects

The design process that leads to the realization of an energy tunnel goes beyond specific reference standards and cannot be merely reduced to a number of structural and/or geotechnical verifications. It necessarily encompasses a broad spectrum of issues that impact urban planning and the area energy procurement and distribution. The possibility to thermally activate a tunnel will have to be scheduled well in advance and since the stage of an infrastructure feasibility study. Only then can it be guaranteed that the infrastructure contributes to sustainable development thanks to its full integration into municipal or district energy planning. There are no current regulations, however, recent recommendations were published for some European countries (e.g. in France, Switzerland and Italy).

Having said this, as described by Barla and Insana (2023), thermal activation of energy linings entails at least two technical aspects that need to be taken into account during the project stages, after specific investigation. An energy optimization analysis, aimed at maximizing the performance under the same costs and evaluating the thermo-hydraulic interaction with the ground, is run first (thermal design). This is followed by the geotechnical design, which identifies the mechanical effects in the structural elements following the thermal loading, assessed from the previous stage so that long-term integrity can be guaranteed. These aspects can be tackled through thermo-mechanical (TM) and thermo-hydraulic (TH) numerical modelling respectively. The adoption of fully coupled thermo-hydro-mechanical (THM) simulations can be limited to specific cases (e.g. when the contribution of convection from the tunnel internal air is relevant) to provide more reliable outcomes, as in most cases the computational effort and the increase in calculation time are not necessarily reflected in a more accurate result.

The procedural proposal for the design of energy tunnels is outlined in the flow chart in Fig. 4 (Barla and Insana, 2023). It is highlighted that sizing of the hydraulic circuit also needs to be carried out.

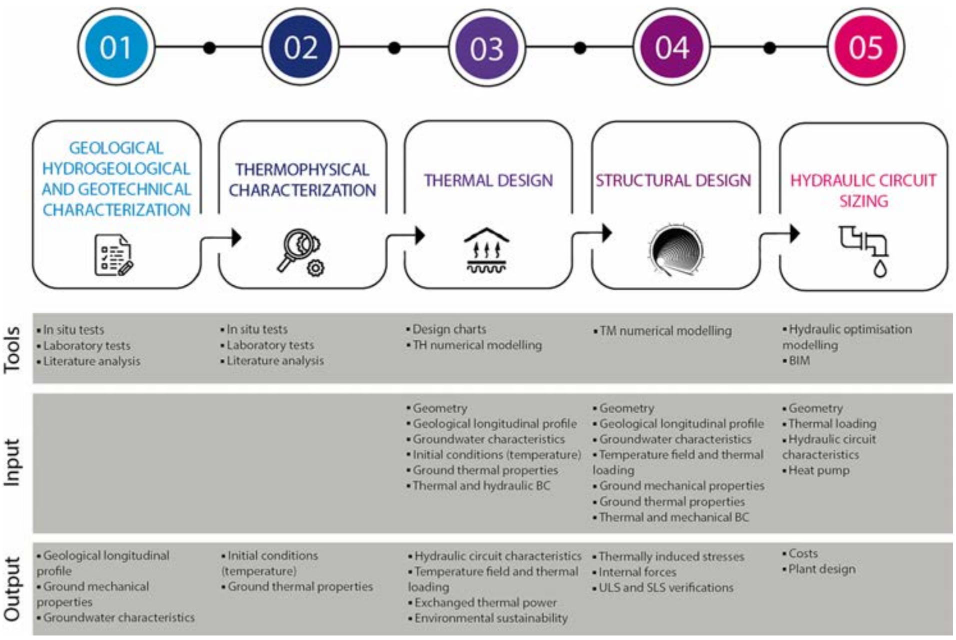


Fig. 4 Design flow for an energy tunnel (Barla and Insana 2023).

4 Examples of thermal energy exploitation from tunnels

As previously anticipated, the thermal activation of tunnels can be obtained by means of different solutions, the applicability of which will depend on the tunnel and lining characteristics, the construction method, the lifetime, the usage (motorway, railway, utilities, etc.) and the context in which the tunnel is localized (urban area, mountains, etc.). As previously mentioned, the best is to thermally activate a tunnel during construction, however, solutions do exist to be applied for tunnels under maintenance or retrofitting process.

Depending on the type of excavation method adopted, the final usage and the rock mass quality, the tunnel design and construction method may differ substantially. Typically, circular cross sections are characteristic of TBM excavation while horseshoe-shaped geometries are used in conventional tunneling. In poor ground conditions, precast or cast-in-place concrete final lining is used, in combination with preliminary steel sets and/or shotcrete as well as face support systems. For fractured rock masses (GSI<60) shotcrete, rock bolts, or steel ribs are installed as excavation progresses to stabilize the tunnel, while for good quality rock masses (GSI>60) the support measures may, at times, be limited to rock bolts and shotcrete.

It is of interest to describe the different available options for thermal activation of tunnels and to show some examples of planned or real applications to highlight the diversity of possible uses. To this extent, Fig. 5 illustrates the technological solutions available to achieve the thermal activation of a tunnel lining. The attention here is limited to tunnel construction in poor or good quality rock masses, i.e. specific tunnelling methods for poor ground conditions (cohesive or non-cohesive soils) are disregarded. Moreover, Table 1 shows how the methods can be applied to new and existing tunnels.

In the case of mechanized tunnelling, pre cast energy segments are the best available option (solution A). This is also one of the most cost-effective solutions in general for tunnel applications. The main reason lies in the possibility to embed the exchanger pipes directly in the pre cast plant, reducing operational time during construction and benefitting from more controlled conditions. Diverse Authors have discussed fruitful applications of such technology (e.g. Frodl et al. 2010; Barla et al. 2019b).

In very good quality rock masses, where there is no need for concrete lining and an open TBM is used, the heat exchanger elements can be implemented through rock bolts (solution E) or specifically excavated borehole heat exchangers (solution D). It is clear that this last solution, which has the advantage of being applicable also to existing tunnels, is among the less cost-effective ones, considering the need to drill ad hoc boreholes to achieve heat exchange. While this aspect can be seen as a disadvantage for the application of solution D it has to be said that it can be seen as an alternative to vertical borehole heat exchangers drilled from the ground surface. Moving the BHE into the tunnel may allow one to reduce land consumption.

In the case of conventional tunnelling (full face, NATM, drill and blast, etc.), the thermal activation technology to be adopted is a function of the tunnel's final geometry and the type of support methods adopted. Exchanger pipes can be embedded into the cast-in-place lining during construction or during refurbishment, when partial or full demolition of the lining is planned. In this case, energy mats placed directly on the rock or suspended to the remaining concrete, can be used when the restoration plan includes demolition and reconstruction (solution B). Alternatively, energy predalles (pre cast concrete elements that constitutes the mould for casting the new lining) can also be used (solution C). Predalles are used at tunnelling refurbishment sites to allow for quicker intervention and reduce the time of inactivity of the infrastructure (Agresti et al. 2022). Similarly to energy segments, in this case, the exchanger pipes can be prepared in the factory and moved to the site ready for installation.

Additional options available are the heat exchange from the drainage water (solution F) or the use of the entire tunnel as an underground tank (solution G). While solution F has seen interest and real scale applications (Wilhelm and Rybach 2023; Tinti et al. 2023), solution G is more on the research level. However, interest it his last possibility has been shown and a new project REgENEraTE - REuse for ENergy Exploitation and storage of existing urban Tunnels in Europe has just been launched within the Driving Urban Transitions programme (Regenerate 2024).

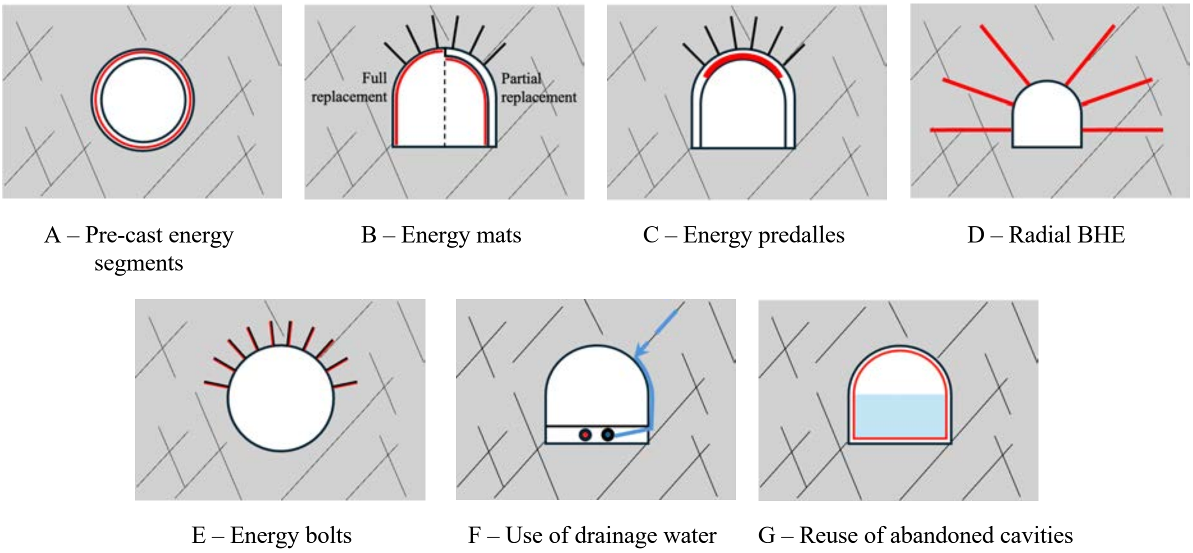
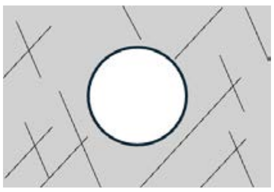


Fig. 5 Examples of the technological solutions to achieve the thermal activation in new and existing tunnels in rock masses.

Table 1 Solutions for new and existing tunnels in rock masses

Excavation method		**New tunnel**	**Tunnel abandoned or under refurbishment**
Tunnels excavated with conventional methods		B - C - D - E - F	A - B - C - D – E – F - G
Mechanised tunnels		A - E	A - D

Some examples of possible applications are discussed in the following. Attention is posed to the application to urban metro tunnels for heating and cooling of metro stations, motorway tunnels for de-icing of viaducts, cooling systems for deep mountain tunnels and other possible applications.

4.1 Application to metro lines

The application to underground tunnels in urban environments is one of the most interesting applications of energy tunnels as it maximizes the benefits considering the proximity between the production and the potential users. In the case of metro lines, the thermal activation of tunnels can be obtained depending on the construction technique. All the structures can be activated (e.g. tunnels, stations, pedestrian underpass). The thermal energy exploited can be directly used for conditioning the stations of the line or, alternatively, delivered to external users on the surface.

A unique example of a study on the geothermal potential of the tunnel infrastructures along the line, carried out up to the outline design stage, is that of the Turin Metro Line 2 (Barla et al. 2019a; Barla et al., 2020). Construction should start in 2027. Tunnel construction is planned to be performed by mechanized excavation with TBM, conventional excavation as well as by the Cut & Cover, mainly in alluvial soil and conglomerate, characterized by different degrees of cementation (σ_{ci} up to 4 MPa). The two different structural typologies which can be thermally activated are the lining made of precast reinforced concrete segments in the tunnel sections built by TBM (the use of Enertun system is envisaged, solution A) and the cast-in-place reinforced concrete vertical diaphragm walls, for the sections of the tunnel excavated by C&C and for stations. Both technologies have been already tested in the ground conditions of Turin (Barla et al. 2019b; Barla et al. 2023).

To assess the overall geothermal potential resulting from the thermal activation of the line the approach described in Barla et al. (2020) was adopted. At first, the global geometrical, geotechnical, thermal and hydrogeological picture of the subsoil around the tunnel was gathered by means of in situ and laboratory investigation. Then the line was subdivided into a number of homogeneous sections with respect to the geothermal behaviour of the tunnel. Coupled Thermo-Hydro Finite Element numerical models were then built for each homogeneous section and adopted to study the geothermal potential. Interpretation of the Thermo-Hydro numerical analyses allowed to determine the thermal energy produced (kWh) and the energy potential for each homogeneous section. Thus the Line 2 overall deliverable geothermal potential was assessed to be up to 18.7 and 11.9 MW respectively in winter and summer. This remarkable thermal energy available could be used for conditioning the stations along the line. Considering the availability of extra heat with respect to the thermal needs of the stations, a spatial analysis of the area interested by the ML2 construction was performed in order to evaluate potential additional external users of the energy. This procedure was carried out through GIS analysis with the aim of identifying potential thermal energy users located in the surroundings of selected extraction points i.e. the stations and the ventilation shafts where there is enough room for heat pump installation. Based on plant running costs issues related to circulation pressure drops, potential users have to be located sufficiently close to the above-mentioned energy extraction points. Hence, a buffer zone of 100 m around the stations and ventilation shafts was evaluated (Fig. 6).

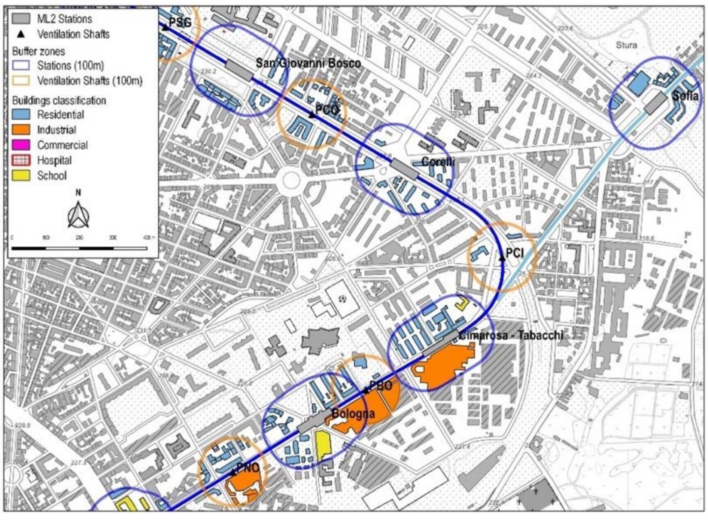


Fig. 6 Example of identification and classification of the potential receivers along a section of the Turin ML2 line.

This study, which still represents the first and more comprehensive study of the application of the technology to such an extensive scale and its potential implementation, has allowed to show the potential of such applications. The satisfaction of the heating/cooling demand of all the planned stations along the line plus an extra heat to be delivered to external consumers results into an exciting payback time of the investment in the order of 7 years together with a reduction up to 60% of the greenhouse emissions with respect to the use of natural gas. The project would represent a noticeable technological and innovation challenge.

A further favorable perspective can be envisaged as it is generally known that the metro line construction can boost new urban and building development. In view of sustainable urban development, the integration possibilities with district heating systems are indeed particularly attractive. Local, prospective district heating networks at different temperature levels, directly connected to the underground infrastructure could be accomplished.

4.2 De-icing of infrastructures

Ice and snow removal are a compelling need to ensure road users' safety. Suspended structures like bridges and viaducts are particularly prone to ice formation due to the lower thermal inertia compared to earth-contact structures. The need to avoid slippery surfaces is even more important when roads present a significant grade, e.g. hilly and mountainous areas such as the Alpine region. Indeed road winter maintenance is often based on the use of chemicals and fine aggregates such as are calcium and sodium chloride (Kuemmel 1994) due to their faster action that however result in structural damages to pavements and concrete structures as well as environmental damages (Corsi et al. 2010; Hintz and Relyea 2017).

These challenges can take advantage of the typical alternance between tunnels and viaducts occurring in motorways in mountain environment where the exploitation of the heat from the tunnels could be used for controlling the temperature on the pavements in the exposed outside area.

The activation of an anti-icing geothermal system can be composed of a geothermal serpentine installed in a tunnel (this can occur during construction or during lining rehabilitation works; De Feudis et al. 2024a; 2024b), which connects to other heat exchanger pipes placed within the infrastructures embedded in the pavements. These applications not necessarily require connection to heat pumps as the free-heating system takes advantage of the thermal inertia of the ground behind the tunnel lining to heat up (or cool down) the infrastructure during winter and summer, respectively.

In the example shown in Fig. 7a and b a typical situation of an Alpine region road with a bridge passing through a gully and two adjacent mechanically excavated tunnels is analyzed (Baralis et al., 2021). The two tunnels were constructed in a metamorphic crystalline rock mass by conventional excavation method and are characterized by an internal radius of 6.3 m. The preliminary lining consisted of 15-20 cm thickness fiber reinforced shotcrete layer, completed by MN24 swellex dowels and 2IPN160 steel ribs where necessary. The final lining is a 70 cm thick reinforced concrete layer. Thermal activation of the tunnel lining was studied by means of numerical simulation to assess the viability of a geothermal-based solution for bridge deck deicing. The study conducted by Baralis et al. (2021) showed that the temperature of the bridge deck could be controlled in order to avoid formation of ice, even in extreme weather conditions, by the connection to two 5 m-long circuits located 10 m after the portals of the adjacent tunnels.

A similar technology has been installed in a tunnel in the A26 motorway in Northern Italy taking advantage of the refurbishment work undergoing that required the partial demolition of the existing cast-in-place concrete tunnel. Fig. 7c shows the thermal activation of the lining obtained by installing the exchanger pipes on the residual lining before casting the new concrete lining (solution B, Politecnico di Torino and Autostrade per l’Italia SpA, 2024).

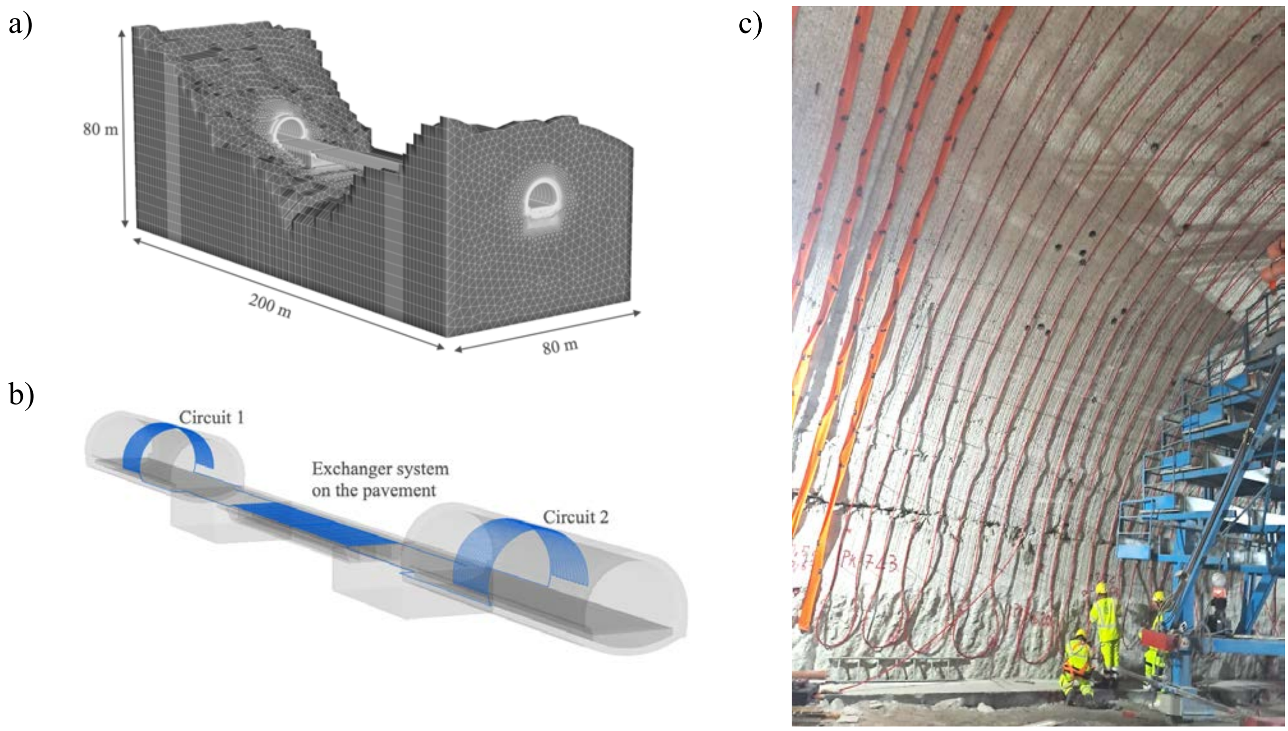


Fig. 7 Numerical model of the Turinella viaduct, the La Turina and Craviale tunnels a); sketch of the embedded pipe network b); a picture from the installation of an anti-icing geothermal system in a motorway tunnel under refurbishment in Italy c).

4.3 Deep tunnels in the mountain environment

Thermal activation of tunnels can also be used effectively to reduce the tunnel air temperature. This specific application finds an interest for hot tunnels such as, for example, old metro tunnels and deep mountain tunnels. In this case, the absorber pipes are to be installed closer to the intrados of the lining, if not directly applied to the lining so to exchange heat preferably with the internal air.

A peculiar example of an application where this technology could provide large benefits is the Lyon-Turin base tunnel, under construction between France and Italy, where a 10 km-long portion of the infrastructure is to be excavated under the huge cover (more than 2 km) of the Ambin massif. In this area temperatures up to 50°C are expected at the depth of tunnelling. These excessive temperatures will require ventilation and cooling of the tunnel during construction and operation. If the thermal activation of the tunnel lining is achieved, not only a system able to exploit energy from a renewable resource (which would be otherwise ignored) could be accomplished, but the tunnel internal climate conditions could be monitored and adjusted as well. Considering that the tunnel construction is expected to take place by TBM, energy segments could be installed (solution A). Due to the length of the tunnel the circuit in the segments could be connected during construction, when the TBM is advanced and the heat recovery could initiate during construction. Not only would this allow for starting energy extraction long in advance to tunnel completion but will also allow to reduce ventilation costs necessary during construction to guarantee proper working conditions for workers.

Alvi et al. (2022) conducted a study to investigate this application. The Air configuration of the Enertun system was considered so that the circuit of embedded pipes is found at the intrados of the concrete lining segments and allows for heat exchange with the air inside the tunnel. The rings are hydraulically connected in pairs forming a subcircuit and the circuit of each segment is linked to that of the adjacent ones by hydraulic connections to form lining ring circuits. The pipes are included in the concrete segments close to the internal boundary (at 10 cm from the air-lining interface), with a spacing of 30 cm, external diameter of 20 mm and thickness of 2 mm (cross-section area of 201 mm^2). Thermo-hydro coupled finite element numerical analyses were conducted to study the thermal performance of the system (Fig. 8). The results obtained show that the system may allow cooling of the tunnel from the actual temperature down to the required working temperature (set to a maximal value of 32 °C by LTF, 2013). Potentially, the heat exploited during the cooling of the 10 km plant could be transferred to the nearest tunnel portal and used to satisfy energy needs in the area.

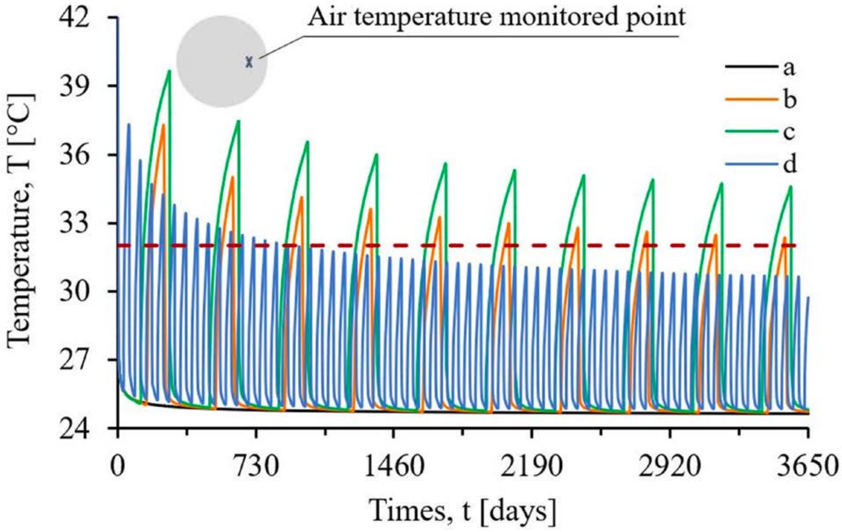
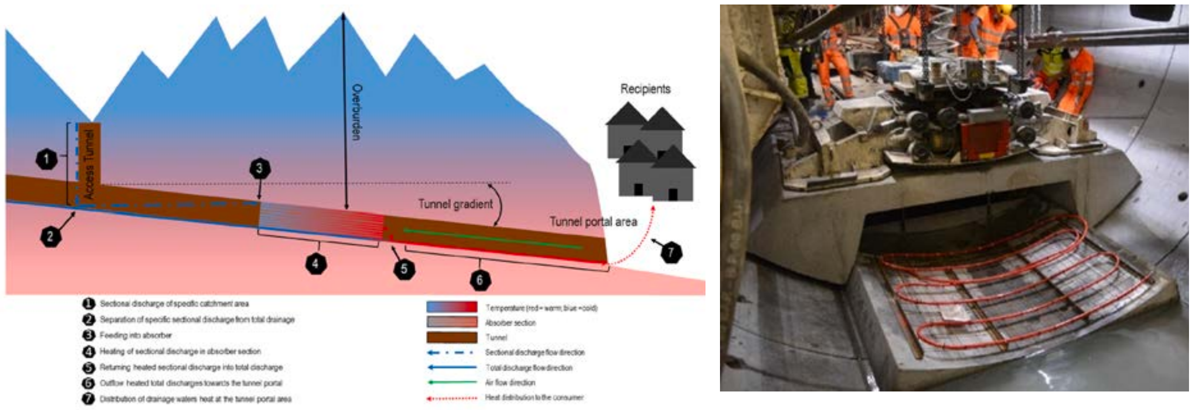


Fig. 8 Internal air temperature with (a) continuous; (b) cyclic (no 3 months); (c) cyclic (no 5 months); and (d) cyclic monthly activation (in red is the established temperature threshold of 32 °C for internal air (Alvi et al. 2022)

Similarly, Tinti et al. (2017) has explored the possibility of thermal exploitation from the Mules access tunnel of the Brenner Base Tunnel project. They proposed installation of absorber pipes upon the preliminary lining (solution B). Although the integration of energy lining in the preliminary design of underground infrastructures is the best solution to optimise space and reduce costs, this is not mandatory for in-situ installation of absorber pipes. The case study showed that, for tunnels excavated with drill and blast technique, the timeframe between primary and secondary lining provides operating space for the GHE designers.

Still with reference to the Brenner Base Tunnel Project, Geisler et al. (2024) investigated the use of an open geothermal system to raise the temperature of colder sectional discharges and enhance the geothermal performance of the total drainage water. They developed a concept in which absorber pipes are either mounted on or into the tunnel lining, being thus applicable to existing or under construction tunnels, to capture the sectional discharge (Fig. 9a). Pipes are installed in the warmest sections of the tunnel and water flows through them purely by gravity. Such concept was studied numerically over a timeframe of 50 years hypothesizing continuous heat extraction and performing sensitivity analyses. The temperature increase ranges from 2.58 to 4.63°C after 50 years, starting from an initial temperature of 12.2°C, corresponding to 0.16-0.29 MW of additional power. They found that the system with pipes embedded in the lining is more efficient, though with greater performance loss over time. However, this solution has to be included already in the early stage of the tunnel's planning phase. Additionally, flow velocity in the pipes should be kept as low as possible, leveraging high temperature tunnel sections to increase the temperature difference between the fluid and the absorber environment. Systems in which the absorber pipes are attached to the lining surface are less effective but offer a possibility in terms of optimization and retrofitting of existing tunnels.

The Brenner Base Tunnel also hosted an experimental prototype of another solution (F), here named Smart Flowing, to exploit drainage water heat in contact with the prototype itself, as described by Tinti et al. (2023). It was designed, constructed and installed in the exploratory tunnel near the border between Italy and Austria. The prototype, belonging to the family of closed-loop systems, was submerged in the water drainage channel, above the invert lower segment and protected by the invert upper segment (Fig. 9b). It comprised a water-air heat pump, a circulation pump and a storage tank. The monitoring campaign revealed that the system could provide 80 W/m of pipe and 282 W/m^2 of exchange area.



a) b)

Fig. 9 Sketch of the concept developed by Geisler et al. (2024); b) picture of the Smart Flowing prototype (Tinti et al., 2023).

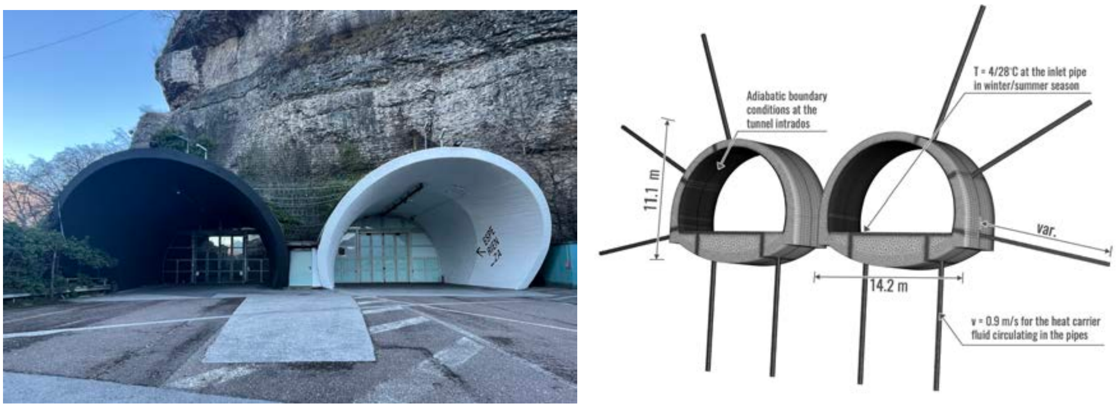


Fig. 10 View of the Piedicastello tunnels and sketch of the thermal retrofitting solution.

Finally, within the European research project ARV (2021), the thermal activation of the existing Piedicastello tunnel in Trento, Italy, is under design. The tunnel was formerly a motorway and now it is used as an exhibition hall (Fig. 10). By adopting the conceptual solution D, radial boreholes are to be installed within the twin tubes by radial drilling from the tunnel. The borehole heat exchangers will allow for exploiting thermal energy for the conditioning of the conference hall of the museum (De Feudis et al., 2023).

The examples described highlight that a huge amount of thermal energy could be exploited by deep mountain tunnels. However, the effective use remains an issue to solve, with a general absence of potential end-users near the tunnel entrance. One potential solution involves distributing and selling low-grade heat to nearby villages and buildings through the establishment of a new district heating network. Achieving this would require exploring innovative collaboration models with local heat and gas providers, as well as developing participation schemes that benefit local administrations and communities.

4.4 Underground energy storage

A large heritage of tunnels and underground spaces exists and some have also reached the service life being abandoned or turned to other uses. Among these mining spaces, metro tunnels, underground air shelters from the II World War are the most common (Fig. 11). This tunnel heritage represents a unique opportunity to develop local renewable energy sources that could be used to promote sustainable, climate-neutral development and contribute to the decarbonisation of the heating and cooling (H&C) sector. It is, therefore, of interest to study and develop innovative solutions (G) that retrofit existing (operating or abandoned) tunnels and underground spaces for the production and storage of thermal energy, thus supplementing the need for storage and energy stability and reducing the reliance on fossil fuel sources. The numerous tunnels existing could become a future energy resource and be integrated into the cities' local energy grid or spark the implementation of new, local heat networks. Local communities in the vicinity of the tunnel could benefit from a resource directly located beneath their feet.

Fig. 11 Example of typical underground cavities used for air shelters and currently abandoned.

As previously mentioned, a specific European research project has been recently launched to address this challenge (Regenerate 2024) testifying the interest in such applications. In addition to this, research has been already conducted to identify possible solutions. In addition to the thermal retrofitting solutions already discussed, abandoned tunnels could be retrofitted to transform them into a heat source or sink to supply the heating and cooling demands of buildings or into an underground "battery" for thermal energy storage. Multiple sources of heat can be thought of: low enthalpy geothermal energy, directly originating from the ground/groundwater surrounding the tunnel or from wastewater in sewage tunnels, solar thermal energy storable in the ground/water, waste heat from industrial processes and cooling processes in commercial buildings (i.e. supermarkets, data centres, etc.).

In general, Underground Thermal Energy Storage (UTES) systems can be based on underground storage solutions for seasonal storage, enabling the utilization of various sources of heating and cooling and the integration of such renewable energy sources in urban areas. These concepts have been developed in the early nineties and have been tested in the laboratory and real scale test sites (Nordell et al. 1994; Novo et al. 2010; Pavlov et al. 2012; Chicco et al. 2022). The storage medium can be water (contained in a tank), gravel, rock or sand (ground materials) or phase change materials. Working temperatures can rise to a maximum value equal to 95 °C (Evangelisti et al., 2019). Given the range of available UTES technologies, they are feasible to be installed almost everywhere. Compared to other storage systems, UTES have the advantage of being able to manage large quantities and fluxes of heat without occupying much surface area, although the storage characteristics are always site-specific and depend on the geological and geothermal characteristics of the subsoil. Among the possible technologies, it is of interest here to highlight those that make effective use, or reuse, of existing tunnels or cavities as shown in Fig. 12.

Tank Thermal Energy Storage (TTES) | Cavern Thermal Energy Storage (CTES)

Fig. 12 Underground thermal energy storage (UTES) methods (from Janiszewski, 2019)

For efficient operation of heating and cooling grids, underground thermal energy storage (UTES) can be a key element. This is due to its ability to seasonally store heat or cold addressing the large mismatch between supply and demand. For instance, UTES systems based on sensible heat storage, typically offer a storage capacity of 10–50 kWh/t and storage efficiencies between 50–90%, depending on the specific heat of the storage medium, storage size and thermal insulation technologies (IEA-ETSAP & IRENA, 2013; Dahash et al, 2019). With specific reference to energy tunnels, Rotta Loria

(2021) has shown that they may have storage efficiencies (i.e. the ratio between the extracted energy and the stored energy over a given operational cycle) of up to about 70%. Therefore, energy tunnels have marked potential to store massive amounts of thermal energy in the shallow subsurface for subsequent reuse.

The storage methods mentioned in the previous lines involve more or less frequent cycles of energy and/or heat injection and discharge. Accordingly, the need arises to investigate the response of rocks to cyclic loading and temperature changes at the temperature ranges for these applications.

5 Conclusions

The development and application of energy tunnels offer a promising pathway towards integrating renewable energy solutions into rock engineering. These systems, which utilize geothermal energy through thermally activated tunnel linings, demonstrate significant potential for addressing modern energy and sustainability challenges.

The main advantage resulting from combining structural and energy functionalities within the same geostructure lies in the fact that they are built in any case. This involves a significant reduction in installation costs, and environmental footprints compared to standalone geothermal plants. Thermal activation of the tunnel linings is therefore an excellent opportunity to mine the ground heat with great economic and environmental advantages.

Energy tunnels can be utilized in diverse scenarios such as heating and cooling of buildings, subway stations, or infrastructure de-icing, particularly in urban and alpine regions. They offer innovative solutions for retrofitting older tunnels and maximizing the utility of existing underground spaces.

Successful deployment of energy tunnels necessitates detailed geotechnical and thermal analyses. The use of coupled numerical modeling aids in optimizing performance while maintaining structural integrity. Early incorporation of energy planning into infrastructure design ensures seamless integration with local energy networks.

Energy tunnels contribute to decarbonizing urban energy systems and mitigating the effects of climate change. Applications in deep mountain tunnels, urban metro networks, and abandoned underground spaces highlight their adaptability and potential for widespread adoption.

In conclusion, energy tunnels represent a transformative opportunity for sustainable development, blending cutting-edge geotechnical innovation with the pressing need for renewable energy integration. Continued research, technological refinement, and desirable policy support will further enable their adoption and scalability.

References

Adam D, Markiewicz R (2009) Energy from earth-coupled structures, foundations, tunnels and sewers. Geotechnique 59: 229–236. 10.1680/ geot.2009.59.3.229.

Agresti FS, Barla M, Insana A, Marchiondelli A, Migliorino P, Rosso E, Selleri A, Spina B (2022) Integrated approach for the inspection and special maintenance of Italian motorway tunnels: The Scampitella case. Gallerie e Grandi Opere Sotterranee 141.

Alvi MR, Insana A, Barla M (2022) Thermal performance assessment of an energy lining for the Lyon-Turin base tunnel. Soils and Rocks 45 (1), e2022000722.

Amis T, Robinson CAW, Wong S (2010) Integrating Geothermal Loops into the Diaphragm Walls of the Knightsbridge Palace Hotel Project. Proceeding 11th DFI / EFFC Int. Conf. London 10.

ARV (2021) H2020 EU-funded project Climate Positive Circular Communities (grant agreement ID: 101036723). Principal Investigator: Inger Andresen (NTNU, Norway).

Baralis M, Insana A, Barla M (2021) Energy Tunnels for Deicing of a Bridge Deck in Alpine Region. Challenges and innovation in Geomechanics, Proc. of the 16th International Conference of IACMAG 2020: 1061-1068.

Barla M, Baralis M, Insana A, Zacco F, Aiassa S, Antolini F, Azzarone F, Marchetti P (2019a) Feasibility study for the thermal activation of Turin Metro Line 2. Tunnels and Underground Cities: Engineering and Innovation meet Archaeology, Architecture and Art, WTC 2019: 231-240. 10.1201/9780429424441-24

Barla M, Baralis M, Insana A, Aiassa S, Antolini F, Vigna F, Azzarone F, Marchetti P (2020). On the thermal activation of Turin metro Line 2 tunnels. Challenges and innovation in Geomechanics, Proc. of the 16th International Conference of IACMAG 2020, Torino 1-4 July 2020, Vol. 2.

Barla M, Di Donna A (2016) Editorial Themed issue on energy geostructures. Environ. Geotech. 3: 188–189.

Barla M, Di Donna A, Insana A (2019b) A novel real-scale experimental prototype of energy tunnel. Tunnelling and Underground Space Technology 87.

Barla M., Di Donna A, Perino A (2016) Application of energy tunnels to an urban environment. Geothermics 61: 104–113. 10.1016/j. geothermics.2016.01.014.

Barla M, Insana A (2023) Energy tunnels as an opportunity for sustainable development of urban areas. Tunnelling and Underground Space Technology 132, 104902.

Barla M, Insana A, Benincasa di Caravacio A (2023) Lessons learnt from a full-scale installation of energy walls SEG 2023. 10.59490/seg.2023.517

Barla M, Perino A (2014). Energy from geo-structures: a topic of growing interest. Environ. Geotech. 2: 3-7, doi.org/10.1680/envgeo.13.00106.

Bourne-Webb P, da Costa Gonçalves R (2016) On the exploitation of ground heat using transportation infrastructure. Procedia Engineering: 1333–1340. 10.1016/j.proeng.2016.06.157.

Bourne-Webb P, Bodas Freitas TM, da Costa Gonçalves RA (2016) Thermal and mechanical aspects of the response of embedded retaining walls used as shallow geothermal heat exchangers. Energy Build. 125: 130-141. 10.1016/j.enbuild.2016.04.075.

Bidarmaghz A, Narsilio GA (2018) Heat exchange mechanisms in energy tunnel systems. Geomech. Energy Environ 16: 83–95. 10.1016/j.gete.2018.07.004.

Bidarmaghz et al. (2023) Investigating the effectiveness of energy tunnels in cooling underground substations. Challenges and innovation in Geomechanics, Proc. of the 16th International Conference of IACMAG 2020, Torino, 1-4 July 2020, Vol. 2.

Brandl H (2006) Energy foundations and other thermo-active ground structures. Geotechnique 56: 81–122.

Buhmann P, Moormann C, Westrich B, Pralle N, Friedemann W (2016). Tunnel geothermics—A German experience with renewable energy concepts in tunnel projects. Geomechanics for Energy and the Environment 8: 1-7.

Chicco JM, Antonijevic D, Bloemendal M, Cecinato F, Goetzl G, Hajto M, Hartog N, Mandrone G, Vacha D, Vardon PJ (2022) Improving the efficiency of district heating and cooling using a geothermal technology: Underground Thermal Energy Storage (UTES). Lecture Notes in Networks and Systems: 1699-1710.

Corsi SR, Graczyk DJ, Geis SW, Booth NL, Richards KD (2010) A fresh look at road salt: aquatic toxicity and water-quality impacts on local, regional, and national scales. Environ. Sci. Technol. 44(19), 7376–7382.

Cousin B, Rotta Loria AF, Bourget A, Rognon F, Laloui L (2019) Energy performance and economic feasibility of energy segmental linings for subway tunnels. Tunnelling and Underground Space Technology 91, 102997.

Dahash A, Ochs F, Janetti MB, Streicher W (2019) Advances in seasonal thermal energy storage for Solar District Heating Applications: A critical review on large-scale hot-water tank and pit thermal energy storage systems. Applied Energy, 239: 296-315.

De Feudis S, Insana A, Barla M (2023) An example of thermal retrofitting for the Piedicastello tunnel. Symposium on Energy Geotechnics Accelerating the energy transition 3-5 October 2023, Delft, the Netherlands.

De Feudis S, Insana A, Barla M, Baccolini L, Zilli L, Mazzola M (2024a) Anti-icing using the heat recovered in the Lagoscuro tunnel. Procedia Structural Integrity 62: 1105–1111.

De Feudis S, Insana A, Barla M (2024b) Seizing the opportunity of energy retrofitting of existing tunnels. Tunnelling and Underground Space Technology, 154: 106109.

Di Donna A, Barla M, Amis T (2017). Energy geostructures: a collection of data from real applications. 15th IACMAG, 19-23 ottobre, Wuhan, China.

Di Donna A, Cecinato F, Loveridge F, Barla M (2016) Energy performance of diaphragm walls used as heat exchangers. Proc. Inst. Civ. Eng. Geotech. Eng.: 1-14. 10.1680/jgeen.

Di Donna A, Barla M (2016) The role of ground conditions on energy tunnels' heat exchange. Environmental Geotechnics 3.

Directive 2009/28/EC. Directive 2009/28/EC of the European parliament and of the council of 23/4/2009. Off. J. Eur. Union 140: 16-62. 10.3000/17252555.L_ 2009.140.eng.

Dornberger SC, Rotta Loria AF, Zhang M, Bu L, Epard JL, Turberg P (2020). Heat exchange potential of energy tunnels for different internal airflow characteristics. Geomechanics for Energy and the Environment, 100229, 10.1016/j.gete.2020.100229

European Commission (2016) Overview of support activities and projects of the European Union on energy efficiency and renewable energy in the heating & cooling sector. Publications Office of the European Union, Luxembourg. https://doi.org/10.2826/ 607102.

Evangelisti L, De Lieto Vollaro R, Asdrubali F (2019) Latest advances on solar thermal collectors: a comprehensive review. Renewable and Sustainable Energy Reviews 114, 109318.

Franzius JN, Pralle N (2011). Turning segmental tunnels into sources of renewable energy. ICE Proceedings Civil Engineering: 35-40.

Frodl S, Franzius JN, Bartl T (2010). Design and construction of the tunnel geothermal system in Jenbach. Tunnel Engineering: 2-11.

Geisler T, Richter W, Marcher T (2024) Enhancing the performance of open geothermal tunnelwater systems by heat absorbers. Tunnelling and Underground Space Technology 145, 105591.

Hintz WD, Relyea RA (2017) Impacts of road deicing salts on the early-life growth and development of a stream salmonid: Salt type matters. Environ. Pollut. 223: 409–415.

IEA-ETSAP & IRENA (2013) Thermal Energy Storage. Technology Brief E17, 1–20. January 2013.

Insana A, Barla M (2020) Experimental and numerical investigations on the energy performance of a thermo-active tunnel. Renewable Energy. 10.1016/j.renene.2020.01.086.

Insana A (2020) Thermal and structural performance of energy tunnels. PhD thesis, Politecnico di Torino, 436 pp.

Insana A, Barla M, Sulem J (2020) Energy tunnel linings thermo-mechanical performance: comparison between field observations and numerical modelling. Int. Conf. on Energy Geotechnics, La Jolla, California, USA - September 20-23, 2020.

Janiszewski M (2019) Techno-economic aspects of seasonal underground storage of solar thermal energy in hard crystalline rocks. PhD Thesis. Aalto University series 169/2019.

Kuemmel DE (1994) Managing roadway snow and ice control operations. Transportation Research Record, NCHRP, Synthesis 207.

Laloui L, Di Donna A (2013) Energy geostructures: innovation in underground engineering. ISTE Ltd and John Wiley & Sons Inc.

Lee C, Park S, Won J, Jeoung J, Sohn B, Choi H (2012) Evaluation of thermal performance of energy textile installed in Tunnel. Renew. Energy 42: 11–22.

Lee C, Park S, Choi HJ, Lee IM, Choi H (2016) Development of energy textile to use geothermal energy in tunnels. Tunnelling and Underground Space Technology 59: 105–113.

LTF (2013) Ventilazione: studio degli scenari di estrazione fumi dal tunnel (Revisione del progetto definitivo). Lyon Turin Ferroviarie. Chambery, France (in Italian).

Lund JW, Freeston DH, Boyd TL (2011) Direct utilization of geothermal energy 2010 worldwide review. Geothermics 40: 159–180. https://doi.org/10.1016/j. geothermics.2015.11.004.

Ma C, Di Donna A, Dias D, Zhang J (2021) Numerical investigations of the tunnel environment effect on the performance of energy tunnels. Renewable Energy 172: 1279–1292.

Ma C, Di Donna A, Dias D (2022) Numerical study on the thermos-hydro-mechanical behaviour of an energy tunnel in a coarse soil. Computers and Geotechnics 151, 105003.

Makasis N, Narsilio GA (2020) A case study on the application of energy tunnels in Sydney, Australia. In M. Barla, A. Di Donna, D. Sterpi (eds.), Challenges and innovation in Geomechanics, Proc. of the 16th International Conference of IACMAG 2020, Torino 1-4 July 2020, Vol. 2.

Mimouni T, Dupray F, Laloui L (2014). Estimating the geothermal potential of heat-exchanger anchors on a cut-and-cover tunnel, Geothermics 51: 380–387. 10.1016/j.geothermics.2014.02.007.

Moormann C, Buhmann P, Friedemann W, Homuth S, Pralle N (2016). Tunnel geothermics - International experience with renewable energy concepts in tunnelling / Tunnelgeothermie - Internationale Erfahrungen zu regenerativen Energiekonzepten im Tunnelbau. Geomech. Tunn. 9: 467–480.

Nordell B, Ritola J, Sipilä K, Sellberg B (1994) The Combi Heat Store - a Combined Rock Cavern/Borehole Heat Store. Tunneling and Underground Space Technology, 9(2): 243-249.

Novo AV, Bayon JR, Castro-Fresno D, Rodriguez-Hernandez J (2010) Review of seasonal heat storage in large basins: Water tanks and gravel–water pits. Applied Energy, 87(2): 390-397.

Nicholson DP, Chen Q, de Silva M, Winter A, Winterling R (2014). The design of thermal tunnel energy segments for Crossrail. UK. Eng. Sustain. 167: 118–134.

Pavlov GK, Olesen BW (2012) Thermal energy storage—a review of concepts and systems for heating and cooling applications in buildings: Part 1—seasonal storage in the ground. HVAC&R Research, 18(3): 515–538.

Peltier M, Rotta Loria AF, Lepage L, Garin E, Laloui L (2019) Numerical investigation of the convection heat transfer driven by airflows in underground tunnels. Applied Thermal Engineering 159, 113844.

Regenerate (2024) REgENEraTE - REuse for ENergy Exploitation and storage of existing urban Tunnels in Europe. Research project, 2024-2027, DUT – Driving Urban Transition programme. Principal Investigator: Alessandra Insana (Politecnico di Torino, Italy).

Rotta Loria AF (2021) The thermal energy storage potential of underground tunnels used as heat exchangers. Renewable Energy 176: 214-227.

Rotta Loria AF, Di Donna A, Zhang M (2022) Stresses and deformations induced by geothermal operations of energy tunnels. Tunnelling and Underground Space Technology 124, 104438.

Ronchi F, Salciarini D, Cavalagli N, Tamagnini C (2018) Thermal response prediction of a prototype Energy Micro-Pile. Geomechanics for Energy and the Environment 16: 64-82.

Rybach L (1995). Thermal waters in deep Alpine tunnels. Geothermics 24 (5–6): 631–637.

Schneider M, Moormann C (2010) GeoTU6 – A geothermal Research Project for Tunnels. Tunnel 2: 14–21.

Sterpi D, Angelotti A, Habibzadeh-Bigdarvish O, Jalili D (2018). Assessment of thermal behaviour of thermoactive diaphragm walls based on monitoring data. Journal of Rock Mechanics and Geotechnical Engineering 10: 1145–1153.

Tinti F, Boldini D, Ferrari M, Lanconelli M, Kasmaee S, Bruno R, Egger H, Voza A, Zurlo R (2017) Exploitation of geothermal energy using tunnel lining technology in a mountain environment. A feasibility study for the Brenner Base tunnel – BBT. Tunnelling and Und. Space Tech. 70, 182–203. 10.1016/j.tust.2017.07.011.

Tinti F, Spaggiari C, Lanconelli M, Voza A, Boldini D (2023) Exploitation of drainage water heat: A novel solution experimented at the Brenner Base Tunnel. Tunnelling and Underground Space Technology 137, 105131.

Unterberger W, Hofinger H, Grünstaudl T, Adam D, Markiewicz R (2004) Utilization of Tunnels as Source of Ground Heat and Cooling – Practical Applications in Austria. Proc. of the ISRM International Symposium 3rd ARMS, Kyoto: 421–426.

Wilhelm J, Rybach L (2003) The geothermal potential of Swiss Alpine tunnels. Geothermics 32: 557–568.

Zannin J, Ferrari A, Larrey-Lassalle P, Laloui L (2020) Early-stage thermal performance design of thermo-active walls implemented in underground energy infrastructures. Geomechanics for Energy and the Environment 30, 100218.

Zhang G, Xia C, Sun M, Zou Y, Xiao S (2013) A new model and analytical solution for the heat conduction of tunnel lining ground heat exchangers. Cold Reg. Sci. Technol. 88: 59–66.

Zhang G, Xia C, Yang Y, Sun M, Zou Y (2014) Experimental study on the thermal performance of tunnel lining ground heat exchangers. Energy Build. 77: 149–157. 10.1016/j.enbuild.2014.03.043