Energy tunnels as an opportunity for sustainable development of urban areas

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ABSTRACT

The use of renewable energies will be increasingly necessary to reduce carbon dioxide emissions. An important contribution can be provided by energy tunnels, which make it possible to draw on a form of clean, renewable and locally accessible thermal energy for heating and air conditioning of buildings. The paper describes the characteristics of an energy tunnel and the design aspects necessary for its conception. Explicit reference will be made to the studies conducted at the Politecnico di Torino which led to the development of an innovative energy segment which was then used to create an experimental prototype in the true size of an energy tunnel. The data collected allowed to evaluate the performance of the system and to study the possibility of thermally activating the tunnels of the future Line 2 of the Turin Metro, allocating the heat partly to the air conditioning of the stations and partly to external users. With a view to sustainable urban development, the possibility of integration with district heating systems and the possible creation of local heat distribution networks at different temperatures, directly connected to the underground infrastructure, is particularly attractive and promising.

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.

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 in lieu 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 of subway stations and substations (Bidarmaghz et al., 2023) or buildings near the tunnel (Nicholson et al., 2014; Barla et al., 2016) or heating the lining itself (Zhang et al., 2014), to deicing of bridge decks, rails and routes strengthening both safety and durability (Islam et al., 2006; Baralis et al. 2020).

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 was designed at Politecnico di Torino (Barla and Di Donna, 2016b), i.e. Enertun. Next, a full-scale experimental prototype of an energy tunnel was installed in Turin Metro Line 1 South Extension. Data collected between 2017 and 2018 enabled the assessment of the technology performance in the city underground. The research with its promising outcomes was preparatory for launching the feasibility study of the future Metro Line 2 geostructures' thermal activation.

For the quantification of the geothermal potential achievable from the 27.6 km of the Line 2 tunnels, a methodological approach based on numerical finite-elements, thermo-hydraulic analyses was developed. The study resulted in drawing up a proposal on heat utilization which will be partially devoted to stations climate control and partially delivered to external customers. 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. The project embodies the first experience ever worldwide to study the application of the

technology to such an extensive scale and its potential implementation would represent a noticeable technological and innovation challenge.

To provide a comprehensive picture, in the following the main characteristics of energy tunnel linings and their technological and design aspects will be discussed. Then, the experimental prototype built in Turin will be described together with the illustration of the methodological approach used for the application to Metro Line 2 and the results obtained.

2 ENERGY TUNNELS

2.1 The concept of energy geostructures

Energy geostructures are all those geotechnical-structural works such as a foundation or a diaphragm wall able to combine the twofold aim of structural stability and heat exchange with the surrounding ground in one single element (Brandl, 2006; Barla and Perino, 2014). The members of the geotechnical structure are coupled with closed systems able to absorb heat from the ground they are in contact with and to deliver it to the heat pump that will make it available to final users.

The main advantage of heat exchanger loops embedment 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 retrofitting too (Ronchi et al., 2018).

The use of energy geostructures began in the 80s, with the first examples related to base slabs. Then, the use widened to other geostructural assets, such as piles and walls. Many case studies that can be found in literature witness the success of energy geostructures built in Austria, Germany, UK, Switzerland (Brandl, 2006; Adam and Markiewicz, 2009; Preene and Powrie, 2009; Barla and Di Donna, 2016; Di Donna et al., 2016; Di Donna et al., 2017; Bourne Webb and da Costa Goncalves, 2016; Bourne Webb et al., 2016; Laloui and Di Donna, 2013).

Thermal activation of tunnel linings is probably less common. Nevertheless, this application could play a relevant role in coping with the growing energy demand. As mentioned, 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. 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.

2.2 Specific features of energy tunnels

Over recent years there has been a growing interest in the energy mining of tunnel linings. Technologies harnessing the geothermal potential of water available in the rock mass are well-established, especially in Switzerland (Rybach, 1995; Wilhelm and Rybach, 2003) and, generally speaking, 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. 1, where the geothermal loops within the tunnel lining can displace heat from the ground to the surface and vice versa.

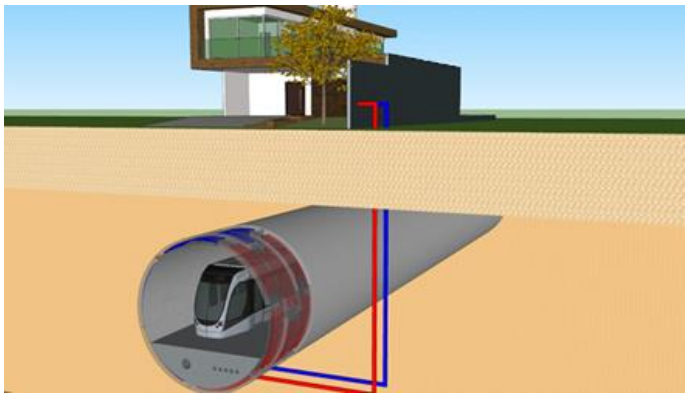


Fig. 1 Schematic view of the operation principle of energy tunnels buildings heating and cooling.

A 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, pipes 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-years 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; Zhang et al., 2014; Zhang et al., 2016) 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, in China, 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 open-cut 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; Bouazza et al., 2011; Sterpi et al., 2014; Bourne Webb et al., 2016; Di Donna et al., 2016; Barla et al. 2018a; Sterpi et al., 2018; Makasis and Narsilio, 2020; Zannin et al., 2020).

For tunnels built by mechanized tunnelling, the final lining is 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, before tunnel opening, where 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 the 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 of 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 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 behavior was investigated by Insana et al. (2020), Rotta Loria et al. (2022) and Ma et al. (2022) for the case of a 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 the application to the city of Turin and will be hereafter described.

2.3 The Enertun technology

The research carried out at Politecnico di Torino from 2013 onwards is particularly relevant for illustrating the milestones achieved, among which there 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 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. 2.), close to the intrados (Air, Fig. 2.) or it 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.

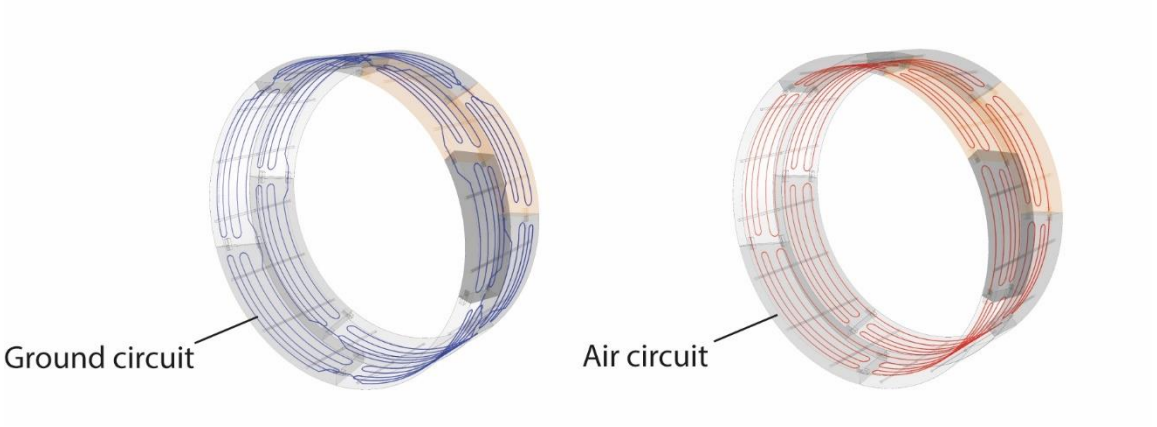


Fig. 2 Ground and air Enertun configurations, which can be eventually combined together.

3 DESIGN ASPECTS FOR ENERGY TUNNELS

3.1 General considerations

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 urban development thanks to its full integration into municipal energy planning.

Having said this, thermal activation of energy linings entails at least two technical aspects that need to be taken into account during the project stages. 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 structural design, that identifies the mechanical effects in the structural elements following the thermal loading, assessed from 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. Fully coupled thermo-hydro-mechanical (THM) simulations can be, initially, avoided as in most cases the computational effort and the increase in calculation time are not reflected in a more accurate result. For these reasons, in the following, the discussion will be limited to the illustration of results stemming from TH and TM coupled analyses (Barla and Di Donna, 2018). A procedural proposal for the design of energy tunnels was put forward during the works carried out at Politecnico di Torino (Baralis et al., 2018; Barla et al., 2020) and is outlined in the flow chart in Fig. 3. It is highlighted that sizing of the hydraulic circuit also needs to be carried out and will be described in the following.

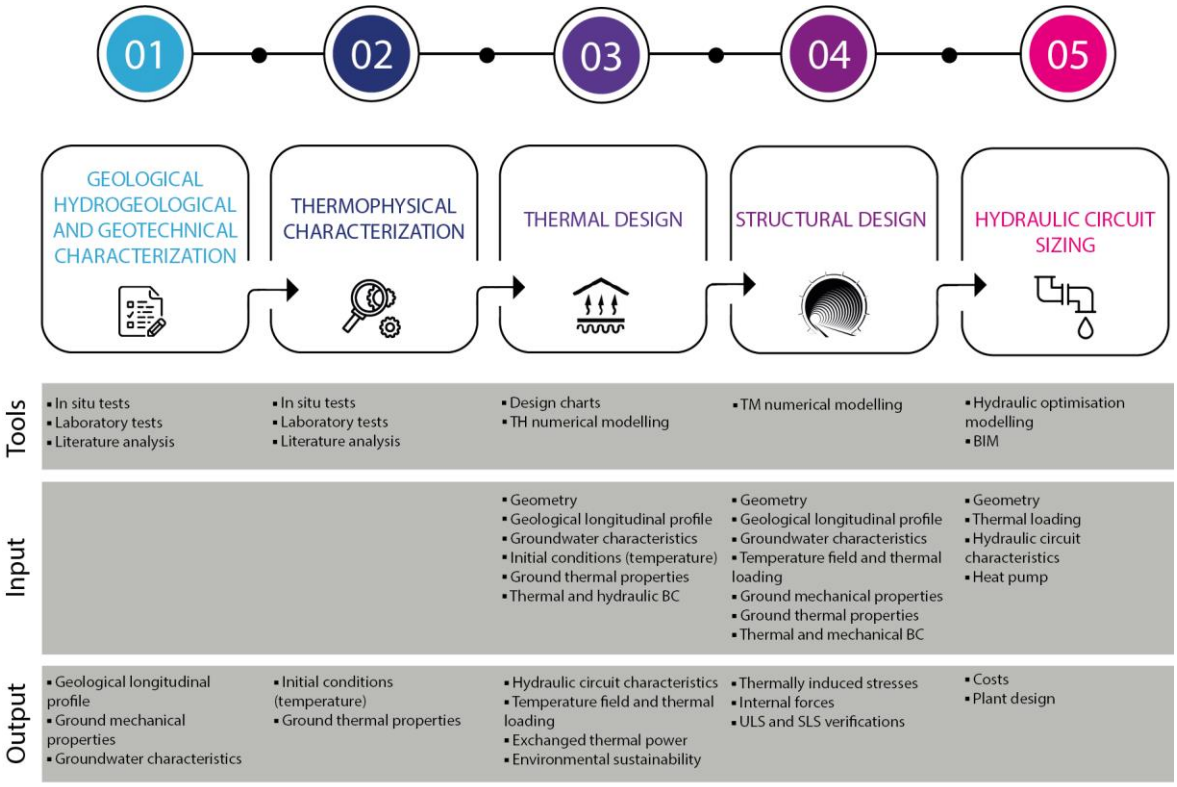


Fig. 3 Design flow for an energy tunnel.

3.2 Thermal design

If structural design can be reasonably deepened later in the design stages, it is the thermal design that has to be addressed as early as the tunnel concept. The aim of thermal design is to quantify the heat power that can be extracted or transferred to the geothermal reservoir through the tunnel lining. This will depend on the specific in situ conditions, and will allow to assess the cost-effectiveness and the environmental sustainability of the system. The latter is about the evaluation of the effects of such systems on the surrounding environment, to limit their impacts as much as possible.

Because this is a relatively new technology, no clear methodological guidance or regulations exist for thermally sizing energy tunnels. Indeed, for other, more widely spread energy geostructures, such as foundation piles, the need to discuss about the introduction of design standards procedures, harmonizing them with the current regulatory framework, only recently showed up. In particular, some considerations on the need to introduce an approach consistent with limit state design emerged in the papers by Preene and Powrie (2009) and Bourne-Webb et al. (2014). As noted by these authors, the lack of codification is related to the fact that, so far, design was ruled by the experience cumulated during the implementation of traditional geothermal plants. For instance, referring to energy piles, it is common practice to simplify the problem to the case of a simple borehole heat exchanger (BHE). At the time of writing recommendations for designing and installing energy geostructures only exist in Switzerland (SIA, 2005), UK (GSHPA, 2012) and France (CFMS/SYNTEC INGENIERIE/SOFFONS-FNTP, 2016). However none of them extensively treated energy tunnels.

First of all, following the flow chart in Fig. 3, supplementary investigations should be carried out, whose level of detail will depend on the design stage, aimed at assessing the ground thermo-hydro-geological characteristics that can influence the heat transfer processes (see Vieira et al., 2017; Vieira et al., 2022). The material parameters that have to be assessed are shown in Table 1.

Table 1 Ground and structural elements properties to be determined for thermal design of an energy tunnel.

Properties	Investigations
Thermal conductivity, λ [W/mK]	TRT, needle probe, transient plane source
Thermal specific capacity, S_c [J/kgK]	Transient plane source
Undisturbed temperature, T_0 [°C]	TRT, measures at different depths with level probe with temperature sensor
Effective porosity, n_e	Classification laboratory testing
Horizontal and vertical permeability, k_h, k_v [m/s]	Pumping tests, slug test
Groundwater flow velocity, v [m/s]	Level probe, existing groundwater maps
Groundwater depth, f [m]	Level probe, existing groundwater maps
Groundwater flow direction, df	Level probe, existing groundwater maps

Among in situ testing techniques, the Thermal Response Test (TRT), very common for BHE and energy piles, is useful to evaluate ground thermal conductivity, heat exchanger thermal resistance and undisturbed ground

temperature. Laboratory testing can be classified into steady-state methods (e.g. hot guarded plate) and transient methods (e.g. needle probe, transient plane source) that allow assessing thermal conductivity, thermal diffusivity and volumetric heat capacity (ASTM, 2012; ASTM, 2014; Loveridge et al., 2017). However, laboratory measurements do not take into account site-specific conditions such as groundwater flow, spatial heterogeneity and scale effects that directly affect real thermal properties (Vieira et al., 2017).

To quantify the geothermal potential, a 3D thermo-hydraulic numerical model able to reproduce a portion of the thermally active lining has to be built. In the case of energy segments, a limited number of tunnel rings equipped with heat exchangers can be reproduced. In general, it is possible to refer to finite elements or finite difference codes.

Typically, the analyses reproduce the operation of the energy lining in correspondence of meaningful cross-sections for a certain number of years, to analyze not only short-term effects but also and especially long-term ones.

A detailed study of hydrogeological conditions is crucial to identify the groundwater regime. Indeed, in geothermal systems, the presence of a hydrodynamic flow plays a particularly favourable role in the heat transfer process given that it constantly recharges the reservoir from an energetic point of view thus preventing the geothermal resource depletion.

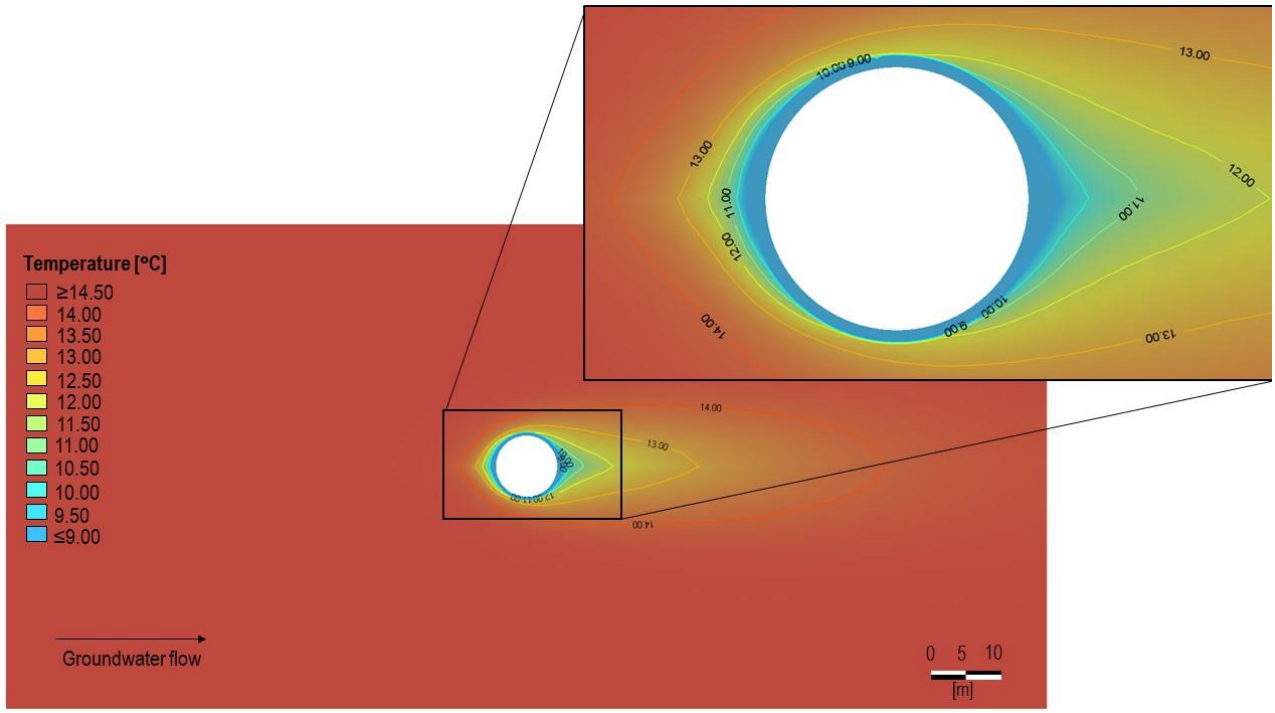
The TH analyses here presented as an example have been performed by means of the finite element code FEFLOW (Diersch, 2009). The thermo-hydraulic problem is dealt with by solving mass and energy conservation equations, by assuming Darcy's law for groundwater flow velocity.

To build the numerical model the correct case study geometry has to be accurately reproduced, including the layout and the geometry of the geothermal circuit and the ground thermal and hydrogeological conditions. In the example shown in Fig. 4, corresponding to a circular tunnel excavated in a saturated sand and gravel subsoil, groundwater flow was reproduced by setting a hydraulic head difference as boundary conditions on the lateral sides of the model, thus leading to a perpendicular flow with respect to the tunnel axis whose velocity depends on the ground permeability. Heat exchangers are simulated thanks to monodimensional elements implemented in the software. The use of these elements to represent geothermal installations pipes was validated and showed good consistency with data from analytical models (Diersch, 2009). Mass and energy conservation laws are fulfilled for these elements as well and the flow within them can be described by the Hagen-Poiseuille law. Hence, it is assumed as being in pure translation and with constant velocity.

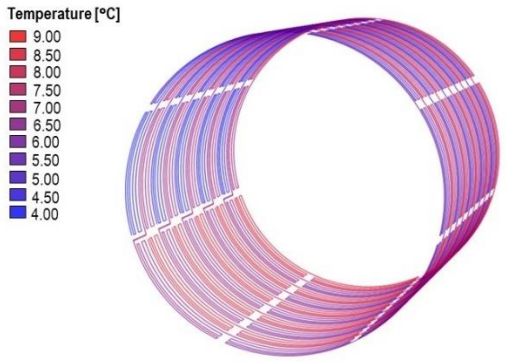
After setting initial conditions, the analysis is carried out by fixing inlet temperature and inlet/outlet velocity in the circuits and monitoring outlet temperature, function of the heat transfer which is reproduced numerically during the simulation.

By changing inlet temperature, the analysis can simulate the system behaviour during the different thermal activation seasons. For instance, if inlet temperature ranges from 24 to 28°C, summer operation is simulated, when excess heat is dispersed in the ground. Conversely, by setting inlet temperature between 3 and 6°C, it is

possible to simulate winter operation, characterized by heat extraction from the ground. This is shown in Fig. 4 where a typical winter result for the Torino case study is displayed in terms of soil temperature profile around the tunnel and within the pipes and inlet/outlet temperatures computed. If inlet temperature varies cyclically, according to the yearly operation, the seasonal plant functioning is simulated and long-term effects can be assessed.



(a)



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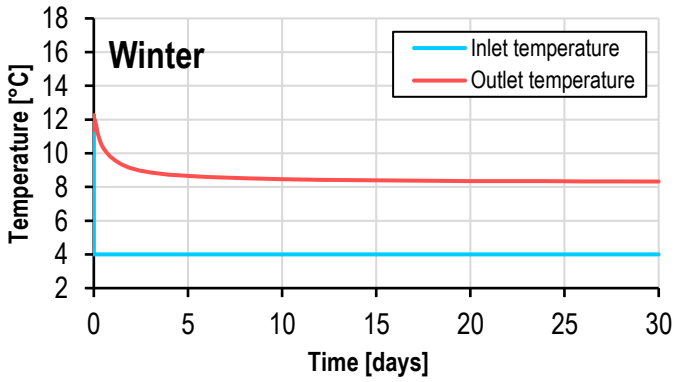


(c)

Fig. 4 Example of results for winter operation: soil temperatures a), pipes temperatures b) and energy segments inlet/outlet temperatures c).

The heat power Q, expressed in W, exchanged during winter and summer can be computed from the difference between pipes inlet and pipes outlet temperatures T_{wi}, T_{wo}, according to the following formulation:

$$Q = mc(T_{wo} - T_{wi}) \quad (1)$$

where *m* is the flow rate in kg/s and *c* is the heat carrier fluid heat capacity. Equation (1) enables to compute the heat exchanged for a specific case, then used for assessing the geothermal potential of the concerned part of the tunnel.

Another alternative approach was proposed by Delerablee (2019). It is based on the Gauss's theorem (divergence theorem) and allows to identify the heat exchanged by each control volume in the numerical model by conduction and by convection.

As already mentioned, several factors affect heat exchange. As a first approximation, to save time and avoid complete numerical modeling, Di Donna and Barla (2016) carried out a parametric analysis to study the influence of some key parameters such as ground temperature, groundwater flow and ground thermal conductivity. The work led to developing design charts to assess system energy efficiency according to the specific site conditions. Later, design charts were updated by Insana and Barla (2020) to account for the favourable configuration of the Enertun segment. The latter charts are more comprehensive as they also consider groundwater flow orientation with respect to the tunnel axis and heat carrier fluid inlet temperature thanks to a correction formula. These design charts are shown in Fig. 5 for winter and summer operations, as well as for three different groundwater flow directions. The specific heat power in W/m^2 is obtained from a triplet of data, that is groundwater flow velocity (x-axis), ground initial temperature (y-axis) and total thermal conductivity (different lines hatchings). The results obtained showed good agreement with real monitoring data available in the literature pertaining to some of the sites described in chapter 2. Therefore, they can be used for a preliminary assessment of the heat exchanged. Further study will be needed at a later stage of design by performing specific numerical analyses for the specific application, as set out above.

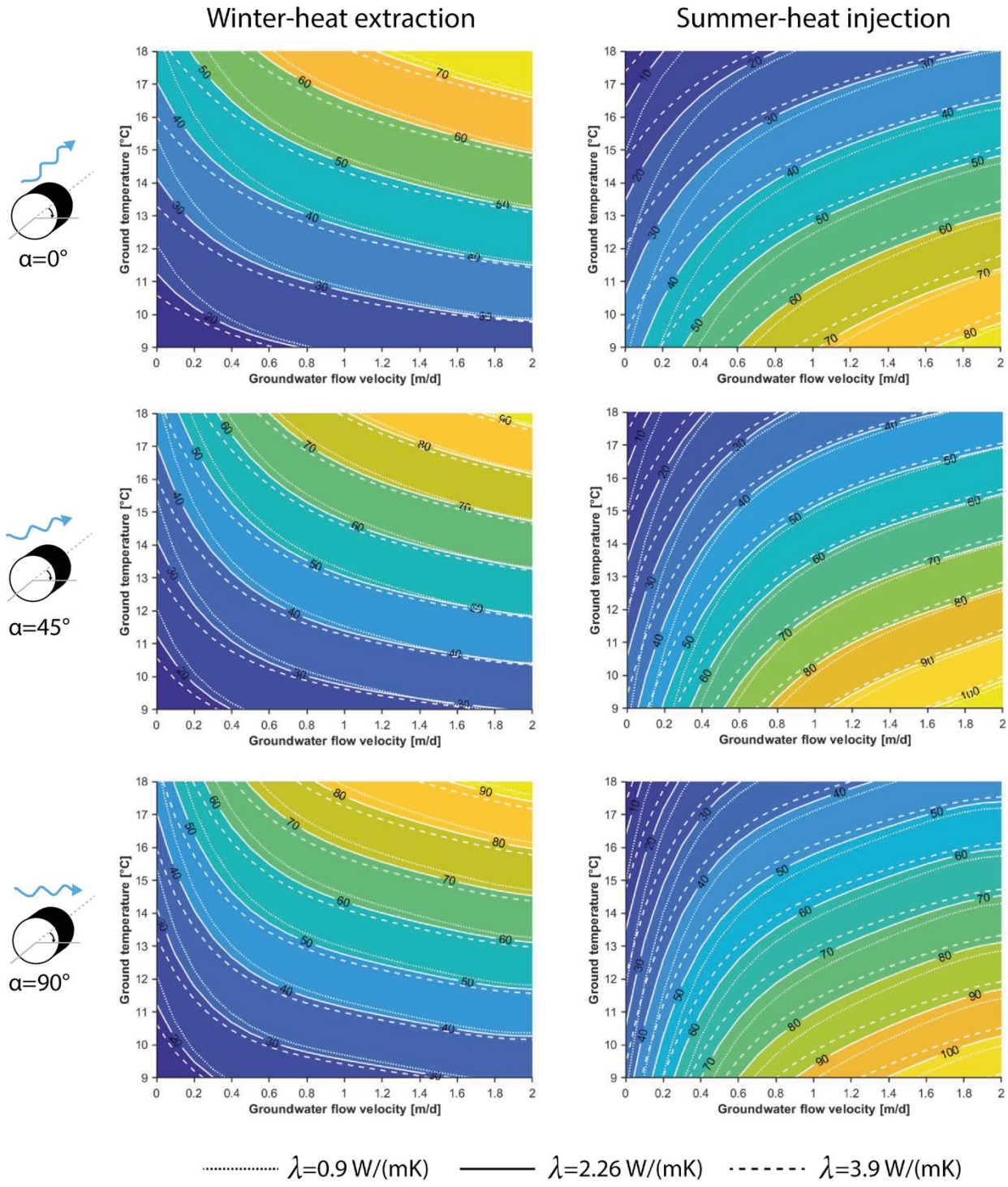


Fig. 5 Example of design charts for the definition of geothermal potential in W/m^2 in winter and summer for multiple groundwater flow directions (0°, 45° and 90°) (Insana and Barla, 2020).

From the analysis of the design charts some general comments on energy tunnels behaviour can be drawn. No matter the flow direction, the highest performance is obtained with maximum ground thermal conductivity, maximum groundwater flow, due to the thermal recharge mechanism that allows the ground to return more rapidly to its undisturbed temperature, and with maximum ground temperature in winter and viceversa in summer. As groundwater flow velocity decreases, thermal conductivity starts playing a role. For perpendicular groundwater flow winter energy performance is in the range 10-95 W/m^2, while summer energy performance

falls between 10-110 W/m^2, slightly higher than in summer. By observing the effect of groundwater flow, it is inferred that the performance is significantly increased when the flow is perpendicular to the tunnel axis as compared to an orientation of 0°, whereas little improvement is attributable to perpendicular flow in comparison to the oblique case.

Environment sustainability analysis completes the thermal design. This analysis aims to check potential impacts of tunnel energy lining on the surrounding environment, assessing the entity of thermal anomalies induced in the groundwater and the ground for different working hypotheses (winter only, summer only or both). Indeed, continuous winter operation could progressively decrease ground temperature leading to drift in time with resulting consequences not only on the following heating season but also on the balance of the surrounding ecosystem. This contingency has to be thoroughly examined taking into consideration, wherever possible, the operation for both heating and cooling. To this end, thermo-hydraulic numerical modeling can help too. As highlighted in Barla et al. (2016), the solution with lower environmental impact is achieved with geostructures working both in summer and in winter, where, at best, the amount of heat extracted in winter is balanced by the amount of heat stored during summer. In this way, a heating or cooling trend of the geothermal reservoir is largely reduced. However, this is not always in line with local energy demands and the environmental analyses should consider the real needs and the geostructure operation. Interaction with the surrounding environment and other possible uses of the resource have to be studied as described by a number of Authors (Bidarmaghz et al., 2017; Barla et al., 2018b; Epting et al., 2020).

Lastly, one of the peculiarities that can significantly affect the system's performance is tunnel climate, as pointed out by several Authors (Moormann et al., 2018; Nicholson et al., 2014; Peltier et al., 2019; Ogunleye et al., 2020; Dornberger et al., 2020; Ma et al., 2021). Heat exchange has been found to depend also on the difference between tunnel air temperature and the circulating fluid temperature and on airflow velocity (associated with the convection heat transfer coefficient). Thereby, knowledge of tunnel environment characteristics is a fundamental precondition for evaluating energy efficiency and technical-economic feasibility and can be accounted for, as done in this study, by means of a Cauchy boundary condition. Should this not be possible, various alternative scenarios can be considered in the coupled thermo-hydraulic analyses.

3.3 Structural design

The goal of structural design for energy tunnels is to examine the effects that thermal activation involves on the stress state in the lining, illustrating additionally the implications on structural dimensioning, if any. This is consequent to the change in internal actions caused by the change in the state of stress. In particular the key aspect is the quantification of the effect that thermal change, due to the fluid circulation within pipes in the lining, induces in terms of stresses. Once this is done, the influence on internal actions can be ascertained and the lining structural design can be updated, accounting for the loading scenario associated with the operation of the geothermal heat exchanger. Indeed, lining thermal activation can be treated as an additional loading stage compared to those ordinarily looked at during design.

With reference to energy geostructures in general, recommendations of some European societies (see GSHPA, 2012) provide suggestions for the assessment of the additional thermal stress and/or strain state for energy piles. No specific directions can be found for tunnels. A detailed work in this perspective was performed by Insana (2020) who relied on experimental data and numerical analyses to understand the trends and the order of magnitudes of stresses and strains variations in the concrete lining in different directions based on the experimental campaign performed in the Turin Metro Line 1 full-scale test site, both in the natural state and under the particular conditions experienced upon thermal activation. Based on such findings with reference to a coarse-grained soil, upon cooling (winter heating mode) temperature decrease in the lining in the conditions studied is in the order of 4-6°C with subsequent contractive hoop strains of some tens of microstrain and a decrease in compressive stresses in the order of the MPa. The opposite behaviour is exhibited upon heating (summer cooling mode) with expansive hoop strains and an increase in compressive stresses, though in this case experimental data indicate an order of magnitude of some MPa. Moreover, the correlation of strains and stresses with temperature highlights an almost reversible behaviour with ranges of strains between ±100 με and of stresses between -2 and 3 MPa when temperature changes are ±8°C. Strain temperature ratio is about 10 με/°C, very similar to the concrete thermal expansion coefficient, whereas stress temperature ratio goes from 0.1 up to 0.5 MPa/°C. Longitudinal stress is null in all cases, showing a plane stress condition.

The problem can be investigated into more detail by resorting to numerical modeling. To analyze the energy lining working condition, a numerical model with thermomechanical formulation is needed, that allows to couple the mechanical and thermal aspects. Mechanical and thermal parameters of the materials involved will be derived from appropriate investigations and testing, as depicted in Fig. 3. The parameters of deformability and strength, the stress history of the site and what is necessary for a typical geotechnical calculation will have to be determined. Furthermore, the determination of the linear and volumetric thermal expansion coefficient for the materials involved (e.g. soil, concrete, filling grout) will be needed.

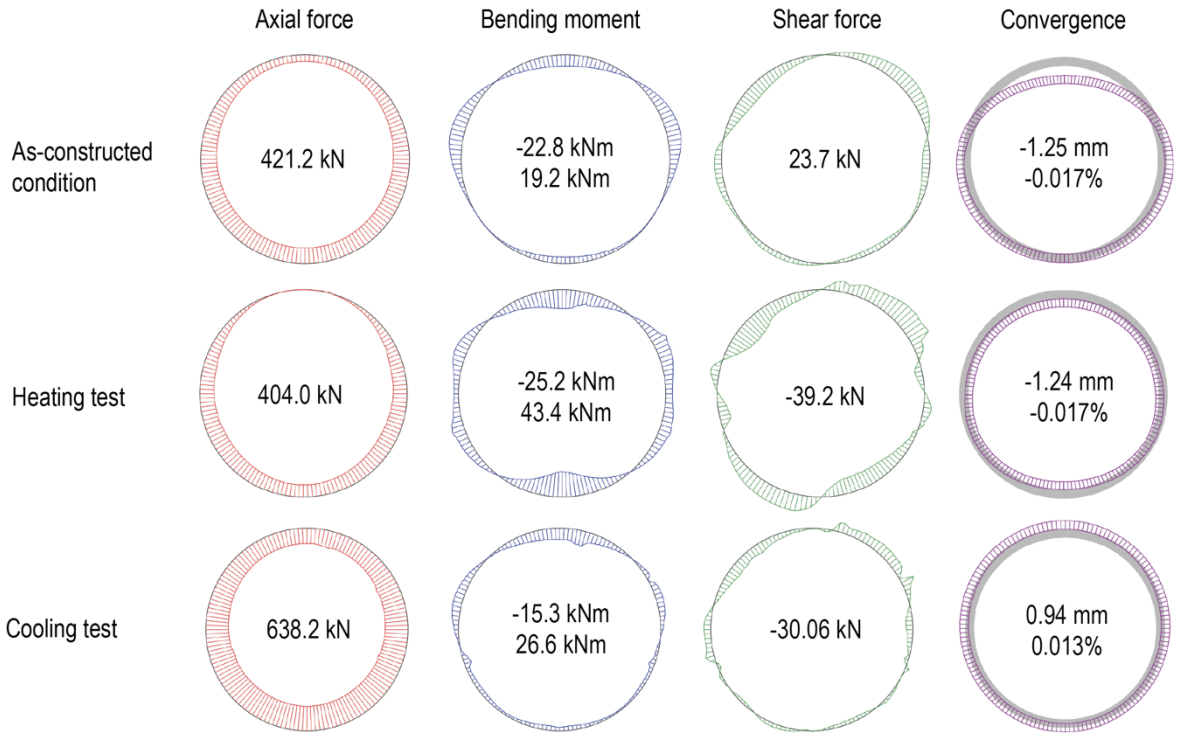
The numerical model will be such as to reproduce the different construction phases of the tunnel until commissioning, adding the heat exchange pipes, and an appropriate law of variation in temperature that reproduces the functioning of the system both in winter and in summer.

In particular, referring to a geothermal system with the double role of heating and conditioning, the structure will be prone to temperature variations during the several seasonal cycles that can trigger internal stress state changes. Such changes can give rise to a stress reduction, that is a compression, or to a stress increase in tension. In view of these aspects, the structural element reinforcement can be calculated. Fig. 3 explains this process schematically.

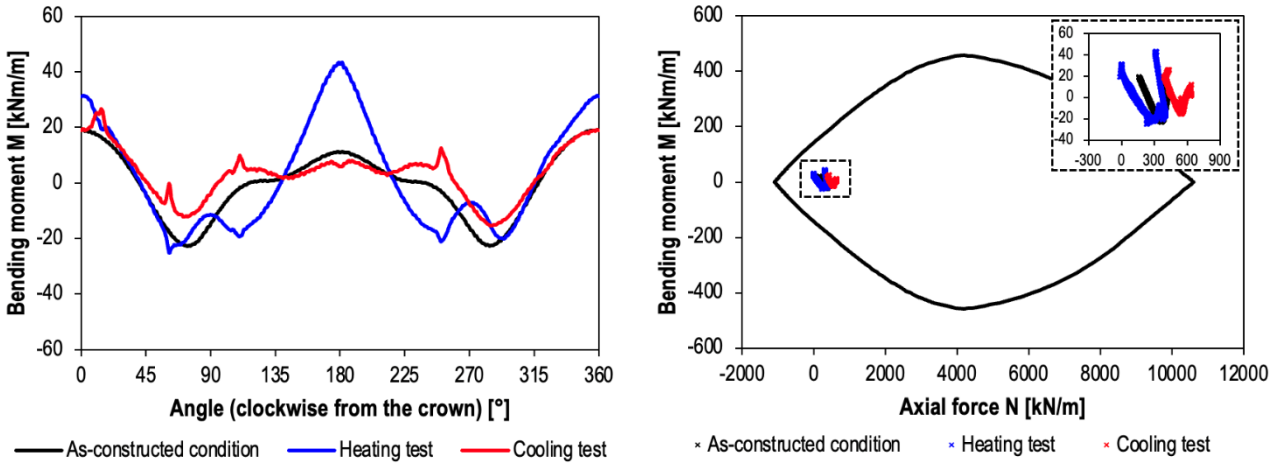
A calculation example for the assessment of internal actions and deformed tunnel shape in the energy rings of a metro tunnel after a heating and a cooling test is shown in Fig. 6 (Insana et al., 2020; Insana, 2020). In this case, thermo-mechanical analyses reproducing soil-structure interaction were carried out using the finite-difference software FLAC (Itasca, 2016). In these simulations, the heat transfer mechanism considered is purely conductive and the mechanical calculation is coupled to the thermal one with the purpose to quantify

thermally-induced stresses and strains. Coupling takes place in one direction only, that is stresses and strains do not have an impact on thermal equilibrium. This simplification is completely acceptable as energy changes for quasi-static mechanical problems are usually negligible.

In the example shown in Fig. 6 it follows that internal action changes with respect to those at the end of tunnel construction are low and that axial forces and bending moments are largely included within the interaction domain. The results obtained in the study illustrate that thermal loads acting on tunnels in alluvial soils involve measurable and quantifiable effects. However, these effects are not considered to threaten the structural integrity nor the serviceability of the lining and in the case analyzed, representative of a typical case study, no need to increase steel reinforcement area or to modify the geometry of the cross section already defined based on the traditional structural design was encountered. Besides, stress and strain changes associated with thermal activation are of the same order of magnitude as those related to the seasonal temperature trend. However this consideration does not undermine the need for additional structural verification since thermal cycles, albeit similar to the natural ones, are imposed within the structures cyclically depending on thermal loads established by the users, allegedly for the whole infrastructure lifecycle and could be of higher magnitudes for example if energy tunnels are coupled to solar energy for storage purposes.



a)



b) c)

Fig. 6 Internal actions in the energy rings (numbers refer to maximum values) at the end of construction and after a heating and a cooling test a), detail of the bending moment b) and interaction domain c).

3.4 Hydraulic network sizing and preliminary cost analysis

Another design point covers the sizing of the hydraulic network for circulating the heat carrier fluid and for connecting the primary circuit to the heat pump. Nicholson et al. (2014) assumed an hydraulic network with return inverse arrangement with five neighbouring rings connected longitudinally to form one circuitry with reference to the Crossrail project in London. Research carried out at Politecnico di Torino (Rosso et al., 2021) showed that the most cost-effective layout is obtained by balancing the primary circuit installation cost, increasing with circuitry cross-section, and pumping costs, decreasing with circuitry cross-section. Such balance is highly affected by economic factors (e.g. pipes installation costs, energy cost), thermal comfort (e.g. utilization rate of the heat exchanger) and plant-related factors (e.g. pipes length and heat carrier fluid temperature changes). Hence, optimization of the hydraulic network has to be defined according to the specific application, based on a cost-benefit analysis accounting for the above-mentioned technological aspects, site geometry and potential customers identification.

Implementation costs for energy geostructures are lowered because the concrete members are already required for structural reasons and do not need ad hoc excavations or drillings as for BHEs. Costs evaluation comes down to assessing the extra costs (both materials and workmanship) needed for thermal activation beyond those for building the geostructure.

For precast segmental lining, the cost of materials is related to PE-Xa pipes embedded in the lining, junctions and further piping for guaranteeing hydraulic connections between segments and the circulation and distribution to the heat pumps. As for workmanship, the process introduces some additional activities, such as pipes embedment in the precast segments. This task takes place in the precast concrete plant with a slightly higher burden of the workforce for laying pipes inside reinforcement and arranging pockets for linking segments to one another. After tunnel excavation and rings erection, for which there are no increases in time or costs, the segments of each ring will be connected to set up a closed hydraulic loop and header pipes will be installed for ensuring the flow.

The analysis of such costs necessarily depends on the specific application, being a function of tunnel diameter, segments size, plant length, construction site organization, etc. Therefore, it is reasonable to evaluate the impact in percentage terms compared to the building costs of the tunnel itself. Based on the literature available and, particularly, in the light of the direct experience related to the experimental site in Turin Metro Line 1 tunnel, this percentage can be estimated at 1-2%.

The result of an optimization analysis accounting for the above-mentioned costs is shown in Fig. 7, where the revenue to costs ratio for variable parameters can be observed. This evaluation supposed an operation over 180 days per year (that is winter heating only), 12 hours/day.

Revenues were obtained by means of thermo-hydraulic analyses that allowed to get the outlet-inlet temperature difference and, hence, the exploitable heat power for the Torino case study (Rosso et al., 2021). Accounting for the cost of 1 kWh_t and for the operation time, the computed thermal power (in kW/m) was turned into the economic benefits deriving from the geothermal use of the tunnel lining. From this analysis the most convenient solution appeared to be that with all-in-parallel rings.

The hydraulic optimisation analysis considered the costs of the circuitry components and the costs for pumping the heat carrier fluid through the primary circuit. It calculated installation costs, head losses and hydraulic power, based on which the pumping energy cost was estimated. The minimum cost was found for the configuration with 5 rings in series.

Both the thermo-hydraulic and the hydraulic optimisation analyses carried out considered different plant solutions (from one to 5 rings connected in series to form one circuitry) and tunnel lengths from 90 to 990 m. The revenue to costs ratio was obtained by dividing the economic benefits and the hydraulic costs obtained as described above. From Fig. 7 it turns out that all-in-parallel rings is the best case up to 450 m. As tunnel length increases, the highest revenue is obtained with two rings in series.

It can be observed that the shortest tunnel length considered has the highest revenue to cost ratio regardless of the number of rings connected in series. This downward trend is because the hydraulic cost increase rate is higher than the thermal gain increase rate when tunnel length increases, hence for higher lengths the revenue to cost ratio decreases.

The results discussed are not of general validity, being related to the economic value of the heat and to its exploitable amount, which, in turn, is a function of boundary conditions in terms of groundwater flow, lithology, tunnel climate, pipes inlet temperatures and so on. Nevertheless, they are suggestive of the kind of economic assessment needed and of energy tunnels cost-effectiveness.

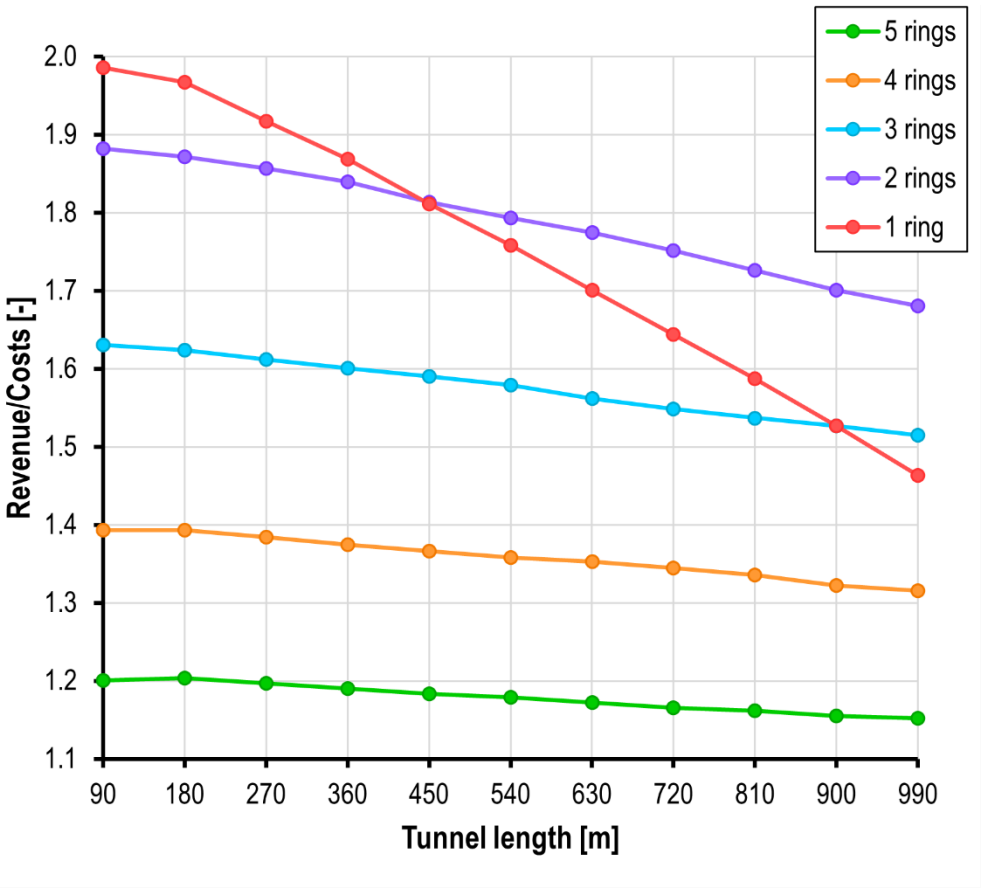


Fig. 7 Revenue to costs ratio for different configurations and tunnel lengths (operation over 180 days, 12 hours per day).

4 TURIN METRO LINE 1 PILOT SITE

After the description of design aspects, it is of interest to describe in the following a real application of energy tunnel. In order to verify the proper operation of the Enertun energy segment, a project for the construction of an energy tunnel experimental prototype began in 2016 in the framework of a joint project between Politecnico di Torino, InfraTo and Consorzio Integra. The prototype was installed in the Turin Metro Line 1 South Extension tunnel during its construction (Barla et al., 2019b), about 42 m northwards from Bengasi station, in the Lingotto-Bengasi section (Fig. 8). It consists of 12 Enertun segments (2 complete lining rings) equipped with the Ground&Air configuration. The precast segmental lining is 30 cm thick and is made of 6 segments (5 plus a key). Each ring is 1.4 m long with an internal diameter of 6.88 m. The groundwater table is about 12 m deep.

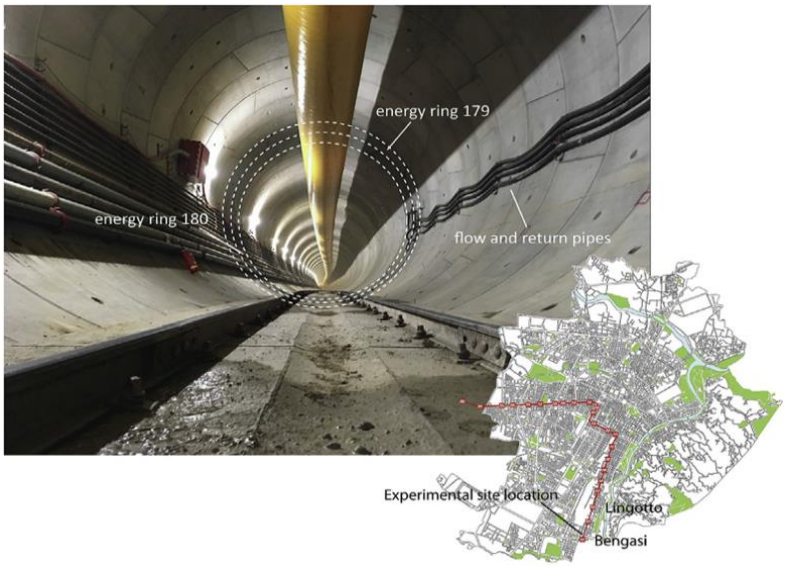


Fig. 8 View of the Enertun experimental site and its location along Turin Metro Line 1 (Insana and Barla, 2020).

Segments precasting took place between December 2016 and May 2017. Fig. 9 shows an example of a segment before casting with geothermal loops fixed to reinforcement.

The rings were mounted by the TBM on-site in July 2017. Next, all hydraulic connections between segments and with the heat pump were provided. All exposed pipes were suitably insulated to prevent heat losses. The heat pump and fan coil were placed in the station area.

Given the experimental nature of the project, a complex and comprehensive monitoring system was installed to help assessing the thermal and structural performance of energy segments (Fig. 9). The system includes stress, strain and temperature gauges embedded within segments before casting, temperature probes along pipes, flow meters and heat meters.

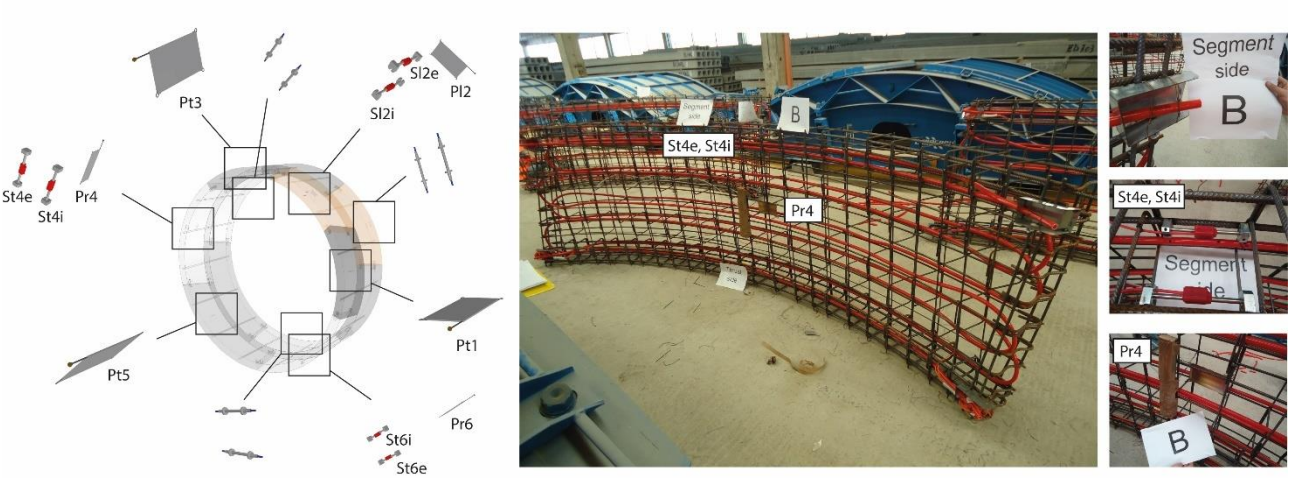


Fig. 9 Measurement sensors arrangement in the two energy rings and view of an energy segment before casting.

Testing started in September 2017 and lasted one year, allowing to study the winter and summer behaviour, for a total of 12 tests, using both the Ground and the Air exchange circuits. The results of the campaign helped

to quantify heat exchange ranging from 40 to 66 W/m^2 based on the type of application (see Barla et al., 2019 and Insana and Barla, 2020). The impact of thermal loads on the lining stress-strain state resulted very limited (Insana et al., 2020).

The promising results obtained allowed to quantify the energy performance of the technology in the Turin context, paving the way for an application at a much larger scale, as described in the following chapter.

5 TURIN METRO LINE 2 APPLICATION

5.1 General features

In the framework of the technical and economic feasibility study for the design of Turin Metro Line 2, a study on the geothermal potential of the tunnel infrastructures along the line was carried out. As anticipated, this is the first study ever involving the whole metro line as a possible source of heat (Barla et al. 2019a; Barla et al., 2020).

The entire route of the line, as detailed in the technical-economic feasibility project, will be composed of a central section winding between the Anselmetti and Rebaudengo stations (blue line in Fig. 10) and two extensions, respectively NE (light blue line) and SW (red line).

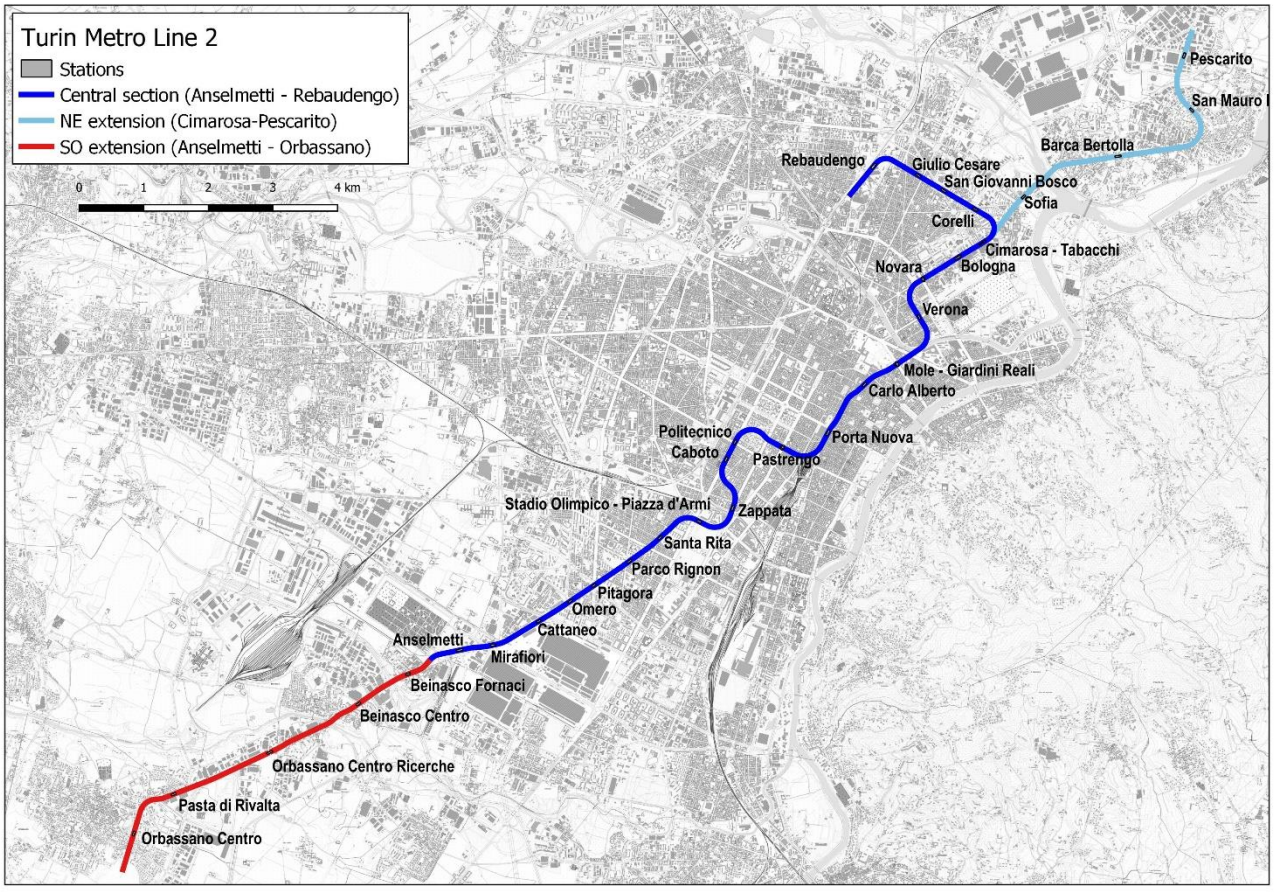


Fig. 10 Turin Metro Line 2 plan.

The central section will cross the city underground for 15.7 km with a rather complex trend. The altimetry of the tunnel includes several and sudden variations along the route with the rail level placed from a minimum of about -10 m in the northern area, between Corelli and Giulio Cesare stations, up to -40 m from ground surface near the Zappata Station below the railway link.

Based on the path described above, tunnel excavation between Anselmetti and Bologna stations is planned to be performed by mechanized excavation with TBM, while the terminal northern stretch of the central section between Bologna and Rebaudengo will be carried out by the Cut & Cover excavation methodology (C&C) or with artificial box. The C&C method will be also adopted for the SE junction building near Cattaneo station. The conventional excavation methodology will be used for a short section between Zappata and Caboto stations to underpass the railway link that connects the stations of Porta Nuova and Porta Susa. The 5.7 km long NE extension will be built by means of mechanized excavation with TBM, except for a short initial and final section, both built by C&C technique. The whole SW extension will be excavated by TBM.

Two different structural types which can be thermally activated emerge from the above: i) lining made of precast reinforced concrete segments in the tunnel sections built by TBM; ii) cast-in-place reinforced concrete vertical diaphragm walls for the sections of the tunnel excavated by C&C or with artificial box and for stations, junction buildings and rear-end buildings.

The two sections planned with conventional excavation method are not considered suitable to thermal activation, based on technical and economic considerations.

5.2 Homogeneous zoning

The working methodology adopted to quantify the geothermal potential along the line chainage consisted of the following steps:

- geological and thermo-hydraulic characterization of the line for the assessment of the data needed for numerical modelling;
- zoning of the line into homogeneous sections;
- development of finite element numerical models with thermo-hydraulic coupling for evaluating the energy efficiency of the different tunnel sections;
- evaluation of the overall power in summer and in winter;
- study of potential customers.

Considering the heterogeneity of the route plan and altimetric trend, of groundwater level and of ground geological-geotechnical conditions, a specific parameterization methodology with distinction into class was developed and implemented on Open Source GIS systems. Through appropriate geoprocessing and map algebra operations it was possible to compare spatially the information pertaining to different sections of the line with the distribution and the plano-altimetric variation of the parameters taken into consideration. Together with these parameters, the excavation techniques are also considered by analyzing separately the sections of the tunnel that will be built by TBM and those that will be built with the C&C technique or artificial box.

For each of the two structural types, TBM and C&C, five parameters have been identified for the classification of the different sections with regard to the ground geothermal potential:

- Position of the piezometric surface with respect to the tunnel;
- Groundwater temperature;
- Groundwater flow direction with respect to the tunnel axis;
- Groundwater flow gradient;
- Lithology around the tunnel.

Fig. 11 shows the matrices with all the classes obtained, for the sections excavated both by TBM and by C&C respectively, which were adopted to zone the entire line in homogeneous sections. The parameters were derived both from the analysis of literature (Bottino and Civita 1986; Barla and Barla 2012; Barla et al. 2015) and from specific investigations carried out as part of the feasibility study.

For the whole development of line 2, based on the subdivision of the parameters into classes, 50 and 16 homogeneous sections were identified for the portions which will be excavated by TBM and by C&C respectively. For each homogeneous section thus identified, a specific FEM thermo-hydraulic numerical model was built to determine the geothermal potential of the corresponding tunnel section. Fig. 12 shows as an example of some geometries of the numerical models for the TBM and C&C sections.

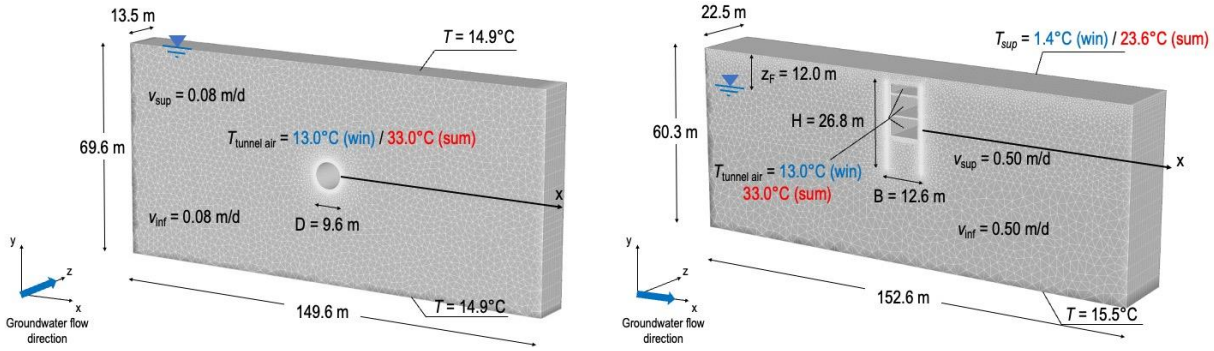
	Position of the piezometric surface with respect to the tunnel [m]	Groundwater temperature [°C]	Groundwater flow direction with respect to the tunnel axis [°]	Groundwater flow gradient [%]	Lithology around the tunnel
Classes for the TBM sections					
1	Above the crown	From 14 to 15	Perpendicular to tunnel axis ± 30°	> 0.40	Completely in sandy-gravel deposits[1]
2	Between crown and invert	From 15 to 16	Intermediate situation	From 0.40 to 0.25	At the contact between sandy-gravel deposits[1] and sand layers[2]
3	Below the invert	From 16 to 18	Parallel to tunnel axis ±30°	< 0.25	At the contact between sandy-gravel deposits[1] and clay layers[3]
4	-	-	-	-	Completely in sand layers[2]
5	-	-	-	-	Completely in clay layers[3]
Classes for the Cut & Cover sections					
1	Above the diaphragm wall median point	From 14 to 15	Perpendicular to tunnel axis ± 30°	> 0.4	Completely in sandy-gravel deposits[1]
2	Between the diaphragm wall median point and the wall base	From 15 to 16	Intermediate situation	From 0.40 to 0.25	The contact between sandy-gravel deposits[1] and sand layers[2] lies between the median point and the diaphragm base
3	Below the diaphragm wall base	From 16 to 18	Parallel to tunnel axis ±30°	< 0.25	The contact between sandy-gravel deposits[1] and clay layers[3] lies between the median point and the diaphragm base

[1] k_h = 1.93·10^{-3} m/s; k_v/k_h=0.05; λ=2.7 W/mK; ρ_c=2.6 MJ/m^{3}K; n_e= 0.175

[2] k_h= 4.2·10^{-4} m/s; k_v/k_h =0.05; λ=3.3 W/mK; ρ_c=2.5 MJ/m^{3}K; n_e= 0.125

[3] k_h = 1·10^{-8} m/s; k_v/k_h =0.05; λ=1.7 W/mK; ρ_c=2.3 MJ/m^{3}K; n_e= 0.05

Fig. 11 Summary matrix for TBM and C&C sections with indication of the classes for the five parameters taken into account in the proposed methodology.



(a) (b)

Fig. 12 Example of numerical models' geometry adopted for TBM sections (a) and for C&C sections (b) with indication of thermal and hydraulic boundary conditions.

5.3 Computation of geothermal potential and identification of customers

From each finite element numerical analysis, it was possible to get the temperature difference between inlet and outlet of the heat exchanger in winter and summer. Such a result was used to calculate the specific thermal power in W/m, according to the procedure described in Chapter 3. Total thermal power in kW, for the specific homogeneous section, was then obtained by multiplying the specific thermal power per unit length by the length of the examined section.

Numerical analyses were carried out by simulating a 30-days thermal activation timespan, assumed as a conservative condition for the computation of the heat exchanged through the tunnel lining. Indeed, in this case the most unfavourable conditions in terms of heat carrier fluid inlet temperature and tunnel air, representative of peak hours as concerns passengers and trains frequency, are kept constant for the entire period of 30 days. This assumption, useful to allow the computation, clearly does not match real operation conditions, characterized by both a seasonal and a daily variation. Therefore, the conservative conditions considered in the analyses are likely to occur for few hours a day and for some days of the year, not for the whole timespan. However, this hypothesis was reputed appropriate at this stage of the design.

Results, referred to the last simulated day of thermal activation, allowed to quantify the exploitable heat along all the different sections of the tunnel and to classify them according to the geothermal potential ranging from 400 to 1200 W/m in the most unfavourable and favourable conditions respectively. Fig. 13 illustrates the classification of the line based on winter geothermal potential.

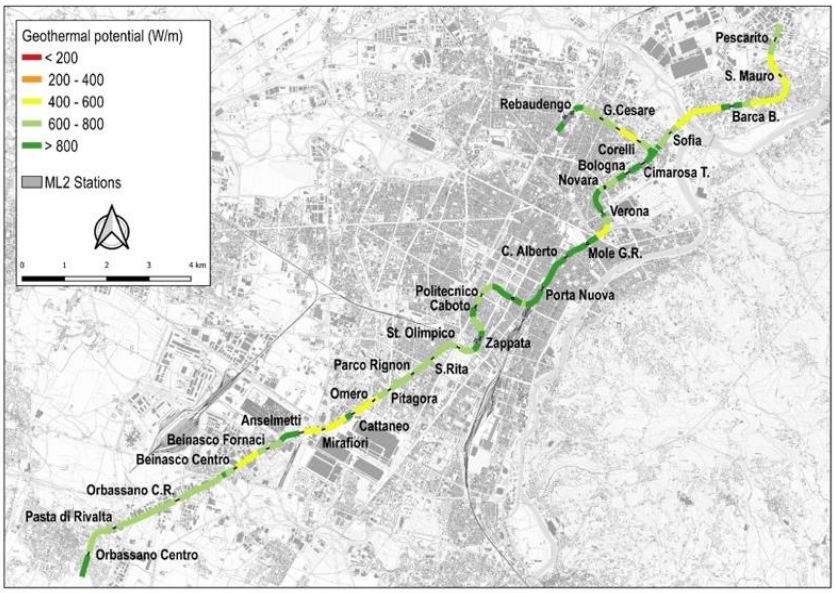


Fig. 13 Example of the line classification according to the winter geothermal potential (W/m).

The winter performance of the technological system was found to be better than the summer one. In particular, the most productive areas were that below the historical city center and, at a larger scale, the central section, followed, in the order, by the SW and the NE extension, both in summer and in winter. Up to 18.7 and 11.9 MW of thermal power respectively in winter and summer can be exploited along the line.

Based on the calculated thermal power and the distribution of potential receivers along the line, a proposal for the use of heat was suggested which fulfils stations' winter and summer thermal needs. Then, any possible surplus of thermal energy which can be distributed to external users was furtherly assessed. Its amount is particularly interesting in winter but, especially in some areas, relevant in summer too. Considering that the stations total thermal needs were evaluated to be of 6.2/7.5 MW (Winter/Summer), an interesting surplus (12.5/4.4 MW) can be made available to the city district heating system or directly to external users.

Finally, to identify possible receivers of the heat exchanged by the tunnel lining, the contact points between the thermally activated infrastructure and the topographic surface (i.e. stations and ventilation shafts) were located. The stations were considered as polygonal elements while ventilation shafts were considered as simple point elements to simplify the analysis. Starting from the contact points, buffer areas with a radius of 100 m were defined around them, within which it is believed that distribution of thermal energy exchanged with the ground would be possible (Fig. 14). Within these areas 1740 potential receivers (buildings) were identified, of which 1045 around the stations and 695 around the ventilation shafts. Among them, some appear particularly interesting, such as the school buildings along the route, the San Giovanni Bosco hospital, the new service building for bus lines with commercial premises planned near Orbassano Centro Ricerche station and the newly built areas adjacent to Rebaudengo station, Regaldi boulevard or the area behind the Fiat Mirafiori plants.

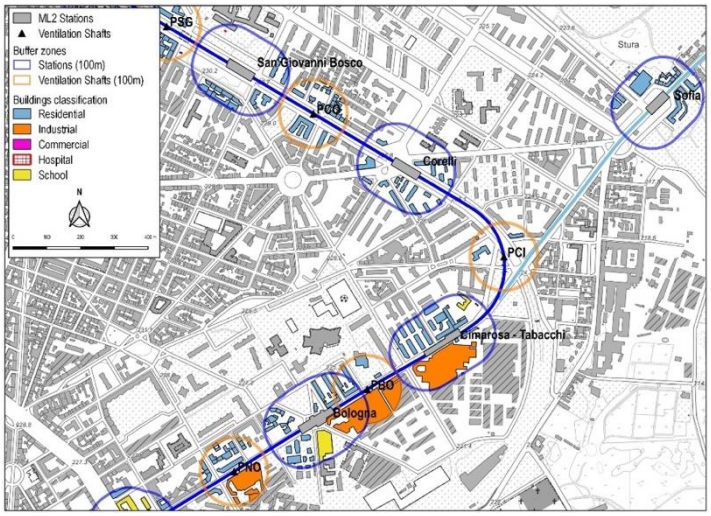


Fig. 14 Example of identification and classification of the potential receivers along the Novara-Giulio Cesare portion of the line.

5.4 Integration with district heating networks

If the extracted heat can be used directly for the line stations or with reference to specific receivers identified among the surface buildings, an interesting possibility which was investigated in this study is to integrate the energy tunnel system within the district heating network. In this case, a scheme like the one shown in Fig. 15 can be assumed. The tunnel (Geothermal Ring) plays the role of thermal source for the low-temperature ring (Primary ring) through the use of a heat pump (Primary heat pump). The geothermal loop is then the source, evaporator side, for the heat pump which raises the temperature from the tunnel operation levels (4-10°C) to around 45°C. The primary network can thus serve directly the newly built volumes and, in general, the users characterized by low specific consumption and equipped with low-temperature thermal plants (New Buildings with radiant floor/fan coil in Fig. 15). This seems to be the most interesting use from a technical and economic perspective. The use of heat pumps as heat sources for district heating or as boosters is common in northern European countries such as Sweden, Netherlands or Denmark (Connolly, 2017; European Heat Pump Association, 2019) while is limited in Italy. Accordingly, Meibodi and Loveridge (2022) state that the connection of energy geostructures to the heat network, operating at different temperature levels, is a feasible solution in the framework of the fifth generation thermal energy network's schematic concept.

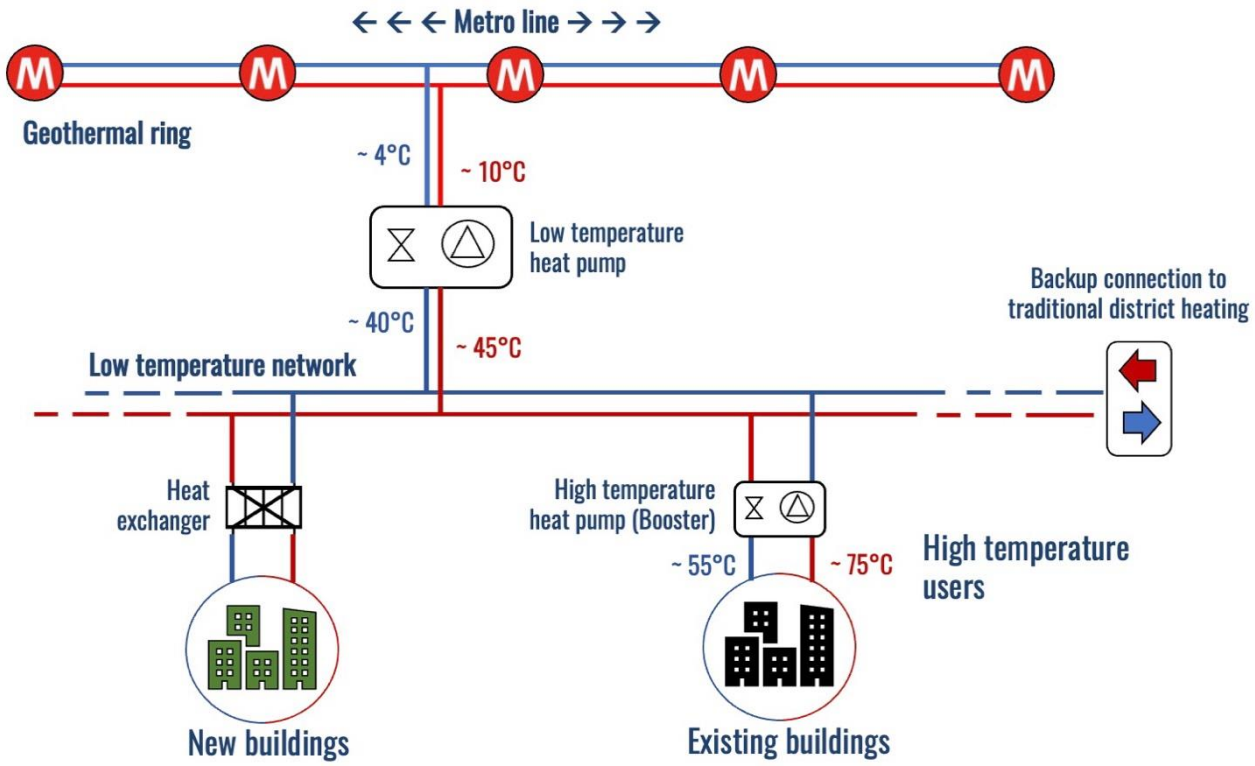


Fig. 15 Conceptual scheme of the geothermal system.

As to existing users and those that require high temperatures, it is possible to think of using a second local heat pump (Booster) to raise the temperature to the 75°C needed by radiators and ensure comfort. To guarantee service continuity and system resilience, it may be necessary to provide a connection with the high-temperature district heating network that can act as a backup in case of failures or maintenance of the network and/or the equipment.

6 CONCLUSIONS

The main advantage resulting from the integration of heat exchangers inside geotechnical structures lies in the fact that they are built in any case. This involves a significant reduction in installation costs, compared to the construction of a traditional geothermal plant. Thermal activation of the tunnel linings is therefore an excellent opportunity to mine the ground heat with great economic and environmental advantages.

The key aspects of the design process were illustrated in this paper making particular reference to the studies carried out at Politecnico di Torino from 2013 to date.

Compared to the structural dimensioning of the segments used for the lining, in the case of energy tunnels and, therefore, of energy segments, design requires two additional stages, identified as thermal design and structural design. The first one concerns the energy sizing of the heat exchanger system. Here the attention of the designer must be focused on the efficiency of the geothermal system, on the design of plants and on environmental

sustainability. The second one aims at quantifying the effects involved on the lining by the system thermal activation from a stress point of view. A third stage ,i.e. hydraulic circuit sizing, is also required.

Tunnels can get to about 10-20 W/m^2 of specific heat power exchanged in the absence of groundwater flow, up to 50-60 W/m^2 in case of relevant groundwater flow.

The use of tunnels as heat exchangers with the ground finds its best application in urban areas as described in this paper. Indeed, in this case, the extracted heat can be easily used to heat the neighbouring buildings and the plant can be integrated into urban district heating systems. In this perspective, careful urban planning is even more necessary to optimize interference between different systems and integration with distribution networks. The cities that will be able to address these issues will certainly be able to benefit from it in terms of life quality improvement. This paper described a study conducted in the city of Turin, which represents the first relevant example of the possible synergies that can be generated by adopting this technology at a large scale. Up to 18.7 and 11.9 MW of thermal power respectively in winter and summer can be exploited along the line and used for satisfying the thermal needs of the stations and/or made available to the city district heating system.

As emerged, research in the field of energy tunnels is highly multidisciplinary and involves skills and disciplines that go beyond pure geotechnics, such as geology, hydrogeology, hydraulics. Broad-spectrum cooperation is needed, with colleagues dealing with energy, hydraulic and environmental engineering, management engineering and public and urban planning policies in order to overcome the obstacles that still hinder the full use of this technology.

Energy tunnels represent a potential element of technological innovation for the years to come, in line with environmental sustainability policies and it is very nice to think that this push comes from geotechnics, a discipline sometimes seen as very traditional. The forward-looking vision of geostructures thermal activation represents in this scenario a new and crucial element that the geotechnical culture provides to the community.

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Data used are available from the corresponding author by request.

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