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Seizing the opportunity of energy retrofitting of existing tunnels

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ABSTRACT

Energy tunnels have emerged as systems that can contribute to the production of clean, renewable thermal energy. Nevertheless, so far applications have been related almost exclusively to new tunnelling projects. Accordingly, no systematic methodologies for the heat exchange instrumentation of existing tunnels have been proposed up until now. Starting from the valuable experience gained from different energy tunnel testbeds worldwide, this paper proposes two approaches that would allow the thermal activation of the existing heritage of tunnels. Different solutions are conceived for both approaches to fit various existing tunnel decay contexts and diverse levels of refurbishment necessity. These are illustrated, outlining characteristics and advantages, describing expected installation details and issues and analysing the possibility of real implementations. The geothermal potential of such solutions is assessed through thermo-hydraulic numerical modelling. Finally, with the aim of investigating their economic attractiveness and profitability, a brief economic analysis is drawn up, considering the geothermal energy produced and the costs involved in installing and running the systems.

1. Introduction

Over the last decades, global warming has become one of the major issues to cope with. Human activities are responsible for a global surface temperature increase of approximately 1.1°C since the pre-industrial age. Climate change is directly linked to global warming, thus affecting different regions around the world in multiple ways: leading not only to increments of heat extremes but also to changes in rainfall patterns, sea level rise, amplification of the permafrost thawing, ocean acidification and much more (IPCC, 2023).

In this context, carbon dioxide emissions due to heating and cooling systems are one of the main enemies in the pathway for reaching the 1.5°C Paris climate goal and energy geostructures could play a relevant role. Energy geostructures are ground-contact structures engineered to accomplish the twofold aim of structural support and heat exchange (Brandl, 2006; Laloui & Di Donna, 2013). The thermal activation of such structures is achieved by embedding heat exchanger pipes inside them. The circulation of a heat carrier fluid within these pipes, usually water or water-glycol mixtures, allows the extraction or the injection of heat from or into the surrounding ground. These kinds of systems fall into the category of low-enthalpy geothermal systems.

Starting from the 80s, energy geostructures have been successfully constructed, taking advantage of a variety of geotechnical structures, such as foundation piles (Pahud & Hubbuch, 2007; Alberdi-Pagola et al., 2020; Prodan et al., 2021), retaining walls (Sterpi et al., 2018; Zannin et al., 2019; Barla et al., 2023), tunnel linings (Adam & Markiewicz, 2009; Franzius & Pralle, 2011; Lee et al., 2012; Zhang et al., 2014; Buhmann et al., 2016; Barla et al., 2019), shallow foundations (Brandl, 2006; Baralis & Barla, 2021) and anchors (Adam, 2008; Moffat et al., 2022). Recently, road pavement structures have also been used to exchange heat (Motamedi et al., 2021; Poulsen et al., 2022). Among them, the thermal activation of tunnels has raised increasing interest in the past few years. In comparison with the other energy geostructures, energy tunnels reap the benefits of a larger surface in contact with the ground, thus improving heat exchange. Indeed, the role of the on-site hydro-geological conditions and ground thermal properties is paramount in geothermal exploitation. For instance, a favourable groundwater flow is able to steadily recharge geothermal reservoirs, thus enhancing thermal production (Insana & Barla, 2020). Furthermore, tunnel intrados lies in contact with the internal air. Depending on the aerothermal conditions, this may improve heat exchange (Dornberger et al., 2022).

To the end of instrumenting tunnel linings for geothermal exploitation, two techniques have already been proposed in the literature depending on the tunnelling method (Barla & Di Donna, 2018). Regarding conventional tunnelling, heat exchanger pipes are generally fastened on fixing rails (Zhang et al., 2014; Buhmann et al., 2016) or attached to non-woven geosynthetics (Adam and Markiewicz, 2009) and

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then placed between the preliminary and the final linings. On the other hand, when mechanised tunnelling is envisaged, lining segments are instrumented and optimised for heat exchange since the prefabrication. Special moulds with box-out pockets allow the realisation of grooves at the ends of the segments for neighbouring pipe connections (Nicholson et al., 2014). Geothermal tunnel segments such as those described above are the so-called Energietübbing (Franzius & Pralle, 2011) and Enertun (Barla et al., 2019).

These full-scale implementations have been related only to new tunnelling projects. The sole exception is represented by the Seocheon abandoned tunnel experimental site (Lee et al., 2012, 2016), where the thermal efficiency of energy textiles was tested. Six 10 × 1.5 m energy textile modules were installed at about 100.0 m distance from the tunnel entrances in three different exchanger pipe arrangements: longitudinal, transverse and slinky. In sequence, the installation envisaged laying a drainage layer, fixing energy textiles and casting the concrete lining on the existing surface of the tunnel wall. During 2010 and 2011, linking together two textile units (transverse and longitudinal), the system was tested in typical cyclic heating and cooling modes, injecting the heat carrier fluid at rates of 1.5÷2.0 lm^{-1} and inlet temperatures, respectively, of 5°C and 30°C. The temperature in the tunnel ranged between 15÷20°C and no groundwater was observed on site. In this experimental setup, an average heat power of 0.5÷0.7 kW has been reported, corresponding to an efficiency of 20 Wm^{-2}.

To the best of the Authors' knowledge, other cases of energy tunnel technology implementation for the existing heritage of tunnels have not yet been either chronicled or investigated. However, the increasing need for rehabilitation interventions aimed at counteracting the ageing and decay of existing tunnels, as well as repurposing strategies for changing their intended use, can pave the way for developing green solutions for converting existing tunnels into energy geostructures.

Starting from the valuable experience gained from different energy tunnel testbeds worldwide, the present work proposes two retrofitting approaches that would allow the thermal activation of existing tunnels. The former would take advantage of the realisation of rehabilitation works, whereas the latter would be suitable for any operating, repurposed or abandoned tunnel. Different solutions were conceived for both approaches to fit several existing tunnel decay contexts and diverse levels of refurbishment necessity.

The following sections illustrate the different energy retrofitting solutions for existing tunnels, outlining characteristics and advantages, describing likely installation details and issues and analysing the possibility of real implementations. Afterwards, the thermal efficiency of these solutions is assessed through thermo-hydraulic numerical modelling. To this end, different internal aerothermal conditions were considered and the positive influence of the groundwater flow was conservatively neglected. The last part is devoted to a brief Levelized Cost Of the thermal Energy (LCOE) analysis to investigate the economic attractiveness of such solutions, contemplating the geothermal energy produced and the costs involved in installing and running the systems.

2. Energy retrofitting of the existing heritage of tunnels

Because of their structural resilience, road and railway tunnels are generally serviceable for much longer than their nominal service life (Grossauer et al., 2017; Seywald et al., 2017; Vetter et al., 2020). However, their increasing ageing and decay require refurbishment to guarantee service continuation in safe conditions (Lunardi et al., 2011; Barla et al., 2021; Agresti et al., 2022; De Feudis et al., 2023a). To this end, four different strategies are generally considered:

- Maintenance, which involves minor repair works aimed at guaranteeing the designed tunnel service life or slightly increasing it, awaiting major repair works to be designed and realised. E.g., repair works for preventing local block detachment;
- Rehabilitation, which involves major repair works aimed at extending the designed tunnel service. E.g., tunnel vault and/or invert integral/partial replacement;
- Upgrading, which involves major repair and construction works aimed not only at extending the designed tunnel service life but also at changing its intended use. E.g., existing tunnel enlargement to host more motorway lines or railway tracks;
- Repurposing, which involves the change of intended use of existing operating or abandoned tunnels. E.g., hosting art exhibitions, bicycle ways, etc.

When facing severe ageing conditions, cost-benefit analyses, as well as technical considerations, frequently demonstrate that rehabilitating existing tunnels represents the optimal solution compared to numerous local interventions of a limited lifespan (Mazzola et al., 2023). Similarly, repurposing abandoned tunnels could enliven infrastructures that fell into disuse, fostering, among others, cultural enrichment, just as the Piedicastello tunnel, in Trento, which was partly transformed into a museum (De Feudis et al., 2023b).

In this context, just as for new tunnelling projects, the thermal activation of existing tunnels represents an opportunity to take advantage of geo-energy that would otherwise remain unexploited. To this end, in this work, two energy retrofitting approaches, consisting of three and two different implementation solutions respectively, are proposed in the following. The aim is to couple different refurbishment requirements with the goal of instrumenting existing tunnels for thermal activation.

2.1. Energy retrofitting of existing tunnels during rehabilitation

The energy retrofitting of existing tunnels during rehabilitation, or thermo-structural retrofitting, would allow their thermal activation during interventions involving the partial or integral demolition and subsequent reconstruction of the vault. This commonly represents the most cost-effective technique when preliminary inspections and investigations reveal an excessive degradation of the lining (Fig. 1a), complex and ramified cracks (Fig. 1b), severe water infiltrations (Fig. 1c) and construction joints deterioration (Fig. 1d).

Fig. 2 shows the typical phases of a rehabilitation intervention. Before its implementation (Fig. 2a), pre-consolidation of the existing tunnel vault is commonly carried out through fiberglass dowels (Fig. 2b). Afterwards, the lining demolition through punctual milling or hydro-demolition takes place (Fig. 2c). This is usually staged for longitudinal sections of 5.0÷7.0 m at a time, thus not markedly affecting the stress condition of the existing tunnel lining. After removing potentially unstable lining blocks, a 3.0÷5.0 cm thick shotcrete layer could be envisaged to regularise the tunnel wall (Fig. 2d). Once the waterproofing and drainage systems are installed (Fig. 2e), the reconstruction of the tunnel vault ensues (Fig. 2f). For this purpose, precast tunnel segments or arched precast predalles can be envisaged. The latter can function as disposable shuttering for casting in place the concrete lining. Alternatively, with the provision of selecting traditional moulds, steel lattice girders are previously hung to the tunnel wall through eyebolts to work as reinforcement.

From the economic and safety points of view, commonly rehabilitation interventions involving only the partial demolition of the tunnel vault are preferred, thus limiting the milling or hydro-demolition thickness to a minimum extent. Furthermore, waterproofing, commonly consisting of a polyvinyl chloride (PVC) or thermoplastic polyolefins (TPO) sheeting coupled with a double geotextile layer, and drainage systems should contribute to the durability of the newly poured or assembled lining and avoid a build-up of excessive hydraulic overload, respectively (Mazzola et al., 2023).

Throughout this rehabilitation workflow, three different solutions, described in the following, were identified to instrument rehabilitated tunnel lining for geothermal exploitation, depending on its realization

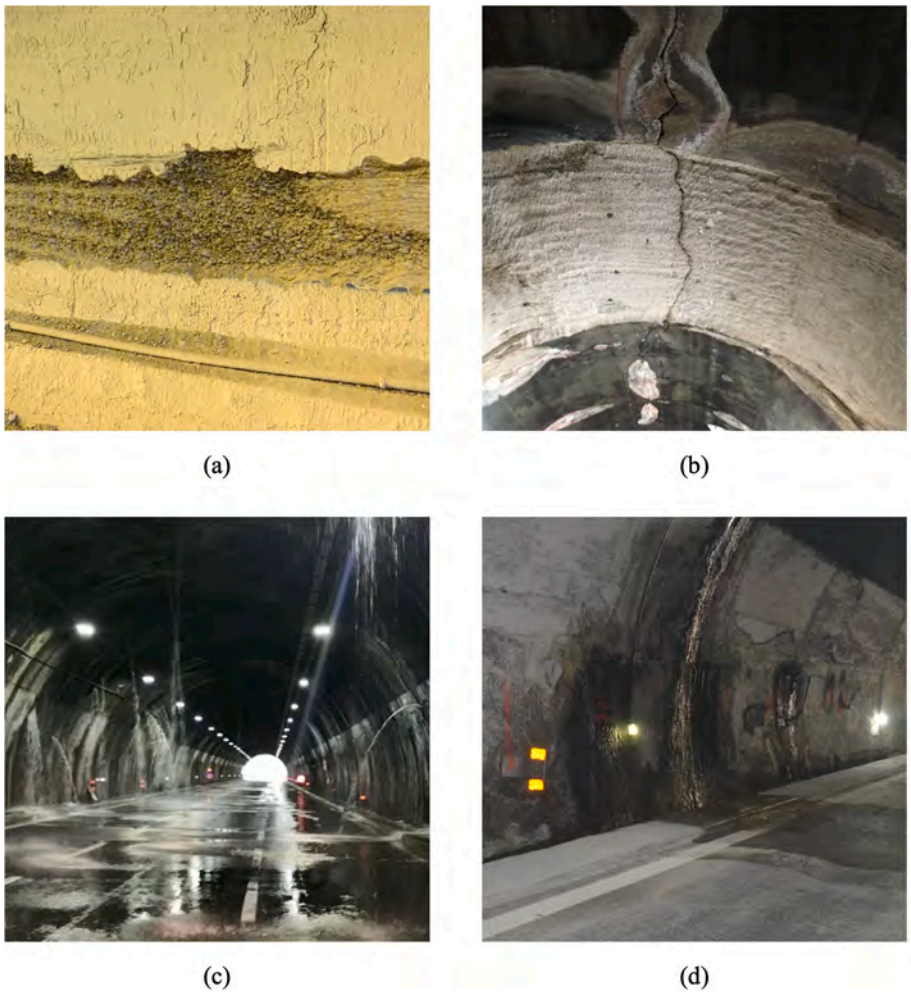

Fig. 1. a) Highly degraded existing lining; b) complex and ramified crown crack; c) severe water infiltration during an intense rainfall (IVG.it, 2021); d) deterioration of a construction joint.

procedure.

2.1.1. Precast energy tunnel segments: Enertun

Depending on the lining thickness, Enertun segments could be used to thermally activate existing tunnels during partial or integral rehabilitation interventions. Differently from other implementations, Enertun (Italian patent number: 102016000020821, European patent number: 16834047.9) has suggested a layout of the net pipes (Barla et al., 2016, 2019; Insana and Barla, 2020; Alvi et al., 2022; Barla and Insana, 2023) predominantly perpendicular to the tunnel axis. This revealed to reduce hydraulic head losses by about 20÷30% and increase heat exchange by about 10% when groundwater flows towards the main arrangement direction of the pipes circuit. To avoid harming the concrete cover excessively, heat exchanger pipes are usually tied by hand inside bending rebars and run in between hoop ones to preserve concrete-rebars adherence (Barla et al., 2019).

As for new tunnelling projects, Enertun segments could benefit from three different configurations:

- The *ground* configuration, which is conceived to exchange heat mainly with the ground, has a unique pipe circuit positioned in the extrados;
- The *air* configuration, which allows to operate mainly on the air inside the tunnel, has a unique pipe circuit positioned in the intrados;
- The *ground&air* configuration is a combined solution that fulfils both previously mentioned tasks.

A conceptual 3D view of an Enertun segment in the *ground&air* configuration is depicted in Fig. 3.

2.1.2. Energy predalles

Whether arched precast predalles are preferred to cast the rehabilitated lining, heat exchanger pipes would be tied to the steel lattices. Resembling precast energy segments, pipes should be placed so as to not thin the concrete cover and affect the adherence between concrete and bending rebars. Energy predalles would be installed on-site just as any other predalle, thus not increasing the workforce's burden during the rehabilitation work implementation.

As for energy segments, box-out pockets should be envisaged to connect neighbouring pipe nets. Moreover, energy predalles could also be engineered to accommodate a double pipes circuit. Indeed, these 10.0÷15.0 cm thick arched slabs commonly host electro-welded wire meshes above which the intrados pipe circuit could be tied.

A conceptual 3D view of an energy predalle in a likely *ground&air* configuration is depicted in Fig. 4.

2.1.3. Extrados energy mats

If traditional moulds are envisaged, heat exchanger pipes would be fixed on the tunnel wall through metallic clamps shortly after the partial or integral demolition of the vault. These would subsequently be

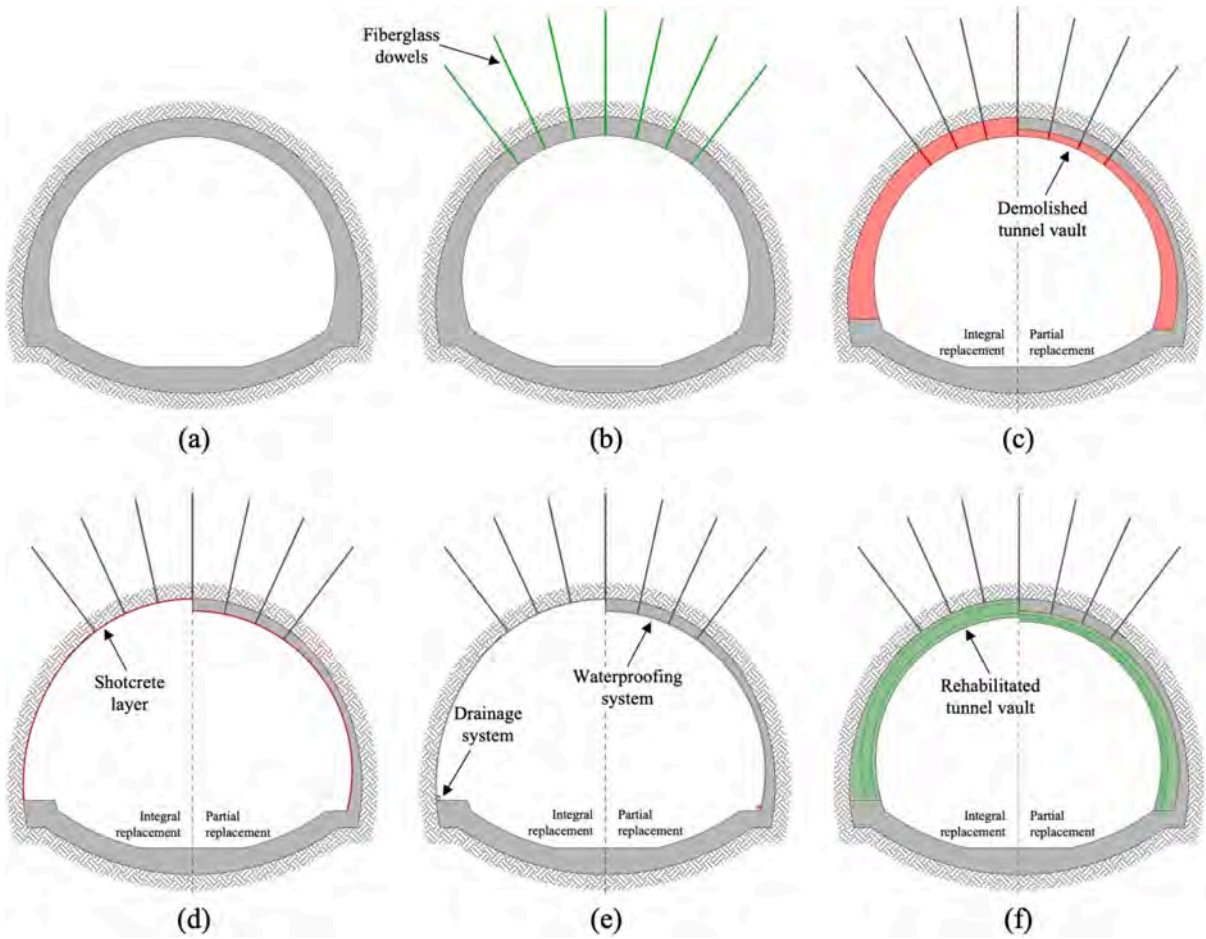

Fig. 2. Typical phases of a rehabilitation intervention: a) Status quo of an existing lining; b) pre-consolidation through bolting; c) integral/partial demolition of the exiting tunnel vault; d) tunnel wall regularisation through shotcrete; e) installation of the waterproofing and drainage systems; f) reconstruction of the tunnel vault.

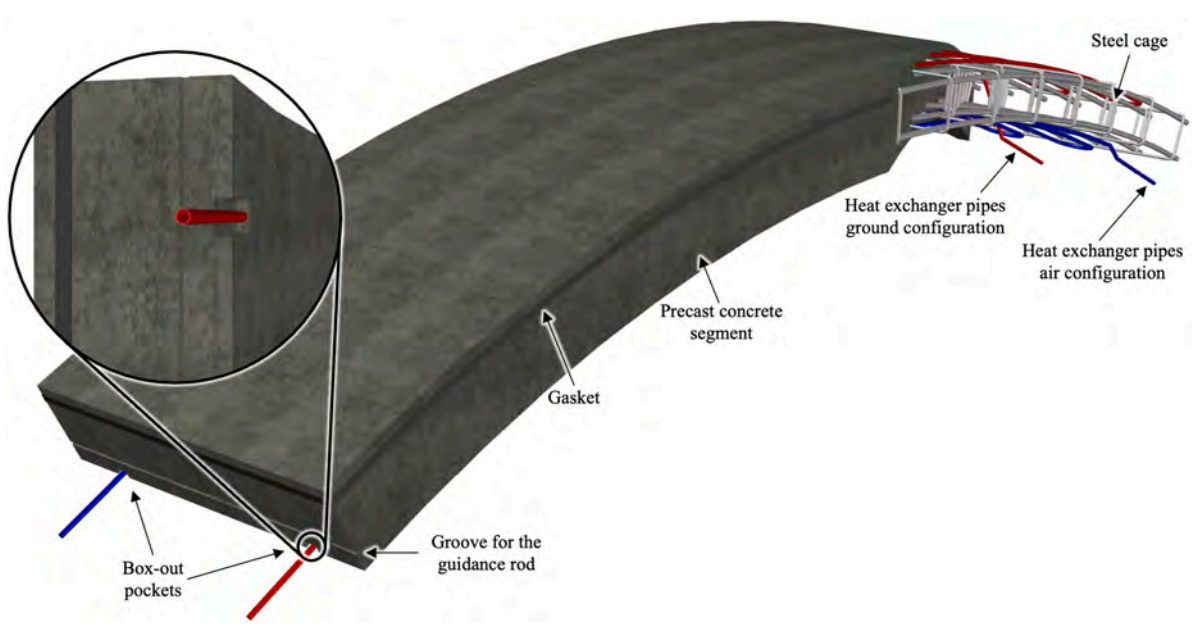

Fig. 3. Conceptual 3D view of an Enertun segment.

embedded in a shotcrete layer between the existing portion of the tunnel vault and the renovated one. Unlike precast energy segments and predalles, in this case, pipes would be arranged and fixed during the implementation of the rehabilitation work.

In comparison with the solutions described above, these extrados energy mats would reap the benefits of heat exchanger pipes placed

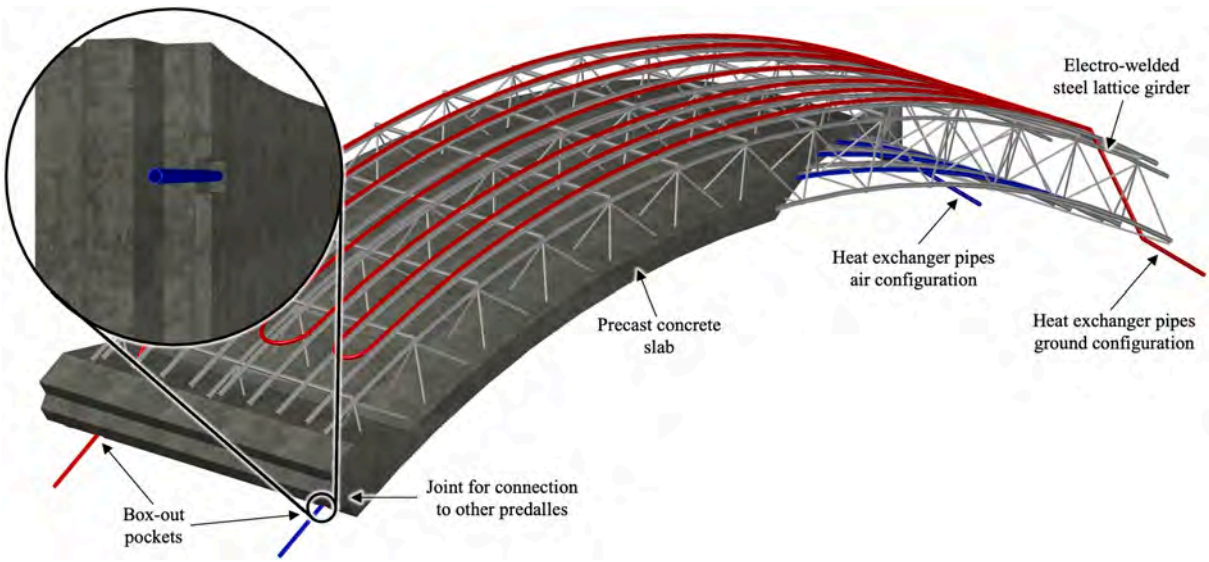

Fig. 4. Conceptual 3D view of an energy predalle.

behind the drainage and waterproofing systems. This would allow the pipe circuit to be less affected by the aerothermal conditions of the underground environment (Lee et al., 2016).

A conceptual 3D view of an extrados energy mat is depicted in Fig. 5a.

2.2. Energy retrofitting of existing tunnels after repurposing or during serviceability

The energy retrofitting of existing tunnels after repurposing or during serviceability, or thermal retrofitting, would allow the thermal activation of existing tunnels that must not undergo a specific rehabilitation process. These could be operating tunnels or abandoned ones to be repurposed. The latter represents a favourable alternative that facilitates leveraging existing inadequate or disused tunnel infrastructure for a wide range of usages, just as pedestrian and cycling pathways, cultural and exhibition spaces or underground storage and logistics. However, in combination with their current usage, existing tunnels can also be exploited for geo-energy-related purposes, thus converting them into energy geostructures. To this end, two different implementation solutions were identified.

2.2.1. Radial BHEs

Drilling radial borehole heat exchangers (rBHEs) would allow taking advantage of the overburden of existing tunnels, thus reducing the excavation costs compared to standard BHEs. Despite this, installation costs and time might not be negligible, depending on the drilling inclination and the strength of the drilled material. Since most of the heat exchanger pipe path would occur within the rock/soil mass, rBHEs would be marginally affected by the aerothermal conditions of the underground environment. This holds even truer if an insulation sheath is used between adjacent rBHEs. By contrast, these would remarkably benefit from the likely presence of groundwater.

A conceptual 3D view of the rBHEs is depicted in Fig. 6.

2.2.2. Intrados energy mats

Intrados energy mats would consist of a thermally insulating or conductive protective casing (based on the needs) embedding a circuit of

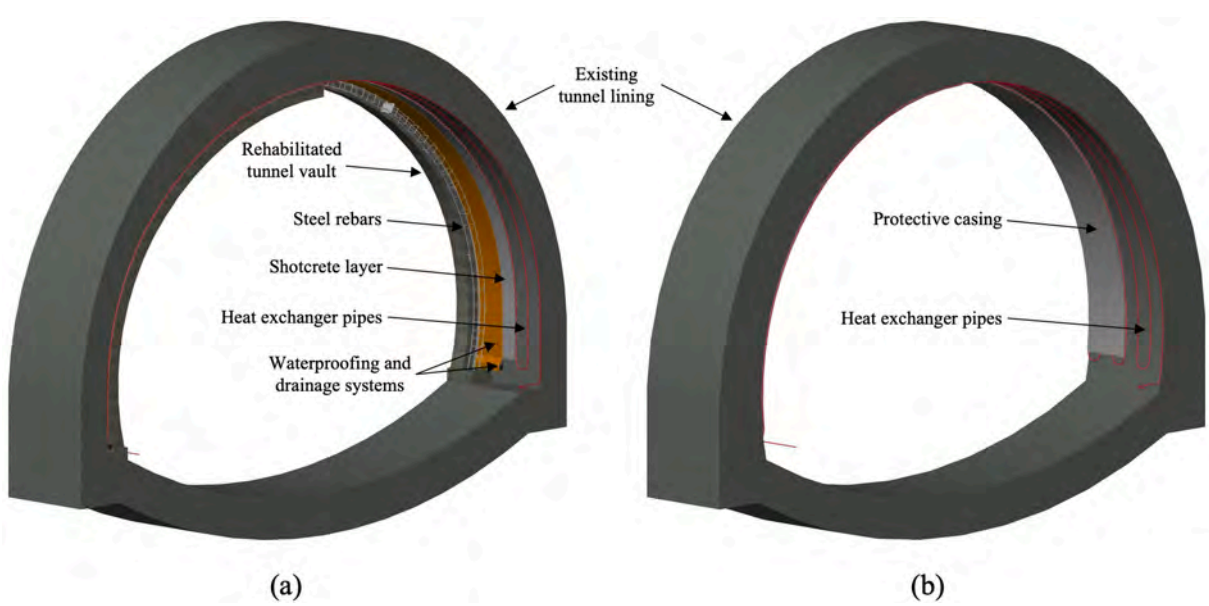

Fig. 5. Conceptual 3D views of a) an extrados energy mat applied to a partial rehabilitation of a tunnel vault and b) an intrados energy mat.

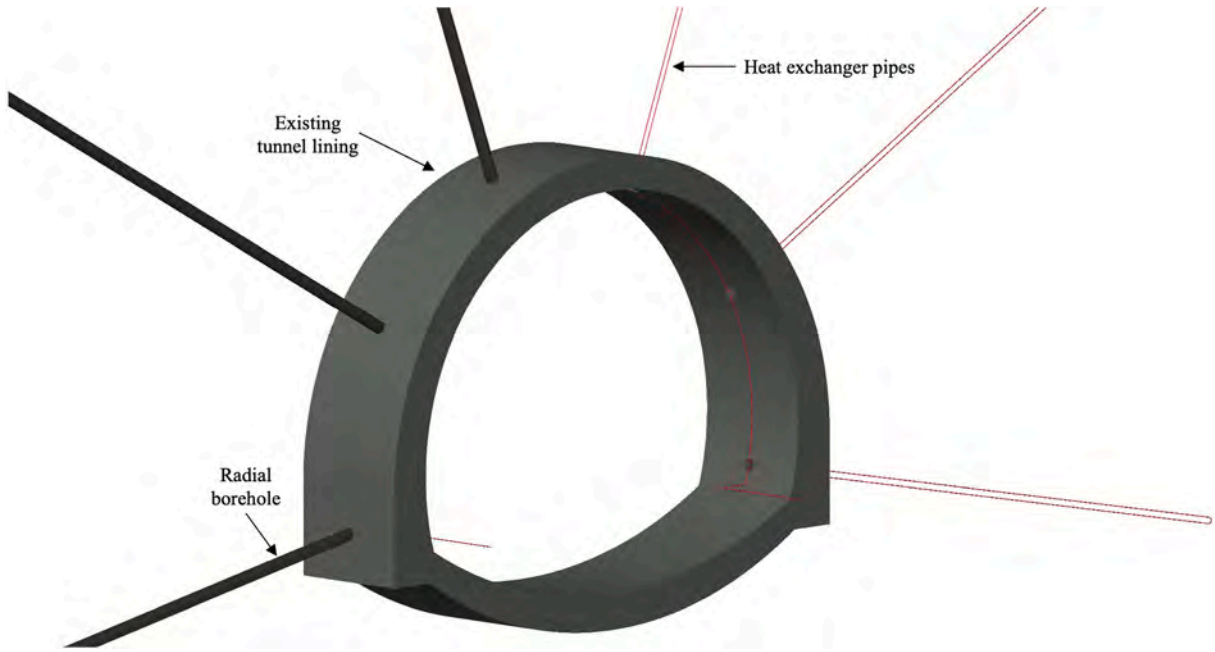

Fig. 6. Conceptual 3D view of rBHEs.

heat exchanger pipes that would be arranged as explained for extrados ones (subsection 2.1.3). However, contrary to them, lacking any rehabilitation works, intrados energy mats would be installed on the existing tunnel wall. Thus, intrados energy mats would be much more influenced by the internal environment of tunnels and would not markedly reap the benefit of groundwater, if any. Lastly, these would hide the view of the tunnel lining intrados, thus representing a problem to cope with during future inspections.

A conceptual 3D view of an intrados energy mat is depicted in Fig. 5b.

3. Numerical model

The thermal potential of the energy retrofitting solutions illustrated in the previous section was investigated through numerical analyses. To simulate their thermo-hydraulic combined behaviour, a 3D numerical model was developed using the finite element code FEFLOW© ver. 7.5 (DHI, 2022) that has been widely validated towards shallow geothermal applications, also in the framework of energy geostructures (Baralis et al., 2020; Insana and Barla, 2020; Alvi et al., 2022). In the current study, a typical Italian motorway tunnel in an Apennine environment was considered, thus allowing the unique selection of a characteristic tunnel geometry and a temperature time history. The numerical model setup and results are described in the following.

3.1. Numerical model setup

The numerical model encompasses all the solutions illustrated in the previous section. For modelling pipe circuitries, 1D elements were adopted, considering the heat carrier fluid flow through the Hagen-Poiseuille law. Therefore, fluid particles are assumed to move in pure translation with constant velocity. Despite neglecting the thermal resistances due to pipe walls and fluid flow regime, these 1D elements were successfully validated for simulating geothermal systems, showing good agreement when compared to analytical solutions (Diersch, 2009). Furthermore, the positive effect of the groundwater flow on heat exchange was conservatively neglected, assuming the entire model domain to be completely dry. Therefore, the thermo-hydraulic problem is governed by the following equations: the mass conservation equation and the Hagen-Poiseuille law only for the 1D elements and the energy conservation equation for both, 1D elements and dry porous media.

The following subsections will illustrate the geometry and material properties of the 3D numerical model, as well as initial and boundary conditions. Lastly, the initialisation of the numerical model will be discussed.

3.1.1. Problem geometry and material properties

The 3D thermo-hydraulic finite element model developed for the sake of this research is illustrated in Fig. 7. This is composed of 1934645 nodes and 3678620 triangular prismatic six-node elements arranged in a 253.0 × 253.0 × 6.0 m domain so that both model height and width are equal to 20 times the tunnel equivalent diameter which ensures no boundary effects.

The horse-shoe shaped tunnel placed in the centre of the domain was modelled to reproduce representative shapes and dimensions of the existing heritage of Italian motorway tunnels. Accordingly, this has an external equivalent diameter of 12.7 m, with a variable concrete lining thickness ranging between 0.80 and 1.30 m. Besides, the road pavement was simulated through three macro-layers: a 25.0 cm asphalt-based surface layer, a 25.0 cm cement-based subbase layer and a 150.0 cm aggregate-based foundation layer (Fig. 8a).

Different setups of the numerical model were envisaged to investigate the thermo-hydraulic behaviour of the energy retrofitting solutions discussed previously. These are illustrated in Fig. 8. Both setups depicted in Fig. 8b and Fig. 8c contemplate a partial rehabilitation of the existing lining for a thickness of 40.0÷80.0 cm (it varies along the vault). However, they consider two different approaches for instrumenting the existing tunnel for thermal activation, employing, respectively, precast energy segments/predalles and extrados energy mats. Due to their similarities in terms of pipe arrangements and thermal performance, precast energy segments and predalles are treated as a sole solution during numerical modelling, where pipes are embedded in the new lining layer. Extrados energy mats, instead, are also investigated through the setup shown in Fig. 8d for integral rehabilitation. Thereafter, Fig. 8e accounts for intrados energy mat installation after repurposing, in which case a protective 50.0 mm shotcrete layer was modelled. Lastly, the setup illustrated in Fig. 8f considers drilling 15.0 m long rBHEs connected in series with 40° in-plane angular spacing and

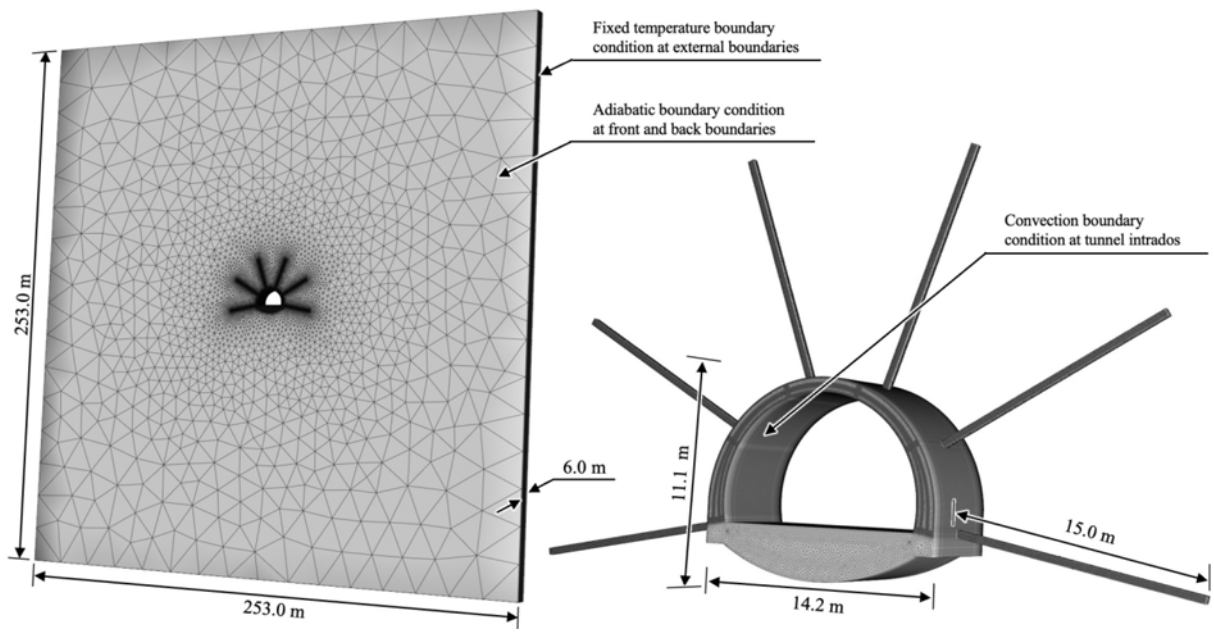

Fig. 7. Schematic of the geometry and boundary conditions of the finite element numerical model.

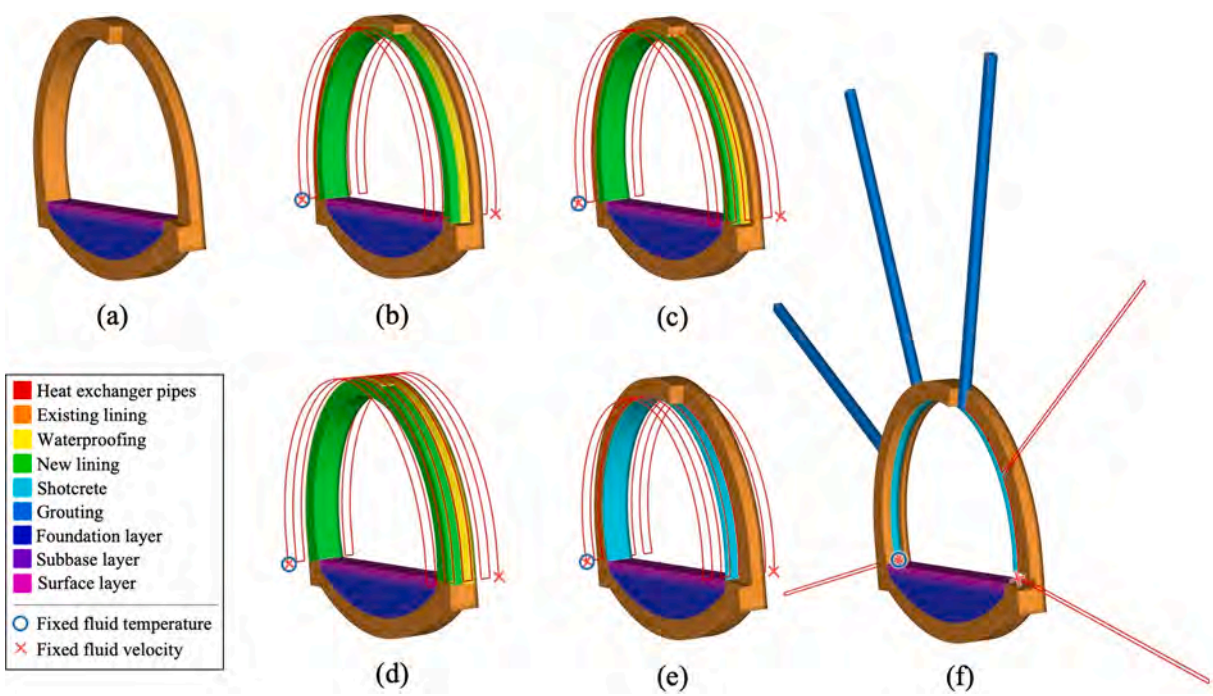

Fig. 8. Numerical model setups investigated and boundary conditions imposed to heat exchanger pipes: a) status quo of an existing tunnel, b) energy precast segments/predalles during partial rehabilitation, extrados energy mat during c) partial and d) integral rehabilitation, e) intrados energy mat and f) rBHEs after repurposing.

6.0 m out-of-plane interaxis distance. This was not modelled explicitly, but by setting the model width to 6.0 m, thus considering no heat interference among subsequent sections of rBHEs, i.e. adiabatic boundary conditions, in agreement with De Feudis et al. (2023b). For each setup, heat exchanger pipes with a cross-section of 201.0 mm^2, corresponding to an external diameter of 20.0 mm and a thickness of 2.0 mm were considered.

The efficiency of the proposed energy retrofitting solutions was compared accounting for an equal pipe net length to be arranged of about 200.0 m. This corresponds to a single series circuit of six rBHEs and a 3.2 m long longitudinal tunnel portion thermally activated with any other energy retrofitting solution, considering a pipe spacing of 40.0 cm.

The material thermal properties adopted in the different model setups are listed in Table 1.

Furthermore, to take into account the role of waterproofing in heat exchange, a fictitious 50.0 mm layer was modelled between the rehabilitated vault and the existing lining or the surrounding ground (Fig. 8b, Fig. 8c and Fig. 8d). Its thermal properties (Table 1) were computed by averaging shotcrete, TPO/PVC and geotextile ones and weighing them

Table 1
Material thermal properties adopted in the different numerical model setups.

Materials	Thermal conductivity [$Wm^{-1}K^{-1}$]	Thermal capacity [$MJm^{-3}K^{-1}$]	References
Ground	2.40	2.30	Casasso & Sethi (2017)
Existing lining	1.50	2.16	Howlader et al. (2013)
Waterproofing	0.74	1.77	As stated in the current study
New lining	2.30	2.19	Howlader et al. (2013)
Shotcrete	1.63	1.85	Lee et al. (2012)
Grouting	1.60	2.29	Zarrella et al. (2017)
Foundation layer	0.80	1.26	Mirzanamadi et al. (2019)
Subbase layer	0.70	1.53	Mirzanamadi et al. (2019)
Surface layer	1.60	2.21	Mirzanamadi et al. (2019)
Heat carrier fluid	0.54	4.11	Insana & Barla (2020)

based on the likely layers' thicknesses. To this end, a scheme composed of a 45.0 mm shotcrete layer, a 3.0 mm TPO/PVC sheeting and 2 × 1.0 mm geotextile layers arranged in series was considered. Despite shotcrete representing 90% of the entire fictitious layer, its thermal resistance weighs only 40% of the overall value. This agrees with the outcomes of the Seocheon experimental site (Lee et al., 2012, 2016), which highlight the insulation feature of geotextile layers.

3.1.2. Initial and boundary conditions

Appropriate initial and boundary conditions were set on the model (Fig. 7 and Fig. 8) to reproduce likely existing motorway tunnel thermo-hydraulic conditions. Accordingly, the temperature at the top, bottom and lateral boundaries of the model, as well as the initial domain temperature, was set to 12.5°C. This corresponds to the past 5-year average ambient air temperature measurements illustrated in the following subsection. These boundary conditions are representative of tunnels with an overburden of at least 15.0÷20.0 m, thus not affected by ambient air temperature oscillation. On the contrary, adiabatic boundary conditions were applied to the front and back boundaries, thus accounting for thermal symmetry in the longitudinal direction.

Heat transfer between the lining and the internal air was reproduced by adopting a convection boundary condition at the interface between the tunnel intrados and the underground environment. Here, the internal air temperature was imposed, as well as the heat transfer rate. This exemplifies the amount of heat exchange between the above-mentioned entities and strongly depends on the average velocity of the air mass flowing in the underground environment (Peltier et al., 2019). In this regard, the results of a research project funded by the Swiss Federal Roads Office and aimed at monitoring longitudinal air speed in road tunnels (Grässlin et al., 2014) gave some further insights. The measurement performed for the Flüelen and Bözberg tunnels highlighted that, under normal traffic conditions, the internal airflow velocity ranged between 0.0÷5.0 ms^{-1}. Accordingly, the representative heat transfer rate interval to investigate through numerical modelling was selected equal to 0.0÷25.0 $Wm^{-2}K^{-1}$.

Lastly, the thermal activation of the existing tunnel was simulated by forcing constant inlet heat carrier fluid temperatures equal to 4°C and 28°C, respectively, in the winter and summer seasons. Notwithstanding the resultant thermal loading profile is not representative of the operability of such a system, this is a validated methodology in literature for comparing different geothermal systems or carrying out sensitivity analyses. The inlet and outlet heat carrier fluid velocities were imposed to 0.90 ms^{-1}. This was assumed based on the experimental data retrieved from the Enertun test site in Turin (Barla et al., 2019; Insana & Barla, 2020).

3.1.3. Model initialisation

To initialise the numerical model, 2-year preliminary simulations were performed with no thermal activation of the lining. Depending on the diverse aerothermal conditions of the underground environment tested, these simulations were aimed at obtaining a prospective field of temperatures for the existing tunnel preceding the energy retrofitting. To this end, a representative temperature time history was identified based on the past 5-year ambient air temperature measurements of an Apennine area in North-West Italy. First, these data were interpolated through sinusoidal regression. Then, the air temperature of the tunnel environment was computed in agreement with the simplified method developed by Buhmann et al. (2016). Such a method estimates the tunnel air temperature starting from ambient air and accounting for the distance from the portals and the tunnel cross-sectional area. It was developed based on the empirical evidence originating from the monitoring activities carried out for the geothermal test plants of the Stuttgart-Fasanenhof and Jenbach tunnels, which included, among others, tunnel and ambient air measurements. In both cases, the underground air temperature trend experienced an amplitude reduction of 15÷35% and a phase shift of about a month with respect to surface air, thus having less marked and time-delayed temperature peaks. The method revealed good correlations with both the test plant underground air recordings, however, it neglects meaningful tunnel features such as its overburden and utilisation or even the role of the groundwater flow.

Accordingly, Fig. 9 illustrates the time history of the underground environment temperature adopted for the initialisation of the numerical model, as well as for the subsequent simulations. This was computed accounting for an amplitude reduction of 20%, a phase shift of a month, a distance from the closest portal of 100.0 m and a tunnel cross-sectional free area of about 72.8 m^2. Fig. 9 also exemplifies the tunnel lining temperature computed during the 2-year initialisation at different distances from the intrados. Within the whole year, the temperature oscillations in the mid axis of the lining were revealed to range between ± 5.0°C with a mean temperature gradient along the thickness of about ± 0.025°C cm^{-1}, which agrees with Nicholson et al. (2014).

Fig. 10a and Fig. 10b, instead, depict the temperature field around

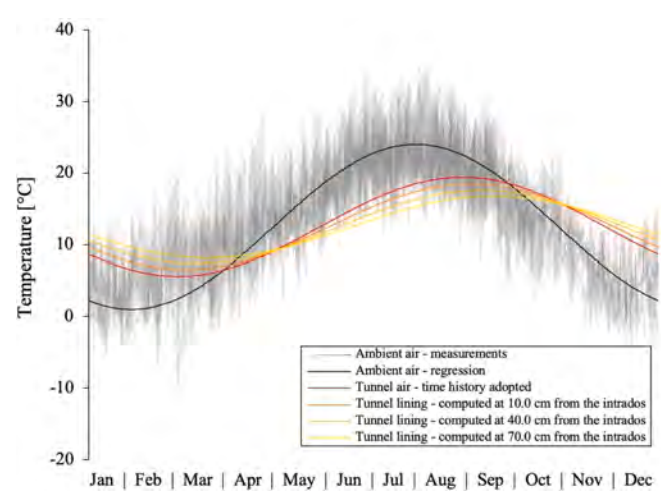

Fig. 9. Temperature of the ambient air (measurements and regression), tunnel air (used in the numerical model) and tunnel lining (computed during the 2-year initialisation phase with a heat transfer rate parameter of 10.0 $Wm^{-2}K^{-1}$).

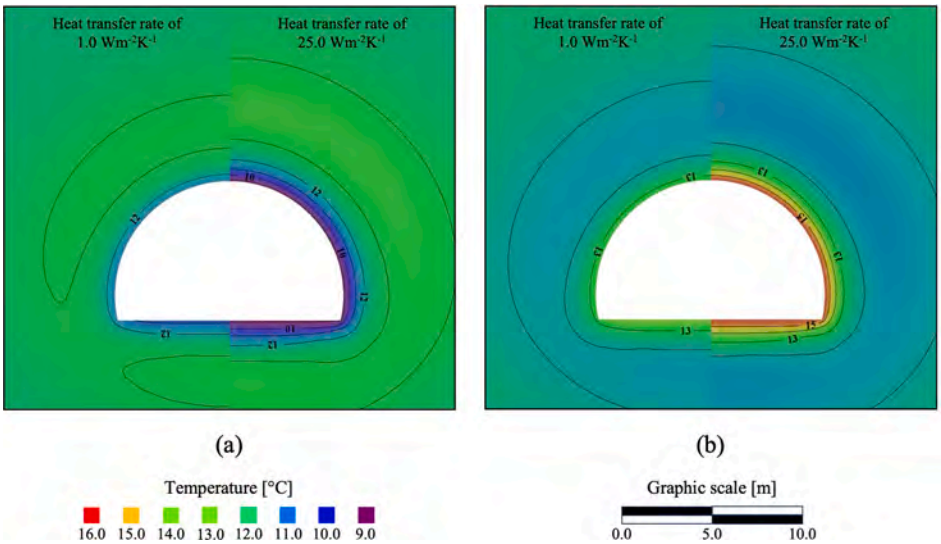

Fig. 10. Computed tunnel lining temperature during the 2-year initialisation phase in a) winter and b) summer as a function of the minimum and maximum heat transfer rate parameter adopted.

the tunnel lining, respectively, for winter and summer during the 2-year initialisation, i.e. with no heat exchange. It points out that the higher the heat transfer rate (which is a function of the underground environment airflow velocity), the more the temperature of the tunnel lining and the ground behind gets colder/warmer during winter/summer.

3.2. Assessment of thermal performance based on analysis results

To assess the thermal efficiency of the proposed energy retrofitting solutions, 30-day thermo-hydraulic numerical analyses were carried out, considering the whole months of January and July for continuous heat extraction and injection, respectively.

To this end, as mentioned in the previous section, different aero-thermal conditions of the underground environment were investigated. On the other hand, the positive influence of the groundwater flow on the heat exchange was conservatively neglected, thus providing base heat extraction/injection ratios depending almost exclusively on the retrofitting solutions themselves. In addition, conservatively, both heat extraction and injection were performed as separate analyses to not be influenced by any previous operational phase of the newly retrofitted tunnel.

Fig. 11 exemplifies the exploitable thermal power by the proposed energy retrofitting solutions in the winter and summer seasons, respectively, and their performance trend as a function of the aero-thermal conditions of the underground environment. Thermal power outputs are higher in summer than in winter. Indeed, the difference between the inlet temperature of heat carrier fluid and the undisturbed temperature of the ground is largely favourable during injection operations.

Fig. 11 also emphasises the non-negligible role of underground environment aerothermal conditions in the heat exchange process. Despite always being a favourable contributor to heat exchange during the injection period, a heat transfer rate parameter increase does not always lead to a rise in thermal performance while extracting heat

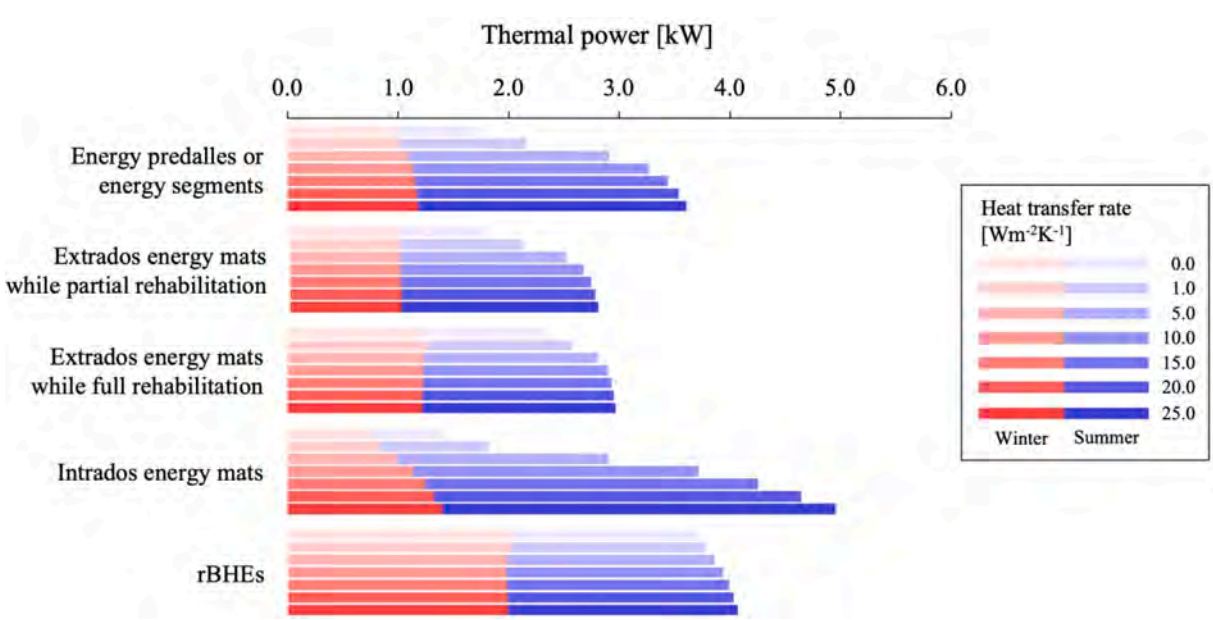

Fig. 11. Exploitable thermal power by the energy retrofitting solutions during winter heat extraction and summer heat injection at the end of a 30-day continuous operational phase.

during winter. This is the case of (i) extrados energy mats installed during full rehabilitation works and (ii) rBHEs. The rationales behind this are explained in the following:

i. Heat exchange involves almost exclusively the ground behind the newly retrofitted tunnel since heat exchanger pipes lie between it and the waterproofing system that performs as insulation towards the underground environment. In such a condition, during winter heat extraction, the colder the ground (see Fig. 10), the lower the thermal performance of the extrados energy mats. Accordingly, an increment of the heat transfer rate parameter implies the above-mentioned ground to cool down during the 2-year initialisation simulation, thus affecting the subsequent heat extraction operation. Nonetheless, the alternation of extraction and injection phases, as well as the insulating feature of the waterproofing system, should smooth and probably reverse this phenomenon over the long term.
ii. Since heat exchange involves also deeper portions of the ground behind the newly retrofitted tunnel, the heat carrier fluid reaches higher temperatures than the underground environment, thus reducing the rBHEs heat extraction performance for increasing values of the heat transfer rate parameter. The insulation of the innermost portions of the heat exchanger pipes should permanently solve this issue.

These phenomena do not occur during summer heat injection because of the nearly doubled temperature difference between the heat carrier fluid at the inlet and the undisturbed ground conditions with respect to winter heat extraction.

The amount of exchangeable heat after 30 days of continuous operation oscillates between 0.8 to 2.0 kW during winter and between 1.4 to 5.2 kW during summer, as a function of the type of energy retrofitting solution and the aerothermal conditions of the underground environment. This corresponds to the normalised extracted and injected heat and the inlet–outlet temperature difference given in Table 2 (the normalisation of the thermal power was carried out considering the activated tunnel length that corresponds to 3.6 m for energy segments, energy predalles and energy mats and 6.0 m for rBHEs). Overall, the thermal efficiencies of the proposed energy retrofitting solutions are in agreement with previous works (Baralis et al., 2020; Nicholson et al., 2014) and experiences (Franzius & Pralle, 2011). However, the thermal power predicted for high values of the heat transfer rate (especially for intrados energy mats) is unlike to be observed in practice due to the transient nature of this boundary condition. Despite this parameter varied among a range selected according to the monitoring outcomes of Grässlin et al. (2014), it is unlikely that it stabilises at large values for long periods. It is a function of the velocity of the internal airflow which, in turn, strongly depends on aleatory circumstances, just as the direction and intensity of the wind or the dimensions, the velocity of the vehicles travelling through the tunnel and the presence of the ventilation systems. Thermal efficiency values of around 1300.0 Wm^{-1} are reported by Barla et al. (2019) and Insana & Barla (2020) for the Enertun prototype test site in Turin. However, this was distinguished by an extremely favourable groundwater flow of about 1.4 md^{-1} able to steadily recharge the geothermal reservoir and a specifically optimised pipes circuit.

In the investigated conditions and neglecting any economic aspects (which will be addressed in the following section), the thermal efficiency of the proposed energy retrofitting solutions seems to be comparable. Extrados energy mats and rBHEs emerge to be well-balanced solutions able to provide stable thermal outputs regardless of the internal airflow aerothermal conditions. Moreover, energy segments or predalles and intrados energy mats, due to the closeness of the pipes to the intrados, appear also suitable to harvest heat from the underground environment of hot tunnels for cooling purposes, thus reducing ventilation requirements (Alvi et al., 2022).

Finally, Fig. 12 depicts the temperature field in the innermost cross-section of the numerical model at the end of the 30-day thermo-hydraulic analyses for each of the proposed energy retrofitting solutions in both winter heat extraction and summer heat injection modes. Soil-structure temperature differences of about 6.0°C during winter and 12.0°C during summer are expected under the simplified operating conditions considered.

4. Economic attractiveness

In order to obtain a comprehensive comparison among the proposed technological solutions, the economic attractiveness of converting existing tunnels into energy tunnels is here assessed, determining the LCOE thus exploitable for each solution. The LCOE represents the average net present energy cost for the generator over its lifetime to recoup the initial investment and earn from it. The lower the LCOE with respect to other energy sources in the same energy market (i.e., coal, oil, natural gas, etc.), the higher the attractiveness towards potential customers. In the framework of thermal plants relying on energy geostructures, validating the profitability of geothermal energy is paramount to justify the embedment of heat exchanger pipes in geostructures and foster the application of the technology (Cousin et al., 2019).

The LCOE is determined by the capital and yearly investments to start the business up and make it work, its productivity and the corresponding profit. For the sake of conciseness, the equations involved in the LCOE computation are not reported in the current study (refer to Cousin et al., 2019).

The capital cost includes the additional initial costs to instrument geostructures to exploit geothermal energy and integrate the system within the district heating network, such as:

- Heat exchanger pipes, whose costs depend mainly on their diameter and material (HDPE, PE-Xa, etc.);

Table 2
Normalised extracted and injected power and inlet–outlet temperature differences for different energy retrofitting solutions (each quantity varies as a function of the heat transfer rate parameter).

Energy retrofitting solution	Normalised extracted power [Wm^{-1}]	Normalised injected power [Wm^{-1}]	Winter inlet–outlet temperature difference [°C]	Summer inlet–outlet temperature difference [°C]
Energy segments/predalles (partial rehabilitation)	262.4÷328.5	478.5÷1009.9	1.27÷1.59	2.32÷4.89
Extrados energy mats (partial rehabilitation)	277.6÷286.3	506.1÷780.7	1.34÷1.39	2.45÷3.78
Extrados energy mats (full rehabilitation)	339.3÷353.9	645.3÷815.7	1.64÷1.71	3.12÷3.95
Intrados energy mats (repurposing)	211.7÷387.5	386.2÷1442.6	1.02÷1.88	1.87÷6.98
rBHEs (repurposing)	329.9÷340.0	619.9÷690.4	2.66÷2.74	5.00÷5.57

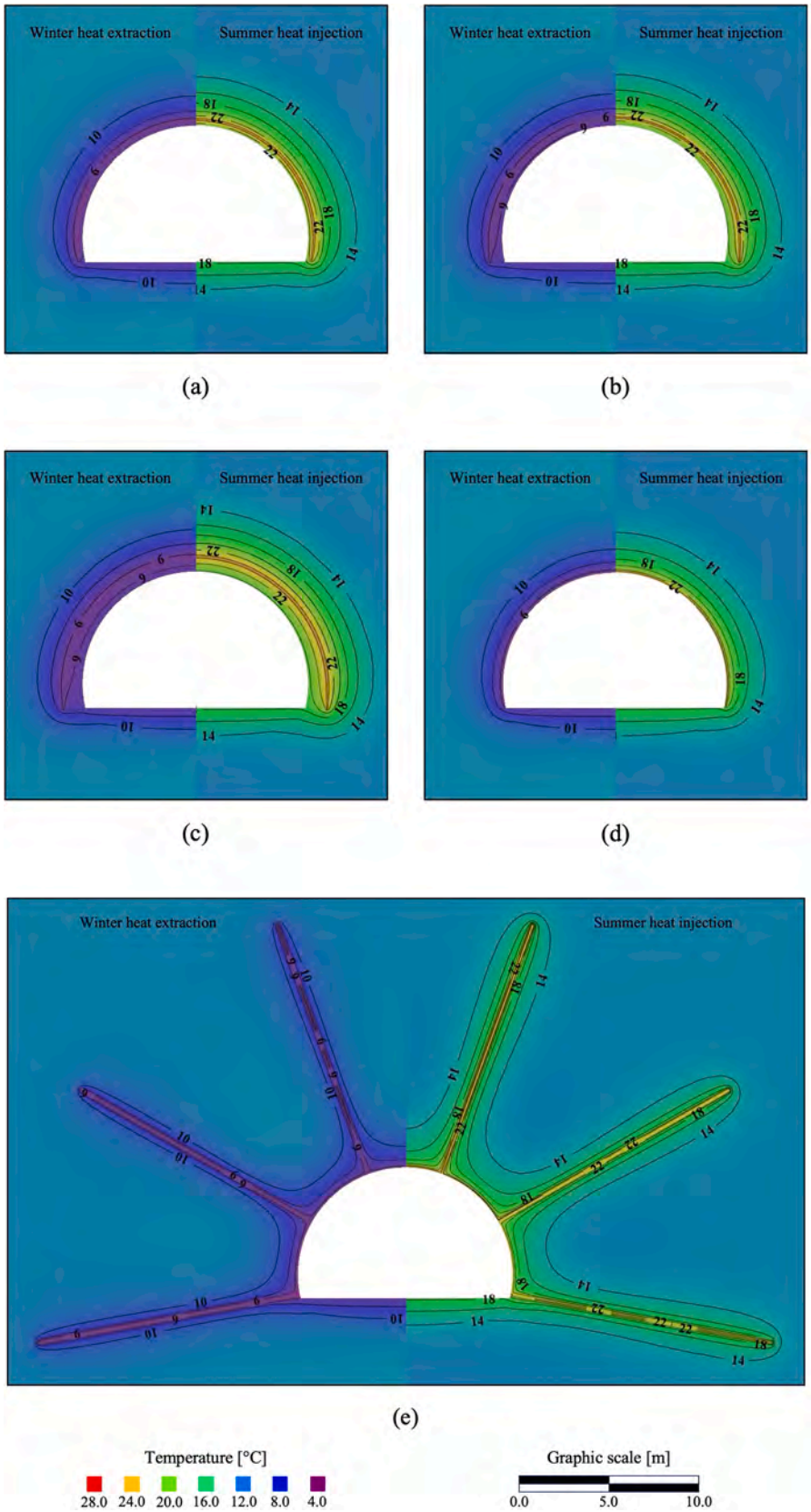

Fig. 12. Temperature field at the end of the 30-day thermo-hydraulic numerical simulations for a) energy precast segments/predalles during partial rehabilitation, extrados energy mat during b) partial and c) integral rehabilitation, d) intrados energy mat and e) rBHEs after repurposing (heat transfer rate parameter of 10.0 $Wm^{-2}K^{-1}$).

- Additional workforce, which is the result of the additional hours needed for specialised labourers to instrument geostructures with heat exchanger pipes, check their integrity and perform pressure tests at the end of the instrumentation phase;
- Header pipes, whose costs depend on their diameter and material (HDPE, steel, etc.), as well as the likely presence of external insulation to avoid heat dissipation;
- Hydraulic pumps, whose initial costs vary as a function of the hydraulic flow rate to deliver and the head losses developed along the hydraulic circuit;
- Heat pumps, whose initial cost mainly depends on their thermal performance, i.e., nominal thermal power, Coefficient Of Performance (COP)/Energy Efficient Ratio (EER), their technology and the installation fee;
- The distribution network, whose cost, as for header and heat exchanger pipes, varies with the type of material, the pipe diameter and the likely presence of insulation. Eventual additional work to bury them under the surface level should be considered;
- Heat boosters, which are local heat pumps needed to allow also old radiator-served buildings to take advantage of the district heating systems (Barla & Insana, 2023). The same observations as for the cost of heat pumps apply here, too.

The running cost comprises the yearly amount of outflow needed to guarantee the operability of the thermal plant, such as:

- Hydraulic pumping costs, which result from the distributed and localised head losses developed in the hydraulic circuit and the cost of the electric energy. Whether distributed head losses develop because of the friction between the flowing fluid and the pipe walls, localised head losses depend on eventual flow disruptions due to valves, elbows, tees, etc.;
- Heat pump compressor working costs, which result from the machinery's thermal performance, the total amount of energy to supply/subtract and the cost of the electric energy. The COP/EER, which exemplifies the ratio of the supplied/subtracted thermal energy provided to the work required, is strongly variable in time, as a function of the temperature of the thermal reservoir (working as a heat source/sink) and the required thermal energy to supply/subtract to ensure the thermal comfort;
- Maintenance, which generally comprises only the upkeeping costs to ensure the operability of heat and hydraulic pumps. Indeed, these commonly have a nominal service life that is half to a quarter with respect to HPDE and PE-Xa tubing.

On the other hand, the productivity of an energy geostructures-based thermal plant results from the amount of thermal energy to supply to or subtract from potential customers. The higher the COP/EER of the heat pump fleet, the more convenient the exploitation of geothermal energy with respect to other thermal sources. The corresponding earnings depend on the Weighted Average Costs of Capital (WACC). This is a metric of the real net profit of the investment as a function of several aspects, among which are the maturity and the level of development of the technology. The more reliable is this, the lower the perceived risks associated with the investment and similarly the WACC.

The LCOE analysis is performed considering a minimum service life of the geothermal plant equal to 25 years. The LCOE after 25 years for the proposed energy retrofitting solutions is depicted in Fig. 13 and results from the input parameters given in Table 3 and Table 4. These were assumed based on a preliminary market analysis (Table 3) and considering the average working conditions of shallow geothermal systems (Table 4). Costs of tunnel rehabilitation were not considered for energy predalles, energy segments and extrados energy mats because these costs would be borne anyway, independently from energy retrofitting; drilling and shotcrete spraying costs were contemplated for intrados energy mats and rBHEs. For the sake of simplicity, the costs related to the distribution of heat to customers were not envisaged.

Besides this, other assumptions at the base of the LCOE computation are listed in the following:

- An overall energy retrofitting length of 180.0 m was considered;
- Due to the tunnel length considered, its rehabilitation is supposed to be carried out in a few months, thus assuming the capital cost as an "overnight cost". As a consequence, no interest on the capital cost is considered as if the whole energy retrofitting was completed "overnight";
- The unit costs adopted for the computation were derived through a straightforward market analysis;
- Hydraulic and heat pump maintenance was included in their corresponding initial costs;
- Localised head losses along the hydraulic circuits were neglected, accounting only for friction (distributed head

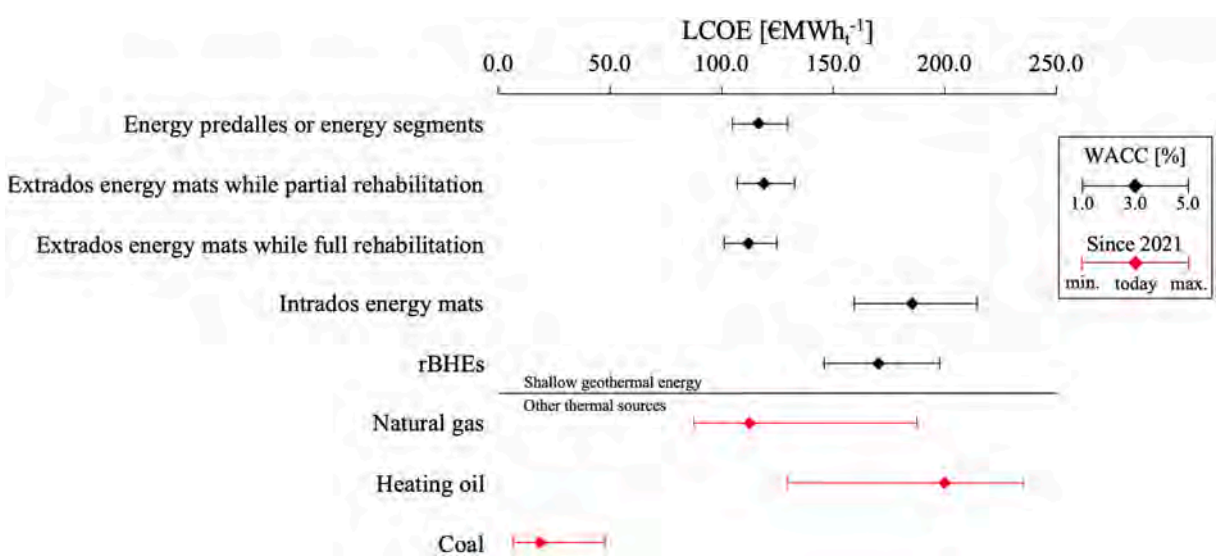

Fig. 13. LCOE after 25 years for the energy retrofitting solutions and comparison with other thermal sources (today refers to October 2023).

Table 3
Input parameters of the LCOE analysis related to the initial costs composing the capital investment of the thermal power plant.

PE-Xa pipes [€m^{-1}]	Additional workforce [€m^{-1}]	HDPE pipes [€m^{-1}]	Hydraulic pumps [€kW^{-1}]	Heat pumps [€kW^{-1}]	Average drilling cost [€m^{-1}]	Shotcrete spraying cost [€m^{-2}]
2.50	2.50	10.00	250.00	1250.00	70.00	30.00

Table 4
Input parameters of the LCOE analysis related to the running costs, productivity and profit of the thermal power plant.

Unit head loss for PE-Xa pipes [mkm^{-1}]	Unit head loss for HDPE pipes [mkm^{-1}]	Coefficient of performance [–]	Weighted average cost of capital [%]	Cost of electric energy [€MWh^{-1}]
80.0	25.0	4.00	1.00÷5.00	200.00

losses). This was estimated through the Darcy–Weisbach formulation for heat exchanger pipes (assumed to be PE-Xa) and header pipes (assumed to be HDPE). For the latter, the friction head loss coefficient was assumed constant, as if the header pipes were engineered to reduce pumping costs, gradually increasing their diameter;

- Header pipes were assumed to run appropriately insulated for 250.0 m to the heat pump fleet;
- Conservatively, only winter heat extraction operations were contemplated in the computation, considering a yearly operating time of 1800 h.

The results illustrated in Fig. 13 agree with Cousin et al. (2019), who computed an LCOE for the thermal activation of the Grand Paris Express oscillating between 80.0 and 110.0 €MWh$_t^{-1}$. These emphasise the attractiveness and profitability of potential investments for converting existing tunnels into heat exchangers, taking advantage of rehabilitation/upgrading works or repurposing strategies. However, the latter was revealed to be less attractive than the former because of the additional initial cost related to borehole drilling and shotcrete spraying.

A comparison with other thermal sources is provided, too. The massive fluctuations since 2021 in the cost of the thermal energy obtained from them are due to the recent energy crisis due to COVID-19 and the Russo-Ukrainian war. Energy geostructures-based thermal energy seems to be as economically attractive as the other sources, with coal-based thermal energy being the only much cheaper. Nevertheless, geothermal energy undoubtedly produces less CO_2 eq. emissions, leading to savings of up to 60%, 74% and 80% with respect to natural gas, heating oil and coal, respectively.

5. Conclusions

The present work proposes systematic methods to convert existing tunnels into energy geostructures. Accordingly, different solutions were conceived to fit various existing tunnel decay contexts and diverse levels of refurbishment necessity. The characteristics, the advantages, the possibility of real implementations and the installation details have been described together with the assessment of their geothermal potential through numerical modelling.

The results obtained allow drawing the following main conclusions:

- The energy retrofitting of existing tunnels would allow the exploitation of a geothermal output of 211.7÷387.5 Wm^{-1} and 386.2÷1442.6 Wm^{-1} during winter and summer, respectively. These results were evaluated neglecting the positive influence of the groundwater flow on the heat exchange and accounting for different aerothermal conditions of the underground environment. The main aim was to provide base heat extraction/injection ratios depending almost exclusively on the retrofitting solutions themselves;
- In the conditions investigated (typical Italian motorway tunnel located in an Apennine area), sensitivity analyses revealed the thermal efficiency of the proposed energy retrofitting solutions to be comparable. Whether extrados energy mats and rBHEs emerge as well-balanced solutions able to provide stable thermal outputs regardless of the internal airflow aerothermal conditions, intrados energy mats and energy segments or predalles also appear suitable to harvest heat from the underground environment. This holds even truer if the *air* configuration is used instead of the *ground* one. Considering only the winter season, for each kilometer of thermally activated tunnel, energy segments, energy predalles and extrados energy mats can heat up around 90 apartments with an average energy consumption of 80 kWh$_t$m^{-2}a^{-1} and a surface of 100 m^2. Intrados energy mats and rBHEs, instead, could heat up around 80 and 100 apartments mentioned above, respectively;
- Sensitivity numerical analyses also highlighted the paramount importance of the aerothermal conditions of the underground environment. These were revealed to affect the performance of the energy retrofitting solutions, especially during summer heat injection. This mainly results from the massive temperature difference between the heat carrier fluid at the inlet and the underground environment with respect to the winter season. An improper estimation of the design values of the internal airflow velocity and temperature could lead to an overestimation of the actual thermal potential of the energy tunnel, particularly when heat exchanger pipes are arranged close to the tunnel intrados. For intrados energy mats, indeed, an injected heat of 60.0 Wm^{-2} was computed accounting for unlikely aerothermal conditions of the underground environment;
- An LCOE analysis was carried out to assess the economic attractiveness of thermally retrofitting existing tunnels. This demonstrated the high profitability of such an investment with an LCOE of about 116.0 €MWh$_t^{-1}$ for energy retrofitting solutions to be applied during rehabilitation/upgrading works (i.e., energy segments and predalles and extrados energy mats). The solutions referred to operating or repurposed existing tunnels (i.e., intrados energy mats and rBHEs), instead, exhibited less attractiveness, being affected by the extra costs related to drilling boreholes and spraying shotcrete. Additionally, the LCOE of energy geostructures-based thermal energy was compared to other energy sources. This was revealed to be less economically attractive only to coal but has undeniable benefits from the environmental viewpoint.

The current need to refurbish most of the existing heritage of tunnels represents a valuable opportunity to renovate the tunnel heritage not only from a structural but also from a sustainable point of view.

CRediT authorship contribution statement

S. De Feudis: Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Conceptualization. **A. Insana:** Writing – review & editing, Supervision, Conceptualization. **M. Barla:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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This manuscript reflects only the authors' views and opinions and the Ministry cannot be considered responsible for them.

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Further reading

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