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BRIEF REPORT **Open Access**

Energy tunnels for a sustainable future

Marco Barla[1*] and Alessandra Insana[1]

Abstract

Energy tunnels are an emerging class of sustainable infrastructure that combines structural, geotechnical and energy functions in a single system. By thermally activating tunnel linings, engineers can extract, store and exchange geothermal heat for applications such as urban heating, cooling and infrastructure de-icing. Beyond improving energy efficiency, this technology contributes directly to the decarbonisation targets outlined in the European Green Deal. This Brief Report summarises the principles, design framework, and strategic potential of energy tunnels, drawing on recent advances and case studies, including the Turin Metro Line 2, the Brenner Base Tunnel, and the Lyon–Turin connection, to illustrate how they can transform underground infrastructure into renewable energy assets.

Highlights

- Energy tunnels transform transport infrastructure into renewable geothermal power sources for cities.
- Thermally activated tunnels can reduce CO_2 emissions by up to 60% in urban energy systems.
- Integrating energy tunnels with district heating and UTES unlocks year-round, low-carbon urban energy storage.

Keywords Geothermal energy, Tunnels, Thermal storage

1 The concept of energy tunnels

Energy tunnels belong to the wider family of energy geostructures, which integrate heat exchange systems into load-bearing underground elements such as foundations, diaphragm walls and tunnel linings [1, 2]. These systems typically use closed-loop circuits of high-density polyethylene pipes embedded in reinforced concrete structures, connected to heat pumps to exchange thermal energy with the ground.

At depths of 8–10 m, ground temperatures remain nearly constant throughout the year (8–16 °C in temperate climates), providing a stable and renewable source of low-enthalpy geothermal energy [3]. Unlike solar or wind energy, this source is continuously available, offering significant advantages for urban heating and cooling applications.

Tunnels offer particularly favorable conditions for geothermal exploitation. The large surface area of the lining in contact with the ground enhances the heat exchange rate compared with foundations or retaining walls (Fig. 1). Moreover, in mechanised tunnelling, precast lining segments can be equipped with heat exchangers during manufacturing, minimising additional costs or on-site disruption [4–6].

Some real-scale examples have been realized in Europe in the last 20 years [4, 5, 7]. At the Politecnico di Torino, a patented Enertun segment was developed to improve energy efficiency by up to 10% while reducing hydraulic head losses by 20%–30% with respect to previous

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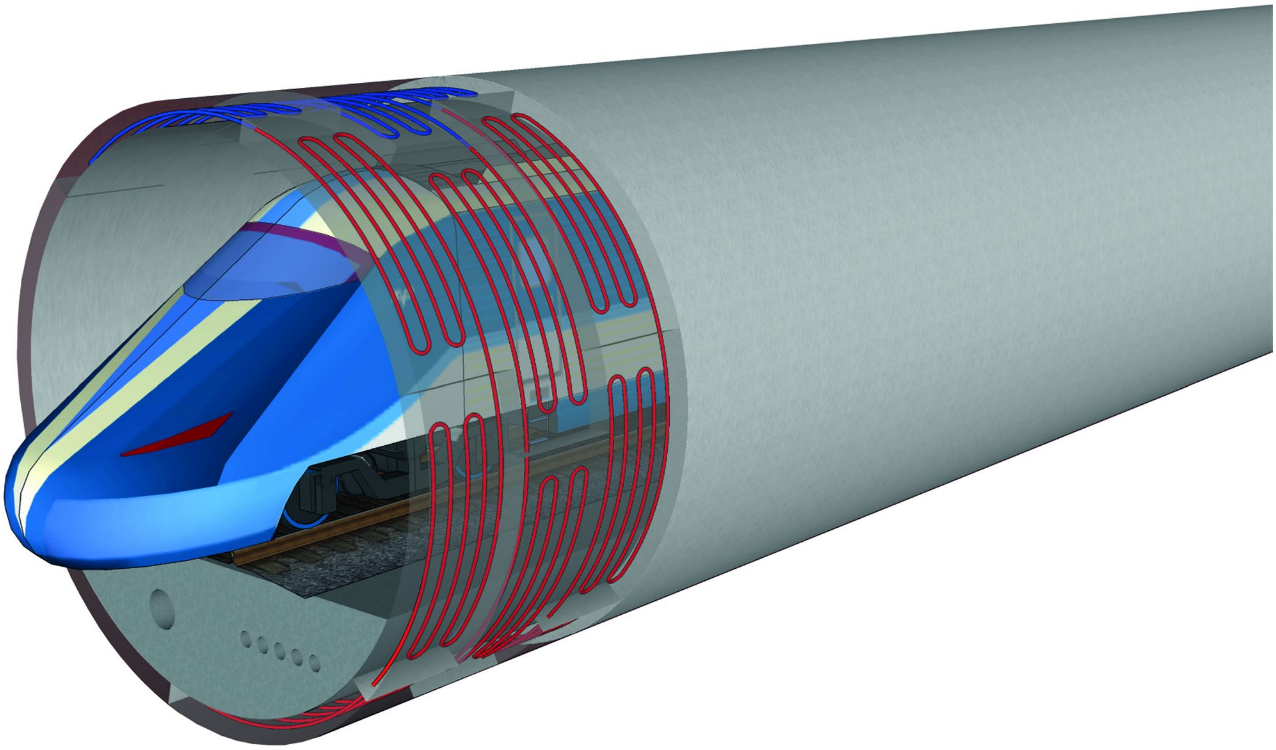


Fig. 1 Conceptual view of an energy tunnel showing heat exchange loops embedded in the concrete lining

configurations where pipes are aligned with the longitudinal axis of the tunnel [6]. Depending on pipe placement, Enertun segments can prioritise heat exchange with the surrounding ground (Ground configuration), the tunnel air (Air configuration), or both (Ground & Air configuration).

2 Strategic potential for decarbonisation

The integration of geothermal systems into transport infrastructure represents a major opportunity to accelerate the energy transition. Energy tunnels can supply clean, decentralised heating and cooling in densely populated areas while reducing reliance on fossil fuels. This aligns with the EU Directive 2009/28/EC and subsequent European Commission roadmaps targeting a climate-neutral economy by 2050 [8, 9].

Beyond Europe, countries such as China, South Korea and Australia have explored similar approaches to exploit geothermal potential in underground transit systems and deep rock tunnels [10–12]. In cold regions, they can prevent frost damage and reduce operational costs, while in hot climates or deep environments, they can dissipate excess heat from the tunnel environment.

Energy tunnels are particularly relevant for urban decarbonisation strategies, as they can be coupled with low-temperature district heating and cooling networks. When integrated into metro systems or transport hubs, they can provide distributed renewable heat directly beneath the urban fabric. The scalability and continuity of such systems make them an attractive complement to photovoltaic and heat pump networks.

Figure 2 shows key projects of energy tunnels worldwide and their energy outputs highlighting the variety of possible applications.

3 Design and implementation framework

The design of an energy tunnel requires multidisciplinary integration of geotechnical, structural and thermal engineering principles. Unlike traditional tunnels, where structural and geotechnical behaviour dominate, the design of energy tunnels must also account for heat transfer mechanisms to assess the exploitable energy and long-term performance under cyclic thermal loading to evaluate its suitability in the environment.

As described in [13], a recommended workflow involves (Fig. 3):

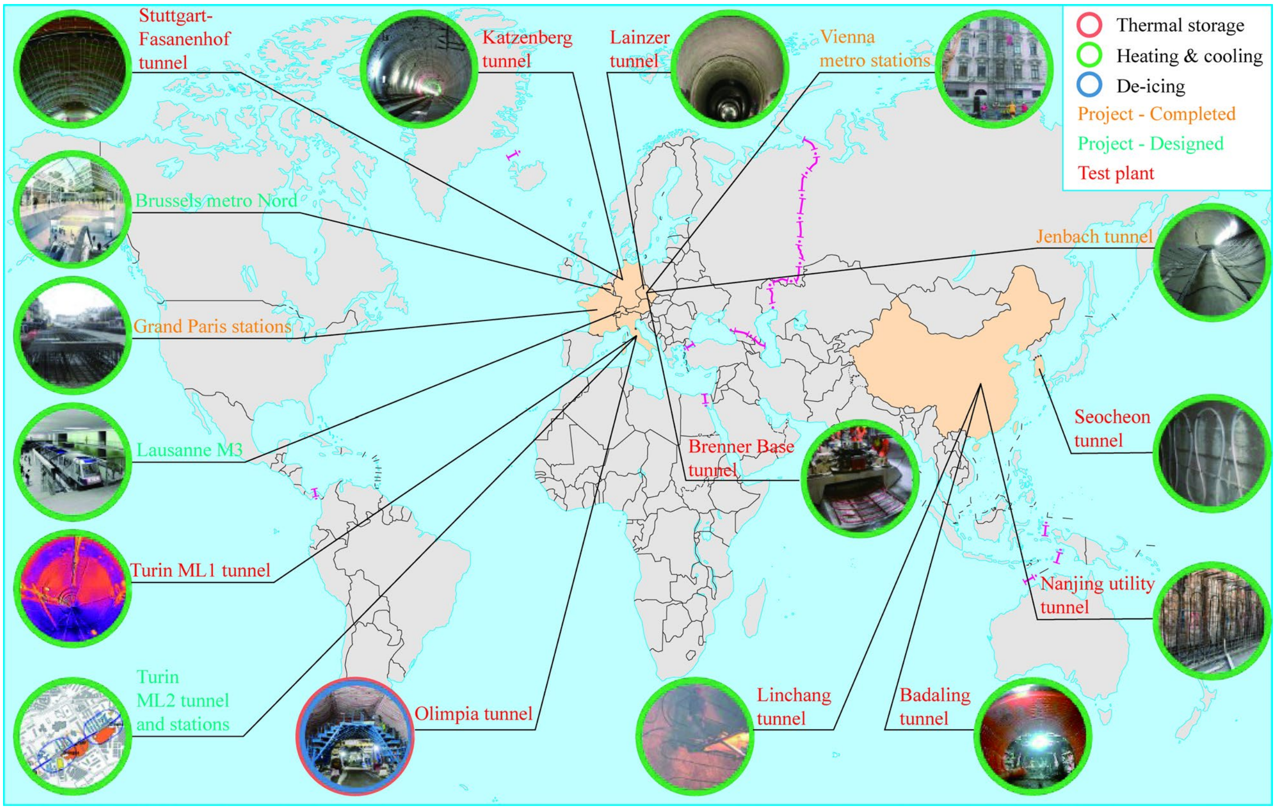


Fig. 2 Infographic showing key energy tunnels projects and their energy outputs in Europe and worldwide

(1) Site characterization - geological, hydrogeological, thermal and geotechnical investigations;
(2) Thermal design - optimisation of pipe configuration, flow rate and layout;
(3) Structural design - assessment of induced thermal stresses;
(4) System integration - connection with heat pumps and networks.

After construction, performance verification is to be assessed through field monitoring to allow for functioning optimization.

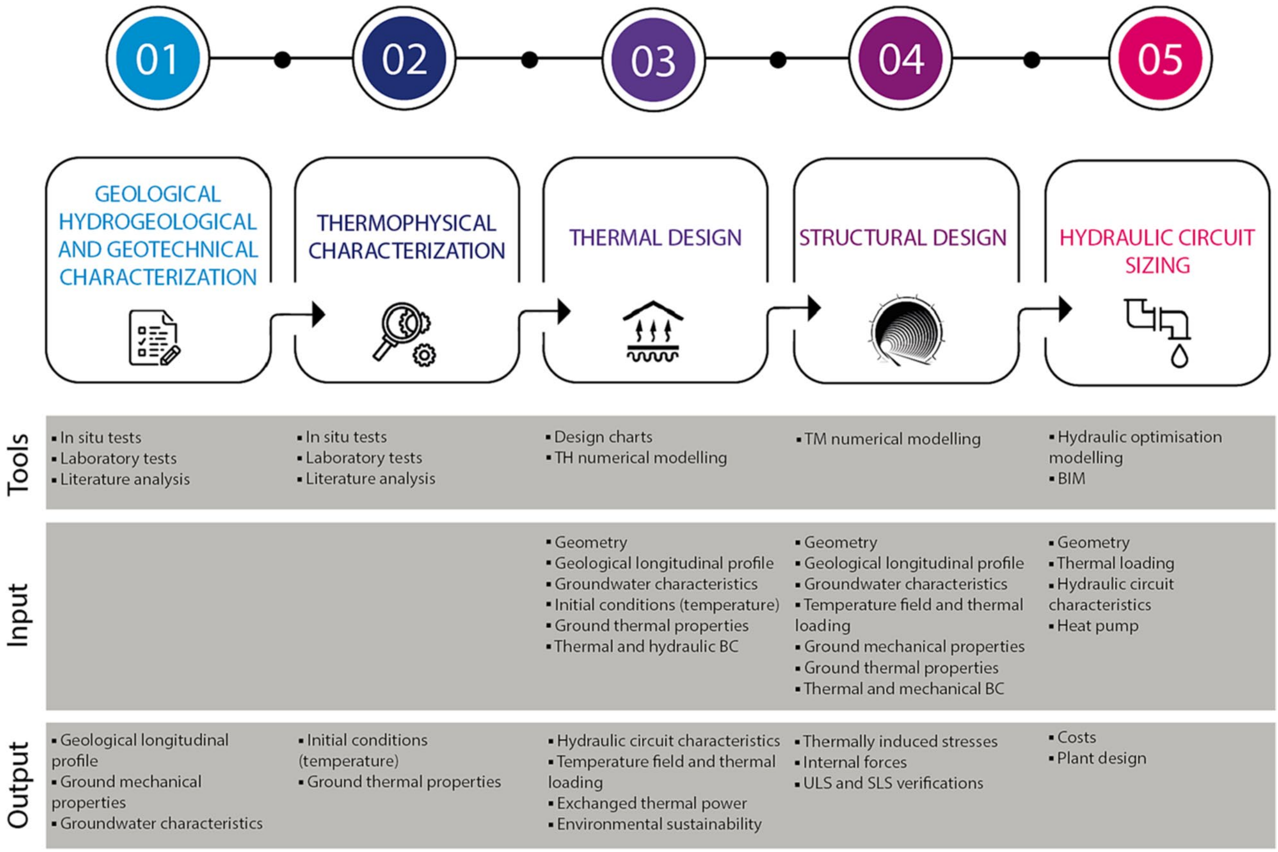
4 Case studies and applications

The strategic potential of energy tunnels can transform underground infrastructure into renewable energy assets. Some key examples are discussed in the following to illustrate, without claiming to be exhaustive, the variety of possible applications.

4.1 Urban metro systems

The Turin Metro Line 2 exemplifies a large-scale feasibility study of energy tunnels in an urban environment [14, 15]. Using a combination of Enertun segments in TBM-driven sections and thermally activated diaphragm walls in Cut & Cover areas, the project is expected to provide up to 18.7 and 11.9 MW of renewable thermal power, respectively in winter and in summer. This is sufficient to meet the heating and cooling needs of all the metro stations along the line as a primary solution. The additional energy supply can be diverted to nearby buildings on the surface (Fig. 4a). An example showcasing the functioning of the energy tunnel can be seen in Fig. 5 which illustrates a summer mode test by using the Enertun prototype in Turin Metro Line 1 South extension.

The Turin Metro Line 2 project anticipates a 7-year payback period and up to 60% CO_2 reduction compared to gas-based systems. Similar experiences are undergoing in the European cities of Bruxelles, Lausanne, Madrid,



	01 GEOLOGICAL HYDROGEOLOGICAL AND GEOTECHNICAL CHARACTERIZATION	02 THERMOPHYSICAL CHARACTERIZATION	03 THERMAL DESIGN	04 STRUCTURAL DESIGN	05 HYDRAULIC CIRCUIT SIZING
Tools	▪ In situ tests ▪ Laboratory tests ▪ Literature analysis	▪ In situ tests ▪ Laboratory tests ▪ Literature analysis	▪ Design charts ▪ TH numerical modelling	▪ TM numerical modelling	▪ Hydraulic optimisation modelling ▪ BIM
Input			▪ Geometry ▪ Geological longitudinal profile ▪ Groundwater characteristics ▪ Initial conditions (temperature) ▪ Ground thermal properties ▪ Thermal and hydraulic BC	▪ Geometry ▪ Geological longitudinal profile ▪ Groundwater characteristics ▪ Temperature field and thermal loading ▪ Ground mechanical properties ▪ Ground thermal properties ▪ Thermal and mechanical BC	▪ Geometry ▪ Thermal loading ▪ Hydraulic circuit characteristics ▪ Heat pump
Output	▪ Geological longitudinal profile ▪ Ground mechanical properties ▪ Groundwater characteristics	▪ Initial conditions (temperature) ▪ Ground thermal properties	▪ Hydraulic circuit characteristics ▪ Temperature field and thermal loading ▪ Exchanged thermal power ▪ Environmental sustainability	▪ Thermally induced stresses ▪ Internal forces ▪ ULS and SLS verifications	▪ Costs ▪ Plant design

Fig. 3 Simplified design workflow illustrating investigation, thermal, structural and hydraulic design steps [13]

Paris and Toulouse. In urban environment it is particular attractive the possibility to integrate energy tunnels with low temperature district heating networks for easing the distribution to the final users. Direct connection is possible with new low energy consumption buildings, while boosters can be adopted to allow satisfying also the needs of old, existing buildings.

4.2 Infrastructure de-icing

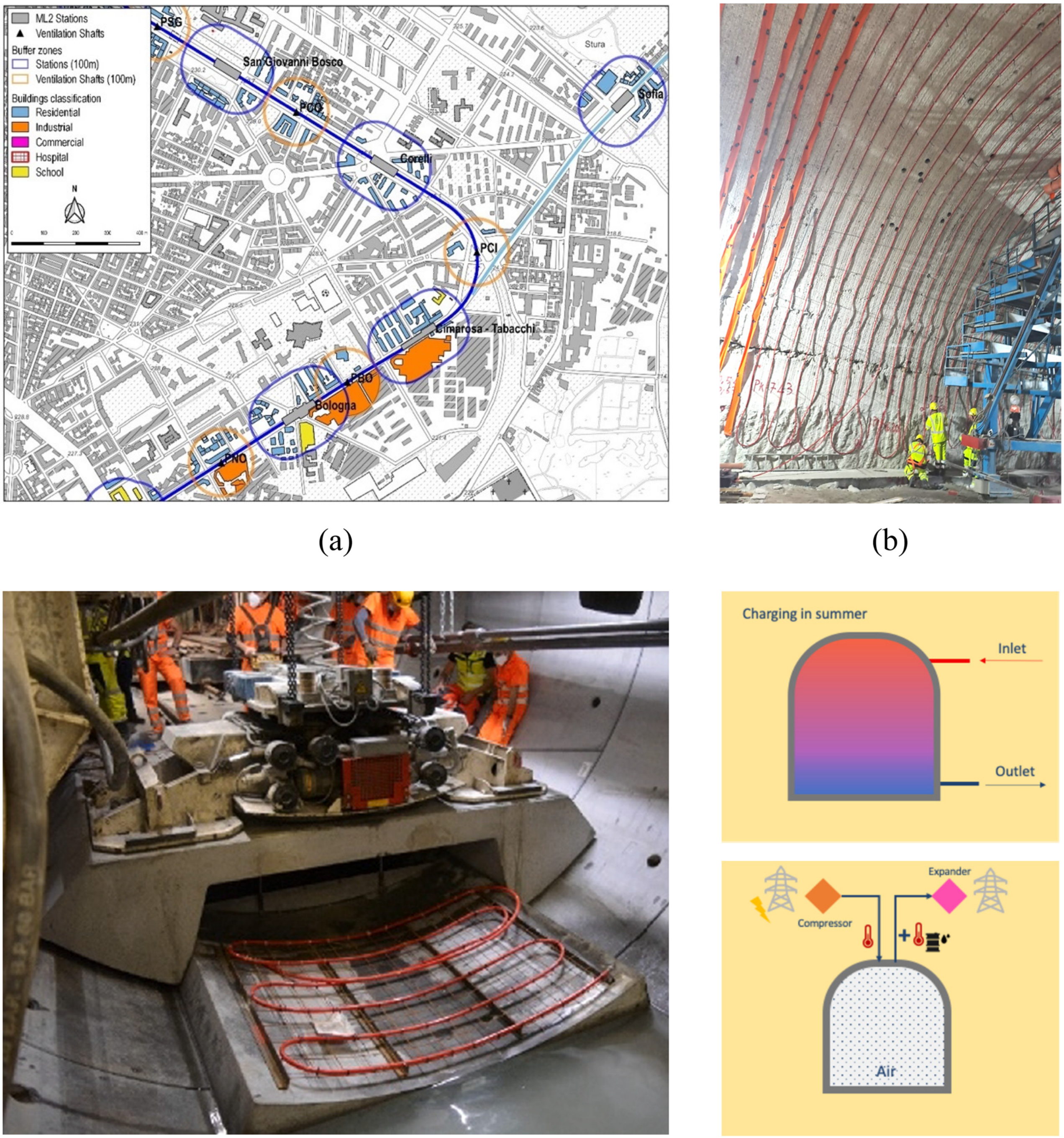
In mountainous regions, tunnels adjacent to bridges or viaducts can be used for anti-icing systems. Heat extracted from tunnel linings can be circulated through pipes embedded in bridge decks to prevent ice formation [16, 17]. This is particularly attractive for motorways as can dramatically reduce the use of chemical salts that impact pavement conservation. Moreover, it allows for reducing costs and time of de-icing, particularly in remote areas, compared to traditional solutions that require long distance travels of road salt spreaders. A pilot project in Northern Italy (Fig. 4b) demonstrated this method's viability during motorway refurbishment works, where exchanger pipes were installed between existing and new linings [17].

4.3 Deep tunnels

The Lyon–Turin Base Tunnel, currently under construction, is an example of a deep and long tunnel. It will pass beneath over 2 km of rock cover, with expected rock temperatures reaching 50 °C. Thermal activation of lining segments could both cool the tunnel environment, reducing ventilation costs, and recover excess heat for external use [18]. Similar strategies are being studied for the Brenner Base Tunnel (Fig. 4c) where absorber pipes and drainage-water heat exchangers have been tested to recover 0.16–0.29 MW of additional power after long-term operation [19, 20].

4.4 Retrofitting and energy storage

Existing or abandoned tunnels can be retrofitted for energy use, transforming them into underground energy storage systems. Many projects are exploring the use of Underground Thermal Energy Storage (UTES) systems that exploit existing cavities for seasonal heat storage and recovery [21, 22]. In the urban environment Tank Thermal Energy Storage (TTES) appear to be the most promising, where water is used to store thermal energy



(a) (b)

(c) (d)

Fig. 4 (**a**) Example of identification and classification of the potential receivers along a section of the Turin ML2 line, (**b**) Energy retrofitting of the Olimpia tunnel (in Italy) for de-icing purposes [17], (**c**) Thermal exploitation from the drainage water in the Brenner base tunnel of the Smart Flowing prototype [20], (**d**) Sketch of the TTES and the CAES systems

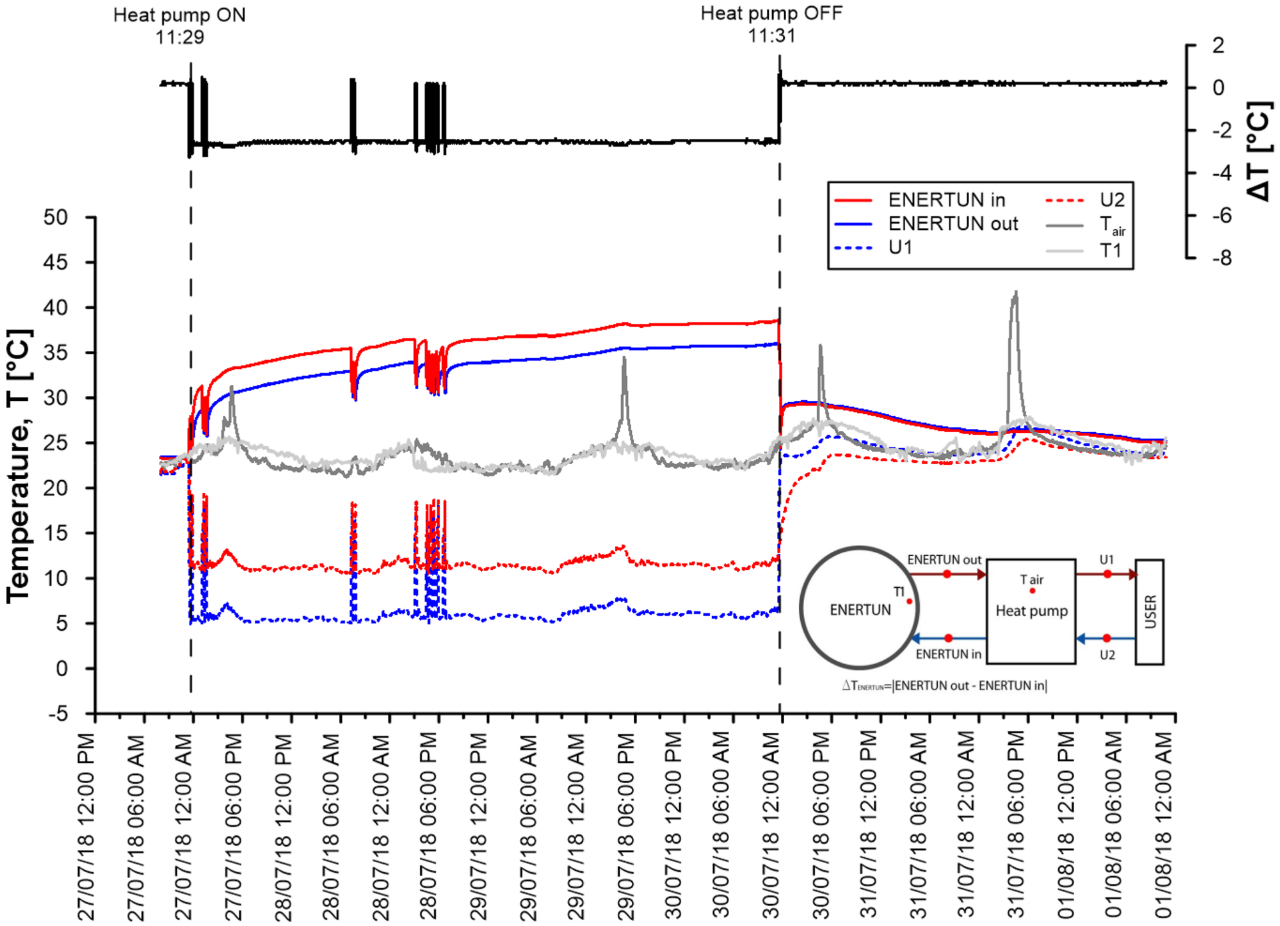


Fig. 5 Example of an illustrative test carried out on the "Enertun" prototype in summer mode (cooling the user, heating the ground; modified from [23])

underground (Fig. 4d). This reuse of existing assets promotes circularity and resilience in the urban energy grid. Also, exciting opportunities lie in the possibility of adopting underground cavities for storing pressurised air, sand or water for electrical energy storage and recovery (e.g. Compressed Air Energy Storage, CAES, and other technologies).

A large heritage of tunnels and underground spaces exists and some have also reached the service life being abandoned or turned to other uses. Among these, the most common are mining spaces, metro tunnels, underground air shelters from World War II. This tunnel heritage represents a unique opportunity to develop local renewable energy sources that could be used to promote sustainable, climate-neutral development and contribute to the decarbonisation of the heating and cooling sector, for the production and storage of thermal energy, thus supplementing the need for storage and energy stability and reducing the reliance on fossil fuel sources.

5 Outlook and future perspectives

Energy tunnels illustrate how underground infrastructure can serve dual purposes, supporting transportation and providing renewable energy. Moreover, abandoned tunnels can be revitalized as energy storage facilities. Their strategic relevance lies in the synergy between civil engineering and energy policy, offering practical means to decarbonise cities and enhance energy security. Cities that will be able to develop policies to manage subsurface urban heat in optimized and integrated way (Fig. 6) will benefit both environmentally and economically.

Future development depends on three key directions:

(1) Standardization: developing design codes, monitoring protocols, and performance benchmarks to ensure reliability across projects;

(2) Integration: coupling energy tunnels with district heating networks and smart grids for demand-responsive operation;

(3) Innovation: leveraging materials with higher thermal conductivity and storage capacity, adaptive flow control, and AI-driven operation models for optimal heat management.

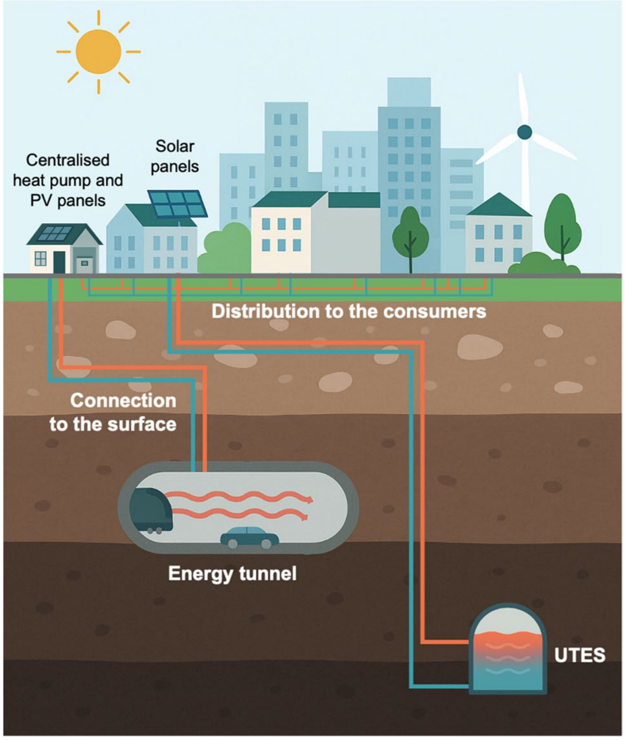


Fig. 6 Conceptual graphic showing integration of energy tunnels into a city-scale renewable energy network with district heating and UTES links

The growing portfolio of projects demonstrates that energy tunnels are no longer experimental. Their scalability across climates and geological conditions positions them as a global solution for sustainable underground energy. As cities expand downward, energy tunnels will become a cornerstone of climate-neutral infrastructure, combining safety, efficiency and innovation beneath our feet.

Authors' contributions

All authors wrote the main manuscript text, prepared figures and reviewed the manuscript.

Data availability

No datasets were generated or analysed during the current study.

Declarations

Competing interests

First Author is bearer of the patent Enertun.

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