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Ruben Stemmle, Kathrin Menberg, Ladislaus Rybach, Philipp Blum

Tunnel geothermics – A review
Tunnelgeothermie – Ein Überblick

Tunnel geothermal systems hold the potential to promote decarbonization of the building heating and cooling sector. They can be integrated into existing infrastructure, resulting in low additional costs. In addition, these systems have large contact areas with the ground leading to larger heat fluxes. However, tunnel geothermics is relatively unknown and rarely used. Thus, the objective of this study is to provide an overview of the two primary tunnel geothermal system types as well as their application and potential. Open hydrothermal systems use the tunnel drainage water as a heat source, whereas closed absorber systems harness the heat flux from the subsoil and the warm tunnel interior via heat exchangers. The evaluation of the global application of existing and planned tunnel geothermal systems shows that all open systems are currently located in mountainous regions with a thick rock overburden. In contrast, closed absorber systems are mostly installed in urban tunnel infrastructures. The spatial distribution of geothermal tunnel systems has a focus in central Europe with Switzerland, Germany and Austria being the countries with the highest number of installed systems. Finally, this study also presents a brief summary of existing methods to determine the geothermal potential of tunnels.

Keywords Tunnels; geothermal energy; heating energy; cooling energy

Tunnelgeothermische Anlagen haben das Potenzial, zur Dekarbonisierung im Bereich der Gebäudeheizung und -kühlung beizutragen. Sie können in bestehende Infrastruktur integriert werden und sind damit nur mit geringen zusätzlichen Kosten verbunden. Zudem haben diese Systeme große Kontaktflächen mit dem Erdreich, was zu größeren Wärmeströmen führt. Tunnelgeothermie ist jedoch vergleichsweise unbekannt und wird bisher selten genutzt. Das Ziel dieser Arbeit ist es daher, einen Überblick über die beiden wichtigsten Systeme in der Tunnelgeothermie sowie über deren Anwendungsmöglichkeiten und Potenziale zu geben. Offene hydrothermale Systeme nutzen das Tunneldrainagewasser als Wärmequelle, wohingegen geschlossene Absorbersysteme dem Untergrund und dem Tunnelinneren mittels Wärmetauscher thermische Energie entziehen. Eine Betrachtung der weltweit existierenden sowie geplanten Systeme für Tunnelgeothermie zeigt, dass sich gegenwärtig alle offenen Systeme in Gebirgsregionen mit mächtigen Gesteinsüberdeckungen befinden. Im Gegensatz dazu werden geschlossene Absorbersysteme vor allem in städtischen Tunnelkonstruktionen genutzt. Die räumliche Verteilung der tunnelgeothermischen Systeme hat einen Schwerpunkt in Mitteleuropa, wobei die meisten Systeme in der Schweiz, Deutschland und Österreich installiert sind. Die Studie gibt abschließend einen kurzen Überblick über bestehende Methoden zu Bestimmung des geothermischen Potenzials von Tunneln.

Stichworte Tunnel; Geothermie; Heizenergie; Kühlenergie

1 Introduction

To achieve a widespread energy transition, the supply of sustainable and environmentally friendly thermal energy is of great importance. In 2018, thermal energy accounted for 50 % of the global final energy consumption, resulting in 40 % of the worldwide carbon dioxide emissions [1]. In the European Union 28 countries, about 60 % of the final thermal energy consumption can be attributed to the building sector including space heating and domestic hot water in 2015 [2].

Compared to power generation with continuously increasing shares of renewable energies in recent years, decarbonization in the heating and cooling sector receives much less attention. In 2018, modern renewable energy types excluding biomass utilization only met 10 % of the global heat demand [1]. These numbers highlight the need for a more climate friendly approach in terms of space heating and cooling.

A promising technology in this regard is the utilization of geothermal energy. Typical near-surface geothermal systems are borehole heat exchangers and subsurface engineering constructions, such as foundations that are thermally activated by embedded absorber pipes [3]. Using the same principle, tunnel infrastructures have been thermally activated to extract heat or inject a cooling load [4; 5]. These so-called absorber systems are one possible design for tunnel geothermal installations, the other being open hydrothermal systems, which energetically use warm drainage water of typically deep-lying tunnels in mountainous regions [6].

Both installation designs have been realised on large scale and pilot project tunnel geothermal systems in re-

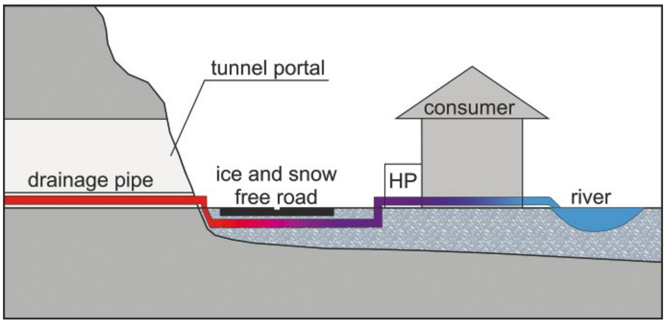

Fig. 1 Illustration of a hydrothermal tunnel system and typical examples for heat utilization.

cent decades. This review describes their operation principles and provides detailed information on one selected site for each system type. In addition, we provide an overview of operational systems as well as systems that are currently in the design stage or for which evaluation studies were conducted and outline methods to determine the geothermal potential of tunnels as described in the literature.

2 System types

2.1 Open systems – Hydrothermal tunnel systems

The hydrothermal tunnel (HT) systems, also referred to as hydrogeothermal tunnel systems, are open systems that use thermal energy of the warm water drained from the rock above the tunnel (Figure 1). Besides energy supply, the thermal energy extraction also cools down the occurring drained water before it is discharged into the receiving surface water. Thus, the construction of cooling ponds or cooling towers, which might otherwise be necessary to comply with regulatory thresholds for the discharged water, can be avoided. This could lead to a higher interest from tunnel companies to equip their tunnels with a hydrothermal installation.

The heat flux $\dot{Q}$ of a hydrothermal system sets in according to its thermal balance with the geothermal heat flux into the tunnel and the heat input from within the tunnel's interior. The available thermal power output in form of the heat flux $\dot{Q}$ can be calculated as:

$$\dot{Q} = \dot{V} \times \rho_{w} \times c_{p,w} \times \Delta T \tag{1}$$

Here, $\dot{V}$ represents the drainage water outflow rate, $c_{p,w}$ is the specific heat capacity of the drained water and ρ_w the tunnel water density. ΔT is the temperature difference of the drained water between its outlet temperature and the temperature after energy extraction [5].

Hydrogeological experience shows that the temperature of the drained mountain water corresponds well with the temperature of the rock at the entry point of the water into the tunnel [7]. This correlation is shown in Figure 2. Due to the geothermal gradient, drainage water temperatures of up to 50 °C are encountered in deep-lying tunnels. Depending on this temperature, the thermal energy can be used directly or indirectly with a supporting heat pump (HP). The temperature is influenced by several factors, such as the thickness of the rock overburden and the permeability distribution. The lithologic structure characterized by the anisotropic thermal conductivity is also an influencing factor [5].

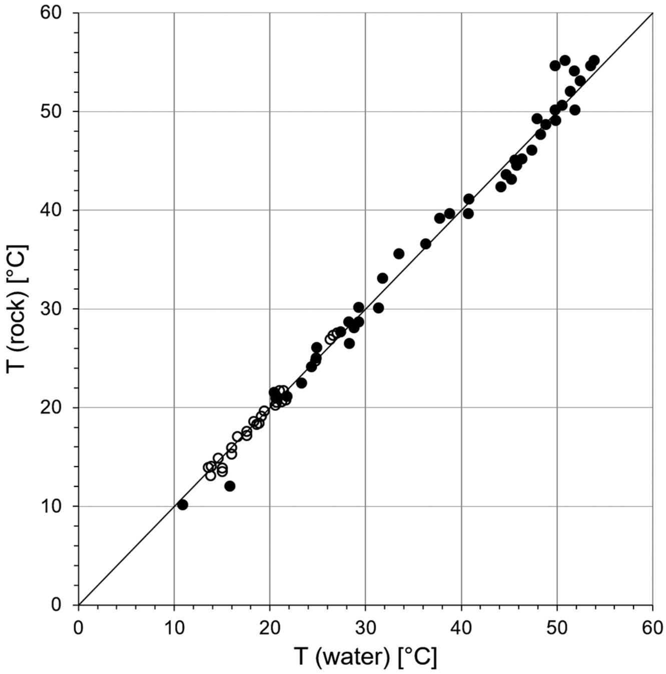

Fig. 2 Temperature of tunnel wall rock and temperature of the inflowing tunnel water. Data from: Simplon railway tunnel (points, [8]), Gotthard road tunnel (circles, [9]). Line: 100 % correlation. The best fit line is T(rock)=1.01×T(water)-0.52°C and has a correlation coefficient of 0.996 (based on [6]).

Besides the temperature of the drainage water, its outflow rate significantly influences the amount of extractable thermal energy. Lateral topographical variations and highly variable hydraulic conductivities dominated by fractured or faulted zones can hinder reliable estimations of the outflow rate [5]. It should be noted that usually a significant decrease of the flow rate into the tunnel can be observed during the first one to two years of operation as a new hydraulic equilibrium is reached in the circulation system [6].

In Swiss tunnels, flow rates were found to be largely constant throughout the year, as was the temperature of the drained water. Other tunnels show a more pronounced variance in flow rate, such as the Rennsteig tunnel in Germany. Here, drainage rate variations between 15 l/s and 65 l/s were measured within one year [10].

A prerequisite for an effective thermal usage of mountain water is the existence of heat consumers in the close vicinity of the tunnel portals. Long distribution pipelines would lead to higher costs and lower thermal efficiencies. Thus, buildings or structures heated by tunnel geothermal systems are typically located close to the tunnel portals.

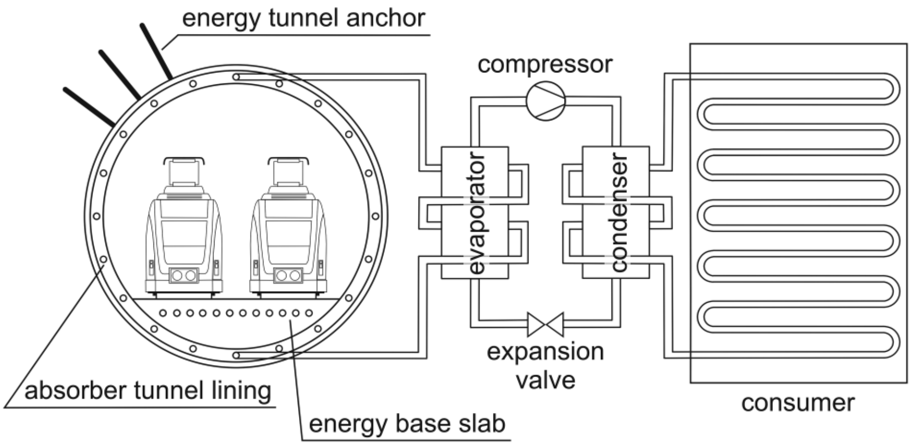

Fig. 3 Principle of absorber tunnel (AT) systems with the illustration of different absorber types (based on [5]).

Exemplary use cases are air conditioning of tunnel operating buildings or de-icing of operating surfaces and roads (Figure 1).

2.2 Closed systems – Absorber tunnel systems

Closed tunnel geothermal systems extract thermal energy from the surrounding subsoil and from the warm tunnel interior via heat exchangers. The heat exchanger elements in these tunnel geothermal systems consist of absorber pipes filled with a heat carrier fluid circulating through the absorber systems. Thus, closed tunnel geothermal systems are also called absorber tunnel (AT) systems (Figure 3).

The first absorber systems were installed in the 1980s in the foundations of buildings. Here, geotechnical structures like piles or base slabs were equipped with absorber pipes. By embedding the pipes into the geotechnical structures, they are turned into so-called energy geostructures that are thermally activated. The combination of structural and energetic purposes requires little effort, but can lead to notable ecological and economic advantages [11].

An essential requirement for an efficient application of heat absorbers in the subsoil is a ground temperature that varies only slightly throughout the year. Beneath a depth of about 10 m, ground temperature is between 8 °C and 16 °C in most of continental Europe, and constant during the course of a year [11]. Most tunnel absorber systems are located within this seasonally unaffected zone.

In recent years, the integration of heat exchanger pipes into tunnels became a focus for investigating the possibilities of geothermal absorber systems. One advantage of tunnel absorber systems compared to absorber building foundations is the higher contact area with the ground, resulting in a larger heat flux into the tunnel walls. Another benefit is that the heat fluxes from both the surrounding subsoil and from inside the tunnel can be energetically used.

The best-suited type of absorber system depends on the tunnel construction method [12; 13]. Cut-and-cover tunnels typically use the above-mentioned energy geostructures developed for thermally activating building foundations, such as bored piles, diaphragm walls and base slabs equipped with absorber pipes. These structures are well proven and widely spread in building engineering. Thus, the application of such systems in cut-and-cover tunnels can benefit from the experience in building construction and deep foundations.

Tunnels that are excavated with conventional drill-and-blast methods can be thermally activated by the application of secondary tunnel linings with embedded absorber pipes. Due to the position of the pipes close to the tunnel interior, the influence of the tunnel air is quite large for this kind of application [12]. A similar application is the so-called energy fleece. It consists of two layers of geotextiles, which enclose the absorber pipes between them. The energy fleece is placed between the primary and secondary lining during the tunnel excavation. Because the installation of a common geotextile between the two linings is a standard process in tunnels, its installation comes with no additional efforts. Another option in drill-and-blast tunnels is the integration of absorber elements into the securing anchors that are driven into the mountain during tunnel construction. There is also the option to use activated base slabs similar to the cut-and-cover tunnels [13].

When the mechanized tunneling method is used, the tunnel boring machine (TBM) places segmental linings such as tubbing segments. These segments protect the tunnel against rock and water pressure but can also be used as heat exchanging structures (Figure 4).

In this case, the absorber pipes for the heat carrier fluid are embedded into the concrete when the lining segment is precast in factory. The pipes in every lining segment form separate circuits, which are connected to the circuits of adjacent segments via hydraulic connections to form a complete lining ring circuit. All circuits are then connected to the main conduit in which the heat carrier

Fig. 4 A thermally activated tunnel lining segment with embedded absorber pipes during its construction (modified from [4]).

fluid is directed towards the consumer. This connection method reduces the number of total connections on the main conduit leading to reduced head losses [14].

Regardless of the absorber system type, the pipes within the absorber elements form the primary circuit that is connected via a heat pump with the secondary circuit located in the consuming building (see Figure 3). The absorber pipe system can also be used for cooling without a heat pump, i.e. in free cooling mode [15; 16].

3 Worldwide application of tunnel geothermal systems

Figure 5 illustrates the spatial distribution of installed, planned or evaluated tunnel geothermal systems. In total 24 tunnel geothermal systems are considered in this review. To our knowledge, all current hydrothermal tunnel systems are in central Europe, dominantly in the mountainous region of the Swiss Alps, which is also the country with the highest number of tunnel geothermal installations with a total of nine installations. In Switzerland, there are currently seven open geothermal tunnel systems in operation with a total annual heat output of 5.3 GWh (in 2017) [10]. Germany and Austria are the countries with the second highest number of tunnel geothermal systems with five installations in each country. Most of these systems are closed absorber systems.

With 55 %, closed absorber systems account for the majority of all systems (see Figure 5). 41 % of the reviewed systems are hydrothermal installations, while there is only one (4 %) open tunnel system, which uses the warm tunnel air with an air-water heat pump. 25 % of all shown systems are currently in a planning or evaluation phase.

3.1 Examples for open hydrothermal tunnel systems

Table 1 provides an overview of the realised and planned open hydrothermal tunnel (HT) systems shown in Figure 5. The geothermal tunnel system realised at the Lötschberg base tunnel is described in more detail. The open thermal system of the Great St Bernard tunnel with the energetic use of warm tunnel air is also included.

Lötschberg base tunnel, Switzerland

The Lötschberg base tunnel is a railway tunnel connecting the Bernese Oberland with the canton of Valais that was put in operation in 2007. Along its length of 34.6 km it passes under the Swiss Alpine crest through a complex sequence of sandstones, schists, carbonate and crystalline rocks [5] with a maximum rock overburden of about 2 km. The tunnel water is drained with a rate of about 100 l/s at a constant temperature of about 20 °C [5]. The drainage water is used in a cascading way. First, it is led to a fish farm in the municipality of Frutigen allowing the

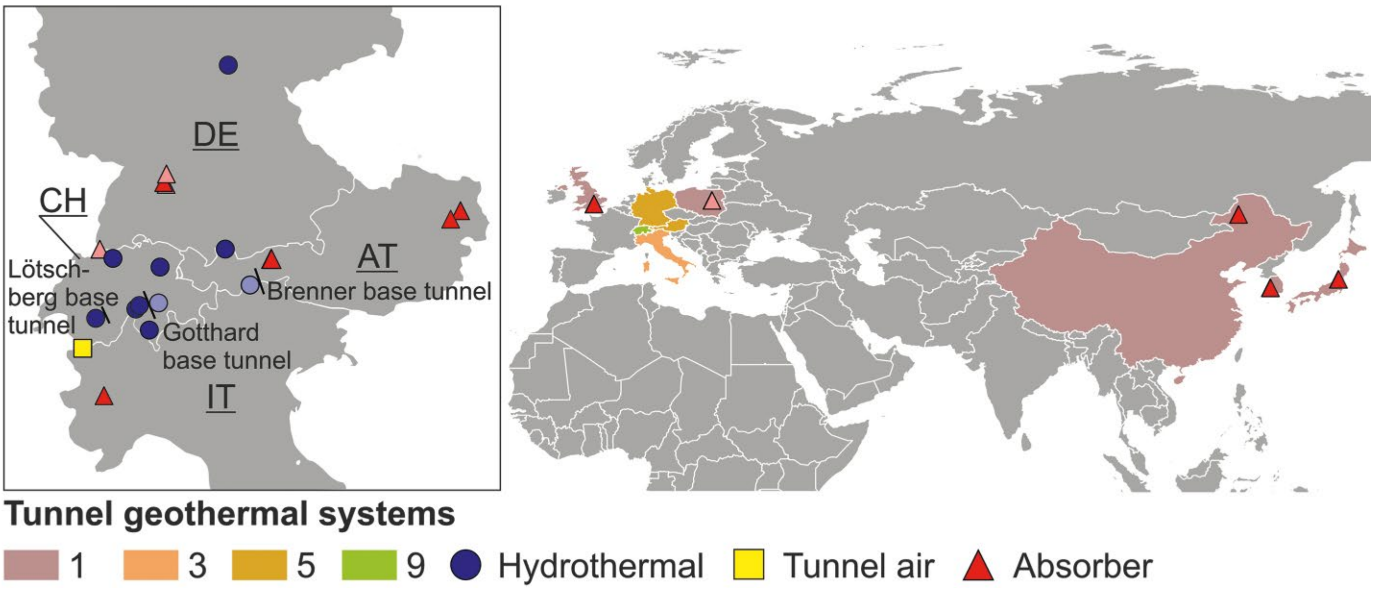

Fig. 5 Global distribution of tunnel geothermal systems. The color fill of the countries represents the corresponding number of installed or planned/evaluated tunnel geothermal systems. The symbols with light colors mark the planned or evaluated systems.

Tab. 1 Overview of hydrothermal tunnel (HT) systems.

Name	Location	Type	Water discharge (l/min) [5]	Water temperature (°C) [5]	Maximum rock overburden (m)	Length (km) [5]	Application [5] H & C = heating and cooling	Status
Ricken tunnel	Switzerland	Rail	660	12.3	570	8.6	Heating of multipurpose hall & kindergarten	In operation
Hauenstein base tunnel	Switzerland	Rail	2520	19	750	8.1	Heating of 150 apartments	
Great St. Bernard tunnel	Switzerland/ Italy	Road	Tunnel air utilization	8[a]	n.a.[b]	5.8	Heating of maintenance center	
Gotthard road tunnel	Switzerland	Road	6720	17	1000	16.9	H & C of highway operating building	
Furka tunnel	Switzerland	Rail	5400	16	1600	15.4	Cold district heating network with > 200 buildings	
Mappo Morettina tunnel	Switzerland	Road	960	16	n.a.	5.5	Heating of sports and recreation center	
Border tunnel Füssen	Germany/ Austria	Road	660	8.3	210	1.2	H & C of operating building, server rooms, keeping roads ice free	
Rennsteig tunnel	Germany	Road	780c 380d	7.7[c] 7.0[d]	205	7.9	Cooling of tunnel operating building	
Lötschberg base tunnel	Switzerland	Rail	6000	20	2000	34.6	Heating of fish farm & tropical house, supply for H network	
Gotthard base tunnel	Switzerland	Rail	n.a.	n.a.	2400	57.1	Heating of thermal center [7]	Planned or evaluated
Brenner base tunnel	Austria/ Italy	Rail	n.a.	n.a.	1720 [17]	64	H & C of city quarters or individual buildings [18]	

[a] Temperature of the extracted tunnel air, [b] Not available, [c] Northern portal, [d] Southern portal.

annual production of 45 t of thermophilic Siberian sturgeon, 20 t of perch and 2 to 3 t of sturgeon caviar [5]. After that, additional heat is extracted using a heat pump to supply a greenhouse. Prior to its discharge into the receiving water, the tunnel water is further energetically used via a district heating network in Frutigen [5].

3.2 Examples for closed absorber tunnel systems

Table 2 provides an overview of the realised, planned and evaluated closed absorber tunnel systems included in Figure 5.

Turin Metro, Line 1, Italy

Line 1 of Turin Metro was opened in 2006. Currently, the subway line has a total length of about 15 km. A southward extension of about 2 km was completed in April 2021 using a TBM. The tunnel has an average cover thickness of 21.5 m and is located below the groundwater table within an aquifer characterized by flowing groundwater. The tunnel lining consists of six precast segments per lining ring. As a testing facility, two lining rings were thermally activated during the construction of the southward extension [4]. Absorber pipes were attached to the prefabricated reinforcement cages inside the segments [5]. In contrast to earlier implementations of energy tunnel lining segments [22], the activated segmental linings in the Turin Metro contain an absorber double circuit allowing to exchange heat with both the surrounding soil and the tunnel air [4]. Figure 4 shows an energy lining segment during the construction prior to its installation in the Turin Metro. A first testing phase of the installation in winter 2017 resulted in measured heat flux densities of about 49 W/m^2 [11]. A later test in 2018 showed a similar thermal power extraction of about 51 W/m^2 [4]. Following the promising results of both tests, a feasibility study for the thermal activation of the planned second line of the Turin Metro was conducted [23].

4 Tunnel geothermal potential

Determining the potential of open hydrothermal systems in existing tunnels is often done in a relatively straightfor-

Tab. 2 Overview of absorber tunnel (AT) systems.

Name	Location	Type	Activated area (m^2)	Absorber type [5]	Application [5]	Status
Nanaori-Toge tunnel	Japan	Road	n.a.[a]	Base slabs	Heating of road surface	In operation
Subway Vienna, Line U2	Austria	Rail	n.a.	Outer tunnel lining, diaphragm walls and base slabs	Air conditioning of operating rooms	
Crossrail	Great Britain	Rail	n.a.	Tunnel lining segments	District heating network	
Seocheon tunnel	South Korea	Rail (abandoned)	90 [19]	Tunnel lining segments	Pilot installation	Pilot project
Linchang tunnel	China	Road	n.a.	Tunnel lining segments		
Tunnel Stuttgart-Fasanenhof	Germany	Rail	360 [5]	Tunnel lining segments		
Tunnel Jenbach	Austria	Rail	2000 [20]	Tunnel lining segments		
Lainz tunnel	Austria	Rail	n.a.	Bored piles, energy fleece		
Turin Metro, Line 1	Italy	Rail	120 [4]	Tunnel lining segments		
Rosenstein tunnel B10	Germany	Road	3330 [21]	Tunnel lining segments	Heating of zoo elephant house	Under construction
Fildertunnel	Germany	Rail	n.a.	Tunnel lining segments, energy fleece [12]	Potential evaluation [12]	Planned or evaluated
Warsaw Metro, Line 2	Poland	Rail	n.a.	Tunnel lining segments [15]	Energy supply of office and retail buildings [15]	
Basel, planned tunnel infrastructure	Switzerland	Rail and Road	n.a.	Tunnel lining segments [16]	Potential evaluation [16]	

[a] Not available.

ward way by calculating the thermal power output of the warm tunnel water according to eq. (1). In Rybach and Kohl [24], numbers are given for the potential thermal power output that could be achieved by implementing open hydrothermal systems in selected Swiss tunnels, assuming a cooling of the tunnel drainage water down to 6°C. Estimating the thermal power achievable by hydrothermal installations in planned but not yet or only partially constructed tunnels is a more challenging task due to uncertainties regarding the expected tunnel water temperature and drainage rate.

The assessment of the possible thermal power output from closed absorber tunnel systems is mainly done by numerical simulations. The simulations aim to predict the feasible heat extraction rate according to the temperature fields in the surrounding subsurface, the tunnel wall and the tunnel interior. In the case of tunnel infrastructures located within a flowing groundwater regime, advective heat transport also has to be considered as a boundary condition for coupled thermo-hydraulic models [5; 16].

Insana and Barla [25] provide design charts for absorber systems, which can be used for preliminary estimations of possible heat extraction and injection in winter and summer mode, respectively. They provide numbers for the heat flux density in dependence of ground temperature, soil thermal conductivity and groundwater flow velocity as well as different directions of the groundwater flow related to the tunnel axis.

5 Conclusion

Six open hydrothermal tunnel installations in Switzerland are successfully in operation, five of which for more than two decades. This proves the applicability of this technology for tunnels with a high rock overburden in mountainous regions. Yet, there are only few hydrothermal (HT) installations outside of Switzerland, indicating a low rate of adoption of this technology. A broader application of open HT systems could be supported by the fact that the retrospective integration of such a system is often relatively straightforward. Contrary to absorber systems, HT installations have the advantage of not having to be considered whilst planning and constructing the tunnel.

Closed absorber tunnel (AT) systems show a more widespread distribution, although most AT systems are also located in central Europe. Compared to HT systems, AT installations are in a lower state of technical maturity, as many of the projects are still in a research and development stage and mainly pilot projects exist. The typical application of absorber systems is in shallow urban tunnels, such as subway tunnels. This entails a favorable close vicinity to possible energy consumers. Furthermore, absorber installations allow for the combined utilization for heating and cooling.

While there is a considerable number of publications considering feasibility and potential studies of tunnel geothermal systems, we identified a lack of research regarding economic and environmental aspects of tunnel geothermics. Further research should therefore also address these aspects. A quantification of possible greenhouse gas emission savings compared to conventional heating and cooling technologies could also facilitate a wider spread of tunnel geothermal systems worldwide.

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Figure 4: Reprinted and modified from Tunnelling and Underground Space Technology 87, Barla, M.; Di Donna, A.; Insana, A., *A novel real-scale experimental prototype of energy tunnel*, Page 6, Copyright (2019), with permission from Elsevier.

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Authors

Ruben Stemmle (corresponding author)
ruben.stemmle@kit.edu
Karlsruhe Institute of Technology
Institute of Applied Geosciences
Kaiserstraße 12
76131 Karlsruhe, Germany

Dr. Kathrin Menberg
kathrin.menberg@kit.edu
Karlsruhe Institute of Technology
Institute of Applied Geosciences
Kaiserstraße 12
76131 Karlsruhe, Germany

Professor em. Dr. Dr. h.c. Ladislaus Rybach
rybach@ig.erdw.ethz.ch
ETH Zurich
Institute of Geophysics
Sonneggstrasse 5, NO F 27
8092 Zurich, Switzerland

Professor Dr. Philipp Blum
philipp.blum@kit.edu
Karlsruhe Institute of Technology
Institute of Applied Geosciences
Kaiserstraße 12
76131 Karlsruhe, Germany

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