Database-Driven Analysis of Energy Geostructures using a Global Dataset: Diffusion, Efficiency, and Environmental Performance

Original
Database-Driven Analysis of Energy Geostructures using a Global Dataset: Diffusion, Efficiency, and Environmental Performance / Salciarini, D.; Gerola, M.; De Feudis, S.; Lupattelli, A.; Dalla Santa, G.; Capati, G.; Rafai, M.; Tihana, J.; Scerbo, M.; Di Donna, A.; Ravera, E.; Nicolino, M.; Insana, A.; Mroueh, H.; Barla, M.. - In: RENEWABLE ENERGY. - ISSN 0960-1481. - ELETTRONICO. - 256:Part F(2026), pp. 1-18. [10.1016/j.renene.2025.124373]

Availability:
This version is available at: 11583/3003037 since: 2025-09-18T10:47:25Z

Publisher:
Elsevier

Published
DOI:10.1016/j.renene.2025.124373

Renewable Energy 256 (2026) 124373

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Database-driven analysis of energy geostructures using a global dataset: Diffusion, efficiency, and environmental performance

D. Salciarini [a,*], M. Gerola [b], S. De Feudis [c], A. Lupattelli [a], G. Dalla Santa [d], G. Capati [a], M. Rafai [a], J. Tihana [e], M. Scerbo [f], A. Di Donna [g], E. Ravera [h], M. Nicolino [f], A. Insana [c], H. Mroueh [i], M. Barla [c]

[a] Department of Civil and Environmental Engineering, University of Perugia, Via G. Duranti 93, 06019, Perugia, Italy
[b] Dipartimento di Scienze della Terra "A. Desio", Università degli Studi di Milano, Via Mangiagalli, 34, 20133, Milano, Italy
[c] Department of Structural, Geotechnical and Building Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129, Torino, Italy
[d] Department of Civil, Environmental and Architectural Engineering, University of Padova, Via Ognissanti 39, 35129, Padova, Italy
[e] The Institute of Sustainable Building Materials and Engineering Systems, Faculty of Civil Engineering and Mechanical Engineering, Riga Technical University, Kipsalas str. 6a, Riga, Latvia
[f] Geosolving Srl, Corso Orbassano 336, 10137, Torino, Italy
[g] Université Grenoble Alpes, CNRS, Grenoble INP, 3SR, Grenoble, France
[h] GEOEG Consulting, Av. de la Gottaz 34, 1110 Morges, Switzerland
[i] IMT Lille Douai, Univ. Artois, Yncrea Hauts-de-France, ULR 4515 - LGCgE, Laboratoire de Génie Civil et géo-Environnement, University of Lille, F-59000, Lille, France

ARTICLE INFO

Keywords:
Energy geostructures
Shallow geothermal energy
Database
Ground heat exchangers
Case studies
Thermal performance

ABSTRACT

Energy Geostructures (EGs) are multifunctional systems that combine structural support with thermal energy exchange using low-enthalpy geothermal energy. This study presents a comprehensive analysis based on a global database of 972 case studies from 27 countries, primarily in Europe, including real-world installations, test sites, and simulations. It focuses on the development and performance of various EG types – particularly energy piles (789 cases), energy walls (79), and energy tunnels (27) – making it the most extensive EG database to date. Geographically, Austria, Switzerland, Germany, and the UK lead in EG adoption, with Italy and France also contributing significantly. The analysis highlights both established technologies and emerging types, such as energy quay walls and barrettes, which show promising potential despite limited representation. The study reveals consistent geometric and design features: energy piles are used in small to medium-scale projects, energy walls offer large, activated surfaces, and tunnels are installed at intermediate depths. Thermal performance is linked to pipe configuration, diameter, spacing, materials, and environmental conditions – most systems are in stratified, moist soils in cool-temperate climates. EGs also offer environmental benefits, notably CO_2 emissions reduction, reinforcing their value in sustainable infrastructure and heating and cooling network development.

1. Introduction

Energy Geostructures (EGs) represent a multifunctional technology that simultaneously fulfils structural and energy exchange roles, making them particularly sustainable for urban development. Their deployment includes energy piles, walls, tunnels, and other geo-structural components integrated with ground heat exchangers. The dual function of EGs offers significant advantages, such as reduced land use, increased energy efficiency, and lower environmental impact compared to conventional heating and cooling systems ([1,2], among others).

The conceptual foundation of EGs was first laid by Brandl [3], who emphasized the feasibility of embedding heat exchange systems within load-bearing elements. This early vision was later substantiated through theoretical modelling and experimental validation by Laloui & Di Donna [4], who developed the fundamental framework for analysing the thermo-mechanical behaviour of EGs. Subsequent works expanded both the range of applications and the understanding of their complex interactions with the surrounding soil and structures. For instance, Barla & Di Donna [5,6] extended the application of EGs to other underground infrastructures, such as tunnels and diaphragm walls, and Laloui & Rotta

This article is part of a special issue entitled: Geothermal heating-cooling published in Renewable Energy.

* Corresponding author.
E-mail address: diana.salciarini@unipg.it (D. Salciarini).

https://doi.org/10.1016/j.renene.2025.124373
Received 22 December 2024; Received in revised form 5 August 2025; Accepted 9 September 2025
Available online 11 September 2025

Loria [7] and Ravera et al. [8] proposed a comprehensive and systematic design methodology applicable to various types of EGs, incorporating sustainability criteria and urban energy planning principles.

From a design perspective, early studies such as Adam & Markiewicz [9] and McCorry & Jones [10] focused on design principles, training, and practical implementation challenges, while Barla & Perino [11] and Di Donna & Laloui [12] addressed issues related to urban integration and coupled thermo-hydro-mechanical behaviour, respectively. These works highlighted that EG performance depends not only on geometric and material parameters but also on boundary conditions, thermal loading history, and soil-structure interaction mechanisms.

In parallel, a growing body of literature investigated EGs through numerical modelling and sensitivity analysis, providing insights into the key drivers of thermal efficiency and mechanical reliability. Notably, Salciarini et al. [13] presented parametric studies on micropiles, while Ronchi et al. [14] validated their findings through full-scale field experiments under cyclic thermal loads. Rafai et al. [15] analysed the long-term thermo-mechanical impact of energy pile operation, whereas Rafai et al. [16] focused on displacements induced by cyclic thermal loads under varying mechanical stress conditions. These contributions underscored the importance of characterizing EG performance under realistic operating conditions, particularly considering fatigue effects and long-term behaviour.

More recent developments reflect an increasing emphasis on multi-physics coupling and site-specific variability. Alqawasmeh et al. [17] examined the influence of spatial variability in hydrothermal properties, showing how heterogeneities in the subsurface can substantially affect thermal response and heat exchange rates. Ding et al. [18] investigated the impact of asymmetric thermal cycles, emphasizing the role of cumulative thermomechanical strains and the potential for serviceability issues. Similarly, Lupattelli & Salciarini [19] analysed temperature recovery dynamics under different intermittency scenarios, a critical factor for optimizing operational schemes. Vardon et al. [20] introduced the role of hydrogeological boundary conditions, such as open water bodies, in modulating EG thermal efficiency, thereby stressing the importance of external environmental factors.

In terms of structural integration, Cotana et al. [21], Fang et al. [22], and Li et al. [23] focused on the interaction between EGs and overlying structures, particularly under intermittent loading, revealing potential design trade-offs between energy performance and structural integrity. Innovations in heat exchanger configurations have also emerged, such as the work of Guo et al. [24], who explored open-ended pipe systems, proposing novel layouts aimed at enhancing thermal efficiency while maintaining constructability.

From a technical and design point of view, EGs encompass a range of ground-embedded structures including deep foundations (*e.g.*, piles, barrettes), shallow foundations (*e.g.*, footings, base slabs), tunnel linings, anchors and earth retaining structures (*e.g.*, diaphragm walls and quay walls). By capitalizing on the ground thermal properties, EGs eliminate the need for additional excavation or drilling solely to implement geothermal systems, thereby delivering significant cost savings. As anticipated, in addition to their original structural support role, the objectives of EGs may encompass two primary functions:

– *Heat exchange*: EGs facilitate the exchange of thermal energy between the ground and the built environment. In colder climates or during winter, the ground acts as a heat reservoir, allowing heat to be extracted and transferred to the superstructure to maintain comfortable indoor temperatures. Conversely, in warmer climates or during summer, excess heat from the superstructure can be extracted and injected into the ground for cooling purposes.
– *Heat storage*: EGs leverage the subsurface of the ground as an effective medium for thermal energy storage. This function is particularly beneficial for balancing seasonal temperature fluctuations and enhancing the efficiency of energy use in buildings. By storing heat during periods of excess thermal energy, such as in summer when the building may generate surplus heat from internal processes or solar gain, EGs, in some conditions, can retain this energy within the ground. This stored heat can then be utilized during colder periods to supplement heating needs.

EGs typically consist of reinforced concrete structures incorporating pipes arranged along the reinforcing cage in varying configurations (Fig. 1).

Examples of pipe configurations, e.g., for Energy Piles (EPs), include the single U-shaped, bent U-shaped, parallel double U-shaped, series double U-shaped, multi U-shaped, indirect double, W-shaped, spiral (or helix), and coaxial pipe configurations. Inside the pipes, a fluid is pumped and used as a thermal energy carrier for the operation of the EGs. The heat carrier fluid circulating in the pipes usually consists of water, with the chemical addition of some antifreeze or a saline solution, primarily to prevent freezing at low temperatures. The usual antifreeze additives employed for such a purpose are ethylene glycol and propylene glycol.

Given such dual role, designing EGs requires an integrated approach that balances both thermal efficiency and structural/geotechnical integrity, unlike conventional ground heat exchangers (e.g., Borehole Heat Exchangers (BHEs) and Horizontal Loop Exchanger). On the energy side, the design must consider soil thermal properties (e.g., conductivity, heat capacity, undisturbed temperature), hydrogeological factors (e.g., water table, seepage), and system configuration (e.g., pipe layout, materials, flow rate). While some design experience can be transferred from BHEs, EGs have distinct characteristics - shorter length, higher thermal mass, structural constraints - that demand tailored analytical and experimental approaches.

From a geotechnical and structural standpoint, EGs must continue to fulfil their primary load-bearing function while withstanding thermal stress due to cyclic heating and cooling. Critical aspects include evaluating deformations, thermally induced stress variations, and potential impacts on load-bearing capacity [7]. As such, the feasibility of EGs as heat exchangers must be verified through comprehensive thermo-mechanical analysis, considering both Ultimate Limit States (ULS) and Serviceability Limit States (SLS). Typically, mechanical loads govern ULS, while thermal effects are more relevant at SLS [25].

Several project-specific numerical studies have contributed valuable insights into the design and behaviour of individual types of EGs. However, these findings are often difficult to generalize due to site-specific boundary conditions, material variability, and system configurations. To support the widespread and standardized adoption of EG technologies, one of the main obstacles lies in the absence of consolidated and widely recognized official standards specifically dedicated to EGs. Most available documents focus almost exclusively on energy piles, offering limited or no guidance for other EG typologies, such as energy walls, energy tunnels, or energy micropiles. Even in countries with more developed practices - such as Switzerland [26,27] and the UK [28,29] guidelines - tend to adopt prescriptive approaches that, while ensuring safety, may constrain innovation and lead to conservative, and potentially overdesigned, solutions. The French recommendations, although built on a performance-based rationale, lack a fully developed methodological framework and occasionally rely on assumptions that may underestimate the effects of thermal loads, raising concerns regarding the long-term safety and serviceability of the structures. Furthermore, there is a general lack of robust case study datasets that can be used to validate thermo-mechanical models, limiting the reliability and transferability of research outcomes. This gap hinders not only the calibration of advanced numerical simulations but also the formulation of empirical or semi-empirical design tools.

In summary, while research and practice in the field of EGs have made significant progress, a number of regulatory, methodological, and practical limitations continue to inhibit their broader diffusion, underscoring the need for coordinated efforts toward the development of comprehensive, accessible, and performance-oriented standards.

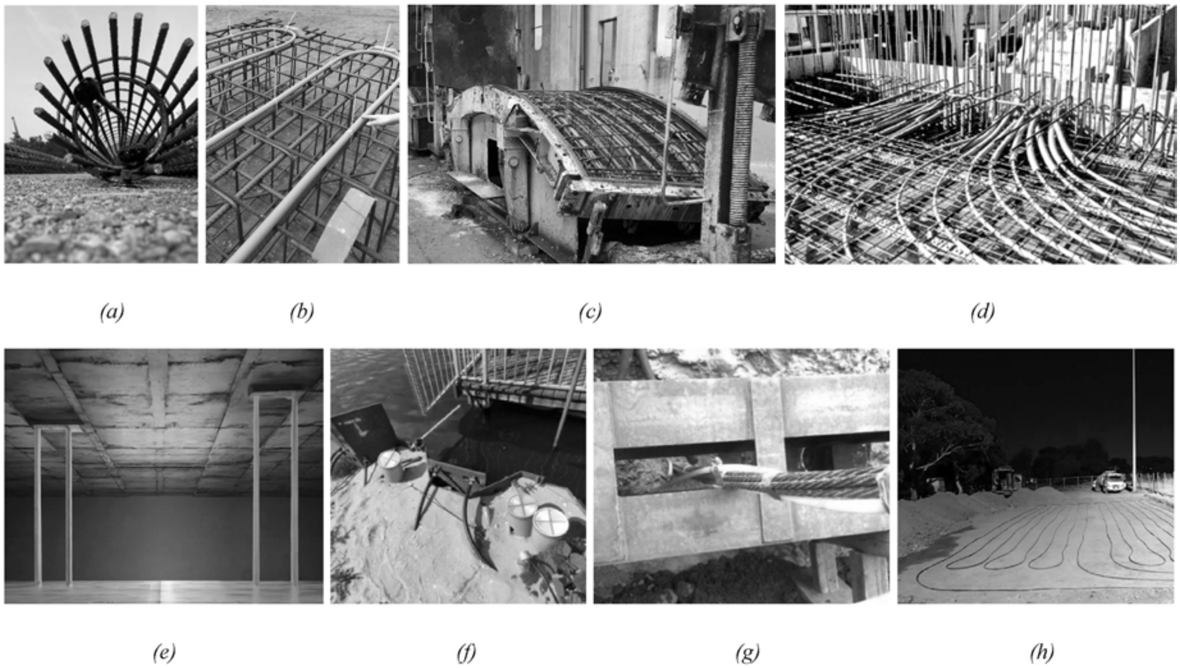


Fig. 1. Pictures of the different types of EGs (real installations): (a) Energy Pile; (b) Energy Wall; (c) Energy Tunnel; (d) Energy Slab; (e) Energy Barrette; (f) Energy Quay Wall; (g) Energy Anchor; (h) Energy Pavement.

Over the past few years, significant efforts have been made to address the challenges associated with the knowledge, dissemination, and adoption of EGs worldwide. Workshops, conferences, and European research networks have played a pivotal role in advancing the understanding and implementation of EGs. Notably, two prominent initiatives have emerged, both under the auspices of the European Cooperation in Science and Technology (E-COST), a renowned funding organization for research and innovation networks. The first initiative, the COST Action TU1405 European network for shallow Geothermal energy Applications in Buildings and Infrastructures (GABI), operated from 2015 to 2019. This initiative focused on addressing various challenges related to shallow geothermal energy applications, including EGs, to foster knowledge exchange and collaboration among researchers and practitioners. The second initiative, the COST Action CA21156 European network for FOstering Large-scale ImplementAtion of energy GEostructure (FOLIAGE), started in 2022 and is expected to conclude in 2026. Building upon the foundations laid by its predecessor, FOLIAGE aims to further advance the widespread implementation of EGs by tackling key barriers and facilitating large-scale adoption. Part of the activities of the FOLIAGE COST Action focuses on compiling a database of operational EGs to overcome the lack of high-quality data pertaining to successful schemes. Learning from existing projects can improve analysis and design practice, allowing for the transfer of knowledge from countries where EGs have been developed to regions where development is still in its infancy.

In the past, collaborative efforts within these COST Action projects, have led to significant progress in compiling case studies and developing comprehensive databases. Building on earlier research by Di Donna et al. [30,31], this database, made available by the Authors, has been updated to encompass the latest advancements and insights in the field of EGs. Recently, newer categories of EGs have surfaced, with energy quay walls [32,33,34], pavements (e.g. Ref. [35]), anchors (e.g. Ref. [36]), and barrettes [37] experiencing a significant uptick in installations since 2018, hinting at promising future applications of this technology. The geographical spread of EG adoption is also expanding, with an increasing number of countries embracing them. Notably, Austria, the birthplace of this technology, along with the United Kingdom, Germany, and Switzerland, have emerged as key hubs for EG construction. However, it's important to acknowledge potential data gaps for certain countries and regions outside of Europe. Furthermore, there is growing anticipation that the United States of America will promote EGs adoption in the coming years, driven by the increasing efforts of large corporations to mitigate their carbon footprint [30].

Di Donna et al. [30,31] conducted a comprehensive review, providing an in-depth analysis of the applications and advancements in EGs worldwide, with the latest update available as of 2017. Their study is grounded in a meticulous survey targeting international practitioner companies, coupled with insights gleaned from a thorough literature review detailing the characteristics and prevalence of constructed EGs. The dataset compiled through their research comprises data from 180 EPs projects, 40 Energy Walls (EWs) projects, and 20 Energy Tunnels (ETs) projects. This extensive dataset serves as a valuable resource, offering insights into the scope, scale, and diverse applications of EG technology across various geographies and project types. By combining survey responses from industry stakeholders with findings from academic literature, Di Donna et al. [30,31] provide a comprehensive overview of the global landscape of EG implementation, shedding light on emerging trends and best practices in the field.

Despite these contributions, a comprehensive and up-to-date analysis of the global development, typological diversity, and performance metrics of EGs has remained fragmented across studies and geographies. This paper addresses this gap by compiling the most extensive international database of EG applications to date, encompassing 972 case studies from 27 countries and 8 different EG types.

The scientific novelty of this work lies in (i) offering the first quantitative, cross-technology comparative analysis based on a harmonized dataset (ii) integrating emerging EG technologies (e.g., barrettes, quay walls, anchors, pavements); alongside established ones; and (iii) highlighting the relationship between geographical trends, technology maturity, and data completeness in performance evaluation.

This paper introduces an extended database encompassing case studies spanning real cases, test sites, numerical studies, feasibility studies, designs, and projects under construction. Covering data up to 2023, the database offers insights into various types of EGs that have garnered increased attention in recent years. The collection highlights the notable growth and diversification within the EG landscape, reflecting the expanding utilization and recognition of EG technology across different structural applications. Through the dissemination of these understandings, stakeholders in the field will gain access to valuable evidence that can inform future research, design, and implementation efforts, driving further advancements in EG technology and its broader adoption.

The paper is structured as follows. Section 2 describes the methodology used to develop the global database of EGs, detailing the data sources, classification criteria, and parameters collected. Section 3 presents the analysis and is divided into five parts: Section 3.1 examines the diffusion of EGs globally and by type; Section 3.2 evaluates the heat exchange performance of different EG systems through selected case studies; Section 3.3 focuses on the geometric and design features of EGs; Section 3.4 investigates the influence of environmental and operational conditions on thermal performance; and Section 3.5 discusses emerging technologies and composite systems. Section 3.6 evaluates the environmental benefits of EGs, particularly their contribution to CO_2 reduction. Finally, Section 4 summarizes the main findings and outlines future research directions to advance the adoption and effectiveness of EG technologies.

2. Materials and methods: database structure and characteristics

The compiled database is structured into 8 sections, each dedicated to a specific type of EG identified thus far (e.g., EPs, EWs, ETs, energy barrettes, energy quay walls, geothermal pavements, energy slabs, and energy anchors). Within each section, data and information on key features are gathered, including installation type and location, installation geometry, pipe configuration, stratigraphic and hydrogeological conditions, heat exchange rate, monitoring, and costs (Fig. 2). Moreover, the database contains references to the sources of all collected information. The modular structure of the database guarantees consistent data collection and allows for the precise definition of fields tailored to different types of EGs. In addition, this framework facilitates further possible expansions by accommodating new sections devoted to newly developed EGs. While the database was compiled through a combination of literature review, industry collaboration, and expert contributions,

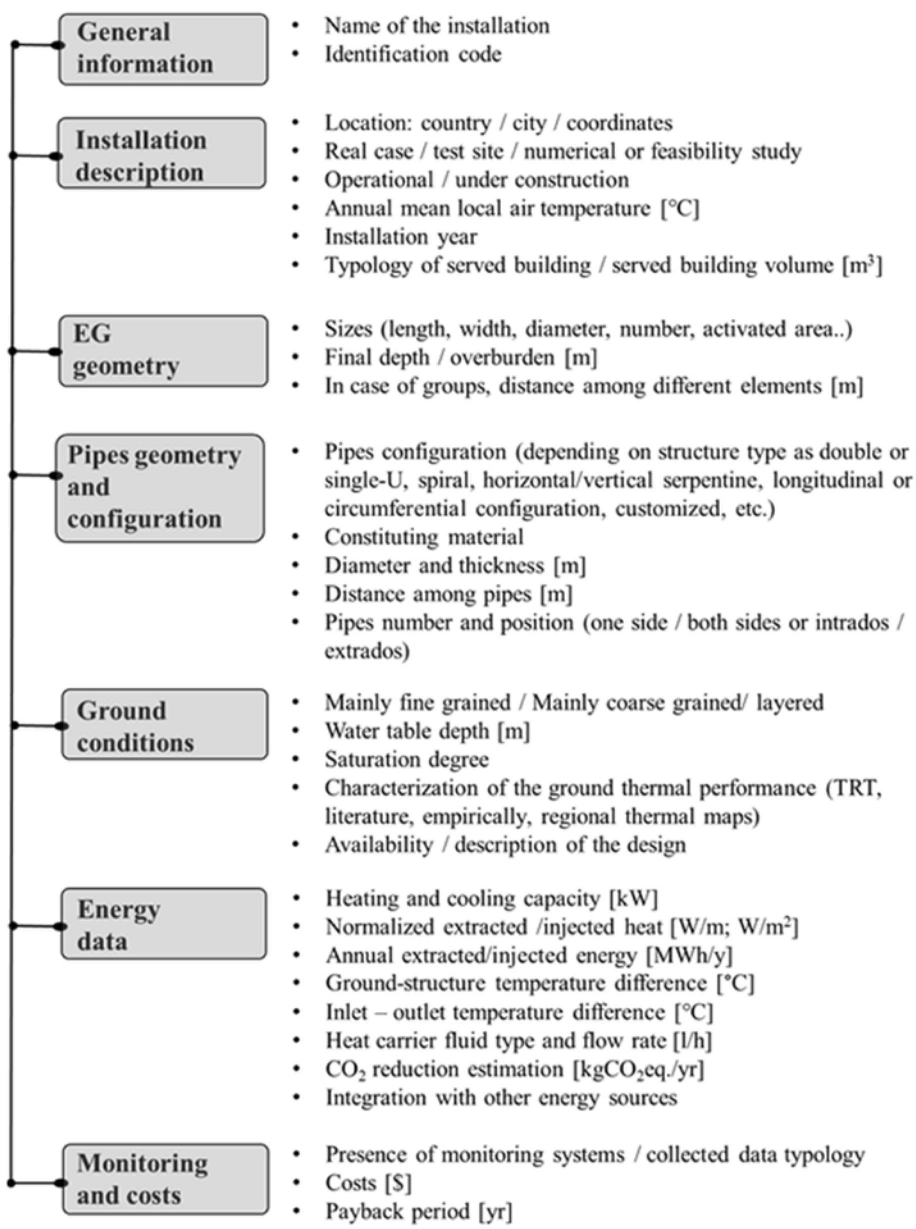


Fig. 2. Information and data collected in the database for each type of energy geostructure.

access is currently limited due to proprietary restrictions and data sharing limitation. Future efforts may explore ways to release aggregated or anonymized versions to support reproducibility and further research.

Geographically, the database covers installations from 27 countries globally (Fig. 3a). The compilation of these EG installations has been sourced from over 80 journal papers and contributions from more than 20 companies, reflecting a robust interdisciplinary effort to document the evolution and deployment of EGs worldwide. Fig. 3 provides a visual representation of the global distribution of EG installations, with a particular focus on Europe. The figure underscores the widespread adoption of EGs across various countries, with a marked predominance of European nations in implementing this technology. This European-centric focus can be attributed to two main factors. Firstly, the database was compiled as part of the activities within the CA21156 European network for FOstering Large-scale ImplementAtion of energy GEostructure (FOLIAGE), naturally directing efforts towards European contexts. Secondly, the geographic origin of the Authors played a role, as their primary base in Europe provided greater access to high-quality, verified, and comprehensive regional data sources. This accessibility facilitated the inclusion of European EGs in the database to a greater extent than extra-European ones. The distribution map shows that Austria, Switzerland, Germany, and the United Kingdom are among the leading countries with the highest number of EG installations. These nations have been early adopters and continue to drive the advancement of EG technologies. This geographical analysis is crucial for understanding the regional differences in the adoption of EGs and provides insights into where future growth might occur, although it is difficult to predict with accuracy as it also depends on the policies and the specific context of each nation. The database exhibits a potential geographical bias, with a predominance of case studies from European countries. This concentration reflects both the maturity of EG applications in Europe and the greater availability of detailed project data. While this focus enhances the depth of the analysis within the European context, it may limit the direct generalizability of some findings at the global scale. Nevertheless, the database also includes approximately 70 well-documented non-European cases (*e.g.*, from the United States, China, Japan, and Australia), which contribute meaningfully to the statistical analysis and broaden the perspective on the international development of EG technologies. Their inclusion - despite the geographical imbalance - enriches the dataset and ensures a more comprehensive and informative overview of existing implementations. Moreover, the methodologies, frameworks, and design principles discussed are inherently transferable and can serve as a solid foundation for future.

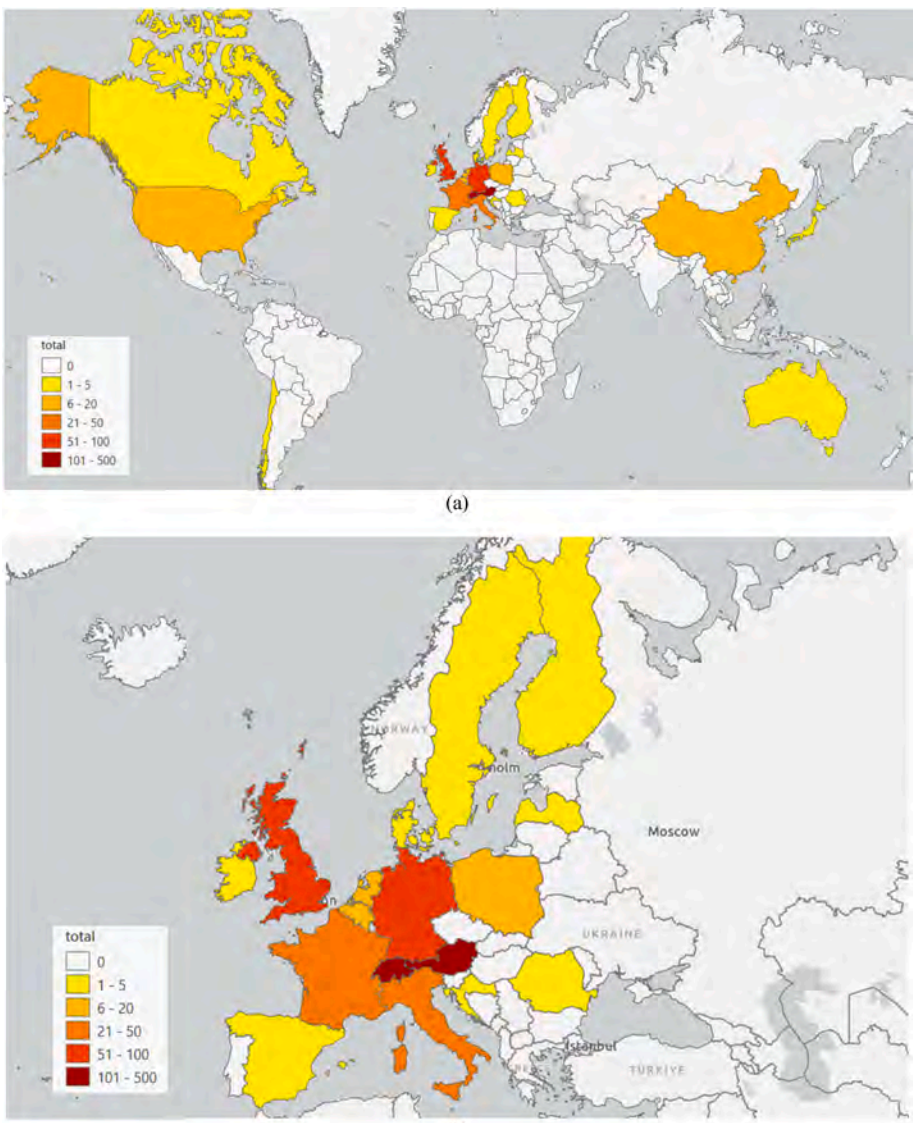


Fig. 3. Map of the (a) worldwide, and (b) European distribution of the energy geostructures collected in the database.

The database includes data from a total of 972 case studies (including real cases, test sites, numerical studies, feasibility studies, designs, as specified above) spanning the period from 1985 to 2023. Specifically, it catalogues 789 EP installations, 60 energy slabs, 79 EWs, and 27 ETs. Additionally, the database documents more recent types of EGs including 9 geothermal pavements, 4 energy quay walls, 3 energy barrettes, and 1 energy anchor installation.

The gathered data aims to provide detailed descriptions of individual EGs while identifying design methodologies, innovative configurations, and best practices to promote the global adoption of EGs. However, completeness and quality of the data vary considerably across case studies, technologies, and sources. For example, while information on location and structural geometry is generally well-documented, with coverage around 100 %, other categories such as pipe dimensions, materials, and layouts are less consistently reported. This disparity can be partly attributed to the stage of technological maturity and the origin of the data: newer technologies (e.g., ETs, barrettes, quay walls) are mostly documented through academic sources and detailed case reports, where data is typically richer but fewer in number. Conversely, more established technologies, such as EPs, are widely adopted in practice but often lack detailed documentation, especially when derived from design summaries or industry sources where only partial technical descriptions are made available.

A preliminary analysis of the data collection across technologies confirms this imbalance: a larger fraction of EWs and ETs include detailed thermal and hydraulic information, while a significant number of EP-related entries omit key parameters such as ground stratigraphy, groundwater conditions, or system monitoring data.

Regarding ground conditions such as stratigraphy, water table depth, and thermal characterization methods, data availability varies significantly: approximately 70 % of tunnel case studies report complete information on these aspects, while the percentage drops to 33 % for barrettes and just 2 % for piles. This low percentage for piles, despite their widespread use, is particularly relevant as it underscores the gap between operational prevalence and documentation quality. Similarly, data on heating/cooling capacity is more frequently available, likely due to its practical relevance and the increasing integration of active monitoring systems in newer EGs. Specifically, coverage in this category reaches about 15 % for piles, 70 % for tunnels and walls, 67 % for barrettes, and 100 % for energy quay walls. This variability may be attributed to the heightened emphasis on energy efficiency in structures and the widespread implementation of monitoring systems in innovative EG designs.

However, even within entries that include monitoring data, standardization remains limited. Recorded parameters vary widely and may include, depending on the case, inlet and outlet fluid temperatures, flow rates, ground temperature, ambient air temperature (for exposed elements), and heat exchange rates. Only a small fraction of the database contains time-series data or clearly identifies sensor types and sampling frequency. This lack of harmonization limits the possibility of conducting statistically robust, monitoring-based comparisons across systems.

Lastly, data related to installation costs and payback remains among the most challenging to obtain. These metrics are often embedded within broader construction budgets and subject to variability depending on location, scale, and co-benefits from structural design. This scarcity of economic data further restricts the depth of cost-effectiveness analysis.

In summary, the database represents a unique and extensive resource, compiling a wide spectrum of EG case studies and offering significant insights into design practices, technology diffusion, and innovation trends. Although some variability in data completeness exists across parameters, technologies, and sources, the dataset is considered sufficiently robust to support general observations and comparative analyses. The diversity and volume of the collected data enable the identification of meaningful trends and patterns, even if certain technologies benefit from more detailed documentation than others. Potential biases arising from uneven data coverage are acknowledged; however, the analyses remain representative of the broader development and application of EGs.

3. Analysis and discussion of energy geostructure data

This section presents a comprehensive analysis of the data collected in the database, highlighting key trends and insights into the diffusion, energy efficiency, and technological advancements of EGs. The discussion is structured as follows: Section 3.1 delves into the diffusion of EG technology, examining the historical evolution and geographical distribution of installations, with a particular focus on the most prevalent types such as Energy Piles (EPs), Energy Tunnels (ETs), and Energy Walls (EWs). The analysis identifies significant trends and provides an overview of emerging EG types like energy quay walls, barrettes, pavements, and anchors. Section 3.2 addresses the heat exchange rate of EGs, evaluating their performance in real-world applications and offering an in-depth analysis of three major types of EGs. Each of these systems plays a crucial role in the extraction and injection of geothermal energy, with their effectiveness depending on specific design and operational factors. Section 3.3 provides an analysis of the geometry and size of EGs across various real-world applications (realised or under construction), test sites, prototypes, feasibility studies, and numerical analyses. It highlights the diversity and prevalence of different configurations, illustrating how EPs are more commonly used in operational applications, while data referred to ETs and EWs are more often explored in feasibility studies. The analysis reveals how certain geometrical features are favoured due to their effectiveness in specific applications. Section 3.4 section includes the analysis of the varying on-site and design factors that affect the EG thermal performance; Section 3.5 extends the investigation to more recent EG typologies, while Section 3.6 focuses on the environmental aspects of EG installations, discussing the available data on costs, payback periods, and the financial viability of different EG types. This section also considers the challenges in obtaining comprehensive economic data and suggests directions for future research to address these gaps.

3.1. Diffusion of the technology

Fig. 4 illustrates the temporal evolution of EG installations from 1984 to 2023, focusing on the most prevalent types: EPs, EWs, ETs, and energy slabs. The figure is divided into two parts: Fig. 4a includes all four types while Fig. 4b omits EPs to better highlight the trends in the other three categories. The aim is to show the historical progression and growing diversification of EG technology over nearly four decades.

Fig. 4a shows a consistent increase in EPs installations particularly from 2001 to 2017, a trend that appears associated with the introduction of more stringent planning requirements and incentives for renewable technology installations, particularly in countries like the UK [30,31]. This trend signifies the widespread adoption and reliability of EPs. Fig. 4b reveals a significant growth in EW installations starting in 2017, highlighting a rising interest in this EG type. Regarding energy slabs, the increasing trend from 1995 onward has been relatively stable, with a slight decline observed over the years. Moreover, it is worth noticing that, after 2015, approximately 50 % of the most recent installations have been integrated with EPs or EWs, reducing the number of standalone energy slab installations.

Among the four types of EG depicted in Fig. 4a, ETs exhibit the lowest number of installations. While utilizing tunnels as ground heat exchangers offers the advantage of involving larger ground volumes, challenges related to heat ownership and resource distribution have slowed down their widespread adoption. Moreover, recent trends indicate a significant shift towards the maintenance of existing tunnels rather than the development of new installations, contrasting with past practices where the tunnelling industry predominantly focused on new

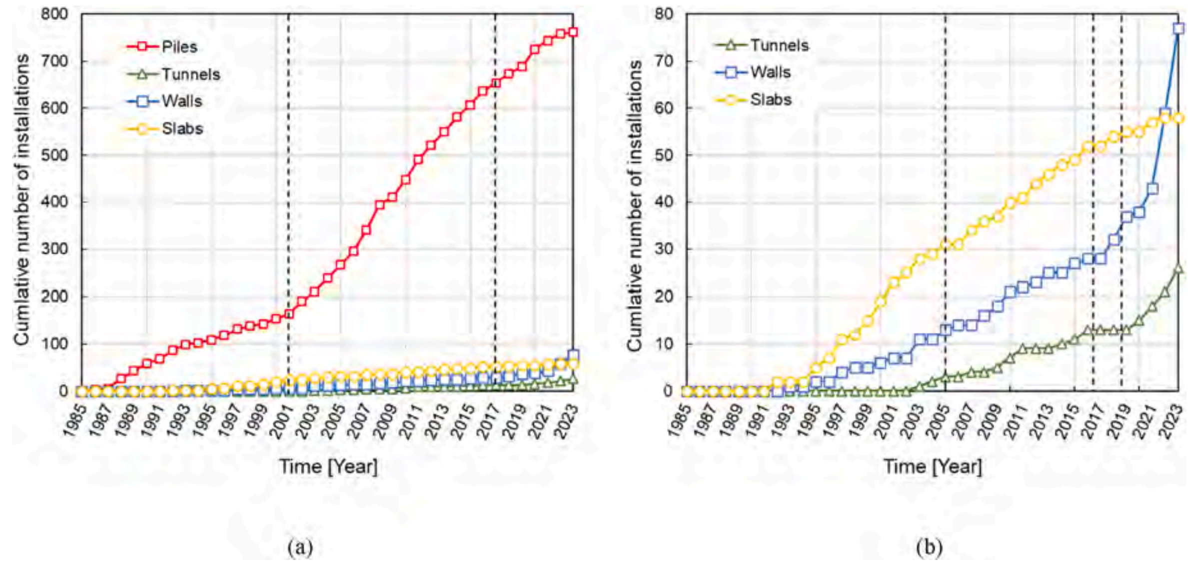


Fig. 4. Evolution of EGs (based solely on actual installations) over time of: a) all the four prevalent types of installations (EPs, EWs, ETs, energy slabs): (b) excluding piles.

excavations. All ETs case studies collected in the database pertain exclusively to new installations. This could explain the comparatively slower evolution of ETs compared to other prevalent EGs, even if some recent examples of energy retrofitting of existing tunnels have been proposed in the literature [38]. Despite these challenges, the growing number of studies and design projects emphasizes the escalating interest in exploiting tunnels as energy sources. It is worth noting that while the installation and design phases for EPs, EWs, and slabs can be completed within a few years, ETs necessitate a more comprehensive design process and have a longer installation period, often spanning several years.

Fig. 5 provides a comparative view of the geographical distribution of EG installations and related studies or design projects. It maps out the global distribution of EG installations across different countries,

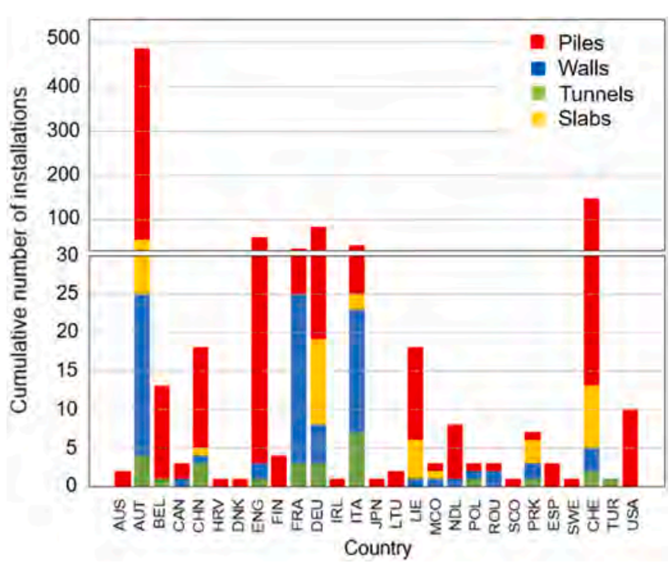


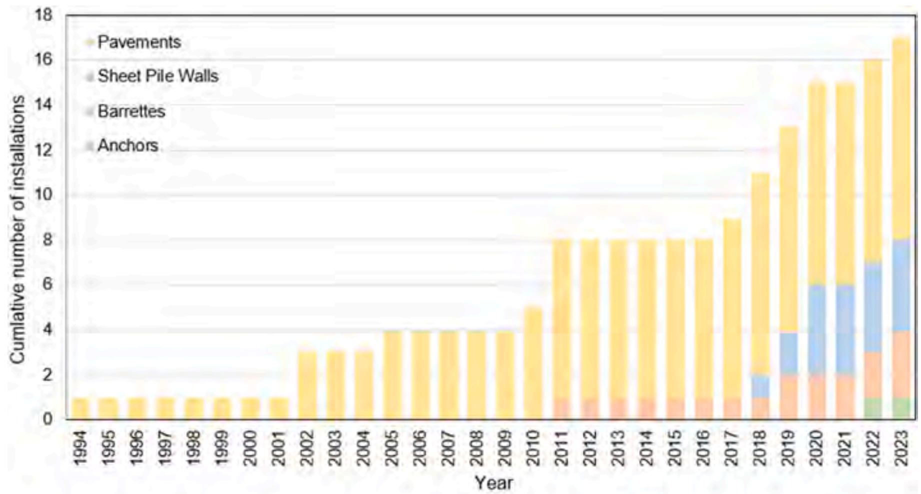
Fig. 5. Geographical distribution of EGs across various countries. AUS = Australia, AUT = Austria, BEL = Belgium, CAN = Canada, CHE = Switzerland, CHL = Chile, CHN = China, DEU = Germany, DNK = Denmark, ENG = England, ESP = Spain, FIN = Finland, FRA = France, HRV = Croatia, IRL = Ireland, ITA = Italy, KOR = Korea, JPN = Japan, LTU = Lithuania, MCO = Principality of Monaco, NDL = Netherlands, POL = Poland, PRK = Czech Republic, ROU = Romania, SCO = Scotland, SWE = Sweden, USA = United States of America.

highlighting key hubs like Austria, Switzerland, Germany, and the United Kingdom. Additionally, Italy and France emerge as significant contributors to the cumulative installations of EGs. These nations not only lead in the number of installations but also demonstrate a comprehensive adoption of various EG types, including EPs, EWs, and ETs. Conversely, the majority of countries predominantly feature EP installations, highlighting the widespread applicability and maturity of EP technology. Notably, six countries (Austria, France, Italy, Germany, Switzerland, and China) also show a greater focus on the development and research of EW and ET technologies, underlining ongoing efforts to enhance their maturity and implementation.

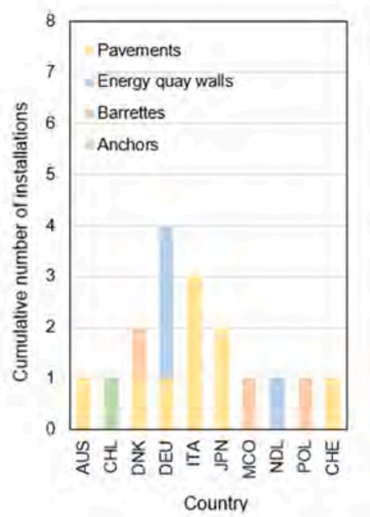
Although the present analysis does not explicitly examine market conditions, it is worth noting that countries with a higher number of EG installations—such as Austria, Germany, France, Italy, and the United Kingdom—are also those where public financial incentives for geothermal heating and cooling technologies have been implemented over the years. For instance, in Germany, the BAFA (Federal Office for Economic Affairs and Export Control) subsidy program has supported geothermal heat pump systems, including ground-coupled applications, with substantial grants since the early 2000s. In France, the *MaPrimeRénov'* scheme, active since 2020, provides direct financial support for residential geothermal installations. Italy has long promoted geothermal systems through the Conto Termico incentive, introduced in 2013 and revised in 2016 (Conto Termico 2.0), which offers up to 65 % reimbursement for geothermal heat pump systems. The UK previously offered incentives under the Renewable Heat Incentive (RHI), which ran from 2011 to 2022 and supported the adoption of low-carbon heating systems, including ground source heat pumps.

However, based on the data collected, a direct and quantifiable correlation between the presence of such incentive schemes and the diffusion of EGs is not evident. This is likely due to the multifactorial nature of technology adoption, which depends not only on economic drivers but also on regulatory frameworks, technical expertise, the scale and type of construction projects, and awareness among stakeholders. A more systematic assessment of national policy and market frameworks would be required to understand their impact on EG adoption. This represents a promising direction for future research.

The growing interest in more recent EG types such as energy barrettes, energy quay walls, energy pavements, and energy anchors is highlighted by the increasing number of installations, as depicted in Fig. 6a. This figure presents the timeline of these installations, showing that energy pavements were the first to be implemented.



(a)



(b)

Fig. 6. Evolution of emerging EG types: (a) over time; (b) across different countries.

Currently, the database includes four energy quay walls, three energy barrettes, and one energy anchor installations. These technologies are relatively recent and still under development, offering innovative approaches to utilizing shallow geothermal energy. The figure also indicates that although the newer technologies have fewer installations, they are already spreading globally. Fig. 6b maps out these installations across various countries, noting that while Europe remains a central hub, these technologies are also being adopted in other regions, such as Chile, Australia, and Japan. This figure is crucial in illustrating the early stages of global adoption for these innovative EG types and hints at their future potential as they become more widely recognized and implemented.

While the current analysis focuses on the documented distribution of EG installations, we acknowledge that factors such as climate conditions, policy incentives, geological characteristics, and technological maturity significantly influence regional preferences. However, due to the lack of consistent and comparable data across countries, these variables were not explicitly analysed in this study. We highlight this as a promising area for future research, where a multi-variable approach could help elucidate the broader drivers behind regional uptake.

3.2. Heat exchange rate

The heat exchange rate (typically expressed in W/m or W/m^2) indicates the rate at which thermal energy is transferred per unit length or surface area and reflects the system's capacity to meet thermal demands over time. This section presents comparative data on the heat exchange rate for different types of EGs – piles, walls and tunnels – based on real-world monitoring and/or numerical simulations collected in the project database. For each system, the figures illustrate either average seasonal values (when data were derived from long-term measurements) or steady-state results from validated simulations. The selection of case studies shown in the figures was limited to those for which sufficiently complete and consistent data were available, enabling reliable cross-comparison. In all figures, the length (used for normalization in W/m) refers to the embedded or active length of the heat exchanger within the ground, while the area (in W/m^2, used especially for tunnels) corresponds to the internal or external surface actively involved in thermal exchange. Where not otherwise specified, the reported values represent average operating conditions over a heating or cooling season, unless peak loads are explicitly indicated. Specific attention is also given to highlighting variability due to seasonal operation, local climate, system geometry, and installation depth or orientation. These influencing factors are discussed in detail in the following subsections through examples from both measured and simulated case studies.

3.2.1. Energy piles

Many research activities on EPs have focused on their application for extracting and injecting thermal energy, with numerous case studies in the existing literature evaluating their effectiveness in meeting energy demands. For example, Gao et al. [39] performed numerical performance assessments, Loveridge & Powrie [40] and Amis et al. [41] conducted thermal response and in-situ efficiency tests, Sutman et al. [42] explored seasonal behaviour, Cecinato & Salciarini [43] and Gerola et al. [44] combined statistical and case study analyses, and Rafai et al. [45,46] alongside Lupattelli et al. [47–49] examined thermo-mechanical responses.

Assessing the efficacy of these systems often requires a case-specific approach, contingent upon the energy demands of the building, number and length of piles, ground thermal properties, and local climate (*e.g.*, Refs. [50–52]).

Fig. 7 presents the average seasonal heat exchange rate (W/m) for a selection of real-world installations drawn from the project database. The values shown were derived from either in-situ measurements or numerical simulations validated against field data, depending on data availability for each project. Only case studies with sufficiently complete and consistent datasets were included to allow for meaningful comparison. The reported heat exchange rates range from approximately 30 to 150 W/m, with variations attributable to several factors that are analysed in more detail in Section 3.4.1. These values reflect average seasonal performance (either heating or cooling), normalized over the active pile length. Notably, climatic conditions influence the thermal load direction: in warmer climates, EPs are typically used to inject heat during summer cooling (recharging the ground), while in colder regions they are employed for heat extraction during winter.

For example, in Sapporo City University (Japan) – a cold climate location – the EP system integrated into the steel foundation piles supports winter heat extraction. After evaluating various systems for the new building, the Sapporo City Council decided in November 2004 to implement a Ground Source Heat Pump (GSHP) system integrated with the foundation piles as part of the Heating, Ventilation, and Air Conditioning (HVAC) system for the University. Based on system monitoring and manufacturer design data [60], the estimated average extraction reaches approximately 126 W/m, one of the highest among the case

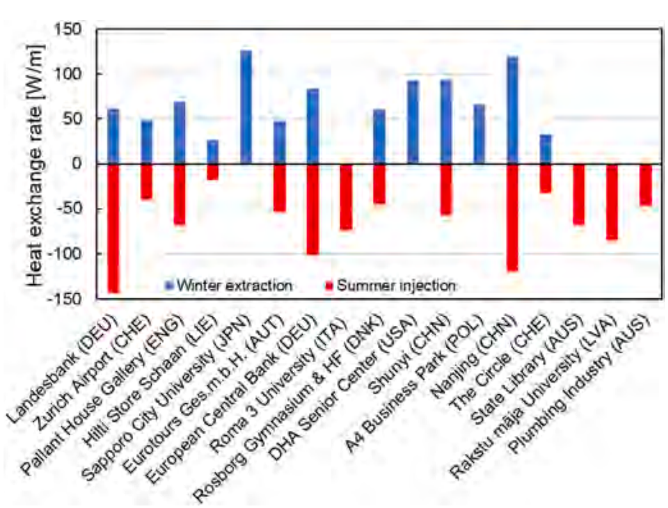


Fig. 7. Heat exchange rate during winter extraction and summer injection of EP (real-world) installations, across different selected projects within the database (from left to right data from: Enercret; [30]; Enercret; Enercret; [53]; Enercret; Enercret; Eneren s. r.l.; Alberdi-Pagola et al., 2016; [54–57]; Geothermie Schweiz; [58]; unpublished project data [59]).

studies. This high performance aligns with the low average air temperature (8.8 C) and suggests that heating is the dominant operational mode. The system demonstrated stable long-term operation, with brine temperature returning to baseline values within five years, indicating good thermal balance. In contrast, the State Library Station of the Melbourne Metro Line [61] represents a summer heat injection scenario. Here, the system injects thermal energy into the ground during cooling-dominated periods. The average seasonal injection rate is 68.75 W/m, with performance influenced by an external air temperature of 14.33 °C and a ~10 °C fluid-soil temperature differential. This highlights the role of external climate and building demand in defining operational strategy.

Some systems are designed for dual-mode operation across seasons. For example, the EP system serving an eight-storey building in Nanjing, China utilizes 105 belled piles to provide both heating and cooling [62]. Thanks to the symmetrical inlet and outlet temperatures relative to the soil (average 19 °C), the system achieves balanced heat exchange rates in both summer and winter, which supports long-term thermal sustainability.

These case studies illustrate how the heat exchange rate is affected by pile geometry, depth, installation conditions, and operating temperature differentials. More detailed analysis of the influencing parameters is presented in Section 3.4.1, where the variability of thermal performance is discussed in light of both geotechnical and design-related factors.

3.2.2. Energy walls

Numerous thermal and thermo-mechanical numerical analyses have been carried out to investigate the factors most significantly affecting the heat exchange rate of EW systems ([63–65], among others). In particular, the complex geometry and boundary conditions of EW systems distinguish them from the most common EPs systems (*e.g.* Ref. [66]).

The heat exchange rate of EW systems – expressed in W/m of wall length – depends primarily on the depth of installation, presence of saturated soil, and configuration of the pipe network embedded within the concrete. Fig. 8 presents a set of average seasonal heat exchange rates (both heating and cooling modes) derived from numerical simulations validated against monitoring data and, where available, field measurements. While this review includes both real-world applications and numerical simulations, particular care was taken to clearly distinguish between the two in both the text and the figures. Numerical studies were only considered when based on realistic geometries and well-documented boundary conditions. Their inclusion is not meant to substitute field data but rather to complement it, especially in cases where real-word data are limited or incomplete.

In terms of system geometry, both the depth of the EWs and the configuration of the heat exchanger pipes significantly influence the system's heat exchange rate. A deeper installation of EWs offers several advantages: increased surface area in contact with the surrounding soil, and a higher likelihood of encountering saturated soil layers, which are characterized by greater thermal conductivity. For instance, the EWs in the "Uniqa Tower" (AUT) and "Bulgari Hotel" (ENG) case studies exhibit some of the highest rates of heat energy extraction and this is associated with the deepest length of the walls (more than two-thirds of their length is below the water table), reaching 35 m and 36 m, respectively.

About pipe configuration, the "Energy Center" (ITA) case study (Fig. 8) employs a customized heat exchanger layout, which is closely linked to the rate of heat injection. Additionally, factors such as the energy demand of the connected building and the external temperature at the exposed wall surfaces (if present) also affect the heat exchange rate of EWs. This influence is observed both in the short term, during the transient phase in the initial years of operation, and in the long term [70]. Maintaining a balanced heating and cooling demand throughout the year is crucial for preserving long-term efficiency in EWs (Gerola et al., 2024b), as well as in all shallow geothermal systems. This balance helps to prevent long-term thermal imbalances in the ground, which can

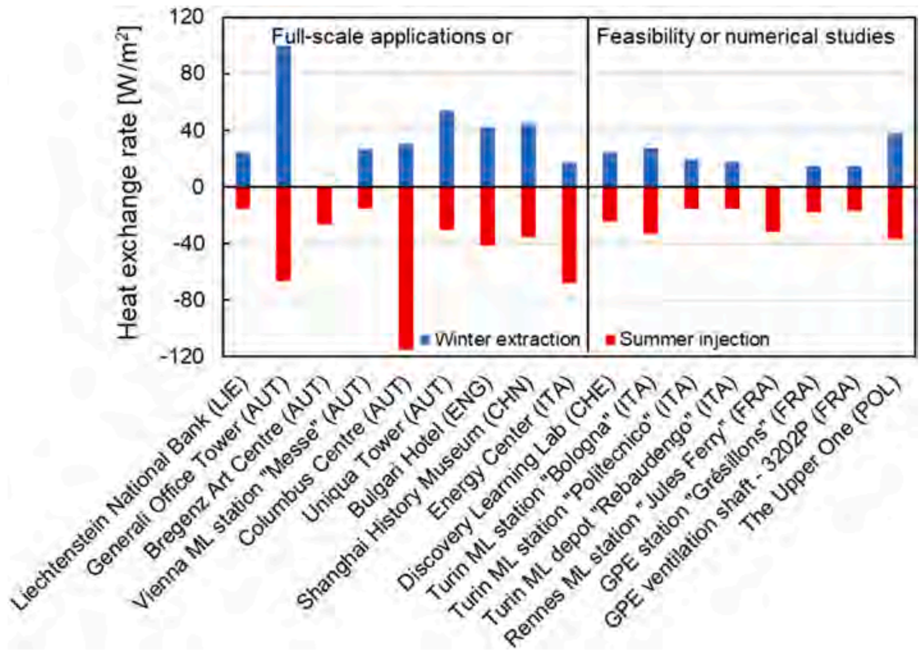


Fig. 8. Heat exchanged rate during winter extraction and summer injection for some of the operational and numerical case studies of EWs within the database (from left to right data from: [3,3,9,9,30,41,67,68]; Baralis & Barla [69]; Geoeg; Geosolving; Geosolving; Geosolving; [30]; Geosolving; Geosolving; Geoeg).

reduce the system's heat exchange rate over time.

Although Fig. 8 shows average heat exchange rates (in W/m), a sustained and symmetrical performance in both extraction and injection phases is a good indicator of thermal balance. For example, in the case of the "Turin ML Station Bologna" (ITA), numerical thermo-hydraulic simulations carried out during the feasibility phase of Line 2 of the Turin Metro demonstrated that systems with balanced heating and cooling loads maintain more stable performance over multi-year periods [71]. The design leverages the seasonal use of the underground tunnel walls, which act as large-area exchangers. This ensures that the ground is not progressively warmed or cooled year after year, a key aspect in preserving the long-term thermal efficiency of the installation.

Similarly, the "Discovery Learning Lab" (CHE), part of the EPFL campus, is designed with a dual-mode geothermal system and advanced energy monitoring tools. While specific longitudinal heat exchange data are not publicly detailed, the system was conceived with symmetrical seasonal operation in mind. The building benefits from balanced thermal loads due to its year-round usage pattern and mixed-use profile, which is favorable for long-term system sustainability [72]. This is evident in case studies show in Fig. 8, such as the "Turin ML Station Bologna" (ITA) and the "Discovery Learning Lab," (CHE) which display consistent heat exchange rates for both heat extraction and injection.

In all the presented cases, the values shown refer to seasonal averages (extraction in winter, injection in summer), normalized by wall length. These results confirm that factors such as depth, groundwater conditions, and thermal load symmetry are critical to achieving consistent and sustainable performance in EWs.

3.2.3. Energy tunnels

Compared to other EGs, such as piles, Energy Tunnels (ETs) involve a greater volume of ground and soil-structure interface, offering extensive opportunities for heat exchange [73–75]. These systems typically run beneath densely populated urban areas, rendering them ideal for harnessing geothermal energy on a district or city-wide scale via energy distribution networks. Moreover, ETs have the capacity to exchange heat not only with the surrounding ground but also with the air within the tunnel, allowing them to harness both geothermal and aerothermal energy [76–78]. This dual capability grants ETs a greater thermal potential compared to other ground heat exchangers.

As shown in Fig. 9, the heat exchange generally ranges between 10 and 40 W/m^2, with some variations. These discrepancies arise mostly from differences in the groundwater regime, the aerothermal conditions within the tunnel and some key operational conditions, such as the inlet fluid temperature. In fact, as an example, the real applications with the ENERTUN configuration in Turin ML1 have shown data outside the mentioned range, thus presenting average heat exchange rate of 48 W/m^2 and 60 W/m^2 during winter and summer functioning, respectively [76,77]. Such a high geothermal energy production was possible due to the favorable groundwater regime of the Turin subsoil. Indeed, being directly perpendicular to the tunnel axis and moving with a velocity of 1.4 m/d, groundwater allows for a steady recharge of the geothermal reservoir. The Nanjing utility tunnel [79] exhibits a high extraction potential of almost 40 W/m^2. In this case, the rationale behind this is the hot environment that develops in utility tunnels due to power and thermal cabins. Regarding the Seocheon tunnel [80], large performance variations were experienced between winter and summer tests, with the latter being approximately four times the former. This is explained by different inlet fluid temperatures and, more specifically, by the larger discrepancy with the internal air temperature during the two tests.

3.3. Geometric features

Fig. 10 presents the geometry and size characteristics of EPs, EWs, and ETs across full-scale installations and prototypes (hereafter the term "real-world installation" is used to distinguish them from the feasibility and numerical studies), as well as feasibility studies and numerical analyses. The total number of case studies for each category, along with the number of full-scale applications (in brackets) is shown above each group of columns. This visualization illustrates the diversity and range of configurations explored in EG projects.

The *x*-axis indicators represent categories or variables related to the geometry or size of these structures. Higher percentages associated with specific geometries can indicate a preference for these configurations due to their effectiveness in particular applications. For example, most case studies report on fewer than 100 EPs per building/installation, while larger pile numbers (over 100) are less common. Most

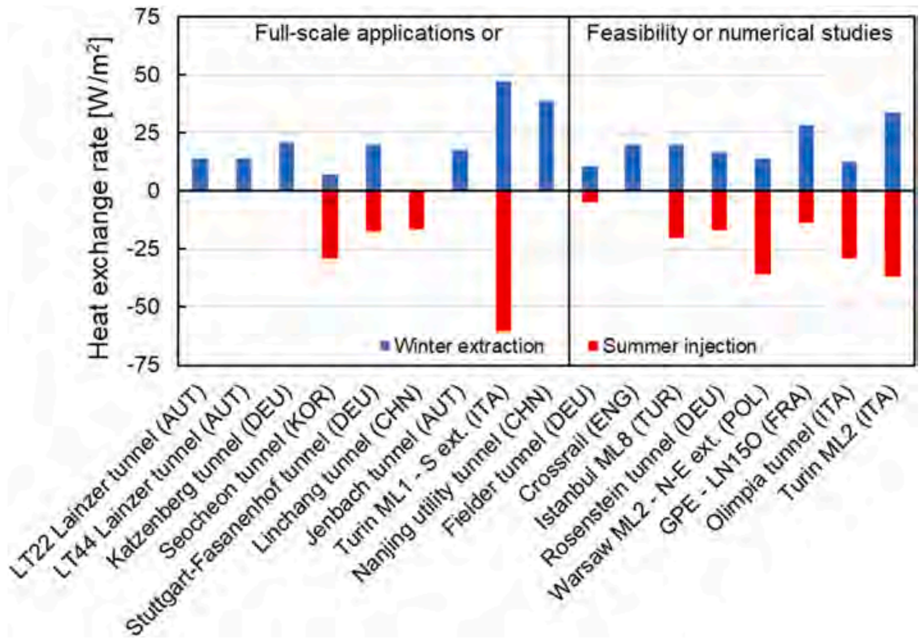


Fig. 9. Heat exchanged rate during winter extraction and summer injection for some of the operational and numerical case studies of ETs within the database (from left to right data from: [76,81,79–88]; Csesznak et al. [89,90]; Geosolving; [91]; Geosolving).

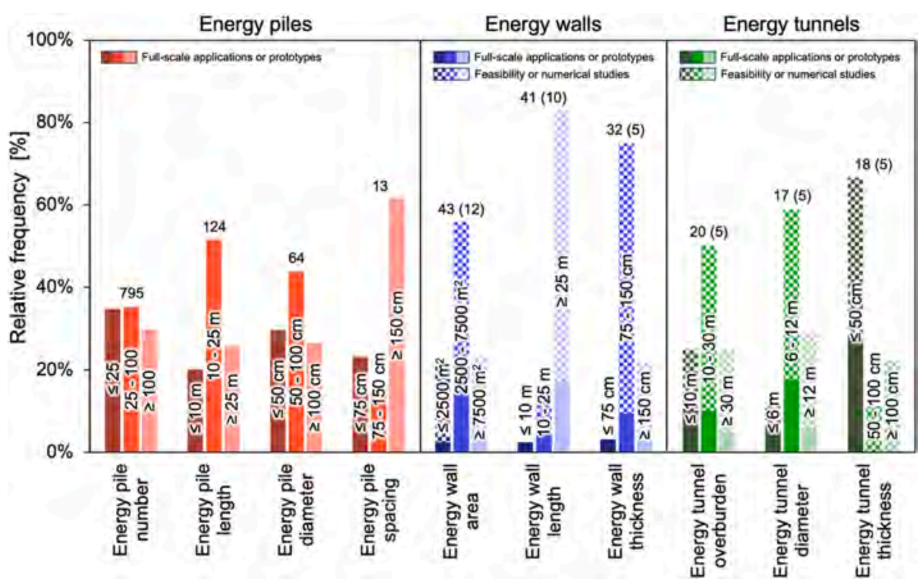


Fig. 10. Geometry and size of the EPs, EWs and ETs full-scale applications or prototypes, as well as feasibility and numerical studies, gathered in the database (the total number of case studies and, within brackets, full-scale applications or prototypes for which that specific information was available is shown above each group of columns).

applications involve EPs with lengths between 10 and 25 m (around 50 %), followed by lengths longer than 25 m. EPs with a diameter of 50–100 cm are the most common (around 40 %), followed by smaller diameter piles (≤50 cm). Most EPs are spaced more than 150 cm apart, though there is also a portion where spacing is less than 75 cm. As for EWs, most of the case studies involve a thermo-activated area between 2500 m^2 and 7500 m^2, while larger and lower numbers are less common. EWs between more than 25 m long are the most frequent, followed by EWs between 10 and 25 m; EW thicknesses are typically greater than 75 cm, with a high number of installations falling between 75 and 150 cm. In general, certain geometrical dimensions of EPs and EWs might be favoured for their optimal performance in terms of energy efficiency or structural stability.

As for ETs, most energy tunnels are overburden between 10 and 30 m, followed by depths of less than 10 m; the diameter between 6 and 12 m are the most frequent, followed by ETs with diameters higher than 12 m. To finish, ET wall thicknesses are primarily up to 50 cm, although thicker ETs are also present. The length of the ET installations was not considered in Fig. 10, as most full-scale implementations are prototypes with longitudinal extensions limited to just a few tens of meters. In contrast to the other EGs analysed in Fig. 10, this restricted extension does not provide a representative description of an ET system at the urban scale, which represents the potential for real-world application.

The percentages depicted in the figure highlight the extent to which these technologies – EPs, EWs, and ETs – are implemented or studied. For instance, a higher percentage of EPs in operational applications suggests their widespread use in real-world scenarios, while a higher percentage in feasibility studies for ETs may indicate their potential for future use, despite currently being less established. Indeed, for EPs, only the real-world case studies were considered due to their higher number, reflecting the maturity and well-established adoption of this technology. In contrast, the data for EWs and ETs include both real-word and numerical studies, as these applications are less common and primarily explored for their feasibility to encourage further implementation. The rapid growth and the high number of EP installations can be attributed to economic growth, their relative simplicity (*i.e.* easier design, cost-effectiveness, and time-efficiency), the straightforward similarity to more common vertical BHEs and the fact that many new buildings supported by piles facilitates the transition from conventional piles to EPs. This contrasts with the relatively lower number of new EWs and ETs being constructed.

3.4. Thermal design parameters

The thermal design of EGs is generally unique and involves the consideration of several parameters to evaluate the energy that can be readily extracted/injected to fully or partially satisfy the thermal energy loads of buildings. Based on the reviewed database, this section includes the analysis of the varying on-site and design factors that affect the EG thermal performance. This includes heat exchanger pipe layout, environmental conditions, and operational conditions of the available studies on EPs, EWs and ETs, guiding into creating a design method that is economically and environmentally sustainable, whilst maintaining a high level of efficiency and reliability. The focus herein is on the main three EG types and the features of each aspect are given in the following Sections.

In general, the design of these structures must carefully consider their ability to efficiently and sustainably exchange heat with the ground, considering various influencing factors. For example, in general, larger dimensions of the EGs (e.g., length and diameter for EPs, length and thickness for EWs, and diameter and thickness for ETs) allow for interacting with a greater volume of surrounding soil and for accommodating more loops of pipes, thus improving heat exchange rate. Consistently, the quantity of thermo-active elements and their relative positioning within the ground likewise play a crucial role in optimizing thermal performance (*e.g.*, number of elements and spacing for EPs, number of elements for EWs, depth and overburden layer for ETs).

Despite EGs technology being adaptable to a variety of ground conditions and external temperatures, the thermal conductivity of the soil significantly impacts the heat exchange ([13,43,92], among others), and the presence of a groundwater flow further enhances system performance by enabling heat transfer through both conduction and convection. Furthermore, for EWs and ETs, being exposed to the external/internal environment on one side, the aerothermal conditions of such environments (velocity and temperature of the airflow) also play a pivotal role in heat exchange ([30,66,70], among others).

Hence, the database is categorized into three primary elements, each comprising features that significantly impact the energy efficiency of various types of EGs, including EPs, EWs and ETs:

- heat exchanger pipe layout: this element encompasses the setup of geothermal pipes, including their diameter, spacing, and material.
- environmental conditions: this category cover factors such as mean external air temperature, ground type and conditions, and the level of ground saturation, presence and characteristics of groundwater flow.
- operational conditions: this element involves factors such as soil-structure temperature, inlet-outlet temperature, and the flow rate of the heat carrier fluid.

These features are consistent across all types of EGs and are described for each typology separately, in Sections 3.4.1 to 3.4.3.

3.4.1. Energy piles

As shown in Fig. 11, for EPs, the heat exchanger pipe layout shows a wide variability, where the least common configuration is the single U-loop, followed by the double U-loop and other configurations, *e.g.* spiral or 3U-loops. Pipe diameter varies according to pile diameter and pipe configuration. The 20–32 mm range is the most frequent (38 %) while diameters starting from 20 mm downwards and 32 mm upwards are equally common (31 % each). Pipe spacing is fairly uniform across the three categories (≤25 cm, 25–40 cm, and ≥40 cm), each with a frequency of about 33 %. HDPE is the most widely used pipe material (62 %), followed by PE (35 %) and a small percentage (7 %) using PE-Xa.

Approximately 29 % and 53 % of EPs are installed in cold and very cold climates, respectively, with the air temperature ranging from 9 to 12 °C and below 9 °C. Only 18 % are in warmer climates with air temperatures above 12 °C, indicating a strong preference for using EPs for heating purposes. Regarding ground type, 78 % are embedded in layered ground, 19 % in fine-grained soils, and only 3 % in coarse-grained. Additionally, 60 % of EPs are in wet grounds, 30 % in partially saturated, and 10 % in dry conditions.

The soil-structure temperature for these piles is predominantly between 5 and 10 °C (58 %), with 12 % below or equal to 5 °C and 30 % above or equal to 10 °C. Similarly, the inlet-outlet temperature is most commonly 2–4 °C (60 %), with 30 % above or equal to 4 °C and 10 % below or equal to 2 °C. The flow rate is generally split between two ranges: starting from 375 l/h downwards and 750 l/h upwards, each with a 40 % frequency, while the 375–750 l/h range is less common, representing only 20 % of cases.

The results highlight the maturity and established use of EPs, particularly in colder climates where their heating efficiency is most beneficial. The uniform distribution of pipe spacing and the predominance of HDPE as a material suggest standardized practices in pile design, which contribute to their widespread adoption. The data also indicate a clear preference for specific pipe diameters and configurations, reflecting optimized design strategies that balance performance and cost. The consistent use of specific configurations and materials across different projects also suggests a growing body of best practices that can inform future developments in this field.

3.4.2. Energy walls

As shown in Fig. 12, for EWs, the geothermal heat exchanger pipe configuration is predominantly up-down type, accounting for 82 % of the total, with serpentine configurations representing just 3 %, and other types making up to 16 %. Pipe diameters show a distinct distribution: the majority, 79 %, have diameters less than or equal to 20 mm, while 16 % fall within the 20–32 mm range, and only 5 % exceed 32 mm. Regarding pipe spacing, pipes with spacing between 25 and 40 cm dominate, making up 78 % of the total. Conversely, pipes spaced less than or equal to 25 cm constitute 10 % and those with spacing greater than or equal to 40 cm account for just 6 %. Regarding pipe material, the majority, approximately 91 %, are made of PE-Xa, with HDPE and PE being used in 6 % and 3 % of cases, respectively. This distribution differs significantly from what is observed in energy piles (EPs), where HDPE is the predominant material (used in approximately 58 % of documented cases), followed by PE-Xa (30 %) and PE (12 %). The dominance of PE-Xa in energy walls may be attributed to the geometric and structural characteristics of diaphragm walls, which require tighter pipe bending radii and benefit from the greater flexibility and thermal stability of cross-linked polyethylene. In contrast, energy piles, particularly those with larger diameters or prefabricated cages, provide more space for conventional HDPE loops and are often built using standardized installation techniques. These differences highlight the influence of structural design and construction method on material selection.

Environmental conditions vary significantly: 69 % of the installations are in climates where air temperature ranges between 9 and 12 °C, 8 % are in colder climates with temperature below 9 °C and 23 % are in warmer climate with temperatures above 12 °C. Similarly, 69 % of

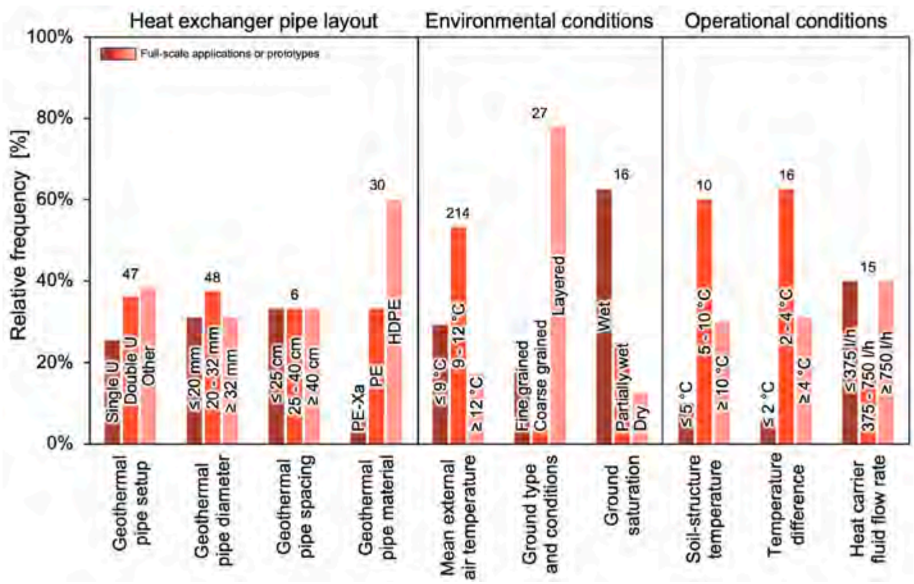


Fig. 11. Heat exchanger pipe layout and environmental and operational conditions of the EPs full-scale applications or prototypes gathered in the database (the total number of case studies for which that specific information was available is shown above each group of columns).

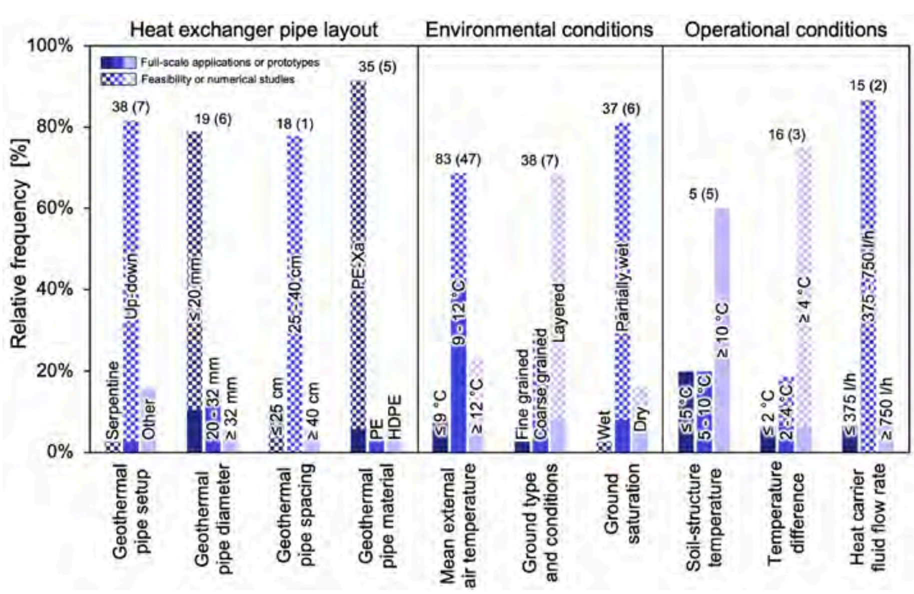


Fig. 12. Heat exchanger pipe layout and environmental and operational conditions of the EWs full-scale applications or prototypes, as well as feasibility and numerical studies, gathered in the database (the total number of case studies and, within brackets, full-scale applications and prototypes for which that specific information was available is shown above each group of columns).

EWs are embedded in layered ground, 29 % in coarse-grained soils, and only 2 % in fine grained soils. Ground saturation levels indicate that the majority, 80 %, are in partially wet conditions, with 17 % in dry conditions and a minimal 3 % in wet environments.

In terms of operational conditions, 59 % of the EWs are in environments where the soil-structure temperature is 10 °C or higher. About 20.5 % are in environments with soil-structure temperatures is 5 °C or lower, and the same percentage is in the 5–10 °C range. Regarding the inlet-outlet temperature, 75 % of the cases exceed 4 °C, 19 % fall within 2–4 °C, and 6 % are 2 °C or lower. About 87 % of the EWs have flow rates between 375 and 750 l/h, with only 6.5 % each starting from 375 l/h downwards or 750 l/h upwards.

The dataset indicates that the up-down pipe configuration is predominantly employed in energy walls (EWs). This preference can be attributed to its straightforward integration within vertical reinforcement cages, which facilitates installation while maintaining structural integrity. Such configurations are particularly suitable for construction environments with spatial constraints, such as urban settings [6], [93].

Regarding pipe dimensions, the widespread use of diameters equal to or smaller than 20 mm reflects a compromise between thermal efficiency and practical considerations. Smaller diameters increase the surface-area-to-volume ratio, thereby enhancing heat exchange rates, while also reducing material costs and simplifying installation logistics [94].

The observed pipe spacing, typically concentrated in the 25–40 cm range, appears consistent with performance-oriented design recommendations. Although the literature suggests that spacings of 40–60 cm are effective for heating and cooling performance [95], the slightly narrower spacing in EWs may be related to the specific geometrical and structural characteristics of wall-type geostructures. The heavy reliance on PE-Xa material (91 %) reflects its suitability for these applications, offering durability and resistance to temperature variations. Environmental conditions highlight that EWs are primarily installed in moderately cold climates, aligning with their use in heating applications. The predominance of layered ground and partially wet conditions among documented EW installations may reflect the typical geological profiles of regions with higher EG adoption. Operational conditions show a preference for higher inlet-outlet temperatures (≥4 °C), which likely enhance the energy efficiency of the EWs but also determine larger soil-structure temperatures (≥10 °C). The predominance of flow rates between 375 and 750 l/h suggests that this range is optimal for maintaining effective heat transfer without excessive energy consumption. Overall, the results reflect a consistent set of design and operational practices that optimize the performance of EWs across various environmental conditions.

3.4.3. *Energy tunnels*

As shown in Fig. 13, for ETs, the predominant configuration for geothermal pipe installation is circumferential, accounting for 59 % of cases, likely due to their efficiency in maximizing heat transfer [73]. The longitudinal setup is less common and counts at 32 %. Other configurations constitute only 9 % of occurrences. Pipe diameters are distributed as follows: 69 % are equal to or below 20 mm, 22 % falls within the 20–32 mm range, and just 9 % exceed 32 mm. Regarding pipe spacing, 19 % of the pipes have a spacing less than or equal to 25 cm, while the majority, 58 %, falls within the range of 25–40 cm. Pipes with a spacing exceeding 40 cm represent the remaining 23 %. In terms of pipe material, around 75 % are made of PE-Xa, 20 % utilized PE, and the remaining 5 % are constructed using HDPE.

The environmental conditions are distributed as follows: 62 % are in climates with air temperature between 9 and 12 °C, 11 % are in colder climates with temperatures of 9 °C or lower, while 27 % are in regions with air temperatures of 12 °C or higher. About 60 % of the installations are embedded in layered ground, 35 % are in coarse-grained soils, and 5 % are in fine-grained soils. Regarding ground saturation levels, 48 % of the sites are wet, and the remaining sites are equally split between dry and partially wet conditions, at 26 % each.

In terms of operational conditions, approximately 71 % of the tunnels are in environments where the soil-structure temperature ranges between 5 and 10 °C. About 20 % are in environments with temperatures of 5 °C or lower, while 9 % are in areas where temperatures are 10 °C or higher. The inlet-outlet temperatures are distributed as follows: 46 % exhibit temperatures of 4 °C or warmer, another 46 % fall within the of 2–4 °C range, and 8 % are equal to 2 °C or colder. Lastly, the flow rates show that 43 % of instances are within the range of 375–750 l/h, 20 % have flow rates starting from 375 l/h downwards, and 37 % from 750 l/h upwards.

The prevalence of smaller pipe diameters (≤20 mm) suggests that these are optimal for the specific thermal and structural requirements of tunnel installations. The dominance of pipe spacing in the 25–40 cm range reflects a balance between effective heat exchange and the structural constraints of tunnels. The widespread use of PE-Xa as the pipe material underscores its suitability for tunnel environments, providing the necessary durability and flexibility. Environmentally, ETs are predominantly installed in moderately cold climates (9–12 °C), which aligns with their use in heating applications. Operational conditions show a strong tendency towards soil-structure temperatures between 5 and 10 °C and inlet-outlet temperatures exceeding 4 °C, which are likely optimal for maintaining energy efficiency in ETs. The varied flow rates, with a significant portion exceeding 750 l/h, indicate that higher flow rates might be necessary to achieve effective thermal performance in ET environments.

3.5. *Further research efforts*

Recent developments in the field of EGs have led to the emergence of new typologies such as energy barrettes, energy quay walls, geothermal pavements, and energy anchors. These systems, while currently underrepresented in terms of case data, offer promising potential for extending the application of shallow geothermal technologies to diverse structural contexts (Gerola et al., 2024a). Energy barrettes are particularly suitable for deep foundations in urban areas with limited surface space, while quay walls allow for geothermal exchange in port and waterfront infrastructures. Geothermal pavements offer distributed surface exchange, making them suitable for retrofitting roads and plazas, whereas energy anchors are being explored for slope stabilization and retaining structures.

Due to their novelty, these systems face specific technical and operational challenges, such as pipe installation in geometrically

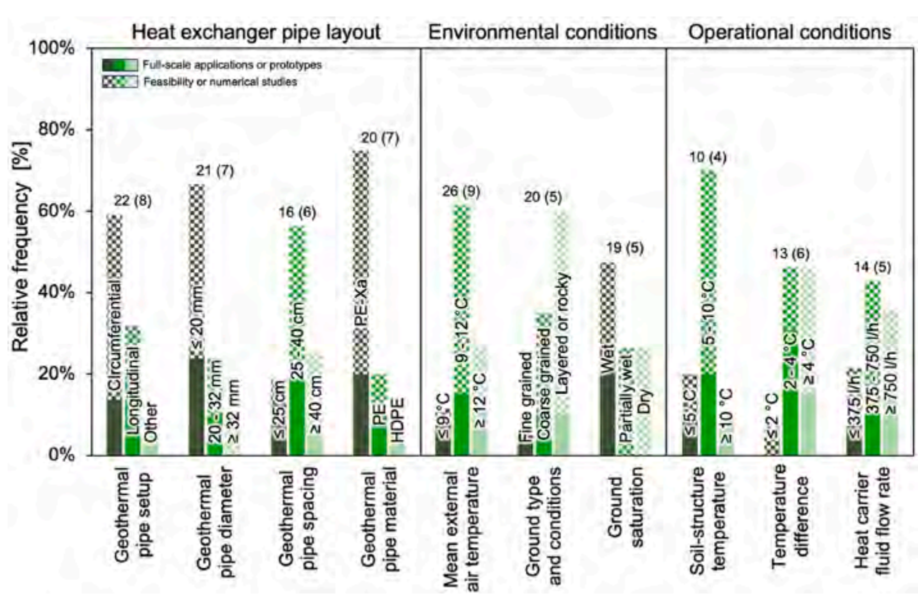


Fig. 13. Heat exchanger pipe layout and environmental and operational conditions of the ETs full-scale applications or prototypes, as well as feasibility and numerical studies, gathered in the database (the total number of case studies and, within brackets, full-scale applications for prototypes or which that specific information was available is shown above each group of columns).

constrained elements, variable thermal boundary conditions, and lack of design guidelines. To fully evaluate their potential, future studies should focus on long-term performance monitoring, the development of tailored design models, and the standardization of performance metrics.

In parallel, there is a growing trend toward the use of composite energy geostructure systems, where multiple EG types are integrated within the same project to maximize geothermal potential and adapt to complex urban conditions. For example, combined applications of EPs and EWs or ETs and energy slabs are increasingly being adopted in large infrastructure projects such as transit stations and mixed-use buildings [7]. These systems can improve thermal balance across seasons and enhance the resilience of geothermal supply, but they also require integrated design approaches and coordination among various construction phases.

The current database highlights the early implementation stages of these technologies, with limited but growing examples collected across Europe, Asia, and the Americas. Further research should aim to expand empirical data, assess installation trends, and explore synergies between structural and energy functions. Developing robust models for the techno-economic evaluation and life-cycle performance of emerging and composite EGs will be essential to support their mainstream adoption.

3.6. Environmental and economic benefits

The reduction of CO_2 equivalent emissions using geothermal energy compared to other energy sources represents the key metric to weigh the environmental benefits that geothermal systems can provide.

To assess this benefit, data on the reduction of CO_2 equivalent emissions achieved by energy geostructures were either collected from existing sources or computed where data was not available. For this purpose, the hypothetical yearly geothermal energy produced by each EG collected in the database was considered, along with emission factors, based on British recommendations [96]. These factors represent the amount of CO_2 equivalent emissions per unit of heat produced and differ as a function of the energy source, as exemplified in Table 1. To calculate the CO_2 equivalent savings for a specific thermal energy source, the yearly produced energy of the EG installations in the database was multiplied by the emission factors of that specific technology compared to geothermal energy. The EGs that presented a lack of data in terms of geothermal energy produced were conservatively not considered in the computation.

For geothermal energy, the emission factor was computed accounting for an electricity emission factor of 0.136 kg/kWh and assuming an average coefficient of performance (COP) for geothermal heat pumps of 4.0. This COP means that 75 % of the useable energy originates from geothermal energy, with the remaining 25 % supplied by electricity. Coherently, only 0.034 kg of CO_2 equivalent is emitted per kWh of geothermal energy produced. A similar calculation applies to the ambient energy and air source heat pump technology, considering a COP of 2.5. This calculation approach is corroborated by Blum et al. [97].

Fig. 14 illustrates the resulting tons of cumulative CO_2 equivalent savings per year, comparing geothermal energy to other commonly used thermal energy sources, including natural gas, liquefied petroleum gas, heating oil, house coal and ambient energy.

The estimation of CO_2 emission savings was limited to operational

Table 1
Emission factors for different thermal energy sources [96].

Thermal energy source [−]	CO_2 eq. emission factor [kg/kWh]
Natural gas	0.210
Liquefied petroleum gas	0.241
Heating oil	0.298
House coal	0.395
Ambient energy	0.055
Shallow geothermal energy	0.034

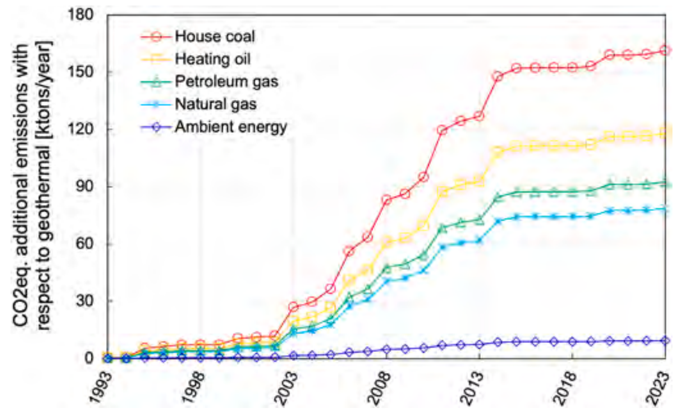


Fig. 14. CO_2 equivalent emissions for thermal energy production from fuels (house coal, heating oil, petroleum and natural gases) or air source heat pumps with respect to geothermal energy.

EGs for which energetic performance data were available. Specifically, the analysis included 132 out of 810 EPs, 24 out of 48 EWs, and 8 out of 11 ETs, accounting for approximately 20 % of the total number of operational EG case studies in the database. Less common EG typologies were not considered in the computation, due to the absence or incompleteness of energetic data. Similarly, EGs were excluded from the analysis when their documented cases were coupled with other EGs (i.e., EPs or EWs) already included in the calculation, to avoid potential double-counting.

From an economic perspective, available data are scarce. In the existing literature, the cost-effectiveness of EGs is often assessed through three main metrics: the additional cost relative to the base construction cost of the geotechnical structure, the payback period, and the Levelized Cost Of Energy (LCOE) produced.

The extra cost to instrument geotechnical structures with heat exchanger pipes generally amounts to 1.0 ÷ 2.0 % of the total construction cost, considering both the additional material and the higher burden of workforce for pipe laying [74,81]. The payback period, indicating the time needed to recoup the initial investment, usually varies between 2 and 15 years, depending on the energy extraction and injection capacity of the geostructures [3,76,84]. Similarly, the LCOE embodies the average net present energy cost for the generator over its lifetime, including the recoup of the initial investment and potential future profits. This represents a finer economic metric that accounts also for potential future profits. The LCOE for energy geostructures ranges between 80.0 and 115.0 € per MWh_t [38,98], making it a competitive and attractive alternative compared to other thermal energy sources. Due to the recent energy crisis because of the COVID-19 and Russian-Ukrainian war, these recorded massive fluctuations in terms of cost: for instance, from around 75.0 to 175.0 € per MWh_t for the natural gas or from around 125.0 to almost 250.0 € per MWh_t for the heating oil in the timeframe 2021–2024 [38].

4. Conclusions

This study provides a comprehensive analysis of EGs as multifunctional systems that integrate structural support with thermal energy transfer by exploiting low-enthalpy geothermal energy. The global database, updated to 2023, offers a broad overview of real case studies, test sites, and numerical simulations, revealing the worldwide expansion and diversification of EGs. The database also underscores the growing role of EGs as a sustainable and energy-efficient technology for the construction sector. Based on the data collected and analysed in this document, the following conclusions can be drawn:

- EGs have proven to be a promising and environmentally friendly technological solution for addressing the increasing energy demands in the building sector while utilizing the renewable energy potential of the subsurface.
- The database, updated to 2023 with 972 case studies from 27 countries, indicates a growing trend in the adoption of EGs globally. Europe leads in this technology, with Austria, Switzerland, Germany, and the United Kingdom, Italy and France having the highest number of installations. Indeed, the database reveals a concentration of EGs implementations, research, and knowledge dissemination primarily in Europe.
- Among the various types of EGs, EPs have emerged as the most commonly used, especially in practical applications, due to their efficiency, cost-effectiveness, and relatively quick installation times. EWs and ETs are gaining popularity, as evidenced by the increase in feasibility studies and numerical analyses, although their practical adoption is still in the early stages. Recent EGs developments, such as energy barrettes, energy quay wall, geothermal pavements, and energy anchors, are in the initial stages of development and implementation but hold promising potential for further diversification of EGs applications.
- The exchanged heat rate of EGs varies depending on specific types, soil conditions, project design, and operational parameters. These systems demonstrate considerable versatility in providing both heating and cooling.
- Environmentally, EGs offer significant advantages in reducing greenhouse gas emissions compared to traditional fossil fuels, making a substantial contribution to global climate change mitigation efforts.
- Despite the promising environmental benefits, widespread adoption of EGs faces challenges related to the availability of comprehensive cost data, payback periods, and long-term financial feasibility, particularly for newer types of EGs.

While the collected database provides valuable insights into EGs, it is crucial to acknowledge the limitations regarding data completeness and consistency, particularly for newer types of such technology and regions outside Europe. Therefore, further research efforts are needed to:

- Expand the database to include more case studies from various geographical areas, especially from countries where EGs adoption is still limited.
- Gather more comprehensive data on costs, payback periods, and economic feasibility of different EGs types to provide policymakers and industry stakeholders with more accurate information.
- Investigate the long-term impact of factors such as soil conditions, operational parameters, and design methods on the performance and durability of EGs.
- Develop standardized design models and tools to optimize energy efficiency and economic viability of EGs in diverse geological and climatic conditions.
- Further explore the potential for integrating EGs with other renewable energy technologies, such as solar and wind energy, to create more sustainable and resilient energy systems.

Addressing these research areas will further promote innovation, overcome adoption barriers, and fully unlock the potential of EGs for a sustainable future.

CRediT authorship contribution statement

D. Salciarini: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **M. Gerola:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **S. De Feudis:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **A. Lupattelli:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **G. Dalla Santa:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **G. Capati:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **M. Rafai:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **J. Tihana:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **M. Scerbo:** Writing – review & editing, Data curation. **A. Di Donna:** Writing – review & editing, Supervision, Data curation, Conceptualization. **E. Ravera:** Writing – review & editing, Data curation, Conceptualization. **M. Nicolino:** Data curation. **A. Insana:** Writing – review & editing, Data curation. **H. Mroueh:** Writing – review & editing, Conceptualization. **M. Barla:** Writing – review & editing, Methodology, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the Authors used ChatGPT to improve the grammar of the text. After using this tool/service, the Authors reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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.

Acknowledgements

This work has been carried out within the scope of **COST Action CA21156** “FOLIAGE”. D. Salciarini, A. Insana, and M. Barla acknowledge the support of the project PRIN2022 “Closing knowledge gaps on energy geostructures for retrofitting of buildings and infrastructures (**GEOREFIT**)”. D. Salciarini, A. Lupattelli, H. Mroueh acknowledge the support by the project CETP22FP-2022-00147 “Large-scale climate neutral Energy Geostructures in District Heating & Cooling systems/networks (**LEG-DHC**)”. D. Salciarini acknowledges the support of the project “National Innovation Ecosystem grant ECS00000041-VITALITY/CUP J97G22000170005. All the Authors thank the many companies and institutes that shared the data collected.

References

[1] M. Adinolfi, G. Rianna, P. Mercogliano, R.M.S. Maiorano, S. Aversa, Behaviour of energy piles under climate-change scenarios: a case study in southern Italy, Environ. Geotech. 8 (8) (2021) 571–585, https://doi.org/10.1680/jenge.19.00093.
[2] H. Ayaz, M. Faizal, A. Bouazza, Energy, economic, and carbon emission analysis of a residential building with an energy pile system, Renew. Energy 220 (2024) 119712, https://doi.org/10.1016/j.renene.2023.119712.
[3] H. Brandl, Energy foundations and other thermo-active ground structures, Geotechnique 56 (2) (2006) 81–122, https://doi.org/10.1680/geot.2006.56.2.81.
[4] L. Laloui, A. Di Donna, Energy Geostructures: Innovation in Underground Engineering, first ed., John Wiley & Sons Inc, London, 2013.
[5] M. Barla, A. Di Donna, Energy tunnels: concept and design aspects, Acta Geotech. 11 (4) (2016) 659–669, https://doi.org/10.1007/s11440-015-0427-5.
[6] M. Barla, A. Di Donna, Themed issue on energy geostructures, Environ. Geotech. 3 (2016) 188–189, https://doi.org/10.1680/jenge.2016.3.4.188.
[7] L. Laloui, A.F. Rotta Loria, Analysis and Design of Energy Geostructures, first ed., Elsevier, 2020 https://doi.org/10.1016/B978-0-12-816223-1.00017-5.
[8] E. Ravera, A.F. Rotta Loria, L. Laloui, Performance of complex energy geostructures, Geomech. Energy Environ. 38 (2024) 100536, https://doi.org/10.1016/j.gete.2024.100536.

[9] D. Adam, R. Markiewicz, Energy from earth-coupled structures, foundations, tunnels and sewers, Geotechnique 59 (3) (2009) 229–236, https://doi.org/10.1680/geot.2009.59.3.229.

[10] M. Mc Corry, G.L. Jones, Geotrainet Training Manual for Designers of Shallow Geothermal Systems, Geotrainet, EFG, Brussels, 2011.

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

[12] A. Di Donna, L. Laloui, Numerical analysis of the geotechnical behaviour of energy piles, Int. J. Numer. Anal. Methods GeoMech. 39 (8) (2015) 861–868, https://doi.org/10.1002/nag.2341.

[13] D. Salciarini, F. Ronchi, C. Tamagnini, Thermo-hydro-mechanical response of a large piled raft equipped with energy piles: a parametric study, Acta Geotech. 12 (4) (2017) 703–728, https://doi.org/10.1007/s11440-017-0551-3.

[14] F. Ronchi, D. Salciarini, N. Cavalagli, C. Tamagnini, Thermal response prediction of a prototype energy micro-pile, Geomech. Energy Environ. 16 (2018) 64–82, https://doi.org/10.1016/j.gete.2018.07.001.

[15] M. Rafai, D. Salciarini, P.J. Vardon, The thermo-mechanical impact of long-term energy pile use, Renew. Energy 244 (2025) 122693, https://doi.org/10.1016/j.renene.2025.122693.

[16] M. Rafai, D. Salciarini, P.J. Vardon, Energy pile displacements due to cyclic thermal loading at different mechanical load levels, Acta Geotech. 20 (2025) 3067–3086, https://doi.org/10.1007/s11440-025-02556-4.

[17] Q.I. Alqawasmeh, M.J. Kreitmair, G.A. Narsilio, The role of ground hydrothermal spatial variability on energy pile group thermal performance, Comput. Geotech. 179 (2025) 106983, https://doi.org/10.1016/j.compgeo.2024.106983.

[18] X. Ding, D. Zhang, C. Wang, A. Bouazza, G. Kong, Thermally induced mechanical interactions of energy pile groups subjected to cyclic nonsymmetrical thermal loading, Comput. Geotech. 167 (2024) 106053, https://doi.org/10.1016/j.compgeo.2023.106053.

[19] A. Lupattelli, D. Salciarini, Investigating the impact of temperature recovery across different thermal activation scenarios of a real-world energy piled foundation, Tunn. Undergr. Space Technol. 158 (2025) 106457, https://doi.org/10.1016/j.tust.2025.106457.

[20] P.J. Vardon, M. Gerola, V. Leclercq, K. de Jong, J. Haasnoot, R. Janssen, P. Stoelhorst, I. Pantev, J. de Vries, S. Bersan, D. Smeulders, F. Cecinato, The energy quay wall: results from a full-scale field test, Renew. Energy (2025) 123552, https://doi.org/10.1016/j.renene.2025.123552.

[21] F. Cotana, P. Belardi, P. Manciola, C. Tamagnini, A.L. Materazzi, M. Fornaciari, A. Petrozzi, A.L. Pisello, G. Cavalaglio, V. Coccia, G. Pagnotta, V. Menchetelli, S. Di Francesco, D. Salciarini, N. Cavalagli, F. Ubertini, F. Orlandi, T. Bonofiglio, TIAR: renewable energy production, storage and distribution; a new multidisciplinary approach for the design of rural facility, Energy Proc. 45 (2014) 323–332, https://doi.org/10.1016/j.egypro.2014.01.035.

[22] J. Fang, G. Kong, Y. Meng, L. Wang, Q. Yang, Thermomechanical behavior of energy piles and interactions within energy pile–raft foundations, J. Geotech. Geoenviron. Eng. 146 (9) (2020) 04020079, https://doi.org/10.1061/(ASCE)GT.1943-5606.0002333.

[23] R. Li, G. Kong, Y. Chen, Q. Yang, Thermomechanical behaviour of an energy pile–raft foundation under intermittent cooling operation, Geomech. Energy Environ. 28 (2022) 100240, https://doi.org/10.1016/j.gete.2021.100240.

[24] Y. Guo, C. Wang, A. Bouazza, G. Kong, X. Ding, Thermal performance of pipe-type energy piles with open-ended heat exchange tubes, Appl. Therm. Eng. 258 (2025) 124573, https://doi.org/10.1016/j.applthermaleng.2024.124573.

[25] A.F. Rotta Loria, Energy geostructures: theory and application, in: 2nd International Conference on Energy Geotechnics (ICEGT 2020) - E3S Web Conf., 205, 2020 01004, https://doi.org/10.1051/e3sconf/202020501004.

[26] Schweizerischer Ingenieur und Architektenverein, Nutzung der Erdwärme mit Fundationspfählen und anderen erdberührenden Betonbauteilen – Leitfaden zu Planung, Bau Und Betrieb, SIA, Zürich, 2005.

[27] Schweizerischer Ingenieur und Architektenverein, Erdwärmesonden, SIA, Zürich, 2021.

[28] Ground Source Heat Pump Association, Thermal Pile; Design, Installation & Materials Standards, GSHPA, Milton Keynes, 2012.

[29] Ground Source Heat Pump Association, Good Practice Guide for Ground Source Heating & Cooling (Version 2), GSHPA, 2017.

[30] A. Di Donna, M. Barla, T. Amis, Energy geostructures: a collection of data from real applications. 15th International Conference of the International Association for Computer Methods and Advances in Geomechanics (15Th IACMAG), 19-23 October 2017, Wuhan, Cina, 2017.

[31] A. Di Donna, M. Barla, T. Amis, Energy geostructures: analysis from research and systems installed around the world. DFI 42nd Annual Conference on Deep Foundations, October 2017, New Orleans, United States, 2017.

[32] M. Gerola, F. Cecinato, V. Leclercq, P.J. Vardon, Energy quay walls: performance analysis and optimisation, Geomech. Energy Environ. 42 (2025) 100664, https://doi.org/10.1016/j.gete.2025.100664.

[33] M. Gerola, F. Cecinato, J.K. Haasnoot, P.J. Vardon, The role of design and site-dependent parameters in the thermal performance of energy quay walls, Energy 325 (2025) 135990, https://doi.org/10.1016/j.energy.2025.135990.

[34] M. Gerola, V. Leclercq, P.J. Vardon, F. Cecinato, Energy performance of cutter soil mix energy walls: a numerical modelling study, Tunn. Undergr. Space Technol. 165 (2025) 106843, https://doi.org/10.1016/j.tust.2025.106843.

[35] N. Makasis, X. Gu, M.J. Kreitmair, G.A. Narsilio, R. Choudhary, Geothermal pavements: a city-scale investigation on providing sustainable heating for the city of Cardiff, UK, Renew. Energy 218 (2023) 119248.

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

[37] A.F. Rotta Loria, E. Ravera, L. Laloui, Thermo-hydro-mechanical behavior of energy barrettes: field experiments and numerical simulations, Geomech. Energy Environ. 34 (2023) 100451, https://doi.org/10.1016/j.gete.2023.100451.

[38] S. De Feudis, A. Insana, M. Barla, Seizing the opportunity of energy retrofitting of existing tunnels, Tunn. Undergr. Space Technol. 154 (2024) 106109, https://doi.org/10.1016/j.tust.2024.106109.

[39] J. Gao, X. Zhang, J. Liu, K. Li, J. Yang, Numerical and experimental assessment of thermal performance of vertical energy piles: an application, Appl. Energy 85 (2008) 901–910, https://doi.org/10.1016/j.apenergy.2008.02.010.

[40] F. Loveridge, W. Powrie, Pile heat exchangers: thermal behaviour and interactions, Proc. Inst. Civ. Eng. Geotech. Eng. 166 (2013) 178–196, https://doi.org/10.1680/geng.11.00042.

[41] T. Amis, C.A.W. Robinson, S. Wong, Integrating geothermal loops into the diaphragm walls of the knightsbridge palace hotel project. EMAP-basements and Underground Structures, 2011.

[42] M. Sutman, G. Speranza, A. Ferrari, P. Larrey-Lassalle, L. Laloui, Long-term performance and life cycle assessment of energy piles in three different climatic conditions, Renew. Energy 146 (2020) 1177–1191, https://doi.org/10.1016/j.renene.2019.07.035.

[43] F. Cecinato, D. Salciarini, Energy performance assessment of thermo-active micro-piles via numerical modeling and statistical analysis, Geomech. Energy Environ. 29 (2022) 100268, https://doi.org/10.1016/j.gete.2021.100268.

[44] M. Gerola, A. Lupattelli, F. Cecinato, D. Salciarini, T. Arola, Numerical analysis of the behaviour of energy micropiles used for heat storage: a case study in Turku (Finland), in: A. Ferrari, M. Rosone, M. Ziccarelli, G. Gottardi (Eds.), Geotechnical Engineering in the Digital and Technological Innovation Era (808–815), Springer, Cham, 2023, https://doi.org/10.1007/978-3-031-34761-0_97.

[45] M. Rafai, D. Salciarini, P.J. Vardon, Full-scale in-situ tests on a displacement cast in situ energy pile: effects of cyclic thermal loads under different mechanical load levels on pile stress and strain, Geomech. Energy Environ. 40 (2024) 100606, https://doi.org/10.1016/j.gete.2024.100606.

[46] M. Rafai, A.M. Tang, T. Badinier, J. De Sauvage, D. Salciarini, Effect of thermal cycles on sand–concrete interface under constant shear stress, Can. Geotech. J. 62 (2024) 1–16, https://doi.org/10.1139/cgj-2023-0140.

[47] Lupattelli, P.J. Bourne-Webb, T.M. Bodas Freitas, D. Salciarini, A numerical study of the behaviour of micropile foundations under cyclic thermal loading, Appl. Sci. 13 (2023) 9791, https://doi.org/10.3390/app13179791.

[48] E. Lupattelli, B. Cernuto, E. Brunelli, D. Cattoni, D. Salciarini, Experimentation of the thermo-mechanical behavior of the soil-concrete interface, in: A. Ferrari, M. Rosone, M. Ziccarelli, G. Gottardi (Eds.), Geotechnical Engineering in the Digital and Technological Innovation Era, Springer, Cham, 2023, pp. 343–350, https://doi.org/10.1007/978-3-031-34761-0_42, 2023.

[49] A. Lupattelli, D. Salciarini, F. Cecinato, M. Veveakis, T.M. Bodas Freitas, P. J. Bourne-Webb, Temperature dependence of soil-structure interface behaviour in the context of thermally-activated piles: a review, Geomech. Energy Environ. 37 (2024) 100521, https://doi.org/10.1016/j.gete.2023.100521.

[50] A. Mehrizi, S. Porkhial, B. Bezyan, H. Lotfizadeh, Energy pile foundation simulation for different configurations of ground source heat exchanger, Int. Commun. Heat Mass Tran. 70 (2016) 105–114, https://doi.org/10.1016/j.icheatmasstransfer.2015.12.001.

[51] S. Park, S. Lee, K. Oh, D. Kim, H. Choi, Engineering chart for thermal performance of cast-in-place energy pile considering thermal resistance, Appl. Therm. Eng. 130 (2018) 899–921, https://doi.org/10.1016/j.applthermaleng.2017.11.065.

[52] P.J. Bourne-Webb, A. Lupattelli, T.M. Bodas Freitas, D. Salciarini, The influence of initial shaft resistance mobilization in the response of seasonally, thermally-activated pile foundations in granular media, Geomech. Energy Environ. 32 (2022) 100299, https://doi.org/10.1016/j.gete.2021.100299.

[53] K. Nagano, Energy pile system in new building of Sapporo City University, in: H.Ö. Paksoy (Ed.), Thermal Energy Storage for Sustainable Energy Consumption, NATO Science Series, vol. 234, Springer, Dordrecht, 2007, https://doi.org/10.1007/978-1-4020-5290-3_16.

[54] J.S. McCartney, Design of Energy Piles Considering Soil-Structure Interaction and Unsaturated Soil Effects, GeoOmaha 2018, February 9th, 2018.

[55] S. You, X. Cheng, H. Guo, Z. Yao, In-situ experimental study of heat exchange capacity of CFG pile geothermal exchangers, Energy Build. 79 (2014) 23–31, https://doi.org/10.1016/j.enbuild.2014.04.021.

[56] M. Jastrzebska, B. Waerzynczyk, The analysis of the direct foundation with energy foundations on the basis of the office building "A4 Business Park" in katowice at Francuska Street, architecture, civil engineering, Environment 9 (2) (2016) 65–76, https://doi.org/10.21307/acee-2016-023.

[57] G. Kong, R. Li, H. Deng, Q. Yang, Behaviours of a belled energy pile under heating-cooling cycles, J. Build. Eng. 72 (2023) 106652, https://doi.org/10.1016/j.jobe.2023.106652.

[58] M. Faizal, A. Bouazza, J.S. McCartney, C. Haberfield, Axial and radial thermal responses of energy pile under six storey residential building, Can. Geotech. J. 56 (7) (2018) 1019–1033, https://doi.org/10.1139/cgj-2018-0246.

[59] L.A. Bandeira Neto, G.A. Narsilio, N. Makasis, R. Choudhary, Y. Carde, Thermal response of energy screw piles connected in series, J. Geotech. Geoenviron. Eng. 149 (7) (2023), https://doi.org/10.1061/JGGEFK.GTENG-11082.

[60] H. Kubota, Y. Zhang, K. Kato, Performance evaluation of energy pile system in cold climate region, Renew. Energy 34 (2009) 2030–2036.

[61] J. Forth, P.J. Bourne-Webb, B. Amatya, Thermal performance monitoring of energy piles installed at state library station, Melbourne, Proc. Inst. Civ. Eng. Geotech. Eng. 172 (6) (2019) 506–517.
[62] H. Liu, J. Liu, M. Li, Y. Yang, Performance of a building energy pile system in Nanjing: field measurements and analysis, Appl. Therm. Eng. 170 (2020) 114979.
[63] P.J. Bourne-Webb, T.M. Bodas Freitas, R.A. da Costa Gonçalves, Thermal and mechanical aspects of the response of embedded retaining walls used as shallow geothermal heat exchangers, Energy Build. 125 (2016) 130–141, https://doi.org/10.1016/j.enbuild.2016.04.075.
[64] A. Di Donna, F. Cecinato, F. Loveridge, M. Barla, Energy performance of diaphragm walls used as heat exchangers, Proc. Inst. Civ. Eng. Geotech. Eng. 170 (3) (2017) 232–245, https://doi.org/10.1680/jgeen.16.00092.
[65] Y. Rui, M. Yin, Thermo-hydro-mechanical coupling analysis of a thermo-active diaphragm wall, Can. Geotech. J. 55 (5) (2018) 720–735, https://doi.org/10.1139/cgj-2017-0158.
[66] A. Di Donna, F. Loveridge, M. Piemontese, M. Barla, The role of ground conditions on the heat exchange potential of energy walls, Geomech. Energy Environ. 25 (2021) 100199, https://doi.org/10.1016/j.gete.2020.100199.88.
[67] A. Bouazza, R.M. Singh, B. Wang, D. Barry-Macaulay, C. Haberfield, G. Chapman, S. Baycan, Y. Carden, Harnessing on site renewable energy through pile foundations, Aust. Geomech. 46 (4) (2011) 79–90.
[68] C. Xia, M. Sun, G. Zhang, S.S. Xiao, Y. Zou, Experimental study on geothermal heat exchangers buried in diaphragm walls, Energy Build. 52 (2012) 50–55, https://doi.org/10.1016/j.enbuild.2012.03.054.
[69] M. Baralis, M. Barla, Development and testing of a novel geothermal wall system, Int. J. Energy Environ. Eng. 12 (2021) 689–704, https://doi.org/10.1007/s40095-021-00407-y.
[70] D. Sterpi, A. Angelotti, O. Habibzadeh-Bigdarvish, D. Jalili, Assessment of thermal behaviour of thermo-active diaphragm walls based on monitoring data, J. Rock Mech. Geotech. Eng. 10 (2018) 1145–1153, https://doi.org/10.1016/j.jrmge.2018.08.002.
[71] P. Trinchero, M. Barla, A. Di Donna, A. Perino, On the thermal activation of Turin Metro line 2 tunnels: numerical modeling and feasibility assessment. Proceedings of the 7th European Geothermal Congress, 2021.
[72] EPFL Energy Center, Geothermal Concepts and Energy Strategy of the Discovery Learning Lab, Internal Project Documentation, 2017.
[73] M. Barla, A. Di Donna, A. Perino, Application of energy tunnels to an urban environment, Geothermics 61 (2016) 104–113, https://doi.org/10.1016/j.geothermics.2016.01.014.
[74] M. Barla, A. Insana, Energy tunnels as an opportunity for sustainable development of urban areas, Tunn. Undergr. Space Technol. 132 (2023) 104902, https://doi.org/10.1016/j.tust.2022.104902.
[75] X. Dai, A. Bidarmaghz, G.A. Narsilio, Energy tunnels: a review of the state of the art and knowledge gaps to harness renewable energy from underground infrastructure, Tunn. Undergr. Space Technol. inc. Trenchless Technol. Res. 142 (2023) 105431, https://doi.org/10.1016/j.tust.2023.105431.
[76] M. Barla, A. Di Donna, A. Insana, A novel real-scale experimental prototype of energy tunnel, Tunn. Undergr. Space Technol. 87 (2019) 1–14, https://doi.org/10.1016/j.tust.2019.01.024.
[77] A. Insana, M. Barla, Experimental and numerical investigations on the energy performance of a thermo-active tunnel, Renew. Energy 152 (2020) 781–792, https://doi.org/10.1016/j.renene.2020.01.086.
[78] Donna Di, M. Barla, The role of ground conditions and properties on the efficiency of energy tunnels, Environ. Geotech. 3 (4) (2016) 214–224, https://doi.org/10.1680/jenge.15.00030.
[79] G. Kong, D. Wu, Y. Wei, Experimental and numerical investigations on the energy and structural performance of a full-scale energy utility tunnel, Tunn. Undergr. Space Technol. 139 (2023) 105208, https://doi.org/10.1016/j.tust.2023.105208.
[80] G. Zhang, C. Xia, Y. Yang, M. Sun, Y. Zou, Experimental study on the thermal performance of tunnel lining ground heat exchangers, Energy Build. 77 (2014) 149–157, https://doi.org/10.1016/j.enbuild.2014.03.043.
[81] M. Schneider, C. Moormann, Geotu6 – a geothermal research project for tunnels, Tunnel 2 (2010) 14–21.
[82] J.N. Franzius, N. Pralle, Turning segmental tunnels into sources of renewable energy, Proc. ICE Civil Eng. 164 (2011) 35–40, https://doi.org/10.1680/cien.2011.164.1.35.
[83] C. Lee, S. Park, H.J. Choi, I.M. Lee, H. Choi, Development of energy textile to use geothermal energy in tunnels, Tunn. Undergr. Space Technol. 59 (2016) 105–113, https://doi.org/10.1016/j.tust.2016.06.014.
[84] B. Moormann, P. Buhmann, W. Friedemann, S. Homuth, N. Pralle, Tunnel geothermics – international experience with renewable energy concepts in tunnelling, Geomech. Tunn. 9 (2016) 467–480, https://doi.org/10.1002/geot.201600048.
[85] P. Buhmann, C. Moormann, B. Westrich, N. Pralle, W. Friedemann, Tunnel geothermics—A German experience with renewable energy concepts in tunnel projects, Geomech. Energy Environ. 8 (2016) 1–7, https://doi.org/10.1016/j.gete.2016.10.006.
[86] R. Stemmle, K. Menberg, L. Rybach, P. Blum, Tunnel geothermics – a review, Geomech. Tunn. 15 (1) (2022) 104–111, https://doi.org/10.1002/geot.202100084.
[87] D. Nicholson, Q. Chen, M. de Silva, A. Winter, The design of thermal tunnel energy segments for crossrail, UK, in: Proceedings of the Institution of Civil Engineers - Engineering Sustainability, vol. 167, 2014, pp. 118–134, https://doi.org/10.1680/ensu.13.00014.
[88] F. Furno, M. Barla, A. Dematteis, S. Lo Russo, Methodological approach for a sustainable management of water inflow and geothermal energy in tunnels, Acque Sotterranee - Ital.J. Groundw. 4 (3) (2015), https://doi.org/10.7343/as-119-15-0146.
[89] A. Csesznak, R. Jarschke, M. Wittke, B 10 Rosenstein Tunnel-Designing a geothermal energy system in a spa protection area/B 10-Rosensteintunnel–Planungeiner Geothermieanlage im Heilquellenschutzgebiet, Geomech. Tunn. 9 (2016) 458–466, https://doi.org/10.1002/geot.201600033.
[90] M. Baralis, M. Barla, W. Bogusz, A. Di Donna, G. Ryzynski, M. Zerun, Geothermal potential of the ne extension warsaw metro tunnels, Environ. Geotech. 7 (4) (2018) 1–37, https://doi.org/10.1680/jenge.18.00042.
[91] S. De Feudis, Energy Retrofitting of Existing Tunnels – from Conceptualization to full-scale Implementation, Ph.D. Thesis, Politecnico di Torino, 2025, https://iris.polito.it/handle/11583/3001707.
[92] G. Dalla Santa, A. Galgaro, R. Sassi, M. Cultrera, P. Scotton, J. Mueller, D. Bertermann, D. Mendrinos, D. Pasquali, R. Perego, S. Pera, E. Di Sipio, G. Cassiani, M. De Carli, A. Bernardi, An updated ground thermal properties database for GSHP applications, Geothermics (2020) 101758, https://doi.org/10.1016/j.geothermics.2019.101758.
[93] M. Krajčík, M. Arıcı, O. Šikula, M. Šimko, Review of water-based wall systems: heating, cooling, and thermal barriers, Energy Build. 253 (2021) 111476, https://doi.org/10.1016/j.enbuild.2021.111476.
[94] M. Sutman, I. Sarbu, C. Pacurar, Thermal and hydraulic design criteria of ground heat exchangers: a comprehensive review, Renew. Sustain. Energy Rev. 147 (2021) 111208, https://doi.org/10.1016/j.rser.2021.111208.
[95] F. Loveridge, W. Powrie, D. Nicholson, Energy piles: design and performance, Geomech. Energy Environ. 24 (2020) 100179, https://doi.org/10.1016/j.gete.2020.100179.
[96] British Research Establishment (BRE), Standard Assessment Procedure 10.2 - the Government's Standard Assessment Procedure for Energy Rating of Dwellings, 2022.
[97] P. Blum, G. Campillo, W. Munch, T. Kolbel, CO_2 savings of ground source heat pump Systems–a regional analysis, Renew. Energy 35 (2010) 122–127, https://doi.org/10.1016/j.renene.2009.03.034.
[98] A. F. Rotta Loria Cousin, A. Bourget, F. Rognon, L. Laloui, Energy performance and economic feasibility of energy segmental linings for subway tunnels, Tunn. Undergr. Space Technol. 91 (2019) 102997, https://doi.org/10.1016/j.tust.2019.102997.