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ABSTRACT

The urgent requirement to decarbonise the construction sector and reduce building-related fossil fuel consumption has positioned energy geostructures as a pivotal multipurpose solution for climate change mitigation. However, despite a growing body of scientific literature and knowledge-sharing initiatives, global adoption remains disproportionately low. This paper aims to identify which issues and barriers remain to be overcome in order to enable the widespread implementation and use of energy geostructures. Such aim is obtained through the analysis of the results of a survey sent to actors in the construction industry and academia. The survey, involving 155 international participants, reveals that the primary barriers are perceived to be economic factors and a lack of specialised expertise, training, and guidelines, rather than fundamental technical limitations. Notably, the data indicate that economic barriers appear dominant during the initial feasibility stages, highlighting an urgent need for improved dissemination of economic viability studies; however, during the implementation of energy geostructures, additional challenges are reported, diminishing the relative weight of economic constraints. Indeed, a lack of expertise and guidelines is widely acknowledged by respondents, regardless of whether projects are ultimately implemented, emphasising the need for targeted educational initiatives to foster the adoption of energy geostructures. Legal aspects as well as coordination between the different actors during energy geostructures deployment also appear among the difficulties linked to the implementation of energy geostructures. By identifying and comparatively assessing these multifaceted challenges through survey responses, this paper provides a strategic evidence base for policymakers and industry leaders to develop the frameworks necessary to foster the deployment of energy geostructures in the transition to net-zero.

1. Introduction

Since the 1990s, global CO_2 emissions have increased by more than 46%, contributing to a significant increase in mean global temperatures. If all the commitments in terms of sustainable development and ecology are effectively implemented, temperatures are predicted to rise by 2.8 °C

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by the end of the century (IPCC, 2021). This will cause an increase in the frequency of droughts, intense precipitation events and cumulative rainfall, thus endangering buildings and infrastructure.

In alignment with recommendations from the Intergovernmental Panel on Climate Change (IPCC), the European Union (EU) aims to reduce net greenhouse gas (GHG) emissions by at least 55% by 2030 and to be carbon-neutral by 2050 (European Parliament and Council of the European Union, 2021). In 2024, within the EU, the principal GHG-emitting sectors have been energy supply, which accounts for approximately 23%, domestic transport which accounts for approximately 26% and industry which accounts for around 20% (European Environment Agency, 2026). To reduce GHG emissions, transformational solutions are urgently needed, and the energy supply sector must be one of the main contributors.

Energy consumption for heating and cooling constitutes approximately 50% of the EU's total energy use (Eurostat, 2023). In 2022, the share of energy from renewables in heating and cooling in the EU represented nearly 25% (Eurostat, 2024). This significant energy demand, combined with the still limited penetration of renewable sources, highlights the need for innovative and efficient technologies capable of simultaneously reducing energy consumption and greenhouse gas emissions in the built environment. In this context, energy geostructures (EGs) can contribute to the decarbonization of the heating and cooling sectors (Brandl, 2006; Adam and Markiewicz, 2009; Laloui and Di Donna, 2013; Menberg et al., 2025; Barla and Insana, 2026). EGs are structures in contact with the ground characterized by a primary structural role whilst also working as heat exchangers. By thermally activating the structural elements of a building or of an infrastructure in direct contact with the ground, a low enthalpy geothermal system can be achieved. Piles, micropiles, tunnels, walls and slabs can be turned into EGs by embedding a circuit of pipes into the geostructural elements and by circulating a heat carrier fluid along it. This multifunctional technology represents an interesting alternative to traditional shallow geothermal technologies, well fitting in the context of an energy system transition that will bring important modifications to the way homes and other spaces will be heated and cooled. Despite the large potential and the concept simplicity, their implementation requires the integration of multiple disciplines (mechanical, energy, geotechnical engineers), the understanding of potential thermo-hydro-mechanical effects on the structure itself, on the surrounding ground and on the groundwater, the analysis of costs and benefits of such ground source heat pump technology compared to competing energy sources, awareness of the technology during early design stages and the availability of standard, accessible and easy-to-use design tools and guidelines.

Following the identification of EGs as a promising solution for the decarbonization of heating and cooling, their development and dissemination have been accompanied by a growing research and innovation effort worldwide. In particular, at the European level, this growing engagement is reflected in the steady increase, since 2009, in the number of events (i.e. conferences, symposiums, etc.), funded projects, and scientific communications dedicated to EGs, all following a similar upward, linear trend (Fig. 1). This demonstrates a growing interest from the scientific community as well as from society in general. Among the projects, the range of topics covered is wide, ranging from education and training to applied and fundamental research. The collected data include 193 events, 17 projects, and 53 papers. The projects were identified through the EU funding platform (link or citation), while the events were identified on the Think-Geoenergy website, and the scientific communications were purposely selected among the ones published in the European and International Conferences on Soil Mechanics and Geotechnical Engineering to emphasize the increased attention given to EGs.

Salciarini et al. (2026) compiled a database of EGs installations, finding that, to the best of their knowledge, only 2 to 7% of all the EGs projects were implemented outside of Europe (Australia, Canada, Chile, China, Japan, South Korea, USA), highlighting the higher maturity level of the technology in Europe. They also demonstrated that energy piles are more commonly adopted compared to the other types of EGs and that energy walls have recently seen significant growth. A less positive outcome was found for energy slabs, where a decline is observed, and energy tunnels that represent the lowest number of installations, though they are characterized by a longer installation period. Furthermore, the study highlighted a notable underrepresentation or absence of EGs in several European countries, including the Czech Republic, Estonia, Greece, Hungary, Latvia, Lithuania, Luxembourg, Malta, Portugal, Slovakia, Slovenia, and Turkiye. In some cases, this is due to lack of publicly available information regarding the diffusion of EGs in specific countries.

By checking the number of new residential building permits in Europe, the total number of new buildings was estimated to be 1.26 million between 2015 and 2023 (Eurostat, 2025). Although this figure includes buildings with diverse foundation systems, not all of which are compatible with energy piles or energy slabs, the number of EGs projects (specifically energy piles and energy slabs) in the same timeframe is 183, i.e. around 0.015% of the new residential buildings. Although these statistics do not cover the full extent of new building permits, as office and industrial buildings are ignored, they are nonetheless significant enough to reveal the lack of EG adoption. Indeed, this figure starkly illustrates the huge unexplored potential of EGs. This potential is even higher if one considers office buildings, for which permits are not as well documented in Europe. It is evident that, despite demonstrable advantages and growing academic interest, EGs remain a niche technology with limited practical implementation.

To facilitate the integration of thermal energy systems into geostructures, it is imperative to evaluate the current state of professional knowledge on this topic and the efficiency of existing design and construction tools. This study addresses this requirement by identifying the persistent barriers that continue to hinder the large-scale adoption of EGs. The investigation is based on a comprehensive international survey developed within the framework of Working Group 1 of the COST Action FOLIAGE (CA21156: European Network for Fostering Large-scale Implementation of Energy Geostructures).[1] By leveraging this collaborative network, the research brings together views from many different sectors, providing an evidence base to diagnose the disconnect between theoretical viability and practical deployment.

2. Methodology

The questionnaire was formulated to cover EGs design principles, execution methods, recommendations, and education and training. By collecting insights regarding the current perception, awareness, and knowledge of EGs and their implementation, the survey involved everybody potentially interested in EGs, that includes practitioners, stakeholders and researchers (herein referred to as "actors"), in order to understand the possible causes of the very limited number of EG applications.

The survey was prepared by means of an online form, collecting the answers in an Excel file. In the following sections, the survey structure and the survey sample demographics will be described.

2.1. Structure of the survey

The questionnaire was divided into four main parts.

The first section was designed to establish a comprehensive profile of each participant, such as affiliation, educational level, professional experience in the field of geotechnical engineering, age, professional country, etc. This demographic information is crucial for contextualising and interpreting the survey responses.

Each of the subsequent sections was designed to systematically

[1] https://www.cost.eu/actions/CA21156/

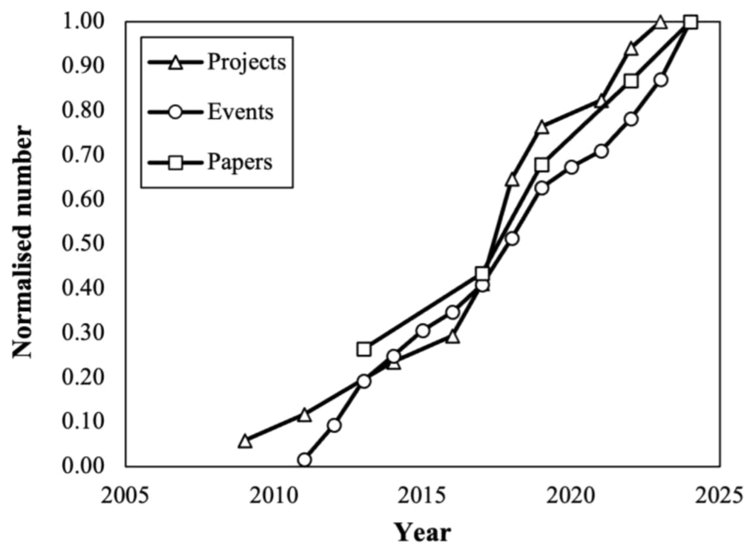


Fig. 1. Number of European funded projects, number of events related to geothermal energy and number of scientific communications related to EGs since 2009 (normalized to the 2024 number).

evaluate perceived deficiencies related to guidelines, knowledge, training, or misconceptions at each step of an EG implementation project. Specifically, the second section was dedicated to potential design-related issues for EGs with the aim of identifying if there are any challenges hindering widespread adoption due to lack of analytical, numerical or empirical tools.

In the same manner, the third section tried to point out obstacles specific to EGs execution such as additional equipment and control phases as well as the potential need for enhanced coordination between the different actors during this stage.

Lastly, the fourth section focused on monitoring aspects related to EGs and aimed to gather the participants' perspectives on the utility of monitoring systems and on the most informative parameters to collect during the EGs service life, as well as on the required frequency of maintenance.

2.2. Survey sample demographic

The survey was initially disseminated to geo-engineers and geo-scientists through the national scientific and professional geotechnical organizations in different countries, predominantly within Europe. In the second stage, the survey was opened to a larger community through its publication on professional social networks. At the same time, the survey was sent to individuals known to be active in the field of geotechnical engineering. A total of 155 completed questionnaires were returned. The majority of responses originated from European countries, with contributions from North America and other global regions (Fig. 2).

The formulation of the initial section of the questionnaire allowed to assess the demographic and professional background of respondents and level of knowledge on EGs, ensuring a comprehensive and diverse survey sample, thus limiting as far as possible bias related to participants selection. Still, bias may exist. For instance, sharing the survey through the professional social network of individual people could include respondents not familiar with EGs or, viceversa, that are particularly familiar with EGs (also reflecting the relatively small size of the EGs research and professional community). It could lead to engage respondents with a specific (technical) background, affiliation, education level, geographical distribution. In the following, the survey sample is characterized highlighting possible bias.

Among the participants to this survey, 52% are working for a private company, while 37% are public servants and 8% are students (Fig. 3). The vast majority of those employed by a private company are either design engineers (39%) or researchers (30%) while only 10% describe themselves as contractors or stakeholders. Among public servants, 91%

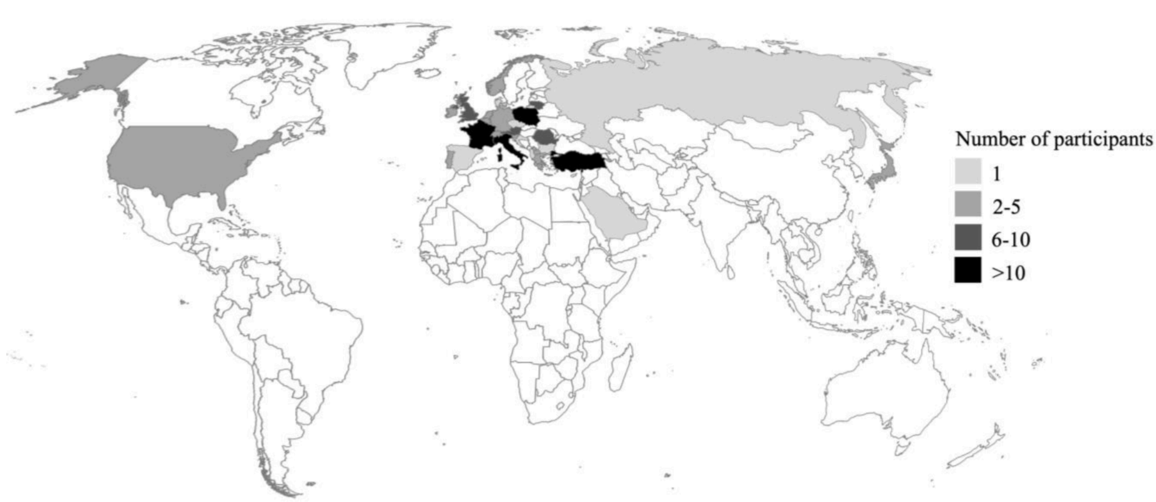


Fig. 2. Geographical distribution of the 155 survey participants.

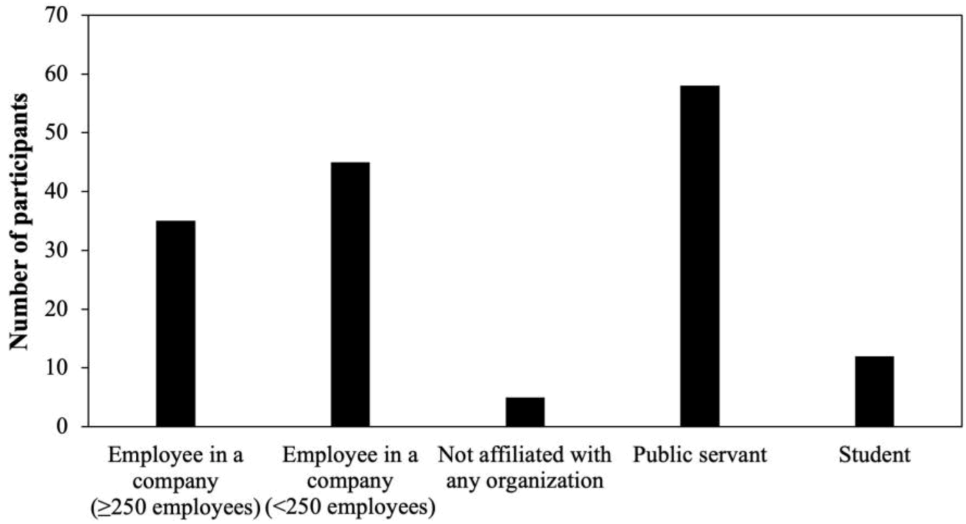


Fig. 3. Distribution of survey participants according to affiliation type.

are university lecturers, researchers, or equivalent. These results can be explained by the fact that the audience reached by approaching national scientific societies includes a large number of academics or assimilated personnel. Therefore, most of the participants are only in a position to recommend the implementation of EGs, while around 5% of participants are in decision-making position. Consistent with this profile, 48% of the participants hold a doctoral degree and 28% hold a Master's degree or equivalent. This demographic composition may influence the survey outcomes, potentially inducing bias towards technical and research considerations over logistical or financial aspects pertinent to developers and investors. The age distribution of respondents was found to be relatively uniform across different groups.

3. Results and discussion

A substantial proportion of participants (81%) affirmed their acquaintance with the concept of EGs, which can be interpreted either as a widespread knowledge of the concept or as a consequence of having solicited participants through scientific and professional channels likely to engage individuals with a pre-existing interest in the subject.

However, when investigating the percentage of people who have been involved in a real-world project where EGs were considered, one can see that the number drops to 41%. Among the employees of a company, this percentage does not change much (36%), reinforcing the observation that the EG concept is still quite new for the majority of the professionals. This percentage decreases further when considering only people involved in projects that were actually implemented: in this case, it drops to 15% when considering all the participants of the survey, and to 18% when considering only employees of private companies. These statistics starkly highlight a critical disconnect between theoretical awareness and practical application of EGs technology. At the same time, they also confirm that any bias introduced in the results by targeting potential participants through scientific and professional organizations is limited.

The main difficulties and challenges encountered during the projects, regardless of whether the implementation of EGs was successful or not, were mostly non-technical, but rather economic (accounting for 27% of the answers) and related to a lack of expertise among the actors (accounting for 23% of the answers). In contrast, the technical issues account for only 12% of the cited challenges (Fig. 4). This suggests a pressing need for wider dissemination of robust studies and empirical evidence concerning the Levelised Cost Of Energy (LCOE), project payback periods, and comprehensive cost-benefit analyses relative to conventional heating and cooling systems and other renewable energy

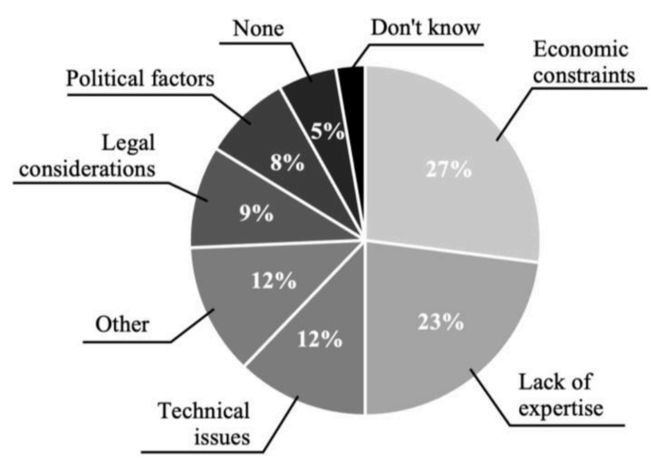


Fig. 4. Repartition of the perceived barriers to EGs implementation.

sources, as well as training for both designers and construction companies.

Strikingly, the observation that challenges encountered in successful EGs projects often mirrored the difficulties reported in unsuccessful ones (specifically economic constraints and lack of expertise) demonstrates that these barriers can be overcome. Therefore, feedback from the successful cases is certainly required to help identify the same solutions to the same problems.

It is also worth noting that among the successful EGs installations reported, 4 out of 15 (nearly 25%), notably from France, the USA, and Austria, answered that there were no challenges to overcome. This suggests that the technology itself is mature and that exemplary projects exist which can serve as valuable references for future adoption. However, through specific questions and corroborating evidence such that presented in Fig. 4 (and later in Fig. 5), the survey also reveals that another significant barrier is the lack of protocols, guidelines, and recommendations for both the design and the execution of EGs. Indeed, only 23% of the participants who stated that they are acquainted with EGs answered that these documents are adequate and sufficiently available for the design of EGs. This percentage drops to just 11% for the execution of EGs.

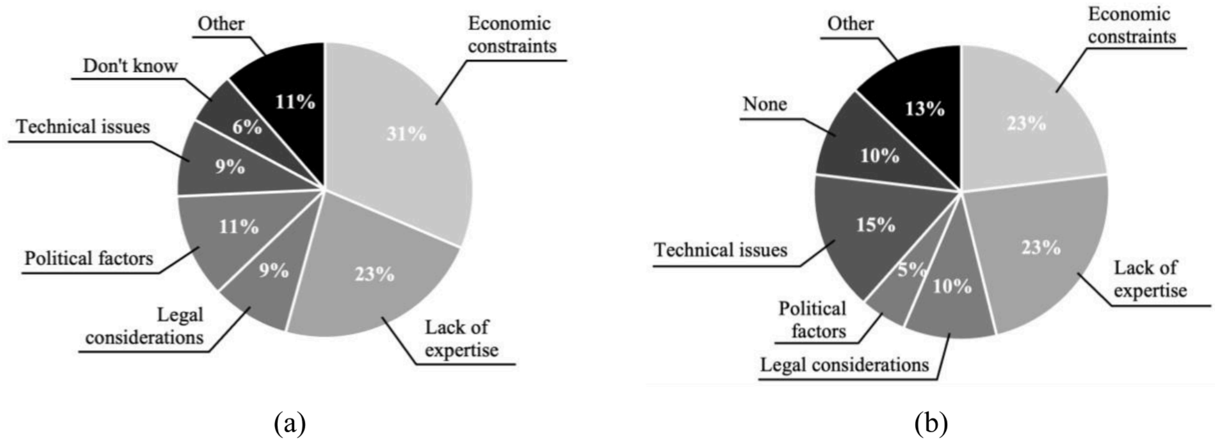


Fig. 5. Repartition of the perceived barriers to EGs implementation in the case of (a) unsuccessful and (b) successful projects.

3.1. Economical barrier

Overall, 27% of the answers identified the economic constraints as the main issue, but when differentiating between successful projects (i.e. designed and also implemented) and the unsuccessful (i.e. designed but not implemented) ones, a significant gap appears. Indeed, when asked about the main reasons for discontinuing the use of EGs, 31% of the answers pointed out that economic constraints were the principal reason (Fig. 5a). This number drops to 23% for projects where EGs were effectively implemented (Fig. 5b). It emerges that, at first, economic barriers seem to be the major issue, but when implementing EGs, other issues are reported by the respondents, diminishing the relative importance of economic constraints.

However, in the literature some studies on the economic attractiveness of EGs are starting to accompany technical analyses. They aim to justify the benefits of installing EGs instead of conventional geostructures and to demonstrate the savings compared to other renewable and non-renewable technologies. For instance, Cousin et al. (2019) analyzed the costs (capital investment, such as pipes, installation, etc., and operating costs) and profitability of an energy segmental lining. It was shown that the most efficient design does not lead to the lowest Levelized Cost of Energy (LCOE) and the earliest profitability. A poor design can jeopardize both the energy performance and economic attractiveness of such applications. Then, De Feudis et al. (2024) performed an analysis of the economic attractiveness of converting existing tunnels into energy tunnels, determining the LCOE, i.e. the average net present energy cost over the technology's lifetime (25 years were considered) to recover the initial investment and earn from it. A LCOE of 80–110 €/MWh$_t$ was calculated, demonstrating that EGs are as economically attractive as other sources, except coal which would be much cheaper. However, compared to the latter, the use of EGs comes with undeniable benefits from an environmental point of view.

As an example of the findings above Barns et al. (2023), referring to the study by Nicholson et al. (2014), report that economic constraints were among the main reasons that hindered incorporation of heat transfer pipes for thermal activation of tunnel linings in the UK, even though it was suggested that energy tunnels at Crewe and Manchester can generate positive financial returns, delivering heat at lower costs compared with air-source heat pumps (ASHPs).

The results of the survey underscore the necessity for more detailed economic evaluations, alongside improved dissemination of existing ones, to robustly demonstrate the economic viability and attractiveness of EGs.

3.2. Training and expertise barrier

Lack of expertise is an issue that is well grasped by all the respondents, regardless of the success of the project (23% of all answers as shown in Fig. 5a and b). Indeed, when asked specifically whether there is a need for training related to design and execution, 90% of the respondents highlighted this urgent need.

Effective dissemination of EGs technology within the broader construction industry necessitates raising awareness. Survey data show that 46% of respondents believe there are comprehensive and user-friendly tools to design energy piles, which are the most commonly implemented EGs. However, a significant proportion (24%) of respondents do not know whether such tools exist for energy piles, indicating a considerable knowledge gap. A further 30% of the respondents affirmed that no comprehensive and user-friendly tools are available.

In this survey, a total of 25 different software or packages were cited. Among them, COMSOL Multiphysics received the highest number of mentions (16 respondents mentioned it out of the 43 referring to a tool, i.e. 36%), especially from academics (10 respondents), likely due to its vast possibilities (thermo-hydro-mechanical coupling) suitable for research. PLAXIS, FEFLOW, PileSIM and FLAC were also suggested by multiple people (10, 9, 5 and 4 respondents, respectively, corresponding to 23%, 21%, 12% and 9%). Other tools were mentioned by 3 or less respondents, such as CESAR-LCPC, Abaqus and Thermopile. Some of the tools suggested specialize in the analysis of piles only (PileSIM, GeoPile, PIThER, and ThermoPile), which confirms that energy piles are the most recognized EGs. General modelling tools like COMSOL Multiphysics and Plaxis were often cited by respondents (especially PhDs and MSc), but these tools were sometimes classified as comprehensive and user-friendly tools and sometimes not, indicating a real subjectivity on the perception of these softwares. It should be noted that most of the respondents considering that software as easy and comprehensive are PhDs. It is acknowledged here that many of the tools mentioned above involving numerical modelling are biased by the survey sample and are rarely used in the design practice due to their costs and to the skills required.

Among the respondents, 58% of the people answering that such tools are available for energy piles were nonetheless unable to cite one. This shows that while there is a general belief that software or tools actually exist, only a small proportion of respondents are able to identify a specific tool. This gap reflects a lack of detailed knowledge in the field and underscores the need for broader communication to professionals regarding the existence of these tools and for university and professional training in general. The survey did not explicitly investigate the reasons for the potential underutilization of existing tools in practice; however, factors such as perceived complexity, software licensing costs, or a lack of specialized training in their application to EGs design could be contributing factors.

At this stage, it should be also acknowledged that the meaning of "comprehensive and user-friendly" terms in the question of the survey can be subjective. Actually, the most cited tool, COMSOL Multiphysics requires some skill in the use of FEM software. The fact that this software is more cited than simpler tools like GeoPile or ThermoPile may reflect that the design of energy piles is seen as a complex task or may mirror a bias in the sample demographic, that included many PhDs. Thermal load-transfer approaches for energy piles have been proposed for many years (Ravera et al., 2020), but practitioners still cite 3D FEM as the major tool. This misconception needs to be addressed in future training programmes. The above-mentioned observations concern only energy piles, and the survey did not provide significant results for other EGs (walls, slabs, etc.), meaning that the question of availability of design tools for them is even more of an issue.

Another potential issue is the lack of knowledge regarding the required input data and the specific investigations required for the design of EGs, reflecting once again the need for dissemination and training. However, it should be noted that over the past few years, initiatives have been taken to fill this gap by proposing new courses for different audiences. Among them, it is possible to mention continuing education programs for professionals and scientists, specific courses for Master students, courses for PhD students. Additionally, this subject is more and more addressed, albeit in less detail, in many general geotechnical-related courses.

3.3. Availability of guidelines and standards

Lack of relevant reference documents is an issue that is well identified by all the respondents, as stated before. Participants were asked to answer two questions regarding the existence of such documents related to the main types of EGs (piles, micropiles, tunnels, walls, and slabs). As shown in Fig. 6, a large majority of respondents either do not know about the availability of standards and guidelines or even affirm that they do not exist. This observation is valid for both design (Fig. 6a) and execution (Fig. 6b). Moreover, these percentages are higher for the execution of EGs. This can be partly explained by the fact that not all EGs projects are ultimately implemented, and also by the relative novelty of the technology, which results in a limited amount of feedback and professional experience.

Fig. 6 also highlights a difference between piles and other EGs. One of the main reasons may be that piles are the most common EGs, in agreement with the findings presented by Salciarini et al. (2026), and therefore are the EGs for which a development of a set of rules was most needed. Tunnels, walls, micropiles and slabs being more niche EGs, related standards and guidelines are still more scarce.

Currently, the European Union doesn't have a technical standard unique and valid for all the members, explaining why national guidelines or standards are needed for EGs.

The Swiss standard (SIA, 2005) has historically been a reference document for the comprehensive design and construction of energy piles. After this, other documents were published in different countries. A review of the available guidelines highlights a strong effort of standardization in Europe and North America, with indications of activity in Asia. Table 1 lists the available documents to the best knowledge of the Authors.

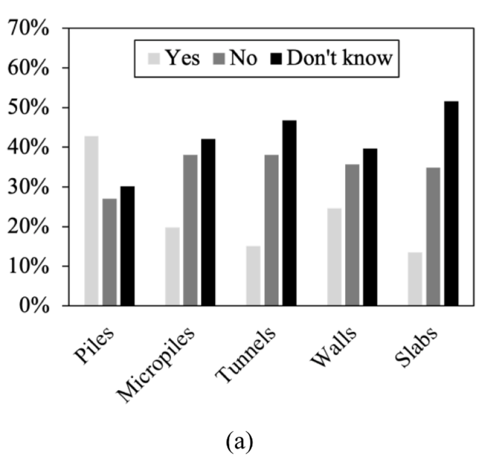
Other national documents exist that partially cover the scope of EGs and are not fully detailed, such as the handbook on energy piles in the Netherlands (TNO, 2003).

It is worth noting that even in the countries where these documents exist, most participants (71%) still reported that they are not aware of their existence. This can be explained by their relative novelty and the lack of dissemination and visibility of these publications, as well as by the lack of training.

The existing documents could be considered insufficient as they are not well harmonized, are heterogeneous in content, do not cover all types of EGs (mainly focusing on piles), and are sometimes mainly focused on groundwater or heating systems. Despite this, it is clear that the geotechnical community is striving to address these issues by producing new and more comprehensive documents, demonstrating a willingness to foster the large-scale spreading of EGs. To name some initiatives, the European Large Geotechnical Institutes Platform (ELGIP) has established an Energy Geostructures' Working Group, which is finalising recommendations for the conceptualisation, design, and construction of EGs. At the same time, the next version of Eurocode 7 will specifically address the design of EGs in one of its informative annexes.

3.4. Legal aspects related to EGs

The legal and regulatory landscape of EGs represents a complex intersection of civil engineering codes, environmental protection laws, and renewable energy directives. In the survey, there was no direct assessment of the participants' knowledge of the legal framework; however, the topic was indirectly addressed in two questions. One question asked whether respondents were aware of any legal requirement for implementing a monitoring system in their country. Over 50% answered “do not know”, while only 14% responded affirmatively, with these responses coming from a variety of countries. Legal issues also appeared in other questions, where participants involved in projects using EGs were asked to describe the challenges they encountered. Only 9% of the answers cited legal considerations as a reason for abandoning the adoption of EGs in the actual project (Fig. 5a). These findings suggest that legislation is not widely perceived as a significant barrier. One



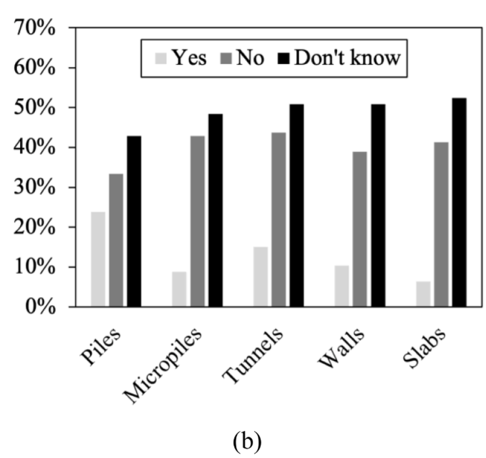


Fig. 6. Percentage of participants acknowledging the existence of comprehensive set of rules and regulations for (a) design and (b) execution of EGs.

Table 1
List of available standards and recommendations regarding thermo-mechanical design and execution of EGs.

Document reference	Document title	Year *	Country	Scope	Type of EGs
SIA (2005)	Utilisation de la chaleur du sol par des ouvrages de foundation et de soutènement en béton: guide pour la conception, la réalisation et la maintenance	2005	Switzerland	EGs	Piles
CFMS, SYNTEC Ingénierie, SOFFONS-FNTP (2017)	Recommandations pour la conception, le dimensionnement et la mise en œuvre des géostructures thermiques	2017	France	EGs	Piles, diaphragm walls, tunnels, slab
GSHPA (2017)	Thermal Pile Design, Installation & Materials Standards	2017	UK	EGs	Piles
Ministry of Housing and Urban-Rural Development of the People's Republic of China (2018)	Technical Standard for Utilization of Geothermal Energy through Piles	2018	China	EGs	Piles
VDI 4640 Part 2 (2019)	Thermal use of the underground. Ground source heat pump systems.	2019	Germany	Use of geothermal energy	Piles, diaphragm walls, tunnels, slabs
AGI (2025)	Raccomandazioni per la progettazione e realizzazione di geostrutture energetiche	2025	Italy	EGs	Piles, diaphragm walls, tunnels, slabs
CSA/ANSI/IGSHPA C448.9:25 (2025)	Design and installation of ground source heat pump systems connected to energy foundations	2025	Canada, USA	EGs	Foundations

* last publication year.

possible reason could be that existence of water protection laws, which limit the exploitation of groundwater and alteration of its temperature, is largely offset by the legal measures promoting eco-friendly buildings, potentially fostering the development of EGs.

Additionally, there is no unified international law or ISO standard specifically regulating EGs. In most countries, EGs are categorized under shallow geothermal energy or ground-source heat pump (GSHP) systems and are governed by civil engineering, geotechnical and environmental codes. Regulatory implementation remains delegated to individual states or ministerial decisions, leading to significant variability (Tsagarakis et al., 2020). Country-specific legislation and regulations also govern shallow geothermal energy. Each jurisdiction tends to apply different rules, creating legal uncertainty and uneven environmental protection. In the absence of a scientifically coherent and harmonized common base regulation, some national frameworks stand out internationally for their maturity and depth of experience with specific technologies (García-Gil et al., 2020; Stemmle et al., 2025). Although legal frameworks remain limited, EGs are increasingly recognized in academic literature and pilot projects, with numerous test sites operated by universities and industry consortia. In the United States, EGs fall under the scope of ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) standards and are subject to general building and environmental codes, particularly concerning groundwater protection and structural safety (Brancher and Steiner, 2024). As for China, EGs are not governed by a national law; instead, the Ministry of Housing and Urban-Rural Development published the standard cited in Table 1 for technical regulation, and this document is complemented by national policy directives promoting shallow geothermal use and by an increasing number of municipal-level geothermal resource management regulations.

Europe appears to be currently the most advanced region in terms of regulatory development for geothermal systems, even though there is no European directive that explicitly addresses all EGs (Tsagarakis et al., 2020; Aresti et al., 2024; Brancher and Steiner, 2024). EGs and shallow geothermal technologies for heating and cooling are initially addressed under the Renewable Energy Directive (EU) 2018/2001 (European Parliament and Council of the European Union, 2018), which was revised in 2023 as RED III (European Parliament and Council of the European Union, 2023). This updated directive sets mandatory targets for the share of renewables in heating and cooling, explicitly recognizing geothermal energy as a key contributor (Rosenow et al., 2025). Complementary legislation includes the Commission Delegated Regulation (EU) 2022/759 (European Commission, 2022), which defines the criteria for renewable cooling, including technologies such as geothermal heat pumps, and the Energy Performance of Buildings Directive (EPBD), updated in 2024 (European Parliament and the Council of the European Union, 2024). Additionally, the European Geothermal Energy Council (EGEC) has issued guidance aligned with environmental legislation, including the Water Framework Directive, the Environmental Impact Assessment (EIA) Directive, and the F-Gas Regulation, all intended to minimize environmental impacts and protect water resources. These legislative developments support broader EU strategies such as the European Green Deal and the REPowerEU plan (2022).

As explained in the previous paragraph, the EU members rely on national standards, and they are waiting for a harmonized one that supports EU legislation and covers deficiencies of national standards. The standardization process is critical for streamlining the "more-thorough" analysis required for EGs compared to conventional renewables. Ultimately, the regulatory constraints identified in this study can be synthesised into three challenges:

1. Procedural complexity: the overlapping of environmental and structural codes increases the administrative burden.
2. Innovation lag: static regulatory frameworks often struggle to accommodate the multipurpose nature of EGs, potentially slowing the transition toward the EU 2050 net-zero objectives.
3. Fragmentation: different national and regional regulations and environmental controls create legal uncertainty, and inefficient management of shallow geothermal resources

3.5. Miscellaneous aspects

Beyond economic and legal barriers, the survey identifies a secondary tier of impediments categorized as technical, organizational, and political. Overall technical issues are identified in 12% of the answers as the main challenge to the implementation of EGs, whether they were implemented or not. However, it is interesting to dissociate the answers, as the technical issues are noted for 15% of them for the successful EGs projects, but only in 9% of the unsuccessful ones. This suggests that technical hurdles are not definitive "deal-breakers"; rather, they are perceived as manageable engineering challenges that are addressed during the execution phase rather than serving as a primary cause for project termination.

Coordination of diverse contractors and coactivity also appear to be among the identified issues. Preparation and awareness are therefore key to the success of the project and the integrity of the geothermal system. There are many parties that will be interacting with the EG solution from design through to system operation. The data suggest that a lack of clearly defined roles and responsibilities across the project lifecycle remains a significant procedural bottleneck which has to be addressed at an early stage. It is also pointed out that appropriate early planning to permit necessary stakeholder engagement and accommodate the design and construction changes is key for successful EGs implementations (Barla and Insana, 2023; Barns et al., 2023).

Concerning political factors, a clear gap between successful and unsuccessful projects (5% vs 11% of the answers) is observed. This can be partly explained with the foreboding concerns existing in a preliminary design phase. Also, it should be noted that the importance of the project may have an impact on the role that politics plays in the project.

Two areas eliciting notably varied responses, indicative of potential misconceptions or a lack of definitive information, were EGs maintenance requirements and operational lifespan. One of the questions dealt with the typical maintenance frequency for EGs. The scattering of the answers suggests some confusion and uncertainty on such topic, which, however, is often raised by stakeholders when illustrating the concept of EGs. Most of the respondents reported that they do not know, while about one third of the answers suggested “annually”. A minority believes that maintenance should take place “biannually”. It is clear that since the pipes are embedded in the geostructure, they cannot be maintained and do not actually require maintenance, whereas the hydraulic connections may need inspection, as well as the heat pump. The user circuit is not taken into account in this analysis. Other specific answers were that an annual check is needed just on the glycol content, or that the check should be done every 2 years instead. Interestingly, one response distinguished the maintenance frequency based on the age of the plant, increasing the frequency from 3–4 to 1–2 years if the system was installed since more than 10 years. Additionally, few answers stated that no maintenance is required. The variety of answers demonstrates, once again, that return on experience from real installations and EGs guidelines specifically addressing maintenance would greatly help in clarifying such an aspect. Discussion between panellists in an international workshop organized at Politecnico di Torino (2025) highlights the facts that the usual inspection frequency is once a year, to check water/-antifreeze quality on site (freeze-point with refractometer, general fluid parameters such as acidity, hardness) and to perform one laboratory analysis (mainly bacteriological). The energy central (heat pump, pumps, sensors, valves etc.) requires some attention twice a year. A well-managed system needs very little maintenance and requires no full-time staff to operate the system as it is fully automated. Misconceptions regarding maintenance and control is a further consequence of the lack of knowledge and training, and may discourage adoption of this technology if it is perceived to involve a high maintenance effort.

Concerns and uncertainties regarding the operational lifespan of EGs also emerged from the survey data. For instance, among participants who indicated general familiarity with EGs, 25% still selected "do not know" when queried about their lifespan, and 11% expressed a belief that EGs have a shorter lifespan than conventional geostructures. These preconceptions and apprehensions may stem from the relative novelty of certain types of EGs (beyond well-established energy piles) and the current scarcity of installations with extensive, long-term performance records. This highlights the critical need for disseminating long-term performance data from successful and "mature" EGs installations. In principle, the geostructural component (piles, walls, slabs, tunnel linings) is designed for a protracted operational life (often 50–100+ years), analogous to conventional structures. The embedded heat exchanger pipework (typically HDPE) also exhibits a very long design life (50+ years) when properly installed and protected within the concrete or grout, shielded from UV radiation and mechanical damage. The effects of thermal cycling are explicitly considered in the design process to ensure they do not compromise structural integrity or the longevity of the pipe network. Therefore, the EGs themselves are engineered to endure for the design life of the overarching structure to which they belong. Ancillary components, such as heat pumps, will have a shorter service life typical of mechanical equipment (e.g., 15–25 years) and would be subject to periodic replacement as required.

4. Conclusions and pathway forward

This paper aimed to identify and critically analyse the barriers impeding the widespread adoption of EGs. By synthesising perspectives from an international panel of 155 practitioners and academics, the research confirms that, while technical maturity is largely established, a significant disconnect persists between theoretical potential and practical adoption, as its implementation remains significantly underdeveloped. Despite the geographical distribution of perspectives being predominantly concentrated in Europe, thereby potentially introducing a degree of regional bias, it is important to note that the current implementation of EGs is likewise largely concentrated in Europe, as discussed in Section 1. Accordingly, the distribution of respondents broadly reflects the present state of practice in the field. Additionally, having disseminated the survey through professional social network of individual people, an inherent selection bias is acknowledged, as respondents may share similar professional backgrounds, interests, or perspectives. This could result in an overrepresentation of specific disciplines (e.g., academic researchers or consulting engineers) and an underrepresentation of others (e.g., policymakers, contractors, or end users). Overall, however, the survey offers valuable insights into the perceptions and experiences of an engaged professional community, which is particularly relevant for understanding current trends and expert perspectives on energy geostructures.

The principal findings indicate that the primary obstacles are not predominantly technical. Instead, respondents identified the main key barriers as economic constraints and a lack of expertise, totaling 50% of the answers, as well as insufficient training and guidelines. The relative relevance of economic barriers decreases (from 31 to 23%) when considering implemented EGs projects, while the lack of expertise and training is perceived as a need in 23% of the answers regardless of the success of the project. More than half of the respondents are unaware of comprehensive and user-friendly design tools for energy piles and this proportion is even higher (between 74 and 86%) for other types of EGs, highlighting a clear knowledge gap. To strengthen this fact, 58% of the respondents answering that such tools are available for energy piles were nonetheless unable to cite one. In addition, most of the respondents either do not know about the availability of design/execution standards and guidelines or even affirm that they do not exist, especially for the execution of EGs and even in the countries where these documents actually exist. Legal issues were cited only in 9% of the answers as a reason for abandoning the adoption of EGs, suggesting that legislation is not widely perceived as a significant barrier. The data indicate that unclear roles and responsibilities across the project lifecycle can represent a procedural bottleneck to be addressed well in advance. A clear gap between successful and unsuccessful projects (5% vs 11% of responses) suggests that political factors play a more significant role due to concerns emerging during the preliminary design phase. Regarding maintenance and lifespan of EGs, the variety of answers demonstrates the critical need for return on experience from real installations, EGs guidelines specifically addressing maintenance and disseminating long-term performance data from successful EGs installations.

However, the study also highlights the fact that the number of EGs projects is steadily growing, proving that these barriers can be overcome. Furthermore, actions are being undertaken to address the lack of training, with multiple dedicated courses and continuing education being established. It is recommended that coordinated efforts between technical organizations of the industry, professional associations (for instance of ground source heat pump systems), and academia be strengthened to develop accessible, comprehensive training initiatives that integrate theoretical background, thermal design, structural design, constructive design and practical implementation including the coordination with the construction site, testing and commissioning. Information and resources related to EGs are presently highly fragmented across countries and should be centralized. This would allow to facilitate access to relevant courses and improve visibility and knowledge dissemination across the sector. At the same time, the geotechnical community is addressing the lack of guidelines by producing recommendations and standards on EGs design and implementation. Moreover, public policies are being established with the aim of promoting this solution by funding research and industry projects and by partially subsidizing geothermal systems. Nevertheless, EGs should be explicitly integrated into existing energy efficiency and heat pump subsidy schemes, with greater regulatory clarity to ensure their recognition alongside conventional geothermal solutions and to increase awareness among architects and project developers.

Therefore, it is clear that the level of societal engagement in the EGs field needs to be increased to enhance knowledge, confidence in the solution, and to help establish a secure regulatory framework. Policy advocacy is necessary to increase financial support opportunities from governments. An increase in public acceptance and civil society's understanding of the opportunities is also needed. Raising awareness and informing all types of stakeholders and contractors about the opportunities offered by EGs will be key if they are to play a significant role in climate change mitigation efforts and to increase their deployment.

CRediT authorship contribution statement

A. Insana: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **F. Szymkiewicz:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **E. Khamis:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **R. Da Re:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **B. Cao:** Writing – review & editing, Methodology, Investigation, Formal analysis, Conceptualization. **A. Gluchowski:** Writing – review & editing, Methodology, Investigation, Formal analysis, Conceptualization. **T. Badinier:** Writing – review & editing, Methodology, Investigation, Conceptualization. **J. de Sauvage:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Ö. Çinicioğlu:** Writing – review & editing, Methodology, Investigation, Conceptualization. **J. Josifovski:** Writing – review & editing, Methodology, Investigation, Conceptualization. **A. Minto:** Writing – review & editing, Methodology, Investigation, Conceptualization. **J. Pieczyńska-Kozłowska:** Writing – review & editing, Methodology, Investigation, Formal analysis, Conceptualization. **R. Vasilescu:** Writing – review & editing, Methodology, Investigation, Conceptualization. **H.J.L. Witte:** Writing – review & editing, Methodology, Investigation, Conceptualization. **H. Mroueh:** Writing – review & editing, Resources, Project administration, Methodology, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

All Authors reports travel was provided by COST Action FOLIAGE. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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