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A systematic review on shallow geothermal energy system: a light into six major barriers

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Review Article

Keywords
Shallow geothermal energy systems
Barriers of geothermal energy
Soil thermal conductivity
Building energy demand

Abstract
Shallow geothermal energy systems (SGES) are being widely recognized throughout the world in the era of renewable energy promotion. The world is aiming to promote and implement the concept of nearly zero energy consumption in the building sector. Shallow geothermal energy systems have huge potential to meet the heating and cooling demand of a building with low carbon emissions. However, the shallow geothermal system exploration rate and its global contribution to renewable energy used in the buildings sector is yet relatively low. Therefore, this study explores specific barriers which hinder the promotion of shallow geothermal energy systems through a systematic review of the literature. The study was carried out by investigating published papers indexed in Scopus and Web of science core collection databases. The selected papers are focused on shallow geothermal energy systems and barriers to their promotion. Only review and research articles types were included in the analysis and constrained to the topic of closed-loop shallow geothermal energy systems. This system's promotion has been influenced by the lack of legislation, little knowledge about the conductivity of soil and by high initial investment cost at its topmost. The least influencing barrier is considered to be the heating and cooling efficiency of shallow geothermal energy systems.

1. Introduction

For efficient cooling and heating of building's indoor environments, SGES offers a clean, lower carbon emission and renewable source of energy. These systems work with ground source heat pumps (GSHP) that are responsible to exchange heat between the ground and the building. The first GSHP was documented in 1945 (Sanner, 2016) and was applied in buildings. Since then, this system typology has been implemented and strongly disseminated in several countries. The evident benefits of direct use of GSHP for space heating and cooling, bathing, fish farms, industry and others are found earlier than 1995 (Freeston, 1996). The exploration of the energy of the surface ground layers has been increasing day by day due to its effectiveness and alternative source of energy for reducing the dependence on fossil energy as well as the building's decarbonization. The use of SGES in urban areas has resulted in an unprecedented boost of 9% market growth during the last decade (García-Gil et al., 2020).

The demand of energy for building heating and cooling has increased expeditiously and is expected to share the global energy consumption by 40% and about 30% of the share of total global carbon emission (Hughes et al., 2011; Yang et al., 2014). By the end of 2020, EU was motivated to achieve 20% of the final energy consumption from renewable sources for the building sector (Witte et al., 2002). Most of the European Union (EU) partners have achieved the target. By the end of 2030, the EU countries have agreed to the aim of attaining at least a 32% share of renewable energy in total energy consumption (EGEC, 2022).

Figure 1 illustrates the publication trend on SGES for heating and cooling purposes of the buildings per year published in the platform *ScienceDirect*. This shows that the published research papers on SGES started in 1995, began to grow visibly only after 2008 and experienced exponential growth after 2010 and nowadays the same tendency still flows.

Figure 2 shows the research on SGES by ten different countries published in *ScienceDirect.* These countries are among the top ten most involved in research on SGES according to their publications on the *ScienceDirect* platform. China is in the lead of the race for the research on SGES as well as the United States, followed by some European countries, that have also shown promising developments, namely the United Kingdom (Figueiredo et al., 2019). Until 2030 the EU has

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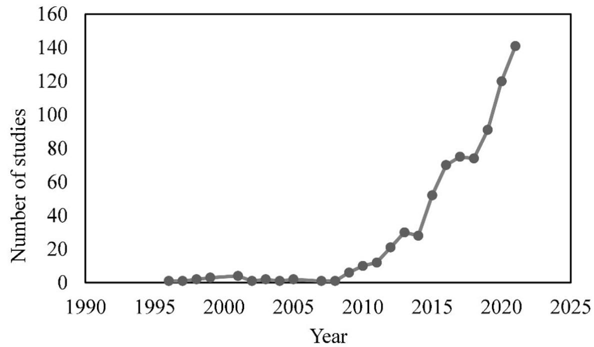

Figure 1. The number of research on the trend of using SGES for heating or cooling purposes on buildings published per year in ScienceDirect.

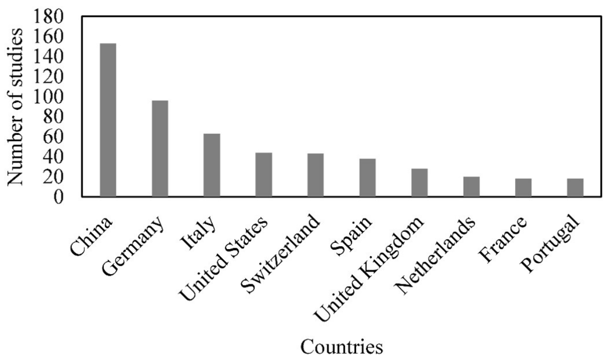

Figure 2. illustrates the research on SGES by ten different countries published in ScienceDirect.

set targets that newly built buildings should use very little conventional energy supply and that the building should be 'nearly Zero-Energy Building' or 'nZEB' (Florence et al., 2013). SGES may be one of the useful energy sources for reaching this target by fulfilling the heating and cooling energy demand of buildings on an urban scale (EGEC, 2022). However, some issues need to be overcome to speed up the development of SGES. Therefore, this paper intends to explore some barriers which might delay the promotion of shallow geothermal systems, to overcome these barriers and encourage the use of SGES which can play an important role to decarbonize carbon emissions from heating and cooling, currently using fossil fuels. Despite being a clean and mature technology that could be installed anywhere in the world, geothermal energy only covers around 2% of total renewable heating (EGEC, 2022). For example, in the case of China which has a huge potential for SGES (Zeng et al., 2021), only about 2.3% of the total potential has been explored to date (Wang et al., 2017).

The potential of using GSHP in Portugal is also significant, though the development of GSHP has not been found to a sufficient extent. Some pilot projects are started to install SGES like in Aveiro University where five buildings are currently equipped with GSHP. The implementation of GSHP in the district heating and cooling context is non-existent in Portugal. However, new studies regarding the SGES applications are essential to explore and extend its application to the district level to cope with the increasing energy demand for heating and cooling of buildings in the country (Nunes et al., 2019).

Table 1 illustrates recent European shallow geothermal energy projects aiming to promote SGES. There are several projects actively involved on the promotion of SGES namely geo trainet, geo power group and ground med etc. Energy use in heating and cooling until 2020 covered by the renewable energy sector in the EU countries has reached about 23.1%, compared to 11.7% in 2004 (European Commission, 2022). Compared to other renewable energy sources, SGES is barely visible in the market despite being sustainable, reliable, stable with no dependence on weather conditions, available near buildings and a renewable source with several advantageous features in comparison to other renewable energy sources (IRENA, 2017). The CO2 emission from any system is a primary concern of the world now to reduce the consequences of global warming. By the use of SGES, there is evidence of a 33% to 88% of reduction of CO2 emissions in comparison to the acclimatization of buildings by conventional heating systems (Saner et al., 2010). In this sense, there is a need to eradicate these barriers and make this technology gain competitiveness. This review will help to contribute to identify barriers that affect the acceleration of the promotion of SGES and will try to analyse the issues mentioned by other authors.

2. Materials and methods

2.1 Research methodology

This systematic search followed a strategy to identify relevant papers on the subject under study. The goal of this review is to explore and enlighten the major obstacles related to SGES indicated by several authors. The search of the literature was focused on the major issues with SGES rather than the general issues. On February 2022, the search strategy was implemented considering two databases; Scopus and Web of Science (WoS) core collection. The search was based on the *keywords* ("Shallow Geothermal Energy" OR "Shallow Geothermal System" OR "Shallow Geothermal Energy System") in all fields. The same searches were performed with Scopus and Web of science core collection databases in the Title, Abstract and Keyword fields. The result obtained were 542 and 191 respectively. The search was narrowed down by adding AND (barriers* OR issues* OR limitations* OR hurdles* OR challenges* OR constraints*) in the Title, Abstract and Keyword field in Scopus and Web of science core collection database. The (*) symbol is a wildcard which helps to increase the flexibility in the searches. This substitutes all possible characters searching

Table 1. Recent European shallow geothermal energy projects aiming to promote SGES.

Citation	Project	Aim	Project activities
Geo Power Group (2022)	Geo.Power	The project aimed to expand the knowledge and skills of SGES from the experienced market to the new market.	Replicating the knowledge and skills through training
GeoTrainet (2022)	Geotrainet	Not sufficiently available appropriately skilled personnel (designers and installers) is one of the barriers to SGES promotion. The project started with a qualified training course for SGES designers and developers, with the objective of capacity building for skilled personnel and the development of a common certification scheme.	-European Geothermal Workshop, France/ The geothermal congress DGK, Germany/Geo Power Global Congress, Turkey-2015. -Know RES geothermal career day, Germany/ Geo THERM, Germany/ International short course on step forward in SGES technology, France/-2016. - Shallow Geothermal Energy Days, Belgium-2019. -Test, Romania-2021
Ground Med (2022)	Ground-med	This project aims to develop cost-effective and attainable for both heating and cooling. Already has been installed series of heat pumps in southern Europe.	- Different field tests of contemporary GSHP were carried out by Fraunhofer ISE. -TERRA THERMA; To manage the residential temperature and terrestrial energy recovery using advanced Stirling heat pumps. -Thermo Map; project helps to develop the map potential of very shallow geothermal energy in Europe. -ASTECH; Provides upgraded Sustainable Technologies for Heating and Cooling Applications.
EGEC (2022)	Re-Geo Cities	The project developed the campaign called “Heat Under Your Feet” for the information and promotion of ground source heat pumps. The aim is to increase awareness in European cities about SGES among policymakers and decision-makers. This has proposed a set of simplified administrative procedures and an intelligence regulatory framework.	- With the motivation of promulgating information about GSHPs in EU, “The heat under your feet” is an ambition launched within the framework of the Re- Geo Cities project to promote their use-2015.

for one or more entries. After constraints 66 and 26 papers were found respectively. Moreover, the search was limited to English language final versions, published in ISI journal, final version only, review articles and research articles excluding conference articles or proceedings. The subject areas of mathematics, economics, agriculture, physics and material science were excluded. This gave the result of 29 in Scopus and 14 in the Web of science core collection. To maintain the quality of the review, all duplications were checked thoroughly using the excel command and 12 duplications found were not considered.

2.2 Screening and inclusiveness

The carried-out review was focused on shallow geothermal energy systems and barriers to their promotion. Therefore, the screening of the paper was performed by checking the abstract of the articles thoroughly for the analysis and refining of the articles which helps to ensure the quality and relevance of academic literature. Only papers dealing with vertical and horizontal closed- loop shallow geothermal energy systems were selected excluding open-loop SGES and deep geothermal systems. In addition, papers trying to explore the various barriers of SGES on promotion were selected. Papers focused on the mechanism of heat pumps, thermal imbalance of soil, groundwater pumps, open well systems, groundwater temperature, climate change impact, design of energy piles and design of heat pumps, were also excluded. The framework for the identification, screening and excluding process is shown in Figure 3.

The papers included in the detailed review were 24 from Scopus and Web of Science core collection. By assessing each article on the aforementioned inclusion and exclusion criteria, 7 papers were excluded. Hence, the review was completely confined to issues with SGES exploration for heating and cooling purposes. Particularly, while reviewing the papers, the focus was given to the identification of the barriers to SGES from a global to a regional perspective.

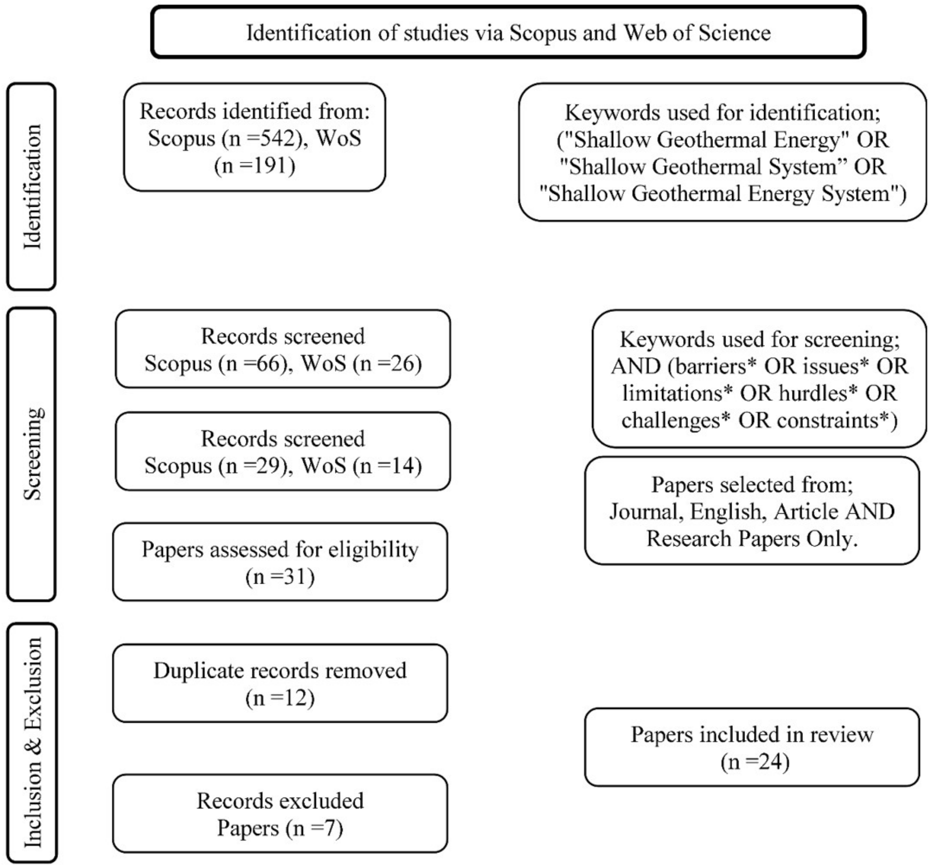

Figure 3. Flow diagram for literature search and filtering research process.

3. Results and discussion

3.1 Definition of barriers in SGES

The term barrier refers to an obstacle or hindrance to progress. SGES are widely considered a highly potential renewable source of energy to cope with future heating and cooling demands which utilize and help to store heat beneath the ground and helps to reduce greenhouse gas emission in the building sector (Cherati & Ghasemi-Fare, 2021). As mentioned before, the progress on the rate of growth in the exploration of this useful energy source is not happening as expected (Tsagarakis, 2020). Any type of hurdles that arose for the progress of propagation of SGES are barriers that should be overcome. Technical, economical, legislative or public awareness are barriers all considered for the analysis, while the mechanical design and operation hurdles in its features are not.

3.2 Identified barriers in SGES

An in-depth review of the papers was performed, specifically focusing on the barriers of SGES. In this sense, six main barriers to the promotion of SGES were identified and are illustrated in Figure 4. A total of 13 papers dealing with the issue of less knowledge on soil thermal conductivity (STC) were found. While the second most discussed issue in literature was related to legislation with 12 papers dealing with this topic. The third main issue detected in the review was that of the initial investment cost, 8 papers dealt with it. Predominantly the papers were indicating the costly nature of system installation. Since SGES is a newer technology that evolved from other existing renewable energy in the

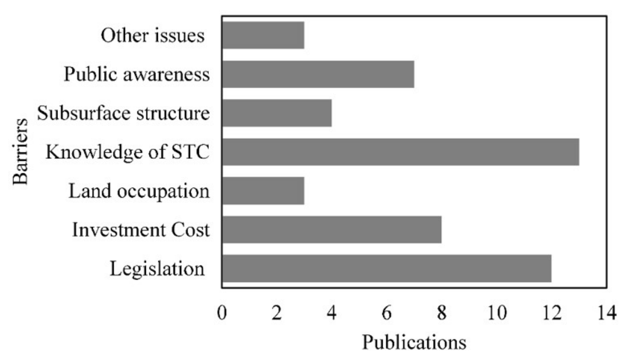

Figure 4. Comparison of the publication numbers with identified barriers on consulted papers.

market, public awareness was also found to be an issue of discussion. For instance, the technology is not familiar among energy consumers and even among technicians. The issue regarding public awareness raised by the authors was found in 7 papers. Papers dealing with an issue regarding subsurface structure were 4 and 3 papers dealt with land occupation. Whereas 3 papers were dealing with heating and cooling efficiency issues and the complex nature of the SGES issues. In summarizing, the majority of papers were raising the issue of little knowledge on the conductivity of underground materials, legislation and initial investment costs. In contrast, the least discussed issue was focused on the topic of land occupation and other issues.

3.2.1 Little knowledge on the thermal conductivity of underground materials

Issues related to little knowledge of STC where SGES are embedded are the most discussed by the authors in this review. A total of 26% of the reviewed papers highlighted the mentioned issue. Revision of the selected papers was done and extracted information on the main view of the authors about STC is presented in Table 2, which eases to compare the views of authors in mentioned issue. The ground thermal conductivity is an important site parameter (Cecinato & Salciarini, 2022) and one of the most influential factors for SGES design (Hoekstra et al., 2020b; Li et al., 2019; Ondreka et al., 2007). This physical property can be measured either by laboratory or in-situ tests (Witte et al., 2002). The high-energy performance of SGES is directly related to the ground thermal conductivity among other site-dependent factors (Cecinato & Salciarini, 2022; Cherati & Ghasemi-Fare, 2021; Ondreka et al., 2007). According to Fourier's law, thermal conductivity is the coefficient of proportionality between temperature gradient and the corresponding heat flux. It can be affected by factors like soil water content, density, composition and mineral properties (Nowamooz et al., 2016). Hence, to determine the potential of the SGES, the ground thermal conductivity must be explored and carefully measured to assess its suitability of SGES (Cecinato & Salciarini, 2022; Cherati & Ghasemi-Fare, 2021; Tinti et al., 2016). Quartz and Dolomite materials present a high thermal conductivity (Cetin et al., 2020; Tinti et al., 2016). This means that soils or rocks with a high percentage of those minerals have greater potential for higher heat extraction rates, which results in better thermal efficiency of SGES. On the other hand, marlstone and siltstones have relatively low thermal conductivity (Cetin et al., 2020; Tinti et al., 2016) hence, low potential for SGES. The thermal conductivity of rocks and soils also shows spatial variability (Janža et al., 2017).

Rocks classification beneath the ground (Tinti et al., 2016) and the degree of saturation of soil (Vieira et al., 2019) determine the potential for heat extraction for SGES. Therefore, rock classification and degree of saturation might be different according to location and that would be the deciding factor for the design and implementation of SGES (Schelenz et al., 2017). Stegnar et. al. (2019) studied the thermal conductivity of different rocks and soils by measuring average values collected from different boreholes.

Summing up, the difficulties in the characterization of the STC with different degrees of soil saturation and porosities create a barrier to the design and implementation of SGES

Table 2. Main views expressed by authors on the issue with knowledge of STC.

Reference	Views of authors on the issue with little knowledge on the conductivity of soil
Cecinato & Salciarini (2022)	Soil conductivity is of predominant importance in SGES installation efficiency.
Hoekstra et al. (2020a)	STC has huge influence in SGES potential.
Assouline et al. (2019)	Measurement of soil thermal property should be determined before extracting heat from the ground.
Zeng et al. (2021)	The heat transfer rate of SGES is unsatisfactory until the STC is determined properly.
Cherati & Ghasemi-Fare (2021)	To get energy from the earth for the long term, soil thermal properties are the most important parameter for determining the potential of shallow geothermal.
Stegnar et al. (2019)	Among the several parameters, the main parameter governing SGES potential is the STC of the ground.
Li et al. (2019)	Almost accurate measurement and estimation of STC are necessary for SGES design and implementation.
Tinti et al. (2018)	There is a spatial and temporal variation in the ground temperature at shallow depths of the earth due to the different properties of the rocks and soils.
Janža et al. (2017)	Efficient and sustainable extraction of ground heat requires proper knowledge of rock and soil types and their thermal characteristics.
Somogyi et al. (2017a)	The SGES system must be designed by considering the properties of soil and its stratification beneath the surface.
Tinti et al. (2016)	A regional variation in STC is mostly in wide intervals.
Ondreka et al. (2007)	The potential of SGES is related to the rock's classification beneath the ground and heat extraction mainly relies on underground STC.
Cetin et al. (2020)	STC is a key parameter for the quantification of the energy efficiency of SGES.

(Zhang et al., 2021). Aljundi et al. (2020) performed a series of thermal conductivity tests in a laboratory using a thermal needle probe under dry and saturation conditions. The result shows that the thermal conductivity was significantly higher in a fully saturated condition than in a dry condition. In the study developed by Aljundi et al. (2020), the field where the borehole heat exchanger installation takes place is composed of soil with variability in-depth, as well as water content and groundwater velocity. This variability cannot exactly be reproduced along the boreholes deep, and thus, leads to a high level of uncertainty on a small-scale. This is a barrier to the design of the SGES as well as a limitation of knowledge in the design phase. A proper evaluation of STC before the design of SGES is thus essential for a proper heat transfer analysis (Aljundi et al., 2020). Consequently, the lack of knowledge on the ground thermal properties where SGES will be embedded could be a barrier to the SGES implementation. To implement the SGES installation and its promotion, a thorough analysis of the ground thermal properties of the soil layers is necessary. The thermal properties of the soil depend on the different factors that made characterizing and mapping the GSHP potential all over the country a challenging task (Assouline et al., 2019).

3.2.2 Legislation

Figure 5 illustrates that the legislation was the second most discussed issue, among the most highlighted issues by the authors during the review. In this case, 24% of the total reviewed papers discussed the legislation issue in SGES. SGES has been studied and applied worldwide over the past 20 years (Zeng et al., 2021), however, it is observed that the legislation issues were highlighted by papers published only after 2015 (see Figure 6). Zeng et. al. (2021) considered that beyond 2015 was a prosperous stage for the execution of SGES. From the literature, it was observed that 8% of the paper published in 2015, 2017 and 2018 discussed legislation barriers to SGES. Furthermore, the majority of papers published in 2019, 42% of them, mention this issue.

Table 3 shows that there is high diversity in the legislation governing the use of SGES. Haehnlein et. al. (2010) summarized several country's laws concerning the use of SGES, which also shows the huge diversity of the laws among the nations. However, more recently the EU published seven directives regarding SGES to simplify and standardize the procedure among its members. Still, the issue persists because the national regulations are diversified. The issue of legislation persists as in many countries the administrative process for obtaining a license or permit to implement the SGES, should go through the approval of more than one department (Zeng et al., 2021). For instance, the complicated system of administration involved as the process goes through the department of land and resources, environmental protection, construction, municipal administration and power in China, resulting in a long time for the approval process.

On the other side, SGES are relatively new and evolving technology, thus, several countries are trying to improve their legislation procedures to ease the installation of SGES. Whereas some countries legislation makes no mention of SGES development (non-existence) (Tsagarakis et al., 2020; Zeng et al., 2021).

According to Tsagarakis et. al. (2020) failure to establish good guidelines, bringing homogeneity and simplification in the legislation for permitting SGES design and implementation are the key drivers that hinder the promotion of SGES. Changes in the legislation to licensing procedure eventually make the licensing process more complicated (Somogyi et al., 2017a).

Table 4 shows that most of the authors are highlighting that there are issues in legislation, legal framework, laws and regulations. The main views about legislation issues in several countries detected by the authors are highlighted.

There are uncertainties, versatilities, imperfections and the diverse nature of legislation, which hinders the propagation of SGES to meet expectations. Only one article was found that mentioned there are few constraints relating to the ground and subsurface laws and policies (Assouline et al., 2019). However, the study shows that many countries are evolving towards the

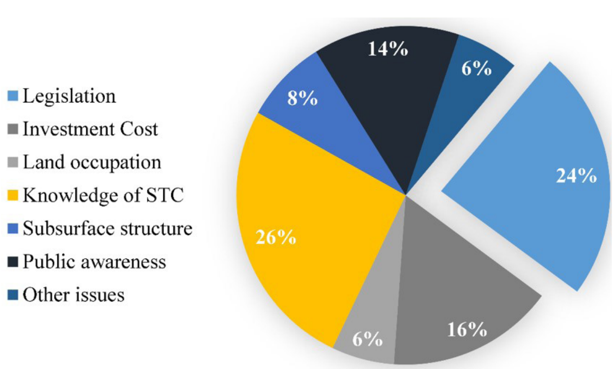

Figure 5. Relative distribution of legislation issue on SGES in percentage.

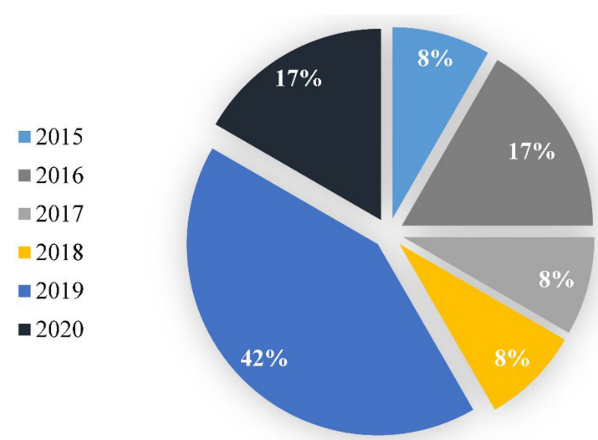

Figure 6. Temporal relative distribution of legislation issue on SGES.

Table 3. Identification of legislation concerning the use of SGES among several countries.

Reference	Country	Laws concerning the use of SGES
Somogyi et al. (2017a)	UK	Groundwater investigation consent- Environmental Agency
Zeng et al. (2021)	China	National Energy Administration (NEA), Ministry of Finance (MOF), Ministry of Land and Resources (MLR) and Ministry of Housing and Urban-Rural Development (MOHURD)
Cetin et al. (2020)	Turkey	The national expert group on SGES, Annex-27, and Heat production from renewable energy has not been regulated.
Somogyi et al. (2017a)	France	Mining Authority, GWHP, Water authority, Environmental agency
Zeng et al. (2021) Somogyi et al. (2017a)	Sweden	Normbrunn Guidelines, Geological Survey of Sweden (SGU) and Research Institute of Sweden (RISE), GWHP- Water operation permit, Local council
Zeng et al. (2021) Somogyi et al. (2017a)	Germany	Geological Survey of the respective state, VDI 4640 guideline series, Water authority
Somogyi et al., 2017a)	Italy	According to provincial provision, (UNI 11466-68:2012) guidelines series
(Somogyi et al. (2017a)	Spain	Mining Authorities, Water Authorities
Ryżyński & Bogusz (2016)	Poland	Geological and mining law, Construction law, Theoretically the existing law doesn't prevent the use of SGES
Somogyi et al. (2017a), Tinti et al. (2016)	EU	Directive 2009/28/EC (7 directives)
Tinti et al. (2016)	Adriatic Area	Do not fall within the laws directing SGES in most Adriatic countries

Table 4. Main views by authors on issues regarding legislation.

Reference	Main views of authors on Issues with Legislation
Zeng et al. (2021)	Incompetent laws and regulations (SGES without scientific planning and legal permits)
Somogyi et al. (2017a)	Wavering nature of licensing procedure
Assouline et al. (2019)	Coercion relating to the ground and subsurface laws and policies
Tinti et al. (2016)	Uncertainties regarding the legal framework regulating
Ryżyński & Bogusz (2016)	Lack of proper regulations isa major inhibiting factor for the use of this technology
Christodoulides et al. (2020)	Lack of systematic design guidelines of SGES.
Cetin et al., 2020)	Heat production from renewable energy has not been regulated.
García-Gil et al. (2015)	The diverse international legal status for the use of SGES created an uncertain situation.
Cherati & Ghasemi-Fare (2021)	Lack of detailed regulations on the exploration of SGES.

modifications of the legislative procedures to some extent for the promotion of SGES (Zeng et al., 2021). Moreover, some countries do not have regulations regarding SGES.

Legislation is a vital factor for the development of SGES, as it regulates, guides, promotes or hinders the total process from beginning to end. In most countries, the involvement of various authorities in the authorization process of SGES, for instance, geological and mining law, water authority, environmental agency, construction law, etc. makes the process very complicated, which might be a discouraging factor for the investor, designer and contractor. The lack of recommendations/technical standards for thermoactive geostructures in most countries is also a barrier to the use of SGES. A common regulatory framework among the countries and simple authorization procedures will surely help to overcome this barrier to the promotion of SGES.

3.2.3 Initial investment cost

Table 5 refers to the highlighted views of the authors from selected papers concerning the initial investment cost of SGES. Issues related to the initial investment cost were discussed in 16% of the selected papers. Cherati & Ghasemi-Fare (2021) indicated in their paper that the price of fossil fuels in middle-east countries like Iran is very low as they have reservoirs of fossil fuels and therefore, they have very easy access to non-renewable energy.

The cost associated with the design and installation for the exploration of SGES is quite high compared to conventional energy in middle east countries. That leads to less concern for the government in its promotion and less public interest in it (Cherati & Ghasemi-Fare, 2021). Additionally, the issuance of SGES permits is expensive in some countries which made the initial investment cost of SGES higher than other energy sources (Hoekstra et al., 2020a). Another aspect is related to the viability of drilling the boreholes for heat exchangers which depends on the hardness of the subsurface geological formations. This site-specific nature of the SGES brings uncertainties to the cost of the installation (Schelenz et al., 2017). Hence this may cause a proportionally high construction cost during implementation (Tsagarakis, 2020).

Table 5. Main views of authors regarding the initial investment cost of SGES.

Reference	Main views of authors about the initial investment issue
Baralis & Barla (2021)	The high initial investment cost is generally showing the shortcoming of the SGSES.
Zeng et al. (2021)	The most notable difficulty in SGES promotion is the high initial investment cost with an average payback period of approximately 4.31 years (Cui et al., 2018) and capital price should be regulated lower to promote SGES.
Cherati & Ghasemi-Fare (2021)	SGES system remains with high initial investment costs for example, drilling and installation costs. Which restricts the popularity of propagation of SGES.
Hoekstra et al. (2020a)	Commencing costs emerge much higher in SGES in comparison to other renewable energy systems. For instance, the installation cost on average for hydropower is USD 1870/Kw, Bio-energy is USD 2543/Kw and Geothermal is USD 4486/Kw in 2020 (IRENA, 2020).
Tsagarakis (2020)	The soaring construction and operational cost of SGES during the enactment stage is due to its site-specific characteristics.
Assouline et al. (2019)	On the contrary, the installation costs will be low with easy operation and maintenance costs that made SGES a manageable resource. Having soil on the shallow depth mostly at depths of 1–2 m with a high value of thermal conductivity, SGES installed in the uppermost 10 m of the ground, the cost will be low.
Stegnar et al. (2019)	The cost of drilling for the vertical borehole and GSHP is quite high which hinders the propagation of SGES in the proper amounts.
Tinti et al. (2016)	Hybrid solutions and buffer tanks of SGES can help to receive ideal economic issues. More than one building may be connected to the same geothermal system, thereby increasing buffer tank cost-effectiveness and lowering the installation cost.

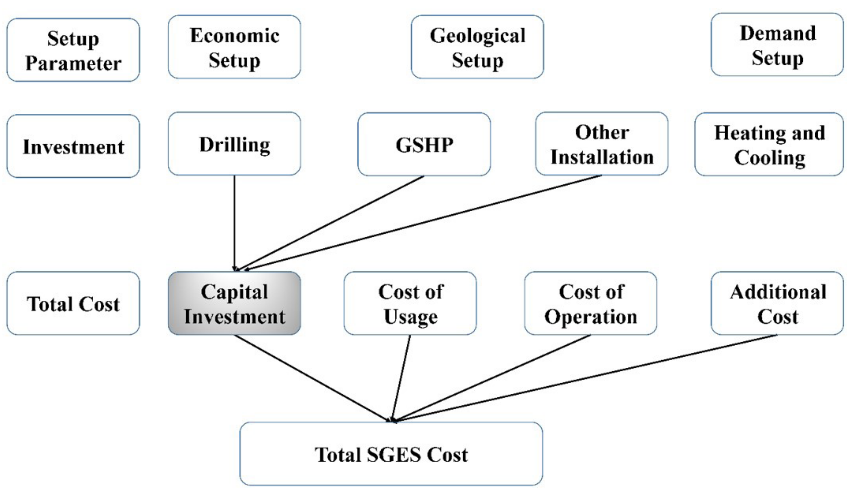

Figure 7. The cost structure of geothermal heat generation, adapted from the source (NEA, 2015) National Energy Authority, amended 2014.

As shown in Figure 7, the investment cost (capital investment) belongs to the cost of drilling, GSHP and other installations. Since the drilling cost of SGES is more than other associated costs for operation and management, the initial investment cost comes high (NEA, 2015; Ramos-Escudero et al., 2021). In the drilling process, is included cost of tubing as well as grouting and piping. In this sense, the cost can cover up to 60% of the total price of the system upfront (Gemelli et al., 2011). The reason behind the low impact of SGES in the renewable energy market is its relatively high initial investment cost (installation cost) which is the obstacle to SGES promotion (Müller et al., 2018).

Despite having low carbon emission and sustainable nature, exploration and utilisation of SGES are not enough as it has to be in several countries because of its high cost of installation and cost of a heat pump. Hence, this results in a non-substantial contribution to the reduction of greenhouse gas (Stegnar et al., 2019). A single SGES could be applied to double or multiple buildings, improving the energy efficiency of the group with lower installation costs associated (Tinti et al., 2016). On contrary, Assouline et al. (2019) mentioned that the SGES system has a low cost of installation and easy maintenance.

The cost will be low where the highest value of thermal conductivity is found and very shallow geothermal installed in up to 10 m of the depth, and generally at depths of 1–2 m. Even though SGES has huge potential to meet the future demand for heating and cooling of buildings, it might not be affordable to every individual who wants to install SGES due to its high installation cost. The focus of future studies should take into account the need to reduce the initial investment cost and increase energy efficiency. The SGES should be designed in such a way by reducing as much as possible the initial investment cost and lowering the payback period to encourage investors and end users to its promotion.

Governmental subsidy policies for the installation of SGES may help to raise the willingness of individuals towards using SGES. The value added tax (VAT) and other associated tax reductions in the equipment purchase and fee reduction on the license would be a good option for the promotion of SGES (Tinti et al., 2016). The investment cost is one of the crucial parameters along with other environmental parameters to the investors, government and individuals for the decision-making process of SGES. Further research regarding the use of SGES in hybrid systems, in combination with other renewable energy sources like solar energy and bioenergy may improve the efficiency and sustainability of the systems. Additionally, the use of SGES through structural elements in contact with the ground, such as retaining walls, pile foundations and tunnel linings (thermoactive geostructures) can be used as heat exchangers (Cherati & Ghasemi-Fare, 2021). When this combination is observed (SGES integrated in the structural elements), the extra costs observed in boreholes for example, were minimized, helping not to burden extra costs for the construction of infrastructures related to these systems. Furthermore, Sterpi et al. (2020) referred that there are improvements in the heat exchange rate due to the introduction of thermoactive geostructures, turning the system more efficient by reducing both costs of installation and exploration. SGES have the potential to reduce 65-85% of CO2 emissions when compared to other fossil fuel systems (Ahmed et al., 2022). The cost associated with the reduction of CO2 emissions by the use of SGES should be taken into account, that is a real concern of the world today (Hakkaki-Fard et al., 2015). The cost of CO2 emission is more than just a monetary value and should be taken into consideration for the sustainable design of SGES.

3.2.4 Public awareness

Public awareness was also identified in the selected papers as one of the major obstacles to the promotion of SGES. The retrieved information is in a table format highlighting the main view of the authors about the issues related to awareness (see Table 6).

Issues related to public awareness were raised in 15% of the reviewed papers. Although SGES is recognized as an emerging technology for building heating and cooling to reduce carbon emissions, the concept of SGES was introduced only in 1969 and propagated around Europe after the 1980s (Zeng et al., 2021). However, technology has begun to spread around the world at the beginning of the 21st century (Eugster & Rybach, 2000).

As the SGES system is new compared to other clean energy sources, the degree of acceptability by society is relatively low (European Commission, 2014). The majority of the population is still dependent on fossil fuels and the projected scarcity of this non-renewable energy is not realized by the people that create the detrimental effects of using conventional energy (Cherati & Ghasemi-Fare, 2021). Additionally, most governments also did not put much effort into publicity, to achieve public acceptance of SGES (Zeng et al., 2021). The social factors and stakeholders' perceptions of SGES may affect the penetration of SGES widely (Tsagarakis, 2020). A small step towards legislation and procedural framework has been taken by some countries like Finland, Sweden and Germany (Tsagarakis et al., 2020). Besides that, the dissemination of information about SGES, its benefits and steps taken by governments for the promotion of SGES is essential for the fast development of SGES (Tsagarakis et al., 2020). According to Tinti et al. (2016),

Table 6. presentation of main views of authors about the awareness issue.

Reference	Main views of authors about awareness issue
Zeng et al. (2021)	The degree of societal approval is low.
Cherati & Ghasemi-Fare, 2021)	Society has not recognised the benefits of SGES due to a lack of awareness.
Hoekstra et al. (2020a)	Still short of expertise to design, construct and maintain the system. Also having inadequate analytical tools and cost data to assess the techno-economic potential of SGES.
Tsagarakis (2020)	Stakeholders' awareness and societal rejection issues may affect the propagation of the sustainable energy sector.
Tsagarakis et al. (2020)	To move forward on the effective development of SGES, an increase in awareness among the public and stakeholders is required.
Somogyi et al. (2017b)	The definition of SGES is different according to country. An information-sharing network among the countries to establish a common legal framework is required.
Tinti et al. (2016)	Training and up-skilling of technicians, contractors and engineers are necessary. The lack of specific knowledge and information about SGES is one of the hindrances to public acceptance.

not only the local authorities but also the technicians and engineers who recommend the SGES to their clients should be trained and upskilled. The lack of specific information and knowledge on what SGES can offer is a major drawback for the exploration of SGES.

It is interesting to know that in some countries like in the middle-east ones, where the price of the fossil fuel is low enough and freely available, the main obstacle to SGES is the social rejection of the new technology (Cherati & Ghasemi-Fare, 2021). Thus, the government could not create a sufficient environment to understand the benefits of clean energy like SGES to the public.

Moreover, the lack of locally available expertise to design, install and maintain SGES might hinder the installation plan. A lack of local expertise creates an environment that should rely on external experts and designers (Tinti et al., 2016). This may also create mistrust in the system when the system is not managed accurately. Pająk et al. (2016), also mentioned in their study that information campaigns are essential to increase awareness about the feasibility of SGES.

Though SGES is continuously available 24 hours per day, having enormous potential to provide reliable and sustainable energy for heating and cooling, this energy is not recognised by the public easily. For the geothermal sector, public perception and awareness about SGES is always a crucial element that the public is not as informed of what SGES has to contribute, compared to other renewable energy sources. Communication between the contractor, engineer, government, investor and public is paramount to obtain a good relationship among them to speed up the promotion of SGES. The governments should take the initiative to make people aware of the contribution of SGES to a sustainable environment. Awareness of the political decision-makers of this novel technology is also required (Goetzl et al., 2020).

3.2.5 Land availability

Only 6% of the reviewed papers addressed the land availability topic. However, land availability is a fundamental parameter that should be considered during SGES planning. In large and dense cities, where the value of land has rocketed high and limited free space is available, SGES with horizontal loop systems is undesirable (Tsagarakis, 2020), as they take significantly more space than SGES mainly composed of vertical borehole heat exchangers (Somogyi et al., 2017a).

The scarcity of land in the cities for the installation of SGES is a challenging task (Baralis & Barla, 2021) and must be taken into consideration. The land required for SGES installation varies according to the country's legislation (Tsagarakis et al., 2020). The drilling and trenches excavation for SGES may have some limitations to the legislation provisions (Stegnar et al., 2019). For instance, Greek law states that the excavation of trenches should be 2m away from the neighbouring property line, 10m away from gas distribution pipelines and 5m away from water and sewerage lines (Tsagarakis et al., 2020). In turn, the Swiss standard recommends a minimum distance of 5m between energy piles to reduce the thermal interference among the energy piles and in consequence a variation of performance in terms of energy (Miglani et al., 2018). These types of provisions in the legislation demand a larger space requirement than the exact trench size.

Povilanskas et. al. (2013) mentioned that the landowner not only owns the land but also the space above and below the land in the city area that made the land expensive (Tsagarakis et al., 2020), which hinders the installation planning of SGES (Povilanskas et al., 2013). In horizontal loop systems, the pipes are laid horizontally at very shallow depths (1.5 to 2 m) because of the horizontal nature the space required is more than in other systems (Sarbu & Sebarchievici, 2014). Zhong et. al (2022) examined the thermal interference between piles, in fact, the larger the spacing of the piles the more reduced the thermal interference, which results in better heat performance (Zhong et al., 2022). This means, the installation of vertical borehole energy piles also demands space for installation. In a highly dense city area where the space availability is very low, installation of vertical boreholes is also difficult.

For vertical borehole systems, the minimum land requirement is 20 m^2 and for horizontal loop systems is 150 m^2 (FROnT, 2019). The land requirement might be affected by different factors like the geology of the land, demand for heat, the efficiency of heat pumps, etc. The extra land requirement for the installation can be reduced by installing a vertical borehole system within the foundation of the building during the construction of the building foundation. Accordingly, to overcome this barrier, combining energy piles with the structural elements of the infrastructures which are in connection with the ground like diaphragm walls, pile foundations and tunnel linings as a thermoactive geostructure help to reduce the extra land required for the construction of infrastructures related with SGES (Haehnlein et al., 2010).

3.2.6 Subsurface structures

One common barrier to the development of SGES is related to the unfamiliarity with the subsurface conditions (Hoekstra et al., 2020a). Issues related to subsurface structures were discussed in 6% of the reviewed papers. It is not easy to predict the situations beneath the ground (Pellegrini et al., 2019) since the cities have developed various networks of services beneath the ground over the years. Subsurface structures create significant barriers to the planning of SGES which has a negative impact on the licensing or authorization phase (Pellegrini et al., 2019). This barrier persists during the design phase and monitoring period also (Tsagarakis et al., 2020). The presence of a drinking water pipe network, sewer pipe network, and high voltage transmission system under the ground could be an important barrier to the drilling and installation of SGES. The different countries have their own rule regarding the drilling distance from other structures or infrastructure (Somogyi et al., 2017a). Underground car parks, city metro lines and tunnel localization in the city area may affect the installation of vertical loop SGES (Ryżyński & Bogusz, 2016).

The presence of infrastructure networks and other structures present beneath the ground makes drilling difficult (Bertermann et al., 2018), which raises the cost of installation (Iba et al., 2018; Somogyi et al., 2017b). This affects the selection of SGES in that area. The process of subsurface data obtaining is often a difficult task that may create uncertainties about the exact subsurface geological conditions (Makasis et al., 2021).

3.2.7 Other barriers

The review identified that 4% of papers raised other issues which could potentially hinder the implementation of SGES like the complexity in application of the SGES (Tinti et al., 2016; Zeng et al., 2021) and 2% of papers mentioned the heating cooling efficiency of the systems (Zeng et al., 2021). According to Tinti et al. (2016) when the building needs energy application is different between thermal zones (not in the whole building or floor), this will bring complexity as the SGES system should be connected to the centralised heating system. This could also be a hindrance factor to the propagation of SGES to a massive extent. Zeng et al. (2021) mentioned the issue of low heat transfer rate (low heating and cooling efficiency). The heating and cooling rates are sometimes unsatisfactory and should be optimised by combining with additional types of renewable energy systems.

In addition, the lack of knowledge on the long-term performance of SGES makes the investors and end users rethink the decision to invest. Continuous extraction of heat from the ground may cause the cooling of the ground and unexpected disturbances on the system with a negative effect on the sustainability of SGES (Miglani et al., 2018). As a consequence, the balance between the heating and the cooling building demands will be affected (Cunha & Bourne-Webb, 2022).

In the case of buildings or spaces with an unbalanced demand, the thermal behaviour of the ground affects more significantly the evolution in time of the whole building's energy performance. This represents another key decision factor actuating as a barrier to the installation of SGES. Consequently, another hybrid system should be adopted to meet the unbalanced demand and influence the overall interest in using SGES due to the increased costs of having a hybrid system.

4. Conclusions

This paper presents the main barriers to the implementation of shallow geothermal energy systems (SGES) identified through a systematic review of scientific papers published in Scopus and Web of Science (WoS) core collection. The review of the literature concerns rigorous information regarding the barriers to shallow geothermal energy systems implementation. There are six main and some other general decelerating factors for the promotion of SGES identified. Almost all studies show that there is still a low rate of contribution of SGES in the renewable energy sector. However, it is recognized that there is a huge potential to extract heat from the ground to meet the growing demand for heating and cooling sustainably. In addition, the majority of the papers raised issues of the legislation as a barrier that needs to be solved. Standardization of the framework governing the SGES exploration is a common issue among nations. In the same way, the majority of papers mentioned the high initial investment cost for the installation of SGES, which is also an aspect of public concern. Moreover, issues with little knowledge of the thermal conductivity of underground materials, availability of land, subsurface structure and awareness of the public are the main hindrance factors to the promotion of SGES discussed in the papers. The focus on the identification of the barriers permits establishing and planning decisive action measures to overcome these hurdles and move forward and support the exploration of shallow geothermal energy systems.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Rajendra Babu Roka: conceptualisation, methodology, visualization, writing – original draft. António José Pereira de Figueiredo: conceptualisation, methodology, writing – review & editing, supervision. Ana Maria Carvalho Pinheiro Vieira: writing – review & editing, supervision. José Claudino de Pinho Cardoso: writing – review & editing, supervision.

Data availability

The authors declare that all data generated or analysed during this study appear in the published article.

References

Ahmed, A.A., Assadi, M., Kalantar, A., Sliwa, T., & Sapińska-śliwa, A. (2022). A critical review on the use of shallow geothermal energy systems for heating and cooling purposes. *Energies*, 15(12), 4281. http://dx.doi.org/10.3390/en15124281.

Aljundi, K., Vieira, A., Maranha, J., Lapa, J., & Cardoso, R. (2020). Effects of temperature, test duration and heat flux in thermal conductivity measurements under transient conditions in dry and fully saturated states. E3S Web of Conferences, 195, 04007. http://dx.doi.org/10.1051/e3sconf/202019504007.

Assouline, D., Mohajeri, N., Gudmundsson, A., & Scartezzini, J.-L. (2019). A machine learning approach for mapping the very shallow theoretical geothermal potential. *Geothermal Energy*, 7(1), 19. http://dx.doi.org/10.1186/s40517-019-0135-6.

Baralis, M., & Barla, M. (2021). Development and testing of a novel geothermal wall system. *International Journal of Energy and Environmental Engineering*, 12(4), 689-704. http://dx.doi.org/10.1007/s40095-021-00407-y.

Bertermann, D., Bernardi, A., Pockelé, L., Galgaro, A., Cultrera, M., de Carli, M., & Müller, J. (2018). European project "Cheap-GSHPs": installation and monitoring of newly designed helicoidal ground source heat exchanger on the German test site. *Environmental Earth Sciences*, 77(5), 180. http://dx.doi.org/10.1007/s12665-018-7343-4.

Cecinato, F., & Salciarini, D. (2022). Energy performance assessment of thermo-active micro-piles via numerical modeling and statistical analysis. *Geomechanics for Energy and the Environment*, 29, 100268. http://dx.doi.org/10.1016/j.gete.2021.100268.

Cetin, A., Kadioglu, Y.K., & Paksoy, H. (2020). Underground thermal heat storage and ground source heat pump activities in Turkey. *Solar Energy*, 200, 22-28. http://dx.doi.org/10.1016/j.solener.2018.12.055.

Cherati, D.Y., & Ghasemi-Fare, O. (2021). Practical approaches for implementation of energy piles in Iran based on the lessons learned from the developed countries experiences. *Renewable & Sustainable Energy Reviews*, 140, 110748. http://dx.doi.org/10.1016/j.rser.2021.110748.

Christodoulides, P., Vieira, A., Lenart, S., Maranha, J., Vidmar, G., Popov, R., Georgiev, A., Aresti, L., & Florides, G. (2020). Reviewing the modeling aspects and practices of shallow geothermal energy systems. *Energies*, 13(16), 4273.

Cui, Y., Zhu, J., & Meng, F. (2018). Techno-economic evaluation of multiple energy piles for a ground-coupled heat pump system. *Energy Conversion and Management*, 178, 200-216. http://dx.doi.org/10.1016/j.enconman.2018.10.042.

Cunha, R.P., & Bourne-Webb, P.J. (2022). A critical review on the current knowledge of geothermal energy piles to sustainably climatize buildings. *Renewable & Sustainable Energy Reviews*, 158, 112072. http://dx.doi.org/10.1016/j.rser.2022.112072.

Eugster, W., & Rybach, L. (2000). Sustainable production from borehole heat exchanger systems. In *Proceedings World Geothermal Congress 2000* (pp. 825-830), Tohoku, Japan. Retrieved in February 3, 2022, from http://www.geothermal-energy.org/pdf/IGAstandard/WGC/2000/R0103.PDF

European Commission (2014). *Guide to cost-benefit analysis of investment projects: economic appraisal tool for cohesion policy 2014-2020.* Luxembourg: Office of the European Union.

European Commission. Eurostat. Statistics Explained. (2022). *Renewable energy statistics.* Retrieved in June 8, 2022, from https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Renewable_energy_statistics#Over_one_fifth_of_energy_used_for_heating_and_cooling_from_renewable_sources

European Geothermal Energy Council – EGEC. (2022). *Regeocities.* Retrieved in February 3, 2022, from https://www.egec.org/research-projects/regeocities/

Figueiredo, A., Lapa, J., Cardoso, C., Macedo, J., Rodrigues, F., Vieira, A., Pinto, A., & Maranha, J.R. (2019). Shallow geothermal systems for Aveiro University departments: a survey through the energy efficiency and thermal comfort. In H. Sigursteinsson, S. Erlingsson & B. Bessason (Eds.), *17th European Conference on Soil Mechanics and Geotechnical Engineering* (pp. 1-8). Reykjavík, Iceland: The Icelandic Geotechnical Society. https://doi.org/10.32075/17ECSMGE-2019-0583.

Florence, J., Angelino, L., Annunziata, E., van Beek, D., Benson, J., Bezelgues, S., Croufer, M., Cucueteanu, D., Cuevas, J., Frey, M., Godschalk, B., Goumas, A., Jardeby, Å., Nielsen, A.M., Pasquali, R., Poux, A., Räftegård, O., Rizzi, F., & Sanner, B. (2013). *Overview of shallow geothermal legislation in Europe. D2.2 General report of the current situation of the regulative framework for the SGE systems*. Retrieved in October 22, 2022, from http://regeocities.eu/wp-content/uploads/2012/12/D2.2.pdf

Freeston, D.H. (1996). Direct uses of geothermal energy 1995. *Geothermics*, 25(2), 189-214. http://dx.doi.org/10.1016/0375-6505(95)00051-8.

FROnT. (2019). *Geothermal heat pumps: the heat under your feet* (pp. 1-2). European Union.

García-Gil, A., Goetzl, G., Kłonowski, M.R., Borovic, S., Boon, D.P., Abesser, C., Janza, M., Herms, I., Petitclerc, E., Erlström, M., Holecek, J., Hunter, T., Vandeweijer, V.P., Cernak, R., Mejías Moreno, M., & Epting, J. (2020). Governance of shallow geothermal energy resources. *Energy Policy*, 138, 111283. http://dx.doi.org/10.1016/j.enpol.2020.111283.

García-Gil, A., Vázquez-Suñe, E., Schneider, E.G., Sánchez-Navarro, J.Á., & Mateo-Lázaro, J. (2015). Relaxation factor for geothermal use development: criteria for a more fair and sustainable geothermal use of shallow energy resources. *Geothermics*, 56, 128-137. http://dx.doi.org/10.1016/j.geothermics.2015.04.003.

Gemelli, A., Mancini, A., & Longhi, S. (2011). GIS-based energy-economic model of low temperature geothermal resources: a case study in the Italian Marche region. *Renewable Energy*, 36(9), 2474-2483. http://dx.doi.org/10.1016/j.renene.2011.02.014.

Geo Power Group. (2022). *About us.* Retrieved in February 3, 2022, from https://www.geopowergroup.com/about-us/

GeoTrainet. (2022). *About GeoTrainet.* Retrieved in February 3, 2022, from https://geotrainet.eu/about-geotrainet/

Goetzl, G., Dilger, G., Grimm, R., Hofmann, K., Holecek, J., Cernak, R., Janza, M., Kozdrój, W., Kłonowski, M., Hajto, M., Gabriel, P., & Gregorin, S. (2020). Strategies for fostering the use of shallow geothermal energy for heating and cooling in Central Europe: results from the Interreg Central Europe Project GeoPLASMA-CE. In *Proceedings World Geothermal Congress 2020*, Reykjavik, Iceland. http://dx.doi.org/10.6084/m9.figshare.13256465.

Ground Med. (2022). *Project summary.* Retrieved in February 3, 2022, from http://groundmed.eu/about_ground_med/

Haehnlein, S., Bayer, P., & Blum, P. (2010). International legal status of the use of shallow geothermal energy. *Renewable & Sustainable Energy Reviews*, 14(9), 2611-2625.

Hakkaki-Fard, A., Eslami-Nejad, P., Aidoun, Z., & Ouzzane, M. (2015). A techno-economic comparison of a direct expansion ground-source and an air-source heat pump system in Canadian cold climates. *Energy*, 87, 49-59. http://dx.doi.org/10.1016/j.energy.2015.04.093.

Hoekstra, N., Pellegrini, M., Bloemendal, M., Spaak, G., Andreu Gallego, A., Rodriguez Comins, J., Grotenhuis, T., Picone, S., Murrell, A.J., Steeman, H.J., Verrone, A., Doornenbal, P., Christophersen, M., Bennedsen, L., Henssen, M., Moinier, S., & Saccani, C. (2020a). Increasing market opportunities for renewable energy technologies with innovations in aquifer thermal energy storage. *The Science of the Total Environment*, 709, 136142. http://dx.doi.org/10.1016/j.scitotenv.2019.136142.

Hoekstra, N., Pellegrini, M., Bloemendal, M., Spaak, G., Andreu Gallego, A., Rodriguez Comins, J., Grotenhuis, T., Picone, S., Murrell, A.J., Steeman, H.J., Verrone, A., Doornenbal, P., Christophersen, M., Bennedsen, L., Henssen, M., Moinier, S., & Saccani, C. (2020b). Increasing market opportunities for renewable energy technologies with innovations in aquifer thermal energy storage. *The Science of the Total Environment*, 709, 136142. http://dx.doi.org/10.1016/j.scitotenv.2019.136142.

Hughes, B.R., Chaudhry, H.N., & Ghani, S.A. (2011). A review of sustainable cooling technologies in buildings. *Renewable & Sustainable Energy Reviews*, 15(6), 3112-3120. http://dx.doi.org/10.1016/j.rser.2011.03.032.

Iba, C., Takano, S., & Hokoi, S. (2018). An experiment on heat recovery performance improvements in well-water heat-pump systems for a traditional Japanese house. *Energies*, 11(5), 1023. http://dx.doi.org/10.3390/en11051023.

International Renewable Energy Agency – IRENA. (2017). *Renewable energy in district heating and cooling: a sector roadmap for REmap*. Abu Dhabi: IRENA.

International Renewable Energy Agency – IRENA. (2020). *Renewable power generation costs in 2020.* Retrieved in February 3, 2022, from https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Jan/IRENA_2017_Power_Costs_2018.pdf

Janža, M., Lapanje, A., Šram, D., Rajver, D., & Novak, M. (2017). Research of the geological and geothermal conditions for the assessment of the shallow geothermal potential in the area of Ljubljana, Slovenia. *Geologija*, 60(2), 309-327. http://dx.doi.org/10.5474/geologija.2017.022.

Li, M., Zhang, L., & Liu, G. (2019). Estimation of thermal properties of soil and backfilling material from thermal response tests (TRTs) for exploiting shallow geothermal energy: sensitivity, identifiability, and uncertainty. *Renewable Energy*, 132, 1263-1270. http://dx.doi.org/10.1016/j.renene.2018.09.022.

Makasis, N., Kreitmair, M.J., Bidarmaghz, A., Farr, G.J., Scheidegger, J.M., & Choudhary, R. (2021). Impact of simplifications on numerical modelling of the shallow subsurface at city-scale and implications for shallow geothermal potential. *The Science of the Total Environment*, 791, 148236. http://dx.doi.org/10.1016/j.scitotenv.2021.148236.

Miglani, S., Orehounig, K., & Carmeliet, J. (2018). A methodology to calculate long-term shallow geothermal energy potential for an urban neighbourhood. *Energy and Building*, 159, 462-473. http://dx.doi.org/10.1016/j.enbuild.2017.10.100.

Müller, J., Galgaro, A., Dalla Santa, G., Cultrera, M., Karytsas, C., Mendrinos, D., Pera, S., Perego, R., O'Neill, N., Pasquali, R., Vercruysse, J., Rossi, L., Bernardi, A., & Bertermann, D. (2018). Generalized pan-european geological database for shallow geothermal installations. *Geosciences*, 8(1), 32. http://dx.doi.org/10.3390/geosciences8010032.

National Energy Authority – NEA. (2015). *Geothermal policy options and instruments for the Andean region: based on Icelandic and International Geothermal Experience.* Iceland.

Nowamooz, H., Nikoosokhan, S., & Chazallon, C. (2016). Seasonal thermal energy storage in shallow geothermal systems: thermal equilibrium stage. *E3S Web of Conferences*, 9, 07003. https://doi.org/10.1051/E3SCONF/20160907003.

Nunes, J.C., Coelho, L., Carvalho, J.M., Do, M., Carvalho, R., & Garcia, J. (2019). Geothermal Energy Use, Country Update for Portugal. In *European Geothermal Congress 2019* (pp. 11-14), Den Haag, The Netherlands.

Ondreka, J., Rüsgen, M.I., Stober, I., & Czurda, K. (2007). GIS-supported mapping of shallow geothermal potential of representative areas in south-western Germany-Possibilities and limitations. *Renewable Energy*, 32(13), 2186-2200. http://dx.doi.org/10.1016/j.renene.2006.11.009.

Pająk, L., Kępińska, B., Kasztelewicz, A., Bujakowski, W., Tomaszewska, B., & Grażyna, H. (2016). Some factors detrmining the geothermal energy uses' development in the Central and Eastern European countries in coming years. *Zeszyty Naukowe*, 92, 337-358. Retrieved in October 22, 2022, from https://meeri.eu/Wydawnictwa/ZN92/pajak-i-inni.pdf

Pellegrini, M., Bianchini, A., Guzzini, A., & Saccani, C. (2019). Classification through analytic hierarchy process of the barriers in the revamping of traditional district heating networks into low temperature district heating: an Italian case study. *International Journal of Sustainable Energy Planning and Management*, 20, 51-66. http://dx.doi.org/10.5278/ijsepm.2019.20.5.

Povilanskas, R., Satkūnas, J., & Jurkus, E. (2013). Conditions for deep geothermal energy utilisation in southwest Latvia:

nīca case study. *Baltica*, 26(2), 193-200. http://dx.doi.org/10.5200/baltica.2013.26.20.

Ramos-Escudero, A., García-Cascales, M.S., & Urchueguía, J.F. (2021). Evaluation of the shallow geothermal potential for heating and cooling and its integration in the socioeconomic environment: a case study in the region of murcia, spain. *Energies*, 14(18), 5740. http://dx.doi.org/10.3390/en14185740.

Ryżyński, G., & Bogusz, W. (2016). City-scale perspective for thermoactive structures in Warsaw. *Environmental Geotechnics*, 3(4), 280-290. http://dx.doi.org/10.1680/jenge.15.00031.

Saner, D., Juraske, R., Kübert, M., Blum, P., Hellweg, S., & Bayer, P. (2010). Is it only CO2 that matters? A life cycle perspective on shallow geothermal systems. *Renewable & Sustainable Energy Reviews*, 14(7), 1798-1813. http://dx.doi.org/10.1016/j.rser.2010.04.002.

Sanner, B. (2016). Shallow geothermal energy-history, development, current status, and future prospects. In *European Geothermal Congress* (pp. 19-24), Strasbourg, France.

Sarbu, I., & Sebarchievici, C. (2014). General review of ground-source heat pump systems for heating and cooling of buildings. *Energy and Building*, 70, 441-454. http://dx.doi.org/10.1016/j.enbuild.2013.11.068.

Schelenz, S., Vienken, T., Shao, H., Firmbach, L., & Dietrich, P. (2017). On the importance of a coordinated site characterization for the sustainable intensive thermal use of the shallow subsurface in urban areas: a case study. *Environmental Earth Sciences*, 76(2), 73.

Somogyi, V., Sebestyén, V., & Nagy, G. (2017a). Scientific achievements and regulation of shallow geothermal systems in six European countries: a review. *Renewable & Sustainable Energy Reviews*, 68, 934-952. http://dx.doi.org/10.1016/j.rser.2016.02.014.

Somogyi, V., Sebestyén, V., & Nagy, G. (2017b). Scientific achievements and regulation of shallow geothermal systems in six European countries: a review. *Renewable & Sustainable Energy Reviews*, 68, 934-952. http://dx.doi.org/10.1016/j.rser.2016.02.014.

Stegnar, G., Staničić, D., Česen, M., Čižman, J., Pestotnik, S., Prestor, J., Urbančič, A., & Merše, S. (2019). A framework for assessing the technical and economic potential of shallow geothermal energy in individual and district heating systems: a case study of Slovenia. *Energy*, 180, 405-420. http://dx.doi.org/10.1016/j.energy.2019.05.121.

Sterpi, D., Tomaselli, G., & Angelotti, A. (2020). Energy performance of ground heat exchangers embedded in diaphragm walls: field observations and optimization by numerical modelling. *Renewable Energy*, 147, 2748-2760. https://doi.org/10.1016/J.RENENE.2018.11.102.

Tinti, F., Carri, A., Kasmaee, S., Valletta, A., Segalini, A., Bonduà, S., & Bortolotti, V. (2018). Ground temperature monitoring for a coaxial geothermal heat exchangers field: practical aspects and main issues from the first year of measurements. *Rudarsko-Geološko-Naftni Zbornik*, 33(5), 47-57. http://dx.doi.org/10.17794/rgn.2018.5.5.

Tinti, F., Pangallo, A., Berneschi, M., Tosoni, D., Rajver, D., Pestotnik, S., Jovanović, D., Rudinica, T., Jelisić, S., Zlokapa, B., Raimondi, A., Tollari, F., Zamagni, A., Chiavetta, C., Collins, J., Chieco, M., Mercurio, A., Marcellini, F., Mrvaljević, D., & Meggiolaro, M. (2016). How to boost shallow geothermal energy exploitation in the adriatic area: the LEGEND project experience. *Energy Policy*, 92, 190-204. http://dx.doi.org/10.1016/j.enpol.2016.01.041.

Tsagarakis, K.P. (2020). Shallow geothermal energy under the microscope: Social, economic, and institutional aspects. *Renewable Energy*, 147, 2801-2808. http://dx.doi.org/10.1016/j.renene.2019.01.004.

Tsagarakis, K.P., Efthymiou, L., Michopoulos, A., Mavragani, A., Anđelković, A.S., Antolini, F., Bacic, M., Bajare, D., Baralis, M., Bogusz, W., Burlon, S., Figueira, J., Genç, M.S., Javed, S., Jurelionis, A., Koca, K., Ryżyński, G., Urchueguia, J.F., & Žlender, B. (2020). A review of the legal framework in shallow geothermal energy in selected European countries: need for guidelines. *Renewable Energy*, 147, 2556-2571. http://dx.doi.org/10.1016/j.renene.2018.10.007.

Vieira, A., Maranha, J.R., Lapa, J., & Figueiredo, A. (2019). Some aspects of measurement of sand thermal conductivity from laboratory tests. In *Proceedings of the XVII ECSMGE-2019*, Reykjavík, Iceland. http://dx.doi.org/10.32075/17ECSMGE-2019-0541.

Wang, G.L., Zhang, W., Liang, J.Y., Lin, W.J., Liu, Z.M., & Wang, W.L. (2017). Evaluation of geothermal resources potential in China. *Acta Geoscientica Sinica*, 38(4), 449-459. http://dx.doi.org/10.3975/CAGSB.2017.04.02.

Witte, H.J.L., Van Gelder, G.J., & Spitler, J.D. (2002). In situ measurement of ground thermal conductivity: a dutch perspective. *ASHRAE Transactions*, 108(Pt 1), 263-272.

Yang, L., Yan, H., & Lam, J.C. (2014). Thermal comfort and building energy consumption implications: a review. *Applied Energy*, 115, 164-173. http://dx.doi.org/10.1016/j.apenergy.2013.10.062.

Zeng, S., Yan, Z., & Yang, J. (2021). Review and forecast of ground heat exchangers development: a bibliometric analysis from 2001 to 2020. *Sustainable Energy Technologies and Assessments*, 47, 101547. http://dx.doi.org/10.1016/j.seta.2021.101547.

Zhang, W., Bai, R., Xu, X., & Liu, W. (2021). An evaluation of soil thermal conductivity models based on the porosity and degree of saturation and a proposal of a new improved model. *International Communications in Heat and Mass Transfer*, 129, 105738. http://dx.doi.org/10.1016/j.icheatmasstransfer.2021.105738.

Zhong, Y., Narsilio, G.A., Makasis, N., & Scott, C. (2022). Experimental and numerical studies on an energy piled wall: the effect of thermally activated pile spacing. *Geomechanics for Energy and the Environment*, 29, 100276. http://dx.doi.org/10.1016/j.gete.2021.100276.