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Development of advanced materials guided by numerical simulations to improve performance and cost-efficiency of borehole heat exchangers (BHEs)☆

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A R T I C L E I N F O

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A B S T R A C T

One promising way to improve the efficiency of borehole heat exchangers (BHEs) in shallow geothermal applications is to enhance the thermal properties of the materials involved in its construction. Early attempts, such as using metal tubes in the 1980s or the utilization of thin—foil hoses, did not succeed in being adopted by the market for diverse reasons (cost, corrosion, fragility, etc…). In parallel, the optimization of pipe size, the use of double-U-tubes, thermally enhanced grout, etc. were able to bring the measure for the BHE efficiency, the borehole thermal resistance, from 0.20 to 0.15 $K/(Wm)$ down to 0.08 −0.06 $K/(Wm)$ in the best solutions today. A further improvement cannot be expected without development of new, dedicated materials, combining the versatility of plastic like PE with an increased thermal conductivity that matches the respective properties of the rock and soil. This goal was included in the Strategic Research and Innovation Agenda of the European Technology Platform on Renewable Heating and Cooling in 2013.

Within an EU supported project, both BHE pipes and grouting materials have been produced prototypically in small amounts, suitable for the first tests in the intended environment.

The present work explains the research pathways envisaged and the resulting sensitivity analysis to highlight the influence of some of the most critical parameters that affect the overall performance of a GSHP system. The results have allowed guiding the real development of more efficient new advanced materials for different scenarios representative of different European regions. Finally the developed materials and their properties are discussed, including a comparative assessment about their compliance with reference material properties as currently seen in the BHE market.

1. Introduction

Shallow geothermal energy systems, comprising Ground Source Heat Pumps (GSHPs) and Underground Thermal Energy Storage (UTES) [1], are being exploited as a stable, reliable and renewable energy source for all types of buildings (including nearly zero energy buildings [2]), district heating networks [3] or solar assisted systems [4]. Implementing it on a large scale, though, presents some setbacks, given the high initial capital required compared to

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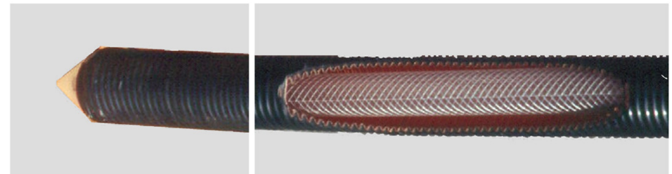
other alternatives such as gas or other fossil fuels, low consciousness, and lack or changing standards.

In this paper, the methodology and results of a sensitivity analysis performed in simulated scenarios are presented, in the framework of the European project GEOCOND. This H2020 research project aims at overcoming different challenges, especially cost reduction, increase in efficiency, reliability and security, longer lifetime, better environmental friendliness and increased acceptance. This sensitivity analysis is aimed at understanding and demonstrating the potential impact that the optimization of new materials may trigger in real installations. It is shown how the combination of optimized products (pipes and grouting materials), adapted to the geological setting and specific locations, can trigger significant reductions in the total length of the installations by reducing drastically the effective borehole thermal resistance. This optimization assessment has further been used in the development of real products that will be tested and evaluated in real environments and installations. In Section 4, the finally developed materials and products are described in comparison with some of the most representative standard reference materials, such as PE100 and well-known grouting formulations. As well, other mechanical and rheological properties are discussed that have been taken into account throughout the product development stages.

2. State of the art

The history of ground source heat pumps has recently been summarized in Ref. [5]. The first idea to use the ground as a source for a heat pump was published already in 1912 in a patent filed by Heinrich Zoelly. He envisaged a closed system, where the heat transfer fluid is circulated in pipes in the underground; the patent shows a helicoidal heat exchanger in a large-diameter hole (Fig. 1a). The first practical application of a ground heat exchanger recorded in literature was in 1945 in Indianapolis, USA, using horizontal pipes in the ground (3 circuits totalling 152 m) to supply heat to a compressor with 2.2 kW electric power input [6]. This was a direct-expansion system, i.e. the refrigerant of the heat pump circuit circulated directly in the buried heat exchanger pipes. Only two years later, a paper [7] presented a collection of ground-coupling

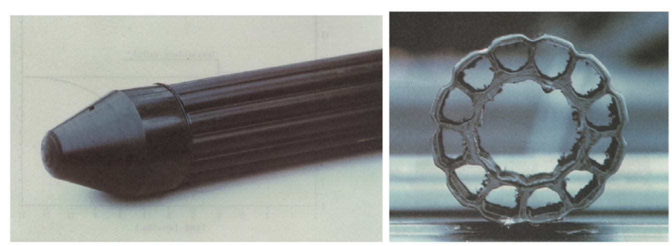


(a) (b)

Fig. 2. Footpiece (a) and cut-out section (b) of coaxial BHE as tested in Schwalbach GSHP research station [11], consisting of corrugated metal outer tube (usually stainless steel, but copper in this sample for exhibitions), protected against corrosion by a PE-coating.

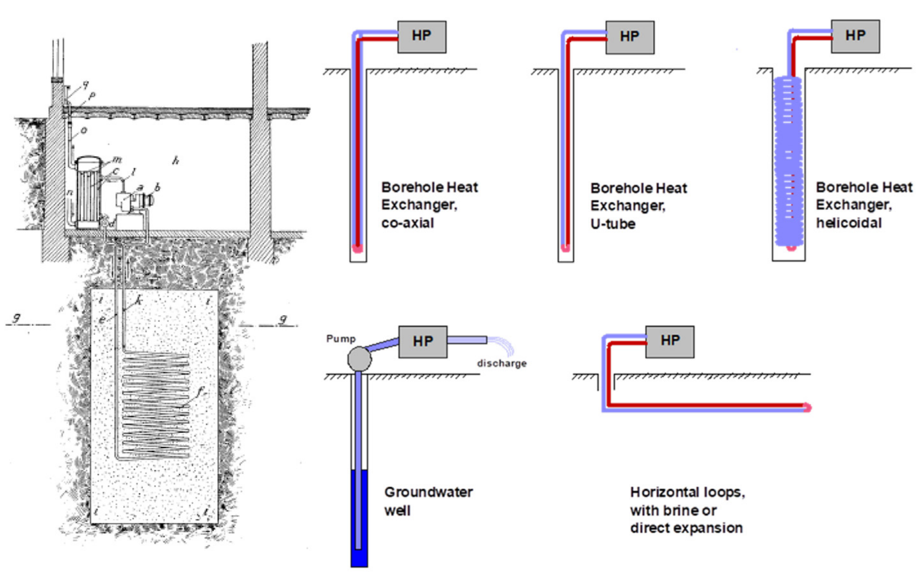
technologies available at that time, among them three types of borehole heat exchangers (Fig. 1b); they comprise the basic geometries to which the BHE in use today can be ascribed to, i.e. coaxial, U-tube and helicoidal ("spiral")

The concern for increasing heat exchange efficiency in ground heat exchangers was soon addressed. The first German BHE installation in 1974 [9] used steel tubes, and attempts then were made to combine the advantage of high thermal conductivity of metal with a continuous pipe that can be coiled and does not need the connection of individual, rigid tubes. A German company brochure [10] shows photos of drilling and installation for a coaxial



(a) (b)

Fig. 3. Footpiece (a) and cross-section (b) of coaxial BHE used formerly in Switzerland, made of PE with multi-chamber outer channel for turbulent flow and increased heat exchange (photos from Ref. [12]).



(a) (b)

Fig. 1. At left (**a**)Ground Source Heat Pump in Swiss Patent 59350 of 1912 (inventor H. Zoelly); at the right (**b**) Ground-coupling methods listed by Ref. [7], re-drawn and harmonized as in [8].

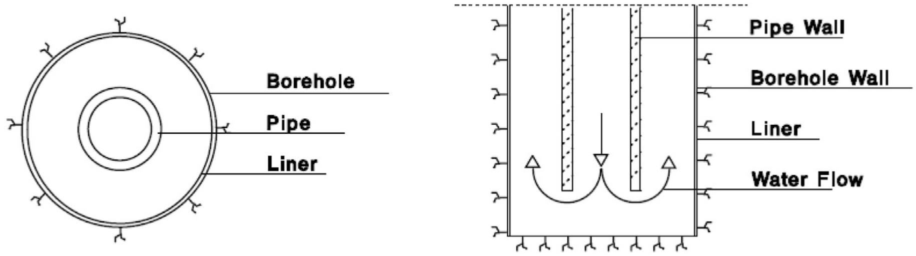


Fig. 4. Coaxial BHE in open borehole (with or without liner, depending on rock quality) as used in Luleå BTES, constructed 1982/83 (graph from Ref. [13]).

BHE, made from corrugated stainless steel for the outer pipe, and a rubber hose for the inner pipe. This design was improved by another company (Helmut Hund GmbH) using a thin PE-coating extruded under vacuum to the outer pipe wall, in order to provide corrosion protection with as little temperature drop as possible (Fig. 2). In Switzerland, where Double-U-BHE made from PE are the norm since the early 1980s, an improved coaxial design (Fig. 3) was successfully tested and used for some years. Alas, the higher cost of the bespoke extrusion compared to standard PE-pipes in U-tube designs were not set off by the better performance, at least not at that time.

The most efficient BHE of the 1980/90s probably was a type of coaxial BHE used e.g. in a BTES-experiment in Luleå in Northern Sweden [13], where the borehole wall in solid rock provided the outer boundary and only an inner pipe had to be inserted (Fig. 4). This technology of course only works in very stable rocks and with water as heat carrier fluid, that can be in exchange with groundwater in fissures and fractures. This technology thus has not found much replication, and experiments with hoses made of plastic foil used to tighten the borehole walls ("liner" in Fig. 4) in another Swedish BTES in Anneberg near Stockholm [14] in 2002 were not quite successful.

2.1. State-of-the-art in materials for pipes

After the early period of experimentation with various metal and plastic materials, and with the emergence of factory-made BHE coils on the market in the late 1980s, high-density polyethylene (HDPE) became the preferred material for decades. The main advantages were cost, easy handling incl. welding, and longevity.

A list of the pipe materials recommended for use with BHE (Table 1) is indicated in the draft version of the new edition of guideline VDI 4640-2,[1] published in May 2015.

Metallic pipes for BHEs have been considered since long because of the significantly higher thermal conductivity compared to the plastic pipes and have been employed in several situations. However, the corrosion problems and the cost of non-corrosive metals were considered a barrier. In situ corrosion tests conducted in 1986–1988 in a groundwater well at Schwalbach GSHP research station [16] showed that a useful life of 30–40 years could be expected with plain steel and copper and that short-term corrosion could not be measured with stainless steel. This is compatible with [17], showing service life for galvanized steel tubes of about 50 years. For metals in general, [17], concludes: "*In geologic formations characterized by low to moderate corrosive potential, stainless steel, aluminum and copper are good metallic alternatives to HDPE … Galvanized steel pipes may also provide competitive alternatives to HDPE in such environments*".

In conclusion, HDPE-pipes dominate the market in Europe due to their cost, corrosion resistance and handling. For the most common design of BHE, the U-tube design (single, double,…), it is very improbable that metallic pipes will have a market share. But looking at mainly coaxial designs, there may be room for non-plastic alternatives in boreholes of limited depth.

2.1.1. Considerations on pipe materials

Parameter studies observed the influence of thermal conductivity of the pipe material on the overall efficiency of the borehole. Such modeling was made e.g. in 2003 within project Groundhit [18], funded by the EU in FP6 [19]. The results in Fig. 5 show clearly that an increase in thermal conductivity of the pipes from about 0.2 W/(mK) to 1 W/(mK) can reduce $R_b$substantially, and a reduction on a smaller scale can be seen up to 4–5 $W/(mK)$; for further increase of thermal conductivity into the realm of metals, the reduction of R_b is only marginal.

2.2. State-of-the-art in materials for grouting

The early BHE had no grouting, they were either immersed in groundwater in open holes, or filled by gravity from top (often using the drill cuttings as filling material). In softer geological layers, the ground was allowed to collapse around the pipes after installation, and in other cases steel pipes were driven directly into the ground, with no annulus. Inserting BHE-pipes into open, water-filled boreholes in hard rock, with just the softer overburden stabilized by a steel tube, still is the norm in most of Scandinavia.

Grouting of BHE by pumping a mixture down a tremie pipe and filling the annulus from bottom to top was presumably first done in Switzerland and in USA in the late 1980s. The first standard to require grouting from bottom to top of the borehole was [20] in Switzerland. The first German standard on GSHP [21], also recommended grouting, but still left room for some exceptions for shallow boreholes. The grout mixtures originally consisted of bentonite, cement and water; [22] gave an example with 25% bentonite, 25% cement and 50% water, resulting in a thermal conductivity of about 0.7–0.8 W/(mK).

The supposedly first publication on the idea of grout with enhanced thermal conductivity is [23]. In the mid-1990s, a thermally enhanced grout came on the market in the USA, with a thermal conductivity of almost 1.5 W/(mK); in American units, this means 0.85 $Btu/(hr\ ft\ ^{\circ}F)$, leading to the name of thermal grout 85. The increase in thermal conductivity was achieved by adding siliceous sand. Experiments in 1996–1999 at Brookhaven National Laboratory in USA targeted different additives for increased thermal conductivity, beside siliceous sand also steel grit, steel microfibers and aluminium oxide; siliceous sand was found the only viable option [24]. Developments in Germany around 2000 resulted in grout mixtures with addition of either quartz powder or graphite, under the brand names Stüwatherm and Thermocem,

[1] VDI 4640 is a widely respected industry standard in Germany and neighbouring countries, first published in 1998, and now comprising 5 parts for different aspects of shallow geothermal energy.

Table 1
Pipe material properties, selected values from [15].

Material	Thermal Conductivity	Maximum operationg temperature for 50 years pipe lifespan[g]	Maximum operationg temperature for 1 years pipe lifespan[g]
PE100 [a]	0.42 W/(mK)	40 °C	70 °C [h]
PE100-RC [b]	0.42 W/(mK)	40 °C	70 °C [h]
PE-RT [c]	0.42 W/(mK)	70 °C	95 °C
PE-X [d]	0.41 W/(mK)	70 °C	95 °C
PA [e]	0.24 W/(mK)	40 °C	70 °C
PB [f]	0.22 W/(mK)	70 °C	95 °C

[a] Polyethylene with minimum required strength (MRS) 10 MPa.
[b] Polyethylene with minimum required strength (MRS) 10 MPa with Resistance to Crack (RC).
[c] Polyethylene for Raised Temperature (RT).
[d] Cross-linked polyethylene.
[e] Polyamide.
[f] Polybutylene.
[g] At given maximum pressure conditions ranging from 0.6 to 1.2 MPa.
[h] Even short-time excess temperatures can damage pipes.

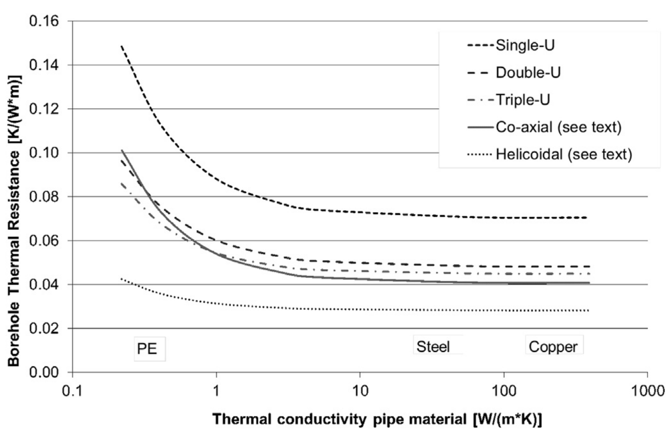


Fig. 5. Borehole Thermal Resistance R_b for different configurations versus thermal conductivity of pipe material, see text for details; helicoidal by approximation only. Data from European project Groundhit.

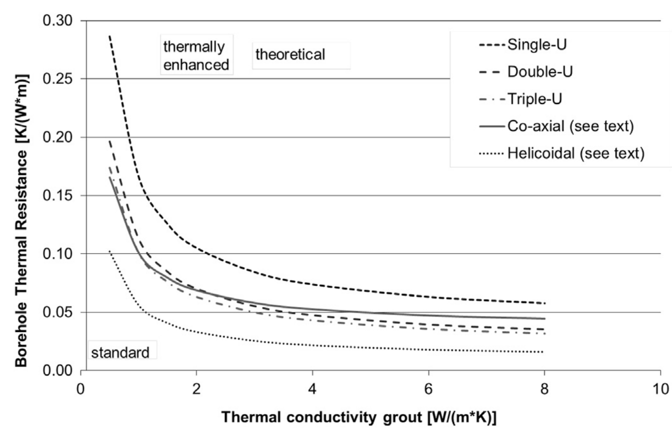


Fig. 6. Borehole Thermal Resistance for different configurations versus thermal conductivity of grout (backfilling); helicoidal by approximation only. Data from European project Groundhit.

respectively. Also in Ref. [22] the addition of quartz sand was suggested to improve thermal properties. Currently, numerous brands of grout ready for use are on the market.

2.2.1. Considerations on grouting material

Similar parameter studies as with pipe material can be made for the grout. The handy range of thermal conductivity for grout is much smaller, extending from around 0.6 W/(mK) with some plain bentonite-cement mixtures to slightly above 2 W/(mK) in currently available materials. A further increase would require new concepts, and considering the other material constraints for sealing properties and cost, more than a doubling of the current achievement seems out of reach. Thus for the calculations resulting in the curves in Fig. 6, the thermal conductivity of the grout was varied from 0.5 to 8.0 W/(mK), and the pipe thermal conductivity fixed at the value for HDPE, 0.42 W/(mK).)

Like for pipe material, a substantial improvement (decrease of R_b) can be seen for grout thermal conductivity increasing to about 2 W/(mK). A further reduction of R_b is visible towards values of 4 W/(mK) for most configurations; the effect is highest for single-U and lowest for the already very low R_b of helicoidal BHEs. Additional increase in grout thermal conductivity has little visible effect only.

These basic findings were experimentally confirmed in Ref. [25], with the conclusion: “*The grout thermal conductivity has a great influence on the borehole thermal resistance. However, when the thermal conductivity of the grout becomes considerably higher, the borehole thermal resistance will assume a constant value, …*”.

3. Parameter sensitivity analysis implementation

3.1. Tools and procedure

Several previous studies have been carried out to analyze the influence on thermal performance of the various geometrical and material parameters of a BHE, including ground thermal profile [26,27]. Yet, the cooperative effect of grout and pipe conductivity has been so far not considered, as pipe material properties were usually regarded as given. In our case, more than 17,000 simulations were carried out to obtain the best specifications, i.e., the best efficiency, for the products to be developed. The core of the simulations was performed using “Earth Energy Designer” (EED) [[28]], a PC based software (Windows platform) for designing borehole heat exchangers based on analytical solutions for the heat exchange process between the borehole and the surrounding ground. This design software has proven to be able to predict borehole fluid temperatures, as can be found in Refs. [29] where the mean brine temperature was monitored from July 1995–July 1996 in UEG (Wetzlar, Germany) and compared with the predicted brine temperature. Also in Ref. [30] a comparison of monitored with forecast values was made, to assess the suitability of the tool for borehole design. Finally [31], describes the comparison of the monitored data from three buildings (Building GEW (Gelsenkirchen), Building FAS (Dortmund) and building HSZ (Salzgitter)) with the data calculated by EED, showing a reasonable match with predicted fluid temperatures.

The simulation process comprised five main steps: defining simulation parameters, generating simulation models, executing the models, filtering the results and, finally, analyzing the obtained values.

The simulations are configured by means of plain text files with self-descriptive elements. The lines of the model file contain the name and value of each of the required parameters. Once the parameter values are decided, a dedicated script creates a set of base model files, each with different values of those parameters.

Since EED has only a Graphical User Interface (GUI) without scripting capabilities or an alternative Command Line Interface (CLI), our team decided to create a robot program simulating an interactive user to enable the automatic execution of hundreds or even thousands of simulation without human intervention.

The procedure produces a result file for each simulation with a similar structure than the model files: plain text files with self-descriptive entries. By means of *shell* and *awk* scripts, results are filtered to extract the desired performance indicators: total installed BHE length and equivalent BHE thermal resistance. The final results of this stage is a comma separated value (CSV) file including the input parameters and its associated performance indicators.

As a further step, it is necessary to define a series of variables or parameters that must be necessarily established for the simulations. Some of the input variables are considered as *fixed variables* according to the defined scenarios. Other variables, coinciding with those variables that will be presumable modified and enhanced are considered as *open variables*. Those *open variables* are varying in the simulations to perform the sensitivity analysis.

3.1.1. Fixed variables

Fixed variable are determined by our so—called *scenario setting*. There are three main categories for the configuration of the different scenarios that will constitute the initial conditions for the simulations of the sensitivity study. Those major categories are named as Ground, Location and Building as defined below.

3.1.1.1. Ground. The typology of the ground will be defined by two variables:

1 The thermal conductivity of the ground: (expressed in W/(mK) and often denoted k, λ or κ) is the property of a material to conduct heat according to the Fourier's Law for heat conduction.
2 The volumetric heat capacity of the ground: (expressed in MJ/(m^3K) describes the ability of a given volume of a substance to store internal energy while undergoing a given temperature change without phase transition.

The above parameters depend on the geological characteristics and the lithologies that are found in each specific location. Three different types of ground have been distinguished: low conductivity ground, medium conductivity ground and high conductivity ground, with the properties listed in Table 2.

Those values represent a generic value for different types of associated lithologies (sandy sediments and conglomerates for low conductivity, well-cemented limestones for medium conductivity and granite and metamorphic gneiss for high thermal conductivity). All those typologies could be found in different European regions and could be generally grouped into non-consolidated sediments, sedimentary rocks, and igneous and metamorphic rocks.

3.1.1.2. Location. The location of the building will provide us with several important input data for the simulations. On one hand, the location of the building is directly related to its climate typology. On the other hand it is closely related to the undisturbed temperature of the ground and the geothermal heat flux value, which can be directly extracted from the EED libraries. Indirectly, the location affects the thermal loads that would be needed to achieve the comfort requirements of different types of buildings.

Two European cities with different climatic regimes were selected. Representing areas dominated by warm/mild climate, Madrid (Classified as Csa according to the Koeppen-Geiger classification), and hot climate, Seville, (Classified as Csa with extremely high temperatures according to the Koeppen-Geiger classification). No city has been selected for a cold climate since it would imply a different method of design (different fluid temperature constraints). In cold regions, the design of the heat exchanger length is carried out, due to the low ground temperature, fixing lower the fluid temperature in the heat exchanger (several degrees below zero) and using glycol water as the fluid heat carrier. Therefore, by using different design conditions, it would not be possible to compare the results obtained, which is why this type of climate has been excluded.

The EED software contains libraries allowing extraction of the most significant values (temperature of the ground and geothermal heat flux) for the modeling. Those values have been established for hot and mild climate with values of ground temperature of 18 °C and 14 °C and values of geothermal heat flux of 0.07 W/m^2 and 0.08 W/m^2 respectively.

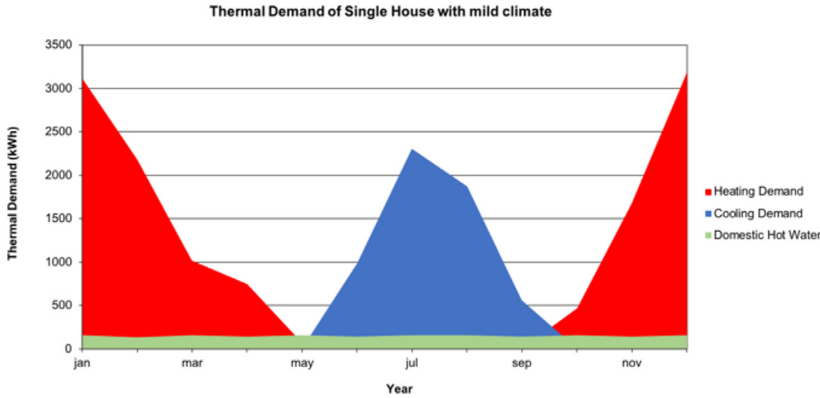
3.1.1.3. Building. The building typologies have been reduced to two main types: residential house and office building. Each typology has totally different thermal demands according to the constructive characteristics and the expected uses. The thermal profile, which will vary according to the type of building, together with the climate associated to the specific locations (explained in the previous section) is analyzed in order to provide the monthly thermal loads.

In order to obtain the thermal loads of the selected building typologies, results from the European project "Policies to enforce the transition to nearly zero energy buildings in the EU-27 (ENTRANZE)" were consulted. Specifically, the results of deliverable 2.3 of Work Package 2 of the Project: "Data from Heating and cooling energy demand and loads for building types in different countries of the EU", regarding the energy needs for Heating, Cooling and Domestic Hot Water were used for: a single-family house of 120 m^2 and an office building of 500 m^2 in the climatological conditions described in the previous section.

The energy data demands used in the simulations, depending on the type of building and climate, has been established according to Figs. 7, 8, 9 and 10.

Table 2
Characteristics of three different typologies of ground conditions attending to the main geological settings around Europe.

Ground typology	kg/m^3x 10^3	$kJ/(kg \cdot K)$	$MJ/(m^3 \cdot K)$	$W/(m \cdot K)$	m^2/sx 10^{-7}
Low conductivity ground	1.45	0.88	1.28	1.2	9.4
Medium conductivity ground	2.3	0.91	2.1	2.3	11
High conductivity ground	2.7	0.93	2.5	3.5	14



	Heating Mode	Cooling Mode
Power Capacity (kW)	13.6	12
SPF	3.8	3.5
Peak Hours (h)	8	6.5

Fig. 7. Thermal loads for a single house in a mild climatic region.

3.1.1.4. Borehole heat exchanger. Two types of borehole heat exchangers have been considered for the simulations. One system is the single–U typology which is the most generally used solution in SGES around the world. The second solution is a standard coaxial geometry, which is currently much less present on the market but posses a high potential for introducing enhancements due to the associated reduction of total length of the installations. Whilst being significantly more expensive and slightly more difficult to install, coaxial BHEs are now in the focus of different European projects (e.g. CHEAPs-GSHP[2] and GEO4CIVHIC[3]) and initiatives to improve its installation time, performances and cost. The data used in the simulations concerning the heat exchangers are listed in Table 3.

3.1.1.5. Heat carrier fluid. The heat carrier fluid in the simulations is water. Water is generally used as heat carrier fluid in a wide range of applications in particular from hot climate to moderately mild climates. In moderate to cold climates, systems often are designed for temperatures dropping down to negative values, and antifreeze additives such as glycol may be added to the water. The heat carrier fluid used for the simulations at this stage is plain water.

3.1.1.6. Fluid temperature constraints. The fluid temperatures are constrained by the generally used design values for the defined locations according to the thermal loads demanded by the buildings. The temperature of the fluid in the heat exchanger is limited to the generally used design values in systems with plain water as heat carrier fluid (including peaks) as given in Table 4.

The minimum and maximum mean fluid temperatures shown in Table 4 have been selected as a common choice for GSHP heating and cooling operation respectively. The actual value would depend on the given location, due to the ground influence. The BHE average water temperature is obtained by means of simulation since it depends on the thermal building loads. For the purpose of our study, the minimum temperature in the exchanger was limited to about 5 $^{\circ}C$ because of the use of water without antifreeze. The maximum temperature is usually limited to around 32.5 $^{\circ}C$, as higher temperatures would impact considerably heat pump efficiency and reduce pipe's lifespan.

3.1.1.7. Simulation period. For all the scenarios contemplated an effective performance period of 25 years was established.

[2] See more information about this project at https://cheap-gshp.eu/.
[3] See more information about this project at https://geo4civhic.eu/.

3.1.2. Open variables

Open variables are those input variables necessary for doing the simulations which values are going to be modified. Our goal is to determine the optimal values for those variables in the different scenarios in order to provide the guidelines and specifications for the product developers. The main considered *open variables* are:

3.1.2.1. Thermal conductivity of the filling grout. This variable considers the thermal conductivity of the grouting products. As highlighted in the introduction, currently the thermal conductivity of standard grouts could vary from 0.8 W/(mK) to 2 W/(mK) depending on the different solutions available in the geothermal product market. Our objective is to increase the range of values in order to optimize the performance of the SGES with lower total BHE length. In the simulation procedure designed, a range of 0.1W/(mK) - 4.0 W/(mK) is being simulated with steps of 0.1 W/(mK).

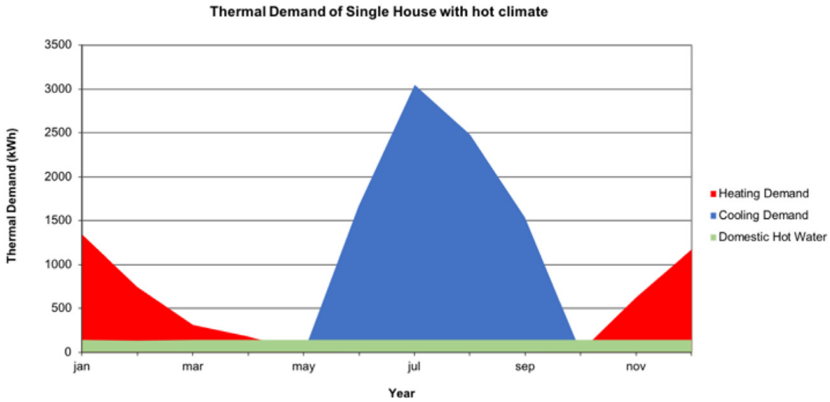
3.1.2.2. Thermal conductivity of the pipe. This variable considers the thermal conductivity of the pipes used as heat exchanger. Currently the thermal conductivity of standard PE pipes is 0.42 W/(mK). Our objective is to increase the range of values in order to optimize the performance of the SGES. In the simulation procedure designed, a range of 0.1W/(mK) - 2 W/(mK) is being simulated with steps of 0.1 W/(mK).

3.1.2.3. Diameter ratio between inner and outer pipe in coaxial borehole. Simulations have also been performed to obtain the outer and inner pipe diameter ratios for coaxial borehole pipes that maximize efficiency.

3.1.3. Simulation output values

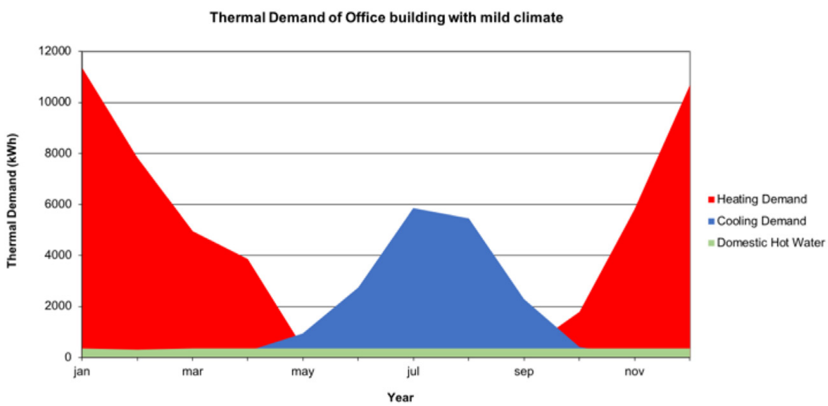
In order to evaluate the effects produced by the enhancements, a detailed analysis of the simulation results has been done, paying attention to two output values: total length of the heat exchangers for covering the energy demands and borehole thermal resistance. Result show that both parameters respond in the same way to the introduced simulations as it was initially expected.

3.1.3.1. Total length of the heat exchangers. This output parameter shows the final total length of heat exchanger that will be required to cover the energy demands of the buildings while limiting the overall temperature increase around the BHE area to a certain value within the operational period of the system under the input conditions described in Section 3.1.2. Hence, the different solutions that will be discussed in the next sections are equivalent from the point of view of heat pump efficiency and can serve as a basis for a comparative cost analysis.



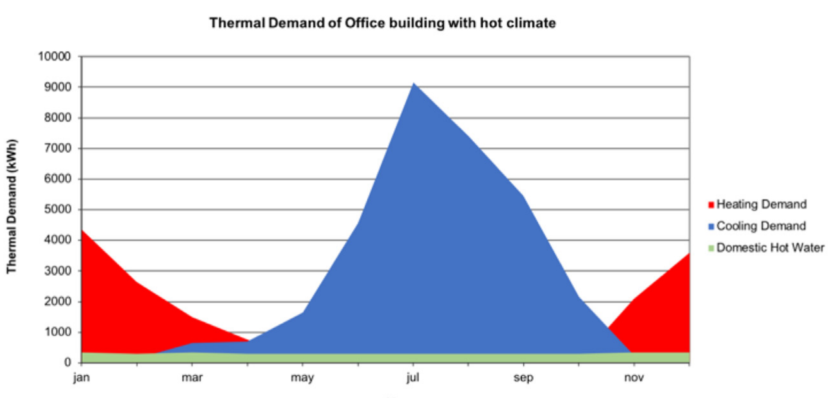
	Heating Mode	Cooling Mode
Power Capacity (kW)	12	10
SPF	3.8	3.5
Peak Hours (h)	4	10

Fig. 8. Thermal loads for a single house in a hot climatic region.



	Heating Mode	Cooling Mode
Power Capacity (kW)	32	30
SPF	3.8	3.5
Peak Hours (h)	12	6.5

Fig. 9. Thermal loads for an office building in a mild climatic region.



	Heating Mode	Cooling Mode
Power Capacity (kW)	32	30
SPF	3.8	3.5
Peak Hours (h)	5	10

Fig. 10. Thermal loads for an office building in a hot climatic region.

3.1.3.2. Borehole thermal resistance. According to the general accepted definition, the borehole thermal resistance (R_b) is the thermal resistance between the pipe fluid and the borehole wall. It is the main efficiency characteristic of a geothermal heat exchanger. Lower thermal resistance of the borehole leads to better efficiency of the geothermal system per borehole unit length and higher Hellström efficiency. Since its original definition by Mogensen [32], there have been several methods proposed for its calculation. EED offers one possible methodology which, inter alia, takes into account short-circuiting thermal flow between the upstream and downstream pipes of the BHE. As will be seen later these effects are critical to explain some of the features observed in our study when varying the open parameters.

As expected, simulations show that the response of R_b when other input variables are modified (thermal conductivity of the pipe or thermal conductivity of the ground together with different geometrical configurations of the pipes) is identical to the response observed in the total length of the heat exchangers. Nevertheless it is important to consider R_b separately in order to be able to compare BHE efficiency regardless of the considered scenario and geometry, since it constitutes an intrinsic system parameter.

Table 3
Main characteristics of simulated BHE.

	Borehole Heat Exchanger (BHE)	
	Single-U	**Coaxial**
Number of Boreholes	Depending on the thermal load	
Depth	Determined by simulation outputs	
Spacing	10 m	
Diameter of the borehole	110 mm	63 mm
Flow rate [a]	0.00011 m^3/s	0.000273 m^3/s
Contact Res. Pipe/Filling		0 m^2K/W
Filling Thermal Conductivity	From 1 to 4 W/(mK)	2.1 W/(mK) (when applicable)
Pipe outer diameters	32 mm	63 mm (outer pipe) and 32 mm (inner pipe)
Shank spacing	0.07 m	Not Applicable
Wall thickness	3 mm	5.8 (outer pipe) and 2.9 mm (inner pipe)
Pipe Thermal Conductivity	From 0.4 to 2 W/(mK)	Inner: From 0.1 to 0.5 W/(mK) Outer: From 0.4 to 2 W/(mK)

[a] The water flow has been chosen according to the thermal power dissipation according to the load balance of the building. It has remained constant at a convenient value because the objective of the simulations was to asses the influence of other parameters (i.e., the conductivity of pipes and grouting) on the thermal resistance of the borehole.

Table 4
Fluid temperatures constraints.

Minimum Mean Fluid Temperature	5 °C
Maximum Mean Fluid Temperature	32.5 °C

3.2. *Configuration of the different scenarios*

All the previously described considerations have allowed the definition of different scenarios where the influence of variations on the thermal conductivity of the pipes and the grouting products could be measured. The scenario configuration has been designed considering the three major parameters referred as building typology, location and geological setting (see Table 5).

3.3. *Simulations to evaluate the sensitivity analysis of parameters*

3.3.1. *Sensitivity analysis of combination of pipe and grouting thermal conductivity in a Single-U borehole*

The aim of this assessment is to analyze the combined effect of varying the thermal conductivity of the pipe materials and the grouting materials at the same time. This sensitivity analysis was done varying the previously described parameters simultaneously, in order to decipher the combined effect that both modifications trigger in the total length of the borehole field and the effective borehole thermal resistance. The total length of the borehole field is directly proportional to the borehole resistance (R_b). Those parameters are going to be realistically modified by means of producing new typologies of piping materials, including new materials and new geometrical configurations; and new thermally enhanced grouting adapted to the ground conditions, in order to optimize the efficiency of the systems. The interval of modeling were defined as follows:

λ_{PIPE} values varying from 0.4 W/(mK) to 2 W/(mK) (step: 0.1 W/(mK))
λ_{GROUT} values varying from 1 W/(mK) to 4 W/(mK) (step: 0.1 W/(mK))

To obtain the surface graphs for each defined scenario, it was necessary to perform 480 simulations according to the procedure defined above. The results are highly valuable to guideline and set practical limits to the development of the new pipes and grouts.

For illustration the combined effect of modifying both parameters, the graphic corresponding to an office building, in a hot climatic region and with a medium value of thermal conductivity of the ground has been selected as representative of the results (Fig. 11). The heat exchanger used for the simulation is a single-U heat exchanger.

The obtained results demonstrate that the optimal range, in terms of total length of the borehole field, correspond to λ_{PIPE} between 1.2 and 1.5 W/(mK) and λ_{GROUT} between 2.1 and 2.9 W/(mK). The reason why higher values of the thermal conductivity of the grouting material are counterproductive in this scenario is related with the increase in thermal short-circuiting between supply and return pipes.

The results of the simulations show that a significant reduction of the total length may be achieved by means of using a optimal configuration ($\lambda_{PIPE} = 2$ W/(mK), $\lambda_{GROUT} = 2.4$ W/(mK), required length = 885.5 m) instead of a standard PE geothermal pipe with a standard grouting ($\lambda_{PIPE} = 0.42$ W/(mK), $\lambda_{GROUT} = 2.0$ W/(mK), required length = 1003.7 m). Fig. 12 shows the corresponding borehole thermal resistance values for the same scenario, where the trend is identical.

Results of this study were done for several possible scenarios considering two different typologies of buildings, the climatic conditions and finally the ground characteristics related to the thermal conductivity.

Table 5
Definition of the scenarios for simulations.

	Ground Thermal Conductivity	Climate	Building Typology
SCENARIO 1	HIGH	MILD	HOUSE
SCENARIO 2	HIGH	HOT	HOUSE
SCENARIO 3	MEDIUM	MILD	HOUSE
SCENARIO 4	MEDIUM	HOT	HOUSE
SCENARIO 5	LOW	MILD	HOUSE
SCENARIO 6	LOW	HOT	HOUSE
SCENARIO 7	HIGH	MILD	OFFICE
SCENARIO 8	HIGH	HOT	OFFICE
SCENARIO 9	MEDIUM	MILD	OFFICE
SCENARIO 10	MEDIUM	HOT	OFFICE
SCENARIO 11	LOW	MILD	OFFICE
SCENARIO 12	LOW	HOT	OFFICE

3.3.2. *Sensitivity analysis of combination of inner pipe and external pipe conductivity in a borehole coaxial without grouting*

In this second example, the effect of a coaxial heat exchanger is analyzed following the sensitivity approach related to the thermal conductivity of the inner and outer pipes. This sensitivity analysis is done to unravel the influence of installing a coaxial heat exchanger instead a conventionally used U-pipe. In this case, the simulations were done by modifying systematically the thermal conductivity of the inner and outer pipes. The assumptions that have been

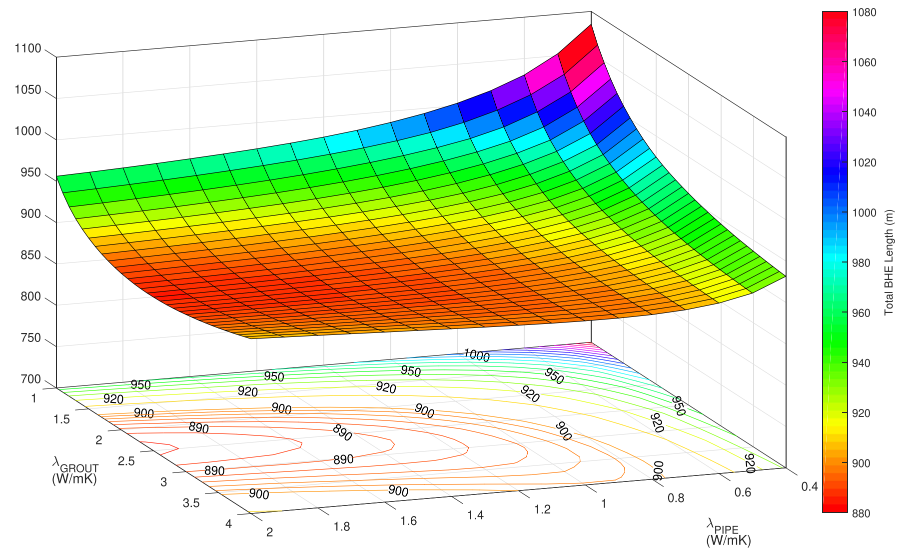


Fig. 11. Graphic showing the simultaneous effect of varying the λ_{PIPE} and λ_{GROUT} in the total length of a designed system for an office building in a hot region with medium thermal conductivity of the ground. Isolines are spaced at 2 m until 900 m and 10 m from that value to 1100 m.

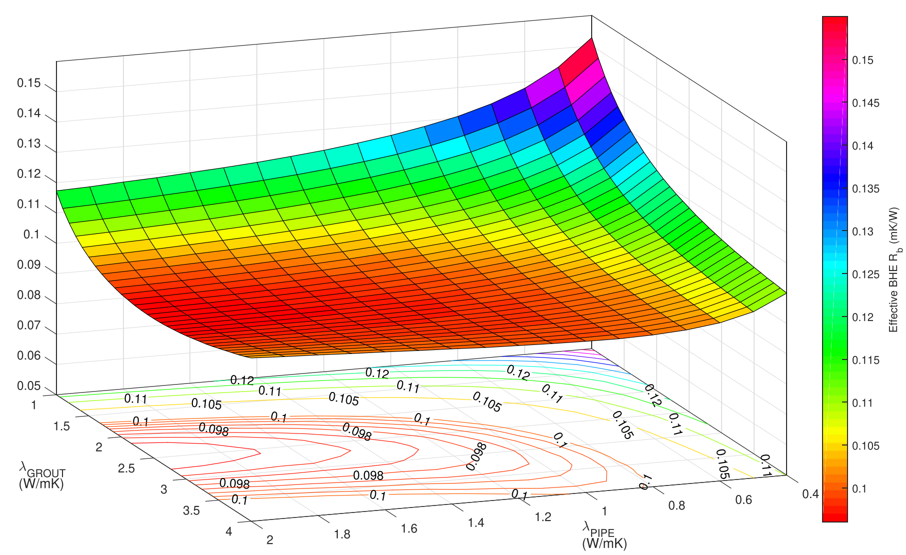


Fig. 12. Graphic showing the simultaneous effect of varying the λ_{PIPE} and λ_{GROUT} in the R_b of a designed system for an office building in a hot region with medium thermal conductivity of the ground. Isolines are spaced 0.0005 mK/W until 0.1 mK/W and 0.005 mK/W from that value to 0.15 mK/W.

considered for the simulations are that:

1 The conductivity range shall be of the order of coaxial pipes manufactured in plastic.
2 Thermal isolation of the inner pipe will produce an enhancement of the efficiency of the system avoiding thermal losses.
3 The outer pipe should have higher thermal conductivity in order to facilitate the heat exchange with the ground.
4 The simulations consider no need for external grouting between the ground and the external pipe of the coaxial BHE (direct displacing installation).

The configuration of the coaxial heat exchanger used in the simulations is:

a. Outer pipe: external diameter 63 mm; wall thickness: 5.8 mm; thermal conductivity from 0.4 (standard PE-100) to 2 W/(mK). (Step: 0.1).
b. Inner pipe: external diameter 32 mm; thickness wall: 3 mm; thermal conductivity from 0.1 to 0.5 W/(mK).(Step: 0.1).

A basic scenario, described as office building in a mild climatic region and with a medium value of ground thermal conductivity has been chosen for illustrating the results of the effect of the typology and geometries of the heat exchanger in the design of the SGE systems (Fig. 13). The results of the simulations show that a significant reduction of the total length may be achieved by means of using coaxial systems with different thermal conductivities in the outer and inner pipes. This reduction is highly significant and might have a considerable impact on costs, passing from a total length of 917 m in a standard PE coaxial system to a total length of

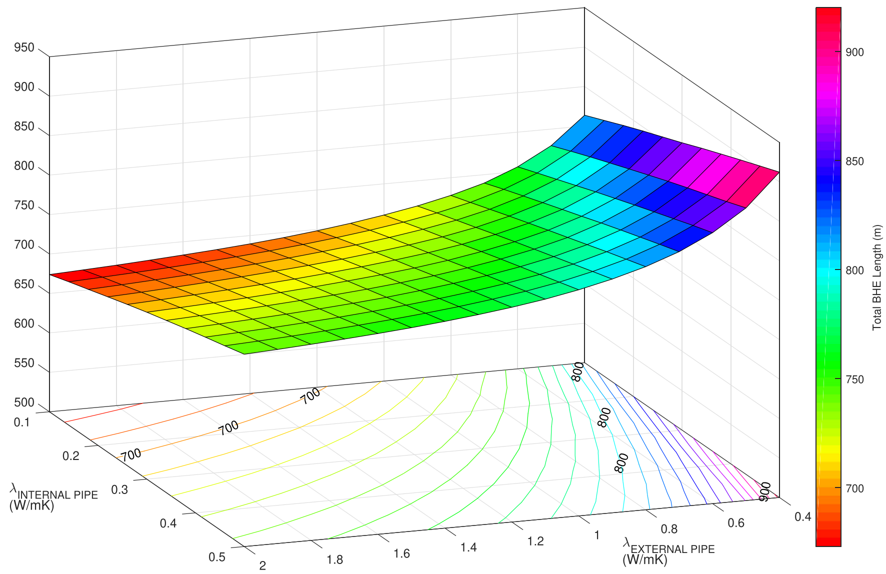


Fig. 13. Graphic showing the simultaneous effect in the total length of a borehole field of varying the λ_{PIPE} in the outer and inner pipes of a coaxial system for an office building in a mild region with medium thermal conductivity of the ground. Isolines every 10 m.

670 m in a coaxial system with values of thermal conductivity of 0.1 W/(mK) for the inner pipe and 2 W/(mK) for the outer pipe.

Finally, the effective borehole thermal resistance calculated for the different configurations shows the same pattern indicating that the optimal configuration corresponds to higher differences in the thermal conductivity of the inner and outer pipes used in the coaxial heat exchanger (Fig. 14).

3.3.3. Sensitivity analysis of influence of the ground typology

The influence of the ground typology for the scenario of a Single-U geothermal system for a house in a mild climate region is be studied next. The following Fig. 15 shows the surfaces obtained for a high conductivity ground (upper graph), a medium conductivity ground (middle graph) and a low conductivity ground (lower graph). The contour shape correlates to the same shape as that obtained in Fig. 12, although less accentuated as the system (house) has a lower thermal load than that obtained in Fig. 12 (office). As is to be expected, there is less need for geothermal exchanger length in the case of high conductivity ground and greater length of geothermal exchanger required in the case of low thermal conductivity ground. In higher ground thermal conductivity environments, the maximum allowable grouting conductivity values would be higher. The three surfaces follow the same pattern without significant differences.

As for the influence the ground typology on R_b (Fig. 16), the pattern of the shape of the three surfaces is identical, although in the case of the surface generated in the case of high conductive ground, a higher influence on R_b can be seen.

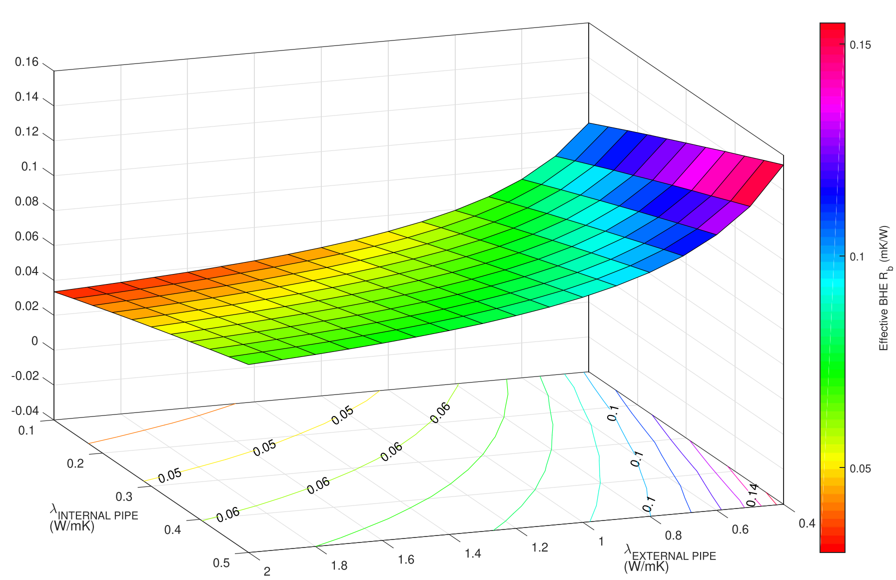


Fig. 14. Graphic showing the simultaneous effect in the effective borehole thermal resistance of varying the λ_{PIPE} in the outer and inner pipes of a coaxial system for an office building in a mild region with medium thermal conductivity of the ground. Isolines every 0.01 mK/W.

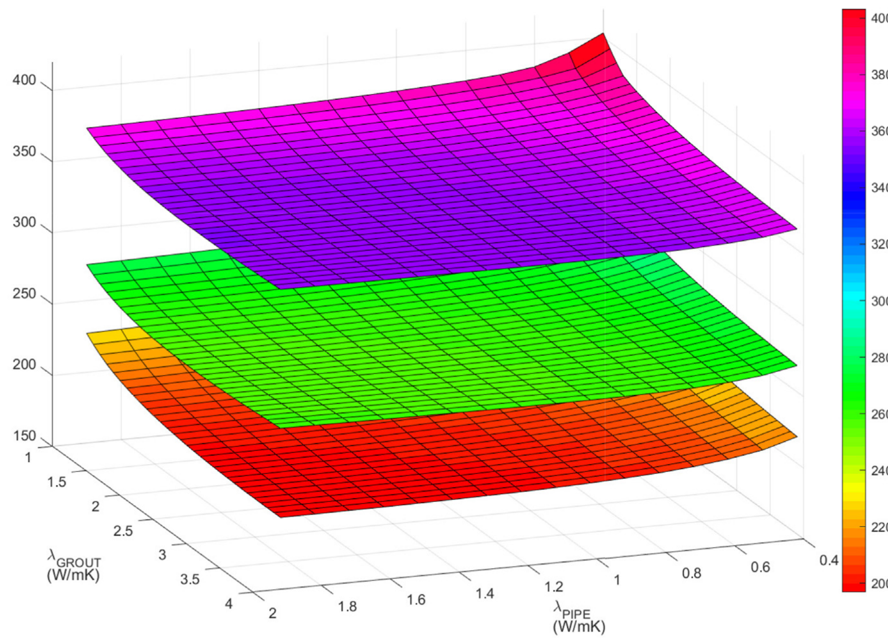


Fig. 15. Graphic showing the simultaneous effect of varying the λ_{PIPE} and λ_{GROUT} in the total length of a designed system for a house in a mild region with high (bottom), medium (middle) and low (upper) thermal conductivity of the ground.

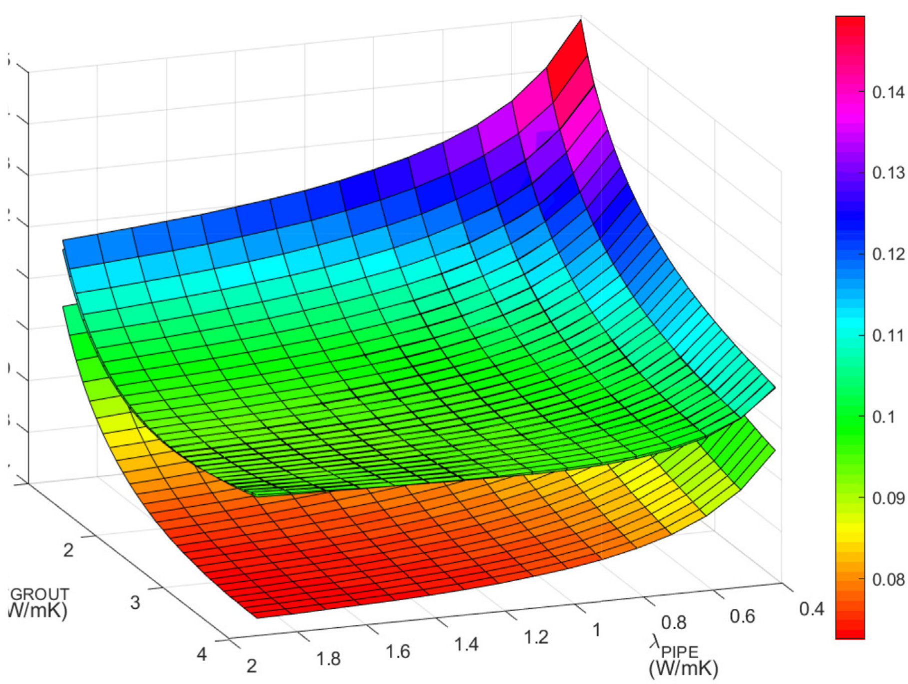


Fig. 16. Graphic showing the simultaneous effect of varying the λ_{PIPE} and λ_{GROUT} in the R_b of a designed system for a house in a mild region with high (bottom), medium (middle) and low (upper) thermal conductivity of the ground.

3.3.4. Sensitivity analysis of influence of the climatic conditions

The influence of the climate for the scenario of a Single-U geothermal system for an office located in an area of medium ground thermal conductivity is studied below. The following Fig. 17 shows the surfaces obtained for a hot region (upper graph) and a mild region (lower graph). As is to be expected, there is less need for geothermal exchanger length in the case of high conductivity ground and more length of geothermal exchanger required in the case of low thermal conductivity ground. The shaping of the two surfaces is similar, although in the case of hot climates, the influence of the "thermal short-circuit" previously explained for high grout conductivities is greater.

As for the influence of the climate on R_b (Fig. 18), almost the same thermal resistance surface as the borehole for both climates is obtained, although in the case of the hot climate surface, the highest sensitivity to "thermal short-circuit" is observed, as in the previous case.

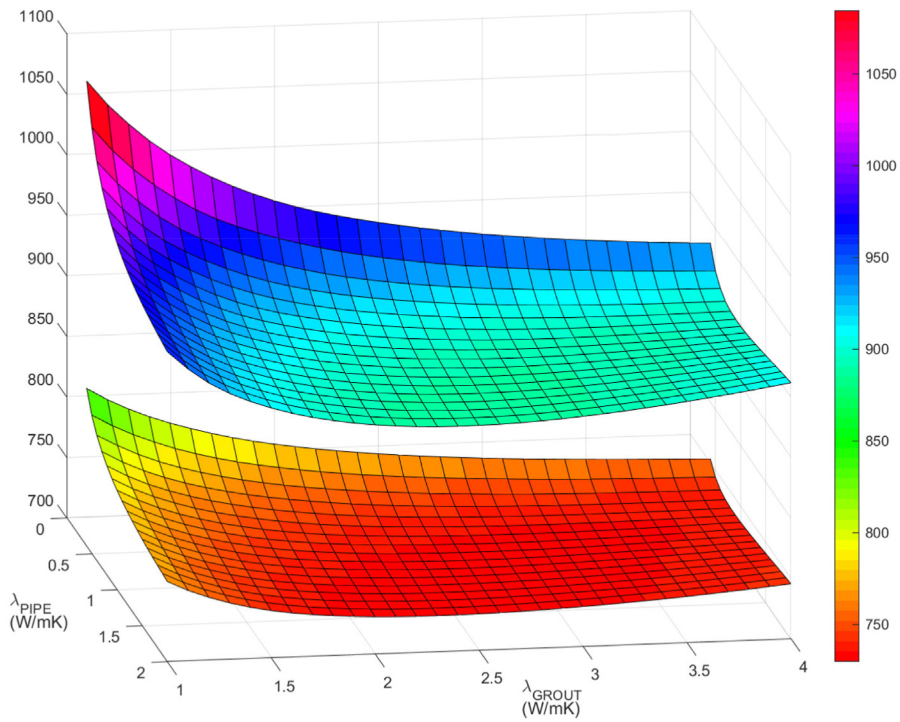


Fig. 17. Graphic showing the simultaneous effect of varying the λ_{PIPE} and λ_{GROUT} in the total length of a designed system for an office building in a hot (upper) and mild (bottom) region with medium thermal conductivity of the ground.

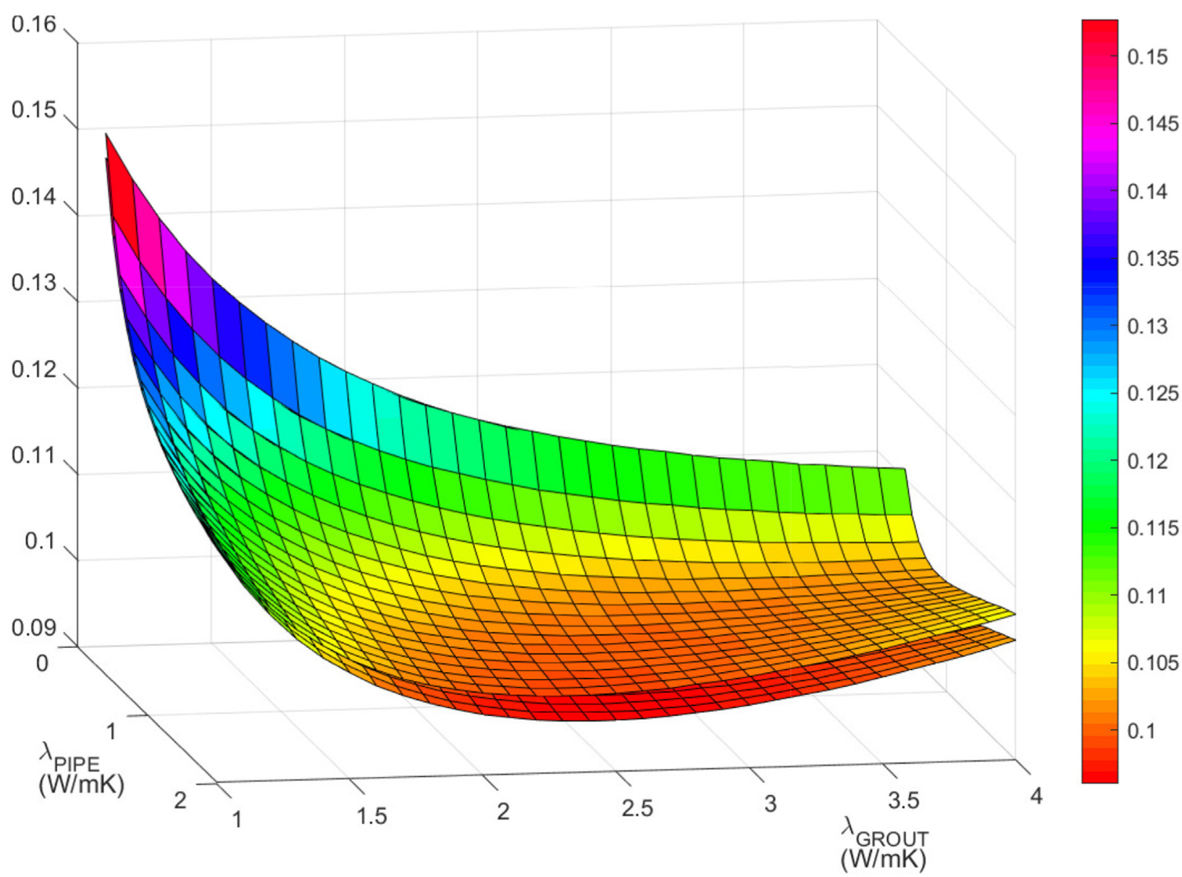


Fig. 18. Graphic showing the simultaneous effect of varying the λ_{PIPE} and λ_{GROUT} in the R_b of a designed system for an office building in a hot (upper) and mild (bottom) region with medium thermal conductivity of the ground.

Table 6
Results of the optimal configuration for each scenario.

	Ground Thermal Conductivity	Climate	Building Typology	Total Length (m) (State of the art)[a]	Total length (m) (Minimum value)	Reduction
SCENARIO 1	HIGH	MILD	HOUSE	240.6	196.8 $\lambda_{pipe} = 1.9$ W/(mK) $\lambda_{grout} = 3.6$ W/(mK)	18%
SCENARIO 2	HIGH	HOT	HOUSE	229.3	178.5 $\lambda_{pipe} = 1.9$ W/(mK) $\lambda_{grout} = 3.9$ W/(mK)	22%
SCENARIO 3	MEDIUM	MILD	HOUSE	287.4	256.0 $\lambda_{pipe} = 1.9$ W/(mK) $\lambda_{grout} = 2.6$ W/(mK)	11%
SCENARIO 4	MEDIUM	HOT	HOUSE	294.7	238.4 $\lambda_{pipe} = 1.9$ W/(mK) $\lambda_{grout} = 3.9$ W/(mK)	19%
SCENARIO 5	LOW	MILD	HOUSE	377.8	354.7 $\lambda_{pipe} = 1.8$ W/(mK) $\lambda_{grout} = 2.7$ W/(mK)	6%
SCENARIO 6	LOW	HOT	HOUSE	519.4	462.9 $\lambda_{pipe} = 1.9$ W/(mK) $\lambda_{grout} = 2.2$ W/(mK)	11%
SCENARIO 7	HIGH	MILD	OFFICE	660.5	584.8 $\lambda_{pipe} = 2.0$W/(mK) $\lambda_{grout} = 1.8$W/(mK)	11%
SCENARIO 8	HIGH	HOT	OFFICE	390.4	333.4 $\lambda_{pipe} = 2.0$W/(mK) $\lambda_{grout} = 3.8$ W/(mK)	15%
SCENARIO 9	MEDIUM	MILD	OFFICE	790.9	729.7 $\lambda_{pipe} = 2.0$ W/(mK) $\lambda_{grout} = 2.4$ W/(mK)	8%
SCENARIO 10	MEDIUM	HOT	OFFICE	1003.7	885.6 $\lambda_{pipe} = 2.0$ W/(mK) $\lambda_{grout} = 2.4$ W/(mK)	15%
SCENARIO 11	LOW	MILD	OFFICE	1078.7	1030.7 $\lambda_{pipe} = 2.0$ W/(mK) $\lambda_{grout} = 2.4$ W/(mK)	4%
SCENARIO 12	LOW	HOT	OFFICE	1754	1591.7 $\lambda_{pipe} = 2.0$ W/(mK) $\lambda_{grout} = 2.4$ W/(mK)	9%

[a] Standard PE geothermal pipe with a standard grouting ($\lambda_{PIPE} = 0.42$ W/(mK), $\lambda_{GROUT} = 2.0$W/(mK).

3.3.5. Sensitivity analysis of the different scenarios

According to Section 3.2, where the different scenarios were configurated, the following results for each scenario are obtained (see Table 6).

4. Material development[4]

The comprehensive numerical analysis by simulations described in the previous section have been a valuable design guideline tool for the specification range of the improved materials for later composing and manufacturing. It has shown that pipe thermal conductivity values above $1.5 - 2$ W/(mK) do not provide a significant improvement in the thermal efficiency of the borehole, compared to the increase of the manufacturing cost and complexity of the formulations. As for the thermal conductivity of the grout, too high values have been shown to be possibly counterproductive depending on ground condition and distance between the U-tube legs and therefore a compromise value must be reached.

4.1. Development of the new plastic material for improved geothermal pipes

This section describes the preparation of different polyethylene (PE) formulations based on carbonous particles, together with the effect achieved over thermal, physical and mechanical properties of the new material. The objective was to develop a PE formulation with high thermal conductive properties, in order to increase the efficiency of geothermal systems, while keeping the material suitability for pipes production in conventional pipe extrusion lines as well as the mechanical performance of the pipes necessary for their installation and during its lifespan. The challenge was to match the thermal and mechanical properties showed by the compounds with the results from the simulations carried out. The work performed for the complete development of the final pipes includes a first stage of selection of basic raw materials for the plastic pipes, the design and testing of master-batches and compounds; then a laboratory production of pipes for testing mechanical and physical properties and finally the up-scaling of the results into a real factory where the real pipes to be installed in relevant environment was achieved.

4.1.1. Selection of the most suitable raw materials: list of additives

Expanded Graphite: Considering all the available data of the recommended graphite grades, it was decided to work with expanded graphites due to their expected higher effect on thermal conductivity, as well as with natural graphite for being the most economical alternative in case that the modulation of the content in the final compounds leads to satisfactory thermal conductivity values. In addition, it is provided in flakes, which will improve handling during compounding compared to graphites in powder

[4] Due to intellectual property (IPR) issues, the indication of specific additives and exact formulations has been omitted.

form.

A **grafted maleic anhydride polyolefin** which is an efficient compatibilizer of polyolefins with different polar polymers and fillers. Indeed the paraffin backbone grants useful interaction with the HDPE matrix while the grafted maleic anhydride groups give adhesion to the aromatic rings of the graphite to promote the dispersion in the polyolefin matrix.

Graphene is a filler reported to have a very high thermal conductivity. Therefore its higher cost could be compensated by the need of minor amounts compared to graphite, with important advantages of polymer compound processability during pipe extrusion and a larger flexibility of the pipe which helps during storage and application.

A **polyolefin elastomer** as a very flexible polyethylene to recover the IZOD impact reduced by the addition of significant amounts of the rigid filler (graphite).

A **copolymer** which with its polyolefin flexible blocks can help the IZOD impact value of the composite, while the aromatic rings in its molecular structure can help the dispersion of the graphite and the graphene thanks to the interaction between the aromatic groups of both components.

An **elastomeric polyolefin grafted with epoxy groups** as compatibilizer. This product was tested at laboratory scale to get information about the role of the innovative epoxy group in assisting the dispersion of the graphite into the polyethylene and to stabilize the ultimate properties of the final blend in terms of structure morphology and thermal conductivity.

4.1.2. Preparation of masterbatches and compounds

Lab-scale compounds were prepared by SPIN-PET laboratory [33] using a mechanical mixer (Brabender mixer) and the successive scaling up in extruders was carried out by SILMA [34]. Brabender mixer is the tool used for the preparation of polymeric compounds by batch mixing in the molten state. This tool allows to simulate at the laboratory scale the processes of mixing and compounding. Experiments performed in the Brabender allow to test the processability of thermoplastic and elastomer polymer in the presence of fillers and evaluate the dynamic of changes occurring in the compounds as consequence of dispersion of the different phases. These effects are easily evidenced thanks to the possibility of recording the torque curve as a function of processing time. The mixer can also be used as a reactor in the molten state for the production of molecular modified polymer samples through reactive processes between two or more different species.

From different proportions of the raw materials previously described, several preliminary formulations were produced and prepared for a detailed physical-mechanical characterization and comparison against standard PE-100, the benchmarking product. Characterization tests over the graphite PE compounds have been performed by AIMPLAS [35]. The characterization included all the standard testing procedures that are currently used for the characterization of the PE-100 pipes because the final produced pipes must fulfill with the basic requirements of those products in shallow geothermal applications.

In those comparisons, the thermal conductivity values and the mechanical properties (including flexural modulus, flexural strength and deflection) were carefully analyzed because those could be the main properties determining the feasibility of the compound for production plastic pipes. From all those tests, two final composition were selected named as COMPOUND 1 and COMPOUND 2. Table 7 lists the main properties and the comparison with the standard PE 100 properties.

From characterization tests performed to the compounds, the following conclusions are drawn:

- Addition of expanded graphite in PE100 increases thermal conductivity significantly. These values are in the range of the required theoretical values of thermal conductivity from the simulations.
- Graphite increases rigidity of PE compounds, which can be reduced with the incorporation of compatibilizers and fluidificants, although the use of these additives results in a decrease in thermal conductivity of the pipe.
- The use of compatibilizer and fluidificant, combined with the preparation of the compound in two steps, led to a compound with balanced mechanical and thermal properties compared to the rest of formulations assessed.

Mechanical properties of the developed compounds are very similar to the properties of the PE-100 (and consequently to those required in a geothermal installation) and hence these compounds are suitable for the production of high efficient pipes for heat exchangers. Therefore, these two final compositions were selected for the production of pipes at full scale.

4.1.3. Full scale production of plastic pipes

Last step of validation of the optimized compound was the use of the compound as a raw material for producing standard 32 mm (2.9 mm wall thickness) pipes. The manufacture was carried out at CAUDAL facilities [36]. The setting of the production line for pipes is totally standard and ready to produce PE-100 pipes including feeders, silos, extruders, cooling baths, etc. In our process, the plasticizing process of the material takes place in the extruder, where the material, once in the hopper, it is picked up and transported by the screw along the barrel, being melted progressively by means of heat provided by the external resistances and the shearing forces caused by the compression of the material between itself and the cylinder, until its plasticization.

The temperature profiles set for pipes production were the same for standard PE100, showing to be optimum for the conductive compounds. The production of pipes proceeded without major difficulties and the final appearance of the pipes was similar to the standards PE100 pipes. Finally, the CAUDAL quality department performed their own control to the product following their protocols and summarising the following conclusions about the pipe:

- From the production point of view, pipe are uniform but with a slight excentricity in thickness. MFI (Melt Flow Index) is also adequate for standard pipe extrusion processes.
- It is estimated an internal pressure resistance at 23 °C of 15–16 bar for 100 h. This is similar to internal pressure resistance of PE100 pipes 32 mm × 2 mm (tube 32 × 10 bar) which withstands 16 bar. However, internal pressure resistance is below PE100 pipes 32 mm × 3 mm (tube 32-16 bar), withstanding 25 bar.
- Tensile strength is slightly lower than that for standard PE100 pipes, but it is enough for the service time and conditions of the pipe for geothermal shallow applications.
- While the presence of some micropores has been observed, attempts are currently being undertaken to eliminate them since the existence of pores limits both mechanical properties and internal pressure resistance.
- Butt welding between pipes from developed compounds and PE100 pipes is compatible.

The rest of parameters determined like OIT (Oxidative Induction Time), longitudinal shrink, black carbon and ash content and black carbon dispersion are suitable for the application.

Table 7
Results derived from the characterization tests.

	Thermal Conduct. ($W/(mK)$)	Flexural properties			MFI[a] ($g/10min)190^oC$,2.16 kg
		Module ($M\ pa$)	Flexural strength ($M\ pa$)	Deflection (nm)	
Standard PE100	0.421	826	21.1	7.2	6.7
Compound 1	1.183	1080	21.0	7.1	7.7
Compound 2	1.021	758	18.0	8.2	4.9

[a] Melt Flow Index (MFI).

4.2. Development of the new grout material

Analogously to the production of thermally enhanced pipes, a new generation of thermally enhanced grouts has also been developed. The target properties of the grout has been defined according to the results of the modeling and numerical simulations that shown that optimal values of thermal conductivity could oscillate between 2.5 W/(mK) and 3.3 W/(mK). Nevertheless, the final properties of the grouts for shallow geothermal applications must fulfill a vast series of standards and rules according to the normative of different countries. After analyzing the different standards, recommendations guides and in force documents (inter alia [15,37–45]), Table 8 is summarising the required values for the grout development based on the different regulations analyzed.

The critical issue is the formulation of a grouting mixture that achieves the range of thermal conductivity defined by the simulations and that complies with the viscosity, flow, bleeding, permeability and compressive strength specifications so essential in this type of grout when used by filling geothermal boreholes. With those premises, the selection of the different raw materials for the grouting included different silica-rich sands with a good granular selection and sizes between 0 and 1 mm; expanded graphite and a filler with a high potential for increasing the thermal conductivity; standard Portland and SR (Sulphate Resisting) cement and finally some additives (superplasticizers and stabilizers) to enhance the rheology of the mixture. Water content was also calculated for covering the fluidicity parameters.

The formulation, preparation and characterization of the samples was performed at RISE [46]. Several hundreds of formulations were performed and tested in order to achieve: in one hand, the expected conductivity values and, at the same time, fulfill the technical requirements stated by the standards. Furthermore, during the development, it was observed that the mixing parameters played also a relevant role in the final properties of the admixtures including not only the experimental values but also the benchmarking studies. In this sense, a deficient mixture procedure may trigger that grouts with declared thermal conductivity of 2 W/(mK) showed values slightly higher than 1.2 W/(mK).

With all those considerations, final grout ready to use after the addition of water in site was prepared and characterized (see Table 8 for final properties), with permeability and freezing-thawing tests done at UBeG [51]. This grout fulfills all the standards in force and shows a thermal conductivity value of 2.93 W/(mK) after mixing according to specifications (colloidal mixer for 4–6 min).

5. Conclusions

Improving substantially the operational efficiency of BHE systems by optimizing the materials for individual components (pipes, grout) and the overall setup has a direct impact on cost savings in installation and operation, allowing for a leap in economic benefits of shallow geothermal technology. Furthermore, a significant reduction of the drilled meters and the amount of pipes used to fulfill the same heating and cooling needs enables a decrease of environmental impact.

As for the parameter sensitivity analysis performed, the results of the simulations that were carried out in the different scenarios are now available for the product developer in order to manufacture the new products under the optimal configurations. Those new product specifications produce reductions of the total length of the boreholes and, subsequently, a reduction of the total costs (CAPEX costs) with the same efficiency of the systems. Furthermore, the correct performance of the installation with a higher coefficient of performance is guaranteed since the conditions of performance have been identical for all the scenarios.

These results have been compared with the current state of the art to calculate the impact in economic terms and evaluate the benefits associated to the expected enhancements. In the tested scenarios (combining different types of buildings, types of ground and types of climates), it was possible to corroborate that the enhancement of the thermal conductivity of the pipe and the grouting products in combination may trigger important reduction of the total BHE length required for the installation, obtaining in simulations of certain cases a reduction in the length required of the borehole heat exchanger of up to 22%.

Moreover, the results have demonstrated that the optimal combination of thermal conductivity for pipes and grouting not always should be the highest possible value, but should be in concordance with the thermal characteristics of the ground. In this

Table 8
Required and achieved grout properties.

Grout Properties	Required range of values	Achieved range of values
Viscosity (Marsh cone time)	50–100s	92–98s
Flow	26–30 cm	27.0–30.2 cm
Bleeding (water separation)	$<2\%$	$<1\%$
Thermal conductivity	2.0–3.0 W/(mK)	2.73–2.91 W/(mK)
Compressive strength	$>1\ N/mm^2$	4.5–7.0 N/mm^2
Density	$>1300\ kg/m^3$	1950–1970 kg/m^3
Heat of hydration (fresh grout temperature)	$<30^oC$	$<30^oC$
Permeability	$<1x10^{10}$	$<1x10^{10}$ m/s
Freezing-thawing (increase of permeability)	<1 order of magnitude	Achieved according to the German Standard VDI 4640
Resistance against aggressive groundwater	Required	Achieved

way, it has been demonstrated that the thermal properties of the grouting products should be adapted to the ground conditions (geological setting) of the place where the geothermal installation will be located. The results show that the implementation of the enhanced products in real installation could produce either a reduction of the total length of the borehole field or an increment of the efficiency of the geothermal system in case that the total length is maintained.

The results achieved in this research therefore constitute a guidance document for the product developers. Finally, for production, techno-logical, economic and optimization reasons, it was decided to manufacture a geothermal plastic pipe with a conductivity of 1.1 W/(mK) and a grout with a conductivity of 2.9 W/(mK). If the results of the thermal tests are satisfactory, these products could soon be on the market, achieving important reductions in the total length to be drilled, resulting in more economical and competitive geothermal installations.

Disclamer

The information and views set out in this article are those of the authors and do not necessarily reflect the official opinion of the European Union. Neither the European Union institutions and bodies nor any person acting on their behalf may be held responsible for the use which may be made of the information contained therein.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Borja Badenes: Conceptualization, Methodology, Visualization, Investigation, Writing - original draft, Writing - review & editing. **Burkhard Sanner:** Conceptualization, Methodology, Writing - original draft, Writing - review & editing. **Miguel Ángel Mateo Pla:** Conceptualization, Methodology, Investigation, Visualization, Software. **José Manuel Cuevas:** Conceptualization, Methodology, Writing - review & editing. **Flavia Bartoli:** Resources, Validation. **Francesco Ciardelli:** Resources, Validation. **Rosa M. González:** Resources, Validation. **Ali Nejad Ghafar:** Resources, Validation. **Patrick Fontana:** Resources, Validation. **Lenin Lemus Zuñiga:** Software, Supervision. **Javier F. Urchueguía:** Conceptualization, Methodology, Writing - original draft, Funding acquisition, Writing - review & editing, Supervision.

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Abbreviations

BHE	Borehole Heat Exchanger
SGES	Shallow Geothermal Energy Systems
GSHP	Ground Source Heat Pump
HVAC	Heating, Ventilation and Air Conditioning
TRT	Thermal Response Test
PCM	Phase Changing Materials
ATES	Aquifer Thermal Energy Storage
UTES	Underground Thermal Energy Storage
BTES	Borehole Thermal Energy Storage
PE-pipe	Polyethylene pipe
PB	Polybutylene
HDPE	high-density polyethylene
EED	Earth Energy Designer (PC-program)
R_b	Borehole thermal resistance
$\lambda_{element}$	Thermal Conductivity of *element*

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