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Efficiency of closed loop geothermal heat pumps: a

sensitivity analysis

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10   **Abstract**

11   Geothermal heat pumps are becoming more and more popular as the price of fossil fuels is

12   increasing and a strong reduction of anthropogenic CO_2 emissions is needed. The energy

13   performances of these plants are closely related to the thermal and hydrogeological properties of the

14   soil, but a proper design and installation also plays a crucial role. A set of flow and heat transport

15   simulations has been run to evaluate the impact of different parameters on the operation of a GHSP.

16   It is demonstrated that the BHE length is the most influential factor, that the heat carrier fluid also

17   plays a fundamental role, and that further improvements can be obtained by using pipe spacers and

18   highly conductive grouts. On the other hand, if the physical properties of the soil are not surveyed

19   properly, they represent a strong factor of uncertainty when modelling the operation of these plants.

20   The thermal conductivity of the soil has a prevailing importance and should be determined with in-

21   situ tests (TRT), rather than assigning values from literature. When groundwater flow is present, the

22   advection should also be considered, due to its positive effect on the performances of BHEs; by

23   contrast, as little is currently known about thermal dispersion, relying on this transport mechanism

24   can lead to an excessively optimistic design.

25

2

1. Introduction

30 Ground Source Heat Pumps (GSHP) are space heating and cooling plants which exploit the soil as a

31 thermal source or sink, through the circulation of a heat carrier fluid in a closed pipe loop. Different

32 pipe arrangements are available, among which the most common is the Borehole Heat Exchanger, a

33 vertical pipe loop reaching depths of 50 to 200 m (Fig.1). Below a depth of a few meters from the

34 ground surface, the seasonal variation of the air temperature disappears due to the large thermal

35 inertia of the soil. Therefore, if compared to the air, the soil is a warmer source for heating during

36 winter and a cooler sink for cooling during summer, and higher system efficiencies can therefore be

37 achieved compared to Air Source Heat Pumps.

38 GSHPs are rapidly spreading in Europe, China and USA, and have a great potential for energy, cost

39 and CO_2 emission saving [1]. About 100,000 low-enthalpy geothermal plants are installed every

40 year in Europe, mainly for new dwellings in Sweden, Germany and France [2, 3]. According to

41 Saner et al. [4], the use of GSHP in place of methane furnaces allows the CO_2 emissions to be

42 reduced by up to 84%, depending on the sources used for the production of electricity. From the

43 economic point of view, the geothermal heat pumps lead to a considerable reduction of the

44 maintenance costs and, although their installation is more expensive than the other heating and

45 cooling plants, the payback periods proved to be reasonable, i.e. less than 10 years [5-7].

46 Since the thermal exploitation of the soil induces a gradual temperature drift, an accurate heat

47 transport modelling of soil and aquifer systems is essential for a correct design of GSHPs. Indeed,

48 the efficiency of the heat pump is strongly influenced by the temperature of the heat carrier fluid,

49 which in turns depends on the temperature of the surrounding soil. To estimate the thermal impact

50 of BHEs and the working temperatures of the heat carrier fluid, different methods have been

51 developed, which can be divided into analytical, semi-analytical and numerical.

52 The Kelvin infinite line source [8] and the infinite cylindrical source [9] are the simplest analytical

53 methods for estimating the thermal disturbance induced by a BHE, since they rely on the

54 assumption of a purely conductive and radial heat transport. Their main limitation is that of not

55 accounting for the vertical thermal gradient and fluxes [10] and for the heterogeneity of the heat

56 exchange over the length. Moreover, the advective and dispersive heat transport occurring in

57 aquifer systems is also neglected. Nevertheless, these analytical solutions are still widely used for

58 the interpretation of Thermal Response Tests [11], since they last for a short time (48÷72 h) and

59 therefore the vertical heat transport can be neglected. The subsurface flow and the seasonal changes

60 of groundwater levels can significantly alter the results of a TRT, as pointed out by Bozdağ et al.

61 [12]. To overcome this problem, Wagner et al. [13] recently developed a method for the

62 interpretation of TRTs in the presence of strong groundwater flow.

63 The semi-analytical method proposed by Eskilson [14] takes into account the finite length of the

64 exchanger and different BHE field layouts, but the advection and the dispersion are neglected. This

65 method is applied by two of the most popular BHE design software programmes, Earth Energy

66 Design [15] and GLHEPRO [16].

67 Analytical models which take into account the beneficial effects of groundwater flow [17], of the

68 finite length of the BHE [18], and both them together [19] have been developed in the last few

69 years, and they could be used in the future for the dimensioning of BHE fields.

70 Recently, numerical modelling has often been applied to the design of BHE fields. The finite-

71 difference modelling software MODFLOW can be used coupled with the solute transport package

72 MT3D (or MT3DMS) and by applying the analogy between heat and solute transport [20, 21], or

73 with the specific heat transport package SEAWAT [22]. On the other hand, the finite element

74 software FEFLOW includes a special package for the simulation of BHEs [23, 24] which is

75 particularly suitable for non conventional BHE field layouts and for taking into account the thermal

76 advection and dispersion in aquifer systems.

77

78 The heat transport simulation of GSHPs permits the assessment of their performances, which are

79 influenced by the properties of the exchanger and the thermo-hydrogeological parameters of the

80   soil. According to Chiasson et al. [25], groundwater flow significantly enhances the performances

81   of BHEs, and the Peclet number is a good indicator for whether advective transport needs to be

82   taken into account or neglected. Wang et al. [26] have developed a method to estimate the velocity

83   of groundwater movement measuring the temperature profiles in a BHE. Lee [27] has investigated

84   the effect of vertical heterogeneities of the soil thermal conductivity, concluding that the adoption

85   of depth-averaged thermal parameters is appropriate. Chung and Choi [28] have found that an

86   increase of the fluid flow rate reduces the heat transfer rate per unit length. Delaleux et al. [29] have

87   studied the increase of the thermal conductivity of grouts with the addition of graphite flakes,

88   concluding that a noticeable heat transfer improvement is achieved by BHEs. Jun et al. [30] have

89   evaluated the influence of running time, pipe spacing, grout conductivity, borehole depth, fluid flow

90   rate, inlet fluid temperature and soil type on the heat transfer length and on the thermal resistance of

91   borehole and soil. Michoupoulos and Kiriakis [31] have found a non-linear relation between the

92   BHE length and the heat pump consumption, which can be used for optimization processes in the

93   dimensioning of large plants. The aforementioned studies deal with single or few parameters, but a

94   thorough comparative analysis of all these factors together is still missing, and constitutes the

95   objective of this work. The functioning of a single BHE was simulated for 30 years, using a

96   benchmark cyclic thermal load and changing the operational parameters of the scenario. The

97   resulting fluid temperatures at the end of the BHE were processed and used to estimate the COP of

98   the heat pump and its annual energy consumption under different conditions. On the basis of the

99   results it is possible to draw some practical conclusions on the margins of improvement of BHEs

100   and on the proper choice of soil parameters for the simulations.

101

102   **2. The modelling framework**

103   The sensitivity analysis has been carried out on the design parameters of the BHE (geometrical

104   setting, properties of the materials, flow rate etc.) and on the physical properties of the soil and the

105   aquifer (thermal conductivity, groundwater flow velocity etc.), with the aim of evaluating their

106   relative impact on the performances of a GSHP (i.e. evolution of the heat carrier fluid temperatures,

107   energy consumption of the heat pump) in a realistic scenario and in long-term perspective.

108   The case study involves the simulations of the heating system of a house in the North of Italy, with

109   a heated surface of 150 m^2 and a good thermal insulation. A geothermal heat pump connected to a

110   BHE with a single U-pipe configuration is used only for heating. A cyclic thermal load (see Fig.2)

111   has been set , with a total heat abstraction of 12 MWh per year (80 kWh $m^{-2}y^{-1}$), which is equivalent

112   to the energy produced by 1200 m^3 of methane or 1250 l of gasoil using an efficient condensation

113   boiler. The simulations last for 30 years, which is a sufficiently long time span to assess the long-

114   term sustainability of the thermal exploitation of the soil.

115

116   The simulation of the heat exchange of the BHE with the soil and the aquifer system has been

117   performed with FEFLOW 6.0, a 3D finite element flow and solute/heat transport model [32, 33]

118   that includes specific tools for the simulation of Borehole Heat Exchangers [23, 24]. The software

119   solves the coupled equations of flow and heat transport in the soil, and the BHE is modelled as an

120   internal boundary condition of the 4th kind (thermal well).

121   The heat transport occurs by conduction (driven by thermal gradients), advection (due to the

122   groundwater flow) and dispersion (due to deviations from the average advective velocity), which

123   are described by the heat conservation equation in the porous medium:

124
$$\frac{\partial}{\partial t}\left[\left(\varepsilon\rho_w c_w +(1-\varepsilon)\rho_s c_s\right)T\right]+\frac{\partial}{\partial x_i}\left(\rho_w c_w q_i T\right)+\frac{\partial}{\partial x_i}\left[\left(\lambda_{ij}^{cond}+\lambda_{ij}^{disp}\right)\frac{\partial T}{\partial x_j}\right]=H$$

125   1

126   where ε is the porosity, ρ_s and ρ_w are the density of the solid and liquid phase, c_s and c_w are the

127   specific heat of the solid and liquid phase, T is the temperature (which has been assumed equal for

6

128 both the phases), x_i is the i-th axis (i.e. $x_1 \equiv x$, $x_2 \equiv y$, $x_3 \equiv z$) and q_i is the i-th component of the

129 Darcy velocity (i.e. relative to the i-th axis), and H is the heat source or sink (the BHE in this case),

130 The first term of Eq.1 describes the soil temperature variation with time, involving the porosity ε

131 and the heat capacity of the solid matrix $(\rho c)_s$ and of water $(\rho c)_w$.

132 The second term describes the advection, which depends on the Darcy velocity q.

133 The conduction and dispersion are respectively described by the tensors of the thermal conductivity

134 λ_{ij}^{cond} and λ_{ij}^{disp} (third term of Eq.1):

$$\lambda_{ij}^{cond} = \begin{cases} (1-\varepsilon)\lambda_s + \varepsilon\lambda_w & for\ i = j \\ 0 & for\ i \neq j \end{cases}$$

136   2

$$\lambda_{ij}^{disp} = \rho_w c_w \left[\alpha_T q \delta_{ij} + (\alpha_L - \alpha_T)\frac{q_i q_j}{q} \right]$$

138   3

139 where λ_s and λ_w are the thermal conductivities of the solid matrix and of groundwater, α_L and α_T

140 are the longitudinal and the transverse dispersivity (with respect to the direction of groundwater

141 flow) and q is the modulus of the Darcy velocity.

142

143 The temperature of the soil at the borehole wall, calculated by the 3D finite-element modelling

144 code, is used to solve the balance of the thermal fluxes inside the BHE according to the Thermal

145 Resistance and Capacity Model (TRCM) of Bauer et al. [34]. The BHE is decomposed into

146 different elements (inlet and outlet pipe, grout zones, borehole wall), which are represented by the

147 nodes of the circuit, connected by thermal resistances, which depend on the geometrical settings and

148 the physical properties of the materials. Thermal energy conservation equations are solved, which

149 describe the balance of thermal fluxes between the components of the BHE, and the temperature of

150 each component is calculated [23]. Since no abrupt changes occur in the thermal load, the analytical

151　method based on Eskilson and Claesson's solution [35], which considers a stationary equilibrium

152　between the soil and the BHE, has been used in the simulations in order to reduce the computational

153　time if compared to the Al Khoury et al.'s [36, 37] transient model.

154

155　A very large square mesh domain, with a side of 1000 m and a thickness of 150m, has been used to

156　avoid boundary effects on the computed BHE fluid temperatures. The 31 flat slices are equally

157　spaced (5m of distance) and the total number of nodes is 15531. The mesh density has been set

158　using the "BHE node rule" [38], positioning the nodes around the BHE on the vertexes of a regular

159　hexagon, with a radius of 0.46 m (6.13 times the borehole radius), since Diersch et al. [24] proved

160　that this mesh density achieves a higher precision in the results, even when compared with finer

161　meshes.

162

163　The thermal balance of the soil around the BHE has been reproduced choosing appropriate

164　boundary conditions. The temperature of the soil is almost constant through the year and, at an

165　infinite distance from the BHE, it is not affected by the thermal exchange. Constant temperature

166　values (1st kind heat transport b.c.) have therefore been imposed at the lateral boundaries of the

167　domain, at least 500 m far away from the BHE. The heat flux coming from the deep layers of the

168　Earth (geothermal flux), which has a mean value of 0.065 Wm^{-2} on the continental crust [39],

169　induces a temperature vertical gradient with typical values around 0.03 °C/m. According to these

170　considerations, a temperature of 12°C has been set at the border or the first slice (which is a typical

171　value of the annual mean air temperature in Northern Italy), incrementing the temperatures of

172　0.15°C every 5m of depth (0.03 °C/m). The initial conditions have been set consistently with the

173　boundary conditions, with a homogeneous distribution of the soil temperature at each slice.

174

175　An unconfined aquifer, with a water table depth of 20m in the centre of the mesh (where the BHE is

176　positioned), has been modelled assigning constant hydraulic head (1st kind) flow boundary

177 conditions along the mesh borders. A homogeneous and isotropic hydraulic conductivity

178 ($K = 10^{-4} \, m/s$) has been assigned, and different hydraulic gradients, ranging between 1‰ and 20‰,

179 have been imposed to change the groundwater flow velocity. Also different values of the saturated

180 thickness of the phreatic aquifer have been adopted, ranging from 10m to 50m in the middle of the

181 mesh, where the BHE is located.

182

183 A large set of simulations has been run in order to ascertain the influence of design parameters

184 (length, pipe spacing, pipe diameter, heat carrier fluid and its flow rate, grout thermal conductivity),

185 soil thermal (thermal conductivity of the solid matrix, thermal dispersivity) and hydrogeological

186 properties (groundwater flow velocity, aquifer saturated thickness) on the performances of a BHE

187 over a long operation period (30 years).

188 The adopted values of the BHE length range between 50 and 100 m, using a default value of 75 m.

189 The borehole diameter is 0.15 m for all the simulations, and the HDPE pipes have an external

190 diameter of 32mm and a wall thickness of 2.9 mm. The pipe spacing depends on the kind of spacers

191 and from the pipe curvature given by the coil shape, which they keep even when they are unrolled:

192 it varies therefore with depth and could not be known precisely. Different values have therefore

193 been adopted, ranging from 35 to 117 mm between the pipe centres.

194 A set of simulation has been run to assess the performances of the most commonly adopted heat

195 carrier fluids, and also different flow rates have been assigned (0.1÷0.7 ls^{-1} with propylene glycol at

196 25% weight concentration). The default fluid is calcium chloride at 20% weight, which proved to be

197 the most performing one.

198 The thermal conductivity of the BHE filling can vary in a wide range, and values between 1 and 5

199 Wm^{-1}K^{-1} have therefore been adopted, while its thermal capacity does not experience great

200 variations, and hence a unique value (2 MJm^{-3}K^{-1}) has been used for all the simulations.

201   Some of the thermal and hydrogeological parameters of the soil have been kept constant for all the

202   simulations, like the thermal properties of water ($\lambda_w = 0.6\,Wm^{-1}K^{-1}$ and $(\rho c)_w = 4.2\,MJm^{-3}$), the

203   thermal capacity of the soil solid phase ($(\rho c)_w = 2.52\,MJm^{-3}$) and both the total and the effective

204   porosity (respectively $\varepsilon = 0.3$ and $n_e = 0.2$), while the others have been changed to assess their

205   influence on the performances of the geothermal systems. As the heat transport occurs by

206   conduction, advection and dispersion, large ranges of the solid phase thermal conductivity (1÷3

207   Wm^{-1}K^{-1}), the Darcy velocity of groundwater (0÷17.32 md^{-1}) flow and the longitudinal/transverse

208   thermal dispersivity (0÷5 m) have therefore been investigated.

209

210   The time series of the borehole fluid temperatures (Fig.3A) have been processed, calculating a

211   cumulative temperature distribution (Fig.3B) during the heating seasons over the whole simulation

212   period (30 years), which serves as a synthetic indicator to compare the different cases and to draw

213   conclusions on the energetic performance of the system. Observing the fluid temperature duration

214   curves in Fig.4 and Fig.5, one can understand how long will the heat pump work in a certain source

215   temperature range. For example, Fig.4A shows that, for a 75m long BHE, the mean fluid

216   temperature is below 0°C for the 19.51% of the heating period (say, 41.37 days a year), while this

217   percentage rises up to 50.86% for a 50m long borehole (107.83 days a year).

218

219   The Coefficient of Performance (COP), which is the ratio between the heating power delivered to

220   the building and the electrical power absorbed by the heat pump, depends on the temperatures of the

221   heat source (the BHE fluid) and of the heat sink (the heating terminals of the building). The

222   relationship of COP from fluid temperatures has been approximated with a linear formula:

223   $$COP = a + b \cdot T_f$$

224   4

10

225   where T_f is the average fluid temperature between the inlet and outlet pipes of the BHE, while a

226   and b depend on the heating terminal. For this study, we have set $a = 4$ and $b = 0.1\,K^{-1}$, which are

227   typical values for radiant panels at 35°C.

228   The estimated COP values at each time step (COP_i) have been used to calculate the energy

229   consumption of the heat pump:

230
$$HPC = \sum_{i=1}^{n} \frac{BHL_i}{COP_i} \cdot \Delta t$$

231   5

232   where BHL_i is the value of the BHE heat load at the i-th time step and Δt is the length of the

233   constant time step (1 day). The electricity consumed by the heat pump gradually increases, as the

234   soil and the BHE fluid is gradually cooling: the average value of yearly electricity consumption in

235   the operation period (30 years) has been therefore used to evaluate the energy performance of the

236   different BHE settings (Fig.6).

237

238   **3.   Results and discussion**

239   The results of the long-term BHE simulations have been processed and compared in order to

240   understand which is the relative importance of each parameter on the performances of the system

241   and which is the margin of error due to the uncertainty in its determination, in particular for soil

242   properties. Statistics about the calculated fluid temperatures (average, RMSE), the Seasonal

243   Performance Factor (SPF) and the heat pump consumption for each simulation are summarized in

244   the tables reported in the supporting information.

245

246   The length of the Borehole Heat Exchanger(s) plays a crucial role in the design process, because it

247   accounts for about half of the total installation cost in single-house plants (see Blum et al. [40]).

248   Varying the BHE length between 50 and 100m, we observe a strong variation of the cumulate

249 distributions of the average fluid temperatures (Fig.4A) and of the value of the minimum fluid

250 temperature, which is a critical parameter in the operation of a GSHP. The effect of the length

251 increase is non-linear and diminishes for larger BHE sizes: for example, incrementing the length by

252 between 50 and 75 m results in an increment of 2.80°C in the mean temperature, and of 1.58°C

253 when the increment is from 75 m to 100 m; the minimum inlet temperatures are incremented

254 respectively by 4.15°C and 1.92°C in the same ranges. The differences in the distributions of fluid

255 temperatures also have a noticeable impact on the energy expense of the heat pump, as shown in

256 Fig.6A. As for the cumulate distributions of the fluid temperatures, the effect of additional BHE

257 length is reduced as the borehole depth increases (- 5.88% between 50 m and 75 m, -2.77% between

258 75 m and 100 m).

259

260 The improvement of the energy performance with longer exchangers is compensated by a rise in the

261 installation costs, which are the main drawback of geothermal heat pumps. In the dimensioning of

262 BHE fields, usually a minimum and/or maximum fluid temperature constraint is imposed, and the

263 minimum required borehole size is calculated [15, 16]. This approach minimizes the installation

264 costs, but the maintenance costs are not taken into account, and the extra-cost due to a low COP can

265 overcome the initial saving incurred with a smaller drilled depth. Starting from the results of the

266 sensitivity analysis on the length of the BHE, we have considered the typical electricity and BHE

267 installation costs of Italy (see Tab. 2) and calculated the total costs of installation and maintenance

268 of the GSHP over a lifetime of 30 years. Since the unit cost of electricity is likely to increase over

269 the next few decades, the analysis took into account different increase rates, in the range

270 between0% and 5%. In Fig.7, the ration between the lifetime cost for each BHE length and the most

271 expensive solution for each scenario of energy cost increase is shown, to identify the optimal size

272 for each case. We observe that higher increments of the unit cost of electricity enlarge the optimal

273 range of the BHE length, and shift it towards larger values; although it is not shown in the graph, a

274 decrease of the drilling cost also achieves the same effect. GSHPs need larger investments

12

275   compared to the other heating and cooling plants, and loan rates have been also considered when

276   evaluating the optimal length. Nevertheless, the influence of the interest rate on the total cost of the

277   plant over its lifetime proved to be negligible, compared to the cost of electricity and its increasing

278   trend.

279   A default length of 75 m was used in the other simulations, since it proved to be a reasonable choice

280   for most of the scenarios depicted in Fig.7. The considerations on BHE length that we have made

281   here concern only the lifetime cost of the plant, without taking into account the effects of very low

282   fluid temperatures. For example, if a GSHP operates at temperatures below 0°C for a sufficiently

283   long time, ground freezing can occur, and the borehole grouting can be fractured by freezing-

284   thawing cycles. In addition, the viscosity of the heat carrier fluid increases as the temperature

285   decreases, therefore the energy consumption of the circulation pump also increases. A low

286   temperature threshold should therefore be established, which excludes some of the BHE lengths

287   considered in this analysis: for example, setting a minimum inlet temperature of -3°C excludes

288   lengths below 70 m.

289

290   Although the borehole depth exerts the greatest influence on the economic balance of a BHE

291   installation, there are also other factors which have to be taken into account. In the U-pipe BHEs

292   (both single and double), which are the most diffused kind of installation, the pipes should be put as

293   far as possible, to reduce both the thermal resistance of the exchanger and the heat exchange

294   between the inlet and the outlet pipes (thermal short-circuit), which impair the performances of

295   these systems. The thermal conductivity of the borehole filling plays an important role: a higher

296   value reduces the borehole resistivity, but also the grout-to-grout resistance, which prevents the

297   thermal short-circuit. Both these factors have been taken into account in the simulations, according

298   to the borehole resistance model of Bauer et al. [34]. The distance between the pipe centres has

299   been varied between 35 mm (i.e. 3 mm between the pipe walls) and 117 mm (i.e. 0.5 mm between

300   the pipe wall and the borehole wall), and the thermal conductivity of the grout has been varied

13

301   between 1 $Wm^{-1}K^{-1}$ (i.e. a poor grout) and 5 $Wm^{-1}K^{-1}$ (i.e. special grouts with highly conductive

302   graphite flakes [29]). Usually, the grouts employed for BHEs have a thermal conductivity of 2÷2.5

303   $Wm^{-1}K^{-1}$, but this value can dramatically decrease due to an incorrect mixing, an excessive water

304   content or an insufficient concentration of thermal additives [41]. Observing the cumulate

305   distributions of the fluid temperatures (Fig.4B-C), we understand that the influence of the thermal

306   conductivity of the grout is very large when the pipe spacing is reduced; on the other hand, a grout

307   with a high thermal conductivity can compensate the negative effects of an insufficient pipe spacing

308   on both the minimum fluid temperatures and the energy consumption of the system (Fig.6B). For

309   example, if a common geothermal grout is used ($\lambda_g = 2 Wm^{-1}K^{-1}$), the consumption of the heat

310   pump diminishes of the 1.99% as the pipe distance is increased from 35mm to 117 mm; on the other

311   hand, if a highly conductive grout ($\lambda_g = 5 Wm^{-1}K^{-1}$) is used, this difference is reduced to the 0.64%,

312   meaning that special grouts noticeably reduce the effect of an insufficient pipe spacing.

313

314   The fluid circulated into the closed pipe loop is usually a mixture of water and antifreeze. The flow

315   rate and the physical properties of this fluid (viscosity, thermal capacity, thermal conductivity)

316   influence the borehole thermal resistance [42]. The main drawbacks of increasing the concentration

317   of the antifreeze additive are a noticeable increase of viscosity, a slight decrease of the thermal

318   conductivity and an additional cost (say 2÷4 €/l, depending on the kind of ethanol or glycol); in

319   addition, the antifreeze is a potential source of contamination in case of a pipe leak, and the anti-

320   corrosion additives can inhibit the bacterial degradation [43]. All these adverse side effects should

321   be minimized when choosing the anti-freeze additive. Simulations have been carried out

322   considering the most common anti-freeze mixtures: propylene glycol (PG) at 25% and 33% volume

323   concentration, ethanol (ETH) at 24% vol., calcium chloride ($CaCl_2$) at 20% weight concentration.

324   Their physical properties are reported in Tab. 1, where also the boundaries of the laminar and of the

325   turbulent regime are shown, since the thermal resistance is much smaller in turbulent one [42]. The

14

326   default flow rate is 0.5 ls^{-1}, which is a typical value for GSHPs. The results (Fig.4D and Fig.6C)

327   show that calcium chloride solutions permit to achieve an appraisable gain in the energy

328   performance (compared to PG25%, minimum temperature: +2.94°C; heat pump consumption: -

329   4.01%), due to their smaller viscosity and their higher thermal conductivity; in addition, it is much

330   cheaper than the other antifreeze additives. On the other hand, the use of saline solutions as a heat

331   carrier fluid requires the adoption of specific anti-corrosion components.

332   The other antifreeze mixtures show negligible variations of the fluid temperatures and of energetic

333   performances. As the thermal resistance diminishes when higher flow rates are circulated, seven

334   simulations (fluid: PG25%, flow rates: 0.1÷0.7 ls^{-1}) have been run to quantify its contribution for a

335   better efficiency of the GSHP. We observe that the energy consumption of the heat pump is reduced

336   of the 4.4% between 0.1 and 0.7 ls^{-1}; nevertheless, circulating larger flow rates implies also a higher

337   energy expense for the circulation pump. We have therefore quantified the distributed friction losses

338   along the 75m long using the explicit approximation of the Prandtl formula (Eq.6) for smooth pipes:

339

$$\lambda_0 = \frac{0.25}{\left[\log_{10} \left(\frac{5.7}{\mathrm{Re}^{0.9}} \right) \right]^2}$$

340   6

341   where $\lambda_0 = 2g \frac{d_{ip}}{u^2} \cdot J$ is the non dimensional friction loss, d_{ip} is the pipe internal diameter, g is the

342   gravity acceleration, J is the hydraulic gradient in the pipes.

343   The energy consumption of the circulation pump increases rapidly with the fluid flow rate (Q_f):

344

$$CPC = \frac{J \cdot 2L \cdot \rho_f \cdot g \cdot Q_f}{\eta} \cdot t_{func} = \frac{16 \cdot \lambda_0 \cdot L \cdot \rho_f \cdot g}{\eta \cdot \pi^2 \cdot D^4} Q_f^{\ 3} \cdot t_{func}$$

345   7

346   where ρ_f is the density of the heat carrier fluid, L is the BHE length [L] and t_{func} is the operation

347   time per year. An energy yield $\eta = 0.8$ has been assumed for the calculation of CPC.

348 Fig.8 shows the strong impact of the flow rate on the total energy consumption (circulation and heat

349 pump). In particular, a strong variation occurs when switching from laminar to transition regime

350 (between 0.2 and 0.3 l/s), with a reduction of 2.07% for the total energy consumption, while the

351 minimum values lie in a range of flow rates (for this case, 0.3÷0.5 ls^{-1}). Noticeable differences are

352 observed in the minimum temperature, meaning that higher flow rates can be adopted when larger

353 amounts of heat are extracted from the soil, in order to avoid the freezing of the ground, or to

354 reduce its extent.

355

356 While the design parameters can be determined with an acceptable precision, the real issue of

357 GSHP modelling is the knowledge of the physical parameters of the soil. The heat transport around

358 the BHE is mainly conductive, especially if no significant groundwater flow occurs, therefore the

359 most important soil physical parameter is the thermal conductivity of the porous medium λ_{ij}^{cond} (see

360 Eq.2).

361 The thermal conductivity of the solid matrix (λ_s) is the parameter which can vary in the widest

362 range, depending on the lithology, the grain size, the water saturation etc.. A wide range of values

363 has been explored in the simulations (1÷3 Wm^{-1}K^{-1}), and the graphs of the cumulate distribution of

364 the fluid temperatures (Fig.5E) and of the heat pump energy consumption (Fig.6D) show that

365 thermal conductivity has a very strong influence on the performances of the system, compared to

366 the BHE length. Especially in smaller installations, this parameter is not measured in situ, but low-

367 precision data from literature are adopted (e.g. the German norm VDI 4640 [44]). For example, the

368 thermal conductivity of a moraine ranges between 1 and 2.5 Wm^{-1}K^{-1}, for which we observe a

369 difference of 5.66°C in the minimum temperature, and 12.5% in the power consumed by the heat

370 pump. An imprecise knowledge of this parameter results therefore in a strong uncertainty in the

371 simulation of the plant, which has to be overcome e.g. with a Thermal Response Test [45].

372

373 The presence of a subsurface flow has been proved to be beneficial for the performances of closed-

374 loop geothermal heat pumps. Indeed, groundwater flow activates advection and thermal dispersion,

375 enhancing the heat transport around the BHE and spreading the thermal disturbance further away.

376 Chiasson et al. [25] demonstrated that the advection has a considerable impact only in coarse-

377 grained soil (sands and gravels) and in fractured aquifers (e.g. karst limestone), while Wang et al.

378 [26] stressed the importance of the saturated thickness, which can vary through the year, influencing

379 also the results of Thermal Response Tests [12]. A set of simulations with different flow velocities

380 and saturated thicknesses has been run therefore to quantify the positive effect of groundwater flow

381 in a typical sand aquifer ($K = 10^{-4} m/s$).

382 As shown in Fig.5B-C and Fig.6E, the influence of the Darcy velocity on the performances of the

383 system is much stronger than the variation induced by different saturated thicknesses. This means

384 that the contribution of the advection can be taken into account, but precise values are needed to

385 avoid undersized design; on the other hand, variations in the saturated thickness - e.g. due to

386 seasonal level variations in surface water bodies - do not exert a strong influence on the operation

387 of GSHPs, if the gradient does not experience significant variations.

388

389 When modelling heat transport in an aquifer, one should consider also the dispersion, which is a

390 strong mechanism of heat transport. The thermal dispersivity has been considered as a scale-

391 dependent parameter, as reported in literature [46]. Sethi and Di Molfetta [21] adopted $\alpha_L = 10\,m$

392 and $\alpha_T = 1\,m$ for the heat transport simulation around a municipal solid waste landfill. Erol [47]

393 assumed $\alpha_L = 2\,m$ and $\alpha_T = 0.2\,m$ for the simulation of a 100 m long BHE. Molina-Giraldo et al.

394 [48] analyzed the extension of the thermal plume downstream of a BHE, for different values of

395 groundwater flow Darcy velocity ($q = 10^{-8} \div 10^{-5}\ m/s$) and for different values of thermal

396 dispersivity ($\alpha_L = 0 \div 2m$), discovering that thermal dispersion reduces the extent of a reference

397 isotherm (e.g. +1°C) of the deviation from the undisturbed soil temperature.

17

398 Wagner et al. [49] also analyzed the effect of α_L for Thermal Response Tests in presence of

399 groundwater flow, concluding that thermal dispersion can lead to a strong overestimation of the

400 thermal conductivity of the soil. This is confirmed by the cumulate distribution of the average fluid

401 temperatures for a Darcy velocity of 4.32 m/day (Fig.5D), which prove that the thermal dispersion

402 is a great factor of uncertainty when modelling BHE fields in presence of subsurface flow. A rule of

403 thumb that is usually employed in the solute transport [50] is:

404
$$\alpha_L = 0.1 L_p$$

405
$$8$$

406 where L_p is the spatial scale of the dispersion phenomenon. The concept of "scale" is not

407 univocally defined for GSHPs: using the BHE diameter (i.e. $\alpha_L = 0.1m$ or less) or its length (i.e.

408 $\alpha_L = 10m$) would imply a difference of some 8÷10°C for the minimum fluid temperature and more

409 than 15% for the electricity consumption of the heat pump (see Fig.6F). It is therefore advised not

410 to rely on thermal dispersion when designing BHE fields, until field tests will be carried to estimate

411 the thermal dispersivity in real-scale setups: especially if a thick and conductive aquifer is present,

412 the overestimation of the thermal dispersivity would lead to an under-dimensioning of the GSHP

413 with a detrimental effect on its long-term sustainability.

414

415 **4. Conclusions**

416 In this work, the most important parameters which influence the performances of Ground Source

417 Heat Pumps have been thoroughly analyzed, running long-term simulations and estimating the

418 energy consumption of the heat pump for each setting. Most of these factors have been already

419 analyzed in other works, but none of them considered all the parameters together, using the same

420 modelling framework and considering the effect on the lifetime of a GSHP. The analysis of the

421 BHE design parameters (length, pipe spacing, fluid, grout) permits to understand which are the

422 margins of improvement, while the physical parameters of the soil (thermal conductivity and

423 dispersivity, groundwater flow) have been analyzed in order to understand their effect on the

424 uncertainty in the project phase.

425 The results of the simulations prove that the length of the BHE is the most important parameter in

426 the design of a GSHP. Indeed, increasing the borehole depth results in a reduction of the thermal

427 disturbance in the subsoil and therefore to achieve a higher efficiency of the heat pump, but also a

428 larger investment is needed for the installation.

429 An optimum length should be found, which minimizes the total cost over the plant lifetime,

430 considering also the trend of increase of the unit cost of electricity. While the drilled depth has an

431 appraisable impact on the initial investment, there are also other important factors to be considered

432 for the optimization of BHEs, like the pipe arrangement, the grout and the heat carrier fluid. A large

433 pipe spacing and a highly conductive grout, reducing the heat losses in the heat exchange with the

434 soil, achieves an appraisable reduction of the energy costs for the heat pump with a negligible

435 expense, compared to the borehole drilling. For the circulation pump, a trade-off can be found for

436 the choice of the correct flow rate for the heat carrier fluid, allowing the minimization of both the

437 energy losses due to the thermal resistance and the friction losses due to the circulation of the fluid.

438 The antifreeze and its concentration heavily influence the energy performance of GSHPs, in

439 particular the borehole resistance and the power consumed by the auxiliary plants. The saline

440 solutions, with a smaller viscosity compared to ethanol and glycols, permit to reduce all these

441 energy losses, although special components are needed to avoid corrosion problems. Optimizing the

442 design and the installation of BHEs is useless without a thorough characterization of the subsoil,

443 which has a large influence on the performances of these systems. When no groundwater flow

444 occurs, the thermal conductivity is the most important parameter for the dimensioning of BHEs.

445 The technical literature provides wide ranges of the thermal conductivity for each lithology, which

446 can vary due to porosity, saturation and other factors; in-situ Thermal Response Tests are therefore

447 strongly advised for large plants to avoid under or over dimensioning. The advection enhances the

448 performances of GSHP, and the groundwater flow should be taken into account using conservative

19

449   values of hydraulic conductivity and gradient, unless they are known by field tests. On the other

450   hand, it is risky to consider also the beneficial effect of heat dispersion, because the thermal

451   dispersivity is still scarcely known in real-scale BHEs. In situ tests to estimate these parameters

452   would be highly desirable to simulate the behaviour of BHE fields with a better precision.

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565
566

Nomenclature

568 BHL Total annual BHE Heat Load (kWh y^{-1})

569 BHL_i BHE Heat Load at the i-th time step (kW)

570 c_f Groundwater specific heat (J kg^{-1} K^{-1})

571 c_s Aquifer solid matrix specific heat (J kg^{-1} K^{-1})

572 COP Coefficient of Performance of the heat pump (dimensionless)

573 CPC Circulating Pump Consumption (kWh y^{-1})

574 d_{ip} Internal pipe diameter (m)

575 d_{op} External pipe diameter (m)

576 g Gravity acceleration (m s^{-2})

577 H Heat source/sink (W/m^3)

578 HPC Total annual Heat pump energy consumption (kW y^{-1})

579 HPC_i Power consumed by the heat pump at the i-th time step (kW)

580 $-\dfrac{\partial h}{\partial x}$ Hydraulic gradient in the aquifer (dimensionless)

581 J Hydraulic gradient in the BHE pipes (dimensionless)

582 K Hydraulic conductivity of the aquifer (m s^{-1})

583 L Length of the BHE (m)

584 L_p Scale dimension (m)

585 n_e Effective porosity or specific yield of the aquifer (dimensionless)

586 Q_f Flow rate of the heat carrier fluid (l s^{-1})

587 q Darcy velocity of groundwater flow (m s^{-1})

588 q_i i-th component of the Darcy velocity (m s^{-1})

589   Re   Reynolds number (dimensionless)

590   RMSE   Root Mean Square Error

591   T Temperature of the soil, both solid and fluid phase (°C)

592   T_f Average fluid temperature (°C)

593   t_{func} Functioning time of the circulation pump (d y^{-1})

594   T_{in} Inlet fluid temperature (°C)

595   T_{out} Outlet fluid temperature (°C)

596   T_s Soil temperature at the borehole interface (°C)

597   u Flow velocity in the BHE pipes (m s^{-1})

598   w Distance between the centres of the pipes in a BHE (m)

599   **Greek letters**

600   α_L Longitudinal thermal dispersivity (m)

601   α_T Transverse thermal dispersivity (m)

602   ε Porosity of the soil (dimensionless)

603   η Energy yield (dimensionless)

604   λ_0 Non-dimensional friction loss (dimensionless)

605   λ_f Thermal conductivity of the heat carrier fluid (W m^{-1} K^{-1})

606   λ_g Thermal conductivity of the grout (W m^{-1} K^{-1})

607   λ_p Thermal conductivity of the BHE pipes (W m^{-1} K^{-1})

608   λ_s Thermal conductivity of the solid matrix of the soil (W m^{-1} K^{-1})

609   λ_w Groundwater thermal conductivity (W m^{-1} K^{-1})

610   λ_{ij}^{cond} Thermal conductivity for conduction (W m^{-1} K^{-1})

611   λ_{ij}^{disp} Thermal conductivity for dispersion (W m^{-1} K^{-1})

612   ρ_f Density of the heat carrier fluid (Kg m^{-3})

613   ρ_s Density of the solid matrix of the soil (Kg m^{-3})

614   ρ_w Density of groundwater (Kg m^{-3})

615     $(\rho c)_f$ Thermal capacity of the heat carrier fluid (J m^{-3} K^{-1})

616     $(\rho c)_g$ Thermal capacity of the grout (J m^{-3} K^{-1})

617     $(\rho c)_s$ Thermal capacity of the solid matrix of the soil (J m^{-3} K^{-1})

618     $(\rho c)_w$ Thermal capacity of the solid matrix of the soil (J m^{-3} K^{-1})

Tables

Fluid	$T_{freezing}$ [°C]	λ_f [Wm^{-1}K^{-1}]	c_f [Jkg^{-1}K^{-1}]	ρ_f [kgm^{-3}]	μ_f [mPas]	Q_{lam} [ls^{-1}]	Q_{turb} [ls^{-1}]
Prop.Glycol 25%	-10	0.45	3974	1026	5.51	0.252	1.097
Ethanol 24.4%	-15	0.426	4288	972	5.85	0.283	1.229
Prop.Glycol 33%	-15	0.416	3899	1015	8.17	0.378	1.644
CaCl$_2$ 20%	-20	0.54	3030	1186	4	0.158	0.689

Tab. 1 – Physical properties of the anti-freeze solutions used in the simulations: solidification temperature ($T_{freezing}$), thermal conductivity (λ_f), specific heat (c_f), density (ρ_f), dynamic viscosity (μ_f), upper boundary flow rate for the laminar regime (Q_{lam}) and lower boundary flow rate for the turbulent regime (Q_{turb}).

Parameter	Values
6 kW heat pump + installation	6000€
BHE drilling + installation	70 €/m
Unit cost of electricity	0.22 €/kWh
Increment of the unit cost of electricity	0%, 1%, 3%, 5%

Tab. 2 – Installation and energy costs used for the optimization procedure of the BHE length.

Figure captions

Fig. 1 – Scheme of a Ground Source Heat Pump (GSHP): the Borehole Heat Exchanger (BHE) exchanges heat between the surrounding soil and the heat pump. A thermal storage tank reduces the frequency of start-up and stop of the heat pump. Radiant panels and fan coils are the most diffused heating terminals for GSHPs. If present, groundwater flow enhances the heat transport around the BHE, permitting to achieve better energy performances.

Fig. 2 – Building Heat Load (BHL) adopted as a benchmark for the BHE in the simulations.

Fig. 3 – A: Time series of the average fluid temperatures, detail of 5 years of simulation. B: Cumulate distribution of the average fluid temperatures in the heating seasons.

Fig. 4 – Cumulate distributions of the average fluid temperatures for different values of BHE length (A), pipe spacing (B), thermal conductivity of the grout (C) and heat carrier fluids (D).

Fig. 5 – Cumulate distributions of the average fluid temperatures for different values of the thermal conductivity of the solid matrix of the soil (A), groundwater flow Darcy velocity with no thermal dispersion (B), Darcy velocity and saturated thickness (C), thermal dispersivity (D).

Fig. 6 – Estimated annual heat pump energy consumption for different values of BHE length (A), pipe spacing and grout conductivity (B), heat carrier fluids (C), solid-phase soil thermal conductivity (D), groundwater flow Darcy velocity and saturated thickness (E) and thermal dispersivity (F).

Fig. 7 – Relative variation of the total cost of a GSHP over a lifetime of 30 years, for different BHE lengths (50÷100m) and different increment rates of the unit cost of electricity (0÷5%).

Fig. 8 – Cumulate distributions of the average fluid temperatures (A) and electric power consumption of the heat pump and circulation pump (B) for different fluid flow rates.

Supporting information

Tab. 1 – Summary of the results of the simulations: mean and RMSE of the average fluid temperature (T$_f$), minimum values of the inlet temperature (T$_{in}$), Seasonal Performance Factor (SPF) and annual Heat Pump Consumption (HPC).

Parameter	value	Parameter	value	mean (T_f) [°C]	RMSE (T_f) [°C]	min (T$_{in}$) [°C]	SPF [-]	HPC [kWh/y]
		BHE length [m]	50	1.83	5.69	-6.39	4.22	2845.8
			55	2.52	5.36	-5.34	4.29	2799.5
			60	3.07	5.01	-4.40	4.34	2765.6
			65	3.46	4.79	-3.94	4.37	2743.0
			70	4.14	4.54	-2.99	4.44	2704.0
			75	4.63	4.25	-2.24	4.48	2678.4
			80	4.99	4.06	-1.71	4.51	2661.4
			85	5.26	3.92	-1.49	4.53	2648.5
			90	5.62	3.76	-1.02	4.56	2631.3
			95	6.03	3.57	-0.47	4.60	2611.1
			100	6.21	3.46	-0.33	4.61	2604.2
pipe spacing [mm]	35	grout thermal conductivity [Wm^{-1}K^{-1}]	1	0.34	7.16	-10.02	4.06	2956.2
	35		2	3.88	4.85	-3.74	4.42	2715.9
	35		3	4.18	4.59	-3.22	4.44	2701.2
	35		5	4.65	4.27	-2.27	4.48	2678.4
	55		1	0.62	6.92	-9.43	4.09	2931.5

Parameter	value	Parameter	value	mean (T_f) [°C]	RMSE (T_f) [°C]	min (T_{in}) [°C]	SPF [-]	HPC [kWh/y]
	55		2	4.05	4.74	-3.46	4.43	2706.4
	55		3	4.29	4.49	-3.04	4.45	2695.5
	55		5	4.64	4.25	-2.20	4.48	2678.0
	80		1	1.32	6.39	-7.95	4.17	2877.8
	80		2	4.20	4.55	-3.10	4.45	2699.6
	80		3	4.60	4.27	-2.31	4.48	2680.9
	80		5	4.68	4.17	-2.06	4.48	2677.7
	100		1	4.23	4.77	-3.41	4.45	2695.1
	100		2	4.74	4.33	-2.33	4.49	2670.7
	100		3	4.67	4.18	-2.09	4.48	2677.6
	100		5	4.74	4.05	-1.97	4.48	2676.9
	117		1	3.09	4.95	-4.29	4.34	2766.9
	117		2	5.03	3.90	-1.36	4.51	2661.9
	117		3	5.07	3.86	-1.31	4.51	2660.7
	117		5	5.07	3.84	-1.32	4.51	2661.3
		heat carrier fluid	PG 33%	1.95	5.96	-6.74	4.23	2834.8
			ET 24%	1.98	5.79	-6.49	4.23	2835.0
			PG 25%	2.49	5.50	-5.62	4.29	2799.7
			CaCl$_2$ 20%	4.43	4.43	-2.68	4.47	2687.4
		solid matrix thermal conductivity [Wm^{-1}K^{-1}]	1	-0.63	6.08	-9.36	3.91	3072.7
			1.5	1.32	5.47	-6.86	4.14	2895.8
			2	2.73	4.99	-4.72	4.30	2790.5

Parameter	value	Parameter	value	mean (T_f) [°C]	RMSE (T_f) [°C]	min (T_{in}) [°C]	SPF [-]	HPC [kWh/y]
			2.5	3.60	4.64	-3.70	4.38	2737.5
			3	4.63	4.25	-2.24	4.48	2678.4
saturated thickness [m]	55	groundwater flow Darcy velocity [m/d]	0.864	5.28	4.37	-1.83	4.54	2640.8
			1.728	5.99	4.37	-1.39	4.61	2601.0
			1.32	6.85	4.17	-0.33	4.70	2552.5
			8.64	7.53	3.77	0.80	4.76	2520.7
			17.28	8.21	3.29	2.14	4.82	2491.9
groundwater flow Darcy velocity [m/d]	0.864	saturated thickness [m]	10	4.67	4.32	-2.27	4.48	2676.2
			20	4.91	4.31	-2.06	4.51	2662.4
			50	5.25	4.36	-1.83	4.54	2642.6
groundwater flow Darcy velocity [m/d]	8.64	saturated thickness [m]	10	5.73	4.23	-1.20	4.59	2615.7
			20	6.43	4.07	-0.54	4.66	2576.8
			50	7.41	3.82	0.62	4.75	2526.6
groundwater flow Darcy velocity [m/d]	0.864	longitudinal thermal dispersivity [m]	0.1	5.32	4.35	-1.82	4.55	2639.0
			0.2	5.35	4.33	-1.81	4.55	2637.7
			0.5	5.46	4.27	-1.74	4.56	2632.0
			1	5.61	4.20	-1.35	4.57	2624.1
			2	5.72	4.11	-1.26	4.58	2619.1
			5	6.32	3.78	-0.44	4.63	2589.9
groundwater flow Darcy velocity [m/d]	1.728	longitudinal thermal dispersivity [m]	0.1	6.04	4.34	-1.32	4.62	2598.7
			0.2	6.10	4.30	-1.27	4.62	2596.1
			0.5	6.23	4.20	-0.89	4.63	2589.8

Parameter	value	Parameter	value	mean (T_f) [°C]	RMSE (T_f) [°C]	min (T_{in}) [°C]	SPF [-]	HPC [kWh/y]
			1	6.43	4.08	-0.80	4.65	2580.5
			2	6.62	3.91	-0.37	4.67	2572.3
			5	7.48	3.39	1.16	4.74	2534.0
groundwater flow Darcy velocity [m/d]	4.32	longitudinal thermal dispersivity [m]	0.1	6.91	4.14	-0.29	4.71	2550.0
			0.2	6.98	4.09	-0.26	4.71	2547.1
			0.5	7.26	3.91	0.29	4.73	2535.4
			1	7.60	3.68	0.93	4.76	2521.6
			2	8.09	3.33	1.86	4.80	2501.3
			5	8.94	2.78	3.44	4.86	2467.8

Tab. 2 – Summary of the results of the simulations with different values of heat carrier fluid flow rate (Q_f): mean and RMSE of the average fluid temperature (T_f), minimum values of the inlet temperature (T_{in}), Seasonal Performance Factor (SPF), annual heat pump consumption (HPC), circulating pump energy consumption (CPC) and total energy consumption (HPC+CPC).

Q_f [l/s]	mean (T_f) [°C]	RMSE (T_f) [°C]	min (T_{in}) [°C]	SPF	HPC [kWh/y]	CPC [kWh/y]	HPC+CPC [kWh/y]
0.1	-0.52	7.34	-16.57	4.09	2932.4	1.3	2933.8
0.2	0.19	7.02	-11.68	4.13	2906.6	8.2	2914.8
0.3	1.71	5.96	-7.51	4.24	2830.6	24.0	2854.6
0.4	2.49	5.50	-5.62	4.29	2799.7	51.9	2851.6
0.5	2.76	5.24	-4.97	4.28	2800.9	94.5	2895.4
0.6	3.14	4.99	-4.17	4.30	2790.8	154.5	2945.3
0.7	3.14	4.94	-3.75	4.28	2803.1	234.4	3037.5

Fig.1

fancoil

radiant
panels

heat
storage
tank

heat
pump

aquifer

aquifer

groundwater flow
q=ki

BHE

Inlet
pipe T_{in}

w

Outlet
pipe T_{out}

Geothermal
grout λ_g

Fig.2

Fig.3

Fig.4

Fig.5

Fig.6

Fig.7

Fig.8