Empirical modeling of maps of geo-exchange potential for shallow geothermal energy at regional scale

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Abstract

An empirical method aimed at generating maps of potential of geothermal energy exchange for shallow vertical closed-loop systems is proposed here. The method uses both geological and technological information. In particular, the ground parameters that mainly influence the heat transfer in borehole heat exchangers, the energetic parameters driving efficient operations of geothermal systems and heating and cooling requirements of a typical residential building are taken into account. Spatial modeling is carried out in a Geographic Information System leading to an effective and easy-to-use digital cartographic tool. An application of the method to four regions of southern Italy is also shown.

Keywords: Shallow geothermal energy; vertical borehole heat exchanger; Ground source heat pump; Geo-exchange potential; GIS.

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27 **Highlights**

- 28 • A new methodology for evaluation of geo-exchange potential is proposed
- 29 • Geo-exchange potential is defined as maximum energy exchangeable per unit area
- 30 • Ground properties, climatic conditions and heat pump efficiency are considered
- 31 • Thematic maps at regional scale are generated and can be used for planning purposes
- 32 • The proposed methodology focuses on vertical closed loop shallow geothermal systems

33

34 **1. Introduction**

35 The increasing use of renewable energy resources both for power and heat generation is a valuable
36 tool to overcome the economic dependence on fossil fuels and ensuring energy supply to the
37 standard of today's development. As stated by the Geothermal Energy Roadmap edited by the
38 International Energy Agency (IEA 2011), in the next future the use of geothermal resource is likely
39 to increase, given its ability to meet part of the global energy needs and to produce low levels of
40 greenhouse-gas emissions (GHG), reducing significantly CO₂ emissions in the atmosphere. The
41 improvement and development of existing technology combined with a better knowledge of the
42 thermal properties of a territory is essential for planning, at national and regional scale, an optimal
43 utilization of underground thermal resources available everywhere.

44 Shallow geothermal energy and new technologies applications could replace air-source heat-
45 pump systems to reduce the use of conventional energy resources (Nam and Oaka 2011). In Italy,
46 where over 20% of total energy consumption is due to domestic heating, the use of this renewable
47 energy is being considered to improve with significant impact in reducing the share of greenhouse
48 gas emissions and the reduction of primary energy consumption of buildings (Gemelli et al. 2011,
49 Bayer et al., 2012).

50 As for any form of energy resource, the estimation of energy potential is fundamental to
51 assess the economic benefits and the management plan of its exploitation. For shallow geothermal
52 energy this requires a reliable quantification of geo-exchange potential of the ground combined with

the use of borehole heat exchangers (BHEs) coupled with a heat pump for heating/cooling purposes of residential buildings. Ground Source Heat pump Systems (GSHP) are conceived to extract heat from the ground in heating mode and/or inject it into the ground in cooling mode. Two main categories of GSHPs are commonly adopted, the so-called open-loop systems (OLSs) and closed-loop systems (CLSs). The OLSs are based on use of groundwater as heat carrier fluid, extract from the ground and brought directly to the heat pump in contact with the surrounding environment. The CLSs, instead, use water or a mix of water and antifreeze as heat carrier medium, circulating inside BHEs and in this way physically separated from the rock/soil and groundwater (Bakirci 2010). The CLSs are becoming increasingly popular due to their ability to be installed virtually anywhere, to be used in heating and cooling mode and to reduce in a tangible way the energy costs related to building conditioning (Ondreka et al 2007; Busby et al. 2009). Use of GSHPs can be an efficient and environmentally friendly technique for different climatic conditions and in particular in temperate zone, where the practices of heat exchange with the subsoil occurs ubiquitously at 'normal' temperatures in the relatively shallow subsurface (Zarrella et al 2013; Østergaard and Lund 2011). For this reason, the present paper focuses on estimating the potential of the CLSs only.

The overall efficiency of a GSHP depends particularly on the heat exchangeable rate with the ground, the energy request of a specific building and correct design of all the components. The heat transfer processes with the ground, as well as the initial GSHP plant costs, which include drilling and piping, are strictly dependent on the geological conditions. Therefore, it is important to accurately estimate the thermal properties of a selected site and predict the heat extraction rate from the ground in order to optimize the design (Signorelli 2004).

The geo-exchange potential at regional scale can be determined by two main components, the resource and the technical potentials. The former highlights the influence of geology, thermal properties, climatic parameters, groundwater presence and ground temperature at surface on quantifying the heat transfer ability of the subsurface rocks and sediments and on determining the BHE well-sound length. The latter is related to the building type and size, the required thermal load

79 and the adopted technological solution (Yeo and Yee 2014). For example, the thermal conductivity
80 of rocks affects the size, the average thermal power and the operating temperatures of a BHE
81 (Clauser 2006).

82 To understand how to exploit this energy resource and evaluate the geothermal potential at
83 regional scale, the use of cartographic tool is fundamental. Nam and Oaka (2011) studied the
84 macro-availability potential in the 23 wards of Tokyo, in order to make optimal use of GSHPs;
85 Noroollahi et al. (2008) analyzed spatial associations between geothermal exploration and
86 environmental evidence layers using GIS as a decision-making tool to determine the appropriate
87 sites for exploration; Gemelli et al. (2011) presented a GIS-based energetic-economic model of low
88 temperature geothermal energy applied to the Italian Marche region. Busby et al. (2009) discussed
89 some of the geological factors that influence the performance and hence design of a GSHP.

90 This paper shows a GIS-based approach maps able to generate thematic maps of geothermal
91 energy exchanged potential by vertical boreholes, where both geological and technological
92 information is used. Since the modelling has empirical character, it was applied to four regions of
93 Southern Italy within the framework of the VIGOR Project (VIGOR 2010) to produce geo-
94 exchange potential maps. The obtained maps are conceived for energy planning purposes at
95 regional scale and, due to the complexity of the different system components (house type,
96 geological conditions, heating/cooling needs), provide a first and rough estimation of the geo-
97 exchange potential of the areas taken into consideration.

98

99 **2. Case study: geological and climatic setting**

100 Since the proposed method has empirical character, a case must be studied in order to show how it
101 works. In the framework of VIGOR Project four regions of Southern Italy characterized by a Gross
102 Domestic Product (GDP) per capita below 75% compared to the European Community average (the
103 so called “Convergence regions”) were chosen in order to promote their development also by means
104 of increasing use of renewable energy. These regions are Apulia, Calabria, Campania and Sicily.

105 They are surrounded by the Adriatic, Ionian, Tyrrhenian and Mediterranean Seas, have an overall
106 surface of around 73,000 km² and have more than 17 million inhabitants (Fig. 1). Although the area
107 includes a fifth region (Basilicata), this could not be included in the study and financing initiatives
108 of the VIGOR Project since this region is characterized by a higher level of social and economic
109 development with respect to the other ones and, therefore, was not eligible under the Convergence
110 Objective.

111 From the geological point of view the south of Italy belongs to the complex structural
112 environment of the Central Mediterranean region, whose origin is related to the opening of the
113 Tyrrhenian Basin and the Africa-Europe plate convergence (Spina et al 2011).

114 The central-southern Apennines chain is a nappes structure with thrust faults and folds
115 verging toward the Adriatic Sea, crossed over the Apulian platform. The platform outcrops are
116 dominated by limestone and dolostone sequences overlain by thin Quaternary deposits (Polemio
117 and Lonigro 2012).

118 On the Tyrrhenian margin metamorphic units are covered by Miocene flysch deposits and
119 other heterogeneous sediments including evaporites as gypsum and salt deposits (Cavazza and
120 Ingersoll 2005). Finally, conglomerates, calcarenites and sandstones, marine terraced deposits
121 (Middle-Upper Pleistocene) and alluvial sediments (Holocene) form the alluvial and coastal plains
122 of the four regions.

123 The late Pliocene—structural-tectonic processes explain, on one hand, the onset of volcanic
124 phenomena in the Phlegraean Fields, Vesuvius, Eolie and Etna areas and, on the other, the presence
125 of high-grade metamorphic and igneous rocks in Calabria (Bosellini 2011). The complex geological
126 history of the area is clearly testified by the heterogeneous lithological distribution of outcrops in
127 the four regions (Fig. 2).

128 [Figure 1]

129 [Figure 2]

130 From a climatic point of view southern Italy is characterized by a temperate Mediterranean
131 climate. In detail, the four regions considered in the study are characterized by dry and hot summers
132 with temperatures sometime exceeding 40°C and mild winters, particularly along the coasts (Claps
133 et al. 2008). During winter season in coastal areas the mean temperature rarely drops below 12°C,
134 whereas in the Apennines chain winters are cold and snowy with temperature sometimes below -
135 20°C. Summers are hot in the valley, progressively cooler at altitude.

136

137 **3. Method**

138 A new approach to modeling maps of geo-exchange potential for shallow geothermal application at
139 regional scale is proposed. The developed methodology focuses on closed loop vertical borehole
140 heat exchangers solutions. Horizontal shallow geothermal installations are out of the scope of this
141 research. A comprehensive and complete overview of feasibility and potential of horizontal systems
142 and their Web-GIS services were realized by the ThermoMap Project (Bertermann et al 2015;
143 ThermoMap 2013).

144 The methodology here described is based on: (1) identification of the main parameters
145 affecting the efficiency of the ground-building systems; (2) definition of a reference model able to
146 summarize the correlation between all these parameters. Fig. 3 shows the flowchart of the proposed
147 method.

148 [Figure 3]

149

150 ***3.1 Ground thermal properties and generation of thematic maps***

151 Performance of a GSHP system depends on both heating/cooling building loads and site-related
152 settings. For this reason, a reliable geological and hydrogeological characterization of the ground is
153 required.

154 From the shallow geothermal perspective, the most significant ground properties required to
155 maximize the efficiency and minimize the installation costs of a BHE, or geothermal probe, are (a)

the average annual air temperature and the corresponding ground temperature at surface; (b) the shallow geothermal heat flow; (c) the thermal conductivity of rocks and sediments; (d) the geothermal gradient up to 50-100 m depth and (e) the monthly energy profile of the building selected as standard case. Among all these parameters, those mostly affecting the dimensioning of a BHE system are the ground surface temperature and the thermal conductivity of the material.

3.1.1 Average annual air temperature and ground surface temperature

In the absence of local geothermal anomalies, the average annual air temperature (θ_m) of an area is assumed equal to the ground surface temperature (θ_g). The climatic time series collected over time in different measurement stations distributed at the regional level allows the characterization of the thermometric regime of a territory (Banks 2012). However, morphological and geographical variables as latitude and elevation above sea level must be taken into account defining the average annual air temperature. A multiple regression model developed by Claps et al. (2008) considering elevation above mean sea level (AMSL), latitude, wind direction and distance from the sea provided the average annual air temperature map of Italy starting from data collected and evaluated on 754 weather stations with fairly homogeneous spatial coverage on approximately 300,000 km² of the Italian territory.

In order to analyze the regions involved in the VIGOR Project, a similar simplified approach was used. Due to the purposes of this work, carried out at regional scale (1:250,000), only the dominant effects of altitude and latitude were taken into account, leading to

$$\theta_m = a + bZ + cLat, \quad (1)$$

where Z is the altitude AMSL (m), Lat is the latitude (deg, i.e. sexagesimal degree) and a , b , c are the constants that have been obtained by the regression model ($a = 39 \pm 7$ °C, $b = -0.0058 \pm 0.0009$ °C m⁻¹, $c = -0.55 \pm 0.17$ °C deg⁻¹ where, as usual, the uncertainties are the corresponding standard deviations). Equation (1) allowed the generation of a thematic map of θ_m .

181

182 **3.1.2 Shallow geothermal flow**

183 The ground temperature at different depths is closely related to the geothermal heat flow
184 contribution of endogenous origin. Generally, the average heat flow on the Earth's surface is equal
185 to 63 mWm^{-2} and in Italy varies from 30 to 100 mWm^{-2} , with peaks up to 450 mWm^{-2} in
186 Tyrrhenian area (Geothopica Project, CNR 2014). These great differences within relatively small
187 areas are due to the extreme geological variation observed from region to region (Cataldi et al
188 1995). In the case study here examined, the regional heat flow maps were generated on the basis of
189 literature data.

190

191 **3.1.3 Thermal conductivity**

192 Such a quantity expresses the ability of a material to exchange heat and is defined as heat able to
193 flow in a unit time through a unit area of a material caused by a unit thermal gradient. The 1-
194 dimension Fourier's Law of heat conduction states that the heat transfer q (W) throw a cross-
195 sectional area A (m^2) in a homogeneous medium is given by

$$196 \quad q = -\lambda A \frac{\partial \theta}{\partial z}, \quad (2)$$

197 where λ is the thermal conductivity ($\text{Wm}^{-1}\text{K}^{-1}$) and $\partial \theta / \partial z$ is the temperature gradient. Therefore, λ
198 plays a fundamental role in sizing the BHEs coupled to heat pumps for buildings' air conditioning.
199 A cartographic representation of this parameter is a useful product for both a first characterization
200 of an area on a regional scale and for territorial energy planning initiatives and pre-feasibility
201 analysis of systems.

202 For each studied region a multistep approach was carried out (Di Sipio et al 2014):

- 203 (1) Compilation of a bibliographic λ database for rocks and sediments based on a comparative
204 analysis of different literature sources;

205 (2) Recognition of the more representative geological formation for each region on the basis of their
206 areal extent in the geological map of Italy, scale 1:250,000 (ISPRA 2005) and selection of those
207 characterized by the highest population density. In this way the more urbanized areas, where the
208 development of GSHPs can be favored, were recognized;

209 (3) Laboratory testing. Since the stratigraphic formations are characterized by two or more different
210 lithologies, outcrop specimens belonging to the top 10 formations were collected in situ and
211 analyzed in laboratory to measure λ . The measurements were performed taking into account the
212 anisotropy factor and the dry and wet conditions (Di Sipio et al 2013);

213 (4) Modeling of the stratigraphic sequence along the whole thickness of the subsoil directly affected
214 by possible BHEs, i.e. ~100 m, and computation of the corresponding thermal conductivity. Two
215 cases were considered:

216 (4a) Rocky outcrops. In each the case of a rocky outcrop the stratigraphic sequence was assumed to
217 be constant for the full depth, i.e. the used λ was the one of the main lithology that constitutes the
218 outcrop. In this way, a litostratigraphic thermal conductivity map was obtained;

219 (4b) Quaternary deposits. In the case of a Quaternary deposit the available stratigraphic dataset was
220 modeled by means of evaluation, for each depth range, of the mode of the geological species
221 distribution recognized in the same depth range from the data of available surrounding wells data,
222 seismic and electrical tomography surveys or other kind of subsoil information (Cultrera et al
223 2012). In this way, an equivalent thermal conductivity map was obtained.

224 The final map of thermal conductivity was achieved by juxtaposition of the litostratigraphic
225 thermal conductivity map and the equivalent thermal conductivity one, and by data processing using
226 GIS tools that provided a geothermal cartography of the whole territory at a regional scale.

227 Due to the limited number of collected samples, the obtained map is an initial rough overview
228 of the ground thermal conductivity distribution of the region that can be used for general planning
229 purposes and in particular as administrative support to the local authorities for the proper and
230 informed land management. Further detailed sampling has to be performed at a local level in order

231 to allow the design of specific geothermal systems. Moreover, it should be noted that the scale of
 232 work and representation couldn't identify local large scale variations of the ground thermo-physical
 233 properties such as the presence of areas affected by fault fracturing, or locally intensely altered by
 234 karst phenomena or recent deposits characterized by high spatial variability.

235

236 **3.1.4 Geothermal gradient**

237 Eq. (2) generally holds for heat transfer in the crust from Earth's interior and, in this case, it can be
 238 rewritten as:

$$239 \quad \frac{Q}{\lambda} = \frac{\partial \theta}{\partial z} = \frac{\theta_{gL} - \theta_m}{L}, \quad (3)$$

240 where Q is the heat flow, i.e. the heat transfer per unit area (Wm^{-2}), positive from Earth's interior to
 241 the crust (i.e. $Q = -q/A$), $\partial \theta / \partial z$ is the geothermal temperature gradient, which normally ranges
 242 between 1–3 °C per 100 m, θ_m is the ground average temperature at surface and θ_{gL} (°C) is the
 243 undisturbed ground temperature at depth L (m) from the ground surface. The fact that the
 244 temperature of the shallow subsurface is largely controlled by θ_m should be noted. However, at
 245 increasing depth, a minor component related to the heat flow migrating from the earth's interior
 246 towards the earth's surface must also be taken into account (Banks 2012). From Eq. (3) it follows
 247 that the ground temperature at a depth z , θ_{gz} , is

$$248 \quad \theta_{gz} = \theta_m + \frac{Q}{\lambda} z. \quad (4)$$

249 Since our reference, which is a typical, average depth of a BHE, is 100 m, the parameter considered
 250 here was θ_{g50} , i.e. the ground temperature at the depth of half BHE length.

251

252 **3.1.5 Monthly energy profile**

253 In this work, a residential building of 100 m² having standard insulation and a transmittance of
254 0.3 W m⁻² K⁻¹, according to reference standards (UNI EN ISO 6946), was selected as reference
255 unit to reduce the uncertainties and the number of variables to be considered in the analysis and
256 modeling phases and to allow comparison of the exchange capacity in different areas. The typical
257 monthly energy profiles for this building were obtained by means of TRNSYS tool (TRNSYS
258 2014) showing the differences between heating/cooling energy needs in five different test sites,
259 each characterized by $\theta_m = 10, 14, 15, 16, 17$ °C respectively, and representative of typical climatic
260 conditions of the studied regions.

261 For example, Table 1 shows the monthly energy loads during the year of a reference
262 residential building located in one of the climate areas of Apulia region. By comparing the
263 simulation results, it is easy to identify the conditions of thermal equilibrium and possible thermal
264 imbalance. In temperate zones, and in particular in southern Italy, the energy requirement of a
265 building corresponds to satisfy the cooling loads. Therefore, over time the system generates a
266 thermal disequilibrium in the ground, increasing considerably the temperature of the subsoil during
267 summer and generating inadequate long-term performances of the heat pump. To restore the natural
268 thermal balance of the ground the system must be properly planned and technological solution must
269 be adapted to the natural and anthropic environment.

270 [Table 1]

271

272 ***3.2 Empirical modeling of geo-exchange potential***

273 GSHP systems are necessary to ensure heating/cooling provision for a standard residential building,
274 defined as the reference unit in different environmental and climatic conditions. The parameter
275 adopted in this work to link the ground thermal properties to the building thermal requirements is
276 the total length of the group of BHEs (field) required to satisfy the energy need. The total length of
277 borehole heat exchangers was computed on the basis of different input parameters, namely the

278 ground source temperature and the average annual air temperature, the geothermal heat flow, the
279 thermal conductivity of rocks and sediments, the monthly energy loads of the building selected as
280 standard case study. Once defined the set of data to be tested, the aim of the simulations is to
281 translate the combination of all these parameters, which can be mapped individually, into a single
282 cartographic representation.

283 At first the set of parameter to be tested was defined (Table 2). The values of θ_m typically
284 range from 10°C and 18 °C in southern Italy (both mountainous and coast areas are considered).
285 The climatic data time series of the 5 test sites taken as reference (Site 1, 2, 3, 4, 5) led to the θ_m set
286 to be considered, i.e. the previously defined $\theta_m = 10, 14, 15, 16, 17$ °C. These values were also used
287 to assess the monthly thermal loads (Subsection 3.1.5). The λ values, i.e.
288 $\lambda = 0.5, 1.0, 1.5, 2.0, 2.5 \text{ W m}^{-1}\text{K}^{-1}$, were chosen according to the results obtained by literature
289 review and laboratory testing. The selected range varied from values typical of anhydrous sediments
290 ($\lambda \approx 0.5 \text{ Wm}^{-1}\text{K}^{-1}$) to saturated sediments or rocks ones ($\lambda \approx 2.5 \text{ Wm}^{-1}\text{K}^{-1}$). Values higher than
291 $2.5 \text{ Wm}^{-1}\text{K}^{-1}$, e.g. found in rocks such as quartzite, granite and dolomite, were not considered for
292 precautionary reasons considering the representativeness in the study areas. In fact, being more
293 conductive, they would favor the efficiency of a GSHP, but their distribution usually is far from the
294 most densely populated areas. This preliminary analysis focused on the possible limiting effect of
295 low heat transfer value on quantifying the total length of BHE. Five values of shallow geothermal
296 heat flow ($Q = 0.01, 0.03, 0.07, 0.1, 0.5 \text{ Wm}^{-2}$) were considered, covering both normal
297 ($Q < 0.1 \text{ Wm}^{-2}$) and anomalous ($Q = 0.1 - 0.5 \text{ Wm}^{-2}$) thermal regions. The calculations were
298 carried out on the basis of reasonable values of coefficient of performance (COP) and energy
299 efficiency ratio (EER) of the heat pump during winter heating and summer cooling phase
300 respectively. The chosen coefficients were $\text{COP} = 4.5$ and $\text{EER} = 4.0$. Over than 100 simulations
301 were carried out with EED software (Eskilson et al. 2000), combining all these parameters by

302 setting the temperature and varying in turn the heat flow and the thermal conductivity. The output
 303 was the total length of BHE field (L_{tot}) suggested for each combination of used input data. Invalid
 304 combinations for real GSHP solutions (i.e. high Q and high θ_m) were not considered. If a
 305 reasonable L_{tot} was obtained, the result was saved to allow its use in the proposed empirical
 306 modeling of geo-exchange potential.

307 [Table 2]

308 The total number of probes for each simulation (n_{p100}), obtained as $n_{p100} = [L_{tot}/100]$, where
 309 $[x]$ is the nearest integer to x , is shown in Table 2. It was used to compute S_g , i.e. the surface area
 310 through which the geothermal energy is exchanged. For a BHE field, such a value was obtained by
 311 assuming that this field is a regular grid of 100 m long vertical probes spaced 7 m (to avoid a
 312 significant thermal interference) located in the square centers (Signorelli, 2004, Teza et al. 2012,
 313 Kälén et al., 1991). Therefore, S_g was calculated as $S_g = n_{p100} S_{SINGLE}$, where $S_{SINGLE} = 49 \text{ m}^2$ is the
 314 area of a single grid square.

315 The monthly energy profiles were computed in each test site as described in Subsection 3.1.5.
 316 The annual balance of thermal energy profiles ($E_c + E_h$) defines the energy disequilibrium required
 317 for conditioning and controls the major utilization of the GSHP system, in cooling or heating mode.
 318 Therefore, to determine the most stressful thermal energy request in each site, the total annual
 319 heating energy (E_h) or the total annual cooling energy (E_c) that BHEs must exchange with the
 320 ground was computed (Table 2).

321 Let E_g be $E_g = E_h$ or $E_g = |E_c|$ when the heating or the cooling phase is dominant,
 322 respectively. A shallow geothermal system must guarantee a heat transfer between ground and
 323 BHEs able at least to satisfy E_g . The ratio $V_g = E_g / S_g$, which is the geothermal energy
 324 exchangeable through the unit area, is a well-defined intensive scalar quantity for each site where
 325 the simulations are performed and can be easily mapped in a whole area by means of a GIS. For this

326 reason, V_g is proposed here as the geo-exchange potential. In Table 2, the dominant E_h , E_c values
327 (i.e. the value chosen as E_g and therefore related to V_g) are highlighted in bold.

328 The distribution of the points in the space of parameters λ , θ_{g50} and L_{tot} (Fig. 4a) suggested
329 that a correlation between them exists. In particular, a simple linear regression provided

330
$$L_{tot} = a\lambda + b\theta_{g50} + c, \quad (5)$$

331 where $a = -67 \pm 7 \text{ m}^2 \text{ K W}^{-1}$, $b = -13.6 \pm 1.5 \text{ m K}^{-1}$ and $c = 480 \pm 30 \text{ m}$, therefore with $\sim 10\%$
332 relative uncertainty. Eq. (5) allows an estimation of L_{tot} from λ , and θ_{g50} taken from thematic
333 maps.

334 Finally, the distribution of the points in the 2-dimension space of parameters L_{tot} and V_g
335 (Fig. 4b) suggested that these quantities are correlated. In particular, the following exponential
336 relation was obtained via least square fitting:

337
$$V_g = E_g / S_g = \alpha \exp(-\beta L_{tot}), \quad (6)$$

338 where $\alpha = 136 \pm 7 \text{ kWh m}^{-2}$ and $\beta = 0.0037 \pm 0.0003 \text{ m}^{-1}$. This equation was used to generate the
339 map of geo-exchange potential.

340 [Figure 4]

341

342 **4. Results**

343 According to the previous Section and the flowchart in Fig. 3, the thematic maps of shallow
344 geothermal heat flow and thermal conductivity were obtained by extending the available punctual
345 information to the whole area by means of interpolation in GIS environment. The standard inverse
346 distance weight (IDW) interpolation was chosen because it can highlight variability at local scale.
347 Since the four studied regions are characterized by different scales of local variability of geological
348 features ($\sim 1 \text{ km}$ for Calabria, $\sim 3 \text{ km}$ for Campania and Sicily, and $\sim 5 \text{ km}$ for Apulia), different IDW
349 parameters were chosen for each region. For each quantity, the four maps corresponding to the four

regions were drawn together to have a single thematic map referred to a 100-m side BHE field regular grid. The thematic maps of mean annual temperature, ground temperature at 50 m depth and geo-exchange potential were generated by implementing in GIS environment the empirical formulas described in Section 3 and using the data of the other thematic maps.

The map of mean annual temperature θ_m (Fig. 5a) was obtained according to Eq. (1) from the available climatic data described in Section 2. The results show values below 10°C in the areas characterized by high elevation, as Mt Pollino (Calabria) and Mt Etna (Sicily) and higher than 16°C along the coastal areas, as expected, reaching the highest temperature (higher than 18 °C) in the Ionian and Mediterranean coasts of Sicily.

The map of ground temperature at 50 m depth, θ_{g50} , was computed in the studied area according to Eq. (4). The results show a clear influence of the average annual air temperature; the lowest values ($\theta_{g50} \leq 13^\circ\text{C}$) belong to the mountain chains, while the highest ($\theta_{g50} \geq 16^\circ\text{C}$) to the coastal and plain areas of regions under investigation (Fig. 5b). Instead, the endogenous heat content is dominant, compared to θ_m , in the volcanic areas of Phlegraean Fields and Mt. Etna.

[Figure 5]

The map of the shallow geothermal heat flow Q (Fig. 6a) underlines local differences due to the geological variability of the territory. The cartographic representation, obtained via standard IDW-based interpolation of data available in literature, shows value of geothermal heat flow $Q \leq 40 \text{ mW m}^{-2}$ mainly in the Apulia territory and in the central and coastal sector of Campania, while in Calabria and Sicily the geothermal flow ranges mainly between 20 and 50 mW m^{-2} . Areas of thermal anomaly are easily identified at the Phlegraean and Mt Etna volcanic structures ($Q > 100 \text{ mW m}^{-2}$).

The map of thermal conductivity (Fig.6b) was obtained by juxtaposition of the lithostratigraphic thermal conductivity and the equivalent thermal conductivity maps, as described in Subsection 3.1.3. In general, incoherent deposits, dominant in the flat and coastal areas of the four

regions under study, show $\lambda \approx 1-2 \text{ W m}^{-1}\text{K}^{-1}$, typical of unconsolidated saturated sediments. Values higher than $3 \text{ W m}^{-1}\text{K}^{-1}$ belong to the mountain areas where dolomite, limestone and metamorphic rocks are present, whereas it is $\lambda \approx 2-3 \text{ W m}^{-1}\text{K}^{-1}$ where rocks characterized by a carbonate composition are dominant, moving to higher values in the dolomite. In volcanic areas, where pyroclastic sediments, ignimbrites and lava materials are recognized, weaving high porosity, it is $\lambda \approx 0.5-1 \text{ W m}^{-1}\text{K}^{-1}$ instead.

[Figure 6]

Once the above-mentioned thematic maps were generated, the total length of the BHE field L_{tot} was computed by means of Eq. (5) and the coefficients obtained by the regressions described in Subsection 3.2. Finally, Eq. (6) allowed the generation of the map of the exchangeable ground heat through the unit area $V_g = E_g / S_g$ (Fig. 7), which is the wanted map of geo-exchange potential. The V_g map highlights a dominance of values in the range $80-100 \text{ kWh m}^{-2}$. The heat exchange with the ground is generally favored by the presence of the highest thermal conductivity values, as in the Apulian carbonate platform, the floodplains and coastal areas of Calabria, Sicily and southern Campania. Levels of $V_g \approx 70-80 \text{ kWh m}^{-2}$ have a discontinuous distribution and are found mainly in mountainous and hilly areas. Instead, the areas where $V_g < 70 \text{ kWh m}^{-2}$ or $V_g > 100 \text{ kWh m}^{-2}$ appear to be typically confined.

[Figure 7]

5. Discussion

Above all, the proposed role of $V_g = E_g / S_g$ as a quantity able to represent the geo-exchange potential is discussed. In order to represent a profitable use of the geothermal resource, this parameter represents the maximum geothermal energy exchangeable through the unit area ($100 \times 100 \text{ m}^2$) taking into account the local geological and climatic conditions, the maximum energy

399 requirements in a year estimated for a reference unit, i.e. a 100 m² residential building with standard
400 insulation and 0.3 W m⁻² K⁻¹ transmittance and usual requirements on heat pump efficiency
401 (COP = 4.5 and EER = 4.0).

402 The considered standard residential building is characterized by the typical properties of a
403 recent or a recently renovated building. This is not a limiting hypothesis because a GSHP is
404 generally installed on new or restructured buildings or at least its installation is accompanied by
405 works aimed at improving the thermal insulation of wall, ceilings, roofs and casings.

406 Since $E_g = E_h$ or $E_g = |E_c|$ depending on the respective dominant energy requirement
407 (heating or cooling), where E_h is the total annual heating energy and E_c is the total annual cooling
408 energy, V_g corresponds to the most penalizing operation conditions of the GSHP, regardless to
409 existence, or not existence, of winter/summer thermal load balancing. The higher is V_g in a place,
410 the lower is the required total length of the BHE field, therefore the lower is the installation and
411 operation cost of a GSHP for a standard residential building and, finally, more suitable is the place
412 for geothermal energy exploitation. Therefore, the higher is V_g in a place, the higher is the number
413 of standard residential buildings that can be conditioned by means of GSHPs.

414 In principle, other quantities could represent the geo-exchange potential. For example, high
415 values of ground thermal conductivity indicate good efficiency in heat exchange between ground
416 and BHEs. However, V_g also takes into account climatic conditions and technological constraints
417 and can be considered as a more complete index of geo-exchange potential. Moreover, since V_g is
418 an intensive quantity and, therefore, thematic maps can easily represent its spatial distribution, it
419 results a suitable indicator of shallow geothermal potential.

420 The maps are generated in GIS environment and, therefore, one or more data interpolation
421 techniques must be chosen. In the specific case, since a significant geological variability can be
422 seen at a scale of a few km, the IDW method was chosen in order to better take into account such

423 variability. In more simple contexts, where variations are limited and no strong discontinuities are
424 expected, more simple interpolation techniques like the natural neighbor or the linear method can be
425 profitably used. In other cases, more sophisticated geostatistical methods like kriging could be
426 necessary. Any GIS software provides several interpolation methods. In any case, the choice of the
427 interpolation method is driven by analysis of the scale of geological variability because the
428 governing parameter is the thermal conductivity of the ground.

429 The chosen functional form for the V_g vs. L_{tot} chart, Eq. (6), is an exponential with negative
430 exponent. Although it can provide a reasonable data description in the specific case study, in other
431 environments other choices could be more suitable. Moreover, the use of an exponential function
432 implies that V_g estimates for small L_{tot} (50-60 m) could be inaccurate. This is not a problem
433 because small L_{tot} for high exchanged energies are infrequent and could be seen in areas
434 characterized by geothermal anomalies.

435 In general, the proposed method can be applied in other regions, characterized by geological
436 and climatic conditions completely different from the southern Italy regions here analyzed. Clearly,
437 other coefficients for the empirical relations (1), (5) and (6) are to be computed by means of
438 observational data and/or simulations, and in some cases, as above mentioned, different functional
439 form could better fit the data.

440 In order to estimate the accuracy of the proposed maps of geo-exchange potential, the case of
441 the Apulian city of Foggia (Site 4 in Table 2) is discussed in detail. In this area the average air
442 temperature $\theta_m = 16^\circ\text{C}$ and $Q = 30 \text{ mW m}^{-2}$. The city insists on Quaternary sediments affected by
443 the presence of shallow aquifers where, according to literature, the corresponding saturated
444 sediments have $\lambda \cong 1.5 \text{ W m}^{-1} \text{ K}^{-1}$. From these data $\theta_{g50} = 18^\circ\text{C}$ was obtained. Moreover, the
445 TRNSYS-based computations provided $E_g = |E_c| = 5306 \text{ kWh}$ and the EED-based simulations
446 carried out with these data provided $L_{tot} = 116 \text{ m}$ and $V_g = 108 \text{ kWh m}^{-2}$. All these results are

447 obtained from real data and have punctual nature, without any use of interpolation. The
448 corresponding results obtained by using the described thematic maps in the Foggia area are
449 $L_{tot} = 135 \text{ m}$ and $V_g = 83 \text{ kWh m}^{-2}$, with differences limited to ~20% for both the quantities.
450 Similar performance can be obtained in other test areas.

451 Since the typical interpolation error in estimating the geo-exchange potential is close to 20%,
452 the results cannot be used for GSHP design purposes. Nevertheless, the accuracy of the results is
453 surely compatible with their use in planning of shallow geothermal resources exploitation. Thanks
454 to these maps, a planner can recognize those areas where the use of geothermal resources can be
455 really cost-effective. Clearly, other factors must be considered in the planning phase, e.g. the costs
456 of drilling that depends on the type of rock and unconsolidated material forming the ground,
457 possible administrative constraints, local legal requirements and the population density. These
458 factors can influence the total cost of the installation and operation work, its feasibility, the energy
459 yield and hence its usefulness for the population and must be taken into account. However, a
460 reliable estimation of the geo-exchange potential is an unavoidable prerequisite for each evaluation
461 about the convenience, or absence of convenience, of shallow geothermal energy use.

462 The fact that the proposed approach provides thematic maps of several quantities should be
463 noted. These maps could be used for different aims, for example planning of land and/or energy use
464 in the studied areas.

465 The proposed methodology focuses on shallow geothermal resources and closed-loop
466 systems. In particular, a site unsuitable for closed-loop solutions could be suitable for open-loop
467 systems and vice-versa because some driving parameters are different. Similarly, the geo-exchange
468 potential for vertical BHEs could be completely different from that of horizontal BHEs.

469 Although the present paper mainly has a methodological value, a specific case study is
470 considered because some proposed relations, i.e. Equations (1), (5) and (6), are empirical ones.
471 From the perspective of the geothermal energy exploitation, Fig. 7 shows that the four studied

regions are on average prone to the GSHPs use, since $V_g \approx 80-100 \text{ kWh m}^{-2}$. It is worth to note that high values ($V_g \approx 100 \text{ kWh m}^{-2}$) can be found in some urban areas characterized by high building density like Salerno (Campania), Bari, Brindisi, Lecce (Apulia), Palermo, Siracusa, Messina (Sicily), where a relatively wide use of geothermal resources is expected in the next years. The areas showing low V_g values generally have volcanic rocks in the shallow ground layers, and require site-specific measurements and analyses in order to obtain conclusive results.

In general, the thematic map of geo-exchange potential show that the shallow geothermal resource can be profitably exploited in large part of the studied regions.

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482 **6. Conclusions**

A methodology aimed at generating maps of geo-exchange potential for shallow geothermal systems at regional scale is proposed. The final product is the map of maximum ground heat exchangeable through the unit area, evaluated on the basis of local geological and climatic conditions, energy requirements for a typical reference residential building and energy requirements on heat pump efficiency. Such a quantity is proposed here as geo-exchange potential.

Besides the map of geo-exchange potential, several additional thematic maps have been produced and discussed. Some of them (maps of shallow geothermal heat flow and thermal conductivity) were obtained by extending the available punctual information to the whole area by means of data interpolation in GIS environment. Other maps (mean annual temperature, ground temperature at 50 m depth that is considered the mid depth of a typical borehole heat exchanger) were generated on the basis of empirical relations evaluated in the case study, i.e. four regions of southern Italy. These additional maps are themselves a remarkable set of information available for pre-feasibility study for geo-exchange plants and for planning land and conditioning energy use in the studied areas at regional scale.

497 An evaluation of the accuracy of map-based prediction of geo-exchange potential in some test
498 sites shows that, typically, it is ~20%. Therefore, the obtained geo-exchange potential map can be
499 used for large scale energy planning purposes, but does not replace detailed site-specific analyses,
500 which, instead, are necessary for GSHP design purposes.

501 The proposed methodology can be easily exported in other contexts where use of shallow
502 geothermal resources is planned.

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514 **References**

- 515 Bakirci, K., 2010. Evaluation of the performance of a ground-source heat-pump system with series
516 GHE (ground heat exchanger) in the cold climate region. *Energy*, 35(7), 3088-3096.
- 517 Banks, D., 2012. An introduction to thermogeology: Ground source heating and cooling. 2nd
518 Edition. Wiley-Blackwell, Oxford, United Kingdom.
- 519 Bayer, P., Saner, D., Bolay, S., Rybach, L., Blum, P., 2012. Greenhouse gas emission savings of
520 ground source heat pump systems in Europe: A review. *Renewable and Sustainable Energy*
521 *Reviews*, 16 (2), 1256-1267.

522 Bertermann, D., Klug, H., Morper-Busch, L. (2015). A pan-European planning basis for estimating
 523 the very shallow geothermal energy potentials. *Renewable Energy* 75, 335-347.
 524 Bosellini, A., 2011. *Storia geologica d'Italia: gli ultimi 200 milioni di anni*. Zanichelli.
 525 Busby, J., Lewis, M., Reeves, H., Lawley, R., 2009. Initial geological considerations before
 526 installing ground source heat pump systems. *Quarterly Journal of Engineering Geology and*
 527 *Hydrogeology* 42(3), 295-306.
 528 Cataldi, R., Mongelli, F., Squarci, P., Taffi, L., Zito, G., Calore, C., 1995. Geothermal ranking of
 529 Italian territory. *Geothermics* 24(1), 115 – 129.
 530 Cavazza, W, Ingersoll, RV, 2005. Detrital modes of the ionian Forearc basin fill (Oligocene-
 531 Quaternary) reflect the Tectonic evolution of the Calabria-Peloritani Terrane (Southern Italy).
 532 *Journal of Sedimentary Research* 75(2), 268-279.
 533 Claps, P., Giordano, P., Laguardia, G. (2008). Spatial Distribution of the Average Air Temperatures
 534 in Italy: Quantitative Analysis. *Journal of Hydrologic Engineering* 13(4), 242–249.
 535 Clauser, C., 2006. Geothermal Energy (Chapter 8). in: *Renewable Energy 3C (Subvolume C*
 536 *'Renewable Energy' of Volume 3 'Energy Technologies' of Landolt-Börnstein Group VIII*
 537 *'Advanced Materials and Technologies')*, Springer, 493-548.
 538 CNR, 2014. Geothopica Project CNR/ENI web site. Available online at: <http://geothopica.igg.cnr.it>
 539 (accessed: 10 October 2014).
 540 Cultrera, M., Antonelli, R., Teza, G., Castellaro, S., 2012. A new hydrostratigraphic model of
 541 Venice area (Italy). *Environmental Earth Sciences* 66(4), 1021-1030.
 542 Di Sipio, E., Chiesa, S., Destro, E., Galgaro, A., Giaretta, A., Gola, G., Manzella, A., 2013. Rock
 543 Thermal Conductivity as Key Parameter for Geothermal Numerical Models. *Energy Procedia* 40(0),
 544 87 – 94.
 545 Di Sipio, E., Galgaro, A., Destro, E., Teza, G., Chiesa, S., Giaretta, A., Manzella, A., 2014.
 546 Subsurface thermal conductivity assessment in Calabria (southern Italy): a regional case study.
 547 *Environmental Earth Sciences*, 72 (5), 1383–1401.

548 Eskilson, P., Hellstrom, G., Claesson, J., Blomberg, T., Sanner, B., 2000. Earth Energy Designer
 549 (EED) web site. BLOCON software, Lund, Sweden. Available online at:
 550 <http://www.buildingphysics.com/manuals/eed.pdf> (accessed: 20 October 2014).
 551 Gemelli, A., Mancini, A., Longhi, S., 2011. GIS-based energy-economic model of low temperature
 552 geothermal resources: A case study in the Italian Marche region. *Renewable Energy* 36(9), 2474–
 553 2483.
 554 IEA, 2011. Technology Roadmap - Geothermal Heat and Power. Technical report, International
 555 Energy Agency.
 556 ISPRA, 2005. Geological Map of Italy. Institute for the Protection and Environmental Research,
 557 Italy.
 558 Kälin, B., Hopkirk, R.J., 1991. Quantitative Empfehlungen über den minimalen Grenzabstand einer
 559 Erdwärmesonden-Anlage (Quantitative recommendations on the minimum distance between the
 560 borders of borehole heat exchangers). Polydynamics Engineering, Zürich. (in German).
 561 Nam, Y., Ooka, R., 2011. Development of potential map for ground and groundwater heat pump
 562 systems and the application to Tokyo. *Energy and Buildings*, 43(2), 677-685.
 563 Noorollahi, Y., Itoi, R., Fujii, H., Tanaka, T., 2008. GIS integration model for geothermal
 564 exploration and well siting. *Geothermics* 37(2), 107-131.
 565 Ondreka, J.; Rüsken, M. I.; Stober, I., Czurda, K., 2007. GIS-supported mapping of shallow
 566 geothermal potential of representative areas in south-western Germany—Possibilities and
 567 limitations. *Renewable Energy* 32(13), 2186–2200.
 568 Polemio, M., Lonigro, T., 2012. Variabilità climatica e ricorrenza delle calamità idrogeologiche in
 569 Puglia. *Geologia dell’Ambiente* 2, 262-266.
 570 Signorelli S., 2004. Geoscientific Investigations For The Use Of Shallow Low-Enthalpy Systems.
 571 Master's thesis, ETH-Swiss Federal Institute of Technology Zurich.

572 Spina, V, Tondi, E, Mazzoli, S., 2011. Complex basin development in a wrench-dominated back-
573 arc area: Tectonic evolution of the Crati Basin, Calabria, Italy. *Journal of Geodynamics* 51(2), 90-
574 109.

575 Teza, G., Galgaro, A., De Carli, M., 2012. Long-term performance of an irregular shaped borehole
576 heat exchanger system: Analysis of real pattern and regular grid approximation, *Geothermics*, 43,
577 45-56

578 Thermo Map, 2013. ThermoMap MapViewer web site, Available online at:
579 <http://geoweb2.sbg.ac.at/thermomap/> (accessed: 12 May 2015).

580 TRNSYS, 2014. Transient system simulation tool web site. Available online at:
581 <http://www.trnsys.com/> (accessed: 12 May 2015).

582 VIGOR, 2010. VIGOR Project web site. Available online at: <http://www.vigor-geotermia.it/>
583 (accessed: 12 May 2015).

584 Yeo, I., Yee, J. J., 2014. A proposal for a site location planning model of environmentally friendly
585 urban energy supply plants using an environment and energy geographical information system (E-
586 GIS) database (DB) and an artificial neural network (ANN). *Applied Energy* 119(0), 99–117.

587 Zarrella, A., Capozza, A., De Carli, M., 2013. Analysis of short helical and double U-tube borehole
588 heat exchangers: A simulation-based comparison. *Applied Energy* 112(0), 358–370.

589 Østergaard, P.,A., Lund, H., 2011. A renewable energy system in Frederikshavn using low-
590 temperature geothermal energy for district heating. *Applied Energy* 88(2), 479-487.

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Table captions

Table 1. Monthly thermal energy profile typical for Apulia Region (where $\theta_m=16^{\circ}\text{C}$), where E_h is total annual heating energy and E_c is total annual cooling energy.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Octr	Nov	Dec	total
E_h (kWh)	976	778	413	55	0	0	0	0	0	0	175	721	3118
E_c (kWh)	0	0	0	0	-135	-848	-1380	-1280	-563	-40	0	0	-4245

599 **Table 2.** Results for the complete set of validated simulations.

test	θ_m	Q	λ	L_{tot}	E_c	E_h	$E_c + E_h$	θ_{g50}	n_{p100}	S_g	E_g / S_g
site	°C	W m ⁻²	W m ⁻¹ K ⁻¹	m	kWh	kWh	kWh	°C		m ²	KWh m ⁻²
1	10	0.01	0.5	471	-160	6872	6712	11.0	5	245	28
1	10	0.03	0.5	360	-160	6872	6712	13.0	4	196	35
1	10	0.07	0.5	277	-160	6872	6712	17.0	3	147	47
1	10	0.1	0.5	220	-160	6872	6712	20.0	2	98	70
1	10	0.01	1	355	-160	6872	6712	10.5	4	196	35
1	10	0.03	1	312	-160	6872	6712	11.5	3	147	47
1	10	0.07	1	243	-160	6872	6712	13.5	2	98	70
1	10	0.1	1	218	-160	6872	6712	15.0	2	98	70
1	10	0.01	1.5	292	-160	6872	6712	10.3	3	147	47
1	10	0.03	1.5	263	-160	6872	6712	11.0	3	147	47
1	10	0.07	1.5	227	-160	6872	6712	12.3	2	98	70
1	10	0.1	1.5	208	-160	6872	6712	13.3	2	98	70
1	10	0.5	1.5	107	-160	6872	6712	26.7	1	49	140
1	10	0.01	2	257	-160	6872	6712	10.3	3	147	47
1	10	0.03	2	238	-160	6872	6712	10.8	2	98	70
1	10	0.07	2	213	-160	6872	6712	11.8	2	98	70
1	10	0.1	2	180	-160	6872	6712	12.5	2	98	70
1	10	0.5	2	109	-160	6872	6712	22.5	1	49	140
1	10	0.01	2.5	233	-160	6872	6712	10.2	2	98	70
1	10	0.03	2.5	221	-160	6872	6712	10.6	2	98	70
1	10	0.07	2.5	202	-160	6872	6712	11.4	2	98	70
1	10	0.1	2.5	174	-160	6872	6712	12.0	2	98	70
1	10	0.5	2.5	111	-160	6872	6712	20.0	1	49	140
2	14	0.01	0.5	209	-2498	5217	2719	15.0	2	98	53
2	14	0.03	0.5	174	-2498	5217	2719	17.0	2	98	53
2	14	0.07	0.5	143	-2498	5217	2719	21.0	1	49	106
2	14	0.1	0.5	146	-2498	5217	2719	24.0	1	49	106
2	14	0.01	1	153	-2498	5217	2719	14.5	2	98	53
2	14	0.03	1	141	-2498	5217	2719	15.5	1	49	106
2	14	0.07	1	127	-2498	5217	2719	17.5	1	49	106
2	14	0.1	1	118	-2498	5217	2719	19.0	1	49	106
2	14	0.01	1.5	126	-2498	5217	2719	14.3	1	49	106
2	14	0.03	1.5	121	-2498	5217	2719	15.0	1	49	106
2	14	0.07	1.5	113	-2498	5217	2719	16.3	1	49	106
2	14	0.1	1.5	108	-2498	5217	2719	17.3	1	49	106
2	14	0.01	2	112	-2498	5217	2719	14.3	1	49	106
2	14	0.03	2	108	-2498	5217	2719	14.8	1	49	106
2	14	0.07	2	103	-2498	5217	2719	15.8	1	49	106
2	14	0.1	2	90	-2498	5217	2719	16.5	1	49	106
2	14	0.01	2.5	100	-2498	5217	2719	14.2	1	49	106
2	14	0.03	2.5	96	-2498	5217	2719	14.6	1	49	106
2	14	0.07	2.5	89	-2498	5217	2719	15.4	1	49	106
2	14	0.1	2.5	85	-2498	5217	2719	16.0	1	49	106
3	15	0.01	0.5	152	-4024	4082	58	16.0	2	98	42
3	15	0.03	0.5	154	-4024	4082	58	18.0	2	98	42
3	15	0.07	0.5	181	-4024	4082	58	22.0	2	98	42
3	15	0.01	1	116	-4024	4082	58	15.5	1	49	83
3	15	0.03	1	119	-4024	4082	58	16.5	1	49	83
3	15	0.07	1	127	-4024	4082	58	18.5	1	49	83
3	15	0.1	1	126	-4024	4082	58	20.0	1	49	83
3	15	0.01	1.5	98	-4024	4082	58	15.3	1	49	83
3	15	0.03	1.5	99	-4024	4082	58	16.0	1	49	83
3	15	0.07	1.5	103	-4024	4082	58	17.3	1	49	83
3	15	0.1	1.5	106	-4024	4082	58	18.3	1	49	83
3	15	0.01	2	88	-4024	4082	58	15.3	1	49	83
3	15	0.03	2	90	-4024	4082	58	15.8	1	49	83
3	15	0.07	2	91	-4024	4082	58	16.8	1	49	83
3	15	0.1	2	92	-4024	4082	58	17.5	1	49	83
3	15	0.01	2.5	82	-4024	4082	58	15.2	1	49	83
3	15	0.03	2.5	83	-4024	4082	58	15.6	1	49	83
3	15	0.07	2.5	85	-4024	4082	58	16.4	1	49	83
3	15	0.1	2.5	86	-4024	4082	58	17.0	1	49	83
4	16	0.01	0.5	195	-5306	2425	-2882	17.0	2	98	54

4	16	0.03	0.5	207	-5306	2425	-2882	19.0	2	98	54
4	16	0.07	0.5	237	-5306	2425	-2882	23.0	2	98	54
4	16	0.01	1	139	-5306	2425	-2882	16.5	1	49	108
4	16	0.03	1	143	-5306	2425	-2882	17.5	1	49	108
4	16	0.07	1	153	-5306	2425	-2882	19.5	2	98	54
4	16	0.1	1	154	-5306	2425	-2882	21.0	2	98	54
4	16	0.01	1.5	89	-5306	2425	-2882	16.3	1	49	108
4	16	0.03	1.5	116	-5306	2425	-2882	17.0	1	49	108
4	16	0.07	1.5	122	-5306	2425	-2882	18.3	1	49	108
4	16	0.1	1.5	122	-5306	2425	-2882	19.3	1	49	108
4	16	0.01	2	98	-5306	2425	-2882	16.3	1	49	108
4	16	0.03	2	100	-5306	2425	-2882	16.8	1	49	108
4	16	0.07	2	103	-5306	2425	-2882	17.8	1	49	108
4	16	0.1	2	105	-5306	2425	-2882	18.5	1	49	108
4	16	0.01	2.5	89	-5306	2425	-2882	16.2	1	49	108
4	16	0.03	2.5	90	-5306	2425	-2882	16.6	1	49	108
4	16	0.07	2.5	92	-5306	2425	-2882	17.4	1	49	108
4	16	0.1	2.5	93	-5306	2425	-2882	18.0	1	49	108
5	17	0.01	0.5	175	-4287	2162	-2124	18.0	2	98	44
5	17	0.03	0.5	184	-4287	2162	-2124	20.0	2	98	44
5	17	0.07	0.5	210	-4287	2162	-2124	24.0	2	98	44
5	17	0.01	1	119	-4287	2162	-2124	17.5	1	49	87
5	17	0.03	1	126	-4287	2162	-2124	18.5	1	49	87
5	17	0.07	1	134	-4287	2162	-2124	20.5	1	49	87
5	17	0.1	1	141	-4287	2162	-2124	22.0	1	49	87
5	17	0.01	1.5	99	-4287	2162	-2124	17.3	1	49	87
5	17	0.03	1.5	103	-4287	2162	-2124	18.0	1	49	87
5	17	0.07	1.5	107	-4287	2162	-2124	19.3	1	49	87
5	17	0.1	1.5	119	-4287	2162	-2124	20.3	1	49	87
5	17	0.01	2	87	-4287	2162	-2124	17.3	1	49	87
5	17	0.03	2	90	-4287	2162	-2124	17.8	1	49	87
5	17	0.07	2	91	-4287	2162	-2124	18.8	1	49	87
5	17	0.1	2	93	-4287	2162	-2124	19.5	1	49	87
5	17	0.01	2.5	79	-4287	2162	-2124	17.2	1	49	87
5	17	0.03	2.5	81	-4287	2162	-2124	17.6	1	49	87
5	17	0.07	2.5	83	-4287	2162	-2124	18.4	1	49	87
5	17	0.1	2.5	85	-4287	2162	-2124	19.0	1	49	87

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Figure captions

Figure 1. Case study: the four regions of Southern Italy related to VIGOR Project.

Figure 2. Main geological outcrops of studied regions.

Figure 3. Flowchart of proposed method. Black connectors are related to punctual, simulated or chosen data. Thick red connectors are related to grid information, i.e. maps. Quantities: λ : thermal conductivity, Q : shallow geothermal heat flux, θ_m : average annual surface (air) temperature, θ_{g50} : ground temperature at 50 m depth, L_{tot} : total length of borehole heat exchanger, V_g : geo-exchange potential, z and Lat : elevation above sea level and latitude of a site respectively, COP and EER: coefficient of performance and energy efficiency ratio of a heat pump respectively.

Figure 4. (a) Relationship between thermal conductivity (λ), ground temperature at 50 m depth (θ_{g50}) and total length of borehole heat exchanger (L_{tot}); (b) relationship between $V_g = E_g / S_g$ and L_{tot} .

Figure 5. Thematic maps of (a) average annual air temperature and (b) estimated ground temperature at 50 m depth.

Figure 6. Thematic maps of (a) shallow geothermal heat flux and (b) thermal conductivity.

626 **Figure 7.** Thematic maps of geo-exchange potential V_g for shallow closed loop systems, expressed
627 as the ratio E_g / S_g between the maximum exchanged thermal energy required by the system, E_g ,
628 and the BHE field area, S_g .

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