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UNIVERSITÀ DEGLI STUDI DI TORINO

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22 **Borehole thermal energy storage (BTES). First results from the injection**
23 **phase of a living lab in Torino (NW Italy).**

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45 **Abstract**

46 The seasonal storage of thermal energy in the ground is a useful application able to provide H&C and
47 DHW demand of commercial or residential buildings. Several examples in Canada and Northern Europe
48 demonstrated the reliability and convenience of these systems in terms of both energy and economic
49 savings, but more demonstration sites are however necessary. The surrounding litho-, hydro- and bio-
50 sphere are influenced by the plant's activity and a trustworthy supervision of the temperature field would
51 bring advantages to both the environment and the system's efficiency. Usually numerical modeling is
52 used to forecast the system behavior but results of simulations can be strongly dependent from assumed
53 material characteristics and should be strictly calibrated on real data. To better understand thermal
54 processes in the ground related to thermal injection and thermal storage, a field scale BTES living lab
55 was build up nearby Torino (Northern Italy) within unsaturated alluvial deposits. Results show that
56 approximately 9.1 GJ were transferred to the ground during the first year, raising the undisturbed
57 temperature by 2°C, and that a correct comparison of monitoring data and numerical simulations can be
58 obtained following a specific site characterization.

59

60 **Keywords:** borehole thermal energy storage; sensible heat; numerical simulation; porous media; Italy

61

62 1. INTRODUCTION

63 The idea of exploiting the energy provided by renewable sources has been always
64 accompanied by the problem that most of these sources can supply energy when the user's
65 demand is low. The thermal energy storage (TES) is a highly debated concept which was first
66 mentioned in the late 1970s. In recent years several storage technologies have been developed
67 in order to find some valid solutions which can assure criteria of reliability, efficiency and
68 economic sustainability.

69 One of these solutions consists in generating the heat from the Sun and accumulating it
70 in the ground in order to face the day/night and summer/winter alternation in the solar
71 productivity. The system uses the ground as a medium for daily (short term - ST) or seasonally
72 (long term - LT) storing of the heat through borehole heat exchangers (BHEs) which connect
73 the heating source and the storage volume. Hence, the ground thermal energy storage falls back
74 in the category of the low enthalpy geothermal systems, which typically exploit the ground as
75 a source using BHEs coupled with heat pumps to cover the thermal energy demand of the
76 buildings. In both cases the ground has an active part in generating thermal energy, but in
77 thermal storage applications it plays a double role: on one side it should accumulate as much
78 heat as possible (storage medium), minimizing the losses through the surrounding subsurface
79 and the atmosphere; on the other it has to provide the stored heat as long as necessary (source).

80 The interaction of such systems with the ground is doubtless non-trivial. Nevertheless,
81 the underground part of the plants is too often modestly debated, minimizing the problem to the
82 number and depth of the BHEs, taking under consideration an average linear productivity value,
83 if specific thermal response tests cannot be carried out. It is conversely necessary to test this
84 part of the plant from multiple points of view in order to construct a system sustainable and
85 perfectly integrated in the litho-, hydro- and bio-sphere. A correct sizing of the plant will benefit
86 not only its efficiency but also the health of the environment.

87 Hence, the present study arises from the necessity to better understand the ground's
88 behavior when affected by thermal injection, both for the efficiency of the energetic system and
89 for subsurface monitoring. This paper presents the natural consequence of a wider research
90 activity firstly applied at laboratory scale consisting in: i) analogical/numerical modeling of
91 thermal injections in porous media, in order to test the ability to transfer and store the heat as a
92 function of the water content [1] and ii) electrical resistivity measurements tested as a
93 monitoring tool for the imaging of the heated plume's distribution [2]. In the light of the
94 laboratory's outcomes, a small scale BTES plant was built up near Torino as a monitoring and
95 field scale laboratory site to evaluate the ground's ability to conduct and store the thermal
96 energy. The plant was officially launched on 2014, April 2 and the results of the first operative
97 year are here presented together with numerical simulation outcomes. The geophysical
98 methodology applied for the monitoring activity will be discussed in a second paper.

99

100 2. STATE OF THE ART ON BOREHOLE THERMAL ENERGY STORAGE

101 The Sun provides an enormous amount of energy, about 3.8×10^{18} J (i.e. 1×10^{12} kWh y⁻¹).
102 Nevertheless, this abundant amount of energy has an intermittent character owing to the
103 day/night alternation and the passing of seasons. This time-dependent supply does not match
104 with the human needs and the misalignment between the source and the demand is one of the
105 longstanding barriers to solar energy technology. The peak demand occurs in the late evening
106 when the solar radiation is no longer available, while the peak supply takes place in the middle
107 of the day when generally both electricity and thermal energy demands are at the daily
108 minimum. The wide solar technology spreading in the last 5 years in Italy and the installation
109 of several small-medium size photovoltaic plants for power production have modified the daily
110 supply curve, lowering the price of the electrical energy at the Stock Exchange at a minimum
111 in the middle of the day. In particular, on 2013 April 14 the electricity price collapsed to almost
112 0 € MWh⁻¹ at 3 PM and rose to about 90 € MWh⁻¹ just 6 hours later [4]. There is therefore a
113 significant amount of low cost energy available that can be exploited.

114 The solar energy can therefore potentially lead the energetic transition from fossil fuels
115 to renewable sources but storage mechanisms have to be implemented in order to bridge the
116 gap between the energy source and its application to buildings and facilities. The development
117 of several storage technologies able to reduce the time and rate of the supply/demand mismatch
118 and the strong commitment of the leading countries in the efficiency are driving the energy
119 revolution of the present decades, aiming at the increasing sustainability of the human activities.

120 Two key factors in selecting the material for the energy storage are the energy density,
121 defined as the amount of energy accumulated per unit volume or mass, and the operation
122 temperature range ([5]). The amount of thermal energy E [J] stored in a volume of material can
123 be expressed as:

$$124 \quad E = \gamma_b \cdot C_{sb} \cdot V \cdot \Delta T \quad [1]$$

125 where γ_b [kg m⁻³] and C_{sb} [J kg⁻¹ K⁻¹] are the bulk density and the specific heat capacity of the
126 storage medium, V [m³] is the volume and ΔT [°C] is the temperature range of operation.

127 According to Pilkington Solar International GmbH [7], any TES system can be classified
128 by storage concept and by storage mechanism. Based on the former, the systems can be active
129 if they are characterized by forced convection and the storage medium itself circulates alone
130 (direct or closed loop systems) or different media are used to collect and store the heat (indirect
131 or open loop systems). Conversely, they can be passive if a heat transport medium passes
132 through the storage medium to charge or discharge it by thermal energy. The storage medium
133 can be a liquid, a solid, a phase change material or a chemical reactant. The storage mechanisms,
134 together with the storage materials involved, have been researched intensively in the frame of
135 Task 32 [8] and Task 42 [9] of the IEA Solar Heating and Cooling (SHC) programme. Three
136 main categories can be identified on the strength of the storage mechanisms: chemical heat,
137 latent heat and sensible heat, the formers being the ultimate innovative technologies while the
138 latter deriving from decades of research and experiments. Details on chemical storage and
139 adopted thermo-chemical materials (TCMs) can be found in *Errore. L'origine riferimento non*
140 *è stata trovata.*[10], [11]. In-depth analysis on techniques and phase change materials (PCMs)
141 involved in latent heat storage applications can be conversely found in [14], [15], and [16].

142 The sensible heat, which is among the storage mechanisms the most popular and most
143 practiced in the last decades, is the internal energy of a substance which undergoes a
144 temperature increase without changing its phase. Sensible heat storage technologies are easy to
145 control and mostly environmental friendly, with material costs far lower than latent and
146 chemical applications. Conversely, they need to involve large volumes owing to the low energy
147 density. The huge volumes required on turn influence the self-discharge problems and the high
148 initial investment due to the construction activities. **Fig. 1** highlights the differences among the
149 three mentioned storing methodologies by showing volumes needed to store 10 GJ of energy
150 with a temperature range of operation equal to 70°C as proposed by [17] in a report of the IEA
151 SHC Task 32. Comparing the volumes necessary when a porous medium fully (quaternary
152 sediments below the groundwater table) or half saturated (quaternary sediments in the vadose
153 zone) by water or a compact granite is used as storage material it is evident that it would need
154 a volume of rock or unsaturated deposits 2 times bigger than a volume of water in order to
155 accumulate the same amount of energy. But a saturated porous medium with an average
156 porosity of 0.35 would require only 25% more volume than what the water needs. Nevertheless,
157 there is no comparison between sensible heat storage materials and those involving latent
158 (PCMs) and chemical (TCMs) heat. Apart from the quantity of material, its dimensions are also
159 important, being fundamental a low surface/volume ratio for minimizing the heat losses [5].

160 Besides density and specific heat of the storage material (energy density), other properties
161 are important for sensible heat storage: the thermal conductivity and diffusivity, the temperature
162 range of operation, the stratification of the storage unit and the heat loss coefficient as a function
163 of the surface areas to volume ratio. Details on stratification concept can be found in [18], [19],
164 [20], [21], [22], [23], [24], and [25]. The most popular material for applying the sensible heat
165 storage is the water, which has noticeable heat capacity ($4.2 \times 10^6 \text{ J m}^{-3} \text{ K}^{-1}$) and it is easy to
166 manage by pumping it. Water is often used alone in artificial tanks ([24], [26], [27], [29], [30])
167 or from aquifers in open loop systems ([30], [32]), solar ponds ([33], [25]) and underground
168 caverns and holes ([35]) sometimes previously used for oil storage. A high thermal conductivity
169 can promote injection and extraction of heat, but at the same time it can cause system's self-
170 discharge. Rocks and geological porous media are used as storage material as well, because of
171 their widespread availability and their low heat loss rate compared to water. Rocks have good
172 thermal capacity ($2\text{-}3 \times 10^6 \text{ J m}^{-3} \text{ K}^{-1}$) and conductivity ($3\text{-}5 \text{ W m}^{-1} \text{ K}^{-1}$), but they often present
173 a high fracturing state which can lead to self-discharge caused by water flows. The quaternary
174 deposits show rather high heat capacity if saturated by water, but groundwater flow could carry
175 away the heat. Rock bed storage systems consist of volumes of pebbles, gravels or concrete
176 bricks completely saturated by a heat transport fluid (air or water) which circulates through it
177 charging and discharging thermal energy ([15], [19], [30], [36]).

178 Nevertheless, this key factor is related not only to intrinsic characteristics of the material,
179 but also to the environmental conditions of the site. Geological materials are therefore freely
180 available, but several geological conditions need to be analyzed beforehand for their fruitful
181 use ([38]). Geological requirements need to be accounted for in the early stages of the project
182 in order to select the system that can provide the best efficiency and the lowest environmental
183 impact. Research studies in this field have to aim at the optimization of storage temperatures,
184 insulation technologies and material properties. In addition, a real scale simulation and a
185 numerical model calibrated on experimental direct or indirect data are essential to understand
186 the ground's behavior and to highlight the affecting factors. Definitely, all these consideration
187 have to be taken into account when choosing the type of system according to available space,

188 geological and hydrogeological conditions, difficulties in the local authority approval
189 procedures and final user's requirements.

190 From an operational point of view, the plant generally consists of a thermal collectors'
191 area (usually on the roofs of the supplied buildings), a ST storage called "buffer storage" (very
192 often simple water tanks), a LT storage and a heat distribution network [30]. The purpose of
193 the buffer storage (when present) is to minimize the transients in the energy delivery due to
194 day/night alternation and bad weather days, which can affect energy collection [7]. It is very
195 important to transfer heat to the LT storage at a constant temperature throughout the warm
196 season, or at least to have the opportunity to choose which part of the volume to supply.

197 The underground can be profitably used for storing the thermal energy in a closed-loop
198 system, involving borehole heat exchangers in vertical (**Fig. 2**) or horizontal disposition (**Fig.**
199 **3**). In the first type a series of BHEs is drilled in the ground (typically in number of 30-50)
200 down to 40-50 m, which is lower than the classical depth of ground coupled heat pumps
201 (GCHPs). The ratio surface to volume should be always as much low as possible in order to
202 minimize the losses towards the surrounding ground. A layer of insulation materials is
203 predisposed on top of the boreholes. The insulation is also applied above the set of pipes linking
204 the storage volume to the buffer storage of the system, because the largest losses occur towards
205 the atmosphere. Sometimes the volume is also insulated at the side walls, but the costs are
206 definitely not negligible. Among all the described applications, the closed-loop ground-based
207 storage systems have the lowest energy density with around 15-30 kWh per cubic meter of
208 ground. The water-based storages possess a 60-80 kWh m⁻³ energy density, while the gravel-
209 water mixtures and the aquifer systems attest to approximately 30-50 kWh m⁻³ [40].

210 A common borehole disposition consists of a circular shape with a radius in the range 15-
211 30 m (on the strength of the needed volume) and a spacing of less than 1 m among the heat
212 exchangers. This arrangement permits creating a warmer core in the center of the cylinder and
213 an annular zone around it becoming colder and colder towards the exterior. The hydraulic
214 circuit usually operates in order to transfer the heat first in the central pipes and then in cascade
215 in the external [41]. Indeed, the boreholes are hydraulically connected in series or in parallel.
216 During the charge of thermal energy, the flow direction is from the centre to the boundaries in
217 order to achieve high temperature in the core and lower values in the externals. In the cold
218 season flow direction is reversed and heat is first extracted from the boundaries progressing
219 towards the core [30]. This working mode allows achieving several targets: (i) the core is always
220 supplied with the warmer thermo-vector fluid and is heated up continuously; (ii) the fluid going
221 out from the central BHEs is still carrying a not negligible amount of heat and this is used for
222 heating up the lateral portions; (iii) the gradient between the core and the undisturbed ground
223 is lowered by the temperature in the annular zone, promoting a low self-discharge of the system;
224 (iv) a modular design allows adding supplementary boreholes afterwards, which can be easily
225 connected for the growth of the system.

226 In the following tables, several plants with BTES technology are reported with detailed
227 features for each system. Sweden (**Tab. 1**) and Germany are the countries with the highest
228 experience since the 1980s until the current time, but other nations have contributed to the
229 knowledge as well (**Tab. 2** and **Tab. 3**).

230 3. MATERIALS AND METHODS

231 3.1 Geographical, climatic and geological context

232 The test site is situated near Torino in the municipality of Grugliasco (geographical
233 coordinates 45° 3' 55'' N, 7° 35' 23'' E). It is located in the north-western portion of the
234 *Pianura Padana*, between the Sangone River on the South, the Po River on the East and the
235 Dora Riparia River on the North. The elevation of the area is 287 m a.s.l., with a difference of
236 approximately 70 m with respect to the Po River level. The site receives a solar radiation which
237 allows producing approximately 1,300 kWh m⁻² per year and is characterized by 2,092 heating
238 degree-days referred to 18°C (**Tab. 4**).

239 The first operative year of the system built up in Grugliasco was characterized by a
240 summer period different from what usually expected in North-Western Italy. This can be noted
241 from a comparison of the average daily temperature and the monthly rainfalls between the
242 periods April - October 2014 and April - October 2005 – 2013 (**Fig. 4**). The 2014 data were
243 registered by a weather station placed in the *Physics Department* [50]; the 2005 - 2013 data
244 belong to *Arpa Piemonte* [51]. The weather station is located in the Torino city being aware
245 that the air temperature in Grugliasco would be approximately 2°C smaller. Since May to
246 September 2014 the temperature was clearly smaller than the average; in particular, July and
247 August registered values around 21°C, being the average standing approximately at 24°C. In
248 addition, July 2014 was the rainiest among the last ten years together with July 2011. June and
249 September were the second and the first driest months among the considered period while
250 August stood around the average.

251 From the geologic point of view the area consists of abundant Pleistocene-Holocene
252 glacio-fluvial coalescing fans connected to the alluvial plain of the Po River, which on turn lays
253 on the Torino Hill lithological units (**Fig. 5**). The plain consists of gravelly-sandy materials with
254 high permeability in the first 60-70 m below the ground level (**Fig. 6**). Within these deposits it
255 is common to find layers of compacted gravels or conglomerate (the “Ceppo”), deriving from
256 the cementation of gravels by a carbonatic cement of fluvio-glacial origin. In the test site the
257 surficial deposits belong to “*Subsintema di Col Giansesco*” (Pleistocene Inf. - Holocene) which
258 is part of the “*Sintema di Frassinere*”: in this unit pebbles of quartzite, serpentinite, gneiss,
259 prasinite and calcareous schist were found [52]. Below this unit, there are deposits of a
260 transitional *facies* between marine and continental environment, being characterized by the
261 alternation of coarse sands and silts due to the progression and regression of the coastal line in
262 the Pliocene Med. – Pleistocene Inf.

263 Drilling activity performed in the site confirmed the overall geological setting and showed
264 30 m of gravels and sands. Sometimes some decimetric layers of compacted gravelly sands
265 were encountered. Samples, pertaining to these levels, collected for laboratory analyses,
266 revealed the presence of carbonatic cement in the matrix. Other samples of un-compacted
267 gravels and sands (sampled at 7.5, 21 and 27 m depths) were moreover analyzed for the
268 determination of the grain size distributions (**Fig. 7**). These samples were also analyzed from a
269 thermal point of view (**Tab. 5**), whereas it was not possible to examine the compacted samples
270 because of the presence of too big pebbles. The devices adopted for thermal characterization
271 were the ISOMET 2114 (*Applied Precision Ltd., Bratislava, SK*) and the KD2 Pro (*Decagon*
272 *Devices Inc., Pullman, WA, USA*), which can measure properties of both porous media and
273 rocks. The ISOMET 2114 (ISO) is based on the transient line source method and it applies the
274 dynamic measurement method in order to minimize the measurement time. For the
275 determination of the thermal conductivity of the examined samples the needle probe IPN 1100

276 was used (measurement range $0.015 - 2.0 \text{ W m}^{-1} \text{ K}^{-1}$, accuracy 5%). The KD2 Pro device
277 (K2D), based again on the transient line heat source method, applies different algorithms on the
278 strength of the selected probe (dual needle or single needle). The conductivity was measured
279 with the TR-1 single-needle probe (measurement range $0.1 - 4.0 \text{ W m}^{-1} \text{ K}^{-1}$, accuracy 10%).
280 Contrary to the ISO, this probe has a larger diameter and provide longer heating time for
281 minimizing the errors related to the contact resistance. In addition, TR-1 heats the sample
282 significantly more than IPN 1100 on the ISO, making possible to measure higher λ values.

283 From the hydrogeological point of view, a phreatic aquifer is hosted in the shallower unit,
284 while the deeper unit is characterized by a multi-level aquifer. The groundwater in the first unit
285 flows eastward, being in direct connection with the Po River. On the strength of the available
286 data, the water table in the examined area is thought to stand to 35-40 m below the ground level.
287 On the basis of the grain size distributions of the 3 collected samples, the hydraulic conductivity
288 $K [\text{m s}^{-1}]$ was calculated with the Kozeny-Carman equation [53]. Values of $K = 2.3 \times 10^{-4}$, 5.6
289 $\times 10^{-4}$ and $3.5 \times 10^{-4} \text{ m s}^{-1}$ were respectively obtained.

290 3.2 Plant's setup

291 In the light of the above described geological conditions and owing to administrative
292 regulations, the plant was set up in the unsaturated zone of the unconfined aquifer. This situation
293 was however a valuable choice in order to test the ability of unsaturated saturated alluvial
294 deposits in storing the heat. Following the evidences of laboratory simulations on similar
295 materials [1] intermediate (25 - 50 %) water content showed indeed great potentiality in storing
296 the heat. The underground part of the system was located nearby the Topography building of
297 the *Department of Agricultural, Forest and Food Sciences of Torino University* (Fig. 8). It
298 stores the heat in the ground by means four 27 m deep BHEs. The arrangement consists of a
299 double-U piped borehole placed in the center of an equilateral triangle (2 m side), and other 3
300 single-U piped BHEs located at the triangle's vertexes (Fig. 9). A 33 m deep monitoring hole
301 was moreover located 2 m away from the double-U heat exchanger. The top of the BHEs is
302 placed at a depth of 1.5 m from the ground level in order to minimize the heat losses towards
303 the atmosphere. The distance between the BHEs and the building is more than 10 m and it was
304 therefore important to cover all the connecting pipes with a 1.5 m thick insulating layer for
305 preventing the heat losses.

306 The grout used for guaranteeing a valuable thermal connection between the pipes and the
307 surrounding ground has a nominal thermal conductivity of $\lambda = 2 \text{ W m}^{-1} \text{ K}^{-1}$. Two days after the
308 end of the drilling activity, 3 samples of the grout were collected and analyzed with both the
309 ISO and the KD2 (Tab. 6). With the first device, the surface probe IPS 1100 was used
310 (measurement range $0.04 - 6.0 \text{ W m}^{-1} \text{ K}^{-1}$, accuracy 10%), while with the second the TR-1 was
311 adopted. In this case the most reliable values should be those measured with the ISO because
312 for compacted and previously smoothed samples the surface probe seemed more appropriate.
313 Measured grout thermal conductivities were notably lower than the nominal one (Tab. 6) and
314 could potentially affect the system behavior for these kind of applications. Nevertheless in the
315 unsaturated deposits at the test site the effective λ of the ground is rather low (see Tab. 5) and
316 thus comparable to the grout. The material surrounding the pipes can be therefore considered
317 thermally homogeneous.

318 The remaining part of the system was located in the Topography building. Two solar
319 thermal panels were placed on the roof with a total net surface of 5.0 m^2 with an inclination of
320 approximately 10° (Fig. 9). Typically, the solar collectors are installed with an inclination of
321 30° for guaranteeing a valuable production also in winter, when the Sun's orbit is low and the

322 delivery daily hours no more than 3-4. Nevertheless, in this case a low inclination arrangement
323 was provided in order to maximize the production in the summer period and in the central part
324 of the day (see **Tab. 4**). The circuit is governed by a 59 W electric hydraulic pump located in
325 the basement of the building, where all the pipes are arranged together. The pump provides the
326 thermo-vector fluid circulation through the whole system at a maximum flow rate of 210 l h⁻¹
327 and a constant pressure of 2.2 bar. The chosen anti-freeze additive is Propylene Glycol at 25%
328 vol. concentration, which prevents the freezing of the thermo-vector fluid up to a temperature
329 of -20°C. In addition, a heat sink was added to the system in order to dissipate the heat collected
330 during the warm season for simulating the heating activity of a real BTES plant.

331 As above described, the whole plant was designed with the idea of a high flexibility field
332 scale laboratory. A management system, with a remote control from the Earth Science
333 Department in Torino, was therefore installed to monitor the activity of the plant and to manage
334 it. Several temperature sensors were placed throughout the circuit and within the ground. An
335 energy recorder was moreover installed for the quantification of the energy injected into the
336 ground (produced by the collectors) during the summer and then extracted in the winter period.
337 A website [54] was furthermore set up for the dissemination of the project's results.

338 A total of 20 RTD 4wire Pt100 (measurement range -50 – 180°C, accuracy 5%) were
339 placed every 5 m down-hole in 3 of the 4 BHEs and in the monitoring hole. In addition, 10
340 temperature sensors of the same type were placed throughout the circuit and on the thermal
341 panels. An ultrasonic flow meter was placed on the pipes for providing flow rate data. Thus, on
342 the strength of temperature T [°C] and flow rate q [m³ s⁻¹], an energy calculator registers the
343 energy produced by the thermal collectors, by first calculating the instantaneous power P [W]
344 by means of the volumetric heat capacity Cv_w [J m⁻³ K⁻¹]:

$$345 \quad P = Cv_w \cdot (T_{out} - T_{in}) \cdot q \quad [2]$$

346 and then the energy E [Wh] by multiplying it for the working hours. All the sensors were
347 connected to a data logger which continuously collects the data, providing a 0.5 h sample
348 interval.

349 With the remote control it is possible to visualize and register the temperature sensors'
350 values throughout the circuit and within the ground, selecting and modifying the working modes
351 as well. The operative mode of the system was decided in the light of the several already
352 working plants, where a core volume benefits from the hottest carrier fluid and an annular
353 volume is powered by the same fluid carrying a lower amount of heat. Therefore, the central
354 BHE was used as the warmer core and the externals as a thermal barrier towards the undisturbed
355 ground. During the summer period, the thermo-vector fluid warmed by solar energy is driven
356 down into the central BHE, then out to the hydraulic pump and re-pumped down into the
357 external BHEs afterwards. This is called the "Charge Phase" in which the ground is charged by
358 the thermal energy provided by the Sun and collected by the panels. The system is able to decide
359 whether to circulate the fluid or not, because a temperature difference constraint has been
360 imposed. If the difference between the collectors' and the average ground's temperature is more
361 than 5°C the system works and the ground is charged by solar thermal energy. Conversely, if
362 $\Delta T < 5^\circ\text{C}$ the circulation is stopped in order to prevent the cooling of the ground. During the
363 winter, the system's circulation is inverted and the "Discharge Phase" occurs. The carrier fluid
364 extracts the heat stored in the ground and brings the energy to the heat sink. The energy
365 calculator placed in the circuit measures the amount of energy injected in the first and extracted
366 in the second phase. The described operative mode has been chosen for the first year of
367 operation (2014).

368 The plant has been officially launched on April 2 with the charge phase and stopped on
369 October 20. In the first year of operation the discharge phase was not adopted immediately in
370 order to observe the natural cooling of the ground. The decision was led by the fact that the
371 summer 2014 was rather cool with respect to a typical one in these geographical and climatic
372 conditions. Nevertheless, this particular situation will be used for describing the natural
373 discharge and comparing it with the laboratory case study data.

374 **3.3 Numerical model's setup**

375 The numerical simulation of the Grugliasco site was performed with the aim of predicting
376 the extension of the thermal plume through the ground. In this case, all the data collected during
377 the drilling activity and the laboratory analysis, together with information from *Arpa Piemonte*
378 [51] and the available literature, were used as input values for the model in order to carry out
379 an as much as possible accurate simulations. The modeling was performed with OpenGeoSys
380 (OGS) code, an open-source initiative for the numerical simulation of thermo-hydro-
381 mechanical/chemical processes. OGS is a flexible numerical framework based on the finite
382 element method, provided to solve multifield problems in porous and fractured media for
383 several geological and hydrological applications. In the numerical environment, a 3D
384 quadrilateral 50 x 50 x 50 m model was developed. A triangular prismatic mesh of about
385 140,000 elements was set up with Gmesh [56] in order to be finer in the center of the model
386 and progressively coarser laterally. The adopted physical properties for the ground are
387 presented in **Tab. 7**.

388 The numerical model was first calibrated on the experimental data of the first year of
389 operation (2014). The adopted boundary conditions were then used for a long-term simulation
390 aiming at the prediction of the plant's behaviour in the next five years, featuring a 6 month
391 alternation between heat injection and extraction. During the warm season each day should be
392 simulated by an injection at about 40°C for 8 h and at 20°C for the remaining 16 h [57].
393 Nevertheless, this kind of discretization would need excessive computation time. In order to
394 speed up the simulations, a weighted average inlet temperature was therefore chosen: 33°C in
395 the central BHE and 25°C in the externals. During the winter period, an inlet constant
396 temperature of 10°C was adopted. After several comparative tests about time discretization, the
397 whole simulation time was divided in 18,250 steps of 0.1 day each.

398

399 4. RESULTS

400 4.1 Plant's monitoring

401 A brief report of the registered plant's parameters is reported and commented in the
402 present paper. For a more detailed description please refer to [58] and the webpage of the living
403 lab [54]. During the first part of the injection period the plant was set to provide the highest
404 possible temperature to the working fluid. The system was therefore set to have a maximum
405 flow rate of 80 - 90 l h⁻¹, which is approximately the 40% of the nominal rate of the pump. On
406 July 10, the working mode was changed by setting the system to optimize the flow rate, with
407 resulting lower fluid temperatures. A lower flow rate allows both the thermo-vector fluid
408 reaching high temperatures and increasing the time of heat release in the ground. In **Fig. 10A**
409 and **Fig. 10B**, data from the sensors placed in the boreholes are reported from April 9 to
410 September 30. Generally, an average increasing temperature trend was observed and heat up
411 rates of 0.4-0.5 °C month⁻¹ were registered; data from BHE show however to be strongly
412 influenced during each day by the temperature of the circulating fluid. In the second part of
413 September (from day 140 to the end of the monitored period), several bad weather days
414 influenced the ground temperature, lowering the recorded data in the central borehole (DU) and
415 in one of the externals (A); the monitoring hole (MH) tended to equilibrium. At the end of the
416 whole charging phase, the ground temperature rose approximately to a rather homogeneous
417 value of 16.3-16.4 °C up to 2 m from the central BHE.

418 A focus on July is reported in **Fig. 11**. The temperature data from sensors in the BHEs
419 and MH are displayed in graph A. The average temperature in BHEs and MH is then compared
420 with those recorded on the collectors (graph B). The inlet and outlet temperature to the BHE
421 field are plotted in comparison with weather data in graph C. Graph D displays the working
422 parameters of the plant (flow rate and instant power) together with the thermal energy
423 progressively produced and injected into the ground. Since July 10, as a consequence of the
424 different operative mode, the flow rate reached values of 200 l h⁻¹ (**Fig. 11D**) and immediately
425 some variations of the other parameters were observed. The difference between the inlet
426 temperatures in the DU and in the external BHEs decreased to an average value of 10-15 °C
427 (**Fig. 11C**). The amplitude of the average temperatures in the BHE field increased, with peaks
428 of 21°C (**Fig. 11B**). It is clear in **Fig. 11A** that the amplitude of A and B after this change in
429 flow rate were doubled with respect to the previous condition, whereas the temperature
430 registered in DU remained approximately unchanged. Moreover, it is interesting to note that
431 the MH registered the highest increasing rate in the period since July 20 to 31. This was a late
432 response affected by the high energy production occurred since 8 to 18. Together with June,
433 July was the most productive month among all, with 514 kWh of thermal energy transferred to
434 the ground. It is important to note that this increase in production was registered although the
435 first and the final days of the month saw bad weather conditions with several rainfalls.

436 In summary, the thermal energy monthly transferred to the ground amounted to 367, 457,
437 528, 514, 498, 353 and 100 kWh since April to October respectively. On the whole 2,830 kWh
438 (about 10.1 GJ) were injected in seven months. In the light of **Tab. 4**, the total energy which
439 can be potentially produced by the collectors in horizontal position since April to October would
440 be approximately 4.2 MWh (considering 82% efficiency of the *Viotosol* collectors). This
441 divergence should firstly be related to the effective inclination of the collectors on site and
442 secondly to the lower amount of solar radiation received during the 2014 summer.

443 To estimate the energy transferred to the ground E_T , the total energy produced should be
444 lowered accounting for the losses which occur throughout the circuit, assumed to be

445 approximately 5 - 10%. Therefore, a reference value of $E_T = 9.1$ GJ can be precautionary
446 accepted. If all the domain influenced by the heat storage is assumed to be affected by a constant
447 temperature increase of 1°C , the ground volume affected by the thermal injection would result
448 in:

$$449 \quad V = \frac{E_T}{\Delta T * c v_b} = \frac{9,100}{1 * 2.1} = 4,300 \text{ m}^3 .$$

450 This amount corresponds to a cylinder with a radius of 7 m and a depth of 28 m.

451 The energy injected, and effectively still present in a volume of cylindrical shape with a
452 2 m radius (the distance between the monitoring hole and the central BHE), can be estimated
453 by observing the temperature registered in the ground at the end of the injection period. On
454 October 22, the equilibrium temperatures were 16.2°C in the MH, 16.4°C and 16.6°C in the
455 external BHEs, 16.4°C in the central. Therefore, the amount of thermal energy collected E_C is
456 in the range 1.6 - 2.0 GJ, with the two end members corresponding to $\Delta T = 2^\circ\text{C}$ or 2.5°C
457 respectively.

458 With the data referring only to the first charge phase, the efficiency of the storage can be
459 estimated to 17 - 22%. A correct estimation of the system's efficiency would be obtained after
460 a complete discharge phase, as the inverted cycle would bring energy to the heat sink. The ratio
461 between injected and extracted energy would output the efficiency of the whole system. It is
462 nevertheless preliminary clear the necessity of an insulation aside the BHEs in order to prevent
463 the dispersion of the heat injected, to improve the storage potential and to facilitate the
464 extraction during the winter season.

465 **4.2 Numerical results**

466 The temperatures registered by the acquisition system were assigned as BC in the model
467 with a discretization equal to the sampling interval (0.5 hours). This input datum is rather heavy
468 from the computational point of view. The comparison between experimental and numerical
469 data is reported in **Fig. 12** (for a simplified visualization one datum per day is reported,
470 averaging the 48 data available for each day). A valid estimation of the real system behavior
471 has been obtained by the numerical simulation. Since July 10, the numerical results show
472 smaller temperature variations (particularly clear in DU) because we changed the inlet
473 temperature by modifying the working mode of the plant. This is also evident in MH, where
474 after a first period with a valid superposition of numerical and experimental data the
475 temperature reached at the end of the simulation is 0.3°C lower than that observed in the field.
476 Obviously, the thermal energy input provided by the plant in the field was the same because a
477 lower temperature is a consequence of a higher flow rate. The monitoring data were therefore
478 not affected by the low inlet temperature. Nevertheless, generally speaking, the values
479 registered in the field are valuably simulated by the code: average errors of 1.54%, 3.36% and
480 0.64% were achieved for external A, central DU and MH respectively.

481 The numerical simulation was also adopted to forecast the temperature distribution within
482 the ground in the next years. The weighted average inlet temperature adopted in the charge
483 phase were 24.5°C and 20.3°C in the central and the external BHEs respectively. The outlet
484 temperature in the discharge phase was 10°C in both the borehole types. The simulation
485 outputted a stationary situation during the 5 years, with a very limited ground influence. After
486 the last injection period, the isotherm $+2^\circ\text{C}$ shows an extension not bigger than the BHE field
487 and the isotherm $+1^\circ\text{C}$ stands at approximately 5 m from the central BHE. The temperature-
488 time prediction's curves in the central BHE and in the MH describe a stationary situation. The

489 ground temperature at the end of each charge-discharge cycle recovers approximately the
490 original temperature with a limited divergence of 0.4 - 0.5°C.

491 **5. DISCUSSION**

492 **5.1 General discussion**

493 The temperature monitoring showed that the sensors placed in the BHE grout are very
494 sensitive to the circulation of the thermo-vector fluid. They registered the day/night alternation
495 and a bad weather period is immediately observable in the data recordings. Conversely, the
496 sensors placed in the MH presented a constant temperature increase since April to the end of
497 September. A standalone sensor chain in an independent borehole should be of primary
498 importance in order to correctly monitor the effect of the heating in the ground without the
499 influence of the plant itself.

500 The different working modes adopted in the injection period revealed different behaviors
501 in the ground. The low flow rate mode, provided until July 10, allowed reaching a high
502 temperature in the circulating fluid, but the amount of heat was almost completely transferred
503 into the ground during the passage in the central BHE. The high flow rate mode, adopted since
504 July 10, provided a lower temperature in the circulating fluid, but the high flow rate guaranteed
505 a more distributed energy transfer among the BHEs.

506 Periods of about 10 days were compared, two before and two after July 10. As an average,
507 the inlet temperature in the central BHE was clearly bigger during the low flow rate mode,
508 except for isolated peaks influenced by fast-changing conditions. The external inlet temperature
509 was conversely higher after July 10. The energy produced in these four periods was 144, 123,
510 192 and 130 kWh respectively. The differences seem to be firstly related to the weather
511 conditions and secondarily to the working mode, which did not drastically affect the energy
512 production.

513 Nevertheless, the high flow rate mode allowed reaching higher temperatures in the
514 external BHEs and thus having a lower thermal gradient between the center of the storage
515 volume and the surrounding environment. In the energy storage applications this is a key factor
516 because the stratification is fundamental for the optimization of the system. In a bigger plant it
517 is crucial to decide whether to have the core dramatically warmer than the annulus or to
518 distribute the heat in a more homogeneous way. In the first case the ground volume could be
519 charged more in the external portions, but at the same time the high thermal gradient would
520 cause high heat transfer within the storage volume and heat losses towards the surrounding (in
521 case of no proper side insulation). In the last case the heat propagation within the storage
522 volume would be minimized, but it would be also difficult to progressively charge the ground.

523 The numerical simulation was useful to predict the behavior of the ground in the next
524 years of operation of the Grugliasco plant. After the calibration with the monitoring data, a 5
525 year simulation showed the limited impact of the BHE field in the surrounding environment
526 thanks to the alternating charge/discharge cycle in two different periods of the year. The 10°C
527 inlet temperature during the cold season would cool down the ground in few days, but it would
528 not lower the temperature below the undisturbed ground's value too much.

529 **5.2 Improvement proposals**

530 In the light of the first operative year of the plant, -some possible implementations of the
531 plant can be defined in order to improve its activity.

532 The direct coupling between the solar panels and the BHE field provided a day/night
533 alternation in the thermal injection. The management system was set up with several conditions
534 which compare the temperature of the carrier fluid in the collectors and the temperature
535 distribution in the BHEs. This prevented the plant to cool down the ground during the night and

536 bad weather days. Nevertheless, a buffer storage could be added to the system in order to limit
537 the alternation and provide the thermal energy at a constant temperature during the warm
538 season. For instance, some other ground thermal energy storage working plants have a short
539 term water tank in order to apply this concept. The collectors warm the fluid up in the tank and
540 this transfers the thermal energy to different portions of the BHE field depending on the
541 temperature of the thermo-vector fluid. As a matter of fact, the energy collected by the
542 Grugliasco plant would increase thanks to a more continuous injection and to lower heat
543 dispersions.

544 With the calibrated numerical model set up for the simulations, some hypotheses in order
545 to enhance the efficiency of the system can be made. The numerical simulation gives indeed
546 the opportunity to predict what would happen if an insulation was provided around the BHEs.
547 The presence of a ring of insulating material was therefore simulated in order to create a storage
548 volume of cylindrical shape with a radius of 3 m from the central borehole. A thermal
549 conductivity of $0.15 \text{ W m}^{-1} \text{ K}^{-1}$ and a specific capacity of $1,300 \text{ J kg}^{-1} \text{ K}^{-1}$ were assigned to this
550 material, which correspond to the thermal properties of clay. The thickness of this clay barrier
551 is 0.2 m. A similar simulation was therefore carried out and the results are reported in **Fig. 13**.
552 The clay prevents the dispersion of the heat allowing the storage volume to increase the
553 temperature more than in the real case (without the insulation). The temperature reached at 2 m
554 from the source is 18.6°C , with an increase of 2.3°C with respect to the situation without the
555 insulation.

556 With the numerical data the thermal energy collected by the defined cylindrical volume
557 was therefore calculated. Each element in the cross section was multiplied for the volumetric
558 capacity of the ground in order to obtain the thermal energy collected with that specific
559 temperature increase. If the X-Z slice drawn in **Fig. 13** is assumed to have a thickness of 1 m,
560 the total volume would amount to 180 m^3 . The summation of the elements gave as output a
561 stored energy equal to 0.95 GJ which can be correlated to the entire volume (790 m^3) by
562 multiplying it for $790/180 = 4.4$. The total E_C in the cylindrical volume surrounded by the clay
563 ring amounts to 4.16 GJ. This value corresponds to the 46% of the total energy produced by the
564 solar collectors (9.1 GJ) and it is clearly higher than the efficiency estimated at field scale
565 without insulation (17%).

566 It turned out that an insulation ring around the BHEs would guarantee a higher amount of
567 stored energy by doubling that stored without insulation. As a conclusion it can be stated that a
568 thin insulation layer can clearly enhance the storage ability of the ground. The clay has a λ lower
569 than the surrounding ground, but thinking about other materials with even lower thermal
570 properties, it is possible to raise more the collected energy. The role of the insulation would be
571 moreover double, because it would also allow to minimize the environmental impact of the
572 plant.

573

574 6. CONCLUSIONS

575 The study derived from a previous laboratory study encompassing analogical, numerical
576 modeling and geophysical surveys aiming at the thermal characterization of geologic porous
577 media towards their utilization for sensible heat storage ([1], [2]). In the light of these laboratory
578 observations, a real field scale system which follows the concept of the ground thermal energy
579 storage was therefore designed. The idea was that of building up a laboratory at field scale in
580 order to assess the ability of the ground to store the heat, to evaluate the influence on the
581 environment of the induced thermal difference. The field scale laboratory provided some
582 fruitful information in the first year of operation. Even though the 2014 warm season did not
583 provide the expected solar energy production, 9.1 GJ of thermal energy were transferred to the
584 unsaturated gravelly-sandy ground since April to the middle of October. In these 7 months, the
585 ground was able to collect approximately the 17% of the total E_T . The main conclusions can be
586 synthesized as follows:

- 587 (i) The unsaturated alluvial deposits of the Po Plain revealed to be able to host a BTES plant,
588 showing interesting information about heat storage and transfer concepts already in the
589 first operative year; the Grugliasco plant will be useful to test several methodology for
590 improving the systems' efficiency and their monitoring activity.
- 591 (ii) As expected, the direct coupling of the BHEs and the solar panels is not useful for the
592 energy collection. A short term storage could enhance the efficiency of the system by
593 providing thermal energy at a constant temperature.
- 594 (iii) Thanks to the numerical simulation, the influence of the Grugliasco plant was predicted.
595 It turned out that the double cycle operative mode (charge + discharge phase) lowers the
596 thermal impact in the surrounding ground. In addition, an insulation ring around the BHE
597 field could enhance the collection efficiency by doubling it.

598 On the whole, it can be stated that the first charge phase of the Grugliasco plant allowed
599 making numerous observations on several key aspects of the ground thermal energy storage
600 systems. Obviously, these will be taken under consideration when there will be the opportunity
601 to implement the plant or to design and set up a real plant, with its management system and
602 monitoring equipment.

603 The future research on the Grugliasco plant will focus on the implementation of the BHE
604 field, the evaluation of a possible insulation ring around it and a buffer tank as STS to enhance
605 the energy collection efficiency. Moreover, the implementation of the monitoring equipment
606 will be undertaken, placing temperature sensors down in standalone boreholes and possibly
607 water content sensors.

608

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730 Captions

- 731 **Fig. 1** - Volume needed to store 10 GJ with different storage mechanisms with a ΔT of 70°C (modified from [17]).
 732 **Fig. 2** - Vertical BHEs linked together to exploit the ground as a storage volume in a closed-loop system. The core
 733 presents higher temperatures than those in the annular zone in order to minimize the heat losses towards the
 734 surrounding undisturbed ground.
 735 **Fig. 3** - Horizontal closed-loop system constructed in Vaulruz, CH (modified from [39]).
 736 **Fig. 4** – Comparison between the 2014 daily temperatures and monthly rainfalls and the average values for the
 737 past years (2005-2013).
 738 **Fig. 5** - Geographical and geological test site location.
 739 **Fig. 6** - Stratigraphic section of the examined area (data from [51]).
 740 **Fig. 7** - Grain size distribution of the 3 collected samples.
 741 **Fig. 8** – Pictures of the living lab. Drilling activity in front of the Topography department (A-B); temperature
 742 sensors placed throughout the circuit (C); ultrasonic flow meter (D); hydraulic circuit of the plant (E); underground
 743 section of the remote control system (F).
 744 **Fig. 9** - Satellite image [51] of the test site area. The arrangement of the BHEs and the monitoring hole are reported
 745 with the indication of the boreholes equipped with temperature sensors. The green roof is that of the Topography
 746 building where the solar collectors are placed.
 747 **Fig. 10** – Whole registration period (April 8 – October 20). DU, A, B = central and external BHEs. MH =
 748 monitoring hole. Uppermost graph: temperature data from the central borehole (green) with the regression curve
 749 referred to the daily minimum (orange). Lowermost graph: temperature data from the A borehole (blue) and the
 750 MH (violet) with the regression curves, referred to the daily minimum (red) for A.
 751 **Fig. 11** July data. DU, A, B = central and external BHEs. MH = monitoring hole. IN, OUT = inlet and outlet
 752 temperature to the BHE field. SR = daily max solar radiation. Description about each graph are reported in the
 753 text.
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 755 simulation (“num”) in external BHE (A), central BHE (DU) and monitoring hole (MH). The data are daily
 756 averages.
 757 **Fig. 13** – Results of the simulation with the clay ring as insulation technique. The X-Y plan view (left) and the X-
 758 Z cross section (right) are reported.

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760 LIST OF SYMBOLS

761 GENERIC SYMBOLS

762	<i>Symbol</i>	<i>Description</i>	<i>Unit of measure</i>
763	C_{sb}	bulk specific heat capacity	[J kg ⁻¹ K ⁻¹]
764	C_{vw}	water volumetric heat capacity	[J m ⁻³ K ⁻¹]
765	d_0	mean diameter of spherical grains	[mm]
766	E	energy	[J] or [Wh]
767	E_C	energy collected by the ground	[J] or [Wh]
768	E_T	energy transferred to the ground	[J] or [Wh]
769	P	instantaneous power	[W]
770	q	flow rate	[l s ⁻¹] or [m ³ s ⁻¹]

771	q'	energy input	$[\text{W m}^{-1}]$
772	SR	solar radiation	$[\text{W m}^{-2}]$
773	t	time	$[\text{s}]$
774	T	temperature	$[\text{°C}]$ or $[\text{°K}]$
775	V	volume domain	$[\text{m}^3]$

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777 **GREEK SYMBOLS**

778	<i>Symbol</i>	<i>Description</i>	<i>Unit of measure</i>
779	γ_b	bulk density	$[\text{kg m}^{-3}]$
780	ΔT	temperature difference	$[\text{°C}]$ or $[\text{°K}]$
781	λ	thermal conductivity	$[\text{W m}^{-1} \text{K}^{-1}]$

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783 **ACRONYMS**

784	A, B	Single U piped BHEs
785	AT	Austria
786	BHEs	Borehole Heat Exchangers
787	BTES	Borehole Thermal Energy Storage
788	CH	Switzerland
789	DHW	Domestic Hot Water
790	DU	Double U piped BHE
791	ENEA	Italian agency for new technologies, energy and sustainable economic development
792	FTP	File Transfer Protocol
793	GCHPs	Ground Source Heat Pumps
794	H&C	Heating and Cooling
795	IEA	International Energy Agency
796	ISO	Isomet 2114 device
797	IT	Italy
798	K2D	K2D Pro device
799	LT	Long Term
800	MH	Monitoring hole
801	NL	The Netherlands
802	OGS	OpenGeoSys
803	PCMs	Phase Change Materials
804	RES	Renewable Energy Sources
805	SE	Sweden
806	SHC	Solar Heating Cooling programme
807	ST	Short Term
808	STES	Seasonal Thermal Energy Storage
809	TCMs	Thermo-Chemical Materials
810	TES	Thermal Energy Storage

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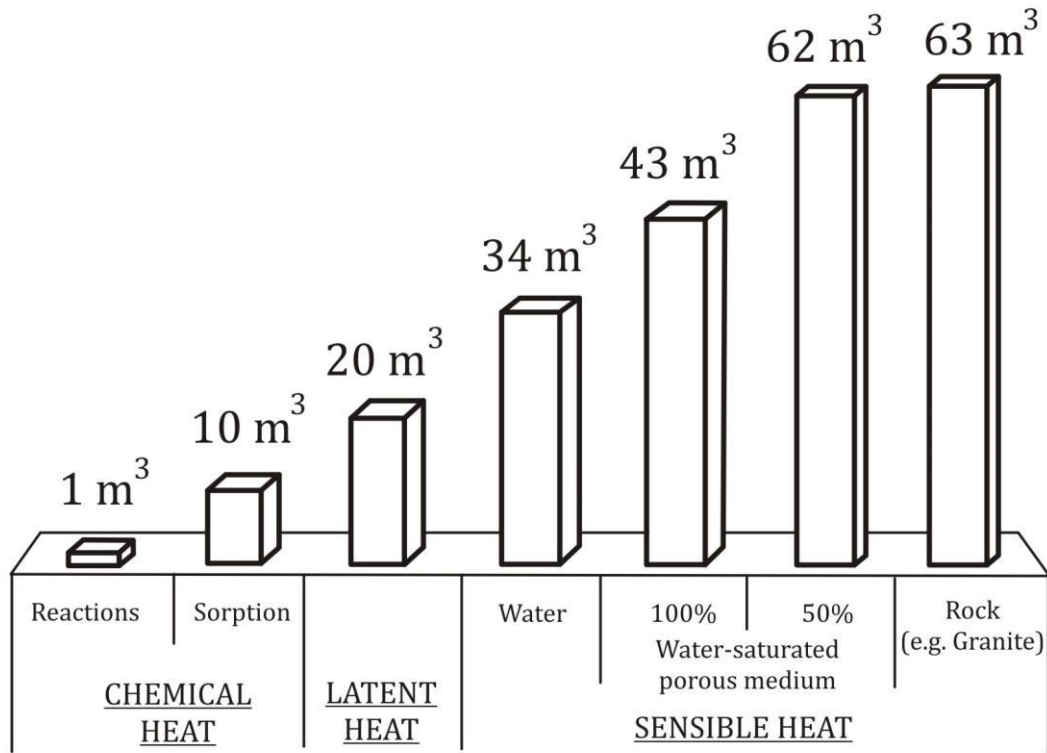
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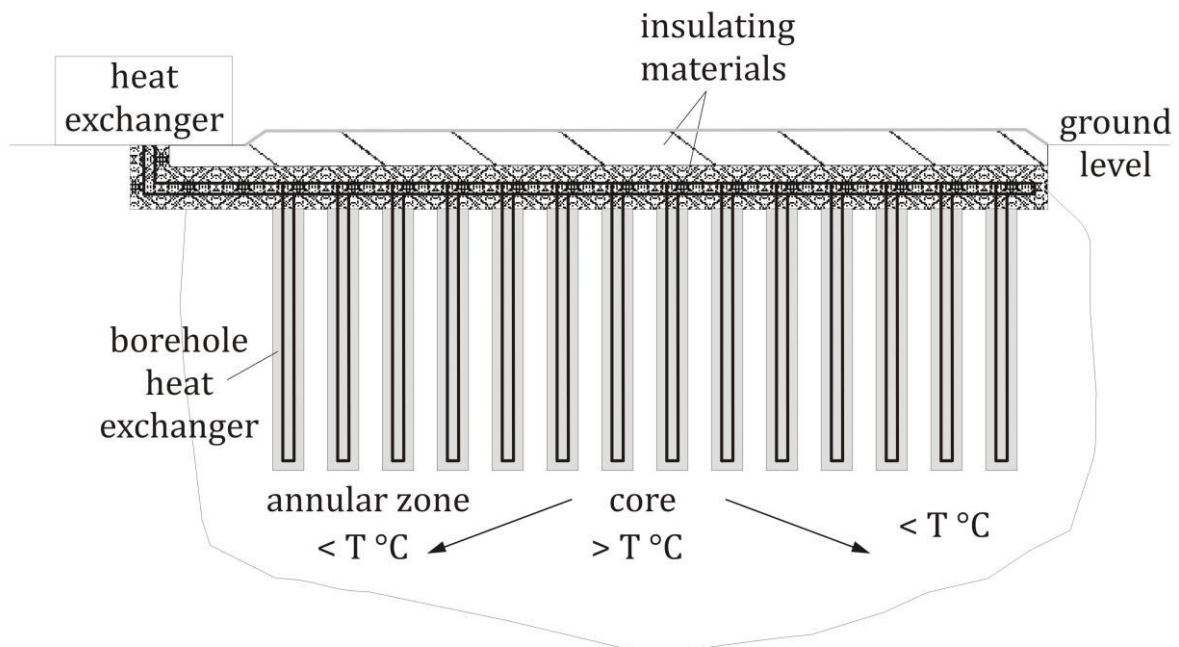
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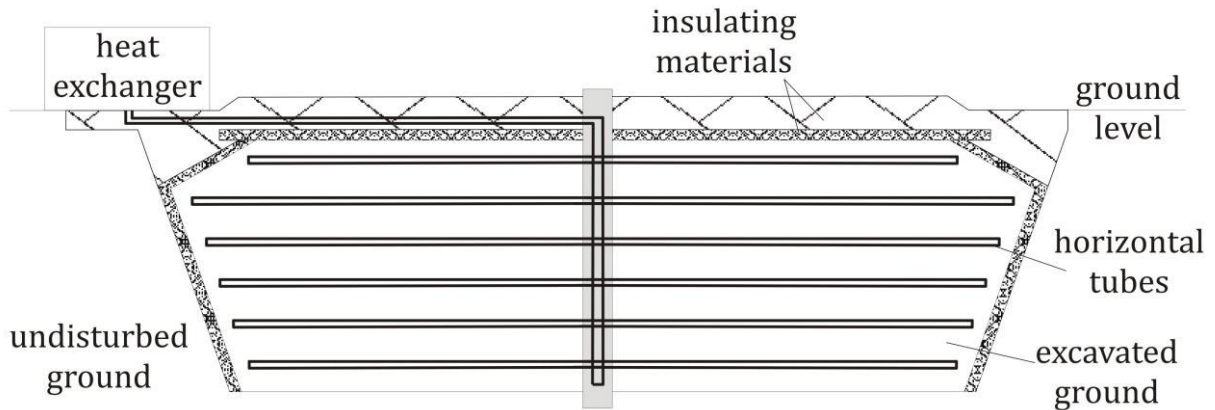


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825 **Fig. 1** - Volume needed to store 10 GJ with different storage mechanisms with a ΔT of 70°C (modified from [17]).
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828 **Fig. 2** - Vertical BHEs linked together to exploit the ground as a storage volume in a closed-loop system. The core
829 presents higher temperatures than those in the annular zone in order to minimize the heat losses towards the
830 surrounding undisturbed ground.

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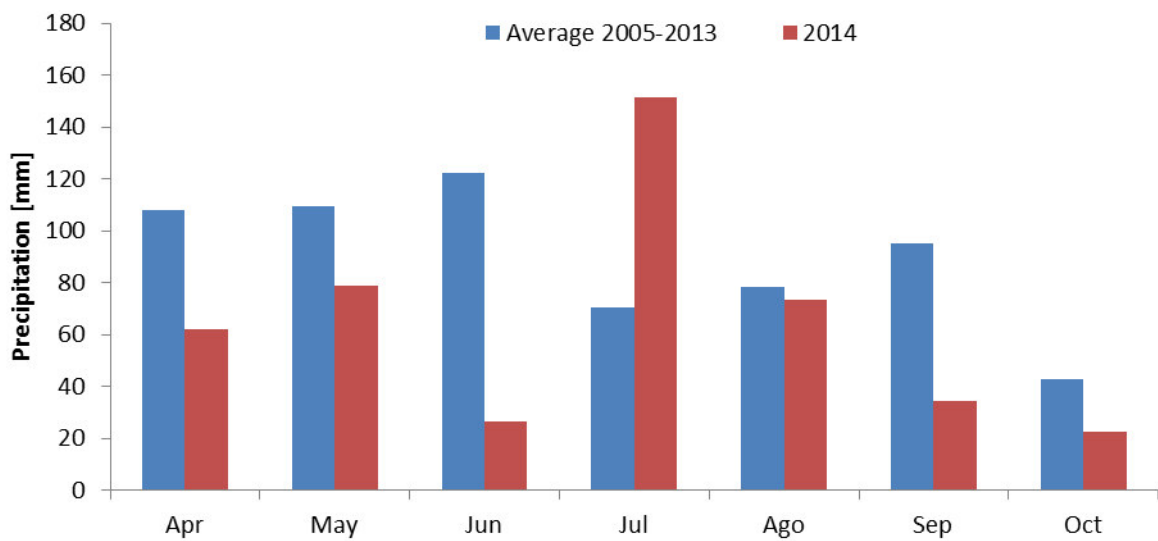
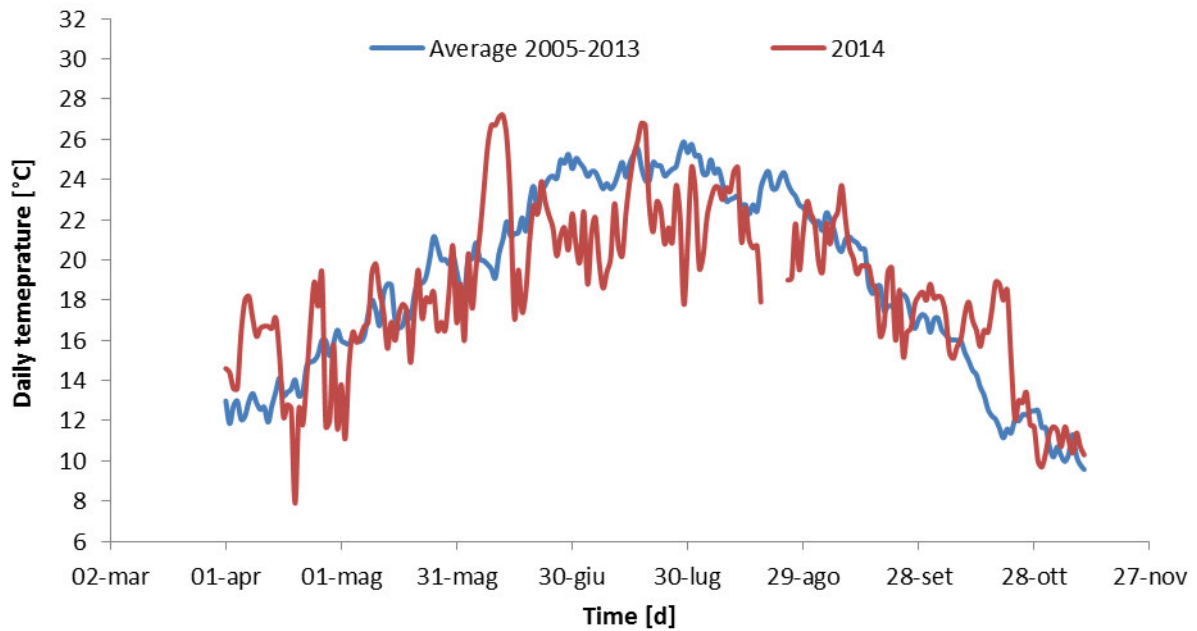


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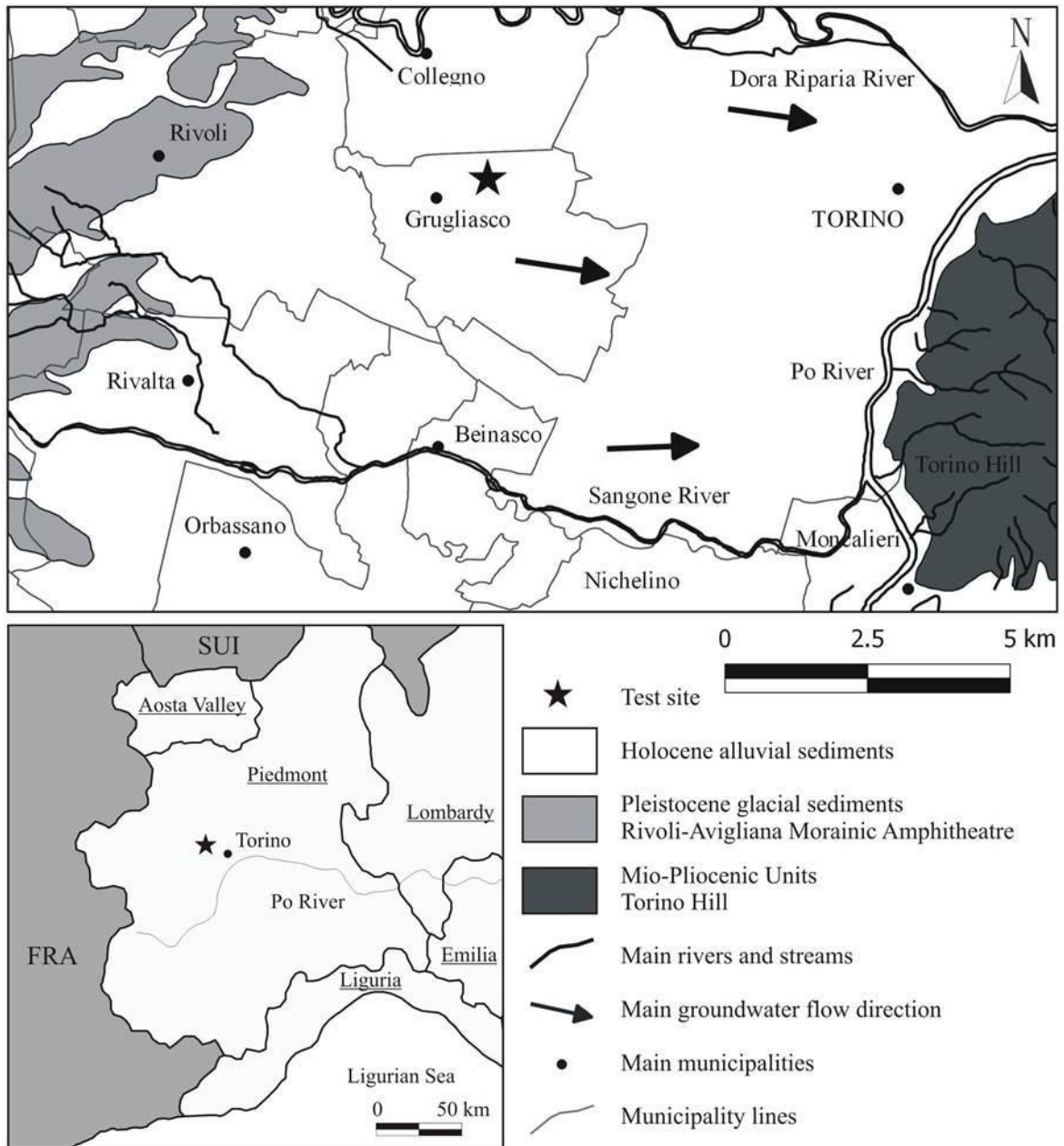
Fig. 3 - Horizontal closed-loop system constructed in Vaulruz, CH (modified from [39]).

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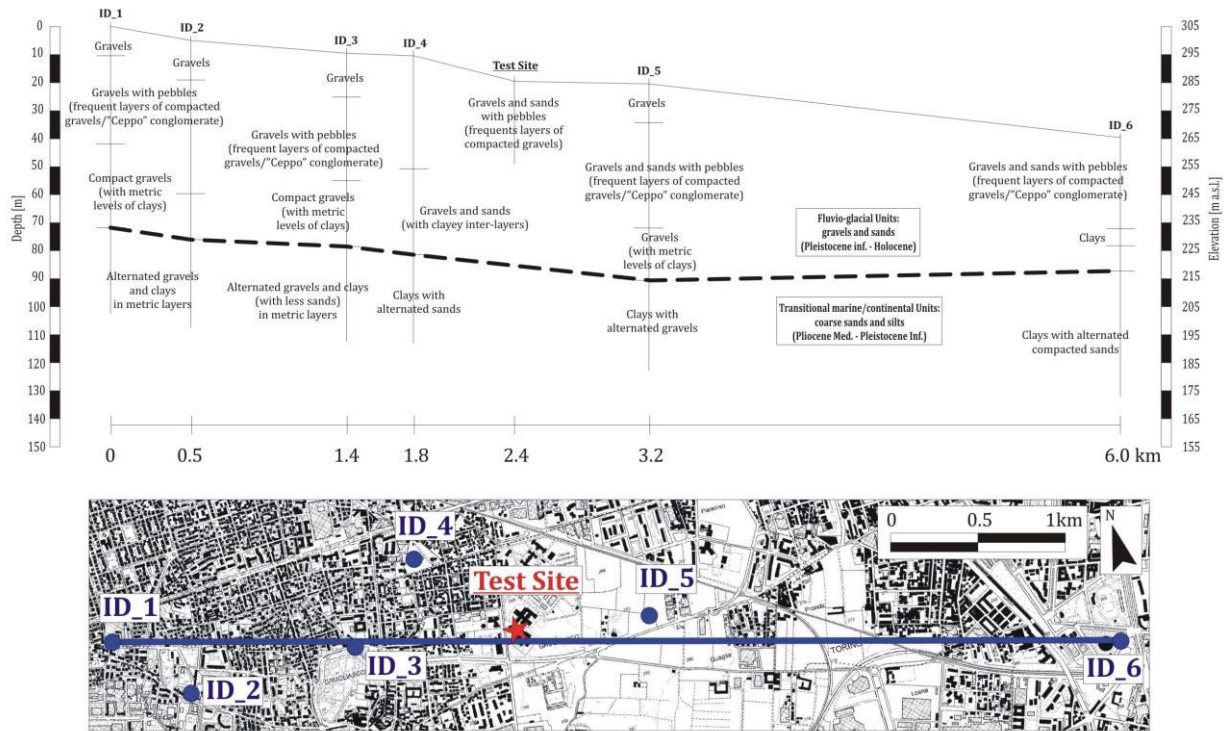


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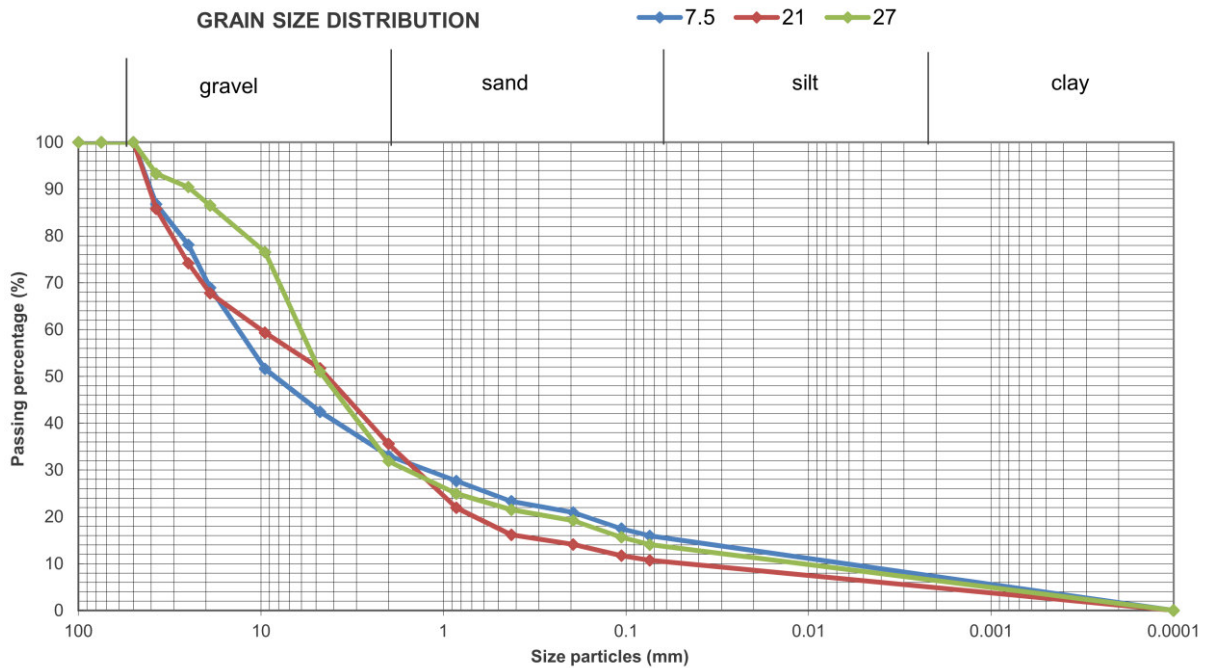
836 **Fig. 4** – Comparison between the 2014 daily temperatures and monthly rainfalls and the average values for the
 837 past years (2005-2013).



838 **Fig. 5** - Geographical and geological test site location.
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 842 **Fig. 6** - Stratigraphic section of the examined area (data from [51]).
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 845 **Fig. 7** - Grain size distribution of the 3 collected samples.
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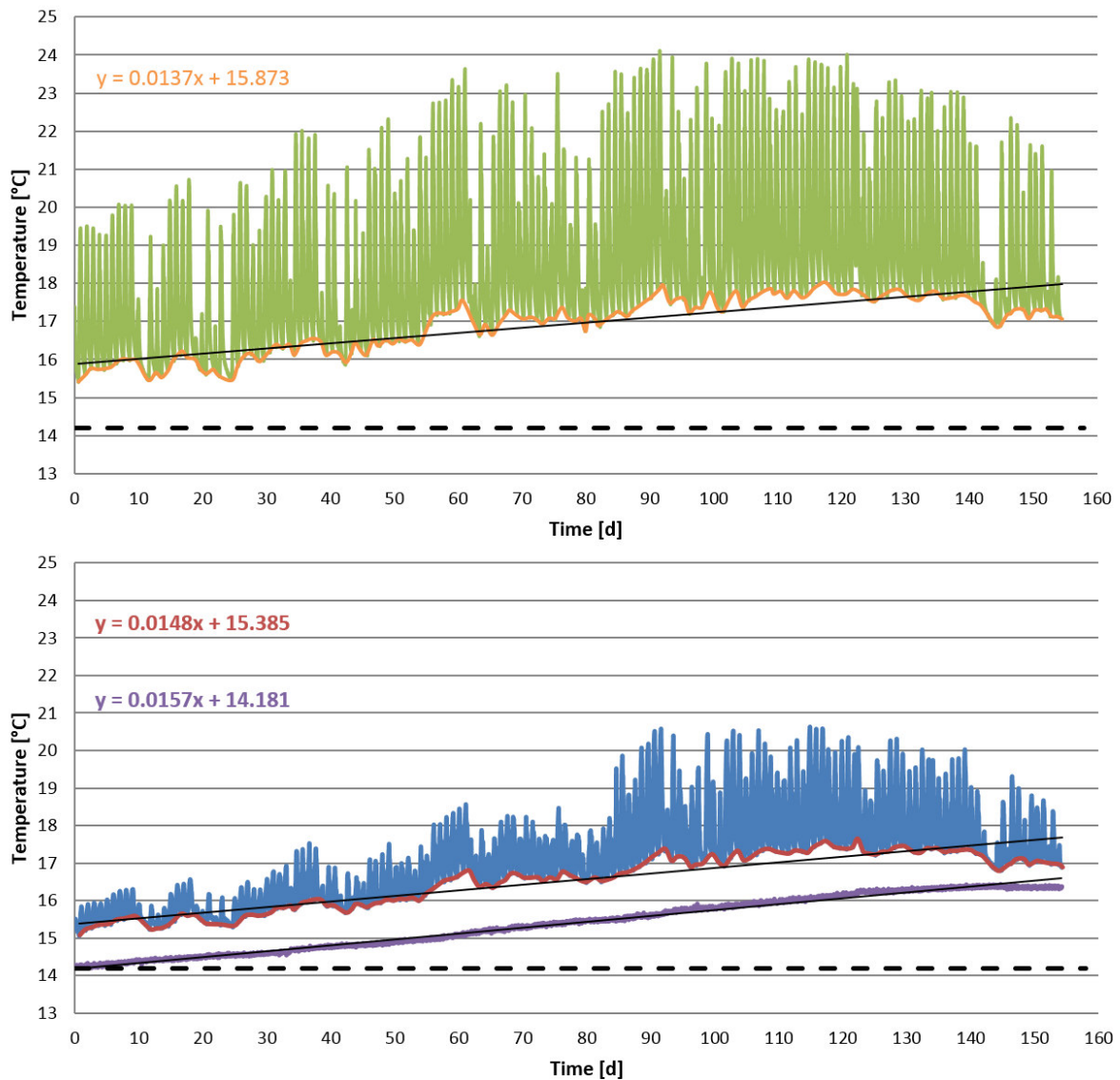
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Fig. 8 – Pictures of the living lab. Drilling activity in front of the Topography department (A-B); temperature sensors placed throughout the circuit (C); ultrasonic flow meter (D); hydraulic circuit of the plant (E); underground section of the remote control system (F).

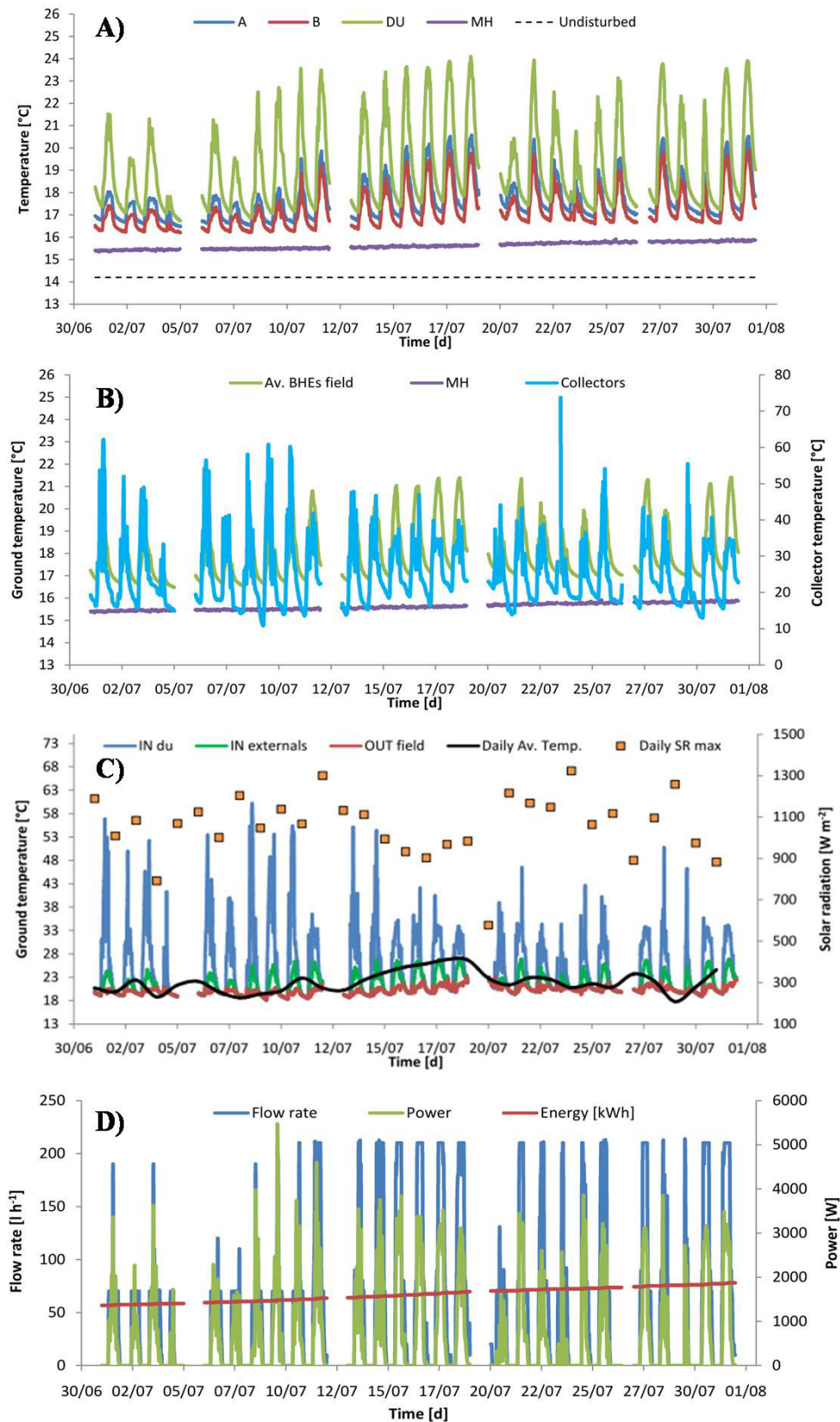


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Fig. 9 - Satellite image [51] of the test site area. The arrangement of the BHEs and the monitoring hole are reported with the indication of the boreholes equipped with temperature sensors. The green roof is that of the Topography building where the solar collectors are placed.

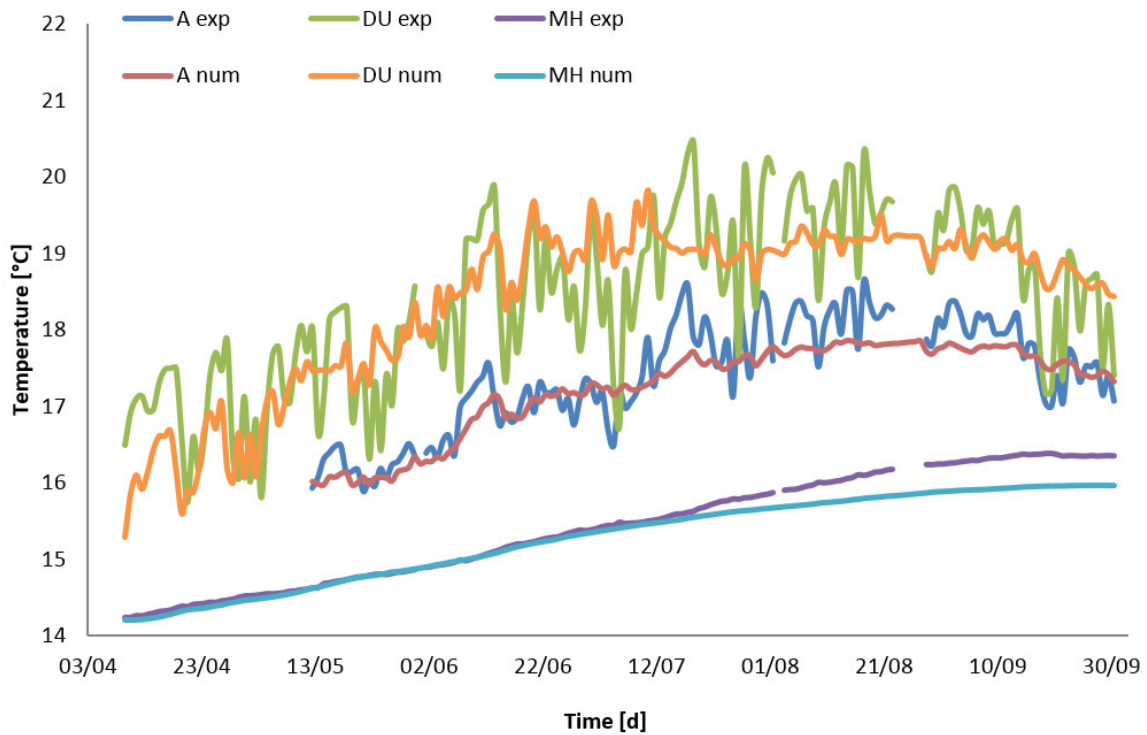


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858 **Fig. 10** – Whole registration period (April 8 – October 20). DU, A, B = central and external BHEs. MH =
859 monitoring hole. Uppermost graph: temperature data from the central borehole (green) with the regression curve
860 referred to the daily minimum (orange). Lowermost graph: temperature data from the A borehole (blue) and the
861 MH (violet) with the regression curves, referred to the daily minimum (red) for A.
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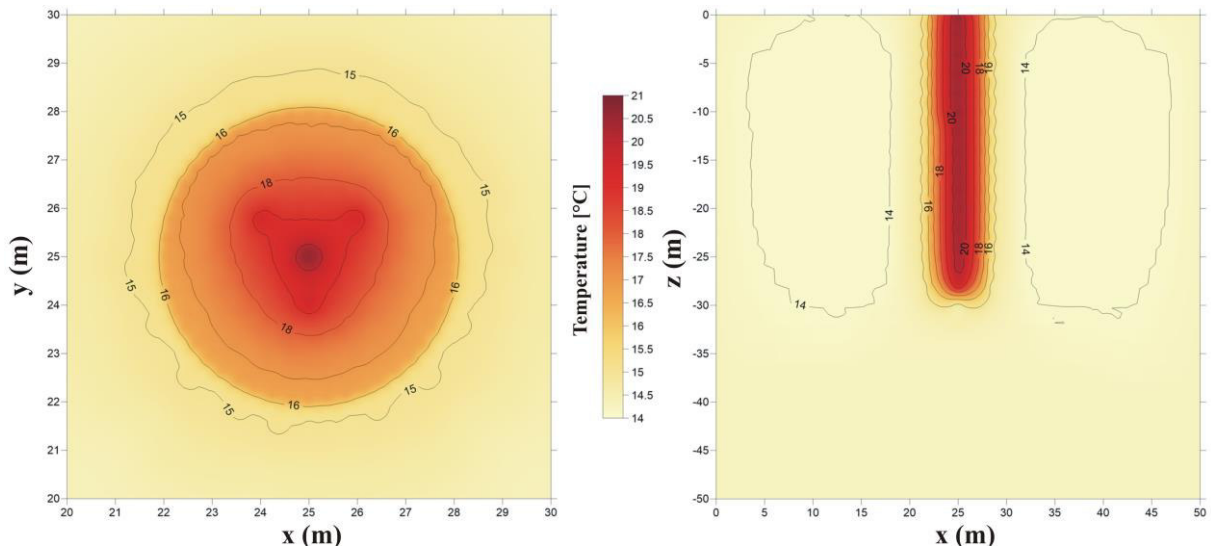


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Fig. 11 July data. DU, A, B = central and external BHEs. MH = monitoring hole. IN, OUT = inlet and outlet temperature to the BHE field. SR = daily max solar radiation. Description about each graph are reported in the text.



867
 868 **Fig. 12** – Comparison between the field data monitored by the system (“exp”) and the numerical results of the
 869 simulation (“num”) in external BHE (A), central BHE (DU) and monitoring hole (MH). The data are daily
 870 averages.
 871



872
 873 **Fig. 13** – Results of the simulation with the clay ring as insulation technique. The X-Y plan view (left) and the X-
 874 Z cross section (right) are reported

875 **Tab. 1** – Borehole thermal energy storage (BTES) projects constructed in Sweden ([42], [43]).

Site	-	Kungsbacka, SE	Store Skuggan, SE	Södertuna, SE	Luleå, SE	Danderyd, SE	Emmaboda, SE ⁽¹⁾
Start-up	year	1980	1982	1982	1983	2002	2010
Housing area	-	1 school	-	525 houses	1 university building	50 houses	Factory building
Global irradiation (Hz)	kWh m ⁻²	940	-	370	-	-	-
Heating degree-days (ref. 20°C)	°C	-	5,000	-	6,250	-	-
Heated living area	m ²	-	-	-	-	6,000	-
Total heat demand	MWh y ⁻¹	1,100	500	6,390	-	550	-
Solar collector area	m ²	1,500	2,200	30,000	(no solar energy but waste heat)	2,400	(no solar energy but waste heat)
Heat storage volume	m ³	85,000 (BTES)	180,000 + 1,000 (BTES + hot-water STS)	105,000	120,000	60,000	200,000
Geologic material	-	Clay	Gneiss and granite	Granite	Gneiss	Granite	Gneiss
Extracted heat from BTES	MWh y ⁻¹	710	430	4,160	1,100	385	3,000
Solar fraction	%	65	85	65	-	70	-
Cost of the system (solar + storage)	M€ ⁽²⁾	0.17	1.03	2.7	0.85	0.54	-

⁽¹⁾ Data from [44]⁽²⁾ Currency conversion functions from [45]876
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879 **Tab. 2** – Borehole thermal energy storage (BTES) projects until 1990 ([26], [42]).

Site	-	Innsbruck, AT	Groeningen, NL	Vaulruz, CH	Ispra, IT	Treviglio, IT
Start-up	year	1980	1982	1982	1982	1985
Housing area	-	1 airport	96 houses	1 maintenance centre	1 JRC building	residential area
Global irradiation (Hz)	kWh m ⁻²	1,090	910	1,180	1,160	1,200 ⁽¹⁾
Heating degree-days (ref. 18°C)	°C	3,235 ⁽²⁾	3,000	3,886	2,500 ⁽³⁾	
Heated living area	m ²	-	-	-	-	
Total heat demand	MWh y ⁻¹	1,220	1,140	340	80	
Solar collector area	m ²	400	2,400	510		2,727
Heat storage volume	m ³	60,000 + 40 (BTES + hot-water STS tank)	23,000 + 100 (BTES + hot-water STS tank)	3,500 (BTES with horizontal pipes)	2,250 + 80 (BTES + hot-water STS tank)	43,000
Geologic material	-	Gravel	Saturated sand with clay and peat layers	Sandy gravel with clay	Clay	
Heat delivery of the solar system	MWh y ⁻¹	640	760	220	64	
Solar fraction	%	52	67	65	80	70
Cost of the system (solar + storage)	M€ ⁽⁴⁾	-	0.71	0.31	-	

⁽¹⁾ Deduced from [46]⁽³⁾ Reference value 15 °C⁽²⁾ Reference value 12 °C⁽⁴⁾ Currency conversion functions from [45]880
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883 **Tab. 3** – Borehole thermal energy storage (BTES) projects from 1990 up to now.

Site		Neckarsulm, DE Phase I (Phase II) ⁽¹⁾	Attenckirchen, DE ⁽¹⁾	Crailsheim, DE Phase I ⁽²⁾	Okotoks, CA ⁽³⁾	Braedstrup, DK ⁽⁴⁾
Start-up	year	1996	1999	2006	2006	2012
Housing area	-	6 multi-family houses, commercial centre, school	30 apartments in single-family houses	260 apartments, 1 school and 1 sports hall	52 apartments in single-family houses	District heating plant, 1,500 consumers
Global irradiation (Hz)	kWh m ⁻²	1,100 ⁽⁵⁾	1,100 ⁽⁵⁾	1,100 ⁽⁵⁾	1,510	1,100 ⁽⁵⁾
Heating degree-days (ref. 18°C)	°C	-	-	-	4,910	-
Heated living area	m ²	20,000	6,200	40,000	6,800	-
Total heat demand	MWh y ⁻¹	1,663	487	4,100	790	3,600
Solar collector area	m ²	2,700 (5,000)	800	7,300	2,300	18,600
Heat storage volume	m ³	20,000 (63,400) (BTES)	9,350 + 500 (BTES + hot water STS tank)	37,500 + 580 (BTES + hot-water STS tank)	35,600 + 240 (BTES + hot water STS tank)	19,000 + 7,500 (BTES + 2 hot water tanks)
Geologic material	-	-	-	Limestones	-	Clay till and sands and gravels
Heat delivery of the solar system	MWh y ⁻¹	832	415	2,050	682	7,000
Solar fraction	%	50	55	50	86	20
Cost of the system (solar + storage)	M€ ⁽⁶⁾	1.5	0.26	4.5	2.3	4.3

⁽¹⁾ Data from [30]⁽²⁾ Data from [47]⁽³⁾ Data from 2011 annual report [41]⁽⁴⁾ Data from [48]⁽⁵⁾ Deduced from [46]⁽⁶⁾ Currency conversion functions from [45]884
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887 **Tab. 4** – Solar energy data of the Grugliasco area with the indication of the optimal inclination of a collector
888 aiming at the maximum production ([49]).

Month	Global irradiation (Hz) [Wh m ⁻² day ⁻¹]	Optimal inclination [°]	Average air temperature [°C]	Heating degree-days [°C]
Jan	1,520	66	3.9	410
Feb	2,070	57	5.6	328
Mar	3,520	46	9.1	221
Apr	4,390	30	12.0	112
May	5,090	17	17.0	12
Jun	6,040	12	20.9	0
Jul	6,310	15	22.9	0
Aug	5,480	26	22.5	1
Sep	4,060	41	18.5	42
Oct	2,590	53	14.3	184
Nov	1,590	63	8.4	352
Dec	1,220	67	4.8	430
Year	3,670	37	13.3	2,092

889 **Tab. 5** – Thermal conductivity measurements on the ground’s samples.
890

Samples’ depth [m]	Thermal Conductivity [W m ⁻¹ K ⁻¹]		Device
	dry	water saturated	
7.5	0.47±0.02	2.55±0.04	ISOMET 2114
21	0.55±0.02	2.52±0.05	ISOMET 2114
27	0.45±0.03	2.31±0.07	KD2 Pro

891 **Tab. 6** – Thermal conductivity measurements on the grout’s samples.
892

Samples	Thermal Conductivity [W m ⁻¹ K ⁻¹]		Device
	dry	water saturated	
1	0.77±0.03	0.93±0.01	ISOMET 2114
2	0.69±0.09	0.84±0.04	ISOMET 2114
3	0.67±0.01	0.83±0.01	ISOMET 2114
4	0.64±0.01	-	ISOMET 2114
5	0.73±0.01	0.62±0.12	ISOMET 2114
6	0.40±0.01	0.78±0.00	ISOMET 2114
7	0.31±0.08	-	KD2 Pro
8	0.27±0.05	-	KD2 Pro

893 **Tab. 7** – Numerical model properties adopted in the OGS simulation.
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Undisturbed T [°C]	14.2
Porosity	0.3

Water content [%]	50
Water density [kg m ⁻³]	1,000
Water specific heat capacity [J kg ⁻¹ K ⁻¹]	4,190
Water thermal conductivity[W m ⁻¹ K ⁻¹]	0.6
Air density [kg m ⁻³]	1.2
Air specific heat capacity [J kg ⁻¹ K ⁻¹]	1,010
Air thermal conductivity[W m ⁻¹ K ⁻¹]	0.024
Solid density [kg m ⁻³]	2,700
Solid specific heat capacity [J kg ⁻¹ K ⁻¹]	800
Solid thermal conductivity[W m ⁻¹ K ⁻¹]	3.0
Grout thermal conductivity [W m ⁻¹ K ⁻¹]	0.45

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