Committente:	**Valle Vento S.a.a.r.l.**
Progetto:	**Underground thermal energy storage at the Valle Vento experimental site**

Final Report

Relazione n:	24-001
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1. Introduction

1.1 Premise

The Valle Vento (VV) agribusiness in 2017 contracted Geonovis srl, Italian leader in geothermal technologies, to install a ground-source heat pump (GSHP) system to cover the heating needs of a residential house and an agricultural building. The system, installed on top of the hill, is made of a 120 kW heat pump fed by 15 150-m-deep borehole heat exchangers (BHEs).

Recently, VV asked Geonovis to install a second GSHP system to cover the energy needs of a new development area that will consist of a greenhouse, laboratories, offices, and meeting rooms. The new system is made of a conventional BHE field, including 16 150-m-deep probes, and an experimental field. The latter is intended to serve as an underground thermal energy storage (UTES) made with boreholes (BTES) to store the energy produced by about 150 m^2 of gross solar collector area. The subsurface storage volume is made of 7 BHEs which layout is a cylinder with a radius of around 9.6 m.

In this perspective, Valle Vento have the three following objectives:

- put in place a BTES research/experimental site for the years to come;
- have a long-term impact strategy in order to give value and promote the BTES site;
- in the short-term, to be advised on the technical requirements of the BTES.

In order to fulfil the Client's objectives, the present project was carried out through the following tasks:

1. describe new system (plant; drillings; conventional BHE field; experimental storage BHE field) with quantification of the performance (amount of energy stored; expected temperatures; potential heat recovery etc.);
2. set up a research and development (R&D) project for the years to come including objectives, hypotheses, and activities to be carried out with suggested methodologies, tools, timelines, expected outcomes, deliverables as well as possible project partners from both academia and industry, and respective roles;
3. define a long-term impact strategy: estimate the relevance of the project in the local and regional context; highlight possible stakeholders from academia, industry, government, NGOs, private individuals; outline key deliverables (websites, seminars, white papers, scientific publications etc.);
4. provide consulting/advising services on technical requirements for BTES: installation of monitoring system (temperature sensors, energy meters, flow meters etc.); design of

software for data management and visualization; BTES optimization and/or implementation; promotion and dissemination.

In light of this, the present document is the final report describing the outcomes of tasks 1 (**Section 2**), 2 (**Section 3**) and 3 (**Section 4**). Task 4 was completed through online and in-person meetings with the Client.

1.2 State of the art

EGEC (European Geothermal Energy Council) states that UTES has the potential to overcome long-term mismatches between demand and supply of renewables and, therefore, support the energy system by providing flexibility and reliability in a sustainable way (EGEC, 2024). UTES can also provide valuable services to the electricity sector through sector coupling, as it allows the absorption of electricity surpluses through power-to-heat solutions, decoupling electricity production and heat demand from short to seasonal timescale. The International Renewable Energy Agency (IRENA) reported that the global market for thermal energy storage could triple in size by 2030 (IRENA, 2020). According to IRENA and EGEC, UTES has two key advantages over other storage solutions: it is the most cost-effective solution, and it has the least impact on surface land use. In March 2023, the European Commission issued a Recommendation (2023/C 103/01) on energy storage listing shallow geothermal as one of the storage technologies. In the next years thermal storage will be a strategic and important tool to implement flexibility in the energy demand and supply side (EGEC, 2024).

Differently from conventional GSHP systems, UTES are intended to store low-cost heat to be used in periods of higher demand (Lee, 2013). The economic advantage is given by the difference between the value of the heat recovered and the cost of the heat produced and stored during the off-peak periods, including the share that cannot be recovered and is therefore considered as a heat loss (Casasso et al., 2022). The temperature of the heat stored is a key parameter for the classification of UTES systems, since it determines the use that can be made of the stored heat. This element is what distinguishes low-temperature (LT) from high-temperature (HT) UTES, whose threshold is generally set to 40 to 50°C (Skarphagen et al., 2019; Casasso et al., 2022). Compared to other types of storage (e.g. water, latent heat with phase change materials, thermochemical heat) subsurface heat storage is made over a long-term (e.g. seasons, years) rather than a short-term scale (e.g. daily) due to its low energy density (Giordano et al., 2016; Wang et al., 2024). Both closed-loop and open-loop geothermal systems are suitable for UTES, with different possible applications, strengths and weaknesses, and design issues. Closed-loop UTES is called Borehole Thermal Energy Storage (BTES), whereas open-loop UTES is called Aquifer Thermal

Energy Storage (ATES). Other possible types of UTES use buried water tanks (TTES) or gravel pits (PTES), existing caverns due to ancient mining activity or geological cavities (CTES), and fractured reservoirs (FTES), each of which has its own pros and cons (**Figure 1.1**). BTES (15-30 kWh/m^3) and ATES (30-40 kWh/m^3) have the lowest energy density among all, but they are the most popular due to their relative easiness of design, realisation, and lower cost of installation (Sadeghi et al., 2024). Moreover, BTES needs fewer environmental considerations compared to ATES. Finally, all shallow geothermal systems operating in both heating and cooling mode store heat and cold into the underground. However, the term UTES typically refers to the systems that store heat from external sources, i.e., solar and/or waste heat, and the other shallow geothermal systems, i.e., GSHP, are defined as “conventional” ones to distinguish them from UTES installations.

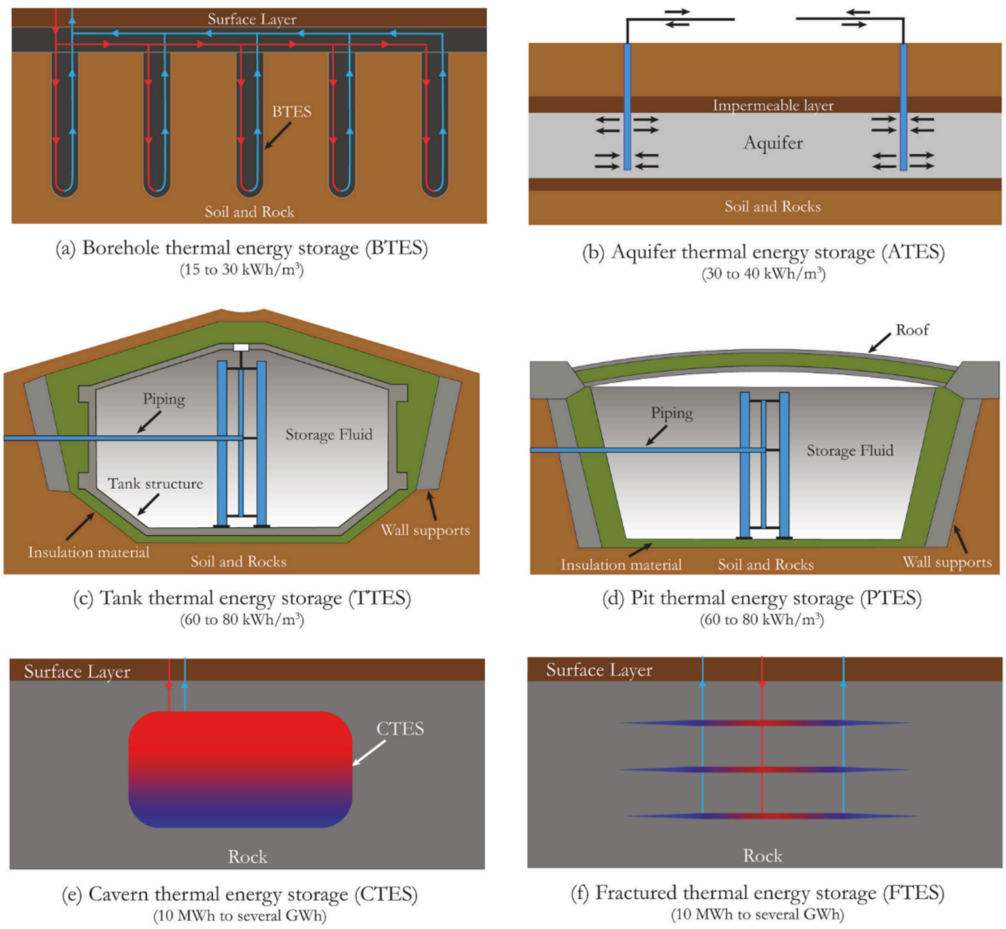


Figure 1.1 - Different types of UTES with associated energy density (from Sadeghi et al., 2024).

The heat sources that can be connected to a UTES system are typically solar thermal collectors and waste heat from industrial processes and from combined heat and power systems. Solar thermal collectors are the most diffused among heat sources for UTES systems because they can be installed on purpose and do not depend on other systems. However, due to the costs of installation and considering the low energy density and overall storage efficiency of UTES (50-60% at full capacity), waste heat has more interesting avenues in terms of financial investment and energy performance.

Waste heat is the by-product of the work produced by machines or of other processes which involve thermal energy (melting, vaporization, heating, cooling, etc.). Although this energy cannot be re-used in the same process, it can be used in others, including electricity production. Forman et al. (2016) reviewed several studies on waste heat potential and found that around 72% of the global energy input is lost after conversion, most of which (63%) is available at temperatures below 100°C. This so-called low-temperature waste heat can be hardly exploited for electrical production (e.g., with Organic Rankine Cycle turbines) as the conversion efficiency would be very low. However, it can be exploited for the heating of single buildings or as a supply for district heating networks and, in both cases, UTES systems can be used for storing heat during periods of low or null demand. Examples of BTES storing waste heat are described in Rapantova et al. (2016), Nilsson and Rohdin (2019), Guo et al. (2020).

Typical users served by currently installed UTES systems are single buildings and district heating and cooling (DHC) networks (AFPG, 2020; Sadeghi et al., 2024), but other heat uses at comparable temperatures are possible (e.g. aquaculture, heating of anaerobic digestors, low-temperature processes for food production, greenhouses, etc.). DHC grids in particular have a bright future considering that they provide efficient energy at large scale for different users at the same time. DHC meet around 9% of the heating needs globally (IEA, 2023) and 2% of the Italian demand with a total installed capacity of 10 GW (Dal Verme, 2022). However, their full potential is still untapped, also considering the ongoing evolution towards more efficient low-temperature grids that can integrate a number of different heat and cold sources mainly from renewables (**Figure 1.2**, Sadeghi et al., 2024). An ongoing Horizon Europe research project called SAPHEA is studying the potential of integrating all kind of geothermal technologies into DHC grids, with interesting avenues in shallow geothermal integration in 5th generation grids (saphea.eu).

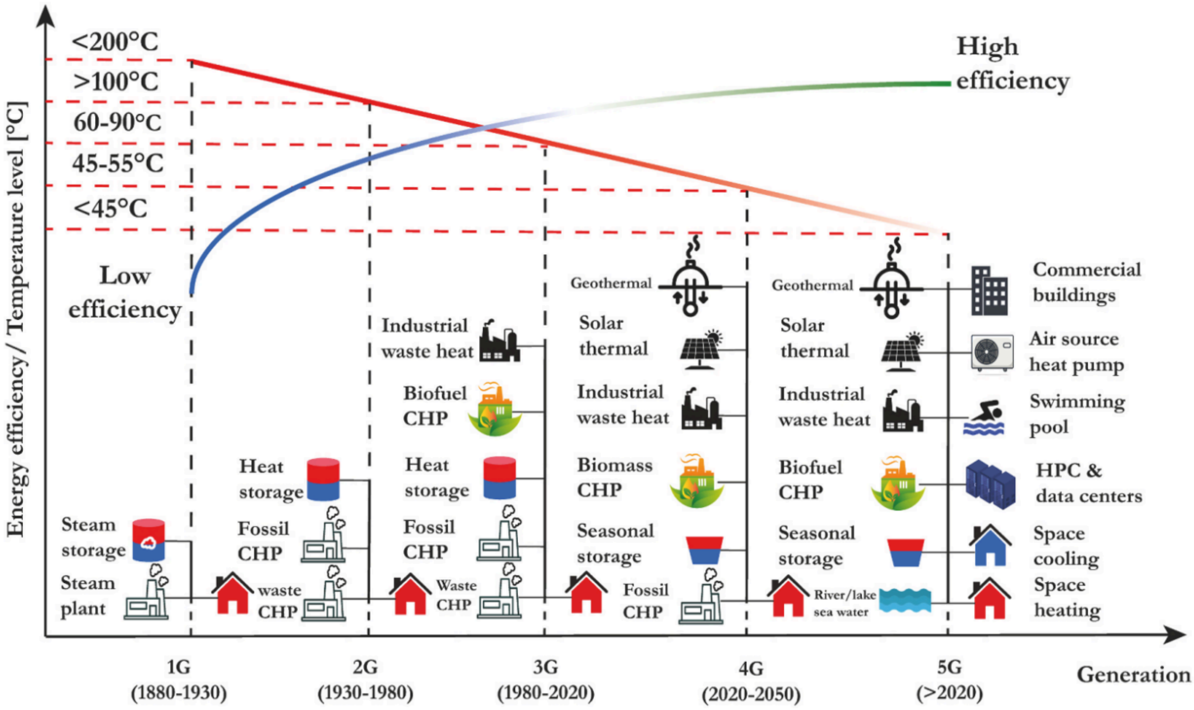


Figure 1.2 – Evolution of district heating and cooling grid generations and associated heat sources and final users (from Sadeghi et al., 2024).

BTES systems are generally composed of a high number of BHEs (from 50 to several hundreds), which are shallower (i.e., less than 80 m) and have a tighter spacing (i.e., below 5 m) compared to conventional BHE fields (Guo et al., 2020). Borehole spacing is one of the main features that distinguishes BTES from conventional GSHPs. Indeed, BTES has the main aim of superposing heat injection of several BHEs to develop a “ warm core ” in the centre, whereas conventional BHE fields (with no heat stored, other than the heat rejected from the building in cooling mode) are designed to minimize mutual thermal interaction among boreholes (**Figures 1.3** and **1.4a**). BTES must reduce heat losses and maximize the heat recovery and for this reason it is necessary to minimize the surface-to-volume ratio (S/V, m^{-1}) of the storage volume containing the BHE field (Skarphagen et al., 2019; Casasso et al., 2022). Optimal shapes for the underground storage volume occupied by BHEs are the cube and the “ideal” cylinder, with depth equal to the diameter (**Figure 1.4b**; Skarphagen et al., 2019).

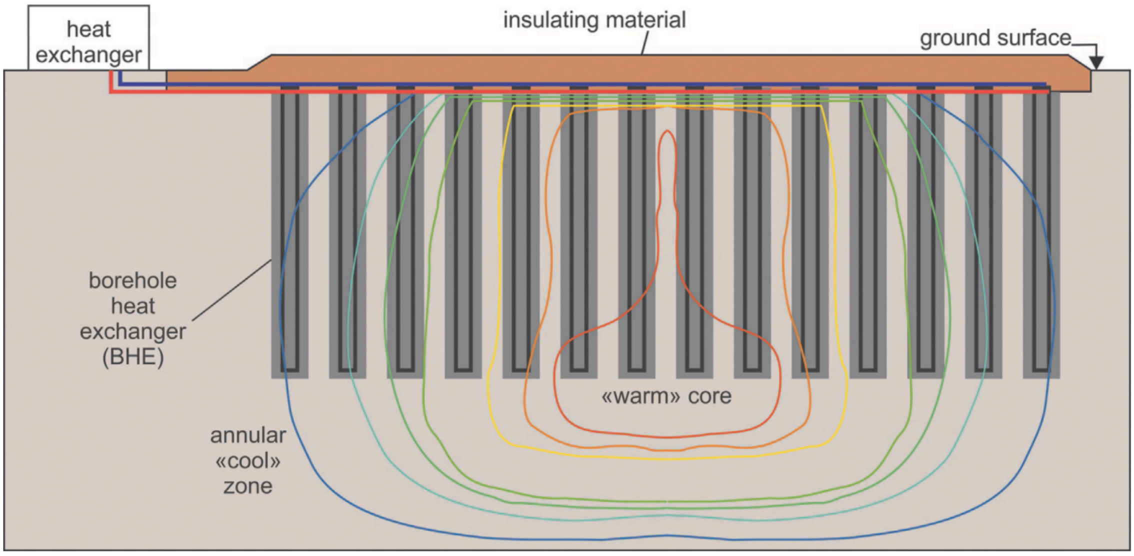


Figure 1.3 – Cross section of a BTES system with typical thermal stratification (from Casasso et al., 2022).

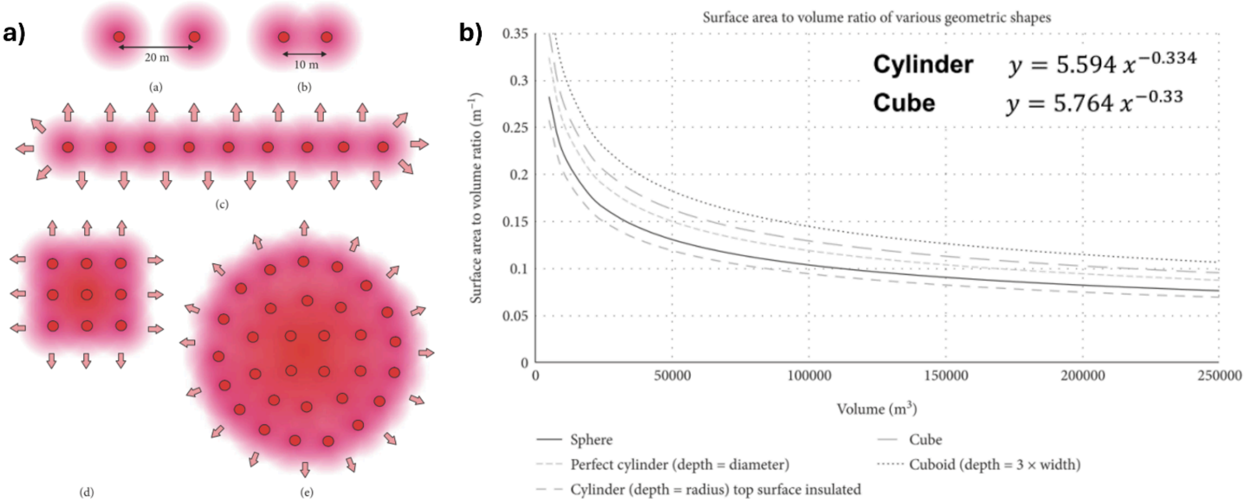


Figure 1.4 – a) different spacing between GSHP and BTES (a, b) and less efficient (c) and more efficient shapes of BTES volumes to reduce heat losses (d, e); b) surface-to-volume ratio of various geometric shapes as a function of volume (modified from Skarphagen et al., 2019).

In BTES boreholes are preferably connected in series rather than in parallel, as done in GSHPs. This allows to divide the volume in different concentric zones with a radial stratification of temperatures, thus preserving the core warmer than the annular zone, as shown in **Figure 1.3** (Casasso et al., 2022). The optimal flow direction of the heat carrier fluid to achieve this radial stratification is from inside to outside in the charging phase, and vice versa during the discharge phase (**Figure 1.5**; Sibbit et al., 2020; Hesaraki et al., 2015; Guo et al., 2020; Baser et al., 2020; Mahon et al., 2022).

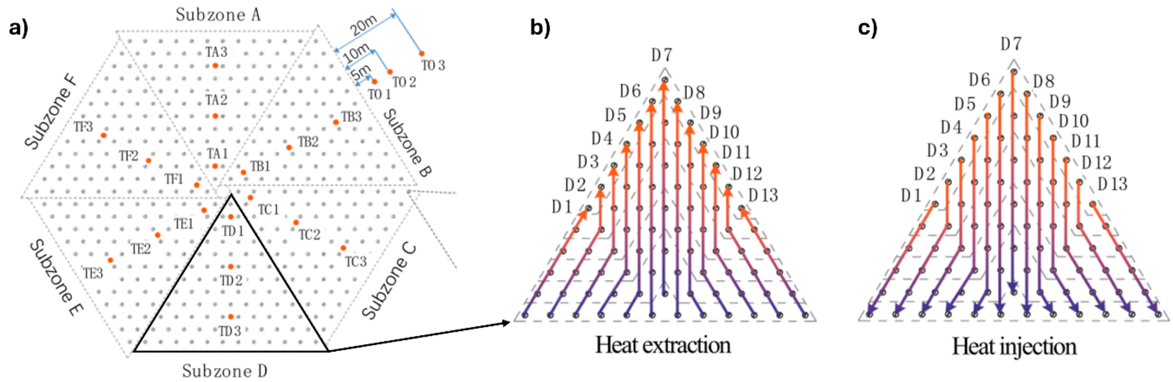


Figure 1.5 – Layout of the BTES living laboratory in Chifeng (China) and location of temperature measuring boreholes (a); borehole connection and flow direction during discharge (b) and charge phase (c) (modified from Guo et al., 2020).

While conventional GSHP can benefit from groundwater flow around BHEs, advection negatively affects the storage efficiency of BTES (e.g., Rapantova et al., 2016). The absence of relevant groundwater flow is therefore a requirement for performing an efficient seasonal heat storage with BTES. In addition, the optimization of borehole arrangement with respect to groundwater flow direction plays an important role in mitigating the dispersion of stored heat (Giordano and Raymond, 2019). Nevertheless, even in the absence of appraisable groundwater flow, BTES undergo some thermal loss, i.e., not all the heat stored during periods of low or null demand can be exploited during the operation in heating mode. These losses are: a) proportional to the temperature difference between the edge of the BTES array and the ambient ground temperature; b) roughly proportional to the thermal conductivity of the subsurface; and (c) related to the geometry of the BTES array (S/V ratio) and to any insulation applied to the BTES (Skarphagen et al., 2019). An indicator used to assess thermal losses in UTES systems is the storage thermal efficiency or heat recovery (HR), which is the ratio of the energy recovered during the heating season over that injected in the previous charging phase. The storage efficiency highly depends on the geological setting, the size of the storage volume and its compactness (i.e., the S/V ratio) (Giordano and Raymond, 2019; Skarphagen et al., 2019; Guo et al., 2020). As already mentioned, lower S/V ratios result in a more efficient heat storage and recovery, and the typical BTES volume shapes are cubic or cylindrical (see **Figure 1.4**). Common values of heat recovery in operating BTES systems are between 40 and 60% (Guo et al., 2020; Rapantova et al., 2016). With values of HR below 40% the storage of solar heat with BTES becomes economically unfeasible; however, such a low efficiency can still be acceptable when using lower-cost industrial waste heat (Nilsson and Rohdin, 2019; Ramstad et al., 2023; Guo et al., 2020). HR is commonly higher for cold storage (50 – 80%) rather than for heat storage (40 – 60%), since natural convection losses are more likely to occur in heat rather than cold storage because of the greater temperature (and hence density) differences involved (Lee, 2013). More details about the quantification of BTES performance can be found in Giordano and Raymond (2019), Guo et al. (2020) and references therein.

Finally, further important elements in BTES design are top insulation (**Figure 1.6**), pre-heating (**Figure 1.7**), and short-term storage (STS) tanks between the heat source and the BHE field (**Figure 1.8**). Top insulation has been found to be significant in reducing heat losses towards the atmosphere and thus increasing overall storage efficiency (e.g. Sibbit et al., 2012; Giordano and Raymond, 2019; Mahon et al., 2022). Baser et al. (2020) also installed a hydraulic barrier on top of the thermal insulation in order to prevent rainfall infiltration that would increase the subsurface thermal conductivity and reduce efficiency (**Figure 1.6d**). It is very-well understood that BTES needs 4 to 5 years to reach the target operation temperature due to the high thermal inertia of geological materials (**Figure 1.7**). Some authors have demonstrated that a pre-heating would help reduce the initial transient charging phase and anticipate the quasi-steady state operation (Giordano and Raymond, 2019; Skarphagen et al., 2019; Guo et al., 2020). Short-term water heat storage is typically installed in BTES in order to buffer against the transient temperature variation (**Figure 1.8**). STS is critical to the proper operation of the system because water can accept and dispense heat at a much higher rate than the subsurface storage which, in contrast, has much higher inertia and capacity (Sibbit et al., 2012; Guo et al., 2020; Mahon et al., 2022). Giordano and Raymond (2019) also demonstrated that two STS tanks kept at different temperatures can increase the solar efficiency due to a lower return temperature to the collectors.

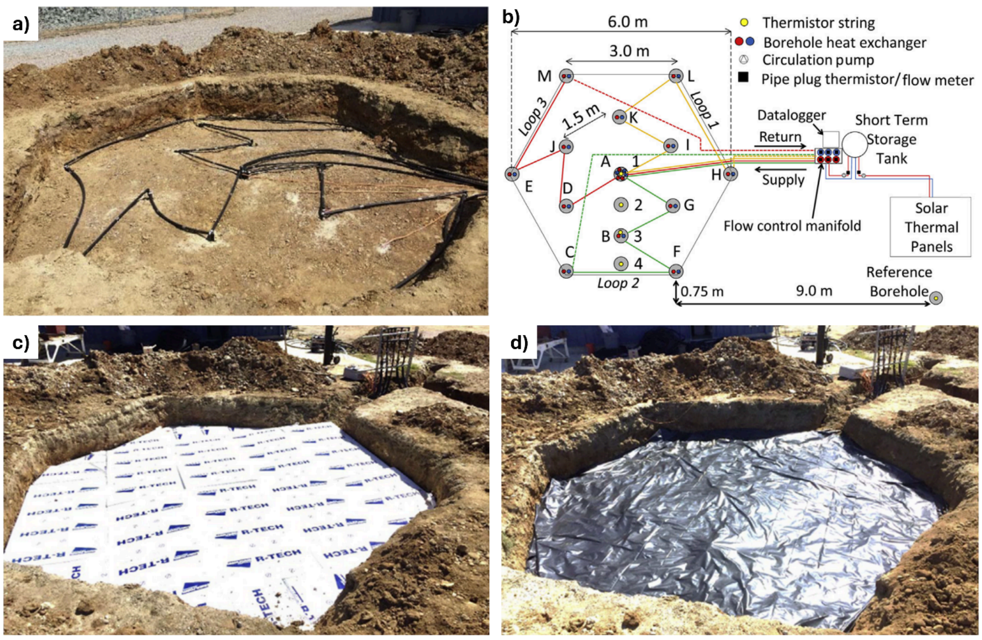


Figure 1.6 – Experimental BTES in San Diego (California, USA) with borehole connection in series (a), diagram of the system (b), top thermal insulation with geofoam (c) and hydraulic barrier (d) to prevent rainfall infiltration (from Baser et al., 2020.)

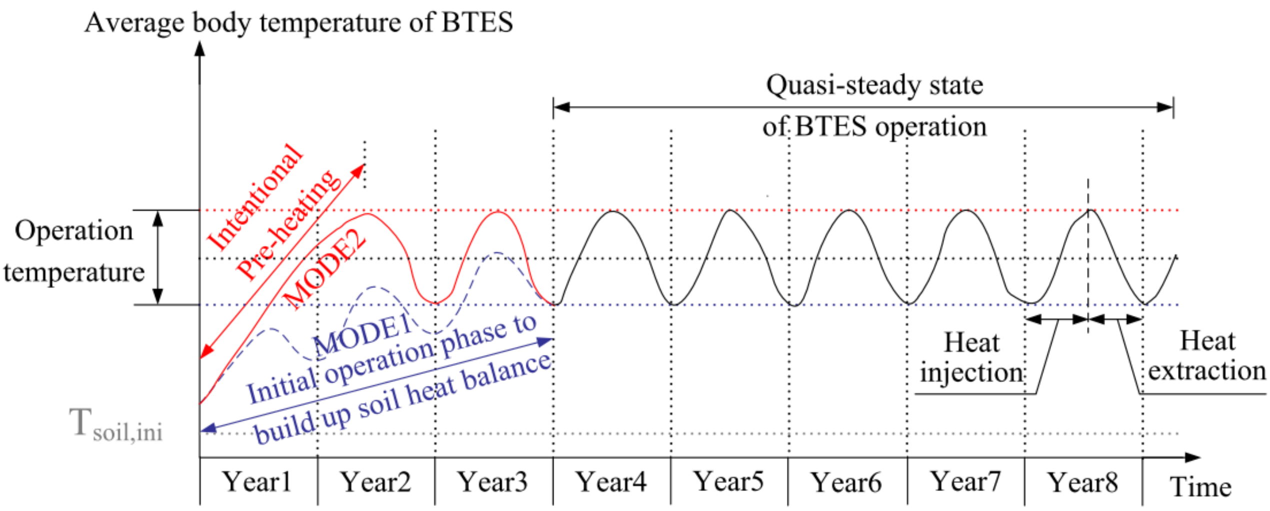


Figure 1.7 – Schematic of the long-term temperature evolution of BTES (from Guo et al., 2020).

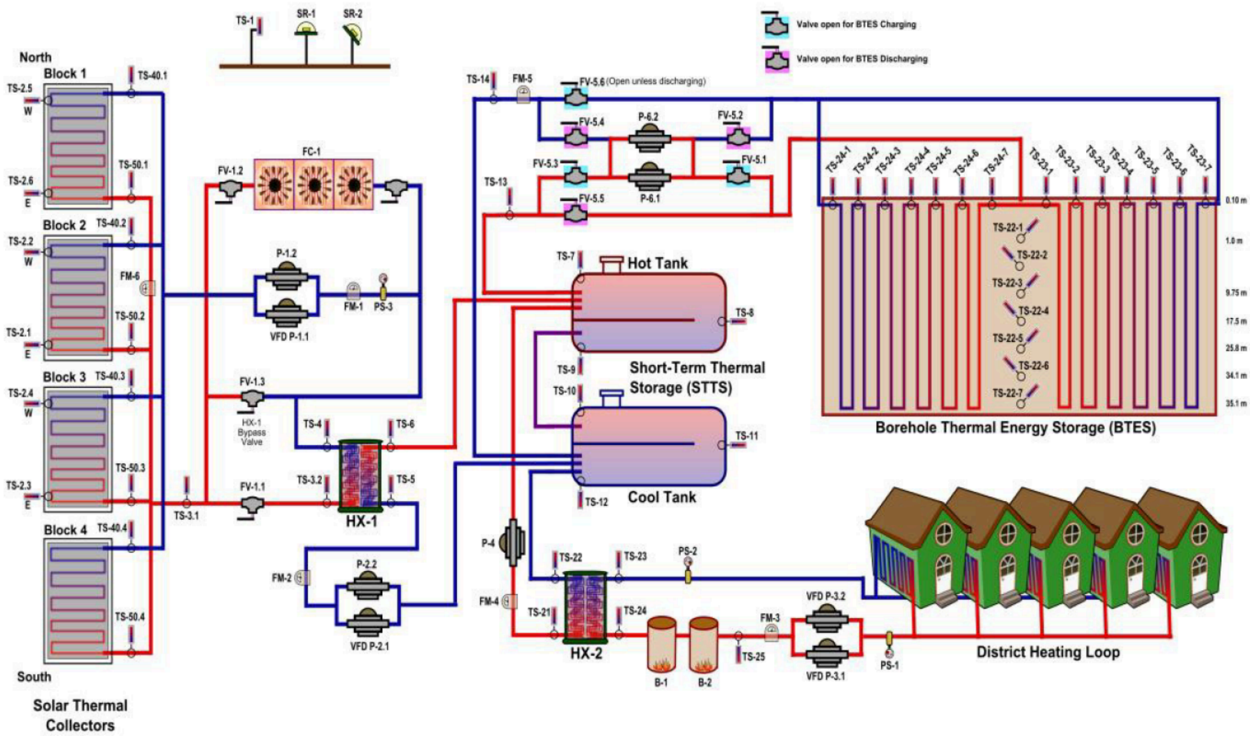


Figure 1.8 – Functional system schematic of the BTES in Okotoks (Alberta, Canada) with monitoring points (from Sibbit et al., 2012).

2. Description of the site

2.1 General and geological setting

The site is located in the Piemonte region of Italy and mainly consists of hilly landscape geared to agriculture. The area, almost flat, slightly sloping towards the E, is located to the hydrographic left of the Rio Valle del Vento which flows at the bottom of a valley oriented approximately N-S. The stream flows into the Belbo River about 4 km N of the site (**Figures 2.1** and **2.2**).

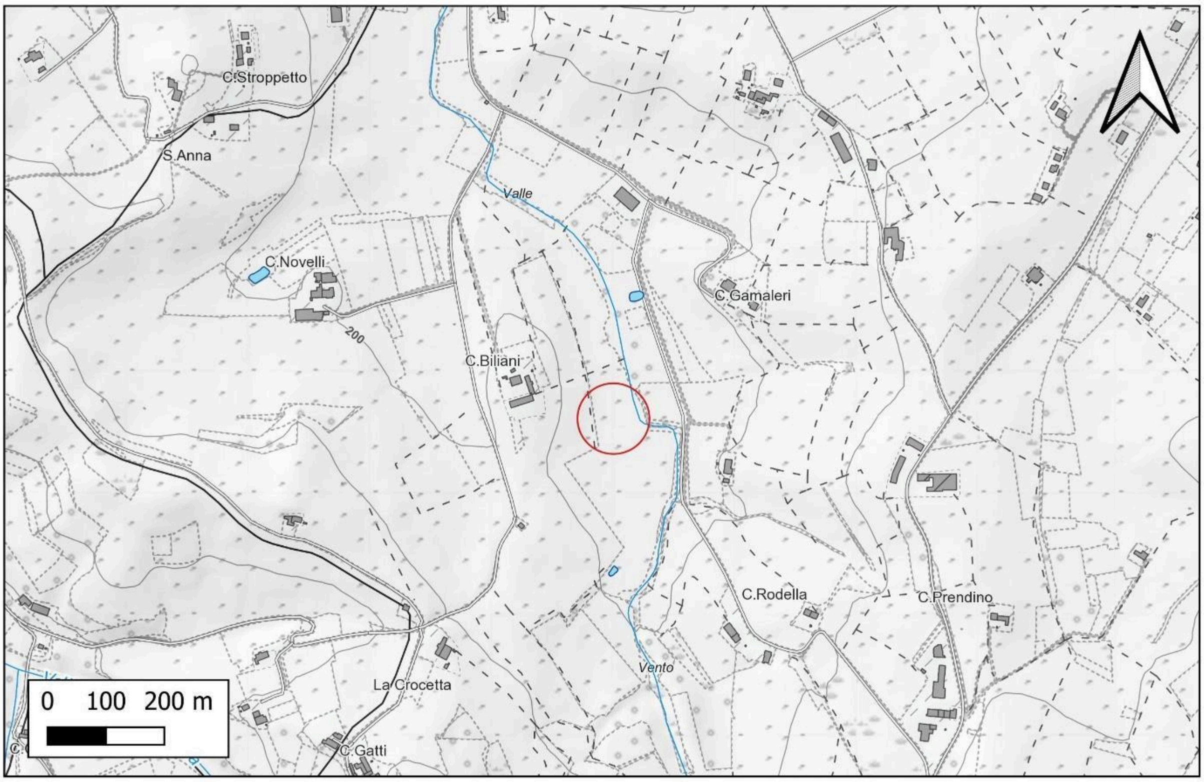


Figure 2.1 – Location of the study site over the Regione Piemonte BDTRE map – Scale 1:10 000.

Figure 2.2 – Location of the study site over the Google Satellite map – Scale 1:5 000.

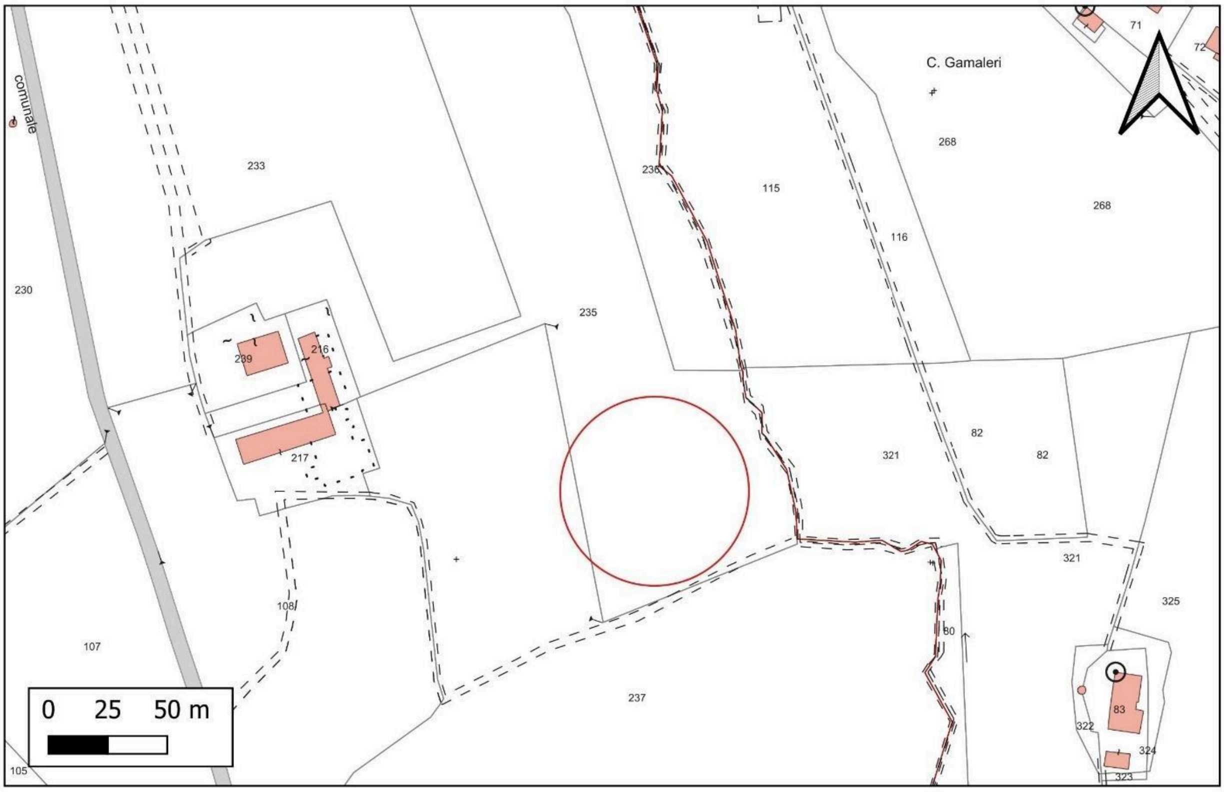


Figure 2.3 – Location of the study site over the Regione Piemonte Catasto map – Scale 1:2 500.

The geological structure is characterised by Oligo-Miocene sediment successions deposited in the Piedmont Tertiary Basin (BTP), an arm of the sea that originated during the post-Paleocene Alpine-Apennine orogenic phases (**Figure 2.4**). The marine sequence, consisting essentially of sandstones and marls, rests on the Alpine basement from the "Unità di Molare" geological unit, the oldest, consisting of marine/continental deposits. Above this first macro-unit is a very thick series of platform, scarp and deep deposits with predominantly re-sedimented arenaceous-marlstone successions alternating with thick pelitic horizons. The Miocene cycle is closed by evaporitic deposits defined as the "Formazione della Vena del Gesso" Unit. From a structural point of view, the Oligo-Miocene deposits follow one another slightly inclined in a monocline plunging towards the NNW, whose base (Molare Unit) outcrops in the Monregalese (South-West of BTP) area and whose top (Vena del Gesso Unit) outcrops mainly along the Tanaro River in the Alba area and in the Nizza Monferrato area.

Figure 2.4 – Tectonic sketch of the studied area (red star) extrapolated from the Geological Map of Piemonte Region at 1:250 000 Scale (Piana et al., 2017). Legend – BTP: Tertiary Piedmont Basin, PS: Pliocene Succession, AB: Alessandria Basin, Vo: Voltri Unit, SVZ: Sestri-Voltaggio Zone.

More in details, the studied area mainly consists of the following geological formations, from bottom to top (D'Atri et al., 2014; **Figure 2.5**):

- “Formazione di Cassinasco” (Serravallian / Lower Tortonian), thick turbiditic succession made of coarse sandstones and marlstones/clays, where sandstones are prevalent at the bottom of the succession while marls prevails towards the top;
- “Marne di Sant’Agata Fossili” (Tortonian/Lower Messinian), bioturbated clayey to calcareous foraminifers-rich marl sediments, showing a gradual transition toward the top into a rhythmic alternation of marls and organic-rich extremely laminated mudstones;
- “Membro di Nizza Monferrato” (Messinian), belonging to the “Formazione della Vena del Gesso” Unit mainly composed of clays, silts, and subordinate sandstones with a variable colour from dark yellow, grey, cream-white, and purple, in which a primary laminated microcrystalline gypsum bed is recognizable;
- “Conglomerates of Cassano-Spinola” (Upper Messinian), a succession of sandy and pelitic layers bordered at the top and bottom by irregular erosional surfaces following in discontinuity the “Formazione della Vena del Gesso”;
- “Quaternary Succession” (Holocene-Present), consisting of sandy-gravelly and silty-sandy fluvial deposits which overlie all the stratigraphic succession and it is mainly present in the valleys with thickness up to 30 m.

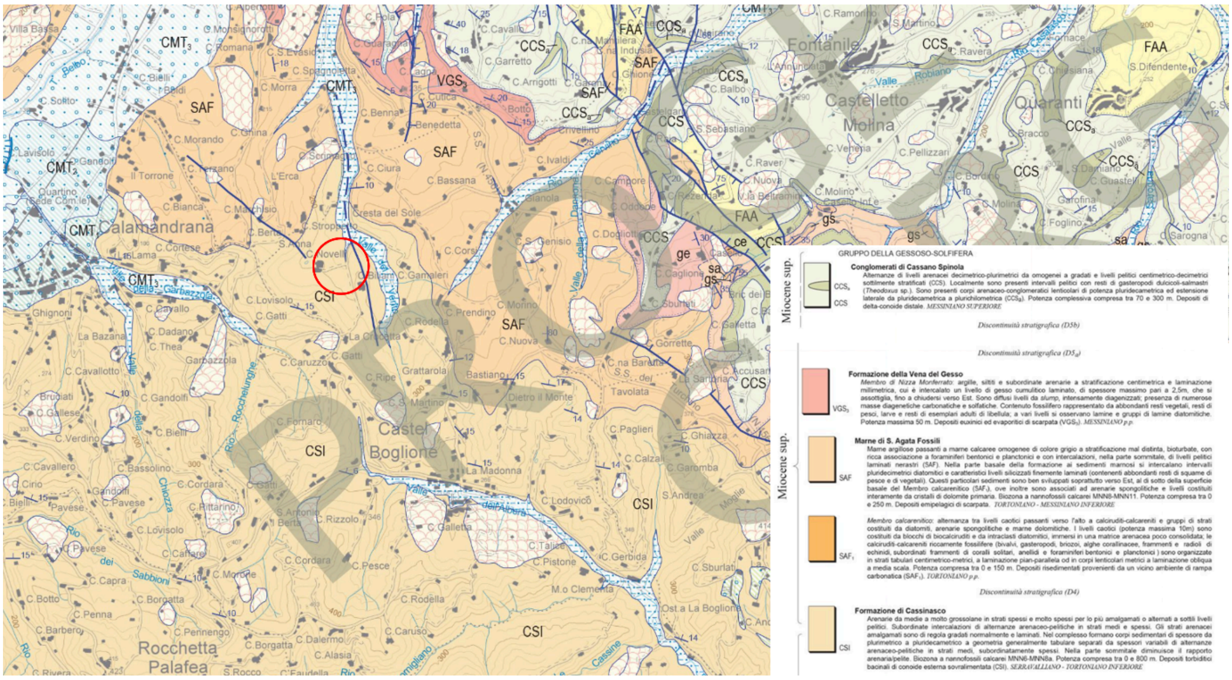
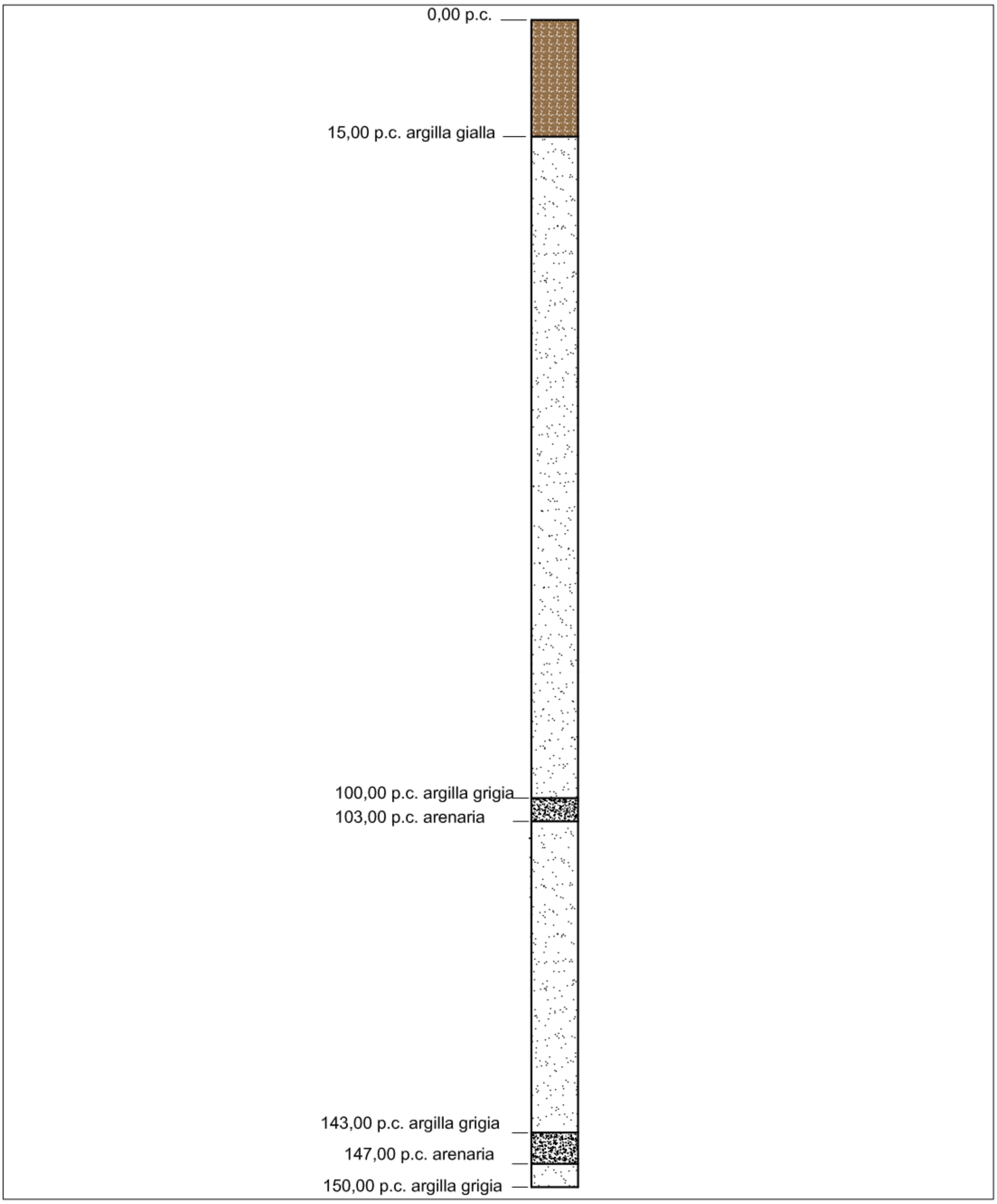


Figure 2.5 – Geological setting of the studiy area (highlighted by the red circle). From the “Carta Geologica d’Italia” Foglio n. 194 Acqui Terme – Scale 1:50 000.

The site of Valle Vento entirely pertains to the “Formazione di Cassinasco”, since this unit has a thickness up to 800 m (**Figure 2.5**). Drillings mainly highlighted the presence of clays and marlstones with little sandstones for the entire depth down to 150 m below ground level (**Figures 2.6** and **2.7**). From a hydrogeological point of view, the effective porosity of the bedrock is very poor (e.g., 0.10 - 0.15) with very low hydraulic conductivity (e.g., 10^{-7} - 10^{-8} m/s) (Woessner and Poeter, 2020). Therefore, the groundwater flow is expected to be limited to periods with heavy rainfalls and having very low velocity with direction towards the Valle Vento stream. BTES heat losses due to groundwater flow (advection) will therefore not be an issue in the study site.



GEONOVIS Energia Geotermica	Soc. Valle Vento S.r.l. Strada Valle Vento Crocetta Castel Boglione (AT)	Stratigrafia sonda n. 3

Figure 2.6 – Stratigraphy of a borehole drilled for the conventional BHE field.

Figure 2.7 – Photo of the site with evidence of yellow clay belonging to the "Formazione di Cassinasco".

2.2 Technical description of GSHP and BTES

The new development area under construction consists of a greenhouse, laboratories, offices, and meeting rooms (**Figures 2.8** and **2.9**). The heating, ventilating, air-conditioning (HVAC) system, designed by Geonovis, is made of the conventional part and the experimental part (**Figures 2.10** and **2.11**). The entire system is made with 4 pipes in order to provide simultaneously heating, cooling and domestic hot water. The conventional GSHP part consists of:

- 16 BHEs with a depth of 150 m, arranged in a rectangular layout (**Figure 2.9**). The heat carrier fluid is a glycol mixture at 20% vol. concentration;
- Two F1345-60 NIBE heat pumps, with nominal capacity of 60 kW each (COP = 4.32);
- One 500 l buffer for domestic hot water;
- One 1000 l buffer for space heating;
- One 1000 l buffer for space cooling;

The experimental BTES part consists of:

- 7 BHEs with a depth of 150 m, arranged in a circular layout with a diameter of about 19.3 m and spacing of ranging from 6.4 to 9.7 m (**Figure 2.9**). The heat carrier fluid is a glycol mixture at 10% vol. concentration;

- Gross solar collector area of about 150 m^2. At the time of writing it is not clear which kind of panel will be installed, either vacuum-pipe (option A) or photovoltaic thermal hybrid (PVT) (option B);
- One 1000 l short-term storage buffer.

Thermal response tests carried out by Geonovis on 3 BHEs of the 2017 system on top of the hill output an average subsurface thermal conductivity λ of around 1.9 W/m/K, in agreement with literature values (Dalla Santa et al., 2020), and an undisturbed underground temperature T_0 of about 14.6°C. The borehole thermal resistance *Rb* of the inspected BHEs varies from a minimum of 0.09 mK/W to a maximum of 0.12 mK/W at a flowrate of about 0.34 l/s. According to literature, heat capacity of the rocks *Cv* is expected to be around 2.3 - 2.4 MJ/m^3/K (Dalla Santa et al., 2020).

Figure 2.8 – Valle Vento new development area.

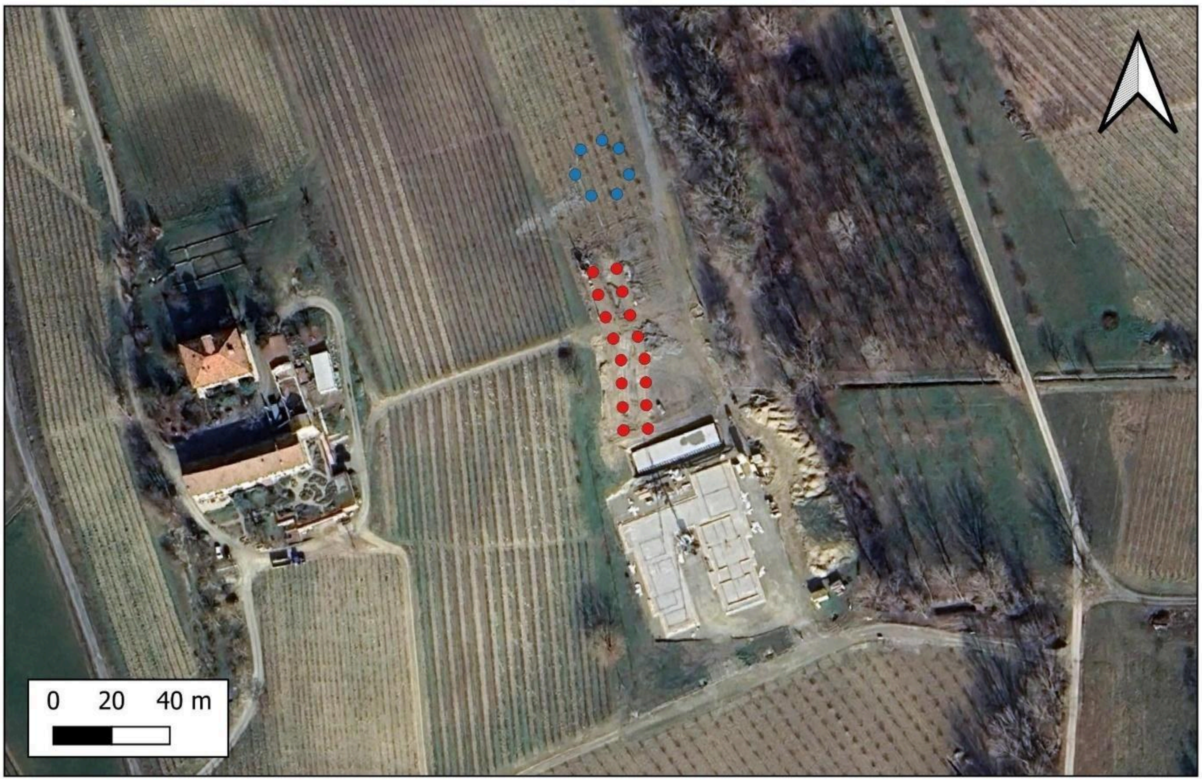


Figure 2.9 – Satellite image of the new development area with location of the 16 BHEs of the conventional GSHP system (red dots) and the 7 BHEs of the experimental BTES (blue dots).

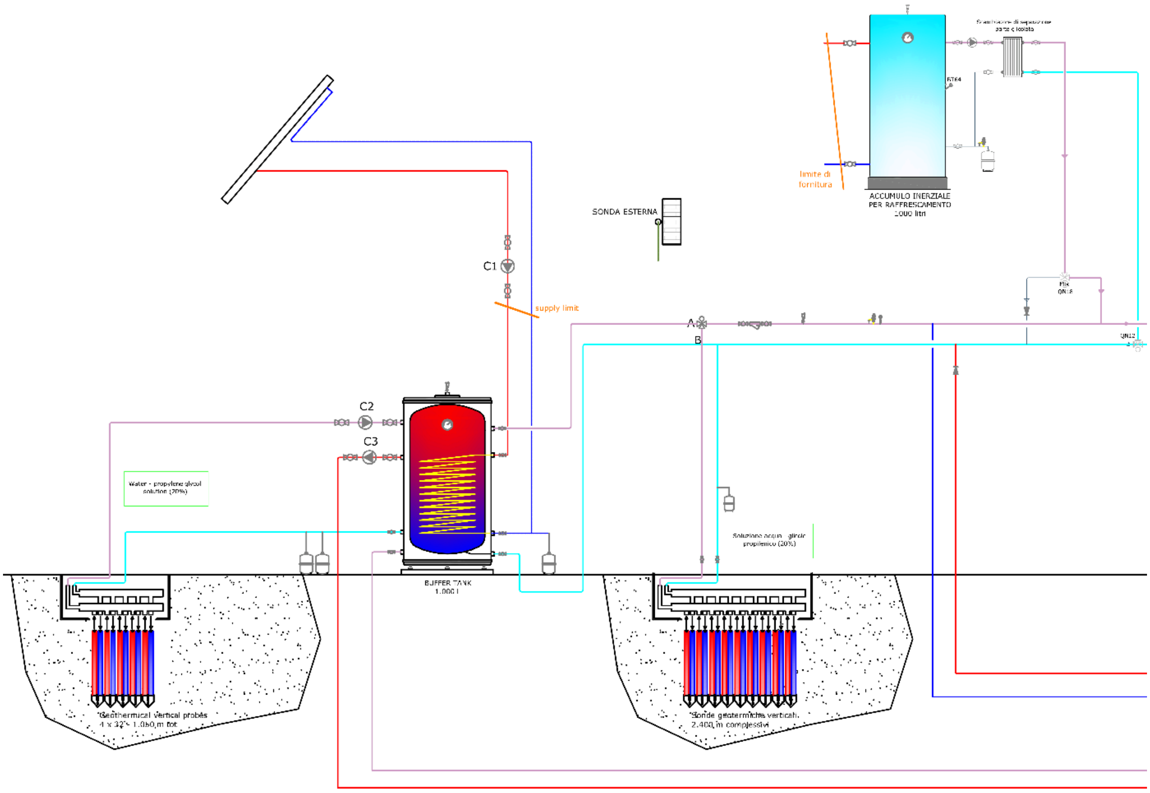


Figure 2.10 – Diagram of the HVAC system made by Geonovis, part A. The BTES is on the left, composed of solar panels, short term storage tank and BHEs. The BHEs on the right pertains to the conventional GSHP.

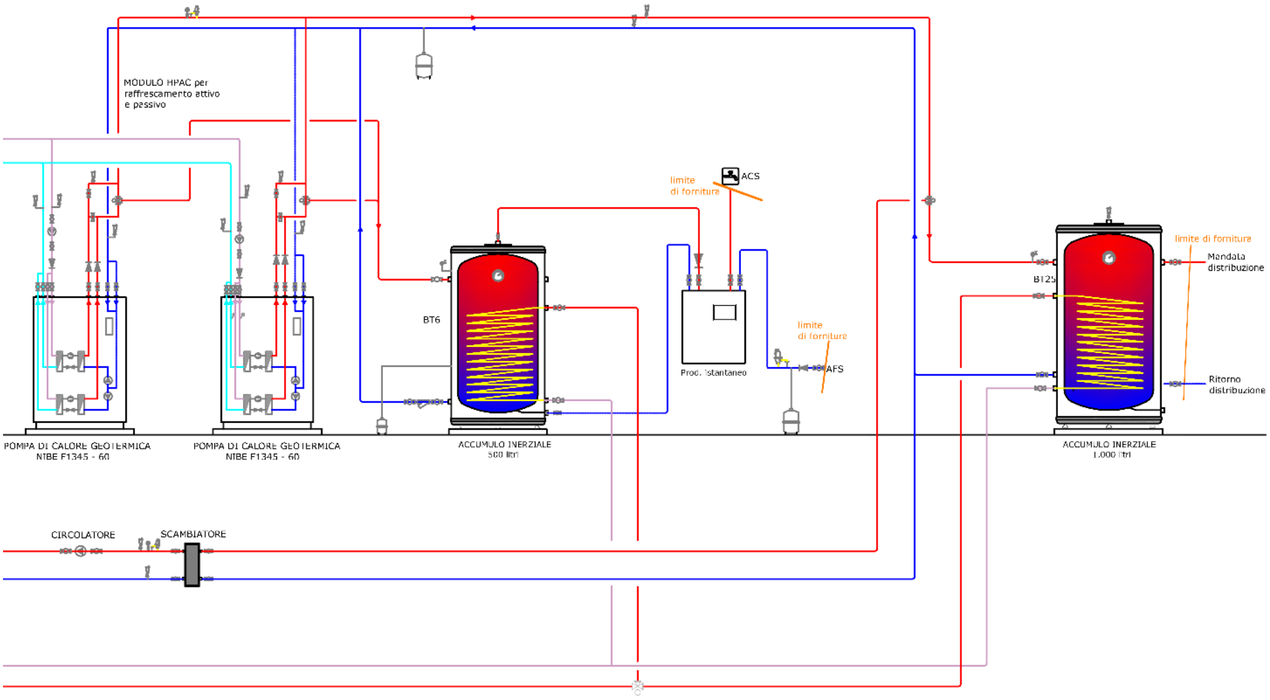


Figure 2.11 – Diagram of the HVAC system made by Geonovis, part B. Two NIBE heat pumps plus buffers for domestic hot water and space heating and cooling are visible.

2.3 BTES expected performance

According to data from the closest available weather station in Asti (CTI, 2024), the global solar irradiance expected in the study site ranges from a minimum of about 200-400 W/m^2 in December and January to a maximum of 900-1000 W/m^2 from May to August (**Figure 2.12**). Considering to produce energy from the 1st of April to the 30th of September, the gross solar collector area assigned to the BTES system (150 m^2) could produce around 180 GJ per year (50 MWh/y), with peak load of 45 to 50 kW (**Figure 2.13**). As already mentioned, at the time of writing two options of solar collectors are under evaluation. Option A are vacuum-pipe collectors that could guarantee higher efficiency (ca. 76%) compared to the option B using hybrid PVT panels (ca. 51%). Since PVT have a better ratio of net over gross area (1.45 over 1.67 m^2) compared to vacuum-pipe (1.63 over 2.69 m^2), calculations made with both collector options ended up to similar values of total solar energy production (185 GJ option A vs. 177 GJ option B). BTES calculations that follows have been carried out considering option A (vacuum-pipe) with a value of solar energy produced of 185 GJ.

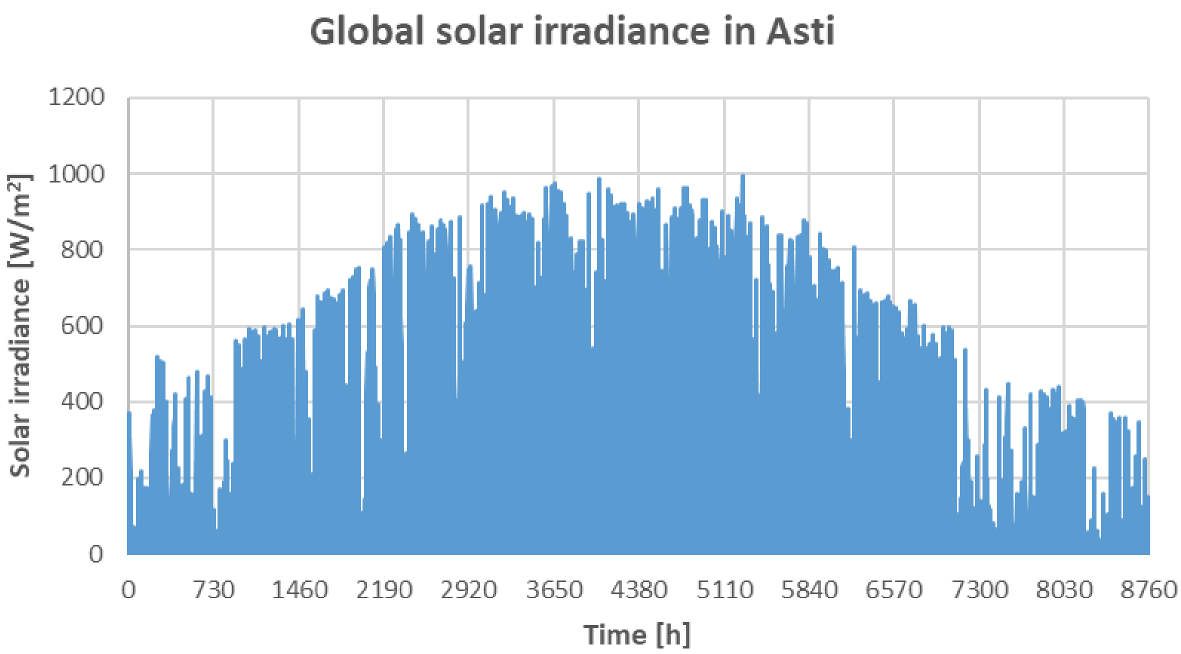


Figure 2.12 – Global solar irradiance [W/m²] in Asti (CTI, 2024).

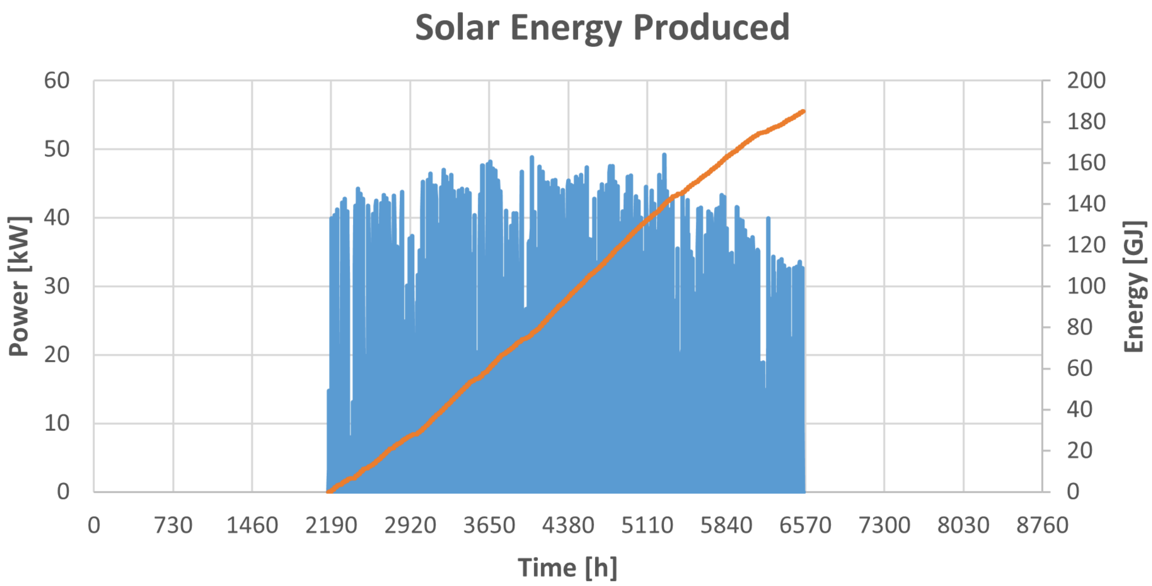


Figure 2.13 – Expected solar energy produced by the gross solar area assigned to the experimental BTES from the 1st of April (2161 h) to the 30th of September (6552 h).

As mentioned in the previous section, the BTES experimental system under study is made of 7 BHEs arranged in a circular layout with a diameter of about 19.3 m and average spacing of about 9 m. In light of the state of the art and the existing BTES systems operating worldwide (**Section 1.2**), the BTES volume, as it is, would not be able to properly store and retrieve energy to/from the subsurface, mainly due to high values of S/V ratio and BHE spacing. In order to improve the BTES volume and optimise the storage, three scenarios (2, 3 and 4) are proposed and compared to the current scenario (1).

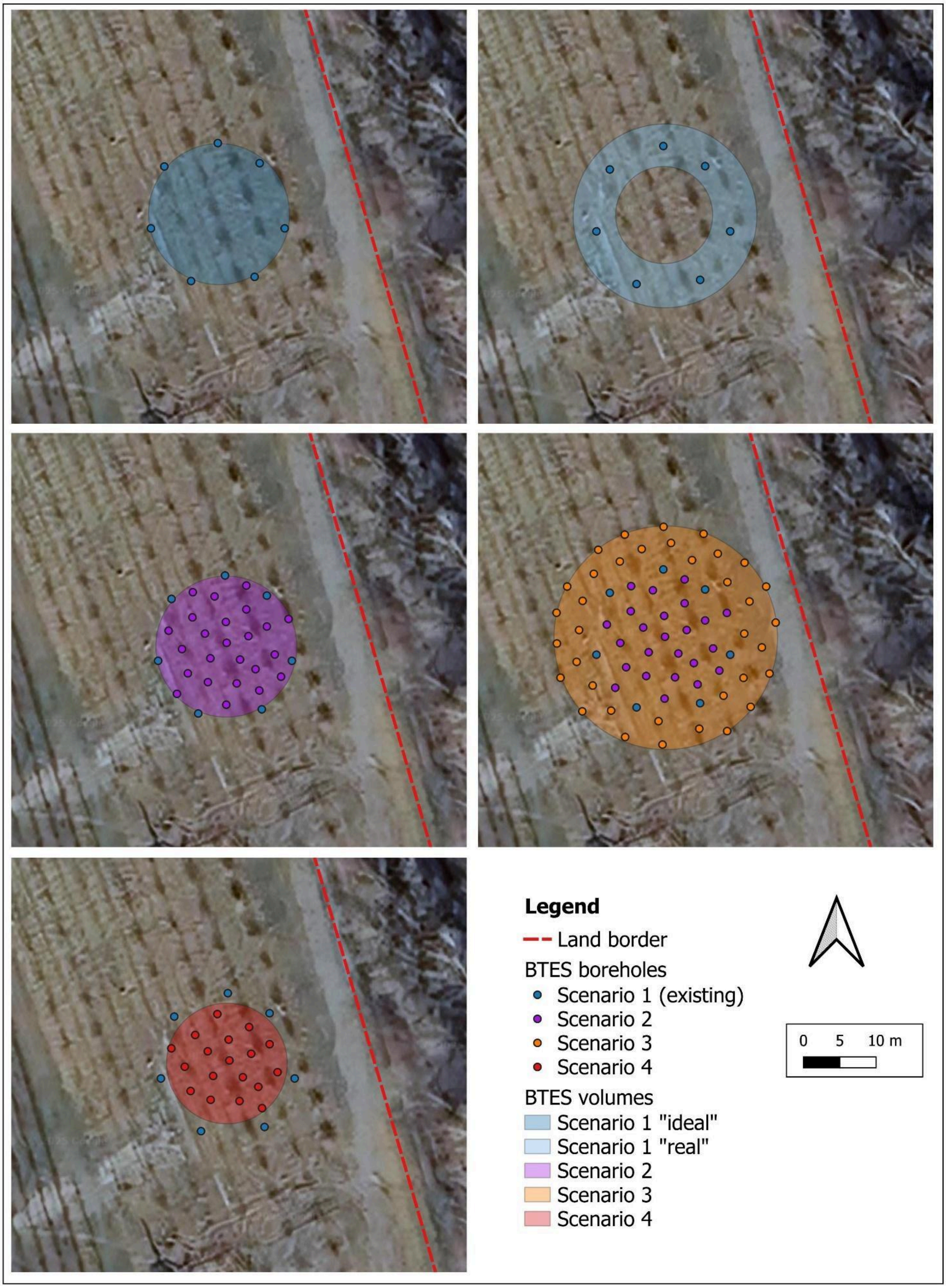

Legend
Land border
BTES boreholes
Scenario 1 (existing)
Scenario 2
Scenario 3
Scenario 4
BTES volumes
Scenario 1 "ideal"
Scenario 1 "real"
Scenario 2
Scenario 3
Scenario 4
0 5 10 m

Figure 2.14 – BHE and volumes of the different BTES scenarios considered in the calculations.

The existing BHEs form a cylindrical volume (scenario 1 ideal) which is not likely to be filled by the injected solar energy due to the spacing and the absence of BHE drilled inside the circle. Therefore, the real volume subject to heat injection/extraction by the existing BHEs is “scenario 1 real”, only made of the annulus of the cylinder (**Figure 2.14**). In order to exploit the entire cylinder, new BHEs should be drilled inside and outside the circle such as in the proposed scenarios 2, 3 and 4. Scenario 2 is made of 24 new BHEs (total of 31) drilled with reduced spacing (average ca. 3.3 m) and smaller depth (20 m). Scenario 3 is made of 60 new BHEs (total of 67) with average spacing of about 3.5 m and depth of 30 m (**Table 1**). Scenario 4 is made of 18 new BHEs drilled with average spacing of about 3.6 m and a depth of 16 m and it does not include the 7 existing ones. All the optimised scenarios keep the S/V ratio close to the ideal curve of a perfect cylinder, with diameter = depth (**Figure 2.15**).

Table 1 – Calculations of the existing scenario (1 real and ideal) compared to the optimised scenarios (2, 3 and 4). Shape factor is depth/diameter.

	Scenario 1 Ideal	Scenario 1 Real	Scenario 2	Scenario 3	Scenario 4
N bhe [-]	7	7	31	67	18
Depth [m]	150	150	20	30	16
Total lenght BHE [m]	1050	1050	620	2010	288
Spacing [m]	6.5	9	3.3	3.5	3.6
Shape [-]	cylindre	annulus	cylindre	cylindre	cylindre
Volume of BTES [m3]	38414	53721	5846	21321	3232
Diameter [m]	18.1	19.0	19.3	30.1	16.0
Radius [m]	9.0	9.5	9.6	15.0	8.0
Shape factor [-]	8.3	7.9	1.0	1.0	1
Lateral surface [m2]	8509	17907	1212	2835	806
Top and bottom surface [m2	256.1	358.1	292.3	710.7	202.0
S/V ratio (real) [m-1]	0.235	0.347	0.307	0.200	0.374
S/V ratio (ideal) [m-1]	0.165	0.147	0.309	0.200	0.376
Difference %	29.90%	57.54%	-0.45%	-0.38%	-0.51%
T core [°C]	21.77	16.31	61.68	27.51	99.76
T annulus [°C]	15.94	15.88	23.43	17.02	30.57
Heat Recovery HR [%]	22.0%	negative	26.7%	51.2%	12.81%

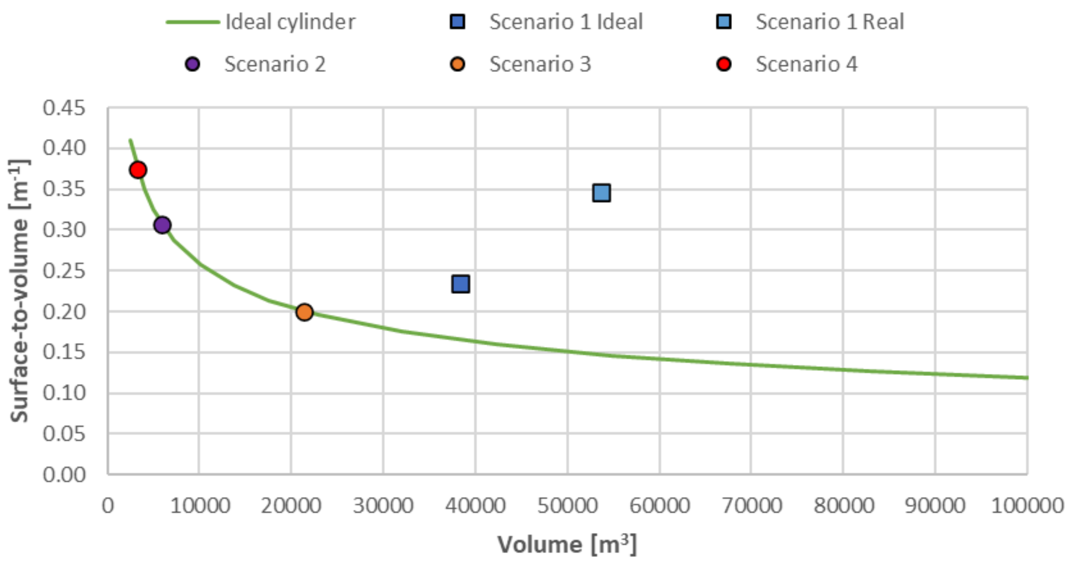


Figure 2.15 – S/V ratio of the different scenarios compared to the curve of an ideal cylinder.

To quantify the performance of the optimized scenarios compared to the existing scenario, some simple analytical calculations have been carried out (**Table 1**). Temperature in the core and in the annulus of the storage volume has been calculated by considering to store 40% of the total energy into the core and 60% in the annulus (stratification), according to data from numerical simulations available in the literature. The temperature increase ΔT [K] induced by heat injection E_{INJ} [J] in a certain volume V [m^3] of subsurface with a certain heat capacity Cv [J/m^3/K] can be easily calculated as follows:

$$\Delta T = \frac{E_{INJ}}{V \cdot Cv}$$ [1]

Heat recovery has been then calculated from the heat losses due to thermal conduction through a subsurface area A [m^2] with a certain thermal conductivity λ [W/m/K] and the calculated temperature gradient ΔT from the annulus to the undisturbed environment. The characteristic length L [m] was assumed to be 2.5 m after calibration with numerical simulations (Giordano and Raymond, 2019). Heat losses due to conduction can be calculated as follows:

$$q_{cond} = \frac{\lambda \cdot A \cdot \Delta T}{L}$$ [2]

Advection has not been considered since groundwater flow is not significant in the study site (see **Section 2.1**). Results (**Table 1**) show that scenarios 2, 3, and 4 improve the heat recovery of the BTES volume, allowing to recover some 50 to 90 GJ. Scenario 2 and 4, due to their small volume, are able to increase the temperature of the underground in the core of the volume up to 60°C and

100°C, respectively. On the other hand they show low HR. Higher HR of scenario 3 is due to its bigger volume in agreement with literature data (e.g., Skarphagen et al., 2019).

Finally, it is important to state that calculations here performed are based on simplified analytical models valid for a single BHE, do not reflect the real subsurface behaviour, and should only be considered for qualitative considerations. More detailed analyses would only be possible via 3D hydrogeological numerical modelling of the subsurface or via dynamic modelling of the entire BTES system (solar collectors + STS + BTES volume), which are not the purpose of the present document. This kind of analysis, as detailed in **Section 3.3**, is crucial to predict the BTES operation and make a final custom design.

2.4 Recommendations

Some recommendations are hereby given in order to implement and optimize the existing BTES in order to meet the Client's objectives. As discussed by Guo et al. (2020), the factors affecting the BTES performance are ascribable to three categories: design; sizing and integration; operation and control. While design parameters are decided at the design stage and are difficult to change afterwards, the other two categories contain parameters that can be tested directly on the plant during its operation, provided that the system has a high degree of freedom and flexibility in terms of modularity, changeability and integration of heat sources, adjustable operation parameters and control strategies. This kind of system is called "living laboratory" and can play the three following roles (**Figure 2.16**):

- Sustainable space heating and cooling plant for the defined user;
- Experimental platform for testing various operation modes, control strategies, heat sources;
- Data source for field-scale long-term monitoring.

The data and operational experience of the living laboratory can be used for supporting various other functions such as model validation, performance assessment, thermodynamic studies, life span economic analysis, and advanced control strategy development.

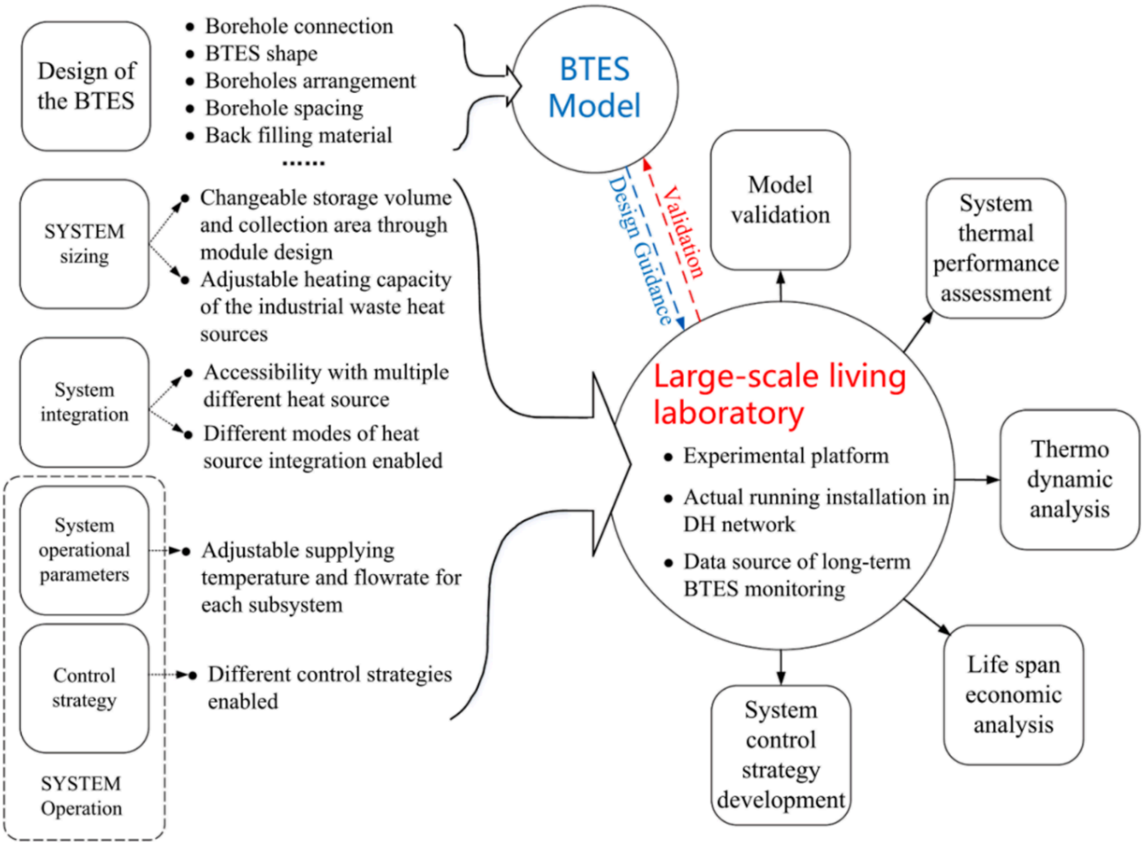


Figure 2.16 – Basic conceptual design of a large-scale living laboratory for seasonal BTES integrated in a district heating network (Guo et al., 2020).

In light of the expected performances before discussed and the state of the art in the BTES domain, it is suggested to further implement the system as follows:

- At least 18 new BHEs should be drilled inside the circle defined by the 7 existing BHEs. Given the diameter of the cylinder (ca. 20 m), the depth of the new BHEs should be 15 to 30 m in order to keep low the S/V ratio. Connection of the new BHEs should be in series allowing for a fluid circulation from the core to the annulus in summer (charge) and vice versa in winter (discharge) in order to improve stratification and preserve the heat in the core of the cylinder (e.g., Casasso et al., 2021; Mahon et al., 2022). Due to the difficulty to have a bi-directional circuit that automatically switches between charge and discharge, a manual switch can be done at specific dates depending on the solar irradiation and the user demand (e.g., 1st of April and 1st of October). BHEs can be arranged in 6 series of 3 boreholes, with a BHE in the centre suggested but not mandatory; the central position can be occupied by sensor chains only. Spacing between the BHEs should be around 2.5 to 3.5 m, the lower the better (e.g., Skarphagen et al., 2019; Mahon et al., 2022).

- Proper thermal insulation on top of the BHE field is suggested in order to reduce the heat losses towards the atmosphere, which is the highest amount among the overall heat losses (e.g., Giordano and Raymond; 2019). Borehole top should be placed at 1.5 ÷ 2 m below ground surface and covered with a layer of insulating material (e.g., EPS or XPS geofoam). A hydraulic barrier on top of the thermal insulation (e.g., impermeable sheet) can also be considered in order to prevent rainfall infiltration into the BTES volume, which would increase subsurface thermal conductivity and thus heat losses. The remaining part of the pit can be backfilled with the excavated material. Several examples of insulating materials for BTES are given in Sibbit et al. (2020), Giordano and Raymond (2019), Baser et al. (2020), and references therein.
- The subsurface monitoring should be provided by both temperature sensors in the ground and boreholes equipped with electrodes in order to perform cross-hole electrical resistivity tomography (**Figure 2.18**). Temperature sensor chains should be installed in boreholes at specific depths, depending on the total depth. Since the existing BHEs are 150-m-deep, at least one sensor chain should go down to 150 m, while the others can be 20 to 30-m-deep. Due to the general low heterogeneity of the subsurface, 10÷15 m and 3÷5 m spacing is suggested in 150-m-deep holes and 20 to 30-m-deep ones, respectively. All temperature and geophysical boreholes can either be equipped with screened piezometer tubes or with heat exchanger pipes (either 2-U or coaxial for performance comparison) to allow for future groundwater and temperature monitoring (see **Section 3.3**), or thermal response testing (TRT). More details about geophysical boreholes installation is given in **Section 3.3**. A quote for installing and providing cross-hole ERT monitoring in the BTES is also given in **Annex 4**.
- It is suggested to add a second short term storage tank of 1000 l between the solar collectors and the BHE field in order to have a hot and a cold buffer. This element is expected to decrease the return temperature to the solar collectors during the charge phase and thus increase the solar efficiency. An example diagram with possible circulation modes is depicted in **Figure 2.17**.
- Circulators should be powered by variable speed drivers in order to change the flow rate of the heat carrier fluid. Typically, GSHPs work with flow circulating in the BHEs in turbulent regime (i.e., Reynolds number $Re > 2300$) in order to reduce borehole thermal resistance, increase BHE efficiency, and inject/extract more energy (Kavanaugh and Rafferty, 2014; Lamarche, 2023). However, this is not always the case in BTES, where the flow rate during the charge phase should be adjusted depending on the ΔT between supply and return temperatures to the BHE field (e.g., Catolico et al., 2016; Guo et al., 2020). This allows to

properly distribute the heat underground and increase the overall efficiency, i.e., minimize the return temperature to increase solar efficiency (this element can be tested together with the previous point, which has the same purpose). In general, it is suggested to have low-velocity flow (*Re* < 2300) during charge and high-velocity flow (*Re* > 2300) during discharge. Flow rate should range between 0.05 to 0.5 l/s per BHE and it should vary according to the system's response (i.e., monitoring data).

- The BTES loop should not contain propylene glycol in the heat carrier fluid or just a minimum amount (e.g., 10% vol.) in order to prevent freezing in periods of no operation. The heat carrier fluid of the BTES loop will circulate with expected temperatures > 10°C, therefore reducing the amount of glycol is important to reduce the electrical consumption of the circulators since the fluid will have lower viscosity.
- It is suggested to carry out a pre-heating period of the subsurface, meaning that the first discharge phase should be done only in the second year of operation. This element will benefit the performance of the BTES by increasing the efficiency and by reaching in advance the full potential of the BTES (e.g., Giordano and Raymond 2019; Guo et al., 2020).
- It is suggested to drill a borehole far away from the BTES (e.g., 20÷25 m) in order to monitor the undisturbed underground temperature and possible impacts of the BTES on the surrounding environment. This hole can be equipped with a 2-U BHE left open to serve as a facility for R&D in thermal response testing (see **Figure 2.18**).

In conclusion, flexibility is key in order to have a living laboratory that could guarantee the highest possible degree of freedom in testing several different operation and control strategies. Ideally, the system should also have the possibility to integrate new heat sources (e.g., cooling of buildings or increase the solar area), increase the number of BHEs in the existing volume (i.e., decreasing the spacing) or while increasing the BTES volume (i.e., keeping the same spacing), and add new monitoring elements (e.g., new temperature sensor chains, new geophysical boreholes).

After discussions with the Client, the final design proposed for the BTES system is reported in **Figure 2.18** (storage) and **Figure 2.19** (plant). This layout will guarantee proper efficiency of the underground storage system with fluid temperature high enough the heat the facilities (e.g. greenhouse) with free heating already after the first charge phase. It is composed of 18 new BHEs with a depth of 16 m that will be connected with 6 series of 3 BHEs each. The 7 existing 150-m-deep BHE will be connected to the system as a 7th series with all the BHEs connected in parallel. Ideally, these existing BHEs will only be used if the underground temperature will exceed a pre-defined threshold to avoid excessive ground and fluid temperature.

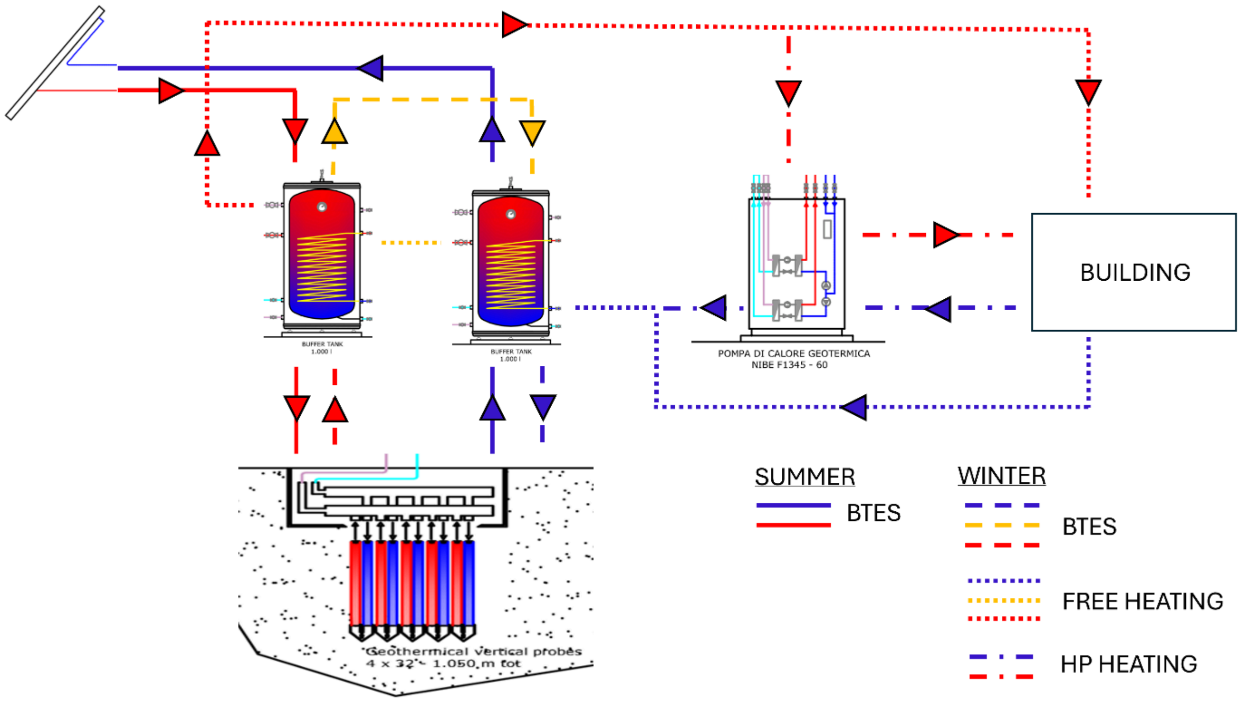


Figure 2.17 – Simplified sketch of BTES operation in summer (charge) and winter (discharge).

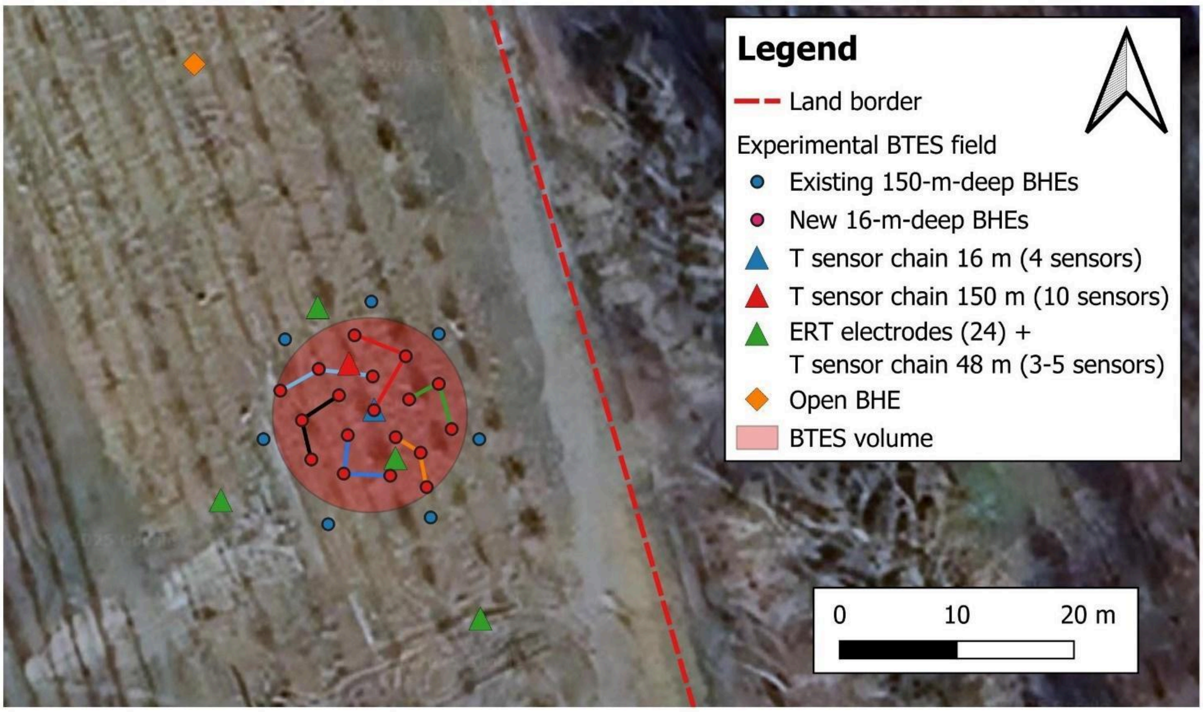


Figure 2.18 – BTES layout with recommendations: 18 new BHEs (red dots) arranged in 6 series of 3 BHEs; four holes with both temperature sensors and electrodes for geophysical monitoring (green triangles); two temperature sensor chains (blue and red triangles); one open BHE for undisturbed ground temperature monitoring and further TRT R&D (orange diamond).

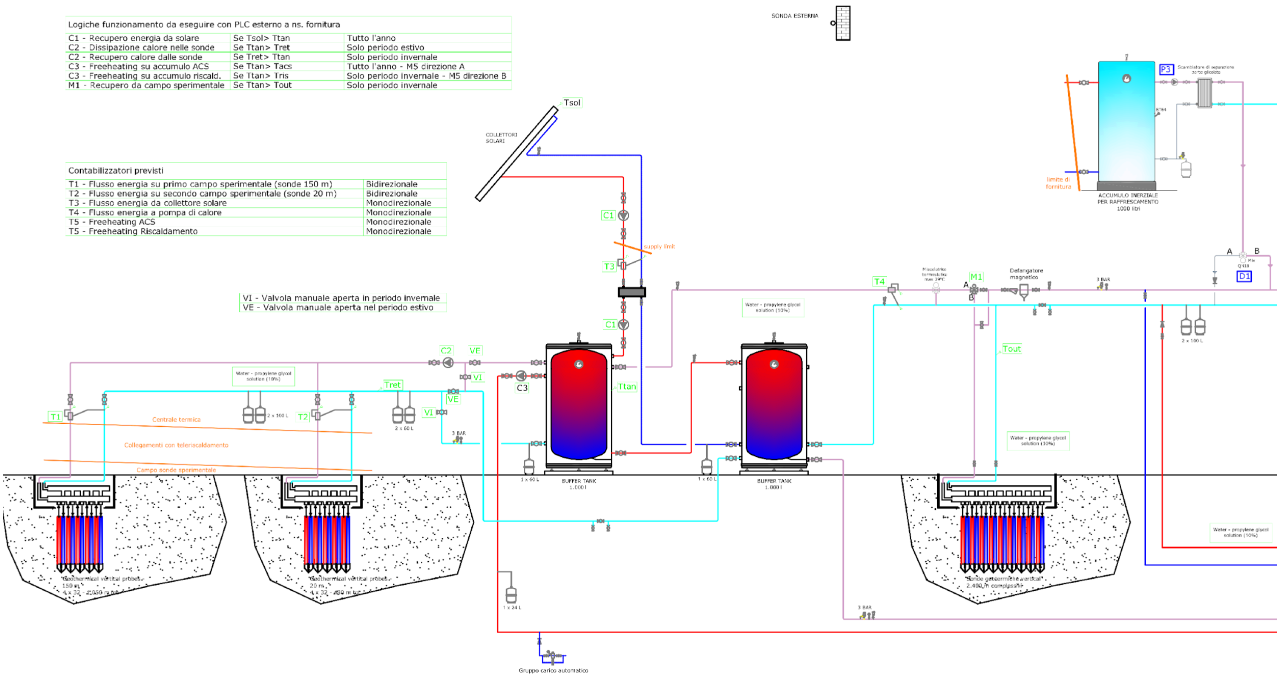


Figure 2.19 – Diagram of the updated HVAC system made by Geonovis, part A. The BTES is composed of two circuits: the first consists of the 16-m-deep BHEs connected in 6 series (right); the second consists of the 150-m-deep BHEs connected in parallel (left). This updated and final version comprises two short term tanks. The location of the heat meters is also reported.

3. Research and development proposal

3.1 Objectives

The main objectives of the project are defined as follows, grouped in three sets:

1. Based on the recommendations provided, design and implement the system with new BHEs, drillings for direct and geophysical monitoring, horizontal collectors and valves and pumps to run the circuit, short-term storage buffers, heat meters, control and management of the whole system including the experimental BTES and the conventional GSHP;
2. Run the system, monitor its operation, quantify the performance, define control strategies, provide optimisation in order to reach its maximum potential;
3. Showcase the system to the community such as private citizens and public entities in order to illustrate its benefits and prevent barriers and obstacles to the deployment of the technology; open the doors to both the industry and the academia such to exploit the living laboratory for testing processes, developing tools, getting feedbacks; build a database of all the monitoring data and make it freely available to the community.

3.2 Timeline, milestones, and deliverables

The proposal for research and development activities to carry out in Valle Vento is designed for the next three years kicking off in March 2025 and wrapping up in March 2028. The activities proposed are grouped into three different work packages (WP) corresponding to the three aforementioned principal objectives (**Section 3.1**). Each WP has a set of tasks (T) to fulfil in order to reach milestones and produce deliverables. The timeline of the project proposal is drafted in the form of a Gantt chart, presented in **Annex 2** and summarised in **Figures 3.1** and **3.2** hereafter.

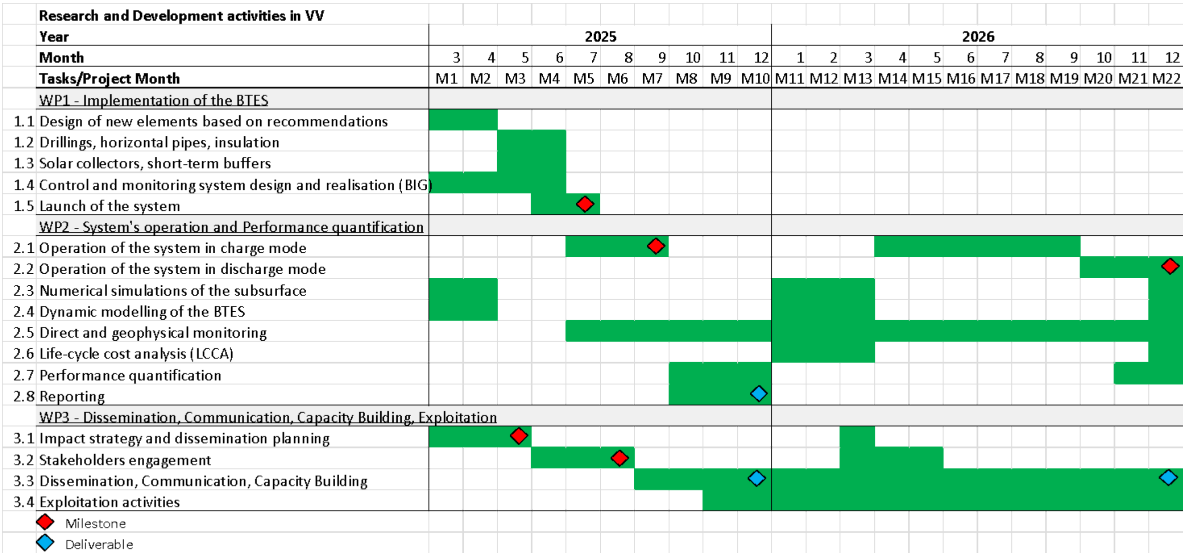


Figure 3.1 – Timeline, milestones, and deliverable of the proposed R&D project in VV (years 2025 and 2026).

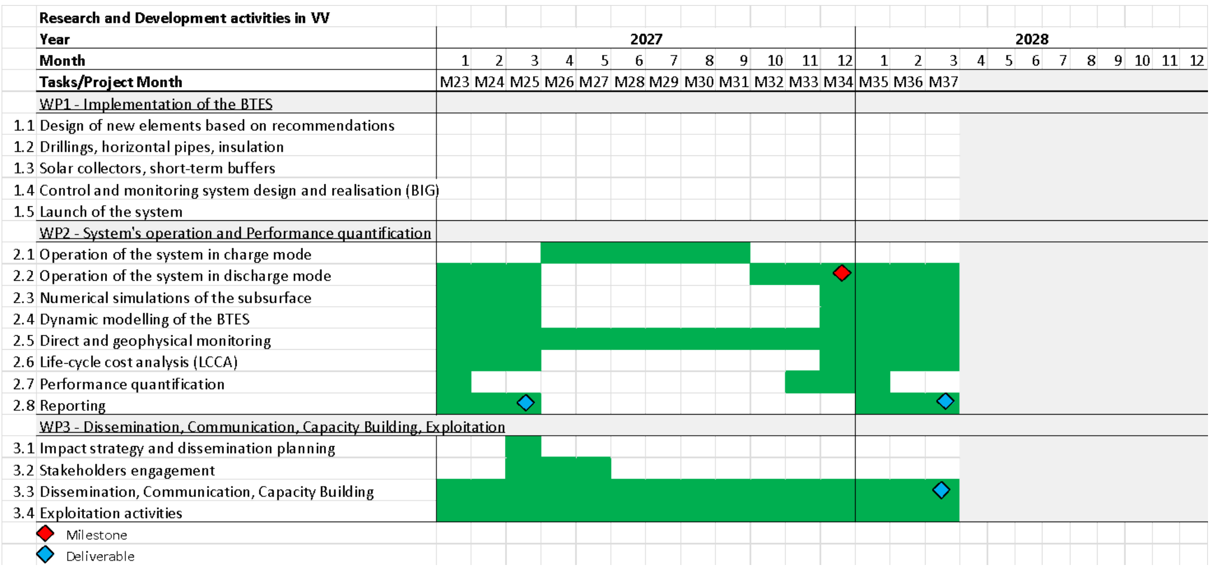


Figure 3.2 – Timeline, milestones, and deliverables of the proposed R&D project in VV (years 2027 and 2028).

In particular, the R&D project consists of the following work packages and tasks.

WP1 – Implementation of the BTES

This work package consists of 5 tasks and is intended to last 5 to 6 months. Tasks included in this work package mainly pertains to the design (T1.1) and installation (T1.2 and T1.3) of the new elements recommended in order to improve the efficiency of the system (**Section 2.4**). Another important task is the design and realisation of the control and monitoring system (T1.4). The launch of the system for the first charge phase is foreseen for late spring / summer 2025 (T1.5).

WP2 – System’s operation and Performance quantification

This work package manages the operation of the system (T2.1 and T2.2) and includes a number of side activities which allow to quantify the performance of the BTES (T2.3, T2.4, and T2.7), monitor the system (T2.5) and evaluate its financial sustainability (T2.6). Subsurface numerical simulations and dynamic modelling of the system are important elements that can also be useful to support T1.1 for optimal design and definition of control strategies (e.g., Catolico et al., 2016; Xu et al., 2021). Periodic reporting (T2.8) is of utmost importance for keeping track of the system's operation year after year and also feeding the activities of the impact strategy (WP3).

WP3 – Dissemination, Communication, Capacity Building, Exploitation

Due to its significant importance for the success of the project, this work package is the only one starting from the kick-off and lasting until the very end. It is intended for developing and managing the impact strategy of the project and consists of 4 tasks dealing with planning of the activities (T3.1), stakeholder engagement (T3.2), dissemination, communication, and capacity building events (T3.3), and exploitation measures (T3.4). The impact strategy is thoroughly described in the following **Section 4**.

Milestones and deliverables are preliminarily pointed out in the timeline (**Figures 3.1** and **3.2**) and defined as follows:

- WP1: one milestone is defined for this WP corresponding to the launch of the system, without which any of the other activities cannot take place. This milestone M1.1 is set in month 5 of the project, but can shift forward depending on the time needed for the realization of tasks T1.1 to T1.4;
- WP2: three milestones and three deliverables are defined for this WP. Milestones correspond to the end of the charge phase in 2025 (M2.1) and to the end of 2026 (M2.2), and 2027 (M2.3). Deliverables (D2.1, D2.2, D2.3) are set three months later, respectively, to allow for a thorough reporting.
- WP3: two milestones correspond to the end of T3.1 (M3.1) and T3.2 (M3.2), without which any activity of WP3 cannot be carried out. Three deliverables are set to December 2025 (D3.1), December 2026 (D3.2), and the end of the project (D3.3) in order to describe what has been deployed in terms of dissemination, communication, and capacity building activities.

3.3 Methodology

In light of the aforementioned WP and tasks, as well as the activities to be carried out throughout the project, some more details about methods and tools are necessary. While WP1's tasks are straightforward and WP3's methodology is thoroughly described in **Section 4**, a description of some WP2's activities is given in the following.

T2.3 – Numerical simulations of the subsurface

Heat transport in porous media is described by the following partial differential equation in 3D radial coordinates:

$$\frac{\partial}{\partial r}\left(k\frac{\partial T}{\partial r}\right)+\frac{k}{r}\frac{\partial T}{\partial r}+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)=\rho C_p\frac{\partial T}{\partial t} \qquad \text{with} \qquad \begin{matrix} r_b < r < \infty \\ 0 < z < \infty \end{matrix}$$

[3]

where *k*, *ρ*, *Cp*, *T*, *r*, *z* and *t* are thermal conductivity, density and specific heat of the medium, temperature, distance, depth and time, respectively. To solve this equation, both analytical and numerical solutions can be used. Borehole heat exchangers of GSHPs are typically modelled via analytical solutions that, despite simplifications and assumptions, allow sizing the system with fast, efficient, and reliable calculations for professional design. Popular sizing software programs are based on analytical solutions (e.g., Hellström and Sanner 1994; Spitler, 2000). However, when it comes to BTES with several BHEs at different depths and displayed in complex layouts, numerical solutions are a better means.

Numerical methods allow to simulate the operation of the system in the years to come and evaluate its performance, energy stored, subsurface and fluid temperatures. A 3D environment is built with BHEs installed in a hydrogeological model accounting for heterogeneity and groundwater. Compared to the analytical approach, numerical methods are complex, costly, and time consuming, but since they can provide significant accuracy and level of detail, they are the norm in the design and performance evaluation of BTES.

Several numerical codes are available on the market to perform hydrogeological modelling and they can be free of charge, open-source or commercial (**Figure 3.3**). The most popular commercial codes to work with GSHP and BTES are FEFLOW and COMSOL Multiphysics, which allow to easily simulate BHEs, with the first more prone to large-scale systems, and the latter best suited for discretized single-BHE studies (e.g., Giordano and Raymond, 2019; Guo et al, 2024; **Figure 3.4**). MODFLOW is a modular hydrologic code developed by the United States Geological Survey (USGS) first published in 1984 and considered an international standard for simulating and predicting groundwater conditions. The source code is free and several graphical user interfaces are available (either free or commercial) to build models and perform simulations. Some modules can also be used to simulate BHEs (e.g., Barbieri et al. 2022), however assumptions, simplifications, and a high degree of complexity do not make this code the preferential option for professionals.

Code name	Numerical method	Processes	Availability	References
AST/TWOW	FD	T-H	Commercial	Schmidt and Hellström (2005)
BASIN2	FD	T-H-S	Free code	Bethke et al. (2007)
COMSOL Multiphysics	FE	T-H-S	Commercial	Oberdorfer et al. (2013)
FEFLOW	FE	T-H-S	Commercial	Diersch (2014)
FRACHEM	FE	T-H-S	Scientific	Bächler and Kohl (2005)
FRACTure	FE	T-H	Scientific	Kohl and Hopkirk (1995)
OPENGEOSYS	FE	T-H-M-S-C	Scientific	Kolditz et al. (2012a)
HEATFLOW-SMOKER	FE	T-H-S	Free code	Molson and Frind (2012)
HST3D	FD	T-H-S	Free code	Kipp (1987)
HYDROGEOSPHERE	FE	T-H-S	Scientific	Brunner and Simmons (2012)
HYDROTHERM	FD	T-H	Free code	Kipp et al. (2008)
HYDRUS 2D/3D	FE	T-H-S	Commercial	Yu and Zheng (2010)
MT3DMS	FD	T-H-S	Scientific	Zheng and Wang (1999)
SEAWAT	FD	T-H-S	Free code	Guo and Langevin (2002)
SHEMAT	FD	T-H-S	Commercial	Clauser (2003)
SUTRA	FE/FD	T-H-S	Free code	Voss and Provost (2002)
SVHEAT 2D/3D	FE	T-H-S	Commercial	Thode and Fredlund (2008)
TEMP/W	FE	T	Commercial	Geostudio (2007)
THETA-STOCK	FE	T-H-M	Scientific	Gatmiri and Arson (2008)
TOUGH2	FD	T-H-S	Commercial	Pruess et al. (2012)
TRADIKON 3D	FD	T-H	Free code	Brehm (1989)
VS2DH	FD	T-H	Free code	Healy and Ronan (1996)

FD = finite difference, FE = finite element; T = thermal, H = hydraulic; S = solute, C = chemical reactions; M = mechanical

Figure 3.3 – Numerical codes for hydrogeological modelling (from Giordano, 2015).

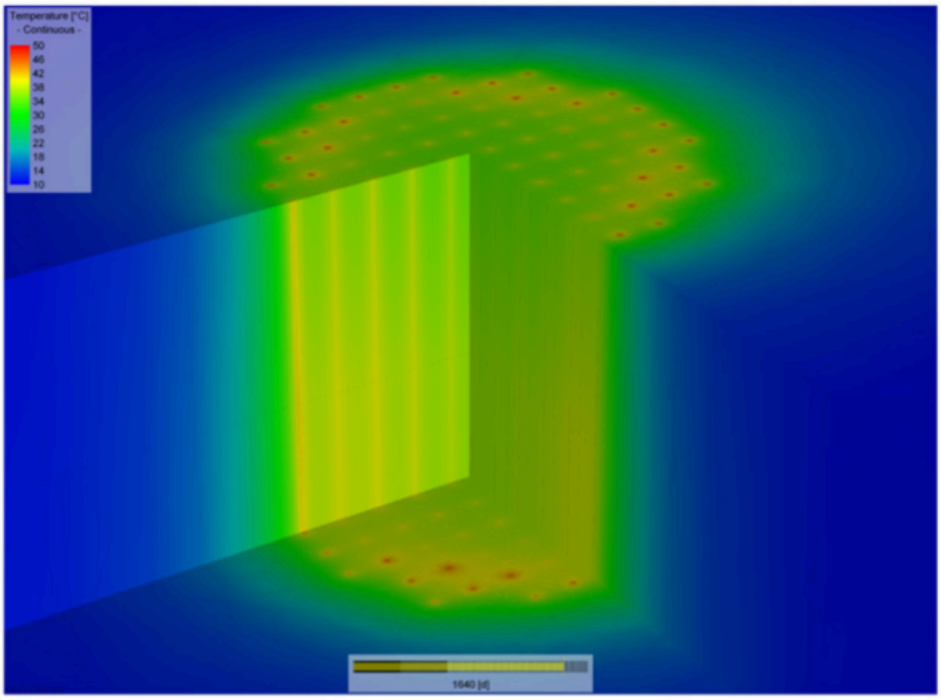


Figure 3.4 – BTES hydrogeological simulation with FEFLOW (modified from Diersch et al., 2011).

<u>T2.4 – Dynamic modelling of the BTES</u>

Dynamic modelling is a powerful tool to predict the time-varying behaviour of any complex dynamic system, e.g., HVAC, containing mechanical, electrical, hydraulic, and thermal components. A number of modelling languages, environments, libraries have been developed in the last 30 years to provide designers with tools with multi-engineering capabilities in order to simulate processes in multiple domains.

One of the most popular codes for dynamic transient modelling of energy systems is TRNSYS (Klein et al., 2017), a commercial modular environment written in Fortran and made of several components (Types) which are individually solved by single systems of equations and then coupled together to achieve the final outputs required by the user. The code has been widely adopted to simulate underground thermal energy storage systems in the last 20 years (e.g., Sibbit et al., 2012; Giordano and Raymond, 2019; Wang et al., 2024; **Figure 3.5**). Recently, the specific Type to model BHE has also been updated to account for groundwater flow (Antelmi et al., 2023) making TRNSYS a very efficient tool to simulate the synergy between the solar source and the subsurface.

An alternative option is Modelica, a freely available object-oriented, declarative, multi-domain modeling language for component-oriented modeling of complex systems (Olson, 2017). Free (e.g., OpenModelica) and commercial (e.g., Dymola) environments based on Modelica exists to build and run dynamic models for energy systems (e.g., Schweiger et al., 2017). Modelica has already been used to simulate BTES and a specific toolbox has been developed (e.g., Formhals et al., 2020; **Figure 3.6**). Comparisons between TRNSYS and Modelica have also been performed (Wetter and Haugstetter, 2006; Xu et al., 2021).

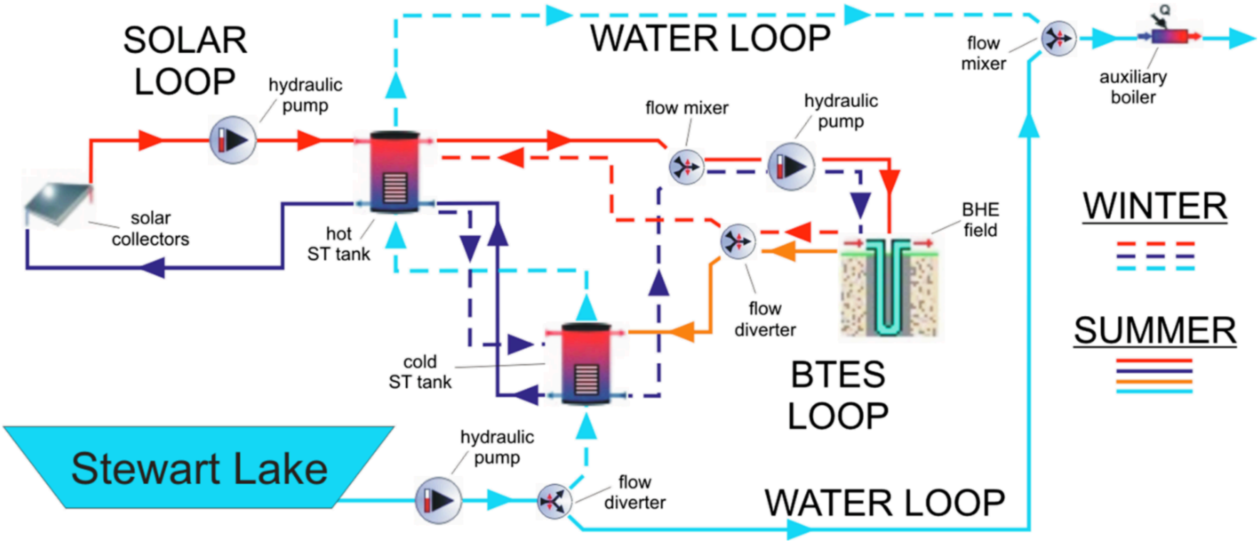


Figure 3.5 – BTES simulation with TRNSYS (modified from Giordano and Raymond, 2019).

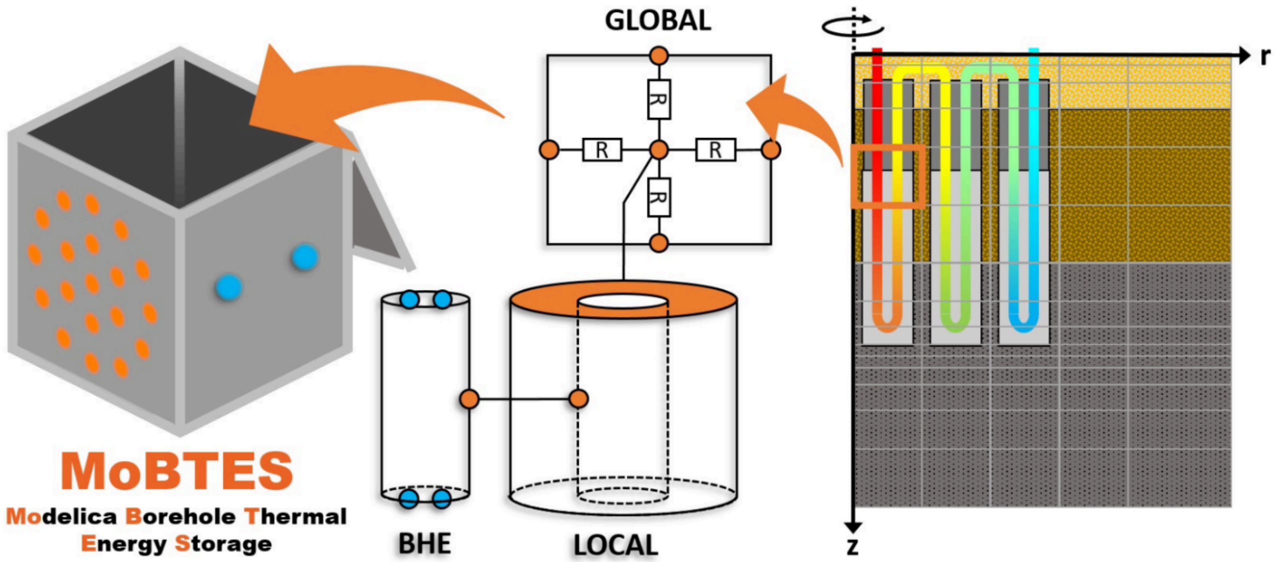


Figure 3.6 – BTES toolbox developed for dynamic modelling in Modelica (modified from Formhals et al., 2020).

T2.5 – Direct and geophysical monitoring

The operation of GSHP and BTES generates a thermal impact into the subsurface which is commonly known as thermally affected zone (Lo Russo et al., 2012; Comina et al., 2019). Modelling and monitoring the underground thermal behaviour of these systems is of paramount importance to evaluate both the overall system’s performance and its impact on the surrounding environment. Indeed, the induced temperature change in the subsurface can stimulate trace elements mobility, redox processes, and microbial activity variations. Since the concern for possible impacts on groundwater quality often led to the issuing of strict regulations for shallow geothermal systems (Hähnlein et al., 2013), care must be taken in providing proper monitoring as well as dissemination activities to inform the community and the policy makers about benefits and potential impacts (see **Section 4**).

Several research activities have been carried out in recent years to assess the impact of the operation of shallow geothermal systems on the groundwater chemical composition (Casasso et al., 2022). While no appraisable impact has been observed so far for conventional GSHP operating at temperature differences < 6°C (Casasso and Sethi, 2019), some subsurface alteration was observed in laboratory and field studies on UTES systems as a consequence of relevant temperature increase, such as the proliferation of pathogenic bacteria at temperatures around 30 – 40°C; the dissolution of organic carbon and metals (Fe, As, Ni, Cd, B) at temperatures above 40°C; the reduction of dissolved oxygen, pH, and moisture content (Bonte, 2013; Casasso et al., 2022; Sadeghi et al., 2024, and references therein). These impacts strongly depend on the pre-existing subsurface environment, hence, the results of the cited studies must not be generalized. Possible positive effects were also observed, such as the enhanced degradation of pollutants (e.g., chlorinated hydrocarbons), leading some researchers to consider ATES as a possible way to remediate contaminated sites (Zuurbier et al., 2013). So far, UTES has been proven to be safe. However, for further large-scale commercial use of this technology, broader studies should be considered regarding the geochemical alteration of groundwater, cross-contamination, and thermal impact of neighbouring systems in dense urban areas (Sadeghi et al., 2024).

While fluid temperature monitoring is a standard in both GSHP and BTES and only needs heat meters along the circuit, the spatial and temporal monitoring of the subsurface temperature evolution is more complex and expensive. Currently, it can be provided through two main approaches (**Figure 3.7**): a) direct monitoring with temperature sensor chains installed along boreholes (e.g., Sibbit et al., 2012; Giordano et al., 2016; Guo et al., 2020, and references therein) or with fiber optic distributed temperature sensing (e.g., Hermans et al., 2014; Ramstad et al., 2023); b) indirect monitoring via geophysical surveys, such as electrical resistivity tomography (ERT; Hermans et al., 2015; Giordano et al., 2017; Robert et al., 2019; **Figure 3.8**) and self-potentials (e.g., Ikard and Revil, 2014). ERT surveys have been thoroughly adopted as heat tracer technique due to the known inverse relationships existing between temperature and resistivity. A temperature increase of 1°C induces a decrease in resistivity of about 1.8 ÷ 2.5 % at 25°C (Giordano et al., 2017 and references therein).

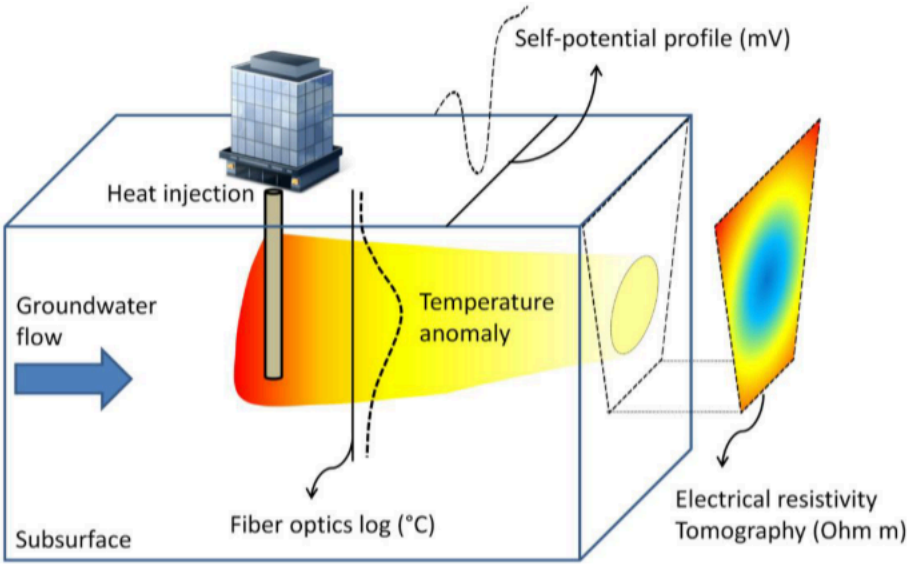


Figure 3.7 – Direct and indirect methods for subsurface thermal impact monitoring (modified from Hermans et al., 2014).

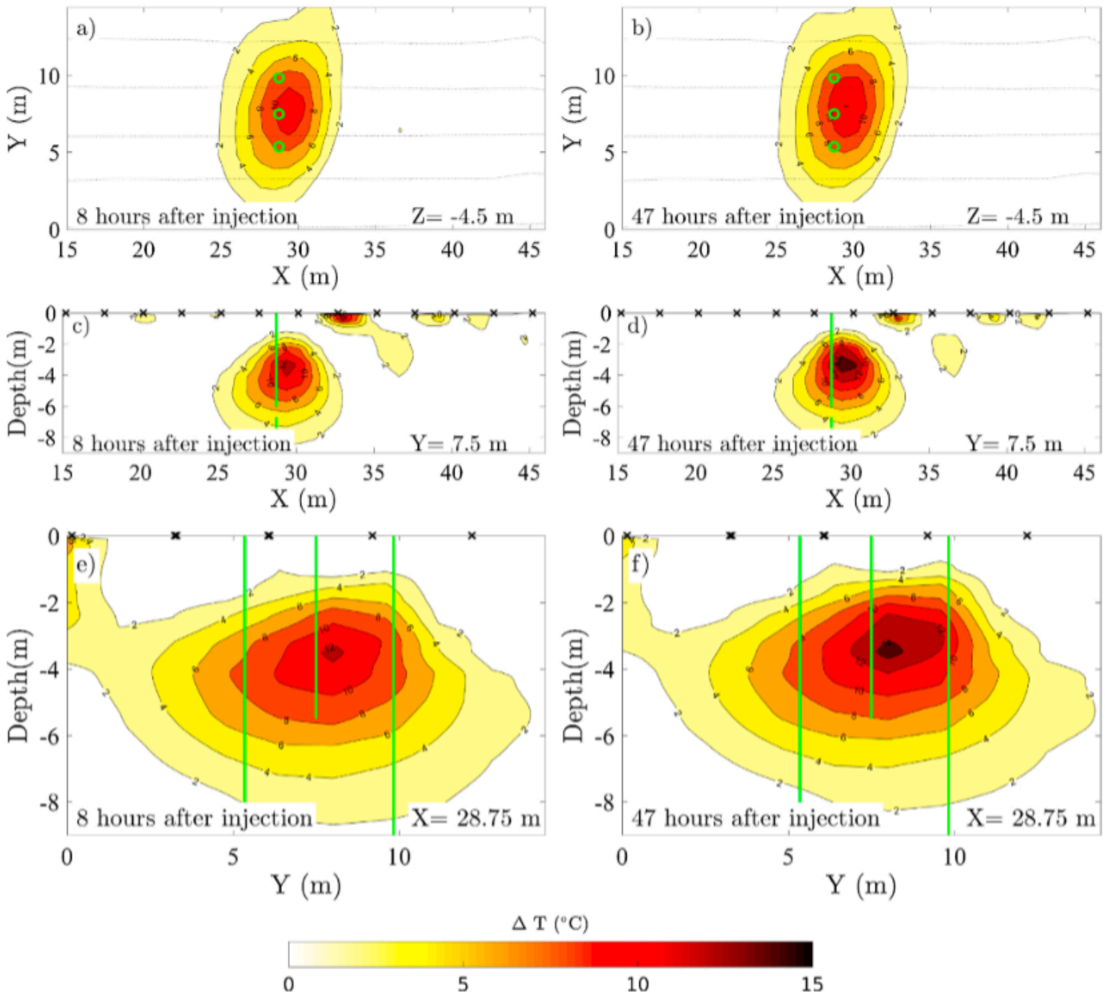


Figure 3.8 – Cross-hole ERT monitoring of ATES heat injection (modified from Lesparre et al., 2019)

Both approaches have strengths and flaws, and they mainly differ in temporal and spatial resolution, cost, complexity of installation and data analysis. Direct monitoring allows measuring reliable temperature values with very high temporal resolution (e.g., a few seconds). On the other hand, the spatial resolution is limited to tens of meters due to budget caps. Moreover, if temperature sensors are located within the BHEs, the recorded temperatures may be affected by the presence of the heat exchanger pipes and may not reflect the real ground temperatures (e.g., Comina et al., 2019). Geophysical investigations have better spatial resolution (a few meters) at a lower cost, and could image the variability of the thermal plume related to subsurface heterogeneity. However, temporal resolution is limited to days in case of in-person surveys, or a few hours in case of automatic remote acquisitions. Moreover, the geophysical inverse problem suffers from non-uniqueness and usually regularization is necessary for the convergence of the inversion procedure (Hermans et al., 2014; Comina et al., 2019). It is therefore important to couple these techniques in order to improve the global understanding of the subsoil physical variability and to validate the results with multiple monitoring strategies. Finally, these methods can feed numerical and dynamic models with real data allowing for calibration, validation, and enhanced prediction of the system's behaviour.

The ERT method consists of reconstructing the distribution of the real electrical resistivity of the subsurface by injecting electric current I [A] and measuring the potential difference ΔV [V] from a series of electrodes (typically 4, making a quadrupole, **Figure 3.9**) placed on the ground surface, in boreholes, or in vertically equipped electrode chains in contact with the ground (**Figure 3.10**). Electrical resistivity ρ is closely related to the chemical and physical characteristics of the medium, therefore ERT provides a very realistic and reliable subsurface section allowing for 2D or 3D interpretation. The physical principle on which electrical resistivity measurements are based is the Ohm's law, which governs the current flow in an ideal medium whose resistance R [Ohm] is given by:

$$R = \frac{\Delta V}{I} \quad [4]$$

Since field measurements are conducted on non-ideal (and therefore heterogeneous) media and the resistance varies in a 3D space, from I and ΔV the apparent resistivity ρ_a [Ohm·m] is calculated by multiplying the measured resistance R by a geometric factor k [m] that depends on the electrode configuration adopted:

$$\rho_a = k \frac{\Delta V}{I} \quad [5]$$

This apparent resistivity is a value that corresponds to the resistivity that a homogeneous volume would provide in the same electrode configuration.

Cross-hole ERT is performed by vertically translating the quadrupoles, changing the mutual distance among the electrodes (**Figure 3.10**). Therefore, information about lateral and vertical variations in resistivity can be obtained. The major advantage of cross-hole surveys is the maintenance of spatial resolution even at depth, which is only function of the distance between the electrodes. In contrast, it is not possible to increase the distance between equipped wells due to the loss of lateral resolution of the survey. Literature data indicate an optimal ratio between borehole spacing and borehole depth in the range of 0.2 to 0.5 (Labrecque et al., 1997; **Figure 3.10**).

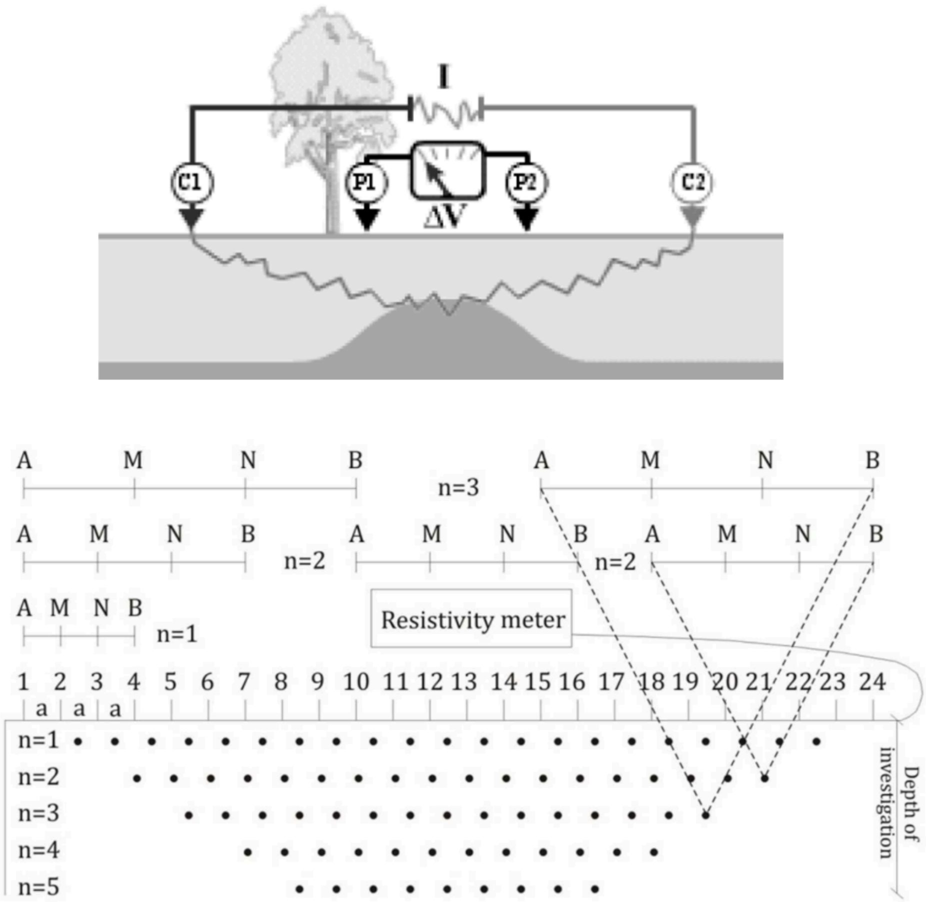


Figure 3.9 – Details about the ERT method and surface electrode configuration (modified from Giordano, 2015).

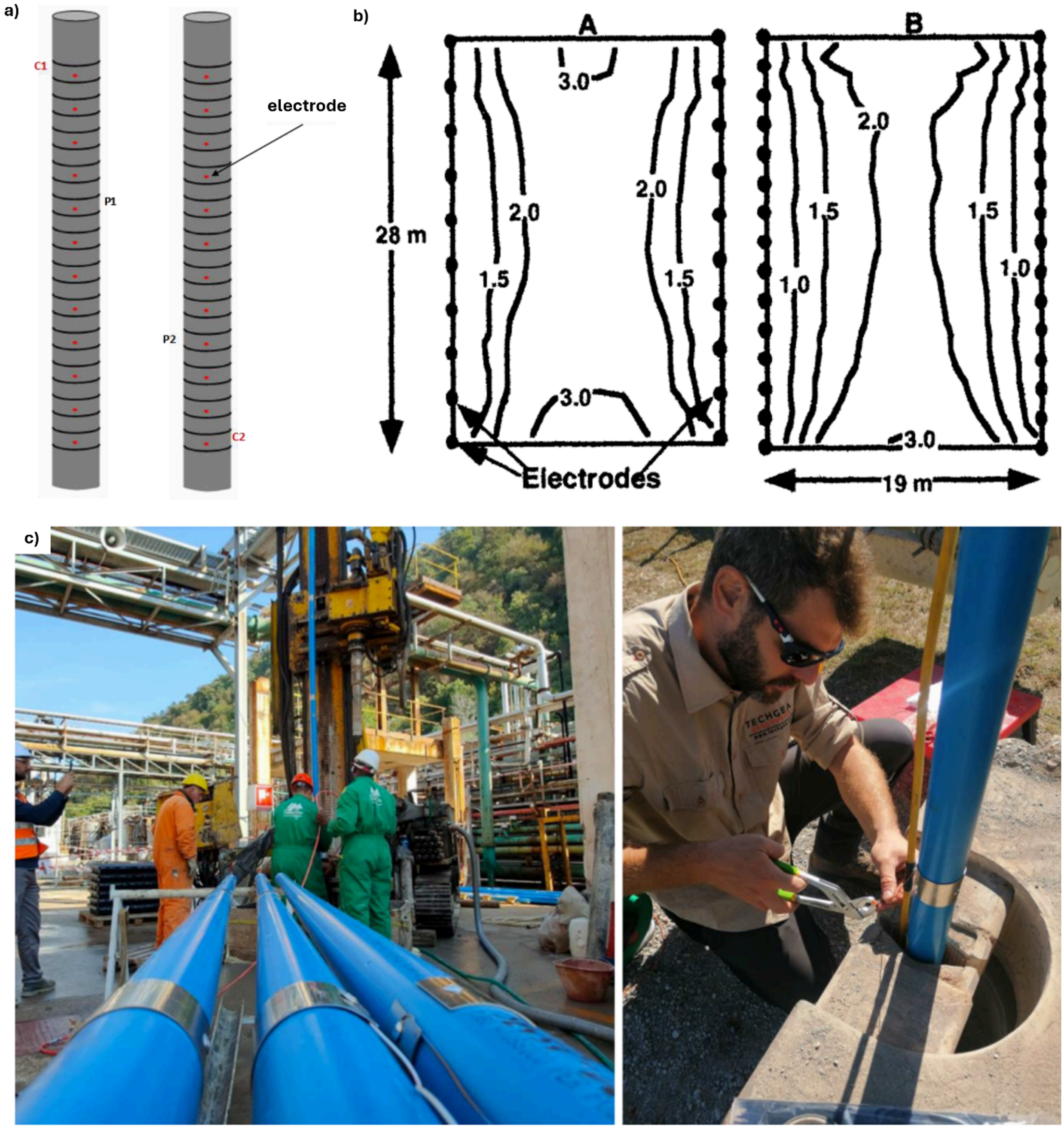


Figure 3.10 – Electrode layout in cross-hole ERT method (a) with details about vertical and lateral resolution in meters (b, modified from LaBrecque et al., 1997) and on-site installation (c, with permission from Techgea).

<u>T2.6 – Life-cycle cost analysis (LCCA)</u>

LCCA analysis allows to assess the cost or value of a plant by considering all the cash flows over a certain period of time, usually the system's lifetime (Lamarche, 2023). The analysis typically includes initial investment costs (CAPEX), operation costs (OPEX), periodic maintenance and replacement costs, interest costs due to banks or private parties, government subsidies, etc. Considering the timeframe of the analysis, usually 20-30 years, it is of paramount importance to consider potential inflation and the money discount rate, a value that indicates the potential interest that capital could generate if it were invested in financial markets instead of investing in the system (real economy).

The LCCA is an excellent tool for evaluating what type of plant to install in a building. For example, it is usually performed by considering 3-4 different scenarios of renewable energy systems compared to the business-as-usual (BAU) conventional case (e.g., gas-fired burners). The final result, expressed in today's currency, gives a fairly accurate idea (net of the uncertainty of the data) of which scenario is the most attractive over the timeframe considered, and thus which investment is the most cost-effective (e.g., Gunawan et al., 2020; **Figure 3.11**). The final result is the net present cost (NPC), expressed in € and given by:

$$NPC = I + \sum_{k=1}^{N} \sum_{j=1}^{M} \frac{C_{k,j}\,(1+i)^{k-1}}{(1+t)^{k}}$$

[6]

where *I* is the initial investment, *N* the timeframe in years, *k* the year of analysis, *M* the number of cash flows considered, *j* the cash flow, *C* the cost of the cash flow, *i* the inflation, *t* the discount rate of money. If NPC1 > NPC2, scenario 1 is less attractive than scenario 2 because it has a higher cost over the life cycle considered.

The levelized cost of energy (LCOE), also known in literature as levelized cost of heat (LCOH), is an additional way to rank alternative projects. Compared to the NPC method, LCOE considers both the total LCC and the total amount of energy produced. It indicates the minimum cost per unit of energy that will recover the lifetime costs of the system and is measured by dividing the NPC of the system by its total lifetime energy output, i.e., the lifetime accumulated annual energy output E_t of each scenario (e.g., Novelli et al., 2021; **Figures 3.12** and **3.13**). LCOE, expressed in €/kWh, is calculated as follows:

$$LCOE = \frac{NPC}{\sum_{k=1}^{N} E_{t,k}}$$

[7]

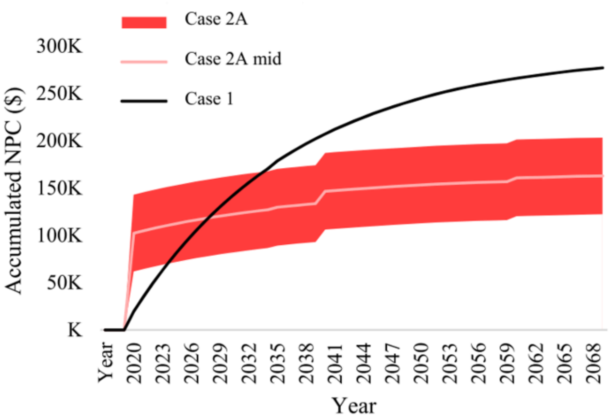


Figure 3.11 – NPC of two GSHP scenarios with different subsidies (red and green lines) compared to the conventional heating system (diesel, black line) in the Kuujjuaq Inuit community in North Québec (modified from Gunawan et al., 2020).

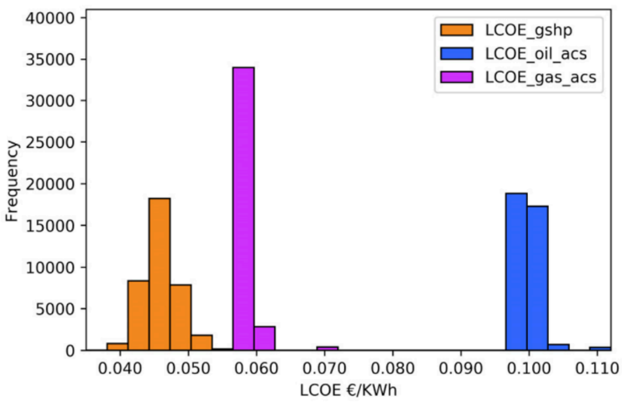


Figure 3.12 – LCOE of GSHP systems compared to oil-fired or gas-fired burners in Aosta Valley, with (left) and without (right) subsidies (modified from Novelli et al., 2021).

	Capital cost (USD)	Annual cost (USD)			Periodic cost		Total NPC (USD)	LCOE (USD kWh^{-1})
		Energy	Maintenance	CO_2	Cost (USD)	Parts replaced		
BAU	36 949	81 165	1000	2048	6977	oil tank	2 054 682	0.214
					29 957	oil furnace		
BTES 224	1 426 681	92 152		1767	3560	oil tank	3 419 089	0.357
					12 005	oil furnace		
					1877	hydraulic pumps		
					579 437	solar panels		
BTES 37	783 137				3560	oil tank	2 846 336	0.297
					12 005	oil furnace		
					1877	hydraulic pumps		
					579 437	solar panels		
BTES 224 Subsidised	750 836	63 195			3560	oil tank	2 326 917	0.243
					12 005	oil furnace		
					1877	hydraulic pumps		
					289 718	solar panels		
BTES 37 Subsidised	429 064				3560	oil tank	2 040 541	0.213
					12 005	oil furnace		
					1877	hydraulic pumps		
					289 718	solar panels		
BTES 37 PV Subsidised	429 064	62 719		1413	3560	oil tank	1 905 958	0.199
					12 005	oil furnace		
					1877	hydraulic pumps		
					289 718	solar panels		

Figure 3.13 – 50-years LCCA results of five BTES scenarios compared to BAU in the Kuujjuaq Inuit community in North Québec. Capital, annual, and periodic costs are reported together with NPC and LCOE (Giordano et al, 2019).

3.4 Partners

The proposed R&D activities can be carried out independently or through the collaboration with different partners and/or consultants. A number of research groups and private companies are listed hereafter based on their potential contribution to specific tasks of the project.

Research groups from Academia

Prof. Giuseppe Mandrone – Interuniversity Department of Regional and Urban Studies and Planning (DIST POLITO UNITO)

Professor Mandrone and his team are geologists mainly working on ground-source heat pumps, underground thermal energy storage systems, and 5th generation district heating systems. Their research activity spans from laboratory modelling of borehole heat exchangers to real case studies of BTES such as the living lab in Grugliasco (TO) developed in 2013 (Giordano et al., 2016). The group can contribute to T2.3, T2.5, and T2.7. Contacts giuseppe.mandrone@unito.it jessica.chicco@unito.it.

Prof. Cesare Comina – Department of Earth Science (DST UNITO)

Professor Comina and his team are geophysicists with significant experience in geophysical field and lab surveys. Their research activity is aimed at developing low-cost and efficient geophysical techniques in the domain of engineering geology, e.g., 4D electrical resistivity tomography (ERT) to monitor BTES. The group can contribute to T2.5. Contacts cesare.comina@unito.it.

Prof. Alessandro Casasso – Department of Environment, Land and Infrastructure Engineering (DIATI POLITO)

Professor Casasso and his team are groundwater engineers working on ground-water and ground-coupled heat pumps. Their research activity focuses on numerical simulations, subsurface monitoring, dynamic modelling, and life-cycle cost analysis from single-dwelling to district and regional case studies. The group can contribute to T2.3, T2.4, T2.5, T2.6, and T2.7. Contacts alessandro.casasso@polito.it.

Prof. Federico Vagnon – Department of Environment, Land and Infrastructure Engineering (DIATI POLITO)

Professor Vagnon and his team are geologists and environmental engineers working on ground-water and ground-coupled heat pumps mainly focusing on subsurface monitoring and dynamic modelling. The group can contribute to T2.3 and T2.7. Contacts federico.vagnon@polito.it.

Private companies

Geonovis srl (geonovis)

Geonovis is a national leader in designing and installing ground-source heat pumps as well as providing life-time system assistance. Geonovis designed and installed the conventional GSHP and UTES in Valle Vento and can keep providing services within tasks of WP1 and T2.1, T2.2, T2.6, T2.7, and T2.8. Contacts Ing. Simone Pronsati spronsati@geonovis.com.

EQ Ingegneria (eqingegneria)

EQ Ingegneria is an engineering firm mainly focused on driving energy efficiency and providing energy management consulting. The firm conceived and designed the UNITO BTES living lab in Grugliasco (TO) together with Prof. Mandrone’s team. EQ Ingegneria can provide services within tasks of T1.4, T2.4, and T2.7. Contacts Ing. Andrea Cagni info@eqingegneria.it.

Techgea srl (techgea)

Techgea is a service company specialized in non-invasive methods for the exploration of the subsoil and the non-destructive diagnostics of structures and civil engineering works. With decennial experience in this field, Techgea geologists and engineers successfully designed and installed borehole electrodes for cross-hole ERT and 4D time-lapse ERT within contaminated sites. Techgea can be provide services within T1.2 and T2.5. Contacts naldi@techgea.eu arato@techgea.eu.

All the listed groups from both academia and industry can also be part of the targeted stakeholders for exploitation activities included in the impact strategy (**Section 4**).

4. Impact strategy

The long-term impact strategy is a crucial element to ensure the success of a project. In particular, dissemination, exploitation, communication, and capacity building measures can be deployed in order to raise awareness on the BTES technology and highlight its benefits within the energetic transition. To support the impact strategy, a dissemination (D) tool has been produced in the form of a worksheet that can be used to coordinate all the activities. The Dtool (**Annex 3**) aims at planning, controlling, and documenting the overall impact strategy of the project and it is structured in several sheets dealing with: objectives (1), stakeholder mapping (2), communication messages to deliver (3), channels (4), and a draft plan of the foreseen activities (5). The tool, which took inspiration from the ongoing European project SAPHEA (saphea.eu), is intended to be a dynamic instrument that need to be updated little by little as the project progresses. The specific sections of the worksheet are described in details hereafter.

4.1 Objectives

The principal objectives of the impact strategy are highlighted as follows:

- Inform about the project in order to make BTES more visible in the society and raise the awareness on its benefits;
- Providing knowledge transfer by disseminating results, findings, lessons learned to stimulate follow-up activities;
- Train professionals, regulators, and decision-makers to BTES design, operation and maintenance, monitoring;
- Engage stakeholders to exploit the experimental site by fostering cooperation.

These goals can be achieved by several activities and channels of communication, dissemination, exploitation, engagement, capacity building according to the targeted stakeholders. These objectives can also be implemented, improved, re-focused as the project moves forward.

4.2 Stakeholder mapping

Stakeholders of the project are grouped into 6 different categories and defined as local (LS) or international (IS) depending on their geographical area of relevance and jurisdiction:

- Public administrations/entities defined as decision-makers, regulators, authorities devoted to policy making, regulating and controlling. Communication and knowledge-transfer activities to this stakeholder are crucial to foster a widespread dissemination of the technology by removing in advance obstacles and barriers within the regulatory framework;

- Private citizens and their associations devoted to environmental protection are critical stakeholders who need proper and targeted communication activities such that the technology is well understood and a widespread support is guaranteed. Having them on the boat is a strategic element to make it a win-win approach;
- Renewable Energy Communities (CER in Italian) and the whole environment around these entities, recently regulated by the Italian law following European directives. CER are regulated only for electricity and very little has been said about space heating and cooling. Therefore involving them in the loop of the dissemination activities can be highly profitable considering that storage is a key element of the energetic transition and BTES technology can be an option for both electrical and thermal energy;
- Professionals, designers, installers with their associations, networks and consortiums act both as adopters and multipliers of the technology. Farmers and agribusinesses can choose to implement BTES in their agricultural processes or facilities. Trained designers and installers can spread the technology within their business;
- Research and academia entities are strategic partners to engage for fostering cooperation in the years to come. Italian universities and research centres in particular lack of fundings to implement experimental facilities to do fieldwork, educate/train students, do research activities, participate to European projects. Engage them by offering an open living laboratory to develop, test, and validate several different technologies and ideas related to BTES can boost the impact of the VV project, provide high visibility and long-term durability;
- Funding agencies who contribute by both financing projects and incentivizing the society to use certain technologies based on long-term political views. This stakeholder group acts as a multiplier since the technology must be known, tested, and demonstrated to be of no-harm to the environment and the society in order to be incentivized together with other renewable energy systems. Therefore, funding agencies need to be targeted by knowledge-transfer activities.

Finally, a total of 28 stakeholders have been mapped, and a detailed list of them with general info and contacts is included in the tool.

4.3 Communication messages

All dissemination, exploitation, communication activities revolve around key messages that the project developers want to communicate to the defined stakeholders. A few important messages have been created and are described in details in the following, but more can be generated in order to strengthen the impact strategy and the success of the project.

- Storing solar heat into the subsurface via BTES technology is a market-ready and low-environmental-impact solution for reducing energy consumption and increasing sustainability. This message is mainly intended for LS1, LS2, LS3, and LS4 groups;
- Storage is a key element in the energetic transition due to non-programmable renewable sources such as solar and wind. BTES is an effective solution to foster the synergy among different renewable sources and benefit CER. This message is mainly intended for LS2, LS3, LS4, and LS6 groups;
- BTES is part of the shallow geothermal energy technologies, however its design is different from conventional GSHP. Crucial elements needs to be known to correctly design the subsurface storage volume in order to increase the heat recovery and optimize the overall performance of the system. This message is mainly intended for LS1, LS4, and IS1 groups;
- The VV project aims at being a living laboratory for BTES systems, open to anyone (students, researchers, professionals, private companies, public entities, citizens…) who wants to visit, be informed, do research activities, and use the facilities with the purpose of cooperating altogether to spread the technology. This message is intended for all stakeholders, but in particular for groups LS1, LS4, LS5, IS1, and IS2.

4.4 Channels

The key messages can be delivered to the stakeholders via several means and ways which have to be chosen according to the targeted group. Certain channels perfectly work for some stakeholders, while not necessarily suit for others. Several examples have been proposed in the tool (see “categories” sheet). A few channels thought to be particularly successful for the present project are listed in the following with an indication of preferential stakeholder categories to be addressed to.

- A project website, while being quite old, is still a fair channel to deliver several messages to a number of different stakeholders;
- Social media profiles are powerful means to deliver messages and keep followers up-to-date about the progress of the project and publish upcoming events. However, multiple profiles are needed to reach out a wider number of people since certain social media are targeted to specific categories of populations (e.g., Facebook for 40-60 years-old people; Instagram for

25-45 y.o.; X for 30-60 y.o.; TikTok for 15-25 y.o.; Linkedin for professionals, designers, installers, etc.);

- Public events, either onsite or somewhere else, are efficient means of communication, dissemination, capacity building, and exploitation for all categories. However, individual events have to be planned in order to focus the messages to a specific target. For example LS2 and LS3 can participate to the same event, as well as LS4 and LS5. Instead, an event grouping together LS2 and LS5 would probably not be as successful;
- Webinars are short (half-a-day maximum) public events held on the internet and are particularly efficient, direct, and require a relatively low effort from both the actors and the public. As for public events, but more importantly here given the short-time, individual focused webinars must be organized with specific messages to deliver to targeted groups. LS1, LS4, LS5, LS6 are stakeholder groups particularly prone to this kind of communication channel;
- Trainings, focus groups, and workshops are in-person or online events of maximum one or two days particularly fit for training professionals, designers, and installers (LS4) or discuss and confront each other about a topic (LS1, LS3). Online professional courses deployed to designers and installers (LS4) also fall into this type of channel (e.g., Geocorsi, Beta Formazione etc.);
- Townhall meetings and science cafés are dissemination events specifically targeted for LS2 and LS3. In these occasions, designers and researchers meet the civil society to explain in simple words the objectives of the project and the features of the technology. Science cafés have become pretty popular around the world for dissemination activities to the citizenship (e.g., a pint of science);
- Technical and scientific reports and papers are long-lasting means of communication and dissemination to LS1, LS4, LS5, and LS6. Reports/papers can keep track of the progress of the project, contain a lot of information, results, lessons-learned, and can be referred to even after a number of years. Although needing an important effort to be published, these are fruitful means to ensure the long-term impact of the project and to strengthen collaboration and cooperation with stakeholders of groups LS4 and LS5.

5. Conclusions

The present document is the final report about the underground thermal energy storage system installed in Valle Vento. The study was conducted to fulfil the Client's objectives, which are: the technical description of the system, the quantification of the expected performance, and recommendations for improvement and optimisation of the storage volume, given in **Section 2**; a proposal for future research and developments activities to be carried out, as well as academic and private partners to collaborate with, proposed in **Section 3**; and the definition of an impact strategy to ensure the success of the project, described in **Section 4**.

Limitations of the study mainly pertain to the quantification of the expected performance of the existing BTES as well as the optimized proposed scenarios. Calculations here performed are based on simplified analytical models valid for a single BHE, do not reflect the real subsurface behaviour, and should only be considered for qualitative considerations. More detailed analyses would only be possible via 3D hydrogeological numerical modelling of the subsurface or via dynamic modelling of the entire BTES system (solar collectors + STS + BTES volume), which are not the purpose of the present document as agreed with the Client. This kind of analysis is however crucial to predict the BTES operation and is highly suggested in order to make a final custom design.

Cuneo, 19th March 2025

Geol. Nicolò Giordano

References

- AFPG (2020) – "La boucle d'eau tempérée à énergie géothermique – Les guides techniques AFPG", Association Française des Professionnels en Géothermie, 80 p.
- Antelmi M., Turrin F., Zille A., Fedrizzi R. (2023) - "A new type in TRNSYS 18 for simulation of borehole heat exchangers affected by different groundwater flow velocities". Energies, 16(3), 1288.
- Barbieri S., Antelmi M., Panday S., Baratto M., Angelotti A., Alberti, L. (2022) – "Innovative numerical procedure for simulating borehole heat exchangers operation and interpreting thermal response test through MODFLOW-USG code". Journal of Hydrology, 614, 128556.
- Bonte M. (2013) – "Impacts of shallow geothermal energy on groundwater quality: A Hydrochemical and Geomicrobial Study of the Effects of Ground Source Heat Pumps and Aquifer Thermal Energy Storage". Ph.D. Thesis, Vrije Universiteit, Amsterdam, The Netherlands.
- Casasso A., Giordano N., Bianco C., Sethi R. (2022) – "UTES-underground thermal energy storage". In Encyclopedia of Energy Storage (Vol. 1, pp. 382-393). Elsevier Science Ltd.
- Catolico N., Ge S., McCartney J.S. (2016) – "Numerical modeling of a soil-borehole thermal energy storage system". Vadose Zone Journal, 15(1), 1-17, https://doi.org/10.2136/vzj2015.05.0078.
- Comina C., Giordano N., Ghidone G., Fischanger F. (2019) – "Time-lapse 3d electric tomography for short-time monitoring of an experimental heat storage system". Geosciences, 9(4), 167.
- CTI (2024) - https://try.cti2000.it/page.php?id=1 (accessed in October 2024).
- Dal Verme M., Lipari D., Liberatore P. (2022) – "Teleriscaldamento e teleraffrescamento 2020. Diffusione delle reti ed energia fornita in Italia – Nota di approfondimento Giugno 2020". Gestore dei servizi energetici (GSE), 56 p.
- Dalla Santa G., Galgaro A., Sassi R., Cultrera M., Scotton P., Mueller J., ... & Bernardi A. (2020) – "An updated ground thermal properties database for GSHP applications". Geothermics, 85: 101758.
- D'Atri A., Irace A., Piana F., Tallone S., Varrone D., Bellino D., Fioraso G., Cadoppi P., Fusetti E., Morelli M., Lanteri L., Paro L., Piccini C., Trenkwalder S., Violanti D. (2014) - "Carta Geologica e Note illustrative della Carta Geologica d'Italia alla scala 1: 50 000, Foglio 194 Acqui Terme", Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA), 1-229.
- Diersch H.-J.G., Bauer D., Heidemann W., Ruhaak W., Schatzl P. (2011) - "Finite element modeling of borehole heat exchanger systems Part 2. Numerical simulation". Computers and Geosciences, 37:1136–47. https://doi.org/10. 1016/j.cageo.2010 .08.002.
- EGEC (2024) - Geothermal market report 2023.
- European Commission. Commission Recommendation of 14 March 2023 on Energy Storage – Underpinning a decarbonised and secure EU energy system 2023/C 103/01 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.C_ .2023.103.01.0001.01.ENG&toc=OJ%3AC%3A2023%3A103%3AFULL
- Forman C., Muritala I.K., Pardemann R., Meyer B. (2016) – "Estimating the global waste heat potential". Renewable and Sustainable Energy Reviews 57: 1568 – 1579. https://doi.org/10.1016/j.rser.2015.12.192.

- Formhals J., Hemmatabady H., Welsch B., Schulte D.O., Sass I. (2020) – “A Modelica Toolbox for the Simulation of Borehole Thermal Energy Storage Systems”. Energies, 13(9), 2327. https://doi.org/10.3390/en13092327.
- Giordano N. (2015) – “Ground Thermal Energy Storage: analogical and numerical modeling coupled with geophysical monitoring from laboratory to field scale”. PhD thesis, University of Torino, 236 pp. (https://doi.org/10.13140/2.1.3671.5843).
- Giordano N., Comina C., Mandrone G., Cagni A. (2016) – “Borehole thermal energy storage (BTES). First results from the injection phase of a living lab in Torino (NW Italy)”. Renewable Energy, 86, 993–1008.
- Giordano N., Arato A., Comina C., Mandrone G. (2017) – “Time-lapse electrical resistivity imaging of the thermally affected zone of a Borehole Thermal Energy Storage system near Torino (Northern Italy)”. Journal of Applied Geophysics, 140, 123–134.
- Gunawan E., Giordano N., Jensson P., Newson J., Raymond J. (2020) – “Alternative heating systems for northern remote communities: Techno-economic analysis of ground-coupled heat pumps in Kuujjuaq, Nunavik, Canada”. Renewable Energy, 147, 1540-1553.
- Guo Y., Zhao J., Liu W.V. (2024) – “Effects of varying heat transfer rates for borehole heat exchangers in layered subsurface with groundwater flow”. Applied Thermal Engineering, 247, 123007.
- Guo F., Zhu X., Zhang J., Yang X. (2020) – “Large-scale living laboratory of seasonal borehole thermal energy storage system for urban district heating”. Applied Energy, 264, 114763.
- Hähnlein S., Bayer P., Ferguson G., Blum P. (2013) – “Sustainability and policy for the thermal use of shallow geothermal energy”. Energy Policy 59, 914 – 925. https://doi.org/10.1016/j.enpol.2013.04.040.
- Hellström G., Sanner B. (1994) - “Software for dimensioning of deep boreholes for heat extraction”. Proceedings Calorstock, 94, 195-202.
- Hermans T., Nguyen F., Tanguy R., Revil A. (2014) – “Geophysical Methods for Monitoring Temperature Changes in Shallow Low Enthalpy Geothermal Systems”. Energies, 7, 5083–5118.
- Hermans T., Wildemeersch S., Jamin P., Orban P., Brouyère S., Dassargues A., Nguyen F. (2015) – “Quantitative temperature monitoring of a heat tracing experiment using cross-borehole ERT”. Geothermics, 53, 14–26.
- Hesaraki A., Holmberg S., Haghighat F. (2015) – “Seasonal thermal energy storage with heat pumps and low temperatures in building projects — A comparative review”. Renewable and Sustainable Energy Reviews 43, 1199 – 1213. https://doi.org/10.1016/j.rser.2014.12.002.
- Ikard S.J., Revil A. (2014) – “Self-potential monitoring of a thermal pulse advecting through a preferential flow path”. Journal of Hydrolgy, 519, 34–49.
- IRENA (2020) – “Innovation outlook: Thermal energy storage”. ISBN: 978-92-9260-279-6.
- Kavanaugh S., Rafferty K. (2014) – “Geothermal heating and cooling: design of ground-source heat pump systems”. ASHRAE, Atlanta, GA, USA, 442 pp.
- Klein S.A., Beckman W.A., Mitchell J.W., Duffie J.A., Duffie N.A., Freeman T.L., et al. (2017) – “TRNSYS 18: A Transient System Simulation Program”.
- LaBrecque D.J., Morelli G., Lundegard P. (1997) – “Effective electrical resistivity tomography surveys for environmental monitoring”. In Symposium on the Application of Geophysics to Engineering and Environmental Problems, pp. 881-887, Society of Exploration Geophysicists.

- Lamarche L. (2023) - "Fundamentals of geothermal heat pump systems: Design and application". Springer, 295 pp. https://doi.org/10.1007/978-3-031-32176-4.
- Lee K.S. (2013) – "Underground thermal energy storage". In: Green Energy and Technology. London; New York: Springer.
- Lesparre N., Robert T., Nguyen F., Boyle A., Hermans T. (2019) – "4D electrical resistivity tomography (ERT) for aquifer thermal energy storage monitoring". Geothermics, 77, 368–382.
- Lo Russo S., Taddia G., Verda V. (2012) – "Development of the thermally affected zone (TAZ) around a groundwater heat pump (GWHP) system: A sensitivity analysis". Geothermics, 43, 66–74.
- Nilsson E., Rohdin P. (2019) – "Performance evaluation of an industrial borehole thermal energy storage (BTES) project – Experiences from the first seven years of operation". Renewable Energy, 143, 1022 – 1034. https://doi.org/10.1016/j.renene .2019.05.020.
- Novelli A., D'Alonzo V., Pezzutto S., Poggio R.A.E., Casasso A., Zambelli P. (2021) – "A spatially-explicit economic and financial assessment of closed-loop ground-source geothermal heat pumps: A case study for the residential buildings of Valle d'Aosta region". Sustainability, 13(22), 12516.
- Olsson H. (2017) – "Modelica—A unified object-oriented language for physical systems modeling", Modelica Association. https://www.modelica.org/documents/ ModelicaSpec34.pdf (accessed in December 2024).
- Piana F., Fioraso G., Irace A., Mosca P., D'Atri A., Barale L., Falletti P., Monegato G., Morelli M., Tallone S., Vigna G.B. (2017) – "Geology of Piemonte region (NW Italy, Alps-Apennines interference zone)". Journal of Maps, 13(2), 395–405. https://doi.org/10.1080/174456472017.1316218
- Ramstad R.K., Justo Alonso M., Acuña J., Andersson O., Stokuca M., Håkansson N., ... & Rydell L. (2023) – "The borehole thermal energy storage at Emmaboda, Sweden: First distributed temperature measurements". Science and Technology for the Built Environment, 29(2), 146-162.
- Rapantova N., Pospisil P., Koziorek J., Vojcinak P., Grycz D., Rozehnal Z. (2016) –"Optimisation of experimental operation of borehole thermal energy storage". Applied Energy, 181, 464–476.
- Robert T., Paulus C., Bolly P-Y., Koo Seen Lin E., Hermans T. (2019) – "Heat as a Proxy to Image Dynamic Processes with 4D Electrical Resistivity Tomography". Geosciences, 9(10), 414. https://doi.org/10.3390/geosciences9100414.
- Sadeghi H., Jalali R., Singh R.M. (2024) – "A review of borehole thermal energy storage and its integration into district heating systems". Renewable and Sustainable Energy Reviews, 192, 114236.
- Schweiger G., Larsson P.O., Magnusson F., Lauenburg P., Velut S. (2017) - "District heating and cooling systems—Framework for Modelica-based simulation and dynamic optimization". Energy, 137, 566–578.
- Skarphagen H., Banks D., Frengstad B.S., Gether H. (2019) – "Design Considerations for Borehole Thermal Energy Storage (BTES): A Review with Emphasis on Convective Heat Transfer". Geofluids, 1–26. https://doi:10.1155/2019/4961781.
- Sibbitt B., Mcclenahan D., Djebbar R., Thornton J., Wong B. (2012) – "The performance of a high solar fraction seasonal storage district heating system – five years of operation". Energy Procedia, 30, 856–65. https://doi:10.1016/j.egypro. 2012.11.097.

- Spitler J.D. (2000) - “GLHEPRO - A design tool for commercial building ground loop heat exchangers”. Proceedings of the fourth International Heat Pumps in Cold Climates Conference, Aylmer, Québec, August 17-18, 16 pp.
- Wang X., Zhang H., Cui L., Wang J., Lee C., Zhu X., Dong Y. (2024) – “Borehole thermal energy storage for building heating application: A review”. Renewable and Sustainable Energy Reviews, 203, 114772.
- Wetter M., Haugstetter C. (2006) – “Modelica versus TRNSYS—A Comparison between an equation-based and a procedural modeling language for building energy simulation”. Proceedings of SimBuild, 2, 262–269.
- Woessner W.W., Poeter E.P. (2020) – “Hydrogeologic Properties of Earth Materials and Principles of Groundwater Flow”. The Groundwater Project, Guelph, Ontario, Canada.
- Xu L., Guo F., Hoes P.J., Yang X., Hensen J.L. (2021) – “Investigating energy performance of large-scale seasonal storage in the district heating system of chifeng city: Measurements and model-based analysis of operation strategies”. Energy and Buildings, 247, 111113.
- Zuurbier K.G., Hartog N., Valstar J., Post V.E.A., van Breukelen B.M. (2013) – “The impact of low-temperature seasonal aquifer thermal energy storage (SATES) systems on chlorinated solvent contaminated groundwater: Modeling of spreading and degradation”. Journal of Contaminant Hydrology 147, 1-13. https://doi.org/ 10.1016/j.jconhyd.2013.01.002