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Shallow geothermal potential with borehole heat exchangers (BHEs): three case studies in the Alps

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ABSTRACT

In view of increasing the number of shallow geothermal installations, the assessment and mapping of shallow geothermal potential can contribute to identify the most suitable areas for each technology (closed/open loop). In the framework of the Interreg project GRETA, a study of geological and geothermal characteristics in three alpine pilot areas was carried out, namely Aosta Valley (Italy), Parc Naturel des Bauges (France) and municipality of Cerkno (Slovenia), with the aim of defining the geothermal potential for closed-loop systems (borehole heat exchangers or BHEs). Previous studies on closed-loop shallow geothermal potential assessment have identified two main key parameters: thermal conductivity and undisturbed temperature of the ground. In particular, the greatest challenge is the identification of lithologies in different scales in order to assign thermal property values correctly. While the Aosta valley is characterized by metamorphic rocks with some granite, the studied areas of Cerkno and Parc des Bauges predominantly consist of sedimentary rocks with rapid changes in geological units (sequences) and, consequently, various geothermal properties of rocks. Thermal conductivity (TC) of rock samples was determined with laboratory measurements using the thermal conductivity scanning (TCS) method. The mean values of TC range from 2.8 to 4.0 W/(m·K) for rocks from the Aosta Valley, from 2.4 to 3.5 W/(m·K) (with one exception of 1.3 W/(m·K)) for sedimentary rocks from Parc des Bauges, and in a range of 1.8 to 5.6 W/(m·K) for the rocks from the Cerkno area. With this input, the shallow geothermal potential – i.e. the annual amount of energy sustainably exchangeable with the ground by a single borehole - was determined using the G.POT method for a standard 100 m deep BHE. The G.POT method is based on the fitting of analytical ground heat transport equations and can account for several input parameters: thermal properties of the ground, plant characteristics and usage profile (BHE length, threshold temperature of the heat carrier fluid, duration of the heating/cooling season, and simulated lifetime). Worth to note, the G.POT method allowed to correctly take into account the ground temperature, which strongly varies in the wide elevation ranges characterizing all the three case studies analysed. The resulting maps show that spatial distributed potential for Cerkno ranges from 8 to 15 MWh/y for a 100 m long BHE; for the Aosta Valley from 5 to 17 MWh/y, with over 70% of the mapped territory exceeding 10 MWh/y; for Parc des Bauges, the potential ranges from 5.5 to 15 MWh/y, with the lowest values (<7 MWh/y) determined over alluvial deposits in the two southernmost municipalities.

1. INTRODUCTION

The ground-source heat pump (GSHP) technology is widely recognized as one of the more efficient and cost-effective solutions for heating, cooling and DHW production. Although their use is growing steadily (Sanner, 2019), GSHPs still represent a marginal sector of renewable heat sources (Bayer et al., 2012). In order to promote this sustainable energy source, the 3-year project GRETA (near-surface **G**eothermal **Re**sources in the **T**erritory of the **A**lpine space) was developed by the Technical University of Munich (TUM) with GEOZS, Politecnico di Torino, BRGM, ARPA Valle d'Aosta and 7 other partners from the Alpine countries (Germany, Italy, France, Austria, Slovenia and Switzerland). The project was funded by the EU INTERREG Alpine Space programme and ended in December 2018. The main project aim was to overcome some of the main barriers to the diffusion of GSHPs focusing on the following issues (Casasso et al., 2017a): 1) the simplification of existing regulation and authorisation procedures, based on best practices identified among existing ones (Prestor et al., 2016); 2) addressing design and technical issues of different shallow geothermal techniques with a focus on specific Alpine conditions (Bottig et al., 2016; 2017); 3) assessing the geothermal potential and the possible underground interferences with the installation of borehole heat exchangers (BHEs) and wells; 4) developing tools to include shallow geothermal energy in local energy plans of three pilot areas, i.e. Oberallgäu (Germany), Cerkno (Slovenia) and Aosta Valley (Italy); 5) developing an interaction and knowledge exchange network with stakeholders. The previously reported points are represented by thematic work packages of the project and, in particular, this paper presents activities carried out in the WPT3 led by Politecnico di Torino.

Closed-loop BHE is the most adopted technique for shallow geothermal systems since, contrary to open-loop system, they do not require the presence of a productive aquifer. Their economic viability depends on ability of the ground to exchange heat, which is defined in different ways as the near-surface (or shallow) geothermal potential. The geothermal potential depends on the building thermal demand (energy demand profiles and peak power demand) and site-specific thermophysical characteristics of the underground (thermal conductivity and capacity). Groundwater advection also improves the performance of BHEs, yet it is difficult to evaluate and hence it is generally not considered in geothermal potential evaluation. The importance of shallow geothermal potential has been much acknowledged in the past decade, and several projects have been funded consequently. Among them are worth to be mentioned the maps for Europe (ThermoMap Project (Bertermann et al., 2015)), the southern Italy (VIGOR project (Galgaro et al., 2015)), the Province of Cuneo in the north of Italy (Casasso and Sethi, 2017), the south-western Germany (Ondreka et al., 2007), and the city of Barcelona in Spain (García-Gil et al., 2015). For the mapping of closed-loop NSGE potential, both Ondreka et al. (2007) and Gemelli et al (2011) applied the VDI 4640 method (VDI, 2000, 2001), in south-western Germany and in the Marche region (Central Italy), respectively. The application of VDI 4640 has a major limitation: the undisturbed ground temperature is not considered, thus providing the same specific heat extraction value for a warm ground in the plain (e.g., at 14 °C) and a cold ground in the mountains (e.g., 8 °C). Such a limitation is overcome by the MIS 3005 method (DECC, 2011; Curtis et al., 2013), prepared by the Dept. of Energy and Climate Change of UK, which takes into account the duration of the heating cycle (with a wider choice compared to VDI 4640), thermal conductivity and soil temperature. MIS 3005 tables are therefore more flexible and usable in wider pilot areas (Casasso et al., 2018), yet they do not provide an explicit formula for estimating the shallow geothermal potential.

As part of work within the GRETA project, in this paper we present the assessment of closed-loop geothermal potential as the average thermal load that can be efficiently exchanged with a BHE. The G.POT method was used to assess the near-surface geothermal potential and its applications in the three Alpine pilot area environments: in the Cerkno municipality (Slovenia), in the Aosta Valley region (Italy) and in Parc Naturel des Bauges (France). The open-loop systems are not discussed here, but also this potential was assessed as shown in Böttcher et al. (2019). The paper is structured as follows: Section 2 presents methods for determining the shallow geothermal potential and its input data, focusing on ground thermal properties (thermal conductivity and capacity, undisturbed ground temperature) as well as the usage profile (length of the heating season); Section 3 presents the resulting spatial distributions of the shallow geothermal potential in the pilot areas of Valle d'Aosta, Cerkno and Parc des Bauges; Section 4 discusses and compares these results; and conclusions are reported in Section 5.

2. METHOD FOR DETERMINING THE SHALLOW GEOTHERMAL POTENTIAL

The thermal properties of the shallow underground are mostly influenced by the geological composition (lithology) and by the presence of groundwater. In addition, the BHE's thermal performance (extraction) is also influenced by the mean annual ground surface temperature (GST), terrestrial heat flux, precipitation and duration of solar irradiation, which also depends on topography.

2.1 Identification of lithologies in different scales in the three pilot areas

2.1.1 Geological setting of Cerkno

The largest part of the Cerkno municipality (with 132 km^2 the smallest of the pilot areas) is covered by clastic sedimentary rocks, which show in different geological units (formations) fast exchange in form of different sequences and ratios (Figure 1). In some places, thick layers of carbonate, especially limestone, appear in clastic rocks. Other outcrops are mostly composed of carbonate rocks, dominantly dolomites. Clastic rocks are mainly represented by alternation of sandstone and claystone (or mudstone if not specified). In the Črni Vrh mountain, the alternation is in favour of sandstone, volcanoclastic tuff and tuffite, with claystone and siltstone in minor extent. These layers also characterize a part of Cerkno town, as well as some minor neighbouring settlements. Alluvial sediments as gravel, sand and silt are of very limited extent, deposited only along main rivers and creeks, with a few meters of depth. Soils and unconsolidated sediments are generally less than 1 m thick.

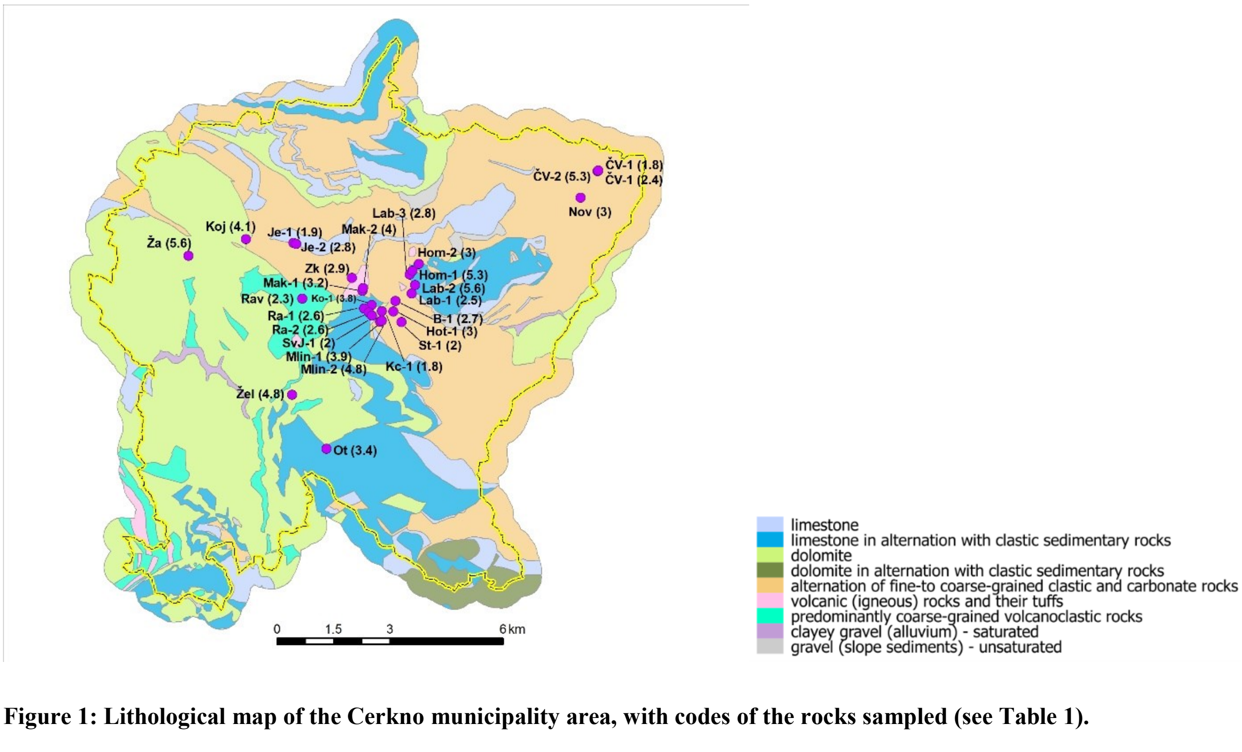


Figure 1: Lithological map of the Cerkno municipality area, with codes of the rocks sampled (see Table 1).

2.1.2 Geological setting of the Aosta Valley

The Aosta Valley is the largest (3200 km^2) and the most mountainous (the average altitude of the territory is about 2100 m a.s.l.) of the six case-study areas in the GRETA project. Three main tectonic domains of the Alps are found (Figure 2):

- Helvetic Domain in the north-western portion of the region, which is the only sector not undergone to metamorphism, consisting mainly of granite and migmatites (i.e. the basement of the Mont Blanc massif);
- Austroalpine Domain can be divided in two sectors:
  - Sesia Lanzo zone, composed mainly by eclogitic micaschists and gneiss with metabasites, located in the south-eastern portion of the region;
  - Dent Blanche unit, composed mainly by kinzingites and amphibolites, located in the central part of the region;
- Pennidic Domain is the most diffused one and refers to a broad set of rocks of originally different geological genesis and paleogeographic position, later deformed during the orogenesis. It can be subdivided in:
  - Grand Paradis and Mont Rose massifs, mainly composed by gneiss;
  - Paleo-oceanic Piemontais zone, consisting of ophiolites (mainly serpentinites and metabasalts) and associated metasediments (mainly calceschists);
  - Briançonnais zone, consisting of various kinds of metasedimentary rocks.

In the main bottom valley, quaternary alluvial sediments (sandy gravels) host very thick and permeable aquifers, exploited mainly for industrial and drinking use and, in recent years, for geothermal use too. Their recharge is granted by seasonal snowfall melting, in addition to several glaciers covering about 5% of the total regional area.

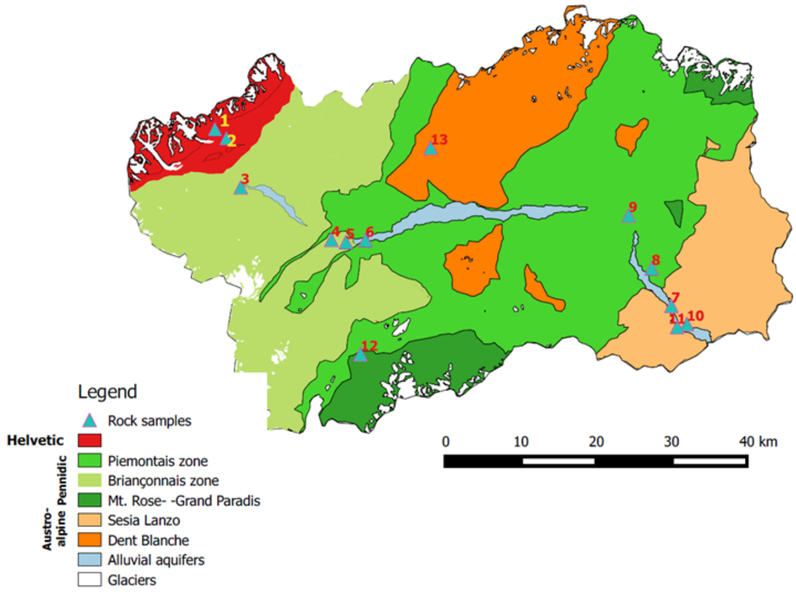


Figure 2: Simplified tectonic map of the Aosta Valley area, with numbers of the rocks sampled (see Table 2).

2.1.3 Geological setting of Parc Naturel des Bauges

The Bauges massif is one of the subalpine massifs along the western edge of northern French Alps (see Figure 3 for the maps of four municipalities). It is mainly made of folded and faulted, carbonated sedimentary rocks, with an increase of deformation to the East. In the west (Revard, Semnoz and Margériaz chains), the Bauges massif reveals asymmetric reliefs (west steep slopes, east regularly dipped ones) induced by the geological structure of Jurassic and Cretaceous formations in folds recumbent to the East. In its eastern part, the Bauges massif presents steeper reliefs in relation to more intense rock deformation, with more folds and numerous faults, induced by the vicinity of the alpine thrust front. The Bauges massif is bounded by obvious physical features. To the West, an important scarp, more than 1 km in height, marks the boundary with the molassic foreland and its low altitudes (200 to 300 m above sea level). It represents the front of Bauges Cretaceous and Jurassic formations thrusting on the Oligo-Miocene perialpine molassic infilling. To the East, the Bauges massif is recognized up to the Isère valley that corresponds to western boundary of external crystalline units of the Western Alps (Lauzière and Belledonne massifs). Northern and southern boundaries of the Bauges massif are found in transverse valleys that are strongly incised: to the North, the Annecy valley that marks the boundary with the Bornes massif; to the South, the Chambéry valley that marks the boundary with the Chartreuse massif. During the last phases of Quaternary, the alpine glaciers advanced and over-dug the valleys. The warming/receding phases resulted in the formation of lakes, and the filling of these over-dug the valleys. Laterally, many alluvial fans (cones) came to feed the valley with more or less coarse materials.

2.2 Sampling and laboratory measurements of thermal parameters

After 2003, a fairly rapid method of measurement of thermal conductivity (TC) of rocks has been applied in the world. The optical scanning method with the thermal conductivity scanner (TCS) is in use also at geothermics lab of Geological Survey of Slovenia

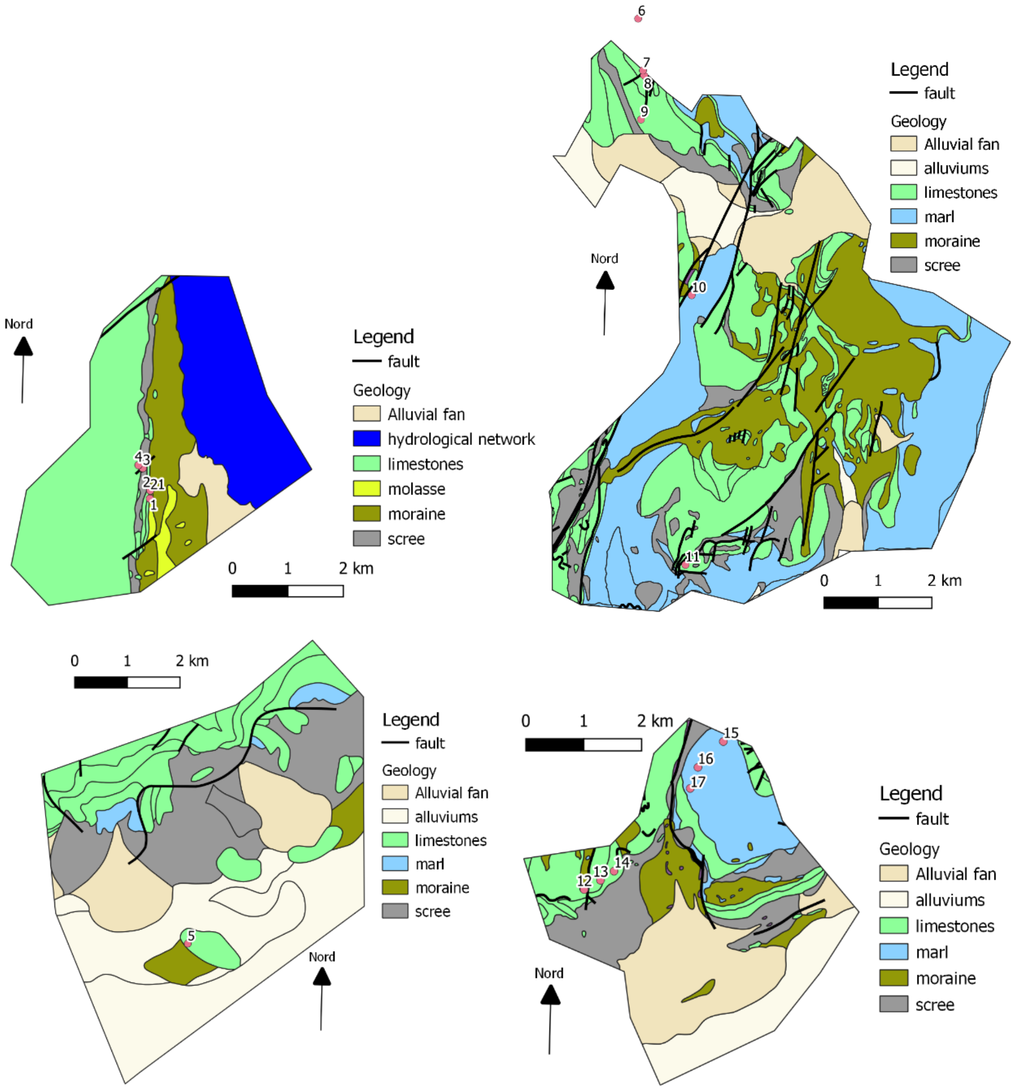


Figure 3: Geological maps of the four municipalities of the Parc des Bauges area with numbers of the rocks sampled (see Table 4); clockwise from upper left: (a) Sévrier, (b) Faverges-Seythenex, (c) Saint Pierre d'Albigny, (d) Montmélian.

(GeoZS). The device provides optionally also simultaneous measurements of thermal diffusivity (TD) (Popov et al., 2017).

- TC (and TD) measurements: Optical Scanning Technology: The TCS has a focused, mobile, continuously operating IR lamp heat source in combination with IR temperature sensors.
- 2 IR sensors measure the temperature before and after heating (3 sensors are used for TC + TD measurement).
- Determination of TC of unknown samples (optional also TD): comparison of excess temperatures (temp. differences) of **standard references** (certified samples with known TC_R) with excess temperatures of one or more **unknown samples**, which are heated by a mobile heat source. Prior to and after the measured samples along the scanning line, standard references with known TC are placed, depending on the expected TC of the measured samples (Figure 4).

For the TCS method, at least one flat plane of each piece of rock is required, for which a small tolerance is prescribed for the samples' flatness (+/- 0.5 mm) and hence the samples are sawn with a circular saw to cope with this requirement. On each piece of rock, a straight black acrylic line of at least 2 cm in width was colored on a flat surface.

2.2.1 The Cerkno municipality area

Altogether, 16 samples (30 single rock pieces) from the Cerkno town area and 16 samples (23 single pieces) from the wider Cerkno municipality were analysed on TC and TD. According to the measurements of TC of rocks and the lithological structure of the Cerkno municipality, geologists have assessed that the best rocks for exploiting the NSGE are in the western part of the municipality, like in the Šebrelje plateau area, which is mostly built with the massive grained dolomite of the middle and upper Triassic age (ca 230 million years). Figure 5 shows the profile of such a rock with quite high TC. However, also in other parts of the area the rock sequences to depths of 100 or 200 m have on average good potential, provided they are mixture of rocks with lower and higher TC values (see Figure 11). Table 1 summarizes the measured TC values by types of rocks (with their geologic ages).

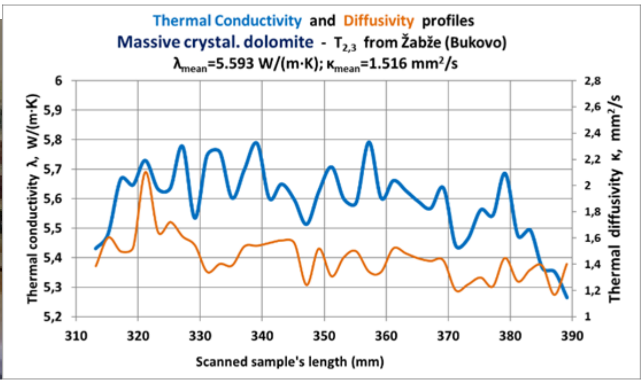


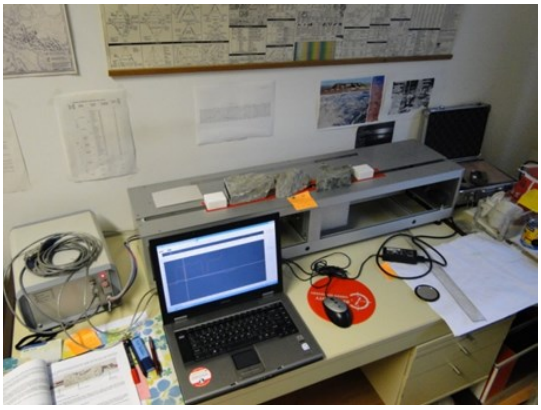
Figure 4 (*left*) and Figure 5 (*right*). *Left*: Two rock samples (i.e. from the Cerkno area) are placed on the scanner platform. The moving optical head (left side of device) will scan both samples. *Right*: Example of the TC and TD profiles along the sample of massive dolomite (sample code Ža in Table 1).

Table 1: Measured TC of rock samples from the Cerkno area with associated volumetric heat capacity. The sample codes are included in Figure 1 (Lithological map of the Cerkno mun. area).

Location	Altitude	Sample code	Surface lithology	Age	Thermal Conductivity, range	Thermal Conductivity, mean	Calculated Volum. Heat Capacity
	z (m)				λ	λ_{mean}	$C_v=\rho\cdot c_p$
Cerkno & immediate surroundings					W/(m·K)	W/(m·K)	MJ/(m³·K)
Košec	374,4	Ko-1	dolomite	${}^{1}T_1^{\,2}$	3.3 - 4.2	3,76	2,65
Magajna	420	Lab-2	dolomite	${}^{1}T_1^{\,2}$	5.2 - 5.9	5,60	2,65
W of the Homec hill	573	Hom-1	dolomite	$T_2^{\,1}$	5.1 - 5.5	5,33	2,65
Hotel Cerkno	316,7	Hot-1	dolomitized limestone	T_1	2.8 - 3.3	3,03	2,55
Rače, along the creek	353,3	Ra-1	limestone	${}^{4\text{-}5}T_1^{\,1}$	2.0 - 3.0	2,64	2,25
Rače, along the creek	334	Ra-2	marl to limestone, tectonized	${}^{5}T_1^{\,1}$	1.4 - 2.5	1,97	2,25
Saint Jernej	324,7	Svd-1	limestone	P_3	1.9 - 2.7	2,36	2,25
Saint Jernej	324,7	Svd-1	black limestone, marly, coalish	P_3	1.7 - 2.4	2,01	2,25
along the road to Labinje	364	Lab-1	limestone, tectonized	${}^{2}T_1^{\,2}$	2.3 - 2.7	2,51	2,25
Na mlin	531	Lab-3	marly limestone	${}^{3}T_1^{\,2}$	2.6 - 3.1	2,82	2,2
Homec hill	637	Hom-2	black limestone	${}^{1}T_2^{\,2}$	2.8 - 3.1	2,96	2,2
Maketon	436,6	Mak-1	tuff, seriticized & lithocrystal.	$T_2^{\,2}$	2.8 - 3.5	3,18	2,2
Maketon	464,1	Mak-2	tuff, of keratophyre & porphyre	$T_2^{\,2}$	3.7 - 4.3	4,04	2,2
Strana	343,2	St-1	sandstone & siltstone	$P_2^{\,2}$	1.4 - 2.6	1,95	2,15
Brdca	344	B-1	siltstone to mudstone	$T_3^{\,1}$	1.6 - 2.2	1,95	2
Brdca, at NOB monument	344,1	B-1	sandstone	$T_3^{\,1}$	2.2 - 3.4	2,75	2,2
Kacan	348,7	Kc-1	shaly claystone	C	1.6 - 2.1	1,84	2,05
Mlin	326,2	Mlin-2	quartz conglomerate	C	3.8 - 5.4	4,83	2,2
Mlin	316	Mlin-1	quartz sandstone w. conglomerate	C	3.5 - 4.4	3,91	2,15
wider Cerkno municipality area							
Jesenica	688	Je-1	shaly claystone, amficlin.	$T_3^{\,1}$	1.5 - 2.2	1,89	2,25
Črni Vrh	1262,3	ČV-1	siltstone & shaly claystone	$T_2^{\,2}$	1.5 - 2.2	1,78	2,1
Otalež	307	Ot	siltstone, light brown	$T_1^{\,1}$	2.9 - 3.9	3,43	2,05
Črni Vrh	1254,3	ČV-1	tuff sandstone	$T_2^{\,2}$	2.2 - 2.7	2,45	2,3
Črni Vrh	1262,5	ČV-2	quartz sandstone	$T_2^{\,2}$	4.9 - 5.7	5,30	2,2
Gorenji Novaki	951	Nov	tuff	$T_2^{\,2}$	2.5 - 3.4	3,00	2,2
Ravne	712	Rav	tuff	$T_2^{\,2}$	2.1 - 2.5	2,32	2,2
Zakriž	579	Zk	diabase	$T_2^{\,2}$	2.5 - 3.3	2,95	2,25
Jesenica	693	Je-2	limestone, amficlin.	$T_3^{\,1}$	2.5 - 2.9	2,76	2,25
Kojca	639	Koj	dolomite, thin-bedded	$T_3^{\,2+3}$	3.6 - 5.1	4,12	2,65
Žabže	535	Ža	dolomite, massive crystal.	$T_{2,3}$	5.3 - 5.8	5,59	2,65
Želin	263	Žel-1	dolomite, bedded	$T_2^{\,1}$	4.7 - 5.0	4,84	2,65

2.2.2 The Aosta Valley region

In the Aosta Valley region, 13 rock samples have been collected (Figure 2), as representative of the main lithologies of bedrock, for determination of TC and heat capacity (from the measured TD). They were also analysed with a TCS device at GeoZS (Figures 6 and 7), and results are presented in Table 2. The alluvial deposits are found in four main lenses in valley bottom (the biggest is the Aosta plain), while glacial deposits are present in smaller lenses in several lateral valleys. Thermal properties of the main lithologies were assigned using the map of ISPRA 1:500.000, while thermal properties of the sediments were estimated according to literature evidences (shown in Table 3).



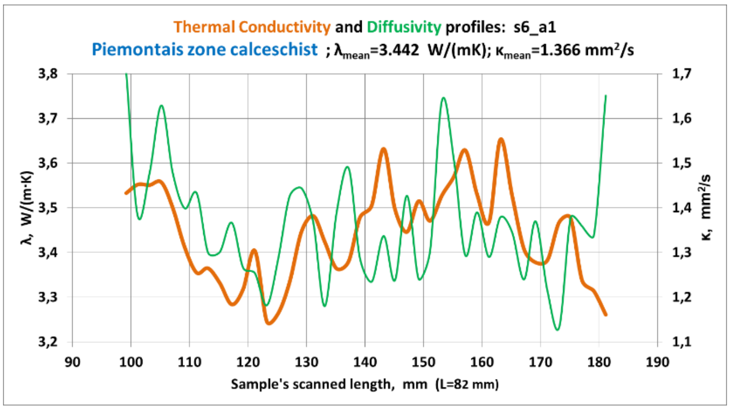


Figure 6 (*left*) and Figure 7 (*right*). *Left*: Three pieces of rock of the sample 6 (Piemontais zone calceschist) during the TC scanning (left). *Right*: Example of the TC and TD profiles along one of the three scanned rock pieces of the sample 6.

Table 2: Measured TC and TD and calculated heat capacity of the collected samples from Aosta (the numbers of samples are indicated on the map in Figure 2).

Sample	Rock type (lithology)	Mean Thermal Conductivity, W/(m·K)	Mean Thermal Diffusivity, mm^2/s	Calculated Heat Capacity $MJ/(m^3 \cdot K)$
1	Mont Blanc granite	3,12	1,62	1,93
2	UltraHelvetic schist	2,82	1,12	2,52
3	Zone Sion Courmayeur flysch	3,23	1,14	2,83
4	Outer Briançonnais micaschist	4,04	1,04	3,88
5	Inner Briançonnais micaschist	3,12	0,94	3,33
6	Piemontais zone calceschist	3,41	1,27	2,68
7	Gneiss minuti	3,42	1,42	2,40
8	Metabasalts	2,46	0,81	3,04
9	Serpentinites	3,41	0,95	3,58
10	Eclogitic Metagranitoids	3,26	1,49	2,19
11	Metagranitoids	3,44	1,82	1,89
12	Grand Paradis gneiss	3,43	1,32	2,60
13	Ortogneiss	3,33	1,51	2,21

Table 3: Estimated TC and heat capacity of sediments, according to average values of the Italian standard UNI (2012).

Lithotype	Secondary lithologies	Thermal Conductivity $(Wm^{-1} \cdot K^{-1})$	Heat Capacity $(MJm^{-3}K^{-1})$
Alluvial deposits (considered mainly saturated)	Silt + Sand + Gravel	1,9	2
Glacial deposits (considered mainly dry)	Diamicton + Clay + Silt	1,7	2,5

2.2.3 The Parc des Bauges

A cartography of the mean ground TC between 0 and 100 m depth, was carried out in the four municipalities of the pilot area, where the most important geological units were sampled. 17 samples within limestones and molasse rocks could be easily sampled, unlike marls which are very poorly exposed and whose low induration prevents the preservation of the sample (Figure 3). Sample rocks are mostly limestones and marls of Jurassic and Cretaceous ages. Clay-rich or poorly indurated geological formations such as alluvium, scree or moraine were not sampled for TC measurements. Values for them were taken from bibliography incl. the Swiss standard (SIA384/6). After the sawing 18 rough samples were scanned for TC and TD with a TCS device at GeoZS (Figures 8 and 9). One interesting result is that, except for sample 6, the conductivity is medium to high for these rock types (>2,3 W/(m·K), see Table 4**Error! Reference source not found.**). Excepted for two out-layers (samples 6 and 8), values of thermal (heat) capacity of the rock samples have a really small range of variation and a marginal impact on the final geothermal potential of the pilot area. Due to this very limited variation, the values of thermal capacity (ratio between TC and TD) were fixed to an average value of 3.00 $MJ/(m^3 \cdot K)$ in the entire pilot area.

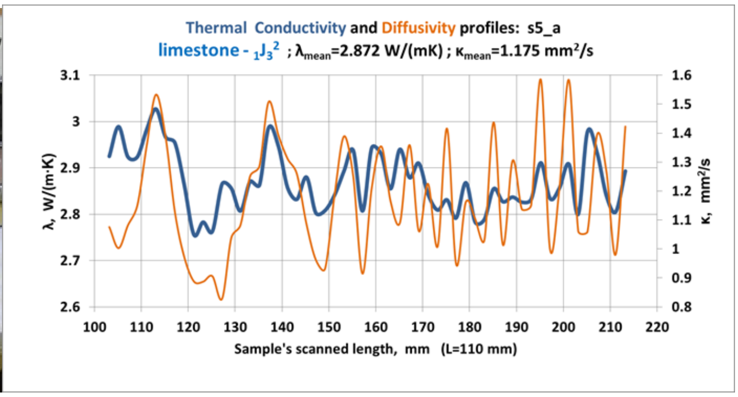


Figure 8 (*left*) and Figure 9 (*right*). *Left*: Two pieces of sample 5 (limestone) and one piece of sample 6 (marl & marly limestone) during the TC and TD scanning. *Right*: Example of the TC and TD profiles along one of the two rock pieces of the sample 5 (limestone of malm age).

Table 4: Measured TC and TD and calculated heat capacity of the collected samples from Parc des Bauges (the numbers of the samples are indicated on four maps of Figure 3).

Sample	Rock type (lithology)	Age	Mean Thermal Conductivity, W/(m·K)	Mean Thermal Diffusivity, mm²/s	Calculated Heat Capacity, MJ/(m³·K)
1	molasse sandstone	Ol_2^1	3,26	1,14	2,86
2	limestone	K_2	2,77	0,89	3,13
2b	limestone	K_2	2,94	0,95	3,09
3	limestone with sand	K_1^{5-6}	3,26	0,97	3,37
4	limestone	K_1^{4-5}	3,34	1,03	3,25
5	limestone	${}_1J_3^2$	2,83	1,16	2,44
6	marl & marly limestone	K_1^{1-2}	1,26	0,97	1,30
7	limestone	${}_1J_3^{2-3}$	2,72	1,23	2,21
8	marl & marly limestone	K_1^{1-2}	2,37	0,56	4,23
9	limestone	J_3^{1-2}	2,86	1,01	2,83
10	limestone/marl with sand	K_1^{3-4}	3,48	0,97	3,61
11	limestone	K_1^{3-5}	3,38	1,08	3,13
12	limestone with slight clay	K_1^{1-2}	2,68	0,85	3,15
13	limestone	J_3^3	2,84	1,01	2,82
14	limestone	${}_3J_3^1$	2,93	0,94	3,14
15	marl/limestone	K_1^3	3,04	1,12	2,72
16	marl	K_1^3	2,84	0,89	3,19
17	marl	K_1^3	2,94	0,96	3,06
average					3

2.3 The G.POT method description

The G.POT method (Casasso and Sethi, 2016) was used for the evaluation of closed-loop geothermal potential for all three pilot areas to estimate the geothermal potential of BHEs. This method, which can be used either for heating and cooling, assumes that the application of a cyclic sinusoidal thermal load induces a time-varying thermal alteration of the ground, thus reaching a threshold fluid temperature (minimum or maximum, depending on the use). Since the thermal alteration of the ground (and, hence, of the heat carrier fluid) is directly proportional to the thermal load exchanged with the ground, the difference between the initial ground temperature (T_0) and the fluid temperature limit (T_{lim}) determines the thermal load (geothermal potential) which can sustainably be exchanged by a BHE with a certain length. The method was first applied to the territory of the province of Cuneo (Casasso and Sethi, 2017) with 100 m as a typical BHE depth of evaluation.

The geothermal potential $\bar{Q}_{BHE}$ (MWh/year) is estimated with the following formula:

$$\bar{Q}_{BHE} = \frac{0.0701 \cdot (T_0 - T_{lim}) \cdot \lambda \cdot L \cdot t'_c}{G_{max}(u'_s, u'_c, t'_c) + 4\pi\lambda \cdot R_b} \tag{1}$$

where $T_0 - T_{lim}$ represents the aforementioned maximum thermal alteration (°C) of the fluid, R_b (mK/W) is the thermal resistance of the borehole (set to 0.1 mK/W for all pilot areas), and $G_{max}(u'_s, u'_c, t'_c)$ is a function of three non-dimensional parameters t'_c , u'_c and u'_s:

$$G_{max(u'_s,u'_c,t'_c)} = -0.619 \cdot t'_c \cdot log(u'_s) + (0.532 \cdot t'_c - 0.962) \cdot log(u'_c) - 0.455 \cdot t'_c - 1.619 \tag{2}$$

where $u'_c = \rho c \cdot r_b^2/(4\lambda t_c)$, $u'_s = \rho c \cdot r_b^2/(4\lambda t_s)$, and $t'_c = t_c/365$ are three non-dimensional parameters as function of the ground thermal conductivity λ ($Wm^{-1}K^{-1}$) and thermal capacity ρc ($Jm^{-3}K^{-1}$), the borehole radius r_b (m) (set to 7.5 cm for all simulations), the length of the sinusoidal cycle of the thermal load t_c (s) (which depends on the local climate), the length of the simulated plant lifetime t_s (s) (set to 50 years in all pilot areas).

The geothermal potential was therefore calculated with Equations 1 and 2 with a few fixed parameter values ($T_{lim} = -3°C$, $L = 100m$, $t_s = 50\ years$, $r_b = 0.075\ m$), while for the other ones spatial distributions were attributed based on measurements (e.g., λ, ρc) or correlations with altitude (T_0, t_c) calibrated with locally available data.

2.4 Derivation of other input data of G.POT method

The G.POT method can be used to assess the heating or the cooling geothermal potential. The method's only limitation is that a single operating mode can be considered and hence, the prevailing operating mode should be considered for mapping. Due to the typical climate range of the Alpine Space, we investigated the heating use only.

As stated in the previous subsection, two spatial distributions (the undisturbed ground temperature T_0 and the heating season length t_c) were derived based on locally valid correlations with climate parameters.

Below a relatively small depth, the ground temperature is assumed constant throughout the year. A few literature sources (Signorelli and Kohl, 2004; Ouzzane et al., 2015) highlighted that this temperature is very similar to the annual average air temperature, i.e. a parameter which is relatively easy to find with a good spatial resolution. For the Aosta Valley (Casasso et al., 2018), we assumed a ground temperature 1°C higher than the annual average air temperature (Figure 10B) which, as shown in Figure 10A, is linearly correlated with the ground elevation. With such correlation, therefore, a Digital Terrain Model (DTM) is enough to derive the spatial distribution of the undisturbed ground temperature T_0. Yet, at higher elevation (above 1500 m a.s.l. according to Signorelli and Kohl, 2004), the ground temperature becomes way higher than the average air temperature, due to the thermal insulation effect of the winter snow cover. For this reason, a cutoff elevation was chosen (e.g., 2000 m a.s.l., corresponding to the average altitude of the whole region) since estimating the ground temperature and hence the geothermal potential at such high elevations would have been impossible without field measurements, and scarcely useful as really a few buildings are present at those elevations. Regarding the length of the heating season, the limit is generally prescribed by national legislation. Yet, the effective one depends on climate. Different approaches were adopted for the pilot areas. For the Aosta Valley and the Parc des Bauges, the number of heating days was estimated as the average number of days with average temperature below 12°C, i.e. with the approach adopted in Italy to calculate heating degree days (UNI, 1987). For Cerkno, heating season lengths from Slovenia were first correlated with Eurostat heating degree days and then with ground elevations, as explained in Casasso et al. (2017b).

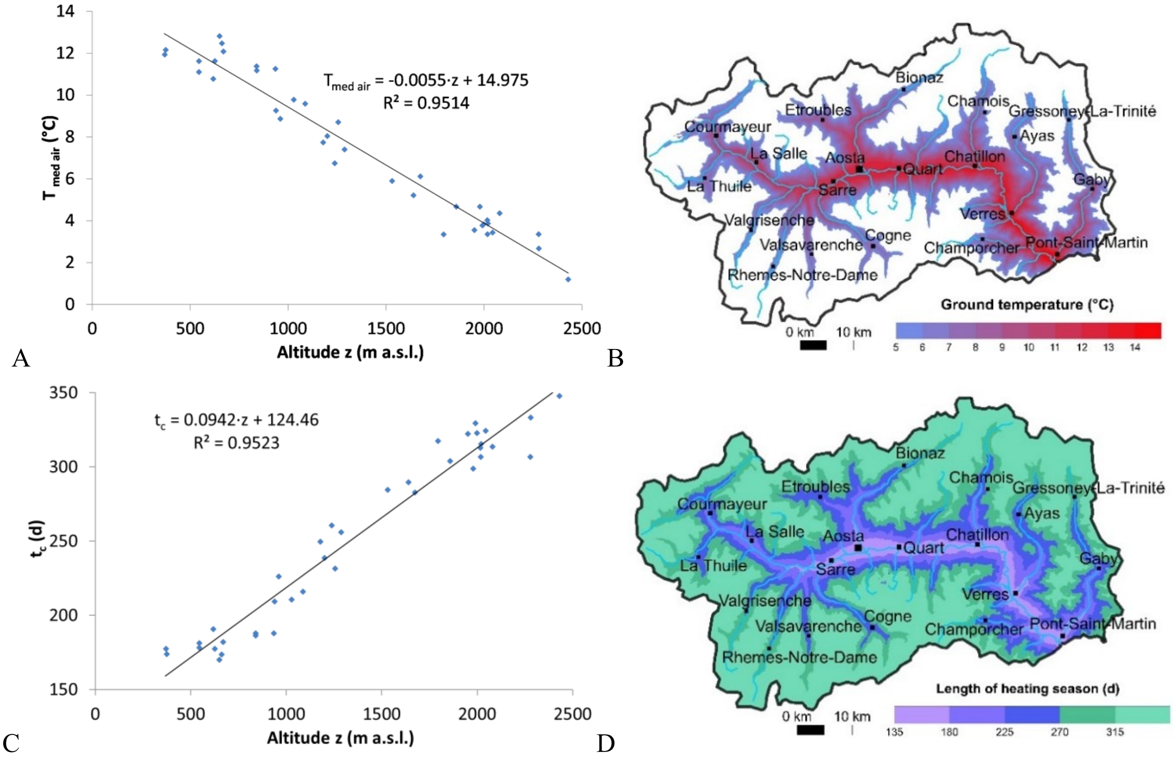
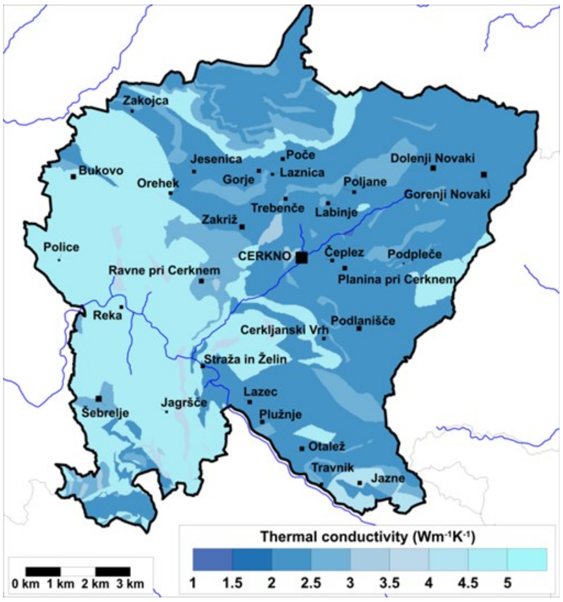


Figure 10: From top to bottom, from left to right: correlation with altitude and spatial distribution of the ground temperature (A,B) and of the length of the heating season (C,D) for the pilot area of Aosta Valley. Source: Casasso et al. (2018).

3. RESULTING MAPS OF SHALLOW GEOTHERMAL POTENTIAL

We present first the spatial distribution maps of the mean ground TC for the Cerkno, the Aosta Valley and Parc des Bauges areas. Within the Cerkno area (Figure 11, Table 1) dolomites (massive and layered), quartz sandstones and conglomerates, dolomitic limestones, and certain tuffs (keratophyre, porphire) proved to be the most conductive rocks, having the best potential for dimensioning shallow geothermal systems. Some other rock types, such as limestones, carbonatic sandstones, siltstones and diabase revealed good thermal properties as well. Lower potential (but again not so bad) for the exploitation of energy is shown by shale claystones, siltstones (mudstones), some marlstones and marly limestones. The range of mean values of 1.8 to 5.6 W/(m·K) for all the sampled rocks shows the geological variability of Cerkno area. In the Aosta Valley (Figure 12, Table 2) values of TC are generally quite high, mostly between 2.8 and 4.0 W/(m·K), and typical of metamorphic rocks, which mainly compose the Aosta Valley basement. The TC map for the Parc des Bauges from the measured values and further geological considerations is shown in Fig. 13.



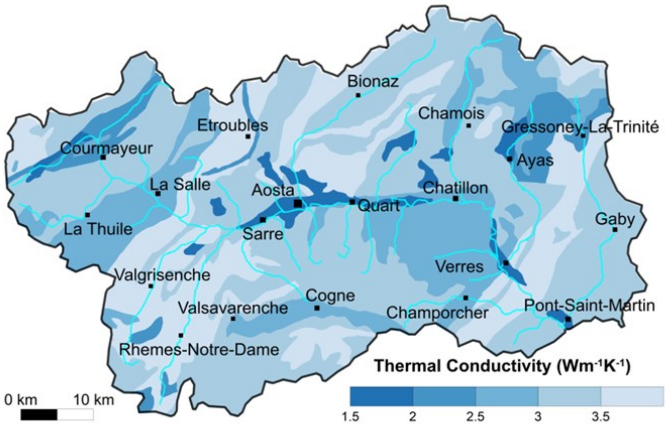


Figure 11 (*left*) and Figure 12 (*right*). *Left*: Spatial distribution of the mean ground TC in the upper 100 m depth in the Cerkno area. *Right*: Spatial distribution of the mean ground TC in the upper 100 m of depth in the Aosta Valley.

The results of TC measurements on rocks from Parc des Bauges (the mean TC values range mostly from 2.4 to 3.5 W/(m·K)) and some estimations influenced that the geological units of the harmonized geological map were classified into 4 major groups of TC, 0.4, 2.0, 2.8 and 3.4 W/(m·K). A simplified evaluation of the thickness (not based on a 3-D geological model) of each unit with the same TC value was done from expert estimates (geological section and BSS) for depths of 50, 100 and 200 m. Weighted average values according to the thickness of the unit were placed on all the sectors and the maps were obtained by doing a triangular interpolation. Uncertainties of various kinds remain and must be kept in mind as part of any subsequent interpretation of results. The loose formations could not be sampled for laboratory measurement. This shows a high degree of uncertainty of the TC values, in particular the value of 0.4 W/(m·K). The hard or soft nature of the ground is very difficult to evaluate. The values chosen are average values and it is not impossible that a value stemming from the map is different from the real TC value encountered in reality. Finally, a very high degree of inaccuracy is attributed to the extension of the formation in depth because there is no 3-D geological model of the Bauges massif. These maps (Figure 13) cannot be used at a cadastral scale. It is up to the expert to decide the accuracy and validity of the values provided by these maps.

3.1 Closed-loop geothermal potential in the Cerkno area

The spatial distributed potential for Cerkno (Figure 14) ranges from 8 to 15 MWh/year, and most of settlements have potential between 8 and 10 MWh/year (Casasso et al., 2017b). Higher values are found in the area covered by highly conductive dolomite in the villages of Bukovo (15 MWh/year), Orehek and Reka (14 MWh/year), Jagršče, Police and Jazne (12 MWh/year). Generally speaking, the high thermal conductivity of the ground compensates for the effect of relatively low ground temperature and, hence, the shallow geothermal potential shows quite high values for this hilly and mountainous area.

3.2 Closed-loop geothermal potential in the Aosta Valley area

The closed-loop geothermal potential for the Aosta Valley is shown below 2000 m a.s.l. (above which the estimation of the ground temperature is not reliably correlated with the Figure 15for elevations). The map shows globally high values of geothermal potential, higher than 10 MWh/y in most of the territory (>70%), due to pretty good TC values. Lower geothermal potential can be found in the alluvial plains located in the bottom valley, due to lower TC of the alluvial sediments. The biggest of these areas is the Aosta plain stretching west–east for about 13.5 km, reaching a width of 2.5 km in the central part, near the town of Aosta (585 m a.s.l.). A few large lenses of glacial deposits, also characterised by low geothermal potential, can be found even in many lateral valleys. The estimation of the shallow geothermal potential with G.POT does not consider the effect of groundwater advection, which may increase the heat exchange rate noticeably. The effect of groundwater advection could be taken into account with numerical models such as FEFLOW, MODFLOW or with analytical formulae. The open-loop potential has been identified for the alluvial plain.

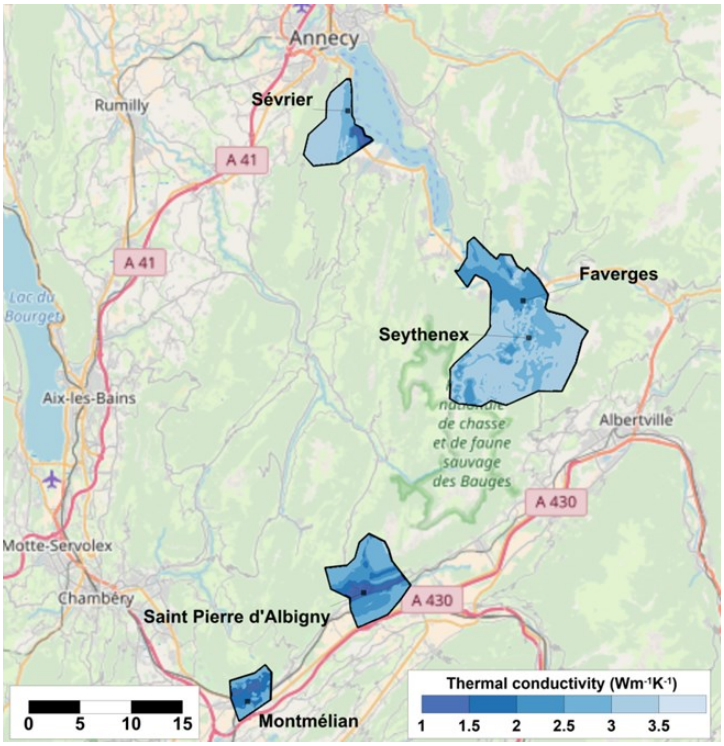


Figure 13: Spatial distribution of the mean ground TC for 100 m of depth in the four municipalities of Parc des Bauges.

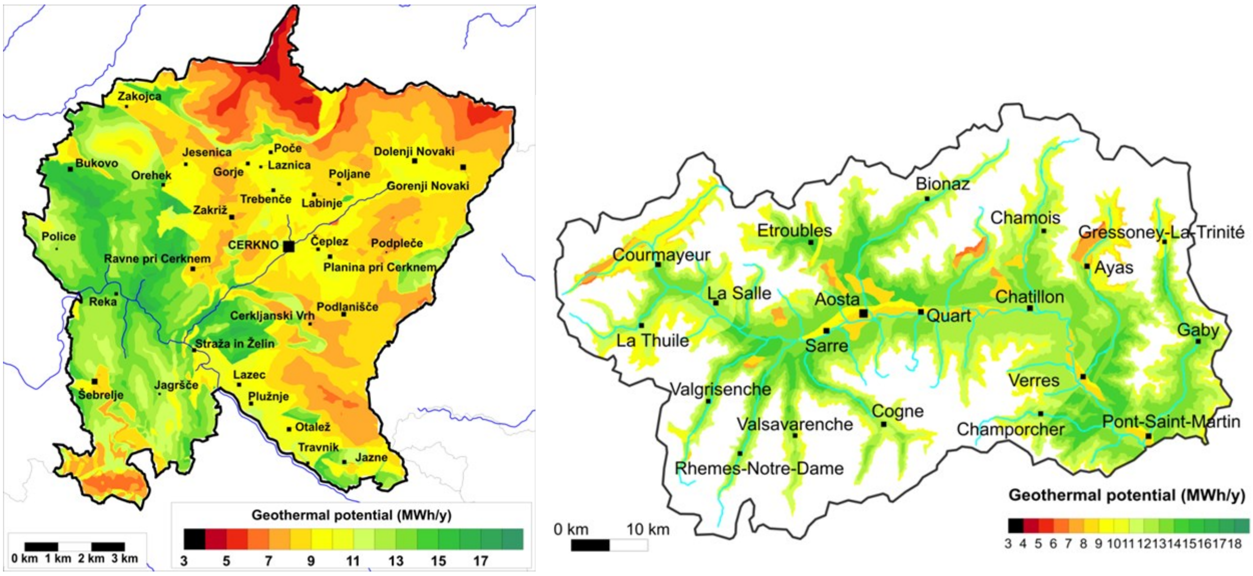


Figure 14 (*left*) and Figure 15 (*right*). *Left*: Map of the closed-loop shallow geothermal potential P_{BHE} (MWh/y) in the Cerkno area. *Right*: Spatial distribution of the closed-loop shallow geothermal potential in the Aosta Valley.

3.3 Closed-loop geothermal potential in the Parc des Bauges area

The map of the closed-loop geothermal potential of the four selected municipalities is shown in Figure 16 (general view). The range of values shown in this map is quite big, if compared to the limited surface. This is mainly due to a detailed analysis of the mean TC, especially over the alluvial deposits. Over these deposits, in fact, the potential values are lower than 10 MWh/y, while on the valley slopes values increase up to 15 MWh/y. Lower values (5.5 to 7 MWh/y) are reached over the Isére plain in the municipalities of Montmelian and Saint-Pierre-d'Albigny.

4. DISCUSSION

The Aosta Valley is, as regard to the mean TC values of basement rocks, a more homogeneous area than the other two, Cerkno and Bauges. On the other hand, due to greater altitude differences the undisturbed ground temperature (T_0) is more variable in the Aosta Valley, and less in the Parc des Bauges and Cerkno areas. The most influential input parameters for the geothermal potential are the ground TC and the T_0. The potential (both for heating and cooling) increases with TC, since the thermal alteration of the ground diminishes; on the other hand, the geothermal potential increases with T_0 if the heating mode is considered (since a larger margin is available for cooling the ground), while it diminishes if the cooling mode is assumed for the opposite reason. The resulting potential maps (Figures 14 15 and 16; also in Prestor et al., 2018) show how much heating energy can be obtained annually from one 100 m deep BHE (Capodaglio et al., 2018; Casasso et al., 2018). The resulting maps highlights that the closed-loop geothermal potential is quite high for all three mountain areas. In the Cerkno area it ranges between 8 and 10 MWh/year with even higher values, up to 16 MWh/year, observed in the western part of the municipality, which is covered by highly conductive dolomites. In the Aosta Valley the potential ranges from 5 to 18 MWh/year, as it shows potential higher than 10 MWh/y in most of the territory (>70%), as consequence of good TC values. In the Parc des Bauges the potential ranges from 5 to 15 MWh/year with Sévrier and Faverges-Seythenex municipalities as more promising. The mentioned heating energy can be directly compared to the energy consumed annually, calculated in megawatt hours (MWh). If we use annually, for example, 2300 litres of fuel oil with an old oil boiler with 70% efficiency, this is equivalent to 16 MWh. Approximately one quarter of this energy comes from a heat pump, the other 12 MWh from the environment, that is, from a borehole. In greenish-colored areas of all potential maps, a 100 m deep or shallower borehole would suffice. In other areas, the borehole should be deeper. One deeper borehole can be replaced by two or more shallow ones.

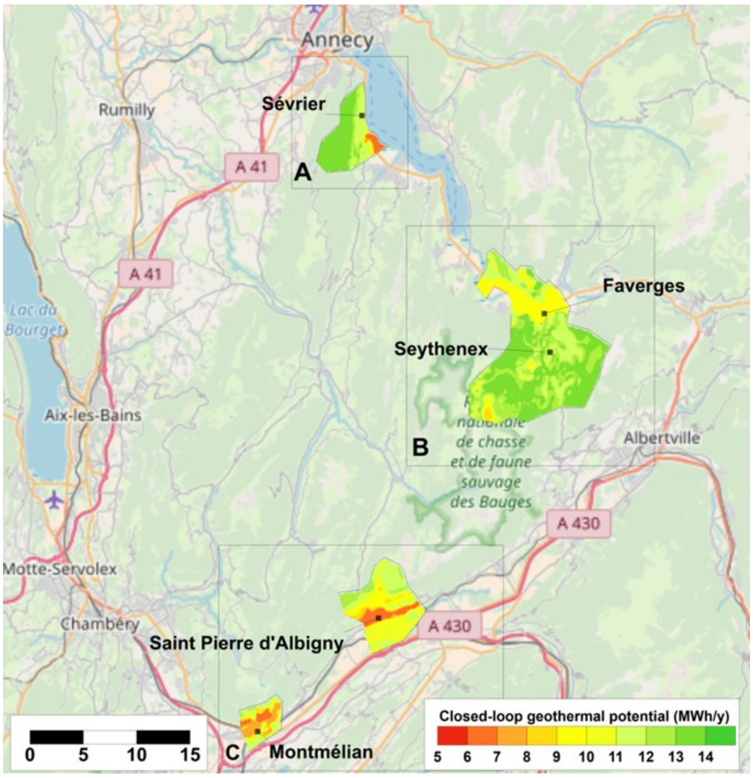


Figure 16: Spatial distribution of shallow geothermal potential referred to BHE of 100 m in the municipalities of Sévrier, Faverges-Seythenex, Saint-Pierre-d'Albigny and Montmélian (from N to S, general view).

Concerning the effect of the elevation, particularly in the Aosta Valley, geothermal potential values are globally lower in the higher part of the valley due to the lower ground temperature, despite the longer heating season imposed in high altitude areas. With the values of closed-loop geothermal potential, already today BHEs may be of interest to replace methane boilers while, in the absence of methane grid, they should be seriously taken into account as an alternative to oil or liquidized petroleum gas (LPG) boilers.

The geothermal potential value calculated over the Aosta plain has been compared to a TRT test performed in Saint Christophe (550 m a.s.l.) (Tagliabue et al., 2013) on a BHE of 90 m depth. During this test, the borehole exchanged 5520 kWh over a period of 1370 h, with a mean value of 44.8 W/m of borehole length. Considering a heating period of 2200 full load equivalent hours (FLEH) and a borehole length of 100 m, the exchanged energy that we can derive is 9.9 MWh/y, very close to the obtained value shown in the map, which is 10 MWh/y in the plain area of Saint Christophe.

5. CONCLUSIONS

This paper presents the assessment and mapping of closed-loop shallow geothermal potential for which the detailed study of geological and geothermal characteristics was performed in the three alpine pilot areas (Cerkno, Aosta Valley and Parc des Bauges) in order to identify the most suitable areas for GSHP technology. The identification of lithologies in different scales to assign thermal property values correctly was the greatest challenge. Then the mean TC values of rock samples (together with thermal diffusivity, which is necessary for acquisition of thermal capacity) were determined using the TCS method. Mostly expected mean TC values were gained according to existing lithology. With this input, the shallow geothermal potential was determined using the G.POT method for a standard 100 m deep BHE. Ground thermal properties were, however, evaluated for the same depth. A strong correlation of climate (annual average air temperature and Heating Degree Days) was observed, especially in the Cerkno and Aosta areas, and therefore the ground temperature and the duration of the heating season were estimated based on a Digital Terrain Model.

All these maps aim to give valid data about the closed-loop shallow geothermal potential to the entrepreneurs, engineers and individuals to help them in their energetic choice in the execution of any shallow geothermal project involving GSHP units. The geothermal potential of each area represents the annual amount of energy sustainably exchangeable with the ground by a single borehole with defined characteristics. This quantity is useful for a preliminary estimation of the installation costs of a closed loop geothermal plant. However, it should not be meant as a replacement of the BHE field sizing.

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