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Ground Source Heat Pumps in Aosta Valley (NW Italy): assessment of existing systems and planning tools for future installations

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ABSTRACT

The economic viability of shallow geothermal systems with Borehole Heat Exchangers (BHEs) strongly depends on the thermal load which can be efficiently and sustainably exchanged with the ground. This quantity is usually defined as geothermal potential and, as reported in literature, it mostly depends on the thermal conductivity and the undisturbed temperatures of the ground.

The GRETA Project funded by the EU Interreg Program Alpine Space aims to produce maps of the geothermal potential in pilot areas across the Alpine territory to identify the most suitable areas for shallow geothermal installations. This paper presents the case study of the Aosta Valley, where the recently developed G.POT (Geothermal POTential) method was adopted. It describes the data sources used and the assumptions made to derive input parameters (ground thermal properties, usage profile, etc.). In addition, the results of a survey on existing geothermal installations are presented.

KEY WORDS: shallow geothermal energy, ground source heat pumps, geothermal potential, borehole heat exchanger, Aosta Valley.

INTRODUCTION

Shallow geothermal systems can be divided into two main groups: open-loop, exchanging heat with groundwater, and closed-loop systems, where the heat exchange occurs through the circulation of a heat carrier fluid in a closed pipe loop buried in the ground horizontally (earth coils) or vertically (Borehole Heat Exchangers and geothermal piles) (Sarbu & Sebarchievici, 2014). The utilization of shallow geothermal energy is growing in Europe due to its low carbon emissions and the saving margins on operational costs (Antics et al., 2016). However, Ground Source Heat Pumps (GSHPs) still represent a marginal sector of renewable heat sources (Bayer et al., 2012). In order to promote this sustainable energy source, the on-going cooperation project GRETA (near-surface Geothermal REsources in the Territory of the Alpine space) is working to overcome some of the main barriers to the diffusion of GSHPs (Casasso et al., 2017b), among which i) the simplification of existing regulation and authorisation procedures, based on best practices identified among existing ones (Prestor et al., 2016), ii) addressing design and technical issues of different shallow geothermal techniques with a focus on specific Alpine conditions (Bottig et al., 2016; 2017), and iii) tools to include shallow geothermal energy in local energy plans of three pilot areas - Oberallgäu (Germany), Cerkno (Slovenia) and Aosta Valley (Italy) - where the shallow geothermal potential for closed-loop and/or open-loop systems is assessed and mapped.

The geothermal potential is usually defined as the thermal load which can sustainably be exchanged by a GSHP with certain characteristics, depending on the local thermal and/or hydrogeological properties of the ground (Ondreka et al., 2007; Gemelli et al., 2011; De Filippis et al., 2015; Galgaro et al., 2015; Casasso & Sethi, 2016; Viesi et al., 2018). It therefore allows a quick estimation of the installation cost, which is probably the strongest barrier to the spread of GSHPs. Although it should not be considered as a design method, the shallow geothermal potential is a useful tool to identify the most suitable areas for the diffusion of these systems. Studies and models for the assessment of shallow geothermal potential mostly focused on the Borehole Heat Exchanger (BHE), since it is the most adopted technique. Numerous studies adopted the well-known method proposed by the German standard VDI 4640 (VDI, 2010), such as reported in Ondreka et al. (2007); Gemelli et al. (2011); De Filippis et al. (2015). This method provides tables of specific power extraction values (W/m) for a few rocks and sediments classes, and for two different utilisation profiles (1800 and 2400 full-load equivalent hours per year), but it does not take ground temperature into account. For this reason, VDI 4640 provides unrealistic estimates where this parameter is highly variable, e.g. in mountaineous areas. The method proposed by UK Department of Energy and Climate Change (DECC, 2011), which also provides tabulated values, overcomes this issue, introducing ground temperature as an input parameter on BHE sizing tables. In addition, lithology classes are replaced by thermal conductivity values. More recently, the G.POT method was developed by Casasso & Sethi (2016), which takes into account a wide range of ground thermal properties and plant parameters. This method can be applied both to only-heating or only-cooling usage profiles, thus being suitable also for hot climates in which the heating energy consumption is negligible compared to cooling needs. The method has already been applied in another pilot area of the project, the Slovenian mountain municipality of Cerkno (Casasso et al., 2017a).

In this paper, we present the assessment and mapping of existing GSHPs and of the shallow geothermal potential in the Aosta Valley (NW Italy). The methods adopted for the survey on GSHPs are explained, identifying possible error margins of the resulting data. Geological and climatic data are then analysed and integrated with laboratory measurements on field samples to derive the thermal properties of the ground on which the shallow geothermal potential depends. Finally, the map of the closed-loop geothermal potential is presented and commented, identifying further improvement margins and possible developments of this work.

ASSESSMENT OF EXISTING GSHP INSTALLATIONS

Concerning shallow geothermal energy, one of the main issues of energy planning is the lack of trusted, consistent and complete data sets on existing installations. Depending on the country, and often on the region or province, different authorisation procedures are set (Prestor et al., 2016), and different authorities are managing data on shallow geothermal utilisations. Most countries have set public or confidential databases on GSHPs, on their positions, the installed power etc. In Italy, public authorities usually have information on open-loop geothermal installations, since a water abstraction permit is required. In this case, the main issue can be the absence of specific information on the geothermal use of groundwater: especially in the past, a number of open-loop systems was considered as industrial use. On the other hand, data on closed-loop installations, i.e. most of GSHP installations, are generally estimated based on communications from market practitioners, while only Region Lombardia set a public database with compulsory registration of existing BHEs and communication of forthcoming installations (Regione Lombardia, 2010).

The Aosta Valley is one of the regions for which data on closed-loop systems are missing. For this reason, a survey on existing geothermal heat pumps was conducted, based on four data sets:

- 32 systems were identified from the regional dataset on building energy assessment, introduced by the EU directives 2010/31/EU and 2012/27/EU, covering buildings which were built, rent or sold from 2011 onwards. These data were corrected by contacting the authors of energy assessments of buildings equipped with a heat pump, since no distinction on the heat source was made in the registry;
- 9 systems were included in the database of renewable energy and energy saving interventions on buildings funded by fiscal incentives since 2007, held by the national energy agency ENEA;
- information on 37 plants from communications by installers and designers of GSHPs operating in Northern Italy;
- 17 open-loop systems were identified in the database of well permits, where the geothermal use is not always explicitly mentioned.

Data from different sources were harmonised, trying to extract basic information (closed/open-loop, year of installation, thermal power, spatial coordinates) and remove errors and duplicates. A total of 67 installations was identified, among which 43 are closed-loop (64%) and 24 are open-loop (36%) (Fig. 1A). The total installed power is 3.9 MW with a total renewable energy production of 6.9 GWh. Although open-loop systems are a minor part of the total installations, they cover most of the installed power and of the heat production (2,903 kW and 5.1 GWh, equal to 74%) since very large systems are installed in Aosta and Pont-Saint-Martin. Most of the geothermal installations are used only or mainly for heating purposes, due to the Alpine climate of the Valley, in agreement with data on the HVAC (Heating, Ventilation and Air Cooling) systems in this region, where only 1.5% of families has a home cooling system (ISTAT, 2014). The survey is a first attempt to assess the current diffusion of GSHP in the Aosta Valley. The resulting data would set this region above the national average: in Italy, a total of 13,200 installations (1 on 4,590 inhabitants) with a capacity of 531 MW (8.7 kW every 1,000 inhabitants) (Antics, et al., 2016); for the Aosta Valley, 1 installation on 2,069 inhabitants and 29 kW every 1,000 inhabitants result from this survey. This result can be attributed to the high GDP per capita (+27% compared to national average, according to ISTAT, 2016) and the highest expense for heating among all Italian regions (2,000 €/year per family, i.e. +22% compared to the national average, according to ISTAT, 2014) due to its cold climate (Heating Degree-Days range between 2,700 and 4,955). Also, renewable energy sources are popular in this region, since 23.4% of families use biomasses for heating, almost the double of the national average (14.5%) (ISTAT, 2014).

This survey can be considered as a starting basis, with some error margins related to:

- mistakes in the building performance certificates, where air-source and ground-source heat pumps may have been wrongly identified;
- missing responses to the survey on the building performance certificates (about half of the professional contacted);
- missing or wrong position of installations communicated by practitioners;
- double-counting of the same installations when no detailed data on its position are available.

ASSESSMENT OF SHALLOW GEOTHERMAL POTENTIAL

As reported in the previous chapter, GSHPs are still a niche market in Valle d’Aosta, although the diffusion is higher than the national average. To support planning future expansion of this technology, we developed the map of closed-loop shallow geothermal potential in this region, identifying the areas which are most suitable for the installation of Borehole Heat Exchangers. In this chapter, the territory surveyed is first described from the geological and climatic points of view, thus deriving the input parameters for the G.POT method, which is shortly explained. The resulting map is then discussed, and examples are shown to explain how the geothermal potential influences the economic feasibility of GSHPs.

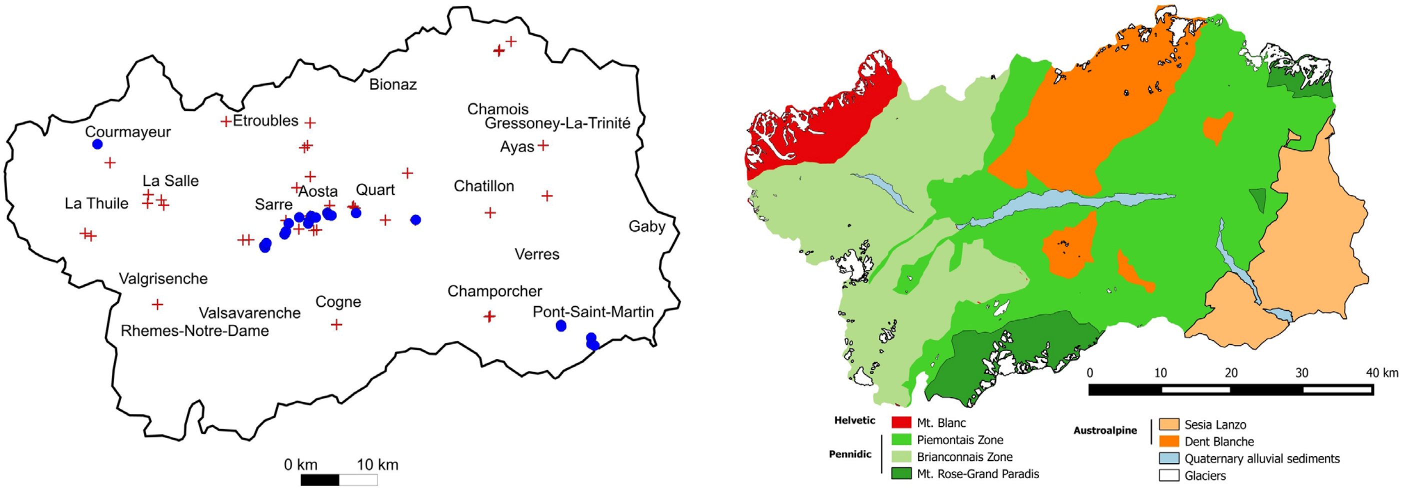

Fig. 1 - A) GSHPs in Aosta Valley, according to the survey presented, divided into closed-loop (red crosses) and open-loop systems (blue circles). B) Simplified tectonic map of the Aosta Valley, derived from the geological map by Regione Valle d'Aosta (2005).

THE TERRITORY SURVEYED

The Aosta Valley is the smallest Italian region, with a surface of 3,200 km^2 and a population of about 128,000 inhabitants. The region coincides with the highest part of the basin of the Dora Baltea river (about 100 km long), and the main towns (among which Aosta) are concentrated along the bottom valley at a average altitude of 350-600 m asl, however some major villages are located at much higher elevations, such as the well-known ski resorts if Courmayeur (1,224 m a.s.l.), Valtournenche (1,528 m a.s.l.), and Cogne (1,524 m a.s.l.).

The Aosta Valley is a mountainous region with an average altitude of 2,100 m a.s.l. and bounded by the highest peaks of the Alpine chain, such as Mont Blanc (4,810 m a.s.l.), the Monte Rosa Massif (4,554 to 4,634 m a.s.l.) and Cervino/Matterhorn (4,478 m a.s.l.). The region is characterised by an Alpine climate, with cold winter and short summer.

GEOLOGY

The Aosta Valley is located in the heart of the Europe-vergent belt of the Alps; three main tectonic domains are represented (Dal Piaz et al., 2003; Schmid et al., 2004; Pfiffner, 2014) as shown in Fig. 1B:

- the Helvetic Domain, in the north-western portion of the region, is the only sector not undergone to metamorphism, representing - in the evolution of the continental collision - the European passive continental margin. It consists of granite and migmatites (i.e. the basement of the Mont Blanc massif) and a poorly preserved liassic sedimentary cover.
- the Pennidic Domain refers to a broad set of rocks of originally different geological genesis and paleogeographic position, later all heavily deformed during the orogenesis. It can be subdivided in i) the inner domain of Grand Paradis and Mont Rose massifs (mainly gneiss) ii) the paleo-oceanic Piemontais zone, consisting of ophiolites (mainly serpentinites and metabasalts) and associated metasediments (mainly calceschists) and iii) the outer domain of the Briançonnais zone, consisting of various kind of metasedimentary rocks.
- the Austroalpine Domain represents the continental crust of the Adriatic tectonic plate; it can be divided in i) a lower unit in the south-western portion of the region (Sesia Lanzo zone, composed mainly by eclogitic micascists and gneiss with metabasites) and ii) an upper one in the central part of the region (Dent Blanche unit composed mainly by kinzingites, amphibolites, and marbles).

Quaternary alluvial sediments (sandy gravels) in the bottom valley are of great hydrogeological importance since they host very thick and permeable aquifers, exploited mainly for industrial and drinking use, and lately even for geothermal use. Their recharge is provided by seasonal snowfall melting, in addition to several glaciers covering about 5% of the total regional area.

THE G.POT METHOD

The shallow geothermal potential $\bar{Q}_{BHE}$ is hereby defined as the thermal load for which an imposed maximum thermal alteration is reached over the lifetime of the BHE in a certain location. In order to draw the map of the shallow geothermal potential of the Aosta Valley, the algorithm G.POT (Geothermal POTential) was used (Casasso & Sethi, 2016). This algorithm is based on the assumption 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), which depends on the following parameters:

- Geological: ground thermal conductivity λ (Wm^{-1}K^{-1}) and thermal capacity ρc (Jm^{-3}K^{-1});
- Average undisturbed ground temperature (°C).
- Annual working rate of the plant: $t'_c = t_c/t_y$, where is the length of the heating season (s), and t_y is the length of the year (s).

- BHE characteristics: length L (m); life time t_s (s); threshold temperature T_{lim} (°C); thermal resistance R_b (mKW^{-1}).

The alteration of the fluid temperature $T_f(t)$ is calculated with the Infinite Line Source solution (Carslaw & Jaeger, 1959), applying the superposition principle in order to consider the variable thermal load. The shallow geothermal potential $\bar{Q}_{BHE}$ (expressed in MWh/y) is then described by Eq. 1:

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

where $T_0 - T_{lim}$ represents the aforementioned maximum thermal alteration and $G_{max}(u'_s, u'_c, t'_c)$ is a function of three non-dimensional parameters t'_c, u'_c and u'_s:

$$\begin{aligned} G_{max(u'_s,u'_c,t'_c)} = & -0.619 \cdot t'_c \cdot log(u'_s) + (0.532 \cdot t'_c - 0.962) \\ & \cdot log(u'_c) - 0.455 \cdot t'_c - 1.619 \end{aligned} \qquad \text{Eq. 2}$$

where $u'_c = \rho c \cdot r_b^2/(4\lambda t_c)$, $u'_s = \rho c \cdot r_b^2/(4\lambda t_s)$, are two non-dimensional parameters.

For the definition of the characteristics of the BHE, typical values for a standard plant were set: length $L = 100m$, borehole radius $r_b = 0.075m$, lifetime of the plant $t_s = 50$ *years*, threshold temperature $T_{lim} = -3°C$, borehole thermal resistance $R_b = 0.1\ mKW^{-1}$. While these parameters are uniform on the territory surveyed, spatial distributions have been derived for the remaining parameters (ground thermal properties and length of the heating season), which are characterized by a high spatial variability and hence determine the distribution of the shallow geothermal potential.

GROUND THERMAL CONDUCTIVITY AND CAPACITY

Ground thermal parameters values were assigned based on the geological map 1:500,000 of ISPRA, included in the project OneGeology (ISPRA, 2009). 13 main lithotypes were identified in the Aosta Valley, each one composed of up to 5 lithologies, according to the classification adopted by OneGeology. Values of thermal conductivity (λ) and thermal capacity (ρc) are reported in Tab. 1 and their spatial distributions are shown, respectively, in Fig. 2A and Fig. 2B. Thermal capacity and conductivity values were attributed to the main lithotypes based on the results of laboratory tests performed with a Thermal Conducivity Scanner (Popov et al., 2003) on rock samples from the Aosta Valley. For a few minor formations and for quaternary deposits, values were assigned according to UNI (2012). The highest thermal conductivities were found in the high-grade metamorphic rocks samples (Micaschists, 3.52 Wm^{-1}K^{-1}; Gneiss, 3.43 Wm^{-1}K^{-1}), and lower values attributed for glacial and alluvial sediments (respectively 1.7 and 1.9 Wm^{-1}K^{-1}). The thermal capacity is less variable: the lower values (1.93 MJm^{-3}) was found in Granite samples and attributed to sediments, while the highest values (up to 3.3 MJm^{-3}) were found in Micaschists.

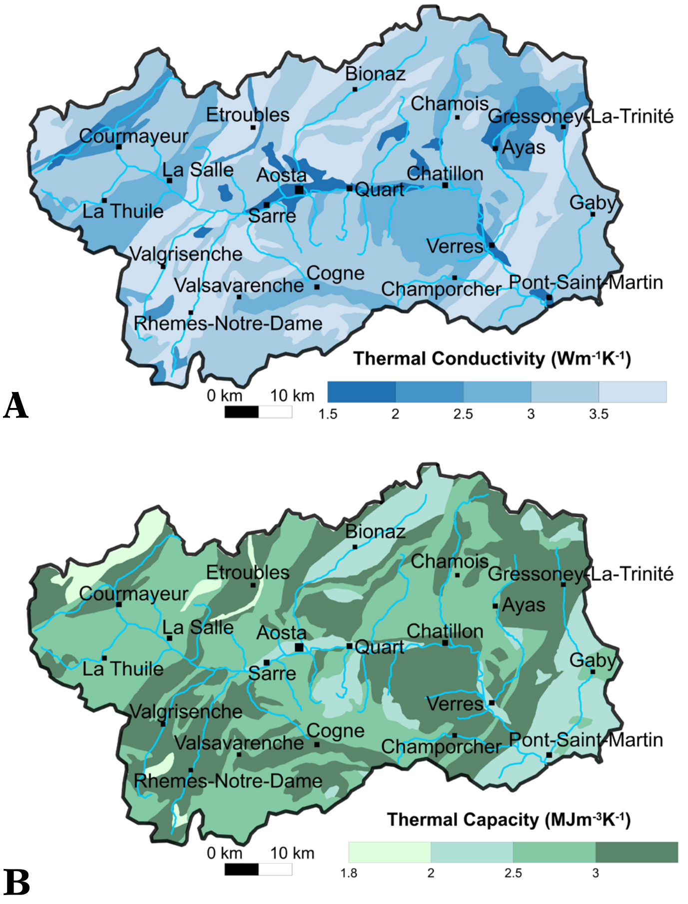

Fig. 2 - Spatial distributions of the estimated thermal conductivity (A) and capacity (B) of the ground.

TABLE 1

Thermal conductivities λ (Wm^{-1}K^{-1}) and capacities ρc (MJm^{-3}K^{-1}) derived from measurements on field samples (indicated with *) and from the Italian standard UNI (2012).

Lithotype	Secondary lithologies	λ	ρc
Alluvial deposits (sat.)	Silt + Sand + Gravel	1.90	2.00
Glacial deposits (dry)	Diamicton + Clay + Silt	1.70	2.50
Ophiolites*	Peridotite/Gabbro/Basalt	2.94	3.22
Limestone	Dolomite	2.40	3.00
Conglomerate*	Sandstone+Mudstone	2.82	2.52
Andesite	Rhyolite	2.70	3.10
Granite*	Granodiorite	3.12	1.93
Monzonite	Quartz diorite	3.20	2.80
Schist*	Quartzite	3.32	2.75
Mica schist*	Gneiss (+ Phillyte)	3.52	3.30
Eclogite*	Schist	3.26	2.18
Gneiss*	Migmatite + Schist	3.43	2.50
Granulite*	Amphibolite	3.39	2.34

UNDISTURBED GROUND TEMPERATURE AND LENGTH OF THE HEATING SEASON

The ground temperature is strongly correlated to the yearly mean of the air temperature, which in turns depends on the altitude. According to Signorelli & Kohl (2004), the ground is 1 to 2°C warmer than the air, and this difference increases with the altitude due to the isolating effect of the snow cover during winter. Yearly average air temperatures $T_{med\ air}$ (°C) were therefore used to derive ground temperatures T_0 (°C), assuming a difference of 1°C:

$$T_0 = T_{med\ air} + 1°C \qquad \text{Eq. 3}$$

Values of were derived from the time series recorded in the period 2006-2015 by 38 meteorological stations managed by ARPA Valle d'Aosta, discarding all years for which more than 3% of recordings was missing. A linear correlation was found (Fig. 3A) and used to derive the spatial distribution (Fig. 3B) of the undisturbed ground temperature T_0 (Eq. 3), using ground elevations from a global 30m-grid Digital Elevation Model (DEM) of USGS & NASA (2011). Values of T_0 below 5°C (corresponding to altitudes above 2000 m a.s.l.) were excluded from the map reported in because at these altitudes the snow coverage lasts for a long time and hence Eq. 3 would strongly underestimate the value of T_0 (Signorelli & Kohl, 2004). Since the average elevation of the Aosta Valley is 2100 m a.s.l., this means that about half of the territory is therefore excluded from the mapping of the ground temperature, and hence of the shallow geothermal potential. However, only a few isolated buildings are present at such elevations.

According to UNI (1987), the length of the heating season (t_c) was defined as the number of days with an average temperature inferior to 12°C. A linear correlation between t_c and the altitude was found (Fig. 3C) using the same meteorological data utilised for the evaluation of the undisturbed ground temperature. The resulting spatial distribution is shown in Fig. 3D.

RESULTS AND DISCUSSION

The raster map of the geothermal potential of the Aosta valley (below 2000 m a.s.l.), obtained with the G.POT method, is shown in Fig. 4 (cell size 30x30m). This map indicates punctual values for a single borehole installed with the above mentioned characteristics and it has been published in a web GIS at https://goo.gl/AR722W (Casasso et al., 2017b). The shallow geothermal potential is highly variable and it is mainly driven by the ground temperature (ranging from 15°C to 5°C, respectively between 300 and 2000 m a.s.l. of elevation) and the thermal conductivity (ranging between 1.7 and 3.52 $Wm^{-1}K^{-1}$). The thermal capacity (ρc) and the length of the heating period (t_c), instead, have a marginal role on , also due to their lower variability.

The highest values of geothermal potential (13 to 15 MWh/year) are found in the piedmont areas below 1000m of elevation, close to the alluvial plains of Aosta, Verres and Pont-Saint-Martin. This is due to the combination of a high

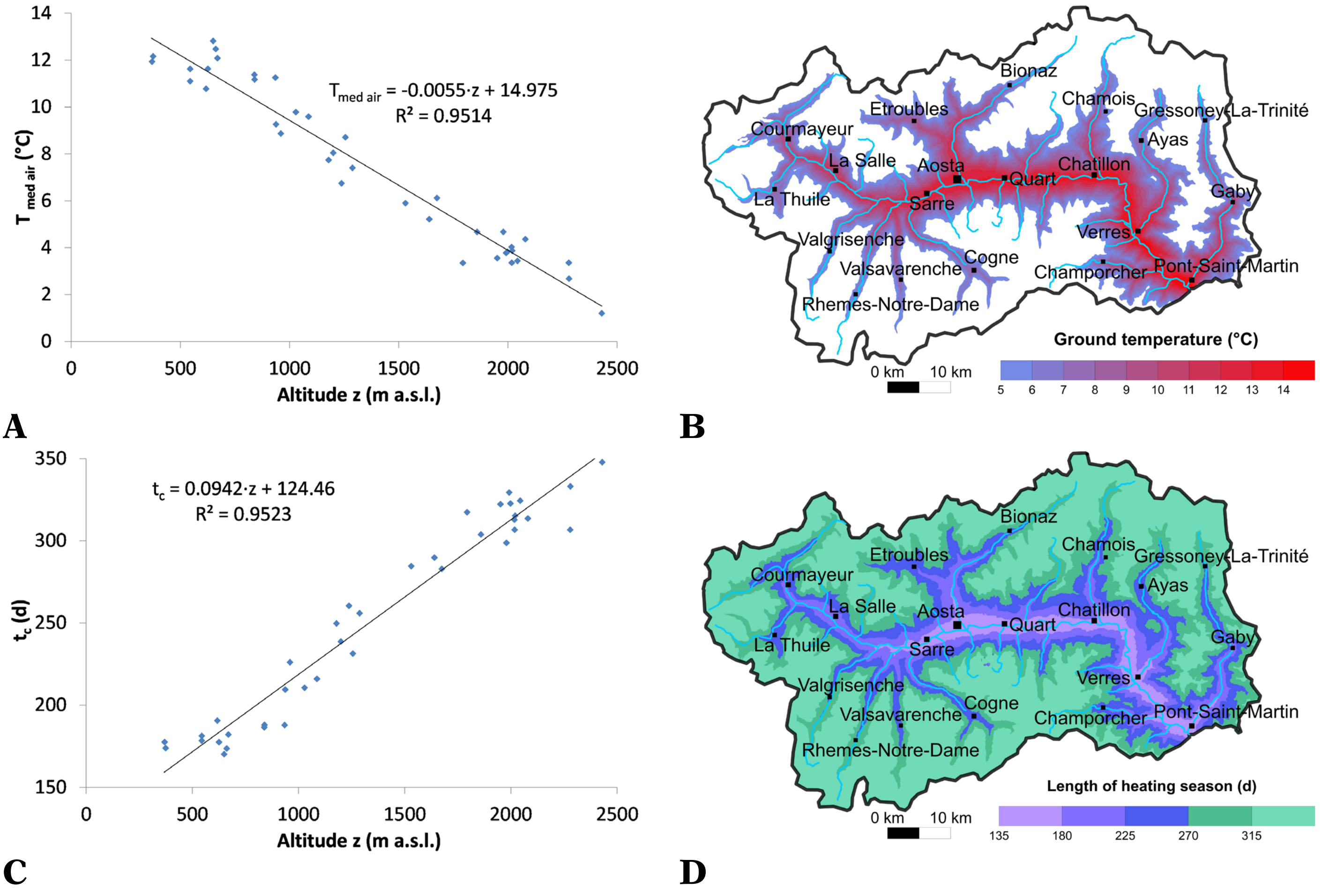

Fig. 3 - From top to bottom, from left to right: correlation with altitude and spatial distribution of the ground temperature (A,B) and of the length of the heating season (C,D).

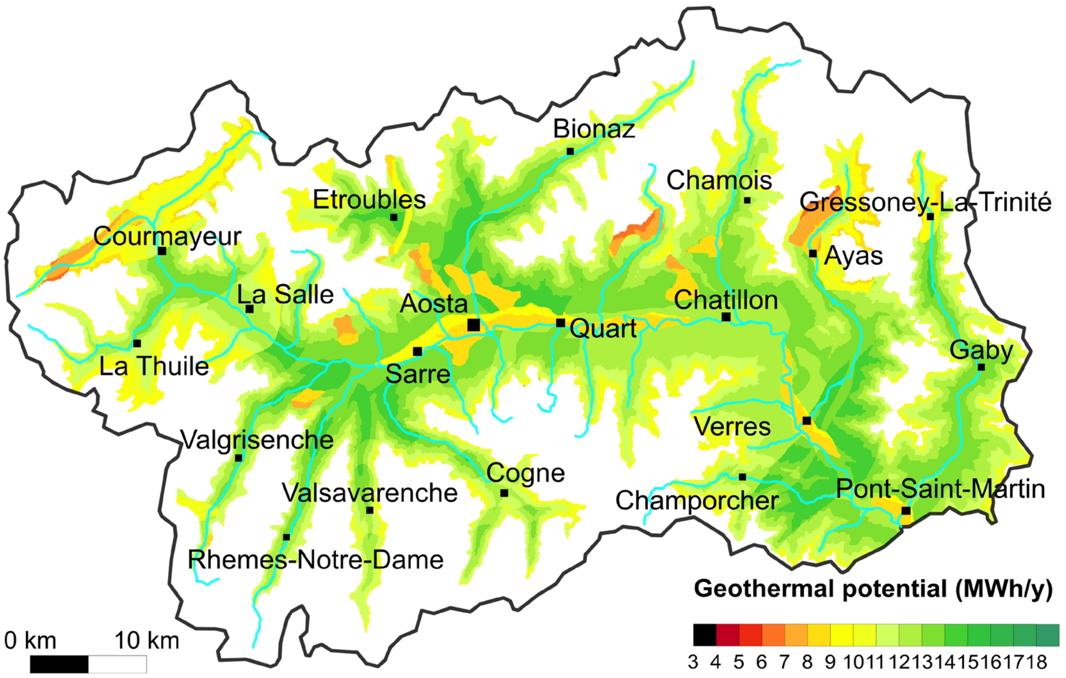

Fig. 4 - Map of the closed-loop shallow geothermal potential (MWh/y) in the Aosta Valley.

thermal conductivity of the schists and mica shists (3.32-3.52 $Wm^{-1}K^{-1}$) and a relatively high ground temperature (above 10°C). Other areas with a good geothermal potential (11-13 MWh/year) are in the highest part of the Aosta Valley (Courmayeur, La Thuile, La Salle) and in lateral valleys such as Valsavarenche, Valgrisenche, Valpelline and Valtournenche (see Chamois). In Valtournenche, a GSHP system is installed at 2,400 m a.s.l. on a ski track, which is the top elevation for a geothermal plant in Italy (Fabrizio et al., 2015).

The alluvial plains of Aosta (from Sarre to Quart, see Fig. 4), Verres and Pont-Saint-Martin have a lower thermal conductivity (1.90 $Wm^{-1}K^{-1}$) and hence the geothermal potential is much lower (8 to 9 MWh/year), which may be considered as a medium value compared to other areas where G.POT was applied (Casasso, et al., 2017a, Casasso & Sethi, 2017). On the other hand, the plain of Aosta hosts a thick and conductive shallow unconfined aquifer (Bonomi et al., 2013) and hence it is suitable for the installation of groundwater heat pumps (which have not been analysed in this work).

ECONOMIC FEASIBILITY OF A GSHP: IMPACT OF THE GEOTHERMAL POTENTIAL ON THE CASE OF A BLOCK OF FLATS

In Tab. 2 a brief example is provided to explain how the shallow geothermal potential affects the costs of an installation in some town centres of the Aosta Valley. A block of flats with an annual energetic heating demand of 140 MWh/y is considered. The cost of the heat pump is constant for all the interested sites, while the number of required boreholes depends on their length and on the geothermal potential of the town.

The cost of a 70 kW power heat pump (considering 2,000 equivalent full load working hours per year) can be estimated at 55 k€; the cost of drilling and installation of each borehole is considered 5 k€, considering a fixed length of 100m, which is a common installation practice since borehole pipes are usually delivered with such standard lengths. The number of boreholes is the ratio between the energetic demand and the geothermal potential of the town and is rounded to the upper unit. The total cost is considered as the sum of both mentioned costs. Cost variations (Δ cost in Tab. 2) are calculated compared to the most favourable case. These variations deeply influence the economic return of a GSHP in these locations, thus driving the choice of the heating technology. In the Aosta plain, for example, due to the presence of a productive and thick aquifer, the installation of open loop systems can be an economic alternative: considering a cost of 15 k€ per well, the total cost for the heat pump and the well doublet can be finally estimated in 85 k€ (-37% than the closed loop solution).

CONCLUSIONS

Shallow geothermal potential maps are useful tools for the evaluation of the installation costs, and hence of the economic feasibility of GSHP at a certain installation site.

In this paper, we presented the assessment and mapping of the closed-loop shallow geothermal potential in the Aosta Valley depending on the ground thermal properties and on the utilisation profile. According to the results, the following conclusions can be made:

- the closed-loop geothermal potential of the Aosta Valley is highly variable, due to the wide range of variability of the thermal conductivity (from 1.70 to 3.52 $Wm^{-1}K^{-1}$) and the undisturbed temperature of the ground (from 5 to 15°C in the elevation range considered);
- the highest values of geothermal potential (12 to 15 MWh/year with a 100 m long BHE) are achieved in schists and mica schists at elevations below 1000 m a.s.l., due to the contemporarily high thermal conductivity (up to 3.52 $Wm^{-1}K^{-1}$) and the intermediate value of ground temperature (over 10°C);

TABLE 2

Installation costs of a standard GSHP plant in different Municipalities. The number of required 100m-deep boreholes is reported, along with the exact required length (in brackets).

Municipalities	P_{BHE} (MWhy^{-1})	Number (and exact length) of BHEs	Total cost (k€)	Δ cost
Ètroubles	14	10 (1000 m)	105	-
Courmayeur (South)	13	11 (1076 m)	110	+5%
Champorcher	12.5	12 (1120 m)	115	+10%
Chamois/Cogne	12	12 (1167 m)	115	+10%
Gressoney la Trinité	10	14 (1400 m)	125	+19%
Aosta Plain	9	16 (1555 m)	135	+29%
Pont St Martin/ Verres	8.5	17 (1647m)	140	+33%

- large areas with a good potential (from 11 to 13 MWh/year) are found in the lateral valleys;
- the alluvial plains of Aosta, Verres and Pont-Saint-Martin have a much lower potential for closed-loop systems (below 10 MWh/year) due to the low conductivity of the alluvial cover.

The work presented in this paper will be further developed in the future. In particular, the potential for open-loop geothermal systems will be studied for the Aosta plain, which seems very promising for the large-scale implementation of this technology. The maps reported in this paper will be published in a web GIS and will serve as a planning tool for future GSHP installations.

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