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Territorial analysis for the implementation of Geothermal Heat Pumps in the Province of Cuneo (NW Italy)

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Abstract

The efficiency of Geothermal Heat Pumps (GHPs) strongly depends on the site-specific parameters of the ground, which should therefore be mapped for the rational planning of shallow geothermal installations. In this paper, a case study is presented for the potentiality assessment of low enthalpy geothermal energy in the Province of Cuneo, a district of 6900 km^2 in Piedmont, NW Italy. The available information on the geology, stratigraphy, hydrogeology, climate etc. were processed and mapped, and conclusions were drawn on the geothermal suitability and productivity of different areas of the territory surveyed.

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Keywords: Geothermal Heat Pump; Borehole Heat Exchanger; Ground Water Heat Pump; Renewable and Sustainable Energy; Smart City

1. Introduction

Geothermal Heat Pumps (GHPs) are an attractive type of technology for the heating and cooling of buildings, which should be promoted in smart city planning in order to improve the air quality in the urban environment. According to Saner et al. [1], a reduction of up to 90% of CO_2 emissions can be achieved, compared to methane boilers. From the economic viewpoint, these plants require a larger investment compared to the other heating and cooling technologies, which is usually recovered in less than 10 years by the reduction of the maintenance costs [2]. In Italy, the cost effectiveness of GHPs is still hampered by the high cost of electricity, and methane is the most adopted fuel for heating; however, this niche market is growing, especially for large size installations [3]. In order to foster a greater use of GHPs, it is necessary to know the most suitable areas for the installation of Borehole Heat

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Exchangers (BHEs) or Ground Water Heat Pumps (GWHPs), and to avoid installing these plants where they are not convenient. The rational planning of shallow geothermal installations requires the knowledge of those site-specific properties that strongly influence their efficiency, like the thermal conductivity of the soil, groundwater flow, ground temperature etc. Several projects on the mapping of the shallow geothermal potentiality have therefore been conducted in recent years. Gemelli et al. [2] developed a regional model for the Marche region (Central Italy) by combining geological and climatic data. The suitability for GHPs of 4 regions of Southern Italy (Campania, Apulia, Calabria, Sicily) was mapped considering both the heating and cooling operating modes and carrying out an extensive campaign of *in situ* measurement of the thermal properties of the ground [4]. Fewer projects have focused on GWHPs, since these plants are usually installed for large size applications and need a thorough site characterization, which cannot conveniently be performed on a large scale [5].

These and other studies represented the basis for the ongoing project of mapping the geothermal potentiality of the Province of Cuneo, in North-Western Italy, which is summarized in this paper. The work started with the collection of available data for the characterization of the subsoil and hydrogeology of the territory surveyed, on its climate and on technical obstacles like landslides, polluted sites etc. The data were processed to produce maps of the most important parameters that affect the efficiency of shallow geothermal plants and to give an indication of their convenience in some of the most important settlements of the Province.

2. Project description

2.1. The territory surveyed

The territory of the Province of Cuneo can subdivided into three main parts: the alpine valleys on the western and southern edges, the plain situated in the centre of the Province and the hills of Langhe and Roero on the eastern side. The main rivers are the Tanaro, which divides the plain and the hills of Roero (on the left bank) and Langhe (on the right bank), and the Stura di Demonte. The Western Alps are the result of a complex geodynamic process which consisted of a first oceanic lithosphere subduction phase (Late Cretaceous – Paleocene, 100Ma-56Ma BP) and a second phase of continental collision accompanied by the formation of an accretionary prism (Eocene – Present). This resulted from different accretion stages characterized by the piling of several geological objects deriving from the Piedmont ocean, Iberic plate, European plate and Adria plate [6]. The prevailing outcropping lithologies in the south-western part are gneiss, limestone, calceschist and, to a lesser extent, clay and granite [7]. The hills of Langhe and Roero, together with the confining hills of Monferrato, were formed in the Miocene (25 Ma BP) by the uplifting of the Tertiary Piedmontese Basin, composed of sedimentary rocks (marl, sandstone, siltstone, evaporite) of marine origin. The capture of the Tanaro river, which deepened its bed and migrated eastward with a sudden switch in the proximity of the town of Bra, led to the formation of a thick network of valleys that split the high plain into the Langhe and Roero hills, and to the excavation of the tributaries of the Tanaro, in particular Stura, Pesio, Ellero [8]. The plain is covered by Quaternary fluvial sediments, with a thickness that ranges from 80÷100 m in the foothills of the mountains to a few metres in the distal portion of the plain, close to the Langhe and Roero. Large unconfined aquifers are present in the plain, which are described in the following chapter.

2.2. Selection of the parameters to be mapped

Geothermal Heat Pumps can be grouped into two main categories: closed loop plants, in which the heat exchange is performed through the circulation of a fluid in a pipe loop buried in the soil, and open loop plants, where heat is exchanged with groundwater extracted from a well [9]. This distinction is essential for the comprehension of the main parameters that influence the efficiency of these two kinds of plants. Closed loop plants are mainly Borehole Heat Exchangers, i.e. vertical boreholes usually of 100÷150m, while energy piles, i.e. pipe loops installed into foundation piles, and horizontal closed loops are niche applications that were not taken into account in this work. Thermal conductivity is the most influential parameter for the performance of BHEs, and thermal advection can noticeably enhance their thermal exchange capacity, depending on groundwater flow velocity and, to a lesser extent, on the saturated thickness of the aquifer [10-12]. On the other hand, the influence of the thermal conductivity of the ground on GWHPs is almost negligible [13]. The efficiency of open loop plants depends on the groundwater temperature, which influences the Coefficient Of Performance (COP) of the heat pump, and on the depth to water table, which influences the energy consumption of the well pump [9]. If water is reinjected into the same aquifer, thermal recycling should also be assessed, since the return of thermally altered groundwater to the extraction well can heavily impair the performance of a GWHP [14]. Following these considerations, we have therefore analysed the spatial distribution of the thermal conductivity of the ground, the temperature of the ground and groundwater, the depth to water table, the transmissivity and the hydraulic gradient of the shallow aquifers of the plain. In the following chapter, the methods of parameter mapping are explained, some preliminary results are shown and conclusions are drawn on the effect of these parameters for the installation.

3. Results

3.1. Thermal conductivity of the ground

The thermal conductivity of subsoil is strongly correlated to the lithology of the layers that are crossed. Literature data show that igneous rocks (granite, quartzite etc.) are the most conductive lithologies, followed by metamorphic (gneiss, calceschists etc.) and sedimentary rocks (marl, sandstone, limestone etc.) [4]. Rocks usually have a low porosity, and the influence of water saturation on thermal conductivity is therefore very limited. By contrast, the thermal conductivity of saturated sedimentary layers is usually 4÷5 times higher (about 1.6÷2.5 $Wm^{-1}K^{-1}$) than that of dry sediments (0.4÷0.5 $Wm^{-1}K^{-1}$). Two different methods were therefore adopted for mapping the thermal conductivity, starting from the Geological Map of Piemonte [7]. In the mountainous and hilly parts of the territory surveyed, the values were directly assigned to the mapped outcropping rock. For the plain, which is covered by Quaternary sediments and contains one or more aquifers, the depth-averaged thermal conductivity was calculated assigning a thermal conductivity of λ_{dry}=0.5 $Wm^{-1}K^{-1}$ to the unsaturated zone (from the ground surface to the water table) and a conductivity of 2$Wm^{-1}K^{-1}$ to the resting depth up to 100m, which is deemed to be water-saturated. The spatial distribution of the thermal conductivity of the ground is reported in Fig.1 and reveals that the values range from about 1 to 3.5 $Wm^{-1}K^{-1}$. The most conductive ground is found in the mountains in the western and souther parts (more than 2.5 $Wm^{-1}K^{-1}$) due to the presence of igneous (granite) and metamorphic rocks (gneiss, calceschists). The least conductive ground (1÷1.5 $Wm^{-1}K^{-1}$) is found in some portions at the edge of the plain and close to the Alps and on the high plains close to Fossano, which are characterized by a high depth to water table (i.e. 30÷60 m). In these areas, Borehole Thermal Energy Storage (BTES), which takes advantage of low ground thermal conductivity, could be considered as an alternative [15]. The hills of Roero (Bra, Canale, Sommariva Bosco) and the Langhe (between Alba, Cherasco and Ceva) are mainly formed by sandstones and marls, with a thermal conductivity of about 2 $Wm^{-1}K^{-1}$. Similar values are found in the northern part of the plain (Saluzzo, Savigliano, Racconigi), where the depth to water table is less than 5 m.

3.2. Temperature of the shallow ground

Ground and subsurface water have a large thermal inertia, and hence the temperature oscillations are dampened, the ground at small depths is almost constant and its value is very close to the annual mean air temperature. This is the main advantage of the ground compared to the air as a heat source, since it is warmer than air during Winter, and cooler during Summer. Since data from borehole measurements were very scarce, the undisturbed ground temperature was estimated from the terrain elevation, adopting the correlation of Signorelli and Kohl [16]. As suggested by the authors, elevations above 1500 m a.s.l. have not been considered in our work, thus excluding 25% of the territory of the Province of Cuneo (but less than 1% of the population), which is located at a higher elevation.

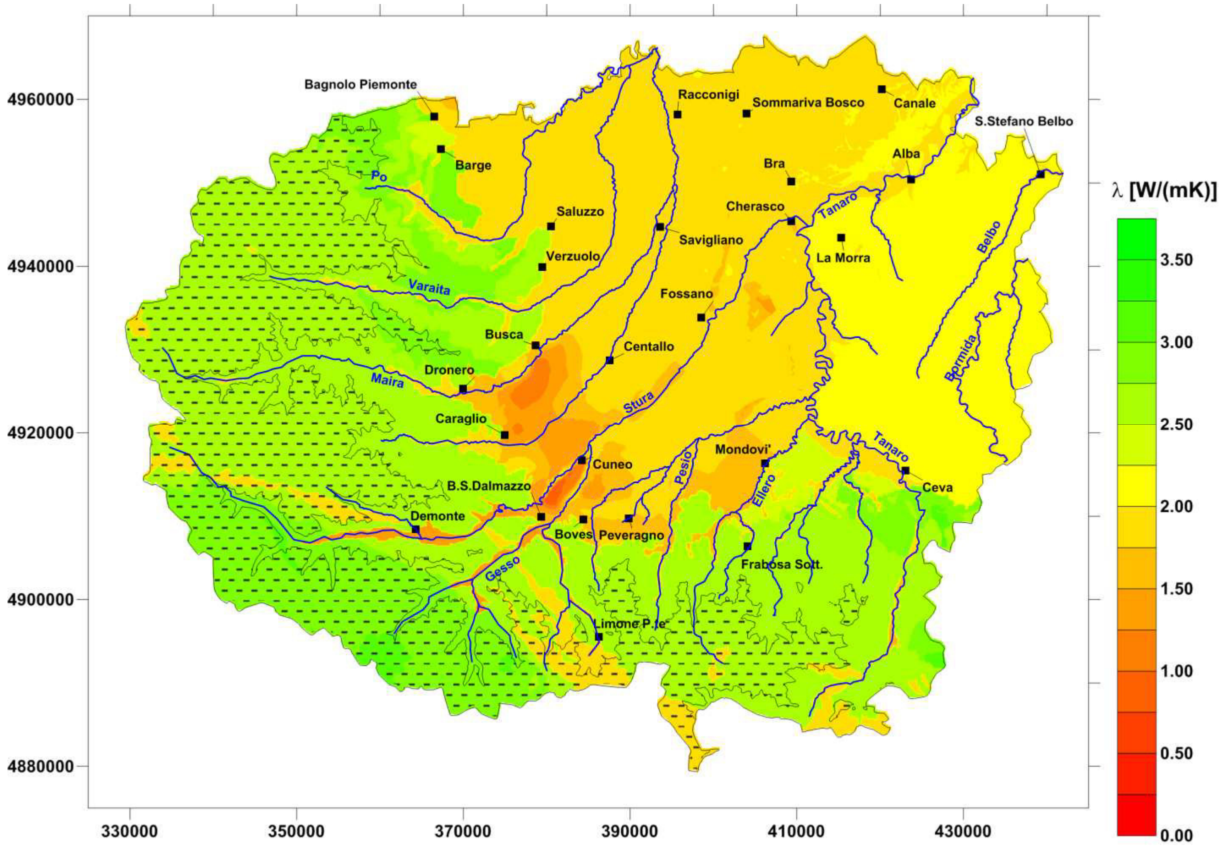

Fig. 1. Map of the estimated thermal conductivity of the ground in the Province of Cuneo.

3.3. Potentiality and efficiency of BHE

The thermal conductivity (λ), the thermal capacity (ρc) and the undisturbed temperature of the ground (T_0) are the most important input for the dimensioning of Borehole Heat Exchangers. Groundwater flow can dramatically enhance the performance of BHEs, but it can only be taken into account with sophisticated numerical methods if site-specific hydrogeological parameters are available [10-12]. The ASHRAE method of Kavanaugh and Rafferty [17], which does not take into account thermal advection and dispersion, was adopted to estimate the length of the BHE to be installed for a heating-only application with a thermal load of 9 MWh/y extracted from the ground, which was modified to take into account the degree-days of different towns and villages compared to Turin (2,617 DD). The results of the dimensioning of the BHEs are reported in Table 1. The length of the probes to be installed varies between 120 m and 267 m, and a strong influence of the undisturbed ground temperature is observed. For this reason, BHEs are hardly sustainable at high elevations. The payback time of BHEs for the replacement of a methane boiler was calculated adopting the unit costs of BHE drilling (50 €/m), of methane (0.10 €/kWh) and electric power (0.23 €/kWh) in Italy. The adopted value of the cost of the heat pump is 6,000 € and the COP was set equal to 4, which is a representative value for a GSHP. The Italian fiscal incentive was taken into account, which is equal to the 65% of the total expense is reimbursed over a period of 10 years.The analysis reported in Table 1 shows that the payback time is quite long (about 11 - 15 years) if the heat pump is fed with electricity from the grid, since its cost is very high compared to other European countries. For this reason, the implementation of a 3 kW photovoltaic (PV) plant equipped with storage batteries was considered, with a total cost of 13,500 €. Such a plant can cover the whole electricity needs of the heat pump and it reduces the payback time to about 9 - 12 years.

Table 1. Evaluation of the adoption of BHEs to heat a small detached house, in different towns of the Province of Cuneo.

Town	Population	Elevation [m a.s.l.]	Degree -days	λ [W/(mK)]	ρc [MJ/(m³K)]	T_0 [°C]	BHE length [m]	Cost of BHE(s) [€]	Payback Time [years]	Payback Time with PV [years]
Cuneo	55697	534	3012	1.8	2.5	10.83	184	9200	13.43	10.77
Alba	30925	172	2528	2	2.5	13.53	120	6000	12.63	11.41
Bra	29298	290	2614	1.8	2.5	12.53	141	7050	13.28	11.49
Fossano	24374	375	2637	1.9	2.5	11.89	145	7250	13.37	11.47
Mondovì	22277	395	2640	1.7	2.5	11.75	156	7800	13.91	11.69
Savigliano	21142	320	2817	1.9	2.5	12.30	150	7500	12.75	10.84
Saluzzo	16834	340	2735	1.9	2.5	12.15	147	7350	12.99	11.10
Borgo S. Dalmazzo	12294	636	3104	1.6	2.5	10.24	214	10700	14.32	11.00
Limone Piemonte	1467	1009	3566	1.8	2.5	8.50	267	13350	14.44	10.42
Frabosa Sottana	1513	641	3110	2.7	2.25	10.22	161	8050	10.93	9.11
La Morra	2751	513	2951	2.1	2.25	10.96	166	8300	11.60	9.59

3.4. Potentiality and efficiency of GWHP

The evaluation of the suitability of GWHPs in such a large territory is very difficult, due to the very different values of the most influential parameters. The dimensioning of these plants is based on site-specific parameters, but a general evaluation of the potentialities of each aquifer can be performed by observing the available pointwise data. The Water Protection Plan of Regione Piemonte [18] individuated three large shallow aquifers in the Province of Cuneo, which are delimitated by the main rivers. The *Pianura Cuneese*, on the left bank of the Stura river, is the largest one (1117 km^2) and it is already exploited by some 15000 irrigation and industrial wells. The transmissivity estimated by well and aquifer tests is in the order of 10^{-2} m^{2}s^{-1}, while the hydraulic gradient usually ranges between 2 and 7 m/km and the thickness is between 20 and 50 m. These values reveal that limited thermal recycling may occur even for very large plants, e.g. 1 MW [14]. In the south-western part of the plain (Cuneo, Borgo San Dalmazzo, Caraglio, Dronero), the high depth to water table (30÷60 m) can partially reduce the efficiency of these plants, due to the higher energy consumption for pumping, while care should be taken if injecting water in the northern part of the plain, where the depth to water table is below 5m and groundwater flooding may occur. The *Destra Stura* aquifer (523 km^2) is positioned on the right bank of the Stura River. Compared to the other bank, the mean transmissivity of the aquifer is smaller (about $5 \cdot 10^{-3}$ m^{2}s^{-1}), the gradient is similar (5÷10 m/km) and the thickness is much smaller (5÷20 m, except for the south-western part close to Cuneo, where it reaches some 40m). The potentiality for GWHP is therefore smaller than on the *Pianura Cuneese*, and installations of more than 100 kW are hardly sustainable. The alluvial aquifer of *Fondovalle Tanaro* (111 km^2) is a very narrow strip (1÷4 km) along the river Tanaro. It is quite thin (about 10 m), with a small gradient (about 2 m/km) and a transmissivity in the order of 10^{-3} m^2/s. Small installations of less than 50 kW may be possible, however care should be taken due to the complex flow field, the presence of close geological boundaries, the small depth to water table (less than 5 m) which could be a problem for the reinjection, and the feeding, which is mainly based on rainfall infiltration.

4. Conclusions

In this paper, we presented the preliminary results of a study on the potentialities of GHPs in the Province of Cuneo. The most important parameters for the dimensioning of closed loop (thermal conductivity, ground temperature) and open loop (aquifer thickness, transmissivity and gradient) geothermal plants were reviewed and processed. The following conclusions can be drawn:

- most of the potential installations of BHE can be performed on the plain and in the hills of Langhe and Roero, where a thermal conductivity of about 1.5÷2 Wm^{-1}K^{-1} is estimated and the ground temperature is sufficiently high (11÷14°C). In addition, a strong groundwater flow is usually present, thus enhancing the thermal transport in the shallow subsoil. In the Alpine zone, very conductive lithologies are present, however the geothermal potentiality is strongly limited by the low ground temperature (i.e. less than 9°C);

- the payback times of BHEs are quite long due to the high cost of electricity in Italy, however they can be reduced with the installation of a photovoltaic plant to cover all the needs for electricity of the heat pump;
- most of the inhabitants live on the left bank of the Stura River (*Pianura Cuneese*), where a thick and permeable shallow aquifer with a strong groundwater flow is present. Large GWHP can be installed, e.g. for supermarkets, blocks of flats, industries. On the other large alluvial plain (*Destra Stura*), smaller installations are feasible, while the small plain along the Tanaro river (*Fondovalle Tanaro*) is scarcely suitable for open loop installations.

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