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Assessment and mapping of the closed-loop shallow geothermal potential in Cerklno (Slovenia)

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Abstract

The economic viability of Borehole Heat Exchangers (BHEs) depends on the ability of the ground to exchange heat, and maps of the shallow geothermal potential are therefore useful planning tools for future installations. In this work, we present the assessment of shallow geothermal potential in Cerklno, a mountain town of 5,000 inhabitants in western Slovenia. The recently developed G.POT method was applied, taking into account site-specific ground thermal parameters and usage profiles depending on climate conditions. This work is part of the EU-funded project GRETA, aiming at supporting the diffusion of GSHPs in the Alpine territory.

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Keywords: Geothermal potential; Ground Source Heat Pump, Borehole Heat Exchanger; Cerklno

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1. Introduction

In recent years, the European Union set the ambitious “20-20-20” strategy to cut 20% of the primary energy consumption and 20% of the greenhouse gas (GHG) emissions compared to 1990 and to cover 20% of the energy demand with renewable sources [1]. Heating and cooling of buildings account for about 40% of the total primary energy consumption [2], and the building sector has large margins of improvement both for energy saving and for the implementation of renewable energy sources. Woody biomass is often the cheapest fuel for building heating,

however its diffusion has already resulted in an unsustainable impact on the air quality, i.e. emissions of particulate matter, volatile organic compounds, polycyclic aromatic hydrocarbons, CO and NO_x [3, 4]. Solar thermal energy requires a large surface of panels for building heating, and hence it is usually adopted as a complementary source for applications such as domestic hot water [5]. The heat pump is acknowledged as the pillar of a strategy for 100% renewable and sustainable building heating both for individual systems [6] and district heating networks [7]. Heat pumps exploit different renewable heat sources, such as the air (aerothermal), surface water (hydrothermal), aquifers and the shallow ground (ground-source). Ground-source heat pumps (GSHPs) are generally the most efficient, since they take advantage of the relatively stable temperature of the subsurface to achieve a higher value of the seasonal performance factor (SPF) compared to aerothermal HPs [8]. The number of such installations in Europe exceeded 1.7 million in 2015, with around 80,000 units sold and a total installed capacity of 23 GW [9]. However, the contribution of GSHP to the reduction of GHG emissions is still marginal, except for countries such as Sweden and Switzerland [10]. The main reason is the high cost of installation for the heat pump and the drilling, especially for borehole heat exchangers [11]. In addition, the cost of electricity is high in most of EU countries, e.g. Germany and Italy, due to high taxation [12]. The growth of the use of shallow geothermal energy is also limited by a complicated regulation and by the scarce knowledge on the possible applications of this renewable energy source. To overcome these issues, the project GRETA (near-surface Geothermal REsources in the Territory of the Alpine space) was developed by the Technical University of Munich with 11 other partners from Germany, Italy, France, Switzerland, Austria, and Slovenia [13]. In this project, the shallow geothermal potential will be quantified in six case-study areas selected in the participating countries. This paper presents the studies performed for the area of Cerklno (Slovenia). The geological and hydrogeological settings of this territory, along with its climate, are studied, gathering data from different sources to provide the input data for the estimation of the closed-loop shallow geothermal potential, which is defined as the amount of heat that can sustainably be abstracted by a borehole heat exchanger (BHE) with a certain length [14]. The map of the shallow geothermal potential identifies the most suitable areas for the implementation of closed-loop GHPs, thus providing a useful tool for energy planners and public administrators of this territory.

2. The territory of Cerklno

Cerklno is a municipality of 4644 inhabitants divided into 30 dispersed settlements, among which the largest is Cerklno (1523 inhabitants), with 13 other hamlets of 100 to 300 inhabitants (Table 1) which are shown in the map of Fig. 1. Ground elevations range between 250 and 1500 m a.s.l., but 90% of the population lives below 700 m a.s.l. and the highest settlement is located at 836 m a.s.l.

Since oil is still the most adopted heating fuel, the municipality of Cerklno is planning a long-term strategy for the gradual transition to carbon-free heating and cooling, and geothermal energy has an important role in this plan. In recent years, a biomass micro-district heating system was implemented, which provides heat to the western part of Cerklno, including two kindergartens, primary school, music school, and a museum (Fig. 1). Furthermore, the system is linked to shallow geothermal energy system from 12 BHEs that currently provides heat and cool only to the Centre for School and Outdoor Education. Besides, at least 2 BHEs are in use for heating of individual houses elsewhere in the town. In the central part of the town, a swimming pool and a hotel are heated with thermal water from the deep and warm predominantly limestone aquifer, encountered in depths between 856 and 2004 m, with the most abundant part between 856 and 1540 m depth [15].

In this context, the assessment and mapping of shallow geothermal potential is a useful tool for the planning of future installations.

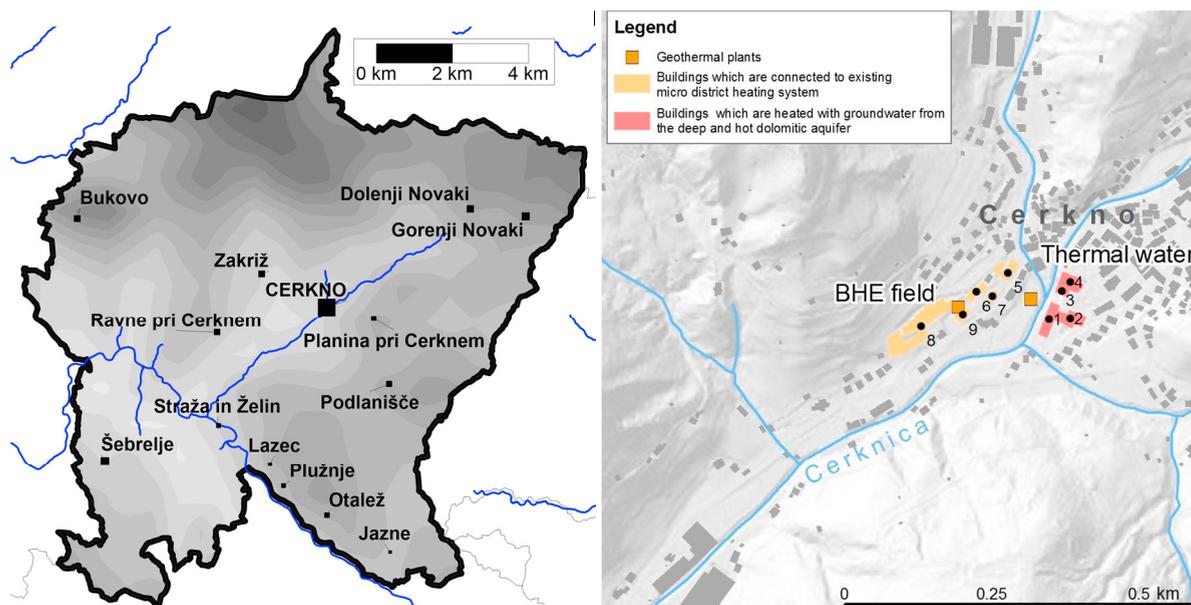


Fig. 1 On the left: map of the main settlements of the municipality of Cerklno. On the right: map of the settlement of Cerklno, the buildings heated with thermal water from deep warm dolomitic aquifer (1,3,4) and of the buildings connected to the micro district heating system (5-9).

Table 1. Main settlements of the municipality of Cerklno, sorted by population, according to Ref.[16], with the estimation of Heating Degree Days (HDD) with the ASHRAE method [17].

Name	Altitude (m a.s.l.)	Area (km ²)	Population	HDD
Cerklno	332	7.50	1523	2764
Šebrelje	639	11.89	289	3314
Gorenji Novaki	754	11.17	232	3283
Dolenji Novaki	628	4.13	211	3308
Zakriž	588	3.66	185	3189
Bukovo	709	8.73	179	3389
Ravne pri Cerknem	684	5.03	163	3513
Podlanišče	789	5.15	148	3735
Planina pri Cerknem	601	1.94	135	3129
Otalež	598	2.67	133	3059
Straža in Želin	252	6.06	119	2381
Plužnje	477	2.07	116	2850
Lazec	566	2.21	112	2974
Jazne	681	5.09	111	3068

2.1. Climate and Heating Degree Days

Cerklno has a typical continental climate, with an Alpine influence. According to data from the local weather station [18], temperatures range between -8°C in Winter during coldest nights in January to 32°C in the hottest days of July; however, average monthly temperatures vary in a narrower range, i.e. from 3°C to 21.5°C . The yearly

amount of precipitation is quite high (1485 mm/year) and well distributed throughout the year (90 to 178 mm/month).

The number of Heating Degree Days (HDD) based on the PVGIS database [19] confirms that the climate in Cerčno is strongly heating-dominated. HDD range from 2311 to 4136 in the 30 dispersed settlements, with a value of 2764 in the principal town (see Table 1).

2.2. Geology and hydrogeology

Most of the Cerčno municipality is covered by clastic rocks, while the rest of the outcrops is mostly composed of carbonate rocks, dominantly dolomites. Clastic rocks are mainly represented by alternation of sandstone and claystone. In the area of Črni vrh, a mountain close to Dolenji Novaki (Fig. 1), the alternation is in favour of sandstone, volcanoclastic tuff and tuffite, while claystone and siltstone are present in minor extent. These layers also characterize a part of Cerčno, as well as some other 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 a thin cover, less than 1m thick.

Clastic and carbonate rocks in Cerčno are mostly of fissured porosity, while karstic porosity is limited to small areas. Dolomites and limestones can be considered as aquifers with a lower permeability. Moderate permeability can be expected in some dolomite layers, especially in tectonized zones. Clastic rocks are mainly aquitards. In particular, sandstones can function as aquifers of weaker permeability while claystones and tuff layers, as a rule, represent hydraulic barriers. The thickness of alternating sandstone layers is usually less than a meter. Generally, groundwater is of favourable quality and weakly mineralized. Thermal water ($>20^{\circ}\text{C}$) is expected deeper than 600 m unless the ascendant flow from deep aquifer is located.

3. Methodology

The information presented in the previous chapter was used to derive the input data for the estimation of the closed-loop shallow geothermal potential. In this chapter, the G.POT method is shortly presented, also providing a background on previously developed methods. The processing of input data is then described, providing hints for future use of G.POT in other territorial contexts.

3.1. The G.POT method

The efficiency of BHEs mostly depends on the ground thermal properties, in particular the thermal conductivity and the undisturbed temperature, and the borehole length; the geometry and the materials adopted for the BHE affect its thermal resistance; groundwater advection and thermal dispersion can noticeably enhance the performance of these systems, but complex models or software are required to take these phenomena into account and an accurate site characterization is needed [20–22]. A number of sizing methods has been developed in the last decades to take into account these factors. The German norm VDI4640 provided the rule-of-thumb tables of the thermal power per unit length which can be exchanged considering two different usage profiles, i.e. 1800 and 2400 full-load equivalent hours per year [23]. Such tables are only based on lithology, without taking into account the ground temperature, which, by contrast, is included in the sizing tables of the British Standard MIS 3005 [24]. More recently, Casasso and Sethi developed the G.POT method for the estimation of the thermal power which can be exchanged with the ground by a BHE with a given length, taking into account a wide range of ground properties and operating parameters [14]. In addition to the aforementioned methods, G.POT can be used also for cooling mode, i.e. for warm climates or for cooling-dominated usage profiles (e.g. for most of office and commercial buildings).

The G.POT method is based on the assumption that the application of a cyclic thermal load (see Fig. 2) on a BHE with a length L (m), for an operating lifetime t_s (s) induces a time-varying thermal alteration of the ground and the heat carrier fluid, with respect to the initial temperature T_0 ($^{\circ}\text{C}$). A threshold temperature T_{lim} ($^{\circ}\text{C}$) is imposed, and the shallow geothermal potential \bar{Q}_{BHE} is the thermal load (expressed in W or in MWh/y) for which the maximum thermal alteration $|T_0 - T_{lim}|$ is achieved over the lifetime t_s . The alteration of the fluid temperature $T_f(t)$ is

calculated with the Infinite Line Source solution [25], applying the superposition principle to take into account the time-varying thermal load. The shallow geothermal potential \bar{Q}_{BHE} is described by the following formula:

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

where λ ($\text{Wm}^{-1}\text{K}^{-1}$) is the ground thermal conductivity, R_b (mKW^{-1}) is the borehole thermal resistance. $G_{max}(u'_s, u'_c, t'_c)$ is a function of three non-dimensional parameters t'_c , u'_c and u'_s :

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

with $t'_c = t_c/t_y$, $u'_c = \rho c \cdot r_b^2/(4\lambda t_c)$, $u'_s = \rho c \cdot r_b^2/(4\lambda t_s)$ where t_c (s) is the length of the heating season (set to 183 days), and t_y is the length of the year; ρc ($\text{Jm}^{-3}\text{K}^{-1}$) is the thermal capacity of the ground; t_s (s) is the simulated lifetime of the plant (set to 50 years).

The input data for the estimation of the geothermal potential are therefore:

- ground thermal parameters: thermal conductivity λ ($\text{Wm}^{-1}\text{K}^{-1}$), thermal capacity ρc ($\text{Jm}^{-3}\text{K}^{-1}$) and undisturbed temperature T_0 ($^{\circ}\text{C}$). For these parameters, the spatial distribution should be provided;
- the length of the heating season (t_c), which depends on the climate and may be fixed for the entire mapped area, or assigned with different criteria (e.g. ground elevation or HDD);
- the properties of the BHE, i.e. its radius (r_b) and its thermal resistance (R_b);
- settings of the plant, i.e. the threshold fluid temperature (T_{lim}) and the lifetime of the system (t_s).

Further information is available at <http://areeweb.polito.it/ricerca/groundwater/geotermia/GPOT.html>

The choice and the processing of such input data are discussed in next paragraphs.

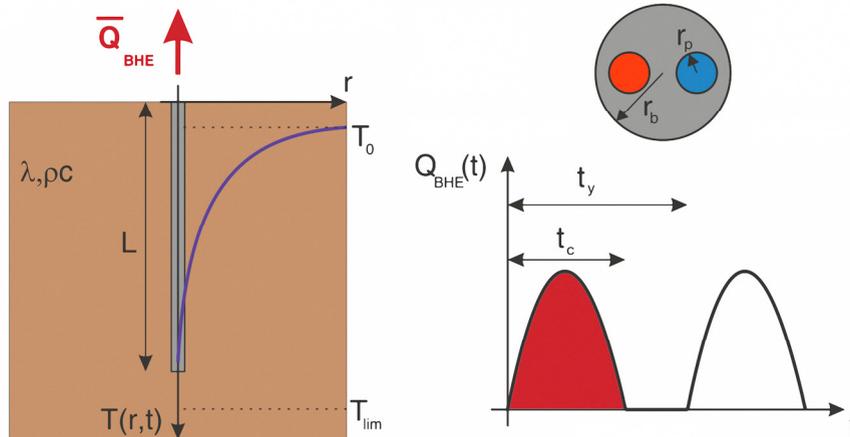


Fig. 2 Conceptual schemes and input parameters of the G.POT method (from Casasso and Sethi, 2016 [14]).

3.2. Processing of input data

3.2.1. Ground thermal parameters

Based on the geological maps, rock samples from the most representative geological units were collected in the field, with multiple samples per column in case of very heterogeneous rock successions (Fig. 3). The samples were prepared for the laboratory measurements with the Thermal Conductivity Scanning (TCS) method [26, 27], keeping

them as intact as possible and with their pristine water saturation. For the TCS method, a low tolerance is prescribed for the flatness of the sample (+/- 0.5 mm), and hence samples are cut with a circular saw to cope with this requirement. A precision of ±3% is achieved in the measurement range of 0.2 to 25 Wm⁻¹K⁻¹.

A total of 16 samples (28 single rock pieces) from the area of the Cerkno town and of 16 samples (23 single rock pieces) from the wider Cerkno municipality was analyzed. Dolomites (massive and layered), quartz sandstones and conglomerates, dolomitic limestones, and certain tuffs (keratophyre, porphire) proved to be the most conductive lithologies, but also other rock types such as limestones, carbonatic sandstones, siltstones and diabase revealed good thermal properties. The observed thermal conductivities matched well with the values in the SIA [28] and VDI 4640 standards [23], as well as to literature values [29]. The thermal capacity values were derived from the mentioned standards. Generally this parameter does not exhibit large ranges, as they are between 1.8 and 2.9 MJm⁻³K⁻¹ for all present rock sequences.



Fig. 3 Scanning of some rock samples (limestone, dolomite, marly limestone) with the TCS meter.

The lithology was interpreted down to a depth of 100 m, which is a typical value for BHEs. With this respect, the geometry of geological unit boundaries and tectonic contacts were taken into account as well as relations between different lithologies. Values of thermal conductivity and capacity were therefore estimated as the depth-weighted average values of λ and ρc for each rock type, according to a simplified lithological distribution.

For the ground-surface temperature map, temperatures profiles from 458 boreholes in Slovenia were processed, and 157 synthetic points based on purely conductive regime were added [30]. Boreholes temperature profiles they were classified according to their position (continental and coastal region of Slovenia) and to their exposition to sun radiation (S - sunny location, facing south, open space, and T - facing north, dark-shadow position, in the woods). Linear correlations with the altitude were found (Fig. 4), with the ground temperature about 1°C higher than the annual mean air temperature, and a high resolution GIS layer (25 x 25 m) was derived based on a DTM.

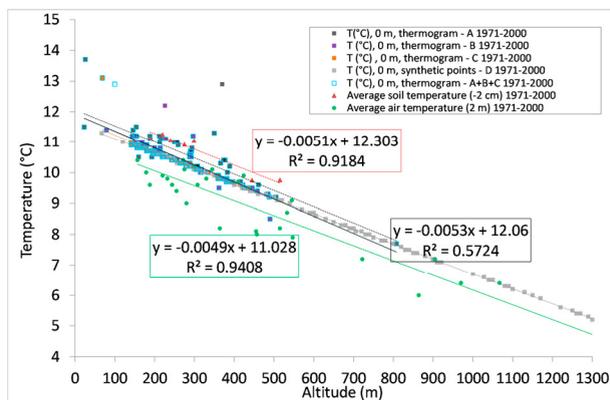


Fig. 4 Graph of temperatures depend on thermograms, soil temperature and air temperature in continental Slovenia [31].

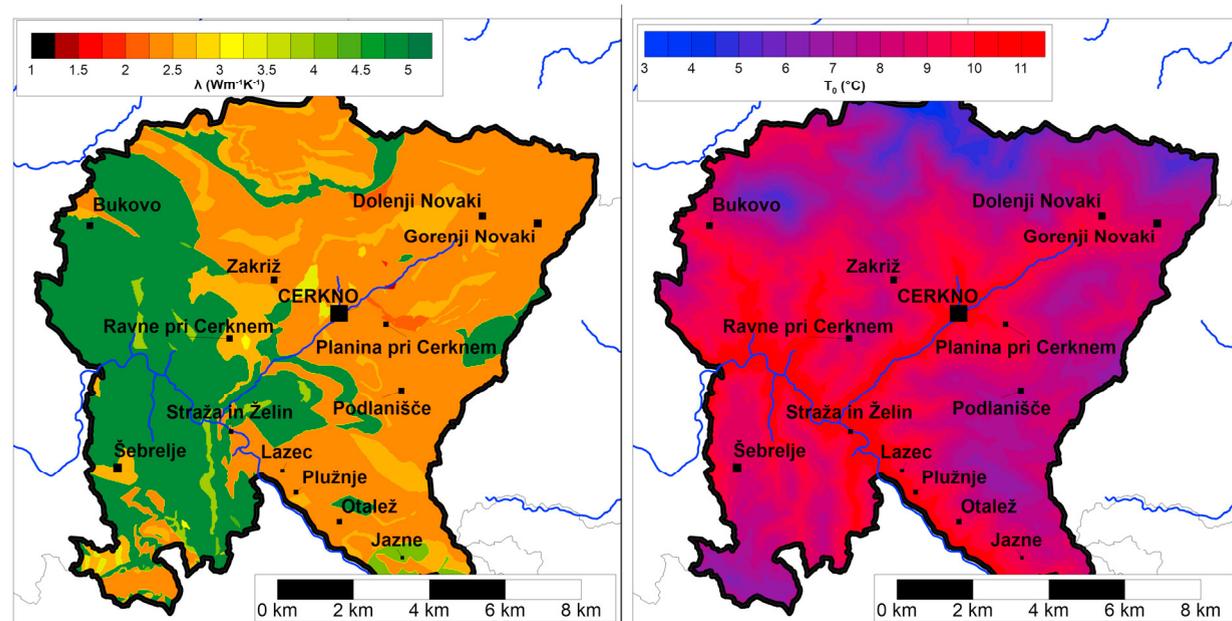


Fig. 5 Maps of the thermal conductivity (on the left) and of the undisturbed temperature of the ground (on the right).

3.2.2. Working parameters of the shallow geothermal system

The shallow geothermal potential also depends on a number of parameters dealing with the HVAC system, which are hereby described. First of all, the heating mode was considered for the assessment of the geothermal potential since, as described in Chapter 2.1, the climate is strongly heating-dominated. The length of the heating season (t_c) was estimated considering a previous study by the Meteorological Office of ARSO (Environmental Agency of Slovenia) [32]. The warmest town in Slovenia is Portorož, in Istria, with 1955 HDD and a heating season length of 191 days (28th October – 6th May), while the coldest site is Kredarica at 2515 m a.s.l., with 7386 HDD which makes it necessary to keep heating plants almost always switched on. Cerklje (2764 HDD) is located in an intermediate climate zone, similar to Maribor (2848 HDD), for which a heating season of 242 days (25th September – 24th May) is foreseen. HDD and ground elevation in the settlements of Cerklje show a strong correlation (Table 1), which is also observed between HDD and length of the heating season in Slovenia [32]. According to such consideration, a classification for altitude range was derived, namely $t_c = 240d$ for elevations below 500 m a.s.l., $t_c = 270d$ for elevations between 501 and 700 m a.s.l., and $t_c = 300d$ for elevations above 700 m a.s.l.. A typical BHE length $L = 100m$ was considered, and the ground thermal parameters reported in previous paragraphs are averaged on this depth. Longer BHEs could be installed to take advantage of higher ground temperatures, in particular at higher altitudes. The BHE radius was set to $r_b = 0.075m$, with a thermal resistance $R_b = 0.1mKW^{-1}$. The minimum fluid temperature was set to $T_{lim} = -3°C$ and the lifetime considered for the system is $t_s = 50y$.

4. Results and discussion

With the input data sets described in the previous chapters, the shallow geothermal potential was calculated with the G.POT method, and the resulting spatial distribution is shown in Fig. 6. The geothermal potential P_{BHE} ranges from 8 to 15 MWh/year, and most of settlements have a potential between 8 and 10 MWh/year. Higher values are found in the area covered by highly conductive dolomite (4 to 4.8 $Wm^{-1}K^{-1}$) in the villages of Bukovo (15 MWh/year), Orehek and Reka (14 MWh/year), Jagrščje, Police and Jazne (12 MWh/year). Generally speaking, the high thermal conductivity of the ground compensates the effect of the relatively low ground temperature, and hence the shallow geothermal potential has quite high values for a mountain area.

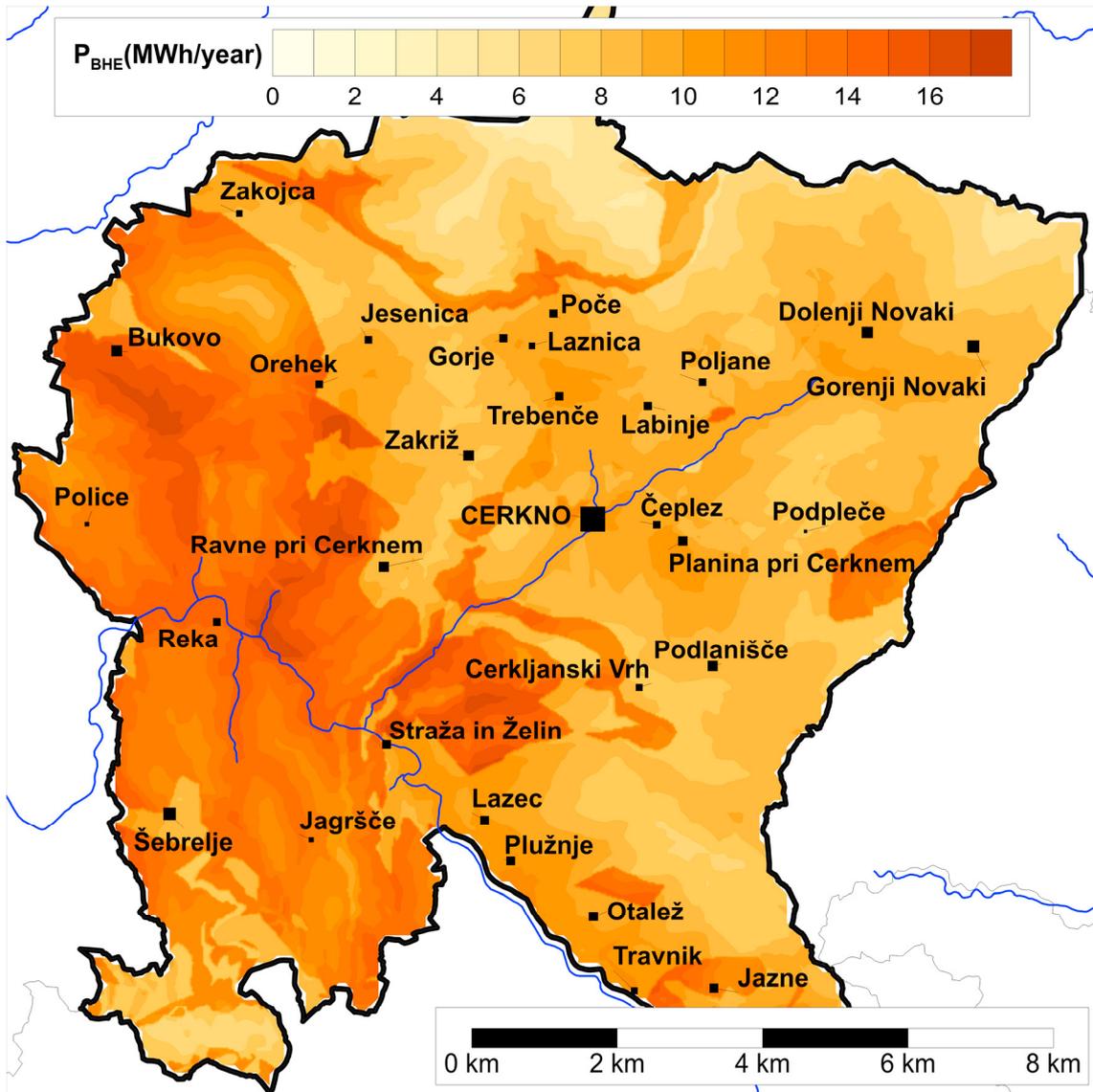


Fig. 6 Map of the shallow geothermal potential P_{BHE} (MWh/year).

A comparison can be made with other methods, such as the VDI4640 [23]. If we consider the highest yearly operating time (2400 hours/year), a heat extraction rate of 50 W/m can be attributed to the clastic rocks, while 70 W/m can be extracted from dolomites. For a 100 m deep BHE, this leads to a potential of, respectively, 12 MWh/year and 16.8 MWh/year, i.e. 20 to 50% higher than the values derived with the G.POT method. Such a difference can be attributed to the fact that the VDI4640 method does not take into account the undisturbed ground temperature, which is quite low in the territory of Cerkljanski Vrh.

The shallow geothermal potential has an impact on the drilling cost for BHE, on the total cost of a GSHP and hence on its economic suitability [33]. For example, if we consider a house with a heating need of 75 MWh covered by a heat pump of 30 kW, it turns out that 8 BHEs will be needed in Cerkljanski Vrh, where the potential is equal to 9.5 MWh/year, while 5 BHEs will be sufficient in Bukovo where the geothermal potential is 15 MWh/year. Hypothesizing a cost of 20 k€ for the heat pump with accessories and of 5 k€ for each borehole, the total installation costs are respectively 60 k€ and 45 k€. An increase of the geothermal potential of 58% therefore results in a

reduction of the installation cost of 25%. The influence of shallow geothermal potential increases at higher thermal power, for which the drilling of BHEs becomes the largest share of the total cost of the GSHP. Indeed, the cost per unit power of a heat pump dramatically decreases with its size, while the unit cost of borehole drilling has minor scale economies.

5. Conclusions

This paper presented the assessment and mapping of closed-loop shallow geothermal potential in the municipality of Cerklno, a mountain town in Slovenia. The shallow geothermal potential is here defined as the quantity of heat which can be efficiently exchanged by a BHE with a certain length, depending on the ground thermal properties and on the utilization profile. The input distributions of ground thermal conductivity and capacity were derived from detailed geological maps and on laboratory measurements on field samples. A length of 100 m was considered for the BHE, and ground thermal properties were therefore evaluated for the same depth. A strong correlation of climate (annual average air temperature and Heating Degree Days) was observed, and hence the ground temperature and the duration of the heating season were estimated based on a Digital Terrain Model.

The resulting map highlights that the closed-loop geothermal potential is quite high for a mountain area, since it ranges between 8 MWh/year and 10 MWh/year with even higher values, i.e. up to 15 MWh/year, observed in the western part of the municipality which is covered by a highly conductive dolomite.

The map of shallow geothermal potential will serve as a decision support tool for future installations. The good suitability for the installation of BHEs, which has been confirmed by this research, makes shallow geothermal energy a promising renewable energy source to achieve the ambitious carbon-free heating targets of the municipality of Cerklno.

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