A Method to Analyze the Performance of Geocooling Systems with Borehole Heat Exchangers. Results in a Monitored Residential Building in Southern Alps

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Abstract: Geothermal heat is an increasingly adopted source for satisfying all thermal purposes in buildings by reversible heat pumps (HP). However, for residential buildings located in moderate climates, geocooling, that implies the use of geothermal source for cooling buildings without the operation of HP, is an efficient alternative for space cooling not yet explored enough. Geocooling allows two main benefits: to cool the buildings by high energy efficiencies improving summer comfort; to recharge the ground if space heating is provided by HP exploiting the geothermal source (GSHP). In these cases, geocooling allows to avoid the decreasing of the performances of the GSHP for space heating over the years. To explore these issues, a method has been developed and tested on a real case: a new residential building in Lugano (southern Switzerland) coupled with 13 borehole heat exchangers. The system provides space heating in winter by a GSHP and space cooling in summer by geocooling. During a 40 months monitoring campaign, data such as temperatures, heat flows and electricity consumptions were recorded to calibrate the model and verify the benefits of such configuration. Focusing on summer operation, the efficiency of the system, after the improvements implemented, is above 30, confirming, at least in similar contexts, the feasibility of geocooling. Achieved results provides knowledge for future installations, underlining the replication potential and the possible limits.

Keywords: geothermal energy; geocooling; borehole heat exchangers; residential space cooling; radiant underfloor systems

1. Introduction

The role of buildings in relation to energy consumption is widely known on a global and local scale. To satisfy the growing energy needs, while reducing the related greenhouse gases (GHG) emissions, academic research and policies have been supported for decades the diffusion of different solutions. Relevant results can be obtained through the implementation of high efficient measures at envelope and HVAC (Heating, Ventilation and Air Conditioning) level. These measures allow decreasing the energy needs and increasing the integration of local RES for electric and thermal purposes, according to goals defined for 2030 and 2050 (reported at www.roadmap2050.eu), as described in [1] and, referring to Switzerland, in [2–4].

According to [5], geothermal energy is a renewable energy suitable for energy conversion to electricity as well as heating and cooling of different buildings and other facilities. The most popular technology to extract the shallow geothermal resources are GSHP (ground source heat pump) systems, which can be properly adopted for low temperature distribution systems such as floor heating and/or cooling systems.

In [6] Ground Source Heat Pumps (GSHP) are defined as energy efficient and environmental friendly systems for space heating and cooling in buildings, underlining the

recent remarkable growth of the installed capacity worldwide and the most important role in the direct uses of geothermal energy. Moreover, they observe that the introduction of the Nearly Zero Energy Buildings (NZEB) concept and standard is expected to further increase the penetration of GSHP in Europe.

A deep review of the worldwide applications of geothermal energy for direct utilization, updated at 2020, is presented in [7], underlining that this technology is one of the oldest, most versatile and most common forms to exploit this source. The paper presents information on direct applications of geothermal heat based on country update papers involving 113 countries and regions. Among these, Switzerland appears in the "top five" countries for installed capacity in terms of thermal power for population; in terms of installed capacity for land area; and in terms of annual energy use for area.

Indeed, in the European area, Switzerland, with more than 100,000 ground source heat pumps (GSHP), is a leader in the use of geothermal energy for heating and domestic hot water and recently has given insights about the appropriateness of using this source also for summer cooling.

In [7] it is included a complete description of geothermal applications in Switzerland, underlining that borehole heat exchangers with heat pumps are still the most spread application and that the number of GSHP, now increasingly used for heating and cooling, are growing constantly. In fact borehole heat exchangers amount to 1843.8 thermal MW and 10,733.8 TJ per year, more than the 80% of the total.

Reversible GSHP can have high performances during the whole year when conventional cooling systems are adopted, i.e., systems for removing sensible and latent heat and with a level of temperature of the carrier around 7 °C. Conversely, when reversible GSHP are coupled with radiant systems for providing heat and cool and the cooling mode is devoted at removing only sensible heat, the EER (Energy Efficiency Ratio, defined as the ratio of cooling capacity provided to electricity consumed and adopted in rating system air conditioners, allowing for straightforward comparisons of different units) can decrease due to the levels of temperature. In fact, the ground temperature is around 14–16 °C while the design temperature of the carrier is around 20–21 °C. In these cases different solutions can be searched, as reported also in [8] that, starting from the temperature comparison among indoor air, envelopes, fresh air and undisturbed soil, suggested an integrated system aimed at combining pipe-embedded walls, pipe-embedded windows, and fresh air pre-handling system with the conventional GSHP system with the aim to utilize shallow geothermal energy more efficiently.

By a different perspective, among the different options for promoting renewable district heating and cooling systems, in a deep review [9] considered also geothermal energy. In particular, the benefit of the geothermal energy used in district cooling system (DCS) worldwide are mentioned because this source is considered sustainable, cheap, and safe.

Among the solutions cited above, geocooling, i.e., "geothermal free cooling", allows removing heat from the buildings in summer exploiting the difference of temperature between indoor temperature and ground temperature, without the adoption of the GSHP. This technology has undergone a fair expansion in the last decade, in particular in Switzerland where there are hundreds of cases, according also to the current regulation that limits the adoption of traditional air conditioning systems. However, geocooling has not been yet very deepened in the technical literature. A state of the art for geocooling technology is presented in [10], summarizing results related to a dozen of existing buildings, underlining the need to design these solutions as an integral part of the whole building and that even if theoretical and technical knowledge is available, practical applications are few. Other contributions were provided by [11–13], dealing with geocooling potential for administrative buildings. More recently, [14] studied the effect of geocooling in combination with thermal energy storage (TES) to decrease the energy and carbon impact of cooling in a small, lightweight commercial building located in a Mediterranean climate. The study addressed the effectiveness of this solution, even if with a seasonal performance lower

than that achieved by the experience documented in the present work. An interesting update is reported in [15], with an investigation about the impacts of free cooling supply using ground-source heat pumps on the basis of the available pertinent literature. On their opinion, according to the few available literature, geothermal systems could also play an important role in meeting cooling demand through free and active cooling. In the comparison to other technologies, they stress the lowest impacts of free cooling configurations as a consequence of negligible electricity consumption and no additional equipment. However, the statement that geothermal free cooling has the lowest impacts cannot be generalized.

Focusing on the methods available for designing geocooling systems, insights are reported in [16] about PILESIM2 and in the recent [17], by a deep review of the modeling aspects and practices of shallow geothermal systems, and [18], which detail the comparison among active chilled beams and thermally activated building systems. In particular, [17] evidenced the lack of systematic design guidelines and reviewed the available modeling options (including PILESIM2) presenting the main analytical and numerical models and methods and discussing the most important supplementary factors affecting such modeling. At country level, the Swiss standards regarding geocooling are [19], the one more considered in the present work, and [20,21], where the term "geocooling" is used in combination with "freecooling" and "natural cooling".

In this framework, the contribution here presented is aimed at defining a method for analyzing the effectiveness of geocooling at least for residential buildings located in climate without extreme summer conditions. The method, described in Section 2 and Figure 1, includes energy simulation, the thermal characterization of the underground and the accurate design and simulation of the BHE field. This allows overcoming the lacks of a proper design of geocooling systems. The method is then tested on a real case and the work benefits from the direct participation of part of the authors in the interventions for improving and monitoring the performance of the same real case for which a large amount of monitored data are available. The described real case application has been promoted by the Swiss Federal Office of Energy and the Renewable Energy Fund of the Canton of Ticino, as a demonstration project deeply analyses in [22].
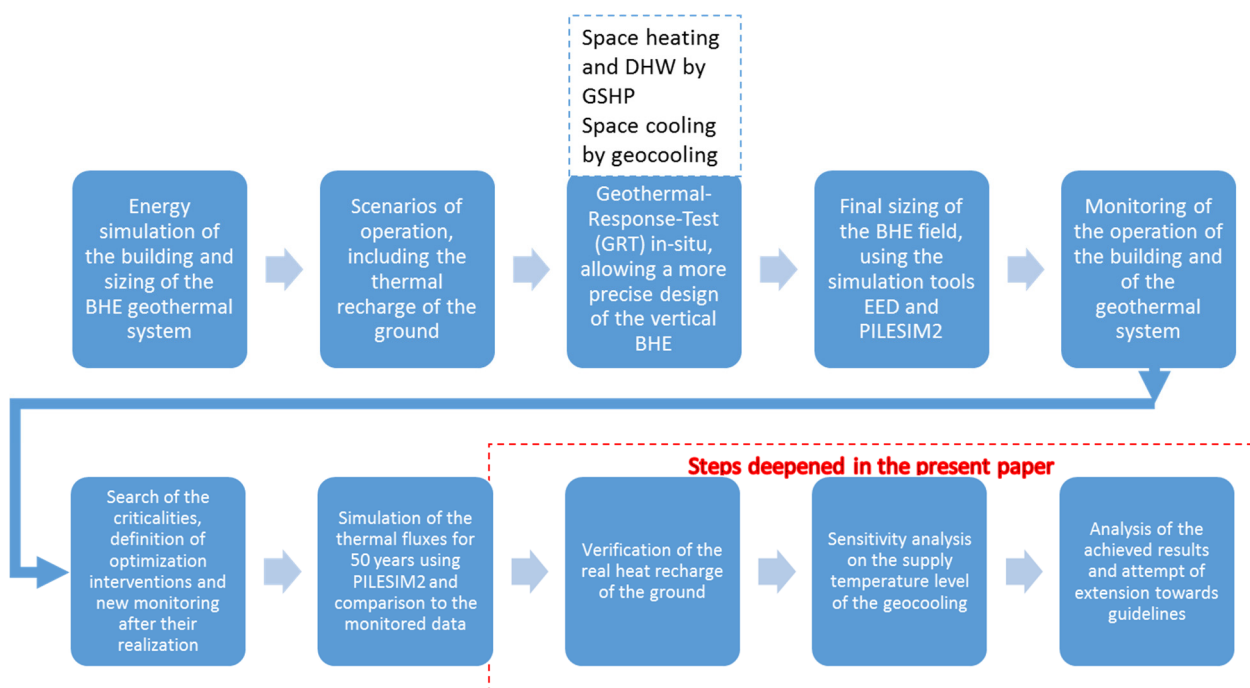

Figure 1. Scheme of the overall method.

2. Materials and Method

A method, able to include simulations and calibration, for analyzing geocooling systems has been developed and the following activities for testing the method in a real case, a new residential building in Lugano (southern Switzerland) have been accomplished:

1. Preliminary energy simulation of the building and dimensioning of the BHE geothermal systems. The total length and the number of BHE and their configuration have been defined to satisfy the building thermal needs. In this preliminary stage, some scenarios has been drawn, suggesting also the thermal recharge of the ground, showing its importance from the economic and energy point of view and stressing the need of deepening the investigation about the thermal behavior of the overall system;

2. Carrying out of the Geothermal-Response-Test (GRT) in-situ for a detailed study of the thermal characteristics of the ground according to [23]; the GRT allows a more precise evaluation of the length of the vertical BHE. When it is properly determined, supplementary costs are avoided;

3. Final dimensioning of the BHE field, using updated thermal needs and ground properties found by the GRT, by the simulation tools EED [24] and PILESIM2 [16]. The system was realized for providing space heating and DHW by GSHP, together with a solar thermal plant. The cooling demand of the building was expected to be satisfied with geocooling technology that can as well as recharge the ground.

4. Monitoring of the operation of the building and of the geothermal system, search of the criticalities, definition of optimization interventions and new monitoring after their realization;

5. Simulation of the thermal fluxes from and to the geothermal field for 50 years using the PILESIM2 program and comparison to the monitored data. This step is mainly aimed at verifying the real heat recharge of the ground in order to show the long-term effects; a sensitivity analysis on the supply temperature level of the geocooling was also set;

6. Analysis of the achieved results and attempt of extension.

The present paper deepens in particular the last steps of the method described and sketched in Figure 1, starting from the output of the simulations by PILESIM2 and on the comparison to monitored data. Further details about each steps of the method are reported in [22], the already mentioned project report, taking into account the same case study.

In relation to steps 1 and 2, the need of a detailed design of geothermal system has been stressed in the technical literature already in the first decade of 2000, as reported by [25] that provided a review of systems, models and applications about ground heat exchangers and, in the conclusions, referred to a typical residential house in Switzerland. More recently, the same need is stressed also by [26] that underlined the importance of the GRT and reported the results of an experimental analysis carried out in France referring to the heating and cooling performance. Within the framework of the IEA-ECES Annex 31, [27] provided a review of configurations, thermal response, analytical and numerical models and, analyzing the seasonal performances, illustrated the effect of proper design and sizing of such systems. In particular they underlined the need to develop general procedures for early stage sizing and with reasonable accuracy for energy piles.

PILESIM2 program has been cited in the technical literature, e.g., recently in the review by [28] that assessed of the impacts of system geometric configuration, pipe material, working fluid, and depth of ground heat exchanger on heat flux, heat transfer coefficient, outlet temperature, thermal resistance, and pressure drop, as a help in overtaking the lacks of knowledge that still affect this technology.

In relation to step 4, in order to verify the real operation of the system, several temperature sensors (thermocouples), flow meters and power meters were installed and connected to a data-logger. In addition, the indoor air temperature and humidity of a sample flat were constantly monitored, paying attention to the control of the heating and cooling system and to the indoor thermal comfort conditions.

It has to be noted that the optimizations have been discussed and then implemented by technical staff (not ever aware) and that each measure requires an entire season to be monitored and eventually corrected only the next year. Main optimization options were:

- Flow rate regulation of the geothermal BHE circuit (underground circuit);
- Adjustment of the intermediate circulation pumps;
- Flow regulation of the circulation pump of the underfloor circuit;
- Increase of the supply temperature of the geocooling circuit.

Further details about the optimization strategies implemented and monitored in relation to the present real case are reported in [22].

Finally, several exchanges with the technicians involved have been organized together with the realization of a survey with the tenants of the building by a questionnaire.

In relation to step 5, the importance of long-term evaluation is stressed e.g., in [29] that developed a detailed, effective and validated numerical model for transient simulation of borehole heat exchangers. PILESIM2, based on TRNSYS (a flexible software environment used to simulate the behavior of transient systems, in particular for assessing the performance of thermal energy systems as described at see trnsys.com), uses hourly thermal energy values (thermal energy actually exchanged with the ground) and then calculates the respective fluid temperature over the years. For the first three years, the simulated supply temperatures have been compared with the monitored ones. Several simulations have been run setting different supply temperature for geocooling, looking at the related effect on the cooling potential of the building.

The present article focuses mainly on steps from 4 and 6, as described in the following sections.

3. Results

According to the steps reported in Section 2, in the following sections are described the real case of study and the achieved results in terms of predesign evaluation and monitoring before and after optimization.

3.1. Case of Study

The building called "City Residence" is located in Lugano (southern Switzerland). It is a Minergie® building in operation since 2014, with 46 flats on 7 floors (see Figure 2) and an energy surface of 5700 m². Heating and cooling are provided by an underfloor radiant systems and a mechanical ventilation system with air-to air heat exchangers is also in operation.

Following the Minergie® standard referred to the age of the building, as average thermal transmittance, a U value of about 0.18 W/m²K was reached for the opaque façade and a U value of about 1.2 W/m²K was reached for windows.

In the beginning of the project and before the development of the study here reported, the energy behavior of the building has been simulated in steady state way, according to the local rules in force, i.e., [21,30], resulting in a design thermal power for space heating and DHW of about 130 kW and for cooling of about 80 kW.

In order to characterize the ground, a geothermal response test (GRT) was carried out in-situ on a BHE. The test revealed a thermal conductivity of the ground of 3.3 W/mK, a ground temperature on the surface of 13.7 °C, and a geothermal temperature gradient of 11 K/km.

Based on the preliminary thermal demands and geological literature data, a system of 17 BHE of 200 m depth was evaluated. The final dimensioning of the BHE field was achieved using updated thermal needs (estimated again in steady state way and before the development of the study here reported) and ground properties and taking into account a proper value of regeneration of the ground, i.e., the ratio between energy injected over energy extracted from the ground.

Figure 2. Rendering (**top**) and photograph (**bottom**) of the building located in the densely populated centre of Lugano (source: [22]).

These design conditions result in 13 BHE, with a depth of 200 m each, i.e., saving 4 BHE in comparison to the initial estimation (see Figure 3).

The thermal demands (heating and DHW) are expected to be satisfied by 3 HP coupled to the BHE field. A solar thermal plant of about 100 m^2 contributes to the supply of the DHW and of the space heating on yearly basis. Solar thermal heat in excess is not injected into the ground to avoid an unbalance of the temperature levels, during the geocooling mode.

According to the expertise of the authors, the thermal recharging of the ground is considered essential to ensure a constant efficiency during the operation of the system in the long term. To that end and based on the features of the building and of the emission system (underfloor radiant panels), a geocooling system coupled to the same BHE field has been implemented. This solution allows also to avoid the use of traditional cooling machines in summer and therefore to lower summer electricity needs for cooling.

As anticipated, the BHE field has been designed based on the winter needs satisfied by the HP. During winter season, the ground is thermally discharged, while during summer season geocooling can recharge the ground.

Figure 3. Position of 13 BHE under the building (source: [22]).

As a result of the sizing carried out by the design team, for a steady long-term operation of the system, it was suggested to set a recharge of the ground in the range between a minimum of 17% and a maximum of 52%. Indeed, if summer recharge is lower than 17%, the extraction of heat from the ground could be excessive compared to the injection; therefore this can cause a rapid decrease in the temperatures of the fluid entering the ground. While, if summer recharge is higher than 52%, the operation would limit the expected potential for geocooling. In addition, according to the expertise of the authors and the local thermo-hygrometric conditions, it was suggested to inlet water into the underfloor radiant system of the flats at temperatures equal or higher than 21 °C, in order to prevent too high relative humidity and vapor condensation on the indoor surfaces, but this suggestion was not considered by the technicians during the first period of operation.

During winter operation the geocooling circuit is switched off, the HP charge the heat storage tank and the system allows to heat the flats.

Figure 4 shows a simplified scheme of the analyzed system with the detail of the main hydraulic components in accordance to during the summer operation.
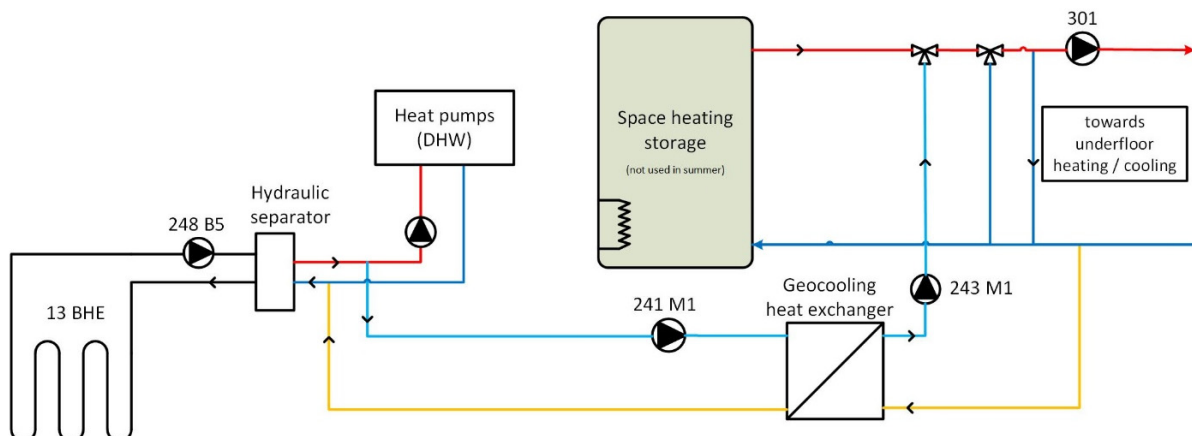
Figure 4. Scheme of the summer operation using geocooling (source: [22]).

3.2. Monitoring System and Campaign

The method is calibrated and tested according to a complete monitoring campaign. In order to analyze and verify geocooling benefits over several seasons, the years 2016 to 2019 have been monitored, starting at the end of June 2016.

For characterizing the outside environment, the weather data adopted are those recorded in the nearest meteo-station in Lugano.

The monitoring system provides the values of temperatures and water flow rates at different points of the circuit. The main ones are positioned upstream of the BHE field to record the thermal exchanges with the ground (in correspondence of pump 248 B5, see Figure 4) and another one downstream of the underfloor circuit (in correspondence of pump 301, see Figure 4). In order to evaluate the efficiency of the geocooling, a monitoring of all the circulation pumps (electricity) necessary for the summer operation mode was carried out.

The monitoring system includes the following components:

- 1 technical cabinet with a data-logger inside;
- 5 volume flow meters (electromagnetic);
- 15 thermocouple sensors–Type T (grade insulated wires);
- 3 electric power-meters installed on the heat pumps (electric metering of heat pumps consumptions);
- 4 electric power-meters on the circulation pumps dedicated to the geocooling circuit (electric metering of circulations pumps consumptions);
- 1 indoor weather station in one flat (temperature and humidity).

The heat meters installed in the technical room are described in Figure 5. In particular:

- Q1: heat meter of the BHE field. This is necessary for the monitoring of the thermal exchange with the ground. In this counter, water with glycol circulates;
- Q2: geocooling heat meter after the hydraulic separator and before the heat exchanger. In this counter, water with glycol circulates;
- Q3: heat meter after heat pumps, only for DHW production. In this counter circulates simply water;
- Q4: heat meter towards the underfloor heating (heating and cooling of flats). In this counter simply water circulates;
- Q5: heat meter after the hydraulic separator towards heat pumps. In this counter flows water with glycol.

The four pumps dedicated to geocooling have been monitored for the evaluation of its efficiency, as the pumps represent its only electricity consumption.

Conversely, the monitoring of the solar thermal pump is outside the scope of the study. In the present real case, solar thermal collectors could contribute to satisfy heating needs, after ensuring DHW production. This contribution was monitored through temperature sensors and without a mass flow sensor. According to the collected data, the energy contribution was negligible, considering the overall and annual thermal balance of the case of study.

The system for data acquisition, visualization and supply runs due to the GSM Internet connection with a dedicated SIM card in-situ. The acquired data have been stored on a server and can be viewed and downloaded via Grafana, an open source platform for the organization and graphic display of data.

The accuracy of the monitoring and related results depends on the measurement methods, the temperature sensors, the data logger, and the measurement circuits used. Considering the technical information available for the sensors and the data logger and the experience acquired by other thermal data acquisition systems, a total accuracy of flow measurement of 2.4% has been noticed, while the total error on temperature measurements is less than 0.3 K. Although all devices installed for the monitoring have been accurately calibrated, these levels of accuracy affects the thermal measurements, depending on the entity of the temperature difference observed on the carrier for providing heating and

cooling. Further details and clarifications about the equipment of the monitoring system are reported in [22].
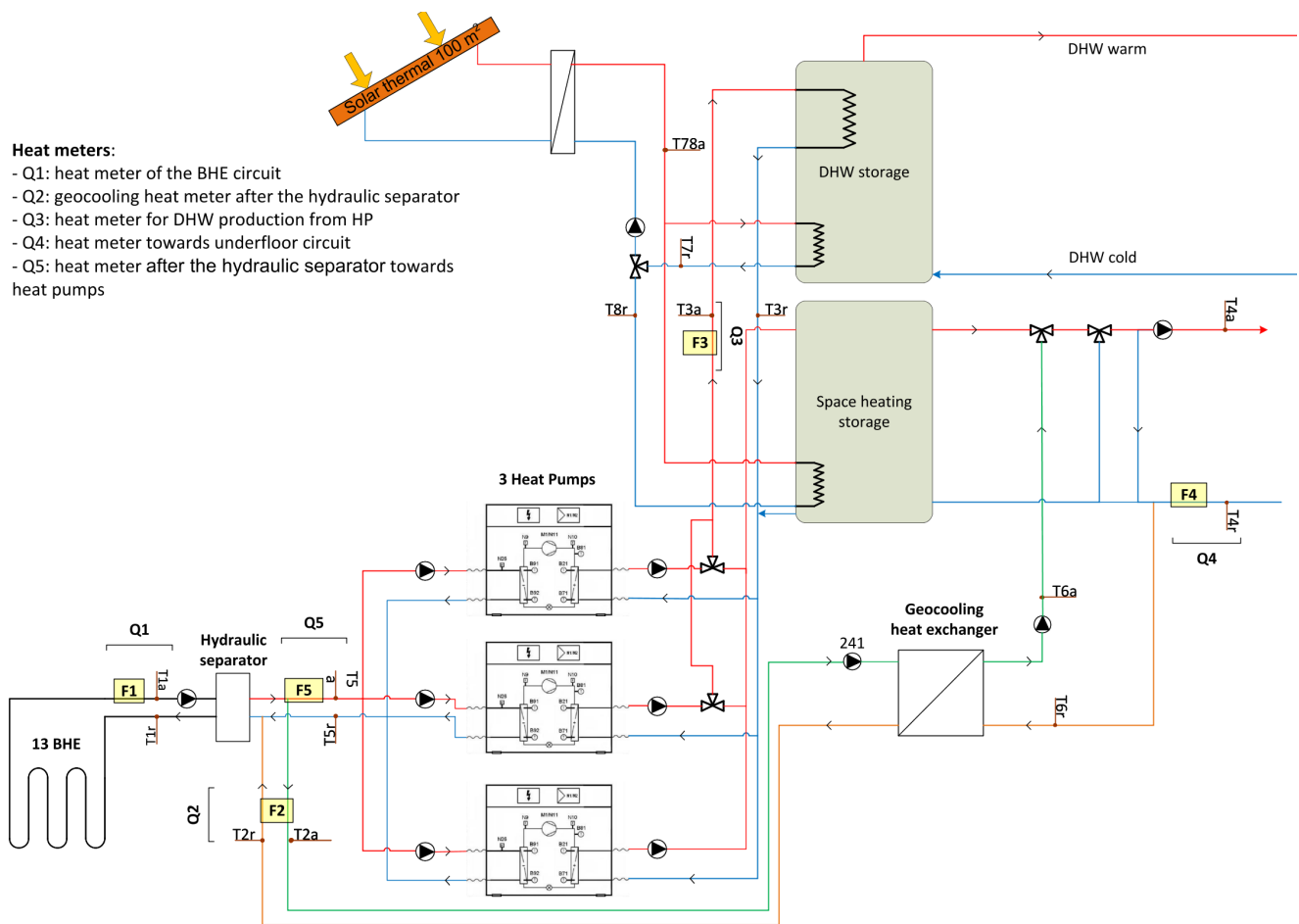

Figure 5. Scheme of the system and of the monitoring concept with the detail of the sensors and of the meters (source: [22]).

3.3. Monitored Seasons

In the technical literature is very rare to find out results of monitoring campaign as long-lasting as in the real case here presented. In fact, the whole monitored period from 2016 to 2019 has been studied in order to obtain more detailed and aggregate results. Table 1 reports the monitored seasons including their duration in days and hours and the number of hours in which the system was in operation (about the 80% of the total hours of the season). It has to be explained that in Switzerland winter seasons are not defined by law depending on climatic data; heating and cooling are provided when needed during a year. In the analyzed real case, the switch between heating and cooling operation mode is done manually by the person responsible for maintenance at the request of the administrator of the building because there is not an automatic control logic. Based on Table 1, the winter season has a duration of about 240 days, while summer season of about 120 days.

Based on the results of the monitoring of the first 15 months, some measures for the optimization of the system were suggested. In autumn 2017, energy efficiency optimization measures were agreed and fully implemented at the end of July 2018. The results of the monitoring of August and September 2018 were representative to show the effects of the optimizations implemented.

Table 1. Duration of the summer (cooling by geocoding) and winter (heating by GSHP) seasons monitored (elaborations based on [22]).

| Season	Start Date	End Date	Season Duration [days]	Seasonal Duration [h]	Working Period [h]
Summer 2016 *	23 June 2016	28 September 2016	97	2328	1858
Winter 2016–17	28 September 2016	23 May 2017	237	5664	4523
Summer 2017	23 May 2017	15 September 2017	115	2760	2203
Winter 2017–18	15 September 2017	23 May 2018	250	5808	4637
Summer 2018	23 May 2018	3 October 2018	133	3190	2571
Winter 2018–19	3 October 2018	4 June 2019	244	5880	4737
Summer 2019 **	4 June 2019	7 October 2019	125	2952	2378

* cooling started later than in the other summer seasons due to technical reasons in the manual switching of the system; ** technical problems occurred affecting the management of the system.

3.4. Energy Balance of the System

The following Figures 6 and 7 show the monthly values of the energy exchanged with the building through the underfloor radiant system (heat meter Q4 in Figure 5) and the monthly energy exchanged with the ground through the BHE field (heat meter Q1 in Figure 5), during the entire monitored period.

3.5. Energy Performance

The overall performance has been evaluated at building level by investigating the heating and cooling demands and at system level investigating the seasonal coefficient of performance of the GSHP, the recharge of the ground and the efficiency of geocooling.
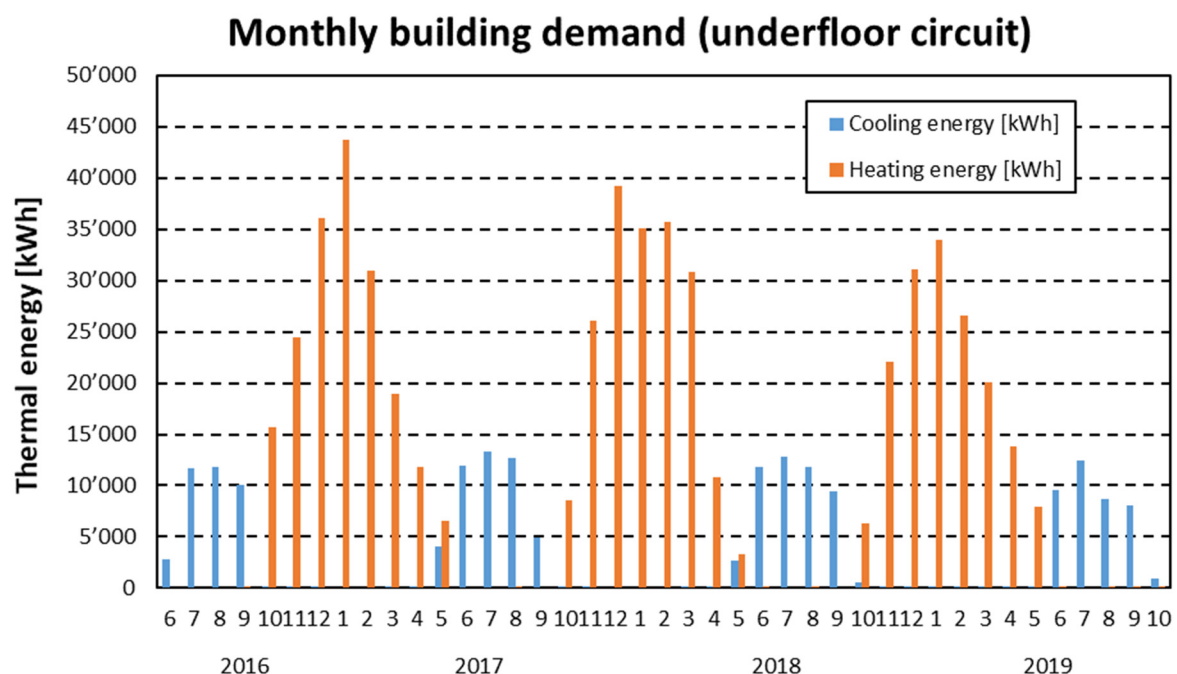
Figure 6. Monthly values of the energy demands (at the heat meter "Q4") during the monitoring (years and months in the abscissa labels; source: [22]). This measure is called demand to differentiate it from the thermal needs at envelope level.
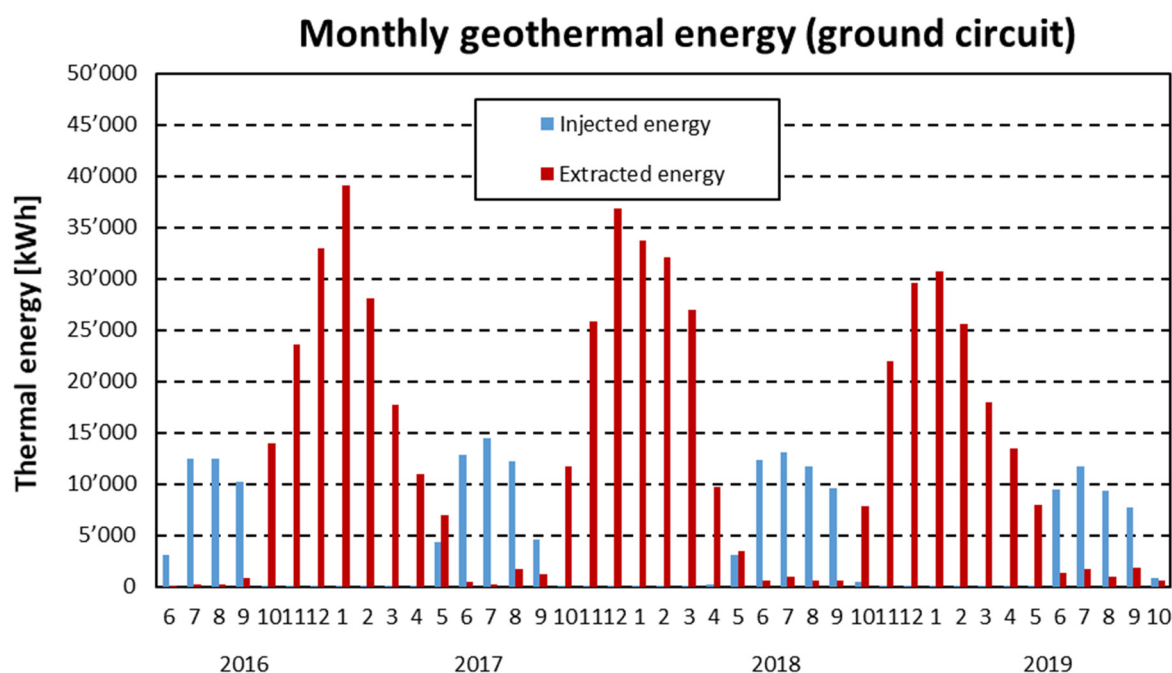
Figure 7. Monthly energy exchanged with the ground (at the heat meter "Q1") during the monitoring (years and months in the abscissa labels; source: [22]).

Based on monitored data and geometric features of the building, such as the reference energy surface, i.e., the surface of the thermal zones to be heated and cooled, the following indicators have been calculated (Table 2). In order to consider the impact of climatic conditions on the monitored results, the heating and cooling degree-days (in Table 2, HDD and CDD respectively, [°Cd]) were taken into account and specific indexes, aimed at overcoming this impact, were calculated (as the ratio between Heating index and HDD and between Cooling index and CDD, respectively) and named normalized heating and cooling indexes.

Table 2. Space heating and cooling demands and related indicators (elaborations based on [22]).

Monitored Season	Heating Demand MWh	Heating Index kWh/m²y	HDD	Normalised Heating Index Wh/m²/°Cd	Monitored Season	Cooling Demand MWh	Cooling Index kWh/m²y	CDD	Normalised Cooling Index Wh/m²/°Cd
					Summer 2016	**36.4**	**6.4**	**73**	**87.9**
Winter 2016–17	188.4	33.1	2279	14.5	Summer 2017	47.8	8.2	106	77.5
Winter 2017–18	190.2	33.4	2350	14.2	Summer 2018	49.1	8.6	112	76.6
Winter 2018–19	162.0	28.4	2041	13.9	Summer 2019	39.3	6.9	113	61.1

The HDD were calculated according to [31], as the sum of differences between the daily mean external air temperature and the set indoor temperature (20 °C), where only days with daily mean external air temperature minor or equal to 12 °C are taken into account. The CDD were calculated analogously but based on a reference internal temperature of 25 °C, taking into account that summer is not defined based on meteo-climatic data, but it corresponds to the period during which geocooling is witched on manually.

The winter normalized heating values (always about 14 Wh/m²/°Cd) describe coherent results, while the summer ones (from 61 to 88 Wh/m²/°Cd) are more variable, mainly depending on the occupants' behavior and on technical management practices.

As anticipated, it has to be taken into account that during summers in 2016 and 2019, the geocooling system has encountered some operative problems that lightly reduced the hours of operation.

Furthermore, the thermal demands monitored differ to the thermal needs estimated in the first stage of the project attesting, a part the difference related to the heat losses along the water distribution system from the technical room to the flats, an initial underestimation of the heating needs and overestimation of the cooling needs.

A realistic index of the efficiency of a HP over the year can be expressed by the Seasonal Coefficient of Performance (*SCOP*), i.e., the ratio between the thermal energy supplied and the electricity required, in a season. In summer, the GSHP of the building provide only DHW, when heat from solar collectors is not sufficient, at higher supply temperature compared to space heating needs in winter. Therefore, due to the different levels of temperature, the *SCOP* in summer is expected to be lower than in winter.

In order to better understand these results, the main features of the three identical GSHP adopted in the present case are described in Table 3, resulting in a nominal thermal power of 133.2 kW. In Table 3, B0W35 and B0W60 are two operative conditions of the heat pump, it means the brine inlet temperature is 0 °C, and the water outlet temperatures are 35 °C and respectively 60 °C.

Table 3. Characteristics of the GSHP provided by the manufacturing company.

	B0W35	B0W60
Thermal Power supplied at condenser [kW]	44.4	41.3
Electrical Power absorbed by compressor [kW]	10.0	13.5
COP [–]	4.4	3.1

Due to the "Q5" heat meter before the GSHP evaporators (see Figure 4) and by the electric monitoring of the GSHP compressors, it is possible to estimate the *SCOP* by the following equation:

$$SCOP = \left(\frac{E_{th\ evaporator}[\text{kWh}]}{E_{el\ compressor}[\text{kWh}]} \right) + 1 \tag{1}$$

where $E_{th\ evaporator}$ is the geothermal heat exchanged to the evaporator and $E_{el\ compressor}$ is the electricity provided to the compressor, while the electricity for the operation of the circulation pumps and other devices has not been considered in the calculation of the *SCOP*.

The obtained results are reported in Table 4, where it is possible to note an intensive growing of the heat exchanged to the evaporator in summer. This condition is mainly due to a different contribution of the solar thermal sysyem devoted to provide DHW because of technical and meteo-climatic issues.

Table 4. Results of the calculation of the *SCOP* (source: [22]).

Seasons	$E_{th\ evaporator}$	$E_{el\ compressor}$	*SCOP*
Winter 2016–17	167,306	59,741	3.8
Winter 2017–18	178,260	63,625	3.8
Winter 2018–19	157,069	55,517	3.8
Summer 2016	1695	887	2.9
Summer 2017	6794	3387	3.0
Summer 2018	8705	4186	3.1
Summer 2019	14,315	6667	3.1

Further, it is important to observe that the seasonal performances of the GSHP (3.8 in winter) are lower than the instantaneous or nominal ones (B0W35 in Table 3). This is mainly due to the DHW production even in winter (at about 60 °C) and to the non optimized control and management system, i.e., to the many switching on and off of heating supply. This result underlines the importance of real monitored data to evaluate the performance of GSHP coupled to low energy buildings, considering that, in general, higher values are reported, often because the different operative conditions and system management options are not taken into account.

As anticipated, another index, related to the global operation of the geothermal system, is the recharge of the ground. According to [16], this parameter affects the long-term dynamics behavior of the ground as heat source and then affects the global performance of geothermal systems.

Indeed, the real thermal recharge must be verified and confirmed over the years and geothermal district heating systems with huge BHE fields must be sized and designed carefully to avoid serious problems (e.g., ground freezing, system shutdown) during their operation.

According to [12], to evaluate the thermal recharge of the ground, in terms of heat injection over heat extraction it is necessary to consider an entire year starting from the winter season. Therefore, the first summer monitored (2016) was neglected. The results of the calculations based on monitored data are reported in Table 5.

Table 5. Annual values of the energy extracted and injected and related thermal recharge (source: [22]).

Operation Period	Energy Extracted	Energy Injected	Thermal Recharge
Winter 2016–2017 + Summer 2017	173.3 MWh/y	44.6 MWh/y	25.7%
Winter 2017–2018 + Summer 2018	181.8 MWh/y	46.9 MWh/y	25.8 %
Winter 2018–2019 + Summer 2019	154.3 MWh/y	32.4 MWh/y	21.0 %

The same calculation has been provided also for all the monitored period (4 summers, considering also summer 2016, and 3 winters) by the following equation, where I (i from 1 to 4) is the injection in the i summer season and E_j (j from 1 to 3) is the extraction from the ground in the j winter season, attesting an average value for "*R*" of 23.7%.

$$R = \frac{\frac{(I_1+I_2+I_3+I_4)}{4}}{\frac{(E_1+E_2+E_3)}{3}} \quad (2)$$

The last performance index elaborated is the geocooling efficiency, defined as the ratio between the cooling demand of the building (all the flats) and the electricity needed for the pumps, following the equation:

$$\varepsilon = \frac{E_{th\_cool}\ [\text{kWH}]}{E_{el}\ [\text{kWH}]} \quad (3)$$

Based on monitored data, the values of the monthly demand, of the monthly electricity consumption and of the geocooling efficiencies are reported in Figure 8.

In Figure 8 is reported an efficiency of 30 achieved in August 2018, after the implementation of the improvement measures. Nevertheless, in September 2018 the electricity consumption remained almost unchanged, while cooling demand was reduced resulting and this means a worse efficiency. Probably, without a better regulation of the pump 301 (Figure 3), it will not be possible to further reduce electricity consumption, especially when cooling demand decreases. Indeed summer 2019 shows the negative effects of an inappropriate management of the system, with the worst efficiencies of the monitoring campaign recorded in August and September.
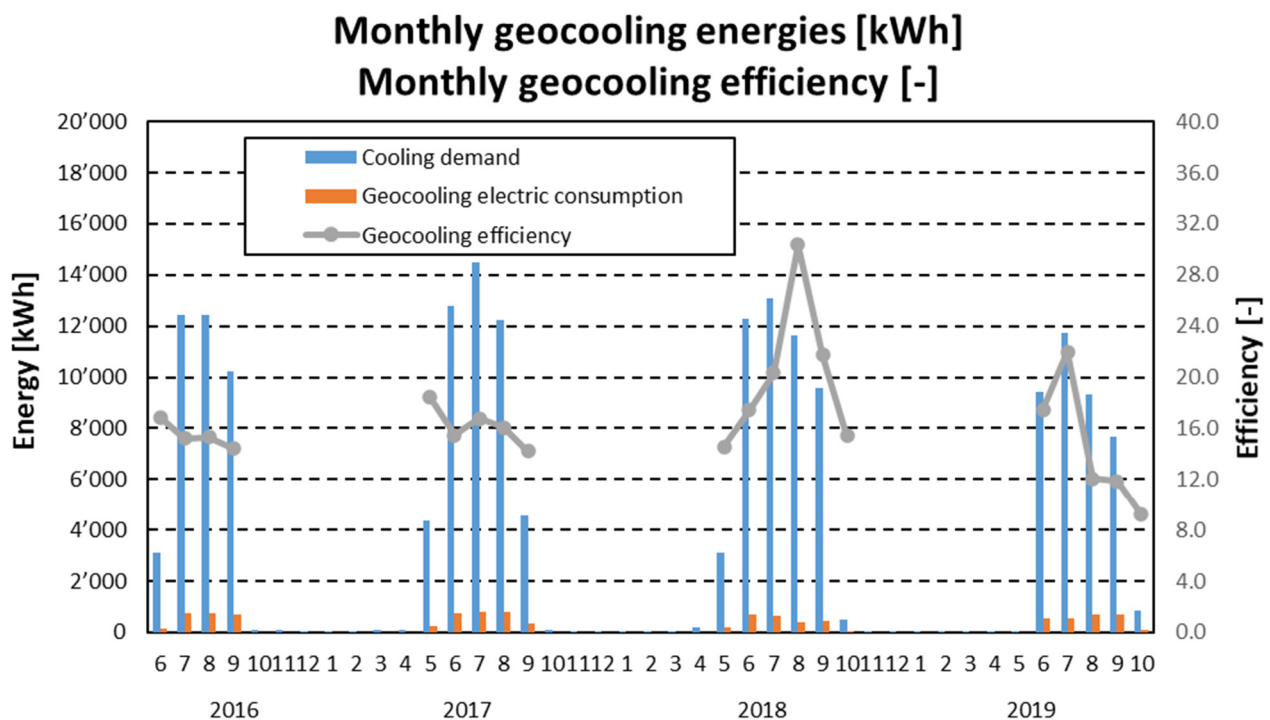
Figure 8. Monthly cooling demand, electricity consumption and related geocooling efficiency (years and months in the abscissa labels; source: [22]).

However, based on results achieved during August 2018, it can be stated that efficiency values of 30 are easily approachable with an optimal regulation of the system. Further, with a regulation of all circulation pumps, it would be possible to reach efficiencies around 35–40.

4. Discussion

The issues explored in the work, bringing interesting insights for the involved stakeholders, can be summarized as it follows:

- The efficiency and potential of geocooling technology;
- The real quantification of a thermal recharging of the ground by geocooling;
- The limits of the system and the performance achievable by an underfloor radiant distribution system.

About the first point, according to the mentioned theoretical studies, the measured geocooling efficiency (defined as the ratio between the total cooling demand and the electricity used by the circulation pumps at monthly level) is in the range between a maximum of 30 and a minimum of 12, depending on pumps settings and other issues. In particular, the circulation pump that set warm/cool water to the flats does not modulate the flow rate setting a temperature difference but by taking into account the pressure difference. Indeed, a different control system would allow a lower electricity consumption and a better modulation of the temperature of the supplied warm/cool water. Values higher than 30 can be also achieved by optimized control and management systems.

About the second point, the value achieved for the thermal recharge of the ground over the monitored seasons was about 24%, in accordance to the recommendations given during the first stages of the project (preliminary analysis, sizing and design). Indeed, to recharge by geocooling allows a proper thermal balance of the ground, in addition to the possibility to provide cooling to the occupants. Further, from the economic point of view, an issues that will be better described in further developments, geocooling can help reducing the initial investment, i.e., saving meters of drilling because less BHE can be sufficient, and developing a new approach about thermal tariffs. This is a critical issue because, according

to [5,6], despite the described pros, the economic barrier of the initial capital cost still affect GSHP. This is mainly due to the excavation cost that represent about the half of the total cost. This condition stimulates research and practice in finding new solutions to reduce or avoid drilling cost such as those proposed by [6] as thermo-active foundations or other energy geostructures. To that end, geocooling represent another effective alternative.

The assessment of the technical and economic factors that influence the design and performance of vertical GSHP is deepened in [5], with a focus on the spatial correlation that these factors have with geographic features such as geology and climatic conditions. By the way they indicated that Switzerland is one of the country with the highest capital costs for vertical GSHP systems at least 10 years ago. Further, they stressed that, as yet subsurface characteristics are not adequately considered in the planning and design phases, under or oversizing can happen, with a long-term effect on the maintenance costs and payback time of these systems.

About the third point, during the first two years of monitoring, some critical issues emerged in relation to geocooling efficiency and thermal comfort in summer. These criticalities are mainly caused by an uncontrolled management of the system. However, some optimizations were implemented to overcome these problems such as the modulation of the circulation pumps and the increasing of about 2 °C of the temperature of the water circulating in the radiant underfloor system in summer. The monitoring in the sample flat demonstrate that cooling was requested by the occupants even with external temperature lower than 25–26 °C. According to thermal comfort theory, the monitored indoor temperature were too low (22–24 °C) and relative humidity too high (70–85%) in many summer hours, underlining again the need of a better regulation of the cooling system, e.g., to switch on when really needed, to supply temperature not lower than 20–21 °C in the underfloor circuit, to consider also the effect of the mechanical ventilation equipped by the air to air heat exchanger. These results demonstrate also that the obtained thermal recharge is the maximum achievable for the monitored building and respective boundary conditions (energy standard, solar gains, typology, loads, and climate). Therefore, it is possible to guess that better performance of the systems can be achieved in terms of comfort conditions in summer in climates more warm and dry.

5. Conclusions and Further Developments

The research here presented is based on a long-lasting research supported by validated tools and expertise and on data collection and elaboration related to a monitoring campaign of about 40 months, involving thermal and electric measurements in the geothermal system and in one sample flat (users' side), collaboration with the technicians involved and with the tenants of the building by a questionnaire survey.

The obtained results prove that geocooling through underfloor radiant distribution is an efficient and applicable technology, at least for residential buildings and moderate climatic conditions. Indeed, it is evident that geocooling cannot be assimilated to conventional air conditioning systems, based on chillers. In the analyzed real case, heat is extracted from the buildings by radiant underfloor systems able to act only on sensible heat. Therefore, if there are not air treatment units, this kind of technology is in general not recommended in case of building with high loads in terms of latent heat (non residential buildings with a high density of occupation). The heat exchange due to the radiant system depends on the temperature level of the water inside. The best temperatures from the point of view of indoor thermal comfort are equal or greater than 21°C, but this condition limits the heat exchange. In addition, to avoid surface condensation problems, it is advisable to satisfy the internal comfort keeping the upper levels of set point temperature inside, according to the reference standards. The survey by questionnaire was carried out exactly to better understand the perception of cooling and to instruct tenants in setting indoor temperatures, underlining the role of the involvement of the occupants in such systems. The relatively high temperature levels suggested for underfloor radiant cooling, compared

to conventional air conditioning, imply a careful preliminary design and management during the operation to guarantee a proper control of the global system.

In addition, since the thermal recharge of the ground is a key parameter for an efficient long-term operation of the system, it has to be designed by accurate energy simulations. If the designed thermal recharge cannot be achieved over the years, the possibility to modify the installation or its operation should be provided, since long-term thermal storage problems can seriously affect the whole effectiveness of the system. Therefore, the achieved results can support strategies for new and existing geothermal systems, giving solutions for effective space heating and cooling systems.

Furthermore, the results reported confirm that large geothermal systems, with a huge extension of BHE, should be planed and sized very carefully in order to reduce the risk of technical troubles and decreasing of performance. In this framework, the work presented gives also an important contribution to the definition of methods and tools needed to design and monitor properly such systems.

The conclusions of this work can be framed also in the recent progress of rules and regulations about geothermal systems (e.g., the [19]) that consider the issue of the thermal interference in case of geothermal plants in the same area, underlining the promising role of properly sized geocooling systems in the next future.

First estimations referred to the real case here presented, which will be better detailed in further developments of the work, indicate that geocooling allows saving in the range 10–25% of the investment cost for installing BHE thanks to the recharge of the ground that allows a minor drilling length (considering the long-term performance of the overall system, at least in similar boundary conditions). Taking into account the overall operation of the system all over the year, ref. [22] estimated that the costs for geocooling devices (about 20,000 euros) are comparable to the economic saving due to the recharge. In addition, the building real estate value would certainly further increase thanks to the better indoor comfort conditions and lower annual operative costs. An economic saving for the final users can be achieved also in comparison to other conventional technologies such as cooling machines that, due to drastically lower efficiencies, imply higher operative costs for final users.

Further efforts are necessary to assess experimentally the energy performance of these systems, to model and analyze the influence of the boundary condition and to optimize the heat exchanger layout, even in the framework of assessment related to geothermal potential in wide areas such as that proposed by [32]. In this paper all these aspects are investigated, starting from the results of the monitoring campaign of the analyzed real case.

The adopted method can be replicated and the results can be generalized to new residential buildings, well insulated and with underfloor radiant systems for providing heat and cool. In fact, it could be possible to calibrate and estimate space cooling needs for residential buildings in different climatic conditions, according to the indexes described in Table 2.

Finally, although the analyzed geothermal system serves only one building of 46 units, the method and part of the achieved results can be extended not only to similar cases but also to geothermal district heating network, where thermal needs of several buildings must be considered for the correct sizing of the BHE field. Following developments of the work will face this issue in the framework of the evolution of district thermal systems to low temperature applications able to provide both heat and cool to the final users.

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Abbreviations

BHE	Borehole Heat Exchanger/Exchangers
CDD	Cooling Degree Days
COP	Coefficient of Performance
DHW	Domestic Hot Water
EER	Energy Efficiency Ratio
GRT	Geothermal-Response-Test
GSHP	Ground Source Heat Pump/Pumps or Geothermal Pump/Pumps
HDD	Heating Degree Days
HP	Heat pump/pumps
HVAC	Heating, Ventilation and Air Conditioning
RES	Renewable Energy Source/Sources
SCOP	Seasonal Coefficient of Performance
SIA	Swiss society of Engineers and Architects (www.sia.ch/en/the-sia/)

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