Geocooling of low energy office buildings with borehole heat exchangers

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Résumé Abstract

Le potentiel de geocooling avec sondes géothermiques verticales est analysé pour des bâtiments administratifs à basse consommation d’énergie. Un outil de simulation dynamique a été développé pour simuler thermiquement le système complet et ses interactions thermiques entre les divers sous-systèmes, incluant le bâtiment, l’émission d’énergie dans le bâtiment, les installations techniques et le champ de sondes géothermiques.


The potentiality of geocooling with borehole heat exchangers is analysed for low energy office buildings. A dynamic thermal simulation tool has been developed to simulate the overall system and the interconnected thermal interactions, including the building, the thermal energy emission, the technical installation and the borehole heat exchanger field.

Building design, system technical feasibility and limits of the ground coupled system are discussed and result from the analysis of the numerous system simulations. Geocooling potential depends on the quality of the building design and its heat emission. The importance of the ground recharge ratio on the system design is highlighted. Simple design sizing keys are proposed for a fast pre-sizing of a borehole field for geocooling.
1. Introduction

Ground coupled systems with borehole heat exchangers (BHEs) are spreading fast in Switzerland. The total annual length of new installed boreholes is increasing every year and reached 2'300 km in 2010 [1]. A BHE is normally coupled to a heat pump for heating purpose. It may also be used for the dissipation of waste heat in the ground for cooling purpose. The meaning of geocooling is to provide cooling without a cooling machine, i.e. by direct heat transfer from the cooling distribution to the ground flow circuit through a conventional heat exchanger.

As a consequence of the success of ground coupled systems, a large system size is more and more frequent, requiring thus a field of BHEs. Relatively to a single family house, the design process is far more complex. It has to take into account not only short term heat transfer effects in the ground but also long term seasonal heat storage effects. A thermal recharge of the ground is often necessary and can, ideally, be fulfilled by geocooling for best system thermal performances.

This study is focused on the analysis of the geocooling potential of borehole heat exchangers’ systems applied to low energy office buildings. It takes advantage of previous studies [2,3], which have highlighted the necessity to adopt a multidisciplinary approach in order to take into account the building design itself. The ground coupled system is simulated together with the building, the heating and cooling distributions with the objective to analyse the technical feasibility and design of geocooling systems by dynamic system simulations.

The main objectives are to assess the geocooling potential related to office buildings and establish simple sizing rules for a pre-design evaluation, highlighting also some design requirements for best system integration and efficiency.

2. Methodology

The ground coupled system is integrated in a low energy office building. This latter is supposed to be well insulated and air tight. A mechanical ventilation system is present to ensure a minimal air change rate for indoor air quality purposes. It is not sized for energy requirements and distribution. Heating and cooling energy is distributed through a proper water system, allowing for low heating and high cooling temperatures.

2.1 Sizing criteria

System sizing is conditioned by the allowed heat carrier fluid temperature variations in the boreholes. The following conditions defines the fluid temperature limits:

- the heating criterion: the inlet fluid temperature in the BHEs is always larger than the minimum allowed one. As the BHEs are supposed to be placed under the building, a minimum fluid temperature of 0°C is fixed. This is important to prevent any risk of shading due to freezing.

- the geocooling criterion: the outlet fluid temperature from the BHEs has to remain below a given value so that the building thermal comfort is satisfied in Summer. In other terms the geocooling criterion is met as long as room air temperatures do not exceed the thermal comfort temperature range, given some tolerance according to SIA Norm 382/1 [4].

The BHEs have to be sized for a long period of time; typically 50 years as stated in Swiss Norm SIA 384/6 [5]. Long term effects are thus included in the system design. The best design is obtained when the heating and geocooling criteria are fulfilled with the smallest possible borehole length.

2.2 Sizing procedure

The initial step is the definition of an office building and location. A reference building geometry is used and the building envelope, building use and building thermal energy distributions are defined together with climatic data for the studied location.

Thermal requirements of the building

In a first step the building control parameters are adjusted so that winter and summer thermal comfort are met with a minimum of heating and cooling energy. A procedure has been established...
and starts by adjusting the parameters related to winter and summer management of solar protections. Then parameters related to technical installation and thermal energy distribution system in the building are adjusted. The one-year simulations performed for this purpose are made with a simple heating and cooling production, to avoid the simulation of the ground coupled system. Heating is provided with a constant design heat rate, corresponding to the design heat rate of the heat pump, and cooling with a design fluid temperature and flow rate, corresponding to geocooling at a given temperature level.

Depending on the building design, the building heating and cooling distribution system is not necessarily adequate to ensure a good enough thermal comfort. This is the case for example when an intense but short-duration heat gain has to be removed, requiring both a fast and powerful response of the cooling distribution system. The consequence would be a large cooling peak power and a low cooling temperature, which are both not compatible with a geocooling application. In this study the heating and cooling distribution concept is based on massive emitters, such as concrete ceilings or light-concrete floors. If the cooling distribution concept is not compatible with the building design, the case is not considered and the sizing procedure shown in figure 1 is aborted.

Figure 1  Sizing procedure for the determination of an optimal system design for a ground coupled system based on geocooling

Sizing of the borehole heat exchangers
In a second step the ground coupled system is simulated. All remaining parameters are defined, from the technical installation to the ground, including number, depth and spacing between the BHEs. The best system design is found by successive iterations of 50-years simulations of the whole building and ground coupled system (see fig. 1).

2.3 Simulation tool
A TRNSED application of the TRNSYS simulation package [6] has been created and called COOLSIM [7,8]. COOLSIM is based on PILESIM [9], which uses the TRNSYS non standard component TRNVDSTP [10] for the simulation of a borehole heat exchanger field. The TYPE56, included in COOLSIM, allows the user to take into account the dynamic thermal interaction between the ground coupled system and the building with its heat distribution system.
Variations of the building envelope, building heat distribution systems, climatic data and ground thermal characteristics provide various system designs that enable the evaluation of the geocooling potential of such systems.

3. The reference building
A low energy building in Chiasso, south part of the Alps in Tessin, is selected for the definition of the reference case, thus fixing reference climatic data as well. The building has a heated floor area of 2'200 m² and a net heated volume of 5'700 m³. Complying to the Minergie standard [11], the building is well insulated on the outside. Half of the building façades are made of triple glazing windows. External solar protections enable to reduce the overall g-value to 0.15.

The technical installation is either providing heating or cooling to the distribution system of the building. As this latter is supposed to have massive concrete slabs between floors, they are used for heat and cold emission. They are so-called thermally activated building systems (TABS). The large heat capacity of the slabs is providing a thermal storage between the technical installation and the heated and cooled spaces.

Internal gains from people, lighting and appliances are fixed according to profiles given in the Swiss technical handbook [12]. Expressed in terms of internal floor area, they reach 26 W/m². On a yearly basis, internal gains correspond to a mean and constant heat emission of 6 W/m².

The specific transmission and ventilation heat losses of the reference building are assessed to 2.3 kW/K. The time constant of the building is estimated to 120 h.

4. Heating and geocooling sizing keys
Sizing keys for a ground coupled system are useful for estimating the required length of BHEs. When a ground system is correctly sized, it is possible to compute its sizing keys, providing helpful values for a future sizing of a comparable system.

4.1 Definition of sizing keys
The most important sizing keys are related to the heat rate that can be transferred by the boreholes. A natural choice for heating is the nominal heat extraction rate of the heat pump, denoted \( P_{\text{ext,nom}} \). It can be specified at fluid conditions B0W35. For geocooling the maximum distributed cooling power, denoted \( P_{\text{cool,max}} \), was found to be most appropriate. The heating and geocooling sizing keys, expressed in W/m, are defined by relation (1) and (2):

\[
q_e = \frac{P_{\text{ext,nom}}}{H_h} \quad (1)
\]

where \( H_h \) denotes the total borehole length required for heating.

\[
q_i = \frac{P_{\text{cool,max}}}{H_g} \quad (2)
\]

where \( H_g \) denotes the total borehole length required for geocooling.

The storage feature of the BHEs is quantified with the ground recharge ratio, i.e. the fraction of the annual extracted energy that is injected back into the ground during an annual cycle (cf. Eq. 3).

\[
\eta_g = \frac{Q_i}{Q_e} \quad (3)
\]

where \( Q_e \) denotes the annual extracted energy from the BHEs and \( Q_i \) the annual injected one. The ground recharge ratio has a strong influence on the heating and geocooling sizing keys.

4.2 Sizing keys in relation to the ground recharge ratio
In order to analyse the ground coupled system sizing in function of various energy requirements obtained with the reference building, internal gains are scaled from 60% to 140%. It should be noted that 140% of standard internal gains is an upper limit for a geocooling solution with TABS. In figure 2, the maximum peak power loads are shown in relation to the ground recharge ratio. Sensitivity of the heating and geocooling sizing keys to the ground recharge ratio is shown in figure
3. They were obtained by simulations made with 100 m deep boreholes spaced with 8 m, equipped with standard double-U pipes. An average ground thermal conductivity of 2 W/(mK) was fixed, as well as an initial ground temperature of 12°C near the surface, with a mean geothermal temperature gradient of 25 K/km.

![Figure 2](image-url) **Figure 2** Maximum peak power loads for heating and cooling are shown in relation to the ground recharge ratio. This latter is directly dependent on the annual heating and cooling energies distributed in the building. The temperature values indicated next to the curve for the maximum thermal power for cooling correspond to the required forward fluid temperature in the cooling distribution to ensure thermal comfort.

![Figure 3](image-url) **Figure 3** Heating and geocooling sizing keys shown in relation to the ground recharge ratio. They were obtained with various intensities of internal gains in the reference building.

The annual extracted energy per borehole length lies between 30 and 40 kWh/m/y, whereas the annual injected energy per borehole length ranges between 10 and 30 kWh/m/y.

As expected the heating criterion dominates and conditions borehole sizing at small values of the ground recharge ratio, due to long term effects resulting in a slow ground cooling. A scarce recharge has to be compensated for by a longer borehole length.
The geocooling criterion exhibits a strong sensitivity to the ground recharge ratio and conditions borehole sizing at larger values. An increase of the ground recharge ratio is caused by greater internal heat gains. It makes the cooling power demand larger, which, in turns, requires a lower design water temperature in the cooling distribution. The available temperature difference between design water temperature and ground is smaller, making the geocooling sizing key significantly decrease.

An optimal borehole length is obtained for a ground recharge ratio of about 50 – 60%, noting that a seasonal performance coefficient of 4 to 4.5 is simulated for heating.

5. Heating and geocooling temperature difference potential
The geocooling sizing key is strongly conditioned by the available temperature difference between the design water temperature in the cooling distribution and the initial ground temperature. In order to highlight the case phenomena problematic and take into account this aspect in the design keys, heating and geocooling temperature differences and losses are illustrated in figure 4 with the building reference case, which has a ground recharge ratio of 60%.

For the heating case a heat pump separates the heating building distribution system from the borehole flow circuit. The magnitude of the heat extraction rate is primarily conditioned by the available temperature difference between initial ground temperature in the borehole region and minimum allowed fluid temperature level in the borehole flow circuit. It defines the heat extraction temperature difference potential, denoted $\Delta T_{\text{extraction}}$. This temperature difference is divided between the long term temperature drift and the short term temperature difference for heat extraction.

The geocooling temperature difference potential is defined by the available temperature difference between the desired indoor air temperature and the initial ground temperature. This temperature difference is divided between the building, including its cooling distribution and the geocooling heat exchanger, and the ground coupled system. The building design temperature loss is necessary to keep some margin and anticipate the indoor air temperature increase due to internal and solar passive gains. It depends on building design and inertia of the distribution system. The ground temperature difference, denoted $\Delta T_{\text{gnd}}$, is related to the ground heat exchanger. It is defined as the difference between the maximal fluid temperature level in the BHEs and the initial ground temperature in the borehole region.

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The geocooling temperature difference potential is shared between the building and the ground. It is thus very important, when a geocooling system is designed, to have the possibility to modify and optimise to some extent both the building design and the cooling emitters. A better system integration is obtained when the building temperature loss is further reduced.

6. Heating and geocooling heat transfer coefficients

Definitions of heating and geocooling heat transfer coefficients are proposed, by analogy to the overall heat transfer coefficient of a heat exchanger, to take into account the temperature difference in the sizing keys.

6.3 Definition of heat transfer coefficients

The definitions are voluntarily simple to make easy a pre-design calculation. The heating and geocooling heat transfer coefficients, expressed in W/m/K, are defined as the ratio of respectively the heating sizing key (Eq. 1) with the heat extraction temperature difference \( \Delta T_{\text{extraction}} \), and the geocooling sizing key (Eq. 2) with the ground temperature difference \( \Delta T_{\text{grnd}} \):

\[
K_e = \frac{q_e}{\Delta T_{\text{extraction}}} \quad (4)
\]

\[
K_i = \frac{q_i}{\Delta T_{\text{grnd}}} \quad (5)
\]

The heat transfer coefficients, based on available temperature differences in the ground, take into account the effect of a different initial ground temperature or deeper boreholes.

6.4 Heat transfer coefficients in relation to the ground recharge ratio

Various building designs were examined relative to the reference one. The fraction of window area, double or triple glazing windows, internal or external solar protections, floor heating or TABS for the heat distribution system were analysed. Different weather data files were defined; the locations are Zurich and Geneva at the north side of the Alps and Chiasso and Bologna at the south side. Rome was also selected but early simulations showed that no geocooling solution was possible, due to the much larger cooling demand relative to the heating demand, and the too high natural ground temperature.

Depending on the building design, the indoor air temperature can not be controlled to satisfy the thermal comfort requirements. This is particularly true with internal solar protections or larger glazing areas. Floor heating also presents more difficulties than TABS to keep indoor air temperature within minimum and maximum limits. Building designs that present difficulties for the control of indoor climate normally require larger heating and cooling powers, which means a lower forward fluid temperature for cooling. Large power and low temperature for cooling are not compatible with geocooling. This study has clearly highlighted that only low energy buildings that integrate passive climate control such as efficient external solar protections and TABS can take full advantage of the geocooling potential.

In figure 5 the heating heat transfer coefficients are shown in function of the ground recharge ratio for all simulated cases that have a ground coupled solution. The 3 cases having a ground recharge ratio greater than 120% where obtained with internal solar protections. They were not eliminated although comfort conditions inside the building were difficult to maintain. These buildings were all simulated on the north side of the Alps.

The heating heat transfer coefficient looks to be stable unless the ground recharge ratios is smaller than 100%. The important decrease is caused by long term effects, which are producing a greater ground cooling when the ground recharge is weaker. The coefficients where obtained for a ground thermal conductivity of 2 W/(mK) and a minimum fluid temperature level of 1.5°C in the borehole flow circuit. A ground thermal conductivity of 1.5 W/(mK) makes the coefficients 0.4 W/m/K smaller, whereas a value of 3 W/(mK) makes them 0.7 W/m/K greater.
Figure 5  Heating heat transfer coefficients shown in relation to the ground recharge ratio for all simulated cases.

Figure 6  Geocooling heat transfer coefficients shown in relation to the ground recharge ratio for all simulated cases.

The geocooling heat transfer coefficients are shown in figure 6 for all cases. They are rather scattered, depending on the building design as well. The lower values were obtained with TABS instead of floors for the heat distribution. However TABS can provide a geocooling solution to a wider range of building designs, thanks to their auto-regulating properties, a moderate maximum distributed cooling power and a large design fluid temperature for cooling.

A value of 5 W/m/K seems to be rather conservative for a pre-design estimation. It is decreased to about 4 W/m/K if ground thermal conductivity is 1.5 W/(mK), and increased to 5 W/m/K with a value of 3 W/(mK). The annual transferred energies lie in the range 1 to 8 kWh/m/K/y.

For Swiss locations like Zurich, Geneva and Chiasso, the use of triple instead of double glazing has the advantage to halve the total required borehole length. Two effects are beneficial: the maximum heating power is smaller and allows for a reduction of the borehole length as sizing is conditioned by the heating criterion. The second important effect is the ground recharge ratio which
is significantly increased towards its optimal value. It is the opposite for the Italian location of Bologna. The only possible solution is obtained with double glazing, otherwise the ground recharge ratio would be far too large. In this case and as expected, sizing is conditioned by the geocooling criterion. However the total required borehole length is large, indicating that geocooling solutions with BHE has reached its southern limit with a climate such as the one in Bologna.

6.5 Pre-sizing example
The ground recharge ratio of the reference building is calculated to about 60%. It can be estimated on the basis of the annual heating and cooling energies distributed in the building and the annual performance coefficient of the heat pump. The heat transfer coefficients computed for the reference building were obtained to 2.5 W/m/K for heating and 6 W/m/K for geocooling. The determination of the borehole length requires to establish the nominal heat extraction rate of the heat pump (56 kW), the maximum cooling power (75 kW) and their associated temperature differences $\Delta T_{\text{extraction}}$ and $\Delta T_{\text{ground}}$, estimated to respectively 12K and 7K. These quantities can be determined from building and heat distribution design characteristics and local ground conditions.

Using Eq. (1) and (4) to calculate $H_h$ and (2) and (5) for $H_g$, the required borehole length is computed to 1'870 m for the heating criterion and 1'790 m for the geocooling one. The pre-design estimation of the borehole length is given by the largest values. The reference case results were obtained with 18 boreholes of 100 m each.

In any case a pre-design calculation has to be done with extremely careful prudence. It can not, in any case, substitute thermal simulations done for sizing purposes.

7. Conclusion
The geocooling potential of borehole heat exchangers has been studied for office buildings. A complete system simulation tool including the building, its heating and cooling distribution and the ground coupled system has been developed, taking advantage of existing and well established tools. A detailed methodology has been developed for building analysis and suitability for geocooling. Borehole heat exchanger sizing is then carried out in a consecutive step.

Definitions of sizing keys and heat transfer coefficients for heating and geocooling were proposed to show the results of all simulations. They were executed for different building locations, building designs, distribution types, borehole configurations and local ground conditions. They provide useful values for a fast pre-sizing of a geocooling system.

Geocooling is not feasible with any kind of building design. Only those complying to low energy standard are potentially interesting. TABS are the most suitable distribution system to minimize both heating and cooling annual distributed energies. They make possible to take advantage of the full geocooling potential.

The ground recharge ratio is a crucial issue for a geocooling system. A value of about 50% was found to be the best one. It depends on the building designs but also from the geographical location. A warmer climate tends to make the ground recharge ratio increase. Another key parameter is the temperature difference between design forward fluid temperature in the cooling distribution and the initial ground temperature. A too low design cooling temperature or a too high ground temperature may compromise the feasibility of a geocooling solution.

The established simple design rules enable a fast pre-sizing of a geocooling system. However they do not substitute a proper system simulation. It is important to have the possibility to simulate, as no generalisation can be stated. A simulation has to be done in any case to validate a pre-design sizing.

8. Acknowledgements
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9. References


