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Cost optimized design of ground probe fields with solar regeneration

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Abstract

Solar regeneration is often used to raise the temperature of the ground above the natural level in order to enable a more efficient operation of heat pumps. The aim of this simulation study was to find the most cost-effective configuration of ground probes in combination with solar regeneration. The results show that with the help of regeneration not only the costs, but also the efficiency of the heat supply can be improved in comparison to the case without regeneration. Besides that, good conditions are achieved for freecooling with the ground probes despite the regeneration, as well.

Keywords: Ground source heat pump, regeneration, ground probe field design, cost-optimal design

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1. Introduction

Heat pump systems enable low-carbon heating of buildings. The ground is often used as a heat source. The advantage of ground-source heat pump systems compared to air-to-water systems, which are also widely used, is the low noise emission, even in large systems, and the lower electrical power requirement in colder weather conditions. However, higher initial investment cost is required for ground-coupled systems. Another problem can occur with large construction projects or refurbishments. For space reasons, the probes may have to be arranged in compact fields, which can lead to a strong temperature decrease in the ground.

One way to prevent this problem is to regenerate the ground using a second heat source. This can limit the long-term temperature degradation during the use of the ground probes over several decades. In addition, the lowering of temperatures during a single winter can be reduced. Furthermore, it was also assumed that the use of solar collectors would result in cost advantages. On the one hand, since the number of probes could be reduced, on the other hand since a part of the domestic hot water can be heated directly and thus less electrical energy and less source energy is needed for the operation of the heat pump.

In practice, the aim of a solar regeneration is usually to raise the temperature of the ground above the natural level in order to enable a more efficient operation of the heat pump. This requires a heat input to the ground that exceeds the heat extraction in the annual balance. The focus thereby is on energy efficiency rather than on cost efficiency.

To determine the potential of a strictly cost-optimized design, a simulation study has been carried out. A residential complex consisting of six buildings with a totally heated area of 16,800 m^2 is used as a case study. Active cooling operation with the heat pump used as chiller was not analyzed for this application, as active space cooling is not common in residential buildings in Switzerland, yet. However, the free cooling potential by the ground are addressed based on the evaluated ground temperatures. Nevertheless, the system configuration has also cooling potential and indeed, in the luxury residential segment also active cooling is more often asked on the market. Thus, further investigations shall also include the space cooling operation as further operation mode of the system.

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2. Method

The aim of the simulation study was to determine the minimum number of probes required as a function of the collector area. In addition, the power consumption of the heat pumps and the pumps for the source circuit were determined. In this way, the level of investment and operating costs as well as the consumption of electrical energy could be determined. The same model has been used for all simulation variants.

The only parameters varied were the number of probes, the distance between the individual probes and the area of the collectors.

The simulation model was created with Matlab/Simlink and the Carnot Toolbox [1]. The model contains very well insulated buildings. The heat demand for DHW (19.8 kWh/(m^2yr)) is slightly lower than the heat demand for space heating (21.2 kWh/(m^2yr)), but in the same range. The location of the buildings is Zurich. The heating period lasts from the beginning of October to the middle of May. Each building has two storage tanks for the hot water system and collectors on the roof. The collectors are oriented to the south with an inclination of 30°. One storage tank serves to preheat the water through the collectors, the second tank is supplied by the heat pump. In order to shorten the calculation time, the buildings were not modelled in detail. Instead, load profiles created in advance were used. In this profiles, space cooling is not taken into account.

An unglazed, selective collector was used. In the first priority, the collectors preheat the domestic hot water, in the second priority they deliver heat to the ground probes. The collectors were distributed evenly on the roofs of the six buildings.

The heat source is a central ground probe field with a bidirectional low-temperature network with a cold and a warm distribution pipe to which all heat pumps and collectors are connected. Each building has its own heat pump. The temperature difference between the warm and cold conductor is 5 K.

A self-developed model is used for the ground probes, which is based on the EWS model developed by Huber [2] for the probe tube and the close range (3 m around the ground probe). For the boundary conditions, the method for the analytical calculation of the g-functions according to Lamarche and Beauchamp [3] was used. In addition, the probe loads are superposed for half a year at an interval of seven days. The probes are installed to 200 m depth, the mean ground surface temperature is 9 °C and the geothermal gradient is 0.03 K/m. Further parameters of backfill and ground are listed in Table 1. The probes are always arranged in squares.

Table 1. Material properties of the backfill and the ground

Component	Backfill	Ground
Thermal conductivity (W/m/K)	0.81	2.4
Specific heat capacity (J/kg/K)	3040	1000
Density (kg/m^3)	1180	2600

The collector area required for differently sized ground probe fields was determined so that the ground does not cool down too much. The design criterion was that the temperature of the cold distribution pipe must not fall below -3 °C during the first 50 years of operation, according to the Swiss standard SIA 384/6:2010 [4].

In order to evaluate the configurations from an energetic point of view, the electrical consumption of the heat pumps and the pumps in the source circuit is evaluated. The characteristic diagram of a commercially available speed-controlled heat pump was used. When calculating the electrical consumption of the frequency controlled circulating pumps, only the pressure drop by the ground probes was taken into account according to the pressure drop calculation tool of Huber et al. [5]. The pressure loss of the horizontal connecting pipes was neglected. The pipes of the ground probes have a diameter of 32 mm. The efficiency of the circulating pumps is 0.5.

Configurations of the following combinations of ground probe fields and probe distances were investigated:

- ground probe fields: 3×3 / 4×4 / 5×5 / 6×6 / 7×7 / 8×8
- ground probe distances: 6 m / 8 m / 10 m / 20 m

An attempt was made in each case to select the collector area in such a way that the minimum temperature in the cold distribution pipe is as close as possible to -3 °C. The exact values for the collector area, the power consumption, the system efficiency and the regeneration share were finally interpolated. The following definitions were used:

- Power consumption: Average electricity consumption of heat pumps and source pumps over 50 years
- System efficiency: Quotient of heat demand for space heating and domestic hot water and power consumption

- Regeneration share: Total collector yield divided by the total source heat demand for space heating and domestic hot water. The source heat demand includes the heat that was directly used for preheating the domestic hot water and heat for the heat pump extracted of the ground probes.

As a comparison, the number of probes necessary to achieve the design criterion without regeneration was also determined for the various probe distances. The results were also interpolated. For this reason, a number of probes can result for the required probes that cannot be arranged in a square.

The system costs are calculated from the interpolated values for the collector surfaces and the number of probes. The following values which are common in Switzerland, were assumed:

Electricity:	0.15 €/kWh
Investment costs ground probes:	80 €/m
Investment costs for collectors:	400 €/m^2 (includes planning, mounting system, piping and installation work)

3. Results

Fig. 1 shows the values for the minimum temperature of the cold distribution pipe in the first 50 years of operation of all simulation variants. The range of the marked square on the left is enlarged in the right figure.

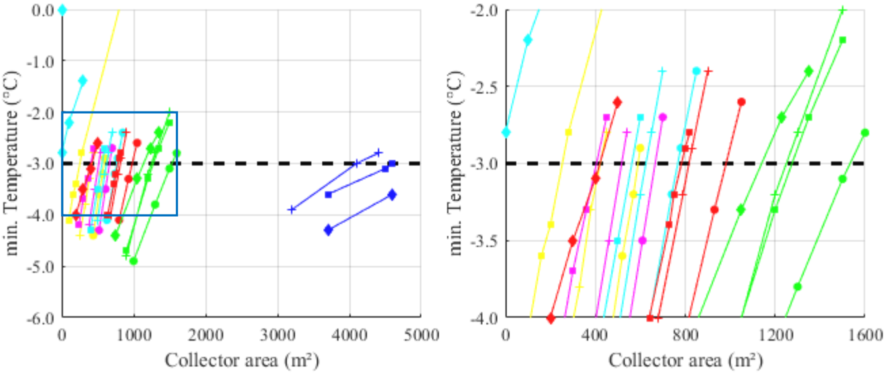

Fig. 1. Minimum temperature of the cold conductor in the first 50 years of operation. (Fields: blue: 3×3, green: 4×4, red: 5×5, cyan: 6×6, violet: 7×7, yellow: 8×8 / Distances between ground probes: dots: 6 m, crosses: 8 m, squares: 10 m, diamonds: 20 m)

Fig. 2 shows the temperature curves of the cold and the warm distribution pipe of a case with and without regeneration as a comparison. It can be seen, that by the reduction of the ground probe length, the system reaches negative temperatures already after a few years of operation, but the temperatures remains more or less constant from then on. The non-regenerated system does not come close to a stationary state even after 50 years. The difference between the maximal and minimal temperature is significantly higher in the regenerated case, because of the smaller usable heat capacity of the ground compared to the larger, non-regenerated field.

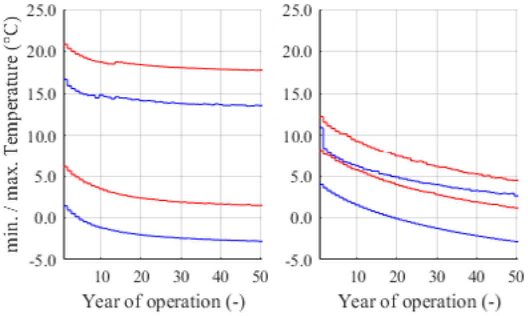

Fig. 2. Plot of the maximum and minimum temperature of the cold (blue) and the warm (red) conductor per year.(left: 5×5 ground probes in a distance of 10 m with 820 m^2 collector area, right: 10×10 ground probes in a distance of 10 m without regeneration)

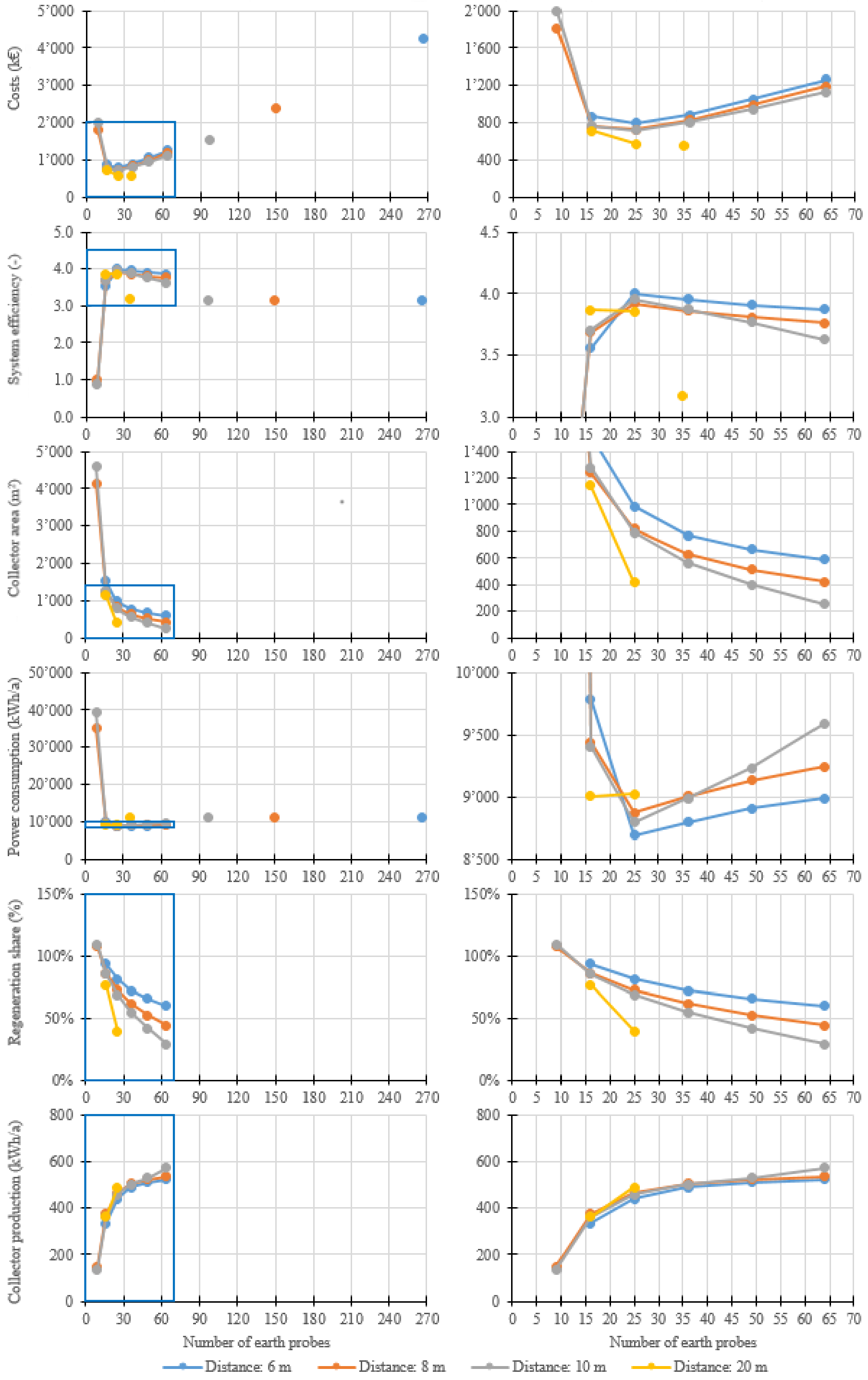

Fig. 3. Costs, System efficiency, collector area, power consumption and regeneration share as a function of the ground probe field

Fig. 3 shows the interpolated values for the required calculated costs, the system efficiency, the collector area, the power consumption and the regeneration share for the various system configurations. The single points represent the cases without regeneration. The marked area in the left figure is depicted enlarged in the right figure.

The results demonstrate that by means of regeneration not only the total cost can be reduced, but also the efficiency of the heat supply can be improved. Besides that, there are still good conditions for free cooling with the ground probes, since the regenerated field is operated colder than with higher shares of regeneration.

The distance between the probes has a large influence on the reduction potential of the cost. The smaller the distance between the probes, the higher the saving potential, which can be evaluated by a comparison of the cost curve with regeneration and the single points without regeneration. In the case with a distance of 10 m, the cost optimum is achieved with approximately 16-25 probes. Compared to the case without regeneration with 97 probes, this is a 74-84% reduction in probe length and about 42% in costs. This can be advantageous for refurbishments when space is limited. But, it can also be beneficial for new buildings. By reducing the need for ground probes with the help of regeneration, the distance between the ground probes can possibly be increased. That could allow a further reduction of the number of ground probes. The lowest overall cost is reached, however, for the largest distance of 20 m.

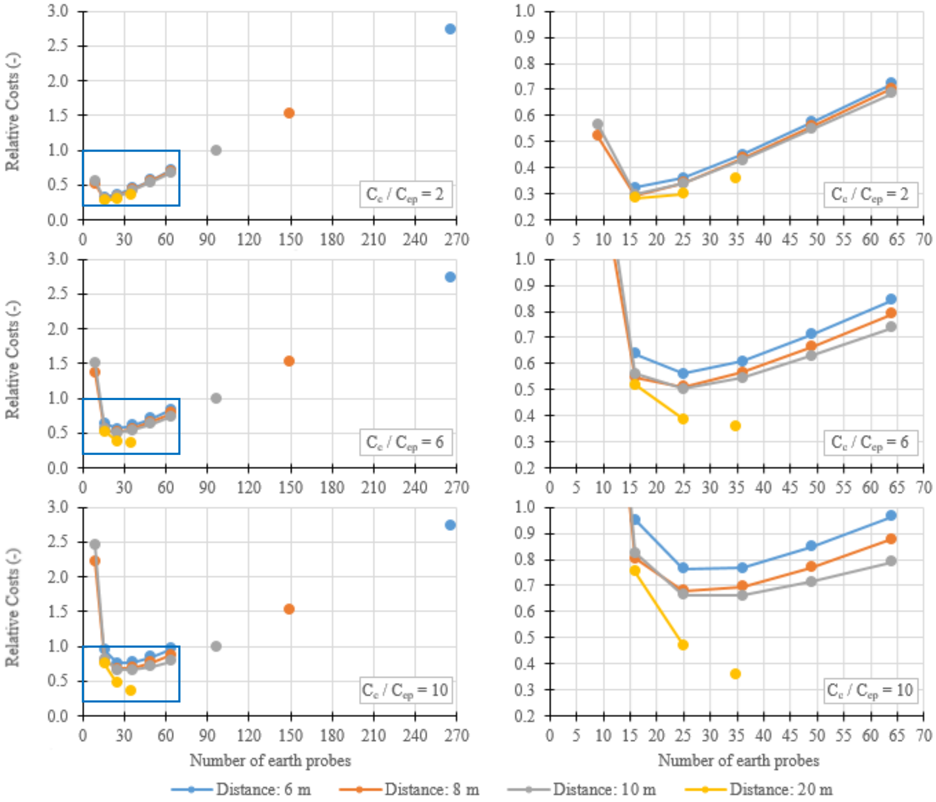

Fig. 4. Relative costs for different ratios of the cost per square meter of collector area (C_c) to the cost per meter of ground probe with the cost of a 5×5 field with a 10 m borehole distance as a basis.

The system efficiency is increased, although the temperatures in the cold distribution pipe in winter already reach negative values after a few years. One reason for this is the partly direct supply of hot water by the collectors, the other reason is the temporarily high source temperatures for the heat pumps. Fig. 2 on the left shows the case with the ground probe field 5×5 and a ground probe distance of 10 m and a collector surface of 820 m^2, which is close to the cost optimum. Fig. 2 right shows the case without regeneration with 100 probes arranged in a square of 10 m distance, corresponding to the minimum number of probes without regeneration.

Due to the lower number of probes the temperatures are lower only during the heating period. During the other seasons, the domestic hot water can be produced very efficiently at higher source temperatures. In the described case, the DHW share produced by the collectors is 49%. Thus, a performance increase can be expected in particular in larger new buildings, where the DHW share reaches the same energy amount or is even higher than the space heating needs.

The energy consumption of the pumps has a significant influence on the total power consumption only for small fields. With the 3×3 fields it can reach up to 80%. With the 4×4 fields it is 6-25% and with the 5×5 fields it is reduced to less than 5%. The higher power consumption with the small fields is due to the higher pipe resistance, since the mass flow is kept the same as in larger fields. Additionally, due to the larger collector area, a higher collector yield has to be transferred to the ground. This is also the reason, why for the small fields the system performance is notably reduced, since the fraction of auxiliary energy expenditure for the pumping of the fluid rapidly increase up to low overall system performance. Due to the large regeneration shares, also the system cost increases disproportionally. These system designs are thus not reasonable neither from the energy performance nor from the cost viewpoint and are henceforth not considered for the evaluation of the results.

The cost of ground probes and collectors can vary significantly depending on the region and system size. Therefore, in Figure 4 the relative costs were calculated as a function of the ratio of the price per square meter of collector area (C_c) to the price per meter of ground probe (C_{ep}). The electricity price was set to 0.00 €/kWh in all cases. The influence of the electricity price in the range of 0.00 €/kWh - 0.20 €/kWh on the total costs is in all cases less than 0.5% and is therefore negligible. The costs for the case with a 5×5 probe array with 10 m probe spacing were taken as a basis. In graph 3 the ratio is C_c / C_{ep} = 5.

It can be seen that the results do not fundamentally change even for large and small ratios C_c/C_{ep}. But, the cheaper the geothermal probes are, the less advantageous is a substitution by collectors.

4. Conclusion and Perspective

Results of the investigations show that a design of the ground source to shorter length by regeneration can yield cost and performance increase, which is also due to a direct production of used energy by the regeneration system, in this case the direct solar DHW operation of the collectors. Since for this investigation, selectively coating unglazed solar collectors have been considered, DHW use temperatures can be reached by the collector in summer operation. However, current investigations only reflect one particular weather data set, load situation and system configuration. Therefore, further investigations are necessary, also e.g. regarding longer cold periods. Due to the smaller number of ground probes compared to a conventional configuration without regeneration, the system is more vulnerable to cold periods. During cold periods lasting several days, the area around the probes can cool down considerably. Due to the lower number of probes, the available heat around the probes is smaller, which leads to a stronger cooling.

For the considered buildings the system performance is increasing with the regeneration, in particular in case of limited space for the ground probes. However, for the considered case, the annual DHW demand is in the same range as the energy demand for space heating, and thus the summer operation is more pronounced. Therefore, for different buildings loads, the effect on the system performance should also be considered. Since the minimal temperature level in winter is lower for the considered regenerated cases than in the reference case without regeneration, see comparison in Fig. 2, the system efficiency could decrease for certain times compared to the reference case.

Moreover, for the regeneration with unglazed solar collectors, a large collector area is needed. The influence of alternative heat sources for regeneration, such as outside air, waste water or free cooling of the connected buildings should also be examined in more detail.

In this context also the low system performance in case of only a few ground probes is to be analyzed in more detail, which, however, is according to the present evaluation not cost-effective due to a very large regeneration need.

Acknowledgements

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