Solar Thermal Regeneration of Borehole Heat Exchangers in Urban and Suburban Districts

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Abstract. To prevent undercooling of the ground in densely populated areas, regeneration of borehole heat exchangers (BHEs), for example by solar thermal heat, may become necessary. However, the usable roof area is often small compared to the building’s heat demand, especially in urban areas. It was investigated how much regeneration is possible in districts that are supplied entirely by heat pumps with BHEs. Example buildings were modelled based on the buildings of two districts in Zurich. Uncovered PVT collectors and glazed flat-plate collectors were used as regeneration sources. The possible regeneration was determined in a simulation process that included the effects of mutual influences between the BHEs of neighbouring buildings. As expected, glazed flat-plate collectors allow for more regeneration than uncovered PVT collectors. For full regeneration, the required usable roof area relative to the annual heat demand is about 1.8 m²/MWh for PVT and 1.2 m²/MWh for flat-plate collectors. Large buildings often do not provide sufficient roof area for full regeneration. A sustainable heat supply of the entire district with regenerated BHEs can be possible in suburban neighbourhoods, if the bigger buildings are distributed rather evenly. In urban neighbourhoods, areas may exist in which solar thermal regeneration alone is not sufficient.

1. Introduction
In densely-populated areas with a large number of borehole heat exchangers (BHEs), sometimes more heat is extracted in winter than what can flow back in summer [1]. The subsequent cooling of the ground reduces the efficiency of the heat pumps. In two field studies conducted in Zurich, it has been found that many BHEs are to be considered ”clearly undercooled”, especially in densely-populated areas [2, 3]. The topic of undercooling is not only an issue in Zurich. In Berne, a district has been analysed exemplary as well [4] and the topic is also given international attention [5, 6].
A possible counter-measure is to regenerate the BHEs by bringing excess heat into the ground during summer, for example by means of solar thermal collectors. Due to the limited amount of available roof area in urban districts, the collectors would have to ”compete” against the increasing use of photovoltaic (PV) panels. This ”competition” can be eased by the use of

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photovoltaic thermal hybrid solar collectors (PVT collectors), which generate heat and electricity in the same area.

In this paper, which is based on a currently ongoing research project [7], the suitability of uncovered PVT collectors and glazed flat-plate solar thermal collectors for the regeneration of BHEs in two districts in the city of Zurich is investigated by means of numerical simulations. As opposed to previous research [8], where only one individual building type was investigated, the entire districts are modelled as a set of 'typical' model buildings and the mutual influence between the BHEs of different neighbouring buildings is taken into consideration.

2. Methodology
2.1. Building models
Five exemplary buildings for both districts, the urban (in Zurich-Altstetten) and suburban (in Loorenquartier) districts, were modelled based on data from Zurich’s building park model [9]. The buildings were categorized in terms of energy reference area with the smallest category (U1, S1) representing single-family houses and the largest one (U5) representing very large residential buildings with twenty-one apartments or more. The prefix 'U' stands for buildings in the urban district and 'S' for suburban. The latter lacks buildings of 'size 5', which is the reason why the building model 'S5' is not present in this study.

The transient heat load of the buildings was simulated in Polysun [10] using the quasi-dynamic building model with a room temperature set point of 22°C. The heating system was modelled as an underfloor heating system with a flow temperature of 45°C. The annual thermal demand of each building model is shown in Table 1. A hot water set point temperature of 50 °C was applied. Figure 1 shows the hydraulic set-up of the Polysun models. The solar thermal collectors were coupled to the borehole heat exchangers in a way that allowed to use their heat either directly as a heat pump source or to regenerate the borehole, depending on the temperature levels and the heat pump status. For reference, also normal operation without regeneration could be simulated. To prevent accelerated ageing of the BHE material, a mixing valve on the cold side of the plate heat exchanger was used to make sure that the fluid temperature in the BHE never exceeded 30°C. For the simulation, weather data from Meteonorm 7.2 for the center of Zurich (47.37°N, 8.54°E) were used. The horizon data provided by Meteonorm 7.2 was included, but close-range shadowing was neglected. To each building category, typical values for total roof area, usable roof area, roof tilt angle and roof orientation (deviation from south) was assigned. The typical values resulted from aggregating roof geometry data from the Swiss Federal Office of Energy [11] for the same selection of buildings as was used for the typical heat demand values.

| Building model | Energy reference area (m²) | Heat demand space heating (kWh/a) | Heat demand hot water (kWh/a) | Total heat demand (kWh/a) | Spec. heat demand space heating (kWh/(m²a)) | Spec. heat demand hot water (kWh/(m²a)) |
|---------------|-----------------------------|---------------------------------|-------------------------------|--------------------------|----------------------------------------|----------------------------------------|
| U1            | 180                         | 14,800                          | 2400                          | 17,200                   | 82.2                                   | 13.3                                   |
| U2            | 360                         | 26,500                          | 6400                          | 32,900                   | 73.6                                   | 17.8                                   |
| U3            | 640                         | 42,700                          | 12,600                        | 55,300                   | 66.7                                   | 19.7                                   |
| U4            | 1420                        | 86,200                          | 27,200                        | 113,400                  | 60.7                                   | 19.2                                   |
| U5            | 4980                        | 238,300                         | 80,700                        | 319,000                  | 47.9                                   | 16.2                                   |
| S1            | 180                         | 13,500                          | 2200                          | 15,700                   | 75.0                                   | 12.2                                   |
| S2            | 360                         | 24,300                          | 5800                          | 30,100                   | 67.5                                   | 16.1                                   |
| S3            | 640                         | 39,100                          | 11,400                        | 50,500                   | 61.1                                   | 17.8                                   |
| S4            | 1420                        | 79,000                          | 24,600                        | 103,600                  | 55.6                                   | 17.3                                   |

Table 1. Annual heat demand of the building models. The specific values are per energy reference area, not per living space area.
The usable roof area was obtained by multiplying the total roof area with a usability factor. The latter is a number between zero and one that was obtained by manually analysing possible collector configuration for 20 randomly selected roofs of each category. More details on the determination of the usability factor can be found in a separate publication [12]. For the simulations, the unglazed PVT collector type "DualSun Spring 310 unisolated" and the glazed flat-plate solar thermal collector "Flachkollektor, sehr gut" were used. The latter is a generic model from the Polysun database. The collectors have a gross area of 1.65 m$^2$ and 2.00 m$^2$, respectively. Table 2 shows the typical roof data and the possible number of collectors for each building model. For the derivation of the typical roof geometry, it was not distinguished between urban and suburban buildings.

| Building model | Usable roof area (m²) | Roof tilt angle (°) | Deviation from south (°) | Number of PVT collectors | Number of pure solar thermal collectors |
|----------------|-----------------------|--------------------|--------------------------|--------------------------|----------------------------------------|
| U1, S1         | 39                    | 28                 | 60                       | 24                       | 19                                     |
| U2, S2         | 57                    | 28                 | 60                       | 35                       | 28                                     |
| U3, S3         | 95                    | 25                 | 70                       | 58                       | 47                                     |
| U4, S4         | 136                   | 20                 | 80                       | 82                       | 68                                     |
| U5             | 245                   | 20                 | 80                       | 148                      | 122                                    |

Table 2. Typical roof geometry and maximum possible number of collectors for each building model.

2.2. Modelling of the influence of neighbour boreholes heat exchangers
To model the cooling effect of the neighbour borehole heat exchangers, a typical neighbour building model and a typical distance was determined for each building model from the building park data. The influence of one single neighbouring BHE can be determined by

$$\Delta T = \frac{1}{4\pi\lambda} Q \text{EI}\left(\frac{D^2}{4a}\right),$$

where $\lambda$ is the thermal conductivity of the ground, $Q$ is the specific heat extraction of the neighbour BHE, $\text{EI}(x)$ is the exponential integral $\int_0^\infty \frac{e^{-u} du}{\sqrt{u}}$, $D$ is the distance between the BHEs, $a$ is the thermal diffusivity of the ground and $t$ is the time of operation. For $\lambda$ a value of 2.4 W/(m K) and for $a$ a value of $10^{-6}$ m$^2$/s were used. The cooling effect of all neighbour BHEs were superimposed and the resulting reduced ground temperature was used to calculate the required BHE length with the software tool "EWS" [13]. A lower ground temperature requires a longer BHE, which in turn reduces the specific heat extraction $Q$ and thus the influence on the neighbour BHEs. This calculation was repeated until no significant changes were observed any more. The results of this iteration are shown in Table 3. Because S2 and S3 had each equally often S2 and S4 as neighbours, the sub-variants a and b were introduced for both.
Building model | Typical neighbour building model | Typical number of neighbours | Typical Distance (m) | Required number of BHEs | Required BHE length (m)
---|---|---|---|---|---
U1 | U4 | 3 | 34 | 1 | 282
U2 | U4 | 4 | 35 | 2 | 350
U3 | U4 | 3 | 30 | 2 | 312
U4 | U1 | 4 | 34 | 5 | 284
U5 | U4 | 3 | 36 | 18 | 295
S1 | S2 | 4 | 34 | 1 | 216
S2a | S2 | 3 | 34 | 2 | 209
S2b | S4 | 3 | 34 | 2 | 245
S3a | S2 | 3 | 37 | 3 | 228
S3b | S4 | 3 | 37 | 3 | 269
S4 | S4 | 2 | 38 | 5 | 312

Table 3. Typical neighbour buildings and required BHE dimensioning (without regeneration) for each building model.

2.3. Simulation Process

Since the dimensioning of the BHE has an effect on the regeneration and vice versa, the required collector area was determined iteratively. First the monthly heat extraction without regeneration was determined with a simulation in Polysun with the standard BHE dimensioning suggested by the built-in wizard. Based on these monthly values, the influence of the neighbour BHEs and the corresponding adapted BHE dimensioning was determined as described in the previous section. The number of BHEs remained unchanged; only their length was adjusted. After that, another Polysun simulation was conducted, this time with regeneration. The collector area was chosen such that the regeneration was as close to 100% as possible. In case of the roof areas limiting the collector number, values of less than 100% were possible. With the new monthly heat extraction values, another BHE dimensioning was made with the EWS tool, which in turn was the basis for a new Polysun simulation. This was repeated until no significant changes in terms of required borehole length were observed any more. With the final BHE design, one more Polysun simulation was conducted with the maximum possible number of collectors to estimate the potential for more than 100% regeneration.

3. Results

3.1. Regeneration with uncovered PVT collectors

Figure 2 shows the possible regeneration for each building model when uncovered PVT collectors are used. The bars on the left indicate the case where

![Figure 2](image)
only the required number of collectors is used, whereas the bars on the right show the case with maximum number of collectors. The grey bars represent the annual gross heat extraction and the orange bars the net heat extraction. Net heat extraction is the total heat extracted from the ground (gross heat extraction) minus the heat brought into the ground through regeneration. A net heat extraction of zero means 100% regeneration and a positive net heat extraction means less than 100% regeneration.

It can be seen that for the larger buildings U4, U5, and S4, full regeneration is not possible, even when the maximum collector number is used. For the smaller buildings, full regeneration is possible, but using the maximum number of collectors will not create considerable amounts excess regeneration. This suggests that on the district scope, there is not enough heat for full regeneration, even when it is assumed that it is possible to 'share' excess heat across property borders.

3.2. Regeneration with glazed solar thermal collectors

Figure 3 shows the possible regeneration when using glazed solar thermal collectors. A considerable regeneration deficit is only present in the large building U5. When the maximum number of collectors is used, many building models exhibit regeneration values well above 100%, especially in the suburban district.

3.3. Required roof area for complete regeneration

Figure 4 shows the possible regeneration in dependence on the ratio of the usable roof area and the annual heat demand ("specific roof area") for PVT collectors and glazed solar thermal collectors. Each data point corresponds to the simulation results of one building model with the maximum possible amount of collectors. For both collector types, a reasonably good linear fit can be obtained. As expected, the possible regeneration for a given specific roof area is greater with glazed solar thermal collectors than with uncovered PVT collectors. To obtain 100% regeneration, around 1.8 m² of uncovered PVT collectors or around 1.2 m² of glazed flat-plate solar thermal collectors are required per MWh of annual heat demand. Or, to put it differently, by using glazed flat-plate collectors, around one third less roof area is needed for full regeneration than with uncovered PVT collectors.

4. Discussion and Outlook

The results suggest that supplying heat entirely from solar-thermally regenerated BHEs is generally possible in suburban districts as long as large buildings are not concentrated and standing close to each other. In urban districts, only the smaller building’s BHEs can be regenerated by solar thermal heat. The usually large count of bigger
buildings, which are often standing close to each other, makes a purely solar thermal regeneration difficult, considering the usually small roof areas compared to the heat demand. Additional heat sources, such as waste heat from cooling, have to be found if the entire district is to be heated by BHE heat pump systems. When comparing the suitability of uncovered PVT collectors versus glazed flat-plate solar thermal collectors, the latter requires around one third less roof area for regeneration. However, the former allows for the simultaneous generation of photovoltaic electricity on the same roof area. When evaluating different collector types for regeneration, this aspect should not be neglected. Even more so, because the increasing popularity of heat pump systems will generate more demand for sustainable electricity, especially during winter, when electricity from PV is scarce. A possibility for further improvement lies in the use of advanced BHE materials that allow for higher BHE inlet temperatures than the 30°C limit of the present study. Increasing the maximum inlet temperature is expected to increase the yield of the solar thermal collectors.

![Figure 4. Possible regeneration depending on the ratio “usable roof area divided by annual heat demand” when using the maximum possible number of collectors.](image)

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