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ITGBES-PRO, a new method for the optimization and integrated design of clustered individual borehole heat exchanger systems

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ABSTRACT

Although several well known design methods for borehole heat exchanger systems exist, none of these allow the simultaneous simulation or sizing of multiple different individual systems. Limitations of the existing software suites are, amongst others: inability to evaluate different energy demand profiles and heat pump types, inability to calculate individual temperature effects considering relative position in the field, inability to size borehole heat exchangers differently and limited capabilities to allow arbitrary field geometries. In the current markets, where large numbers of individual systems are installed, solutions are required to asses thermal interactions, optimize borehole heat exchanger fields in an early stage and support the integrated design of large numbers of individual systems.

In this paper we present a new approach to the integral design of individual ground source heat pump systems with borehole heat exchanger systems. The standard calculation methods are based on the well known Infinite Line Source (ILS) and Finite Line Source (FLS) solutions, the main work horses of ground source energy calculation software. A novel implementation of the FLS allows the simultaneous evaluation of many distinct individual systems coupled to sizing and optimization algorithms. The application of this new approach will be illustrated using two case-studies, one showing optimization of a large borehole field when actual system parameters are not yet known and one applying the methodology to the integrated design of a field of individual borehole heat exchanger systems.

SYMBOLS

ΔT	:	Temperature difference (K)
r	:	Radial distance to source (m)
t	:	Time (s)
q	:	Heat transfer rate (W/m)
λ	:	Ground thermal conductivity (W/mK)
a	:	Thermal diffusivity (m^2/s)
r_{oo}	:	Far field radius
r1	:	$\sqrt{(r^2+(z-h)^2)}$
r2	:	$\sqrt{r^2+(z+h)^2}$
D	:	Buried depth of borehole heat exchanger (m)
H	:	Length of borehole heat exchanger (m)
h	:	Length (distance) of point on line source (m)
z	:	z-coordinate of point (m)

1. INTRODUCTION

As in many countries the number of ground source heat pump systems (mainly heat pumps using a vertical borehole heat exchanger as heat source and -sink) has been increasing rapidly in the Netherlands (Figure 1). Currently between 10.000 and 20.000 systems are realized yearly and a total well over 65.000 installed systems was reported in 2020. The largest share of installations are individual houses that are realized in relative close proximity to one another. As the individual designs often do not sufficiently account for nearby systems, concerns over the long term viability and energy efficiency arose with law-makers and regulators.

Therefore in 2013 legislation[1] was introduced concerning the design, installation and operation of borehole heat exchangers (BHE) systems. Since then it has been mandatory to show that new systems do not have unreasonable negative thermal effects with systems already present in the vicinity.

[1] Besluit van 25 maart 2013 tot wijziging van een aantal maatregelen van bestuur in verband met regels inzake bodemenergiessystemen en enkele technische verbeteringen, Staatscourant 112.

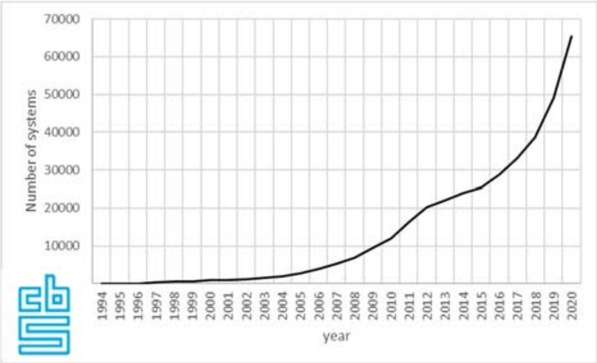


Figure 1: Number of installed closed-loop ground source heat pump systems in the Netherlands 1994 – 2019 (source: Central Bureau of Statistics)

To support the assessment of these thermal interactions between individual ground source heat pump systems tools and procedures have been developed (Witte, 2011; 2018) and made available to the industry and regulators as part of the Dutch protocol for ground source energy systems (SIKB, 2013; 2020).

The principle method of the assessment of thermal interactions is to use the Infinite Line Source (ILS) and Finite Line Source (FLS) methods to calculate thermal interactions between systems, without considering the temperature effect on the borehole wall of the local system itself. Moreover, these thermal interactions can be calculated where each borehole system has different properties (such as length and energy demand profile). To support designers and regulators simplified tools were derived from the analytical models, first based on the ILS and using nomograms (Witte, 2011). Later an automated methodology based on the FLS was implemented in Excel (Groenholland, 2020) which allows up to 20 systems to be processed automatically.

An important limitation of assessing thermal interactions with existing systems, which occurs on a first come first served basis, is the inability to allow for future development of additional systems. Especially in developments where larger numbers of systems are realized by different installers over a period of some years, this would result in sub-optimal use of the ground as a thermal energy source. This has been addressed by allowing regulators (in the Netherlands usually the municipality) to define so-called "zones of interference", where all systems have to obtain a permit and comply with a specific set of rules set out in a "Ground Source Energy Plan". These rules should ensure a fair distribution of the ground thermal energy between users. This can be achieved using a multi objective optimization routine that maximizes the allowed energy extraction of each system while at the same time limiting thermal effects between systems.

It is fairly common nowadays that many individual systems are installed consecutively by the same installer in a small timeframe. For terraced houses the installation of individual heat pumps, each with its own borehole heat exchanger system, is most common. Also in apartment buildings we find that apartments have an individual heat pump which can be coupled to either a collective borehole heat exchanger system or to an individual or small-collective system (where every 3 to 5 apartments share a small collective borehole heat exchanger system). Again, standard design softwares available do not support the integrated design of these diverse systems. We therefore propose to combine the methods developed for assessment of thermal interactions and borehole field optimization with a more standard borehole heat exchanger design methodology for single boreholes to arrive at an optimized design for clusters of individual systems.

In this paper we describe the models and procedures we have developed for these cases and present two case-studies to illustrate their application.

2. METHODS

2.1 Optimization of borehole heat exchanger fields

For the optimization of the distribution of allowed thermal use of the ground in "zones of interference:", where actual energy use and borehole heat exchanger designs are not normally known, the Infinite Line Source (ILS) equation is primarily used as it allows very fast computation that is required for iterative optimization of large numbers of systems. As in this case the final depth of the boreholes is not known, the solutions are calculated using the ILS with specific heat flow per meter borehole (expressed as kWh/m/year). For the final design the designer checks that the total net heat extraction on a yearly basis does not exceed the specified maximum heat extraction allowed.

The ILS was introduced by Carslaw & Jaeger (1947, 1959) and used for the calculation of borehole heat exchanger temperature response by Ingersoll et al (1948, 1954):

$$\Delta T(r,t) = \frac{q}{4\pi\lambda}\int_{\frac{r^2}{4\alpha t}}^{\infty}\frac{e^{-u}}{u}du = \frac{q}{4\pi\lambda}E_i(x)\left(\frac{r^2}{4\alpha t}\right) \quad [1]$$

Which is valid for radii r smaller than the far-field radius:

$$r \leq 4\sqrt{\alpha t} \quad [2]$$

With $E_i(x)$ the exponential integral function:

$$E_i(x) = \int_x^{\infty}\frac{e^{-u}}{u}du \quad [3]$$

Hart and Couvillion (1986) give a solution to the exponential integral:

$$\Delta T(r,t) = \frac{q}{4\pi\lambda}\left[ln\frac{r_\infty}{r} - 0.9818 + \sum_1^n\frac{(-1)^{n+1}y^n}{n(n!)}\right] \quad [4]$$

Using this solution to calculate the temperatures for every potential system location, the optimization starts with a list of X- and Y-coordinates of the system locations and arbitrary starting values for the Net Specific Heat Extraction (NSHE). The ILS is then used to calculate all temperature effects between the systems and optimize the NSHE for all systems such that the maximum NSHE is assigned while a specific temperature limit is not exceeded:

1. Temperature effects of all systems (with the exception of the system itself) are aggregated to calculate the total temperature effect.
2. For each system the temperature effect it causes on its neighbours is aggregated, this value is used as a weighing factor for the adjustment of the NSHE for that system.
3. All systems are evaluated:
    a. Temperature exceeds limit: weights of neighbouring systems is decreased
    b. Temperature does not exceed limit: weights of neighbouring systems is increased
4. New NSHE are assigned using the updated weights and temperature effects are re-calculated, when the change of NSHE is smaller than a specified limit the iterations stop, else a new iteration commences.

The algorithm uses several tuning parameters:

- Minimum temperature effect below which weights are increased.
- Maximum temperature effects above which weights are decreased.
- Minimum distance limit, if the distance between two systems is smaller than this limit, the distance is set to this limit. This is to allow the possibility of alternating borehole positions in narrow lots (which are common in terraced social housing developments).
- Maximum distance limit, if distance between systems is larger temperature effect not calculated (to prevent very small temperature perturbations when evaluating a large number of systems).
- Optional temperature limit below which temperature effects are not included (to prevent very small temperature perturbations when evaluating a large number of systems).

A final sweep will check if each system has been assigned a minimum NSHE. Then the final temperature effects are calculated and for systems with a NSHE that causes some temperature effects on neighbouring systems this is translated to a required adjustment of the design temperature that will be used by the installer.

2.2 Integrated design of individual borehole heat exchanger systems

For the integrated design studies, based on calculation of the thermal interactions between borehole heat exchanger systems and design calculations of individual systems, the Finite Line Source (FLS) equation (Eskilson, 1987) is used as it provides a more accurate calculation of the borehole wall temperature. The finite line source is based on the solution to the problem of a point heat source of strength q_o (Carslaw & Jaeger, 1947; 1959).

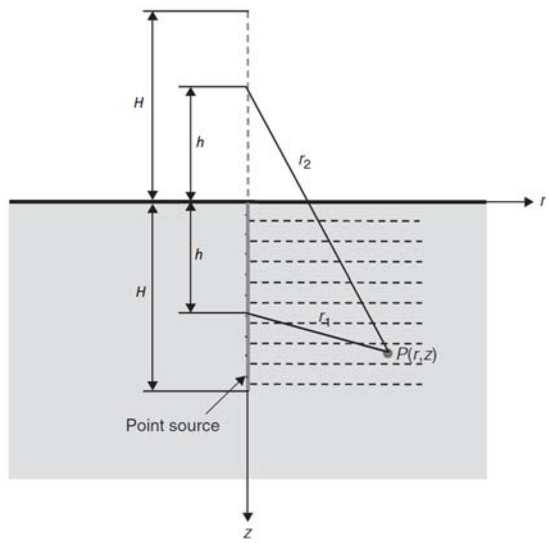


Figure 2: FLS representation of a vertical borehole including its mirror source.

An isothermal boundary condition at the surface is imposed by defining a mirror-source of equal strength but opposite sign, the solution for the borehole heat exchanger is then obtained by integration over the length of the borehole. Figure 2 depicts the FLS for a vertical borehole heat exchanger, with P(r,z) any point at a radial distance of the borehole, H the length of the borehole

Marcotte and Pasquier (2009) give the derivation of the finite line source solution from the point source solution, as a temperature change (with regard to undisturbed ground temperature):

$$\Delta T(r,z,t) = \frac{q}{4\pi\lambda} \int_D^H \left[\frac{1}{r_1} erfc\left(\frac{r_1}{2\sqrt{\alpha t}}\right) - \frac{1}{r_2} erfc\left(\frac{r_2}{2\sqrt{\alpha t}}\right) \right] dh \qquad [5]$$

Where *erfc* is the error function.

Once the borehole wall temperature is calculated the fluid temperature is obtained using the usual equations for the thermal borehole resistance (Hellström, 1991). With the calculation of thermal resistance in our implementation the actual temperature dependent fluid properties are used (based on correlations for fluid thermal conductivity, heat capacity, density and viscosity) and updated during the calculation. An important change for the borehole thermal resistance occurs from laminar to turbulent flow regime, the threshold is generally set at a Reynolds of 2300. This change causes instabilities in the design calculations. It is more realistic (van Doorn, 2014) to assume a more smooth transition from laminar to turbulent flow regime, which can be achieved by linear interpolation between a Reynolds of about 1500 (below which fully laminar flow is assumed) and 3100 (above which a fully turbulent flow is assumed). Background to the calculation of the borehole thermal resistance are discussed in detail in Javed and Spitler (2016; 2017).

The iterative design procedure is as follows:

1. As a starting point a standard collective design calculation is performed by pooling all energy load profiles.
2. For each borehole heat exchanger system the temperature effect on all other BHE's is calculated, using the length from the previous step.
3. A new design calculation is done for each BHE system, where the design temperature target is adjusted using the temperature effects calculated in step 2.
4. If the change in length (or temperature effect calculation) is smaller than a specified small amount the procedure is stopped, else a new iteration commences at step 2.

In general between 3 and 5 iterations are sufficient to obtain a final design.

3. RESULTS

3.1 Optimization of borehole heat exchanger fields

An example of the optimization of a large field of ground source heat pump systems is based on the development "Mannee" in the municipality of Goes, the Netherlands (Figure 3). This development comprises around 360 new houses (Figure 4), distributed over different building types. Total area is over 13 Ha, with an average lot size of 367m^{2}. The smallest lots measure just over 100 m^2 while the largest measures over 2600 m^2 and accommodates an apartment building. The distribution of lot sizes is given in Figure 5. The optimization in this case required about 100 iterations. The solutions of the optimization algorithm for the starting situation (all lots equal NSHE) and for iteration 20, 40, 60 and iteration 100 (the final iteration) are shown in Figure 6 (Temperature evolution °C) and Figure 7 (Net Specific Heat Extraction, kWh/m/y).

Figure 3: Location of Goes (red circle) and Hoogezand (blue circle), Netherlands.

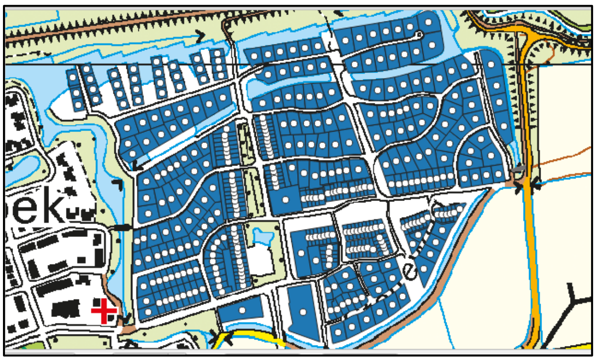


Figure 4: Overview of building lots in development Mannee (Goes, Netherlands). White dots represent the lot centroids.

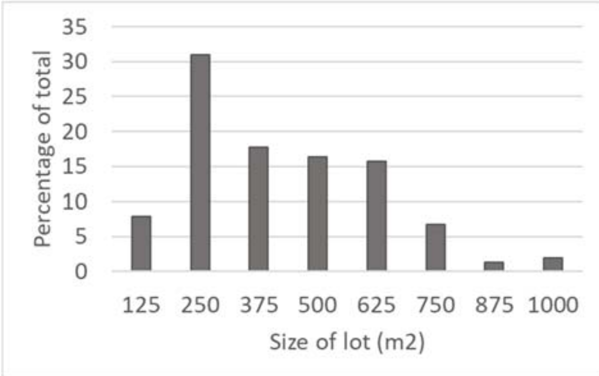


Figure 5: frequency distribution of lot sizes (363 lots total).

The field optimization was performed with a limit on distance of 200 meters, a limit on temperature effect of 0.1K and a minimum distance between lots of 10 meters.

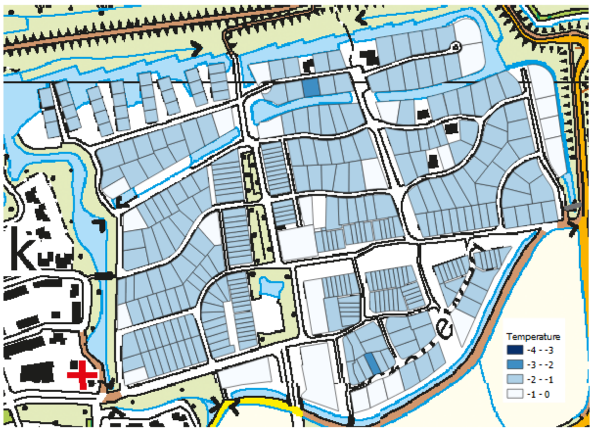
From Figure 6 it is clear that the first calculation of temperatures shows that the small and central lots have a large temperature effect while larger and more peripheral lots have a small temperature effect. By progressively adjusting the NSHE of all lots the temperature effects become more and more evenly distributed. After a few iterations the changes in temperature become smaller, and finally the temperature effects for all individual lots are more or less equal. At the same time it can be observed from Figure 7 that the distribution of the NSHE also changes significantly, large peripheral lots receive a larger NSHE while central and smaller lots are assigned a smaller NSHE. The NSHE assigned varied from -28 kWh/m/y to -70 kWh/m/y.

The temperature effects in the final solution with minimum weights assigned varied from very small (< -0.5K) to considerable (-1.9 K). In the Netherlands a temperature effect of -1.5K between neighbouring systems is considered acceptable. In this case this means that a number of systems will not only have to comply with an assigned NSHE but moreover may have to introduce a compensation for the design temperature used for the system itself. This temperature compensation varies between 0 and +0.5K.

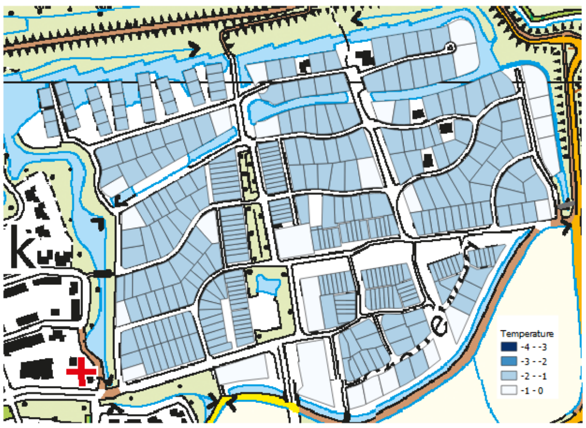
Starting iteration (constant NSHE)

Iteration # 20

Iteration # 40



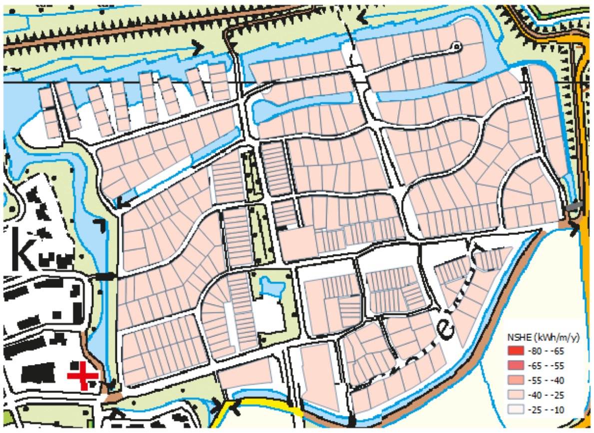
Iteration # 60



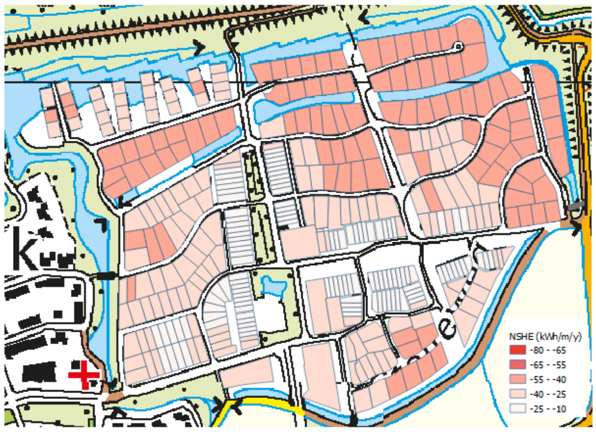
Iteration # 80

Iteration # 100 (final iteration)

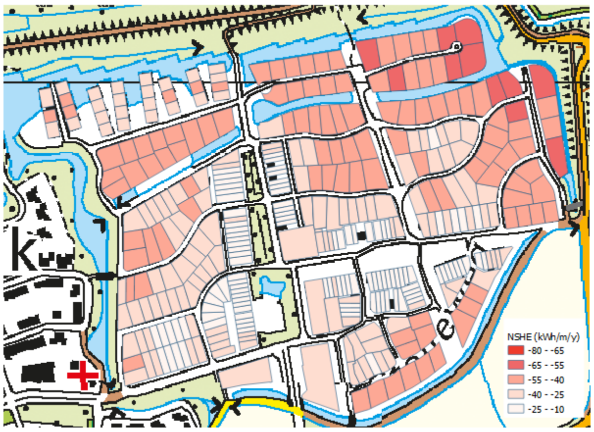
Figure 6: Temperature solutions calculated by the BHE-field optimization algorithm for the starting situation and for iterations 20, 40, 60 and 100.



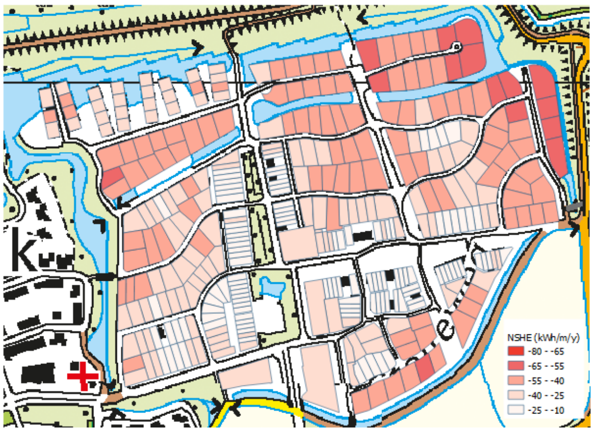
Starting iteration (constant NSHE)



Iteration # 20

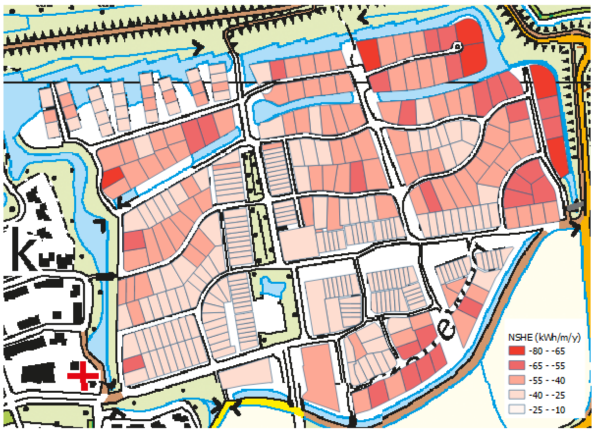


Iteration # 40



Iteration # 60

Iteration # 80



Iteration # 100 (final iteration)

Figure 7: Net Specific Heat Extraction, solutions calculated by the BHE-field optimization algorithm for the starting situation and for iterations 20, 40, 60 and 100.

3.2 Integrated design of individual borehole heat exchanger systems

An example of the integrated design of a field of borehole heat exchangers with individually connected heat pumps is the project Atlantakade (municipality Hoogezand, Netherlands). This project (Figure 3) is part of the research project *OPTIGBES* (www.optigbes.nl) which is a comprehensive research project started early 2020 with detailed monitoring of the evolution of ground temperatures in and around several borehole heat exchangers using Distributed Temperature Sensing (DTS), energy flows to the boreholes and emission system as well as heat pump operational data. An extensive site characterisation, including three thermal response tests, geophysical borehole logging and borehole declination measurements have been performed.

This project comprises 46 apartments (Figure 8), each with a single heat pump and single borehole heat exchanger (Figure 9).

Figure 8. Apartment building Atlantakade, Hoogezand (Netherlands).

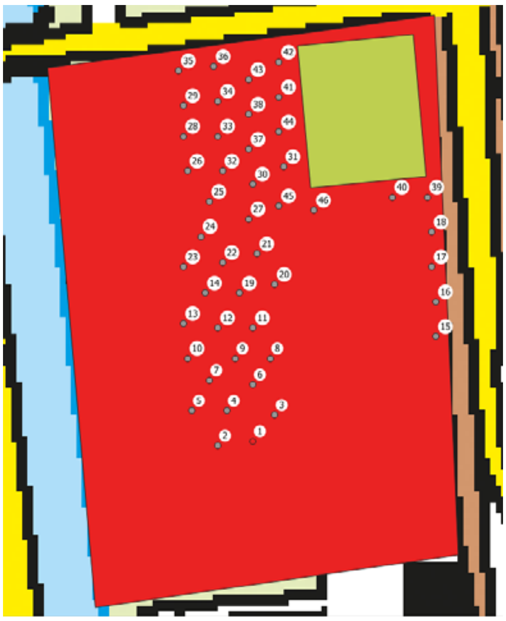


Figure 9. Borehole heat exchanger field layout, Atlantakade, Hoogezand (Netherlands).

For the sake of simplicity all apartments have been assigned a similar energy profile (in reality they will have a different energy demand profile depending on the location in the apartment building). The heat pump installed is an Alpha Innotec WZSV 62H3M. Information on energy demand, heat pump thermal capacity and design-efficiency is given in Table 1.

For the design several soil parameters and borehole design parameters are required. These were derived from borehole logs and literature data and are summarized in Table 2, also the results of the default borehole thermal resistance calculation (at design temperature) is given

Table 1. Energy demand profile and heat pump data, Atlantakade Hoogezand. COP-01: Heat pump compressor efficiency, COP-02: Heat pump compressor + circulation pump efficiency, EER-00: Passive (direct) cooling efficiency.

Parameter	Value
Total Space heating (kWh)	5000
Total Domestic Hot Water (kWh)	1600
Total Space Cooling (kWh)	1192
Heat Pump Condenser capacity (kW)	4.0
COP-01 B0W35 (Heating)	4.9
COP-02 B0W35 (Heating)	4.1
COP-01 B0W55 (DHW)	3.1
COP-02 B0W55 (DHW)	2.8
EER-00 (Passive cooling)	10.3

Table 2. Soil and Borehole design construction parameters and thermal resistance calculation results (at design temperature of 0 °C). Heat exchanger type is single-U.

Parameter	Value
Soil thermal conductivity (W/mK)	2.1
Soil heat capacity (MJ/(m^3.K))	2.5
Soil temperature (°C)	10.5
Geothermal gradient (K/m)	0.026
Borehole diameter (m)	0.168
Backfilling thermal conductivity (W/mK)	2.0
U-pipe outer diameter (m)	0.032
U-pipe inner diameter (m)	0.026
Pipe hart-to-hart distance (m)	0.07
Heat pump flow rate (l/s)	0.29
Fluid thermal conductivity (W/mK)	0.44
Fluid heat capacity (MJ/(m^3.K))	3.88
Fluid viscosity (kg/(m.s))	0.0043
Reynolds number	2740
Effective borehole thermal resistance ((m.K)/W)	0.123

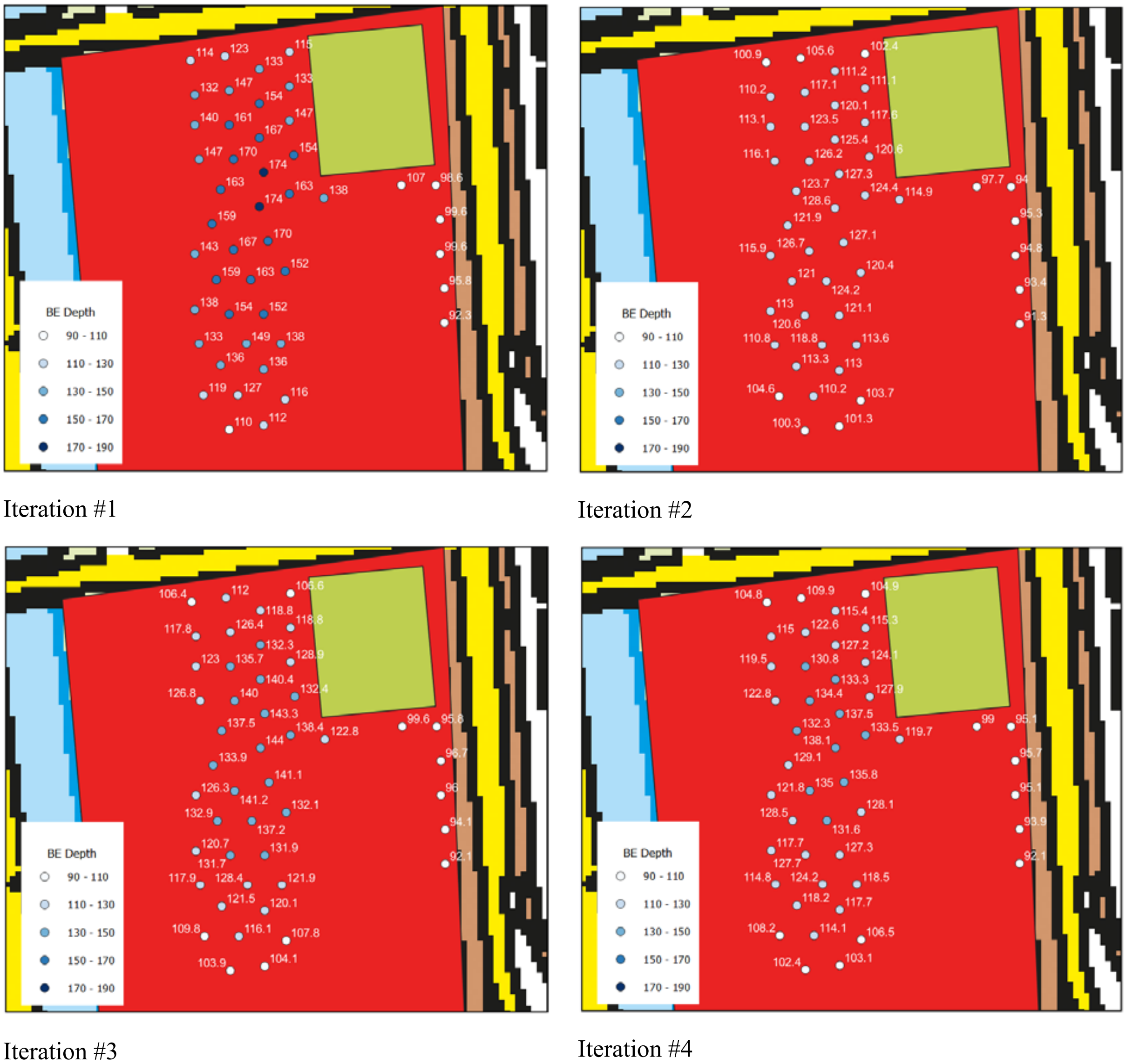


Figure 10. System borehole heat exchanger lengths in the first four iterations of the iterative design procedure.

The first step in the iterative integrated design procedure was to calculate the size required for an individual system and for a collective design where all energy data is pooled. For this calculation the total heating demand was 230.0 MWh, total DHW 73.6 MWh and total cooling load 54.8 MWh. Heating peak load 184 kW for a duration of 18 hours and simulation time of 50 years (in accordance with design lifespan). Design temperature goal was 0 °C average fluid temperature. Calculated conventional design length for a single system with these conditions yields a borehole depth of 81 meters. Calculating the depth required for a collective design of the 46 systems together resulted in a borehole depth of 136.2 meters (6265 m. total).

With the conventional design as starting point an iterative individual design procedure was performed. In this iterative design the temperature effects between the boreholes are calculated and used to adjust the design temperature for the individual system. As the temperature effects depend on the relative position in the field the resulting design temperatures will differ between systems.

A new calculation then results in an adjusted depth, which changes the NSHE for that system. Using the new NSHE the temperature effects calculations are updated and subsequently the required borehole heat exchanger length is recalculated. These steps are repeated until the temperature effects (or borehole lengths) do not change further.

Figure 10 shows the individual borehole depths calculated for the first four iterations in the iterative design procedure. Where in the conventional design the temperature criterion was 0 °C, in this procedure the design criterion is adjusted with the calculated temperature effect caused by the neighbouring boreholes. These varied between -1.4 and -7.0 K in the first iteration and -1.2 and -5.3 K in the final iteration. Average length was 138.6 ± 23.3 m in the first iteration, 113.2 ± 10.6 m in the second iteration and 118.5 ± 13.2 m in the fourth iteration.

For this example more iterations were performed than strictly necessary (Figure 11). In this figure the total length as well as the relative change in total length is shown for 6 iterations. After 3 iterations the change in length is less than 5% and after 5 iterations the change in length is less than 1%. In this case four to five iterations would suffice to obtain a converged solution.

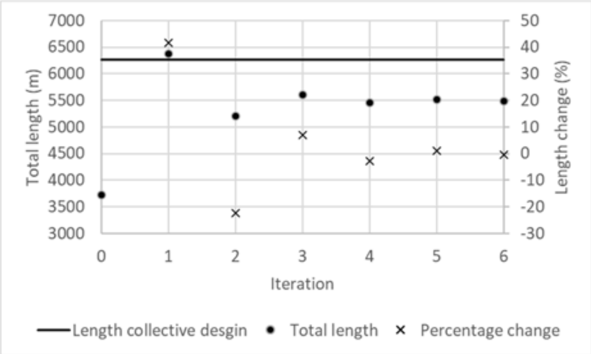


Figure 11. Total length and percentage change iterative design procedure.

4. CONCLUSIONS

In this paper we have discussed the limitations of current state-of-art borehole heat exchanger design methods. Specifically the fact that these cannot be used other than in the design of collective (hydraulically coupled) borehole heat exchanger fields whereas in practice usually large numbers of individual systems need to be sized with different energy demand profiles and relative positions, taking into account thermal interactions between the boreholes.

A new approach is presented, based on the well known solutions for borehole heat exchanger thermal response calculations (the Infinite Line Source and Finite Line Source), that allows the sizing of individual systems accounting for the thermal interactions.

Additionally a method has been presented that allows the calculation of optimal thermal energy harvesting from the ground (with a limit on thermal interactions) that can be applied even when no information on actual heating and cooling demand is available.

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