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A Novel Tool for Assessing Negative Temperature Interactions between Neighbouring Borehole Heat Exchanger Systems

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Abstract

In the Netherlands, as in the most part of Europe, the number of single family houses with a dedicated ground source heat pump system is growing rapidly, especially as many municipalities are moving towards developing a gas-less infrastructure. Not only does the total number of systems increase, also the scale of the projects (ranging from 200 to almost 5000 units) becomes bigger with generally a high density of systems. Due to the small average distances between boreholes in large scale developments the risk of temperature disturbance, which may affect the design performance, by neighbouring systems increases because the total temperature evolution of a system is the result of the superposition of all individual effects in the vicinity.

Although the growth in ground source energy systems is in line with the aim of the government to greatly increase the number of systems in view of the transition to a more sustainable energy-economy, at the same time the aim is to use the subsoil in an efficient way and prevent unwanted (negative) interactions that reduce overall performance. The recently (2013) developed legislation concerning ground source energy systems therefore requires any new system to assess potential negative interactions with surrounding systems and requires reporting of the results of this assessment to regulators.

Unfortunately it is not possible to calculate these effects with standard design software or models. Partly because the information available about the neighbouring systems is very limited, but especially because the standard tools are not able to deal with diverse systems. Systems that have different energy-usage profiles, different borehole depths or different heat exchangers types or that are not spaced equi-distant (to name but a few parameters) cannot be evaluated with the standard design toolkit.

This paper presents a simple method to assess interactions between neighbouring small (< 70 kW thermal capacity on the ground) ground source heat pump systems. The method is based on using the line source method to compute the temperature disturbance at different distances after a long period (30 – 50 years), for a large number of heat rates and soil types. The results are further simplified to linearized nomograms that allow any user to assess the thermal interactions between neighbouring systems with a minimum of information about those systems (typically only the spatial coordinates and the net thermal extraction in kWh/meter/year is available).

Keywords: Line source, thermal interactions, interference, borehole heat exchanger.

1. Introduction

In the Netherlands, as in the most part of Europe, the use of electrically driven heat pumps coupled to borehole heat exchangers, so called ground source heat pump systems, is increasing rapidly. Especially as new developments are moving towards a gas-less infrastructure, the electrical heat pump is becoming the preferred means of heating. For terraced houses the predominant system is an individual system, where every house has its own heat pump and borehole heat exchanger. For apartment buildings and small scale utility, often a central heat pump system with collective borehole heat exchanger is preferred. However, as the number of borehole systems increases and the scale of the developments becomes larger, the need for regulation of these systems also becomes more important.

In the Netherlands in 2013 new laws came into effect that started regulating borehole heat exchanger systems permits (open loop or aquifer thermal energy systems have – with few exceptions - always been regulated and required to obtain a permit, but those systems are beyond the scope of this paper). With this new law, all systems require at least a registration with the authorities while systems with a thermal capacity on the ground exceeding 70 kW require a permit. In parallel with the development of the legal framework, a framework of quality assurance based on a certification scheme for companies working in the field of ground source energy has been implemented.

With the rising number of borehole heat exchanger systems, two important concerns are the protection of the sub-surface and its functions as well as the efficiency of the ground source energy systems. As the original subsurface environment is disturbed during the installation of a borehole heat exchanger and this disturbance is to a certain extent irreversible, the protection of ground water resources is deemed important and the projected energy saving should be guaranteed. The quality protocols describe in detail the design and construction process of the heat pump - borehole heat exchanger systems. The procedures for sealing of aquitards (layers preventing vertical ground water movement) for instance, important for the protection of ground water, is described in the drilling protocol (SIKB protocol 2101) while the quality of design and efficiency of the system is governed by the protocols SIKB 11001 and KvINL 6001-21. However, these protocols only deal with the design and realization of individual systems (small or large) and do not account for the possible thermal interactions due to other systems in the vicinity.

It was recognized that where the number of systems becomes large it is unavoidable that thermal interactions arise that may affect the efficiency of the systems. The law therefore states that any system that comes into operation may not hamper the efficient operation of other systems, or be hampered themselves by existing systems. Moreover, it is required that this is demonstrated through a calculation with the registration procedure or permit application. To provide at least one easy to use method to assess the thermal interference between systems, the ministry of I&M (Infrastructure and Environment) commissioned developing a simple tool (Witte, 2011). This tool would need to:

- Be easy to use, with a clear procedure but without the use of computer code or complicated calculations, making it possible for authorities to evaluate the provided calculations using tabulated values and nomograms.
- Be able to calculate the temperature effect of very different systems, for instance systems that differ in: the number and depth of boreholes, the type of heat exchanger used, the energy demand profile, the design efficiency of the system. Moreover, the distances between the systems are not uniformly distributed.
- Allow the calculations to be performed using only the information that is provided with the registration of the system, which is limited to:
    - X- and Y-coordinate of the centre of the system
    - Total heating and total cooling provided to the building
    - Overall SPF
    - Number and depth of the boreholes

The procedure of calculating the added thermal interference when a new system is being realized has one drawback and that is that it is essentially "first come first served", there is no possibility and no method to account for systems that will be realized in the future. This is especially true for individual heat pump - borehole heat exchanger systems that are implemented in large numbers and relatively close proximity to one another. Therefore, the law allows the regulating body (in this case the municipality), in areas where the number of systems is expected to become large, to declare a so-called "zone of interference". In such a zone all systems need permission and coupled to the permit additional requirements are made with regard to the design of the systems, so that the overall efficiency is guaranteed.

This paper describes the method that was developed and has now been used since 2014 to assess the thermal interactions between borehole heat exchanger systems (SIKB 2014). Also, it will describe the use of the underlying calculation method as a planning tool that can be used to calculate the optimal energy yield of the ground within the so called "zones of interference", zones identified by authorities where special planning permission for ground source energy systems is needed.

2. Methods

The problem that needs to be solved is the thermal interaction between multiple different borehole heat exchanger systems, where each system has different properties. This means that we do not need to calculate the actual temperature response of any borehole heat exchanger system itself, but only the added interactions of all systems present in the vicinity (the neighbouring systems). The calculation can therefore be independent of the design of the boreholes, the thermal borehole resistance (Hellström, 1991) and temperature response to the thermal loading of the borehole heat exchanger itself does not need to be considered.

The principle calculation method selected to solve the temperature change of different borehole heat exchangers due to the energy loading of these systems is the line source approach. This method was developed first by Kelvin (1861) and applied in a practical form by Ingersol (1948, 1954). In 1986 Hart and Couvillion proposed a solution that limits the line source solution to its appropriate far-field radius, depending on the time scale considered and thermal diffusivity of the ground.

The equation for the line source solution is (Carlsaw & Jaeger 1959; Ingersoll et al 1954):

$$\Delta T(r,t) = \frac{q}{4\pi k}\int_{y}^{\infty}\frac{e^{-u}}{u}du \qquad 1$$

Where

$$y = \frac{r^2}{4\alpha t}$$

$$u = \frac{r^2}{4\alpha\tau}$$

ΔT (r,t) : Change in temperature (K) at distance (r) and time (t), note ΔT is independent of the undisturbed ground temperature.

q : heat flux (W/m)

k : thermal conductivity (W/mK)

α : thermal diffusivity (m^2/s) of the ground

r : radial distance to line source (m)

t : time since heat pulse (s)

τ : temporal differential operator

This equation is valid when the radius *r* is smaller than the far-field radius:

$$r \leq r_\infty ; r_\infty = 4\sqrt{\alpha t} \tag{2}$$

The integral from equation 1 can be solved by the expansion (Carlsaw & Jaeger 1959; Yavuzturk 1999):

$$\int_y^\infty \frac{e^{-u}}{u} du = \left[y - \ln(y) - \gamma + \sum_1^n \frac{(-1)^{n+1} y^n}{n(n!)} \right] \tag{3}$$

Where

γ : eulers constant (0.5772157)

n : number of terms in the expansion

Hart and Couvillion give the following final equation for the for the temperature distribution around a line-source:

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

Equation 4 is used to solve the thermal interactions between systems, with the following assumptions:

- The time dependent temperature evolution is obtained by superposition of constant power rates. For the present problem seasonal energy loads (winter heat extraction, summer heat injection) are considered.
- The spatial interactions between the systems is obtained by superposition of the effects of the individual line sources.
- Axial heat transfer is not considered.
- Borehole heat exchangers are considered to be vertically orientated (not inclined) or the inclination is so small that the overall distance between neighbouring boreholes is not significantly affected.
- The ground volume is considered isotropic and homogeneous.
- Only heat conduction is considered, advective heat transport due to e.g. ground water flow or phase changes are not considered.

To be able to apply the method to borehole heat exchanger systems with different design properties and different thermal loadings, the strength of the line source is defined as the energy extraction and energy injection rate in kWh per meter per year (kWh/m/y). An evaluation of data with regard to energy usage of borehole energy systems in the Netherlands resulted in typical heat extraction rate of about 50 kWh/m/y and a maximum heat extraction rate of 130 kWh per meter borehole per year. Almost all systems also provide cooling during summer (passive or free cooling, without use of the heat pump). The associated heat rejection to the ground varies between about 10 and 40 kWh/m/y.

2.1 Applicability of the method with regard to ground water advection

One of the main assumptions is that conduction is the only heat transport mechanism and therefore that advection through ground water flow plays no important role. To assess the possible influence of ground water flow and define when the proposed solution can be used a sensitivity study was performed. In this sensitivity study the effect of ground water flow on a single borehole heat exchanger was calculated in a worst case scenario (130 kWh/m/y heat extraction), a scenario with 50% energy balance and a scenario with 100% energy balance. The temperature effect of ground water flow, as a function of Darcy flow, was calculated for borehole heat exchangers that were exposed to the ground water flow along a certain part of the total length. The calculations were performed with the HST3D model (Kipp, 1986), the temperature difference between the reference case (borehole heat exchanger without ground water advection) and a prescribed Darcy ground water flow velocity are presented in figure 1 (case without energy balance).

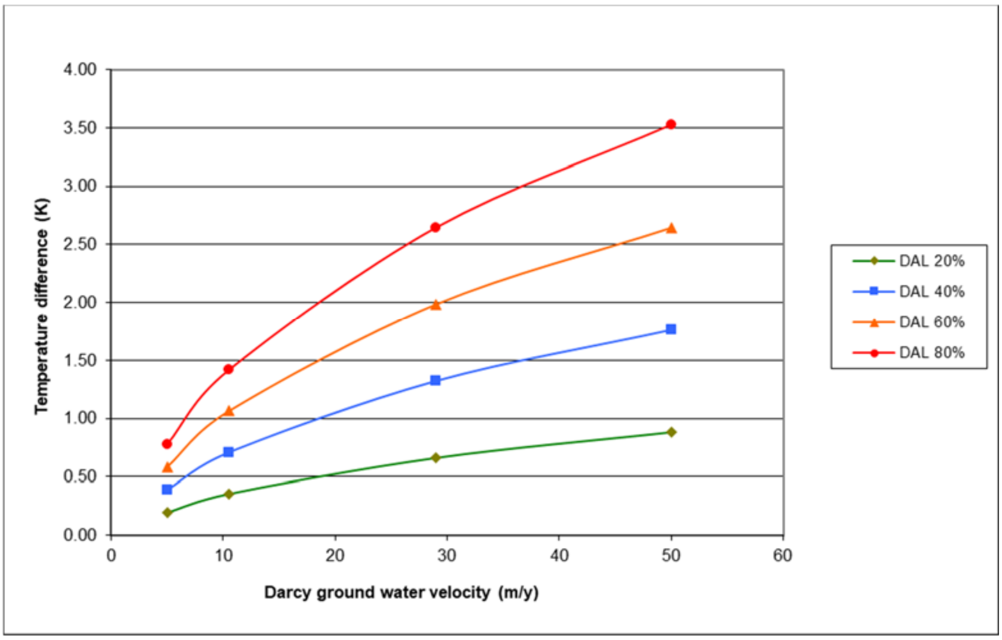


Figure 1. Difference in temperature (K) between systems without and with a prescribed Darcy ground water flow, for different ratios of exposed length (DAL: percentage of Depth in Advective Layer). Case without energy balance, heat extraction 130 kWh/m/y, no heat rejection.

Allowing a maximum temperature effect of 1K, the permissible ground water flow regimes for different energy balance and length of borehole heat exchanger in the ground layers with advective transport is given in table 1.

In the worst case scenario (80% of borehole heat exchanger in formation with ground water flow and no energy balance) the Darcy ground water flow velocity needs to exceed 7 meters per year to achieve a significant effect.

Table 1. Darcy ground water flow (m/y) where the total temperature effect is less than 1K, for a totally unbalanced, 50% energy balance and completely balanced energy extraction of 130 kWh/m/y and different relative lengths of borehole heat exchanger in the advective zone(s).

	Percentage length of borehole heat exchanger in formation with advective transport (ground water flow)			
	20%	40%	60%	80%
No balance	> 60	≤ 20	≤ 10	≤ 7
50% balance	> 60	≤ 33	≤ 20	≤ 15
100% balance	> 60	≤ 50	≤ 32	≤ 27

2.2 Calculation of thermal interference between systems

To evaluate the thermal effects between systems some additional choices need to be made. These choices pertain to the systems in the surroundings that need to be included in the evaluation as well as what (if any) temperature interaction can be allowed.

Firstly, it needs to be decided what systems need to be included in the evaluation, with other words: what constitutes a "neighbouring" system. Taking again a worst case scenario of a heat extraction of 130 kWh/m/y the temperature change as a function of distance from the source (after 25 years of operation) can be calculated (figure 2). Taking a limit of 0.1K as cut-off, the distance where an effect greater than 0.1K may occur is about 60 meters. As the system that is at the limit of the distance where the proposed system may have an effect also experiences effects of systems further away, the so called "search radius" to select systems that need to be included in the evaluation has been set at 120 meters.

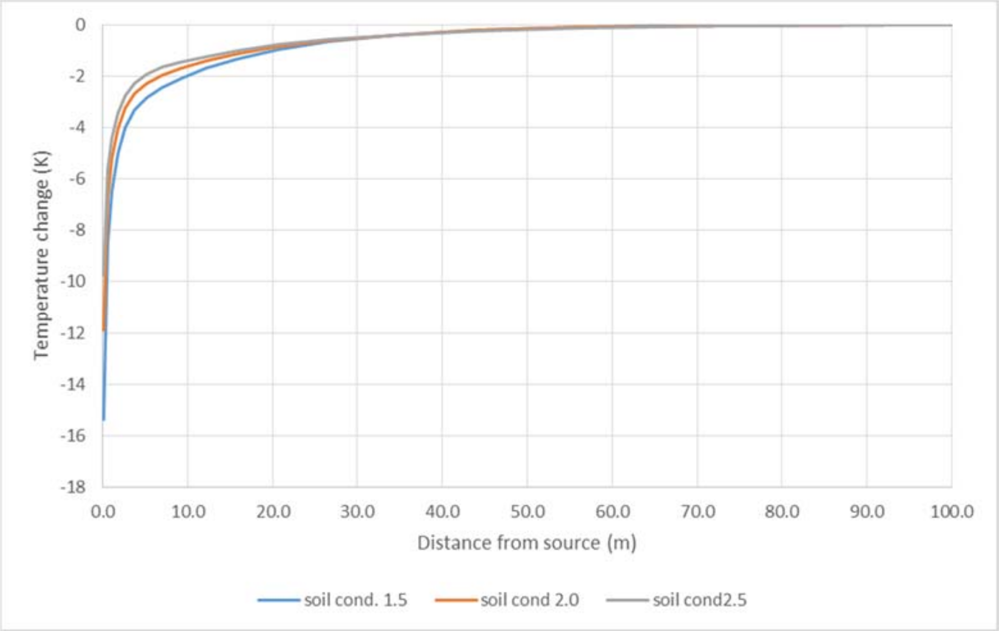
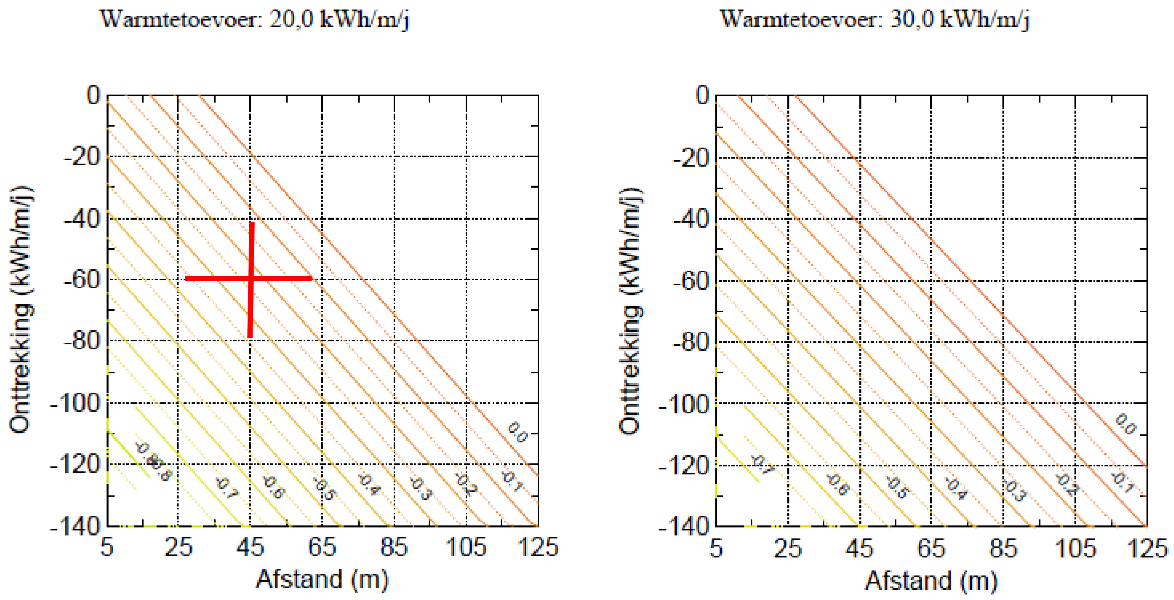


Figure 2. Temperature change after 25 years of continuous heat extraction (130 kWh/m/y) as a function of distance for a soil with a thermal conductivity of 1.5 W/mK, 2.0 W/mK and 2.5 W/mK.

Secondly it was discussed if the allowed total temperature interaction should be set at 0K (no effect at all) or another value. As the purpose is to ensure that the efficiency of the systems should not be affected while at the same time the use of borehole heat exchanger systems needs to be stimulated, it was decided to allow a small effect. Moreover the calculated temperature effects are a conservative estimate, as the line source solution itself as well as the translation to linearized nomograms introduces some over-estimation of the temperature effect.

The maximum allowed temperature effect has been set at -1.5K total temperature change, which translates to a loss of efficiency of about 5%. As this will normally occur only after 25 – 30 years (in unbalanced energy designs, which is the norm) the resulting effect on overall performance is negligible.

Using the equations described above, the temperature effect as a function of distance was calculated for three different soil thermal conductivities (1.5 W/mK; 2.0 W/mK and 2.5 W/mK) representative for the range of soil conditions in the Netherlands and for different energy scenario's (0 to 130 kWh/m/y heat extraction and for each 0 to 130 kWh/m/y heat injection, in increments of 10 kWh/m/y). In total about 600 different energy scenarios and soil conditions were evaluated. To allow the use of the results in a straightforward manner, linear nomograms of temperature with distance were created for all scenarios, with a distance cut-off of 5 meters. An example of the nomograms is given in figure 3. For a system with a heat extraction of 60 kWh/m/y and a heat injection of 20 kWh/m/y, the temperature effect at a distance of 45 meters is -0.23K (red crosshair).


Warmtetoevoer: 20,0 kWh/m/j

Warmtetoevoer: 30,0 kWh/m/j

Figure 3. Example of the temperature nomograms: for the soil thermal conductivity of 2.0 W/mK. The temperature effects are shown as a function of distance ("Afstand") and heat extraction ("Onttrekking", in kWh/m/y) for a heat injection of 20 kWh/m/y (left) and a heat injection of 30 kWh/m/y (right).

As an example, consider the situation depicted in figure 4: six pre-existing systems with one system (red square) being added. The temperature effects that need to be evaluated are:

1. All temperature effects between the existing systems (4b).

2. The added temperature effect of the new system (4c).
3. The temperature effect of the existing systems on the new system (4d).

If any of these effects exceed the agreed limit, mitigating measures need to be taken. If the effect between the existing systems (4b) exceeds the agreed limit the only situation where the new system can be allowed is if the added effect of that system to the existing systems is 0K (a positive effect would be possible for a system with more heat rejection than extraction, but a positive energy balance is not permitted by law). If the temperature effect between the existing systems is smaller than the agreed limit, there are two possible situations:

1) The temperature effect added by the new system does not result in exceeding the limit, no further action needed.
2) The temperature effect added by the new system does result in exceeding the limit, the design of the new system needs to be changed. Possible adaptations are to increase the total length of the borehole heat exchanger or to increase the balance between heating and cooling.

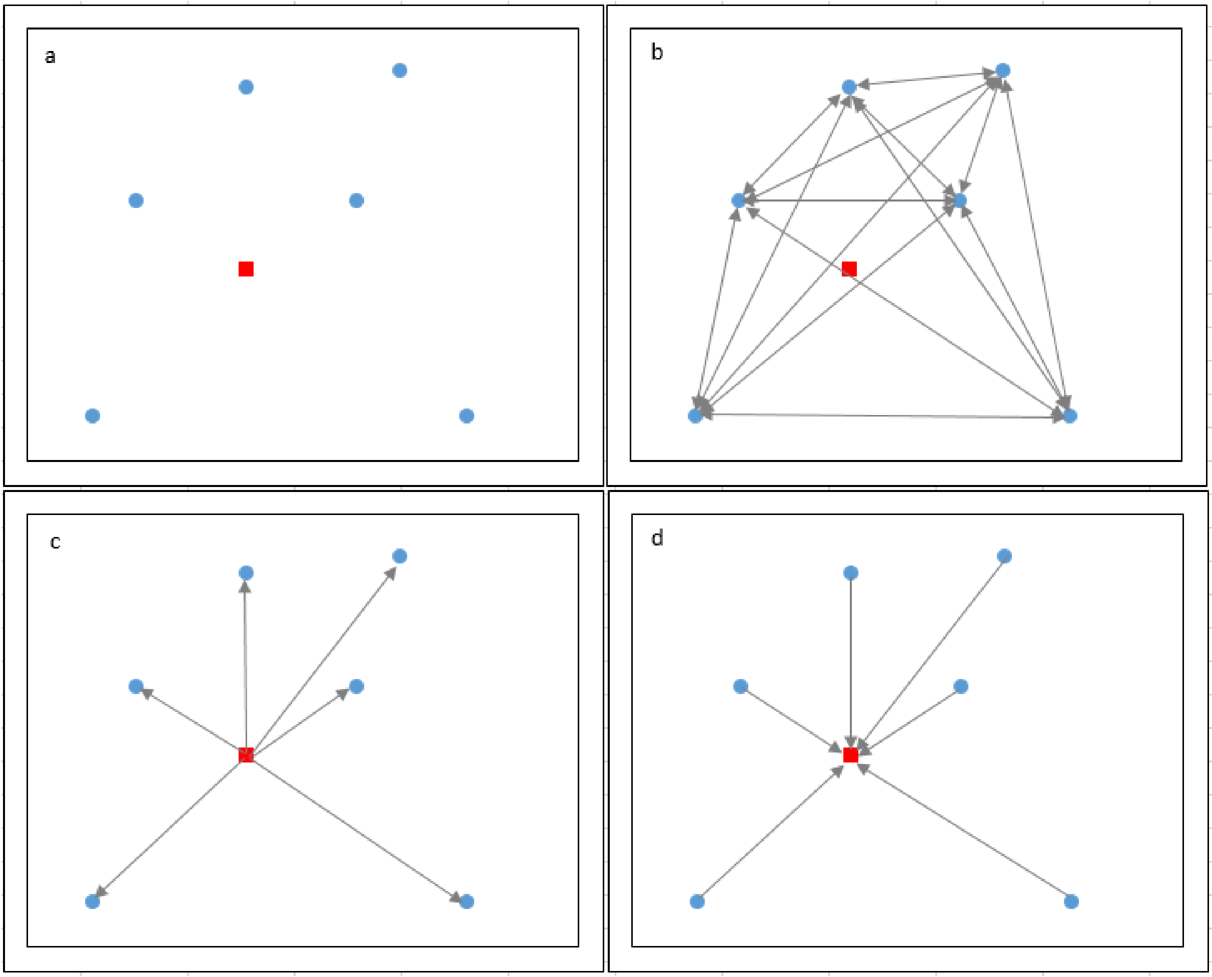


Figure 4. Temperature effects to be evaluated between six existing and one new system (a): temperature effects between existing systems (b), temperature effect added by new system (c) and temperature effect of existing systems on new system (d).

Finally, the temperature effects of the existing systems on the new systems (3d) needs to be evaluated: these are also not allowed to exceed the limit. If the surrounding systems result in a temperature effect that exceeds the limit, the design temperature used to calculate the length of the new system needs to be adjusted. Suppose the design calculation is for a source temperature of 0 °C and the added effect of the surrounding systems is -2.0K. Then to remain within the -1.5K temperature limit agreed, the design temperature needs to be adjusted to at least +0.5 °C.

2.3 Calculation of optimal thermal yield in a large scale planning application

A second application of the developed methodology is in the planning of large scale developments. As stated above, the general practice is "first come first served". In large scale developments where the systems are not all installed at the same time this results in a sub-optimal use of the ground as later systems need to implement an over-sized borehole heat exchanger or even may not be possible at all, due to too large thermal influence by earlier systems. In this case, the municipality can declare a so-called "zone of interference" where all ground source energy systems require a permit. Within the zone of interference additional conditions for the design and installation apply, defined in the ground-source energy plan. There rules may regulate different aspects of the design and installation. For instance, the ground thermal parameters may be given, lower limits on system performance specified, defining specific depth intervals that need sealing to prevent exchange between different water-bearing formations or limits on maximum drilling depth can be imposed. These types of usage-rules are important as they result in a harmonisation of system design and installation.

The main goal of the rules within a zone of interference however, are to optimize the energy use of the subsurface and prevent negative thermal interference between systems. The method described above is especially suited for such an optimization. The calculation of the thermal interactions by the above equations is in this case coupled to an optimization routine that searches for every system location the maximum possible net energy extraction (the energy budget in kWh/m/y) that can be supported without exceeding the set temperature effect limit at any location. Currently this is achieved by a heuristic search algorithm that iterates over all system locations and increases or decreases the energy extraction depending on the total effect, with a distance weighting to give more weight to the local neighbourhood. To obtain a robust solution, this procedure can be repeated with different starting values and different location order. As the calculation method is very fast (7×10^8 evaluations take about 30 seconds on an Intel Xeon E3 running @ 3.3 GHz) it is possible to carry out such an optimization even for very large numbers of systems quickly.

The optimization of the energy budget assigned to the systems takes into account:

- The distance between the systems in the zone of interference, either based on actual X- and Y-coordinates of the lots or on a more general anticipated building density.
- Pre-existing systems, the net extraction for these systems is entered as a boundary conditions and not changed during the search.
- Groups of systems that are designed together (integrated design), the energy budget assigned to these systems takes into account the effects of all other systems, but the interactions between the individual systems within the group are not calculated (as these are considered to have been accounted for in the design).

For the calculation in this approach only the soil thermal conductivity and heat capacity are needed, a-priori knowledge of the energy usage profiles of the buildings, actual ground temperature or even anticipated drilling depths, is not needed.

3. Results

3.1. Calculation of thermal interference between systems

For the example given in figure 4 the thermal interactions are calculated. First the distance between all systems is calculated as well as the specific heat extraction and heat injection per year per meter (kWh/m/y) taken from the permit information, table 2 gives the results.

Table 2. Distances between systems and specific heat extraction and heat injection per year, for the systems depicted in figure 4. System number 7 is the system added to the pre-existing systems.

	System 1	System 2	System 3	System 4	System 5	System 6	System 7
System 1		34.7	24.0	49.4	32.1	45.6	*25.4*
System 2	34.7		32.5	22.1	17.0	20.9	*16.4*
System 3	24.0	32.5		47.1	36.2	46.3	*26.7*
System 4	49.4	22.1	47.1		26.2	14.3	*31.0*
System 5	32.1	17.0	36.2	26.2		20.9	*16.4*
System 6	45.6	20.9	46.3	14.3	20.9		*28.0*
System 7	*25.4*	*16.4*	*26.7*	*31.0*	*16.4*	*28.0*	
	System 1	System 2	System 3	System 4	System 5	System 6	System 7
Heat extracted (kWh/m/y)	40	40	40	50	50	50	40
Heat injected (kWh/m/y)	20	20	20	30	30	30	20

Using the nomograms from figure 3 the temperature effects can be estimated, first the temperature effects between the existing systems and of the existing systems on the new system are calculated (table 3).

From table 3 it is clear that the effects between the existing systems remain within the imposed limit of -1.5K and that the combined effect of all existing systems on the new system also (just) remains within the limit of -1.5K. If the effect of the new system is now added, the situation changes (table 4). As can be seen, the total effect on system 2 and system 5 now exceed the threshold value. The design of the new system (system 7) in this case needs to be changed, by increasing the length of the borehole heat exchanger and thereby reducing the specific heat extraction (but also the heat injection) or by increasing the energy balance of the building. If the heat injection can be increased to 30 kWh/m/y the temperature threshold in this case is not exceeded for any of the existing system.

The nomograms introduced make estimating the temperature effect of any system relatively straightforward and forego the need of any computational tool. Moreover, they allow the combination of many different specific heat extractions and distance combinations in one graph that can also easily be interpolated (interpolation between graphs with different specific heat injections or different thermal conductivity values may also be needed). However, due to the linearization an error is introduced. The difference between the linear nomogram (with a cut-off at 5 meters distance) and the actual curves calculated with equation 5 are on the order of 0.2 – 0.3K for the case presented. As the nomograms overestimate the temperature effect, the estimates are conservative (on the safe side).

Table 3. Temperature effects estimated from figure 3 for the systems of table 2, effects between existing systems (1-6) and of existing systems on the new system (7). The effect of a system (row) on all other systems (columns) is presented. The total effect on a system is summed, this total effect should always be less than -1.5K.

	System 1	System 2	System 3	System 4	System 5	System 6	System 7
System 1		-0.24	-0.25	-0.08	-0.24	-0.12	-0.25
System 2	-0.24		-0.24	-0.26	-0.30	-0.30	-0.30
System 3	-0.25	-0.24		-0.08	-0.20	-0.12	-0.25
System 4	-0.05	-0.22	-0.05		-0.20	-0.30	-0.20
System 5	-0.20	-0.27	-0.18	-0.20		-0.27	-0.27
System 6	-0.10	-0.27	-0.10	-0.30	-0.27		-0.20
Total (K)	**-0.84**	**-1.24**	**-0.82**	**-0.92**	**-1.21**	**-1.11**	**-1.47**

Table 4. Temperature effect added by new system on the existing systems. For system 2 and system 5 the temperature threshold of -1.5K is exceeded.

	System 1	System 2	System 3	System 4	System 5	System 6
Total effect existing systems (K)	-0.84	-1.24	-0.82	-0.92	-1.21	-1.11
Added effect system 7 (40 / 20 kWh/m/y)	-0.25	-0.30	-0.25	-0.24	-0.30	-0.24
Total (K)	**-1.09**	**-1.54**	**-1.07**	**-1.16**	**-1.51**	**-1.35**

3.2. **Calculation optimal thermal yield in a large scale planning application**

The development “Mannee” in the municipality of Goes was among the first in the Netherlands with a natural gas-less infrastructure. For the heating of the houses and the production of domestic hot water, the electrical heat pump coupled to a borehole heat exchanger was the preferred solution. During the initial stages of the project, the municipality noted that the implementation of later ground source heat pump systems was becoming limited due to potential thermal interactions, and that a ground source energy plan was needed. The situation was diverse, although virtually only borehole heat exchanger systems were planned. Most of the lots were sold to individual owners developing their own house, but a small number of collectively realized systems was also present. Moreover, a number of systems had already been installed before the interference zone was declared.

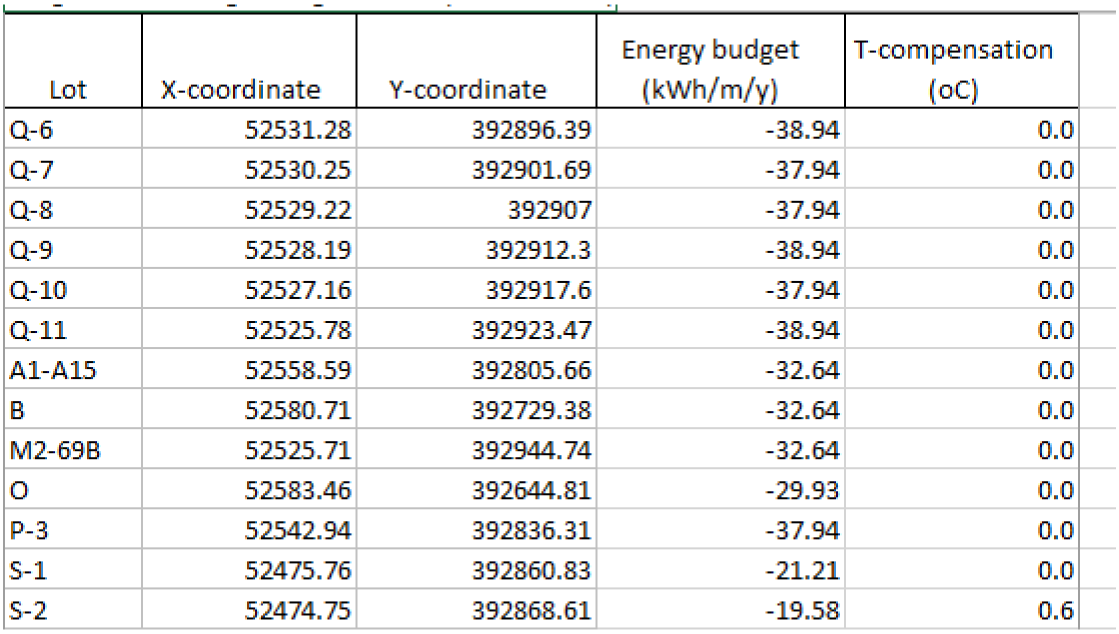
In total about 365 systems were being realized. Based on the planning map and using information on the energy use of the already installed systems, an analysis of the thermal interactions was performed and the optimal energy yield of each lot was calculated. The final result assigns a maximum thermal energy extraction budget to each lot (kWh/m/y), within that budget the designer has complete freedom. This means that either the length of the boreholes or the energy balance (balance between heat extraction and heat injection) can be adjusted. Figure 5 shows the distribution of the energy budgets, in fact to make the calculations easier a reference energy budget (-32 kWh/m/y) is assigned to each lot and weighing factors are calculated with respect to the reference energy budget.

Figure 5. Optimal lot weights, where the weight and reference energy budget (-32 kWh/m/y) defines the maximum allowed heat extraction for each system.

Some lots were assigned relatively low energy budgets, e.g. because they are in an area with local high density of systems at small distances or because they are near a number of pre-existing systems. Where possible, these systems were assigned an energy budget that was greater than the smaller (optimal) one, this then results in a larger than allowed temperature effect in the surroundings. An additional temperature compensation factor is then assigned to those lots where the total temperature effect exceeds the threshold: if the normal design temperature is 0 °C it needs to be increased by the compensation factor to ensure the projected efficiency is obtained.

The main results for the municipality are maps of temperature effects and energy budgets, with a summary table of the energy budgets and temperature compensation factors per lot (table 5). Moreover, a full report with the geology and geohydrology and other background information is provided together with rules of usage pertaining to drilling methods, processing of drill cuttings and drilling mud etc. Finally, a tool for collecting and evaluation of permit applications is provided.

Table 5. Excerpt from the final table with, for each lot, the assigned energy budget and temperature compensation factor.



Lot	X-coordinate	Y-coordinate	Energy budget (kWh/m/y)	T-compensation (oC)
Q-6	52531.28	392896.39	-38.94	0.0
Q-7	52530.25	392901.69	-37.94	0.0
Q-8	52529.22	392907	-37.94	0.0
Q-9	52528.19	392912.3	-38.94	0.0
Q-10	52527.16	392917.6	-37.94	0.0
Q-11	52525.78	392923.47	-38.94	0.0
A1-A15	52558.59	392805.66	-32.64	0.0
B	52580.71	392729.38	-32.64	0.0
M2-69B	52525.71	392944.74	-32.64	0.0
O	52583.46	392644.81	-29.93	0.0
P-3	52542.94	392836.31	-37.94	0.0
S-1	52475.76	392860.83	-21.21	0.0
S-2	52474.75	392868.61	-19.58	0.6

4. Discussion

This paper outlines a procedure and methodology for assessing the temperature effects between borehole heat exchanger systems used as a heat source or heat sink for a heat pump, as far as possible independent of actual system designs. Such a method is needed in situations where the total number of systems is growing, as the mutual temperature effects, although small at distance, need to be added (superposed) and many small effects cumulatively may significantly affect system performance.

For larger developments, the same methods of calculating temperature effects are combined with an optimization strategy to assign optimal energy budgets to systems that are being planned. This is needed as in the normal procedure only already existing systems can be evaluated.

In practice it is recognized that especially the simplified nomograms introduce an error in the calculation of the temperature effect. However, this error is conservative (over estimates the effect). Therefore, when the use of the nomograms results in effects exceeding the threshold, it is then still possible to carry out a calculation with more precision, for instance not using the nomograms but the line source equations directly. If the temperature effect calculated exceeds the threshold, even when a more precise method is used, then the design of the system must be adapted (e.g. by increasing the balance between heat extraction and heat injection).

The method as presented in this paper can be applied to borehole systems comprising more than one borehole. However, for practical purposes and because the national registration system in the Netherlands does not store coordinates of individual borehole heat exchangers, in the simplified method the central coordinate of the system is used. The error that this introduces is relatively small as the resulting difference in distance is on the order of 10%. For larger systems the simplified method cannot be used directly, but distances can be adjusted for the borehole field size or the more accurate underlying calculation method can be used.

Further development of the method is aimed at further automation of the procedure for calculating temperature effects and developing a more objective and mathematically sound optimization algorithm.

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6. References

Carslaw, H.S., Jaeger, J.C. (1959). Conduction of heat in solids, second edition. Clarendon Press, Oxford.

Hart, D., Couvillion, R. (1986). Earth Coupled Heat Transfer. *Publication of the National Water Well Association.*

Hellström G. (1991). Ground Heat Storage. Thermal Analysis of Duct Storage Systems. *Lund, Sweden. Department of Mathematical Physics, University of Lund.*

Ingersoll, L., Zobel, O., & Ingersoll, A. (1954). Heat conduction with engineering, geological and other applications. *McGraw-Hill, New York.*

Kelvin (1861). *Mathematical and Physical papers*. Cambridge University Press London, 1882 – 1911.

Kipp, K.L. (1986). HST3D : A Computer Code for Simulation of Heat and Solute Transport in Three-Dimensional Ground-Water Flow Systems. *United States Geological Survey, Water Resources Investigations Report 86-4095.*

KvINL (2012). KvINL Protocol 6001-21 Ontwerpen, installeren en beheren van WKO-energiecentrales.

SIKB (2014). Methode toetsen interferentie tussen kleine gesloten bodemenergiesystemen, Bijlage 2 bij de BUM's en HUM's bodemenergiesystemen, versie 2.3.

SIKB (2014). SIKB Protocol 11001 Ontwerp, realisatie en beheer van het ondergrondse deel van installaties voor bodemenergie, versie 2.0.

SIKB (2015). SIKB Protocol 2101 Mechanisch boren, versie 3.3.

Witte, H.J.L. (2011). Methode voor het bepalen van interferentie tussen kleine gesloten bodemenergiesystemen. *Rapport GHNL 011103, Ministerie I&M.*

Witte, H.J.L., van Gelder, A.J., Klep, P. (2006). A very large distributed ground source heat pump project for domestic heating: Schoenmakershoek, Etten-Leur (the Netherlands). In: Stiles (ed). *The Tenth International Conference on Thermal Energy Storage, Ecostock 2006 Proceedings. May 31 - June 2, 2006, Stockton College New Jersey (USA).*

Yavuzturk, C. (1999). Modeling of vertical ground loop heat exchangers for ground source heat pump systems. *PHD Thesis, Stillwater, Oklahoma State University.*