Validated combined first and last year borefield sizing methodology

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Abstract

Sizing a borefield is a complex task and a number of methods are available in literature with varying degree of complexity and accuracy. In this paper a novel method is put forward in the medium complexity-accuracy range of the spectrum, by combining two existing methods. This new methodology is validated using the commercial program Earth Energy Designer and dynamic simulations for two cases. It is conceptually shown and numerically proven that the proposed method is more universally accurate than the two existing ones it combines, while maintaining the same complexity of use. The code implementation of this new method, is available as `GHEtool` on GitHub.

Key Innovations

- The combination of two sizing methods, using both the first and last year of operation, is novel and validated.
- More overall accurate results than with the existing methods are obtained.
- Open-source tool `GHEtool` available at `https://github.com/wouterpeere/GHEtool`.

Practical Implications

This novel sizing methodology and open source code implementation provide designers and researchers an easy to use package for borefield size estimation with an improved accuracy and reliability compared to the two existing methods.

Introduction

Various methods[1] with different degree of complexity and accuracy exist to size a borefield. Ahmadfard (2018) listed four different levels of complexity in sizing methodologies for borefields. For an exhaustive description, the reader is referred to his work. In this paper only a brief summary is given (with a focus on the level in which the new method should be placed). In order of increasing accuracy and complexity, the levels are:

- **Level 0** These are the rules of thumb which state that the total borefield length is proportional to the peak power injected in the ground with a region dependent proportionality factor.

- **Level 1** All higher levels are based on one formula which calculates the size of the borefield based on a number of thermal pulses.

$$L = \frac{\sum_{i=1}^{N} q_i R_i + q_h R_b^*}{T_m - (T_g + T_p)} \tag{1}$$

  with the q_i's are the thermal loads, R_i the thermal resistances, q_h the thermal pulse, R_b^* the equivalent borehole resistance, T_m the average fluid temperature, T_g the undisturbed ground temperature and T_p a temperature penalty. This penalty is needed to account for the borehole-to-borehole thermal interaction (Ahmadfard and Bernier, 2018). In Level 1 methods only the peak pulses are used. Because this formula includes thermal resistances and the ground temperature, it is more accurate than the Level 0 methods, however they do have similar shortcomings in accuracy (Ahmadfard and Bernier, 2019).
- **Level 2** This level uses Equation (1) with three thermal pulses: a peak pulse, a monthly pulse and a yearly pulse. This method is known as the ASHRAE three pulse method and is improved by Ahmadfard and Bernier (2018) by using thermal resistances based on the ground response function (g-function). This g-function (explained later in the text) takes into account the borehole-to-borehole interaction, so T_p is no longer needed in Equation (1).
- **Level 3** This level uses two thermal pulses for each month: a peak pulse and a monthly pulse. It is clear that this method is more accurate than the previous ones, however, when considering a study period of 20 years, this method needs 480 pulses instead of just 3 in case of a level 2 method. Earth Energy Designer (EED),

[1]A distinction is made between *methods* and *tools*. *Methods* are interpreted as a mathematical formulation whereas *tools* are (commercially) available programs like EED and GLHE-PRO.

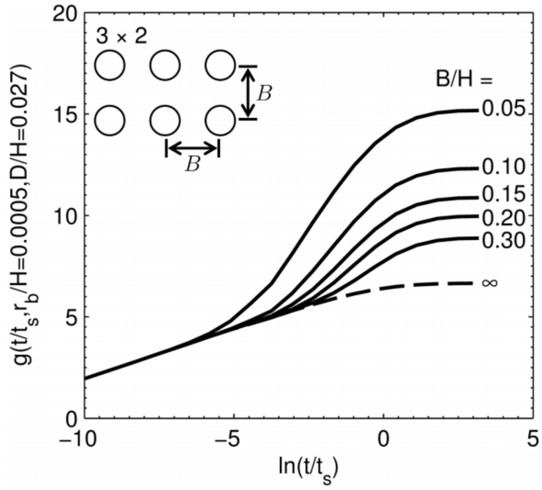

Figure 1: Example of g-functions for different configurations (Bernier, 2015). (B the borehole spacing, H the borehole depth, r_b the borehole radius, t_s a normalised time)

used in this paper for the validation, belongs to this level.

- **Level 4** Level 4 uses hourly pulses and is hence used in detailed simulations of the ground temperature. The dynamic simulation for the validation of the developed method is performed using the IDEAS library (which uses the IBPSA borefield model) in the Modelica language relying on a hourly pulse method, but also simulating the dynamics of the borehole fluid and grout (Jorissen et al., 2018; Laferrière et al., 2020; Shirazi and Bernier, 2013; Bauer et al., 2011).

Calculating the ground temperature evolution in time is complex because it is a three dimensional heat diffusion problem. In order to deal with this complexity, Eskilson (1987) proposed the concept of a g-function: the normalised temperature response to a heat load as a function of a normalised time. This is illustrated in Figure 1.

These g-functions are calculated and available for different borehole configurations within the Python package `pygfunction` (Cimmino, 2018). For a full mathematical elaboration of the g-function, the reader is referred to (Laferrière et al., 2020; Cimmino, 2019). Once the g-function for a particular borefield is known, the borehole wall temperature T_b can be calculated by means of temporal superposition of discrete loads q_i (Cimmino, 2019).

$$T_b(t) = T_g - \frac{1}{2\pi k_s}\sum_{i=1}^{n}(q_i - q_{i-1})g(\frac{t_n - t_{i-1}}{t_s}) \quad (2)$$

with k_s the ground thermal conductivity, q_i and t_i the thermal load and time at instance i.

Ahmadfard and Bernier (2018) used the g-function explained above to redefine the thermal resistances in Equation (1). Traditionally the resistances are defined in a way that they need compensation for the ground temperature due to borehole-to-borehole interactions by means of a temperature penalty T_p. By using the g-functions to define the resistances (now indicated by the subscript g), the ground temperature response is incorporated so the need for a penalty fades (Ahmadfard and Bernier, 2018). These resistances are defined proportional to the difference in g-function evaluations.

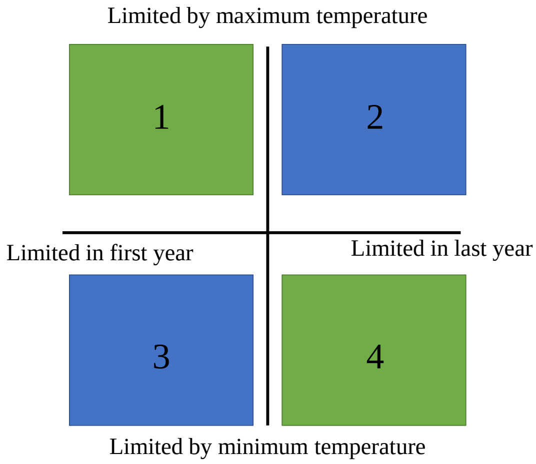

Figure 2: Graphical representation of the four groups of borefields.

$$R_{t,g} = \frac{g(t_r) - g(t_r - t)}{2\pi k_s} \quad (3)$$

with t_r a reference time larger than t.

Sizing methods

A borefield is properly sized if the ground temperature always stays within certain temperature limits (in what follows these limits are set to 0°C and 16°C as the minimum and maximum temperature respectively). When conceptualising this, one can see that either the maximum or the minimum ground temperature can be a limiting factor (respectively the cooling and heating load). Even so, this limit can be reached in the last or the first year of operation (illustrated in respectively Figure 3 and 4), because e.g. an extraction dominated field will lower in temperature year after year, but can reach its maximum temperature in a cooling peak during the first year of operation (see Figure 4). So every borefield can be categorised into four groups, depending on when it reaches the critical temperature and if that temperature is the minimum or the maximum one. This is shown schematically in Figure 2.

It is not a priori known in which of these categories one particular borefield will be, so in order to size it properly, all options should be checked. However, this does not mean that literally all four options should be calculated, because the four options are only pairwise applicable to a particular field (the green and blue coloured quadrants). This can be understood as follows. If a field is dominated by extraction (this is the case when it is coupled to a heating dominated building in which the amount of heat extracted by the heat pump from the ground is larger than the amount of heat injected), it will cool down year after year. So, when thinking about the four categories, one can reason that it is unnecessary to look at the lower temperature limit in the first year of operation because, due to the imbalance, the last year of operation will be even more critical. The same can be said for the maximum temperature in the last year of operation: this will always be lower than in the first year, because of the imbalance. So, for whatever field, only two options should be checked, either the green or the blue options in Figure 2, based on the imbalance.

To the best of the author's knowledge no such (open-source) method checking the different quadrants is available in literature. In order to come up with a novel sizing approach, two methods, for respectively sizing based on the last and first year of operation will be introduced first. In the next section these different methods are put next to each other to show that both methods do not work properly for all possible quadrants of Figure 2 and that the proposed new method is universally applicable.

For completeness, it should be added that there are commercial tools available (like GLHEPRO) which surpass this problem of quadrant identification in practice, by just looking at the maximum and minimum temperature over the whole study period (Spitler, 2000). So in practice when using these tools, one does not need to worry about this, but when implementing an own sizing method, this categorisation is very helpful.

Sizing method based on the last year of operation

As already mentioned, the only relevant quadrant to check in the last year is that of the minimum temperature if the field is coupled to a heating dominated building or the maximum temperature if the field is coupled to a cooling dominated one. For this, the three pulse method is both accurate and easy to use. Based on the adaptations of Ahmadfard and Bernier (2018) using the thermal responses, Equation (1) can be rewritten as

$$L = \frac{q_y R_{y,g} + q_m R_{m,g} + q_h R_{h,g} + q_h R_b^*}{T_m - T_g} \tag{4}$$

in which the different thermal resistances are calculated as

$$R_{y,g} = [g(t_f) - g(t_f - t_1)]/(2\pi k_s) \tag{5}$$
$$R_{m,g} = [g(t_f - t_1) - g(t_f - t_2)]/(2\pi k_s) \tag{6}$$
$$R_{h,g} = g(t_f - t_2)/(2\pi k_s) \tag{7}$$

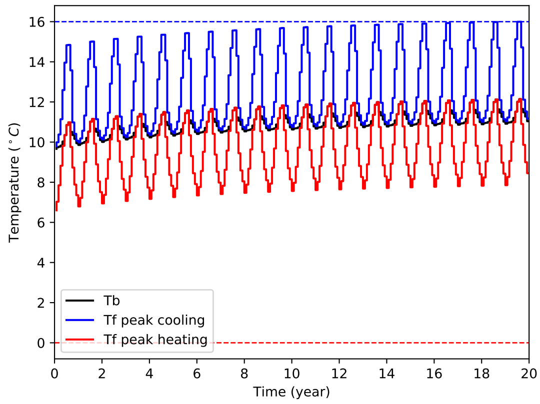

Figure 3: Example of a borefield, dominated by heat injection and limited in the last year of the study period by the cooling peak. (T_f is the mean fluid temperature)

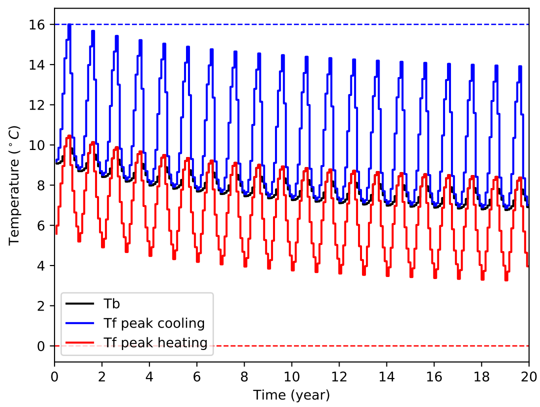

Figure 4: Example of a borefield, dominated by heat extraction and limited in the first year of the study period by the cooling load.

in which $t_f = t_y + t_m + t_h$, $t_1 = t_y$, $t_2 = t_y + t_m$ and t_y is the study time (e.g. 20 years), t_m the time of a month and t_h the time of the pulse.

The sizing starts by estimating a borehole depth (for a given configuration) and calculating all the thermal resistances. After that, Equation (4) is used to recalculate the total borehole length L, in which T_m stands for temperature limit (either the minimum or the maximum temperature) for which the field needs to be sized. The new length will then be used to iterate this process until the new obtained length differs only a small amount ϵ from the previous iteration (Ahmadfard and Bernier, 2018).

Sizing method based on the first year of operation

For the sizing based on the first year of operation, a level 3 method is used to start with, but this will be scaled down to a level 2 method. Monzó et al. (2016) discuss a monthly based sizing method which mathematically comes down to (for month i) Equation (8).

$$L_i = \frac{q_{h,i}R_h + q_{cm,i}R_{cm} + \bar{q}_{pm,i}R_{pm,i} + q_{h,i}R_b^*}{T_m - T_g - T_p} \quad (8)$$

with q_{cm} the thermal load in the current month and $\bar{q}_{pm}$ the accumulated load in the months before the limiting month. By using the same principle as Ahmadfard and Bernier (2018) for the thermal resistances, Equation (8) can be changed to

$$L_i = \frac{q_{h,i}R_b^* + q_{h,i}R_{h,g} + q_{cm,i}R_{cm,g} + \bar{q}_{pm,i}R_{pm,i,g}}{T_m - T_g} \quad (9)$$

In the proposed new method, this level 3 method by Monzó et al. (2016) will only be used in the first year of operation. Instead of calculating 12 sizes for this first year, only the month in which the potentially limiting peak is the highest, will be calculated. This reduces the originally level 3 method to a level 2 one, which does not size the field correctly when limited in the last year. However, as Cullin and Spitler (2011) have shown, the moment at which the peak occurs is not always the moment at which the highest temperature is reached. So this assumption may introduce some error, but it is needed to achieve the level 2 complexity. Moreover, it is the same assumption that underlies the sizing method based on the last year explained above.

Hybrid method

The proposed hybrid method will use both the sizing in the first and the last year of operation and will select the largest value of both to be the proper sizing. Firstly, the imbalance is looked at, in order to define which two quadrants should be examined (Figure 2). After this, both sizing methods (as explained above) will calculate the required size if the field would be limited in this quadrant. The largest of the two results, is the proper size. This approach will be illustrated in the next section.

Results

The validation done in this paper was not done in order to prove the validity of the new hybrid method with regards to the real life behaviour of the borefield. Since the newly proposed hybrid sizing method is just a combination of the above two, its validity can be inherited from the existing methods and be extended.

In order to validate and compare the novel hybrid method with the two existing approaches, four cases are considered (one in each quadrant of Figure 2), given by the load profiles[2] in Figure 5. Both Case 1 and Case 4 are heating dominated and Case 2 and 3 are cooling dominated. Furthermore, Cases 1 and 2 will be limited by the cooling demand and Cases 3 and 4 will be limited by the heating demand. For each of these cases, the borefield size is calculated by the two discussed methods as well as with the new combination of both (called Hybrid). The results of a sizing based on the commercial program Earth Energy Designer is also given as a reference. These results can be found in Table 1, where case 2 and 4 are limited by the maximum temperature (16°C) and case 1 and 3 are limited by the minimum temperature (0°C).

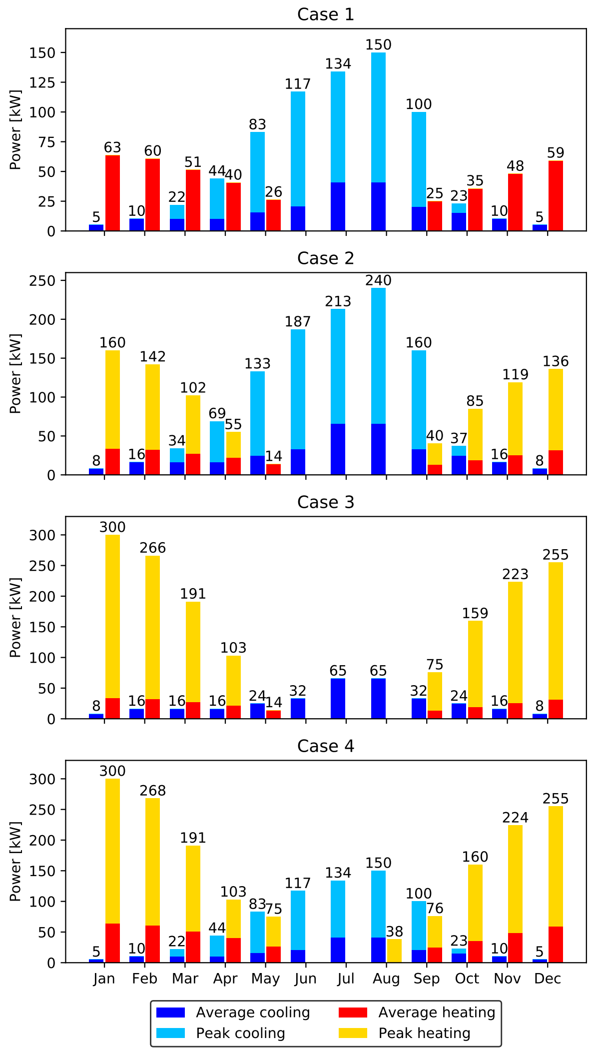

Figure 5: Load profile cases.

Table 1: Results for different borefield sizing methods. (FY and LY stands for respectively sizing based on the first and last year of the study period.)

Case	EED	FY	LY	Hybrid
Case 1	39,41m	56,88m	38,54m	56,88m
Case 2	120,22m	98,36m	120,37m	120,37m
Case 3	57,126m	67,46m	57,96m	67,46m
Case 4	92,71m	70,46m	94,10m	94,10m

As can be seen from Table 1 the sizing based on the last year almost equals the reference sizing done with EED. This is because the automated sizing in EED

[2]These profiles are selected in such a way to test the limits of the existing methods and are not directly related to real existing buildings.

is always based on the last year of the study period. For Case 1 and Case 3, where the field is limited in the first year of operation (Figure 2), the sizing based on the first year of operation is largest, so the reference size of EED is an underestimation of the actual needed size. To show this, Case 1 is dynamically simulated using the borefield model of the IBPSA library (included in the IDEAS library) (Jorissen et al., 2018) in Dymola, showing that the field should be sized based on the first year in this case. The same is done for Case 2.

For the simulation, a time resolution of 8760 hours/year was needed. In order to be able to compare the simulated results with level 2 sizing methods, the same underlying assumptions were used, being: a constant extraction/injection load during the month and a peak of 6 hours at the end of each month. Therefore, there was started with the profiles from Figure 5 and the net ground extraction/injection per month based on the monthly averages for heating and cooling was calculated. This value was applied the first 724 hours of each month. For the last six hours, the peak value of heating or cooling was taken if the month had a net ground extraction or injection respectively. The load values for the dynamic simulation obtained this way are given in Tables 2 and 3 for respectively Case 1 and 2. The borefield parameters used for the simulation are given in Table 4.

For both the simulation results are presented in Figure 6, where the limiting years are shown separately.

In Case 1 the graph for sizing in the first year collides with the hybrid method, therefore only one is visible. The same holds for sizing in the last year for case 2. As was also clear from Table 1 sizing in the last year gives the same profile as sizing by EED. Note however that the hybrid method proposed in this paper also crosses the temperature limit. This is due to the fact that the dynamic simulation is way more complex than the sizing method, because it takes into account an hourly profile (with 8760 pulses instead of three), the evolution of the ground temperature with increasing depth and the dynamic response of the fluid (Jorissen et al., 2018) and grout (Shirazi and Bernier, 2013; Bauer et al., 2011). It is however clear that as a sizing method, the hybrid one does the overall best job, determining a borefield size that guaranties sustainable operation over the full life time.

[3]All the thermodynamic properties of water used are calculated in the simulation itself by using the medium: *IDEAS.Media.Water*.

Table 2: Loads for the dynamic simulation of Case 1. (Negative value is heat extraction)

Month	**Avg. load** kW	**Peak load** kW
Jan	-58.68	-63.70
Feb	-50.55	-60.82
Mar	-41.10	-51.37
Apr	-30.41	-40.68
May	-10.89	-26.30
Jun	20.55	117.00
Jul	41.10	134.00
Aug	41.10	150.00
Sep	-4.52	-25.07
Oct	-20.34	-35.75
Nov	-37.81	-48.08
Dec	-54.04	-59.18

Table 3: Loads for the dynamic simulation of Case 2. (Negative value is heat extraction)

Month	**Avg. load** kW	**Peak load** kW
Jan	-25.75	-160.00
Feb	-16	-142.00
Mar	-10.96	-102.00
Apr	-5.26	-55.00
May	10.63	133.00
Jun	32.88	187.00
Jul	65.75	213.00
Aug	65.75	240.00
Sep	19.51	160.00
Oct	5.59	37.00
Nov	-9.21	-119.00
Dec	-23.34	-136.00

Table 4: Summary of the borefields parameters, used for the simulation.

Description	**Value**	**Unit**
Borehole radius	75	mm
Borehole height	*Table 1*	m
Borehole burial depth	4	m
Borehole spacing	6.5	m
Number of boreholes	120 (10x12)	-
Ground conductivity	3.5	$\frac{W}{mK}$
Ground vol. heat capacity	2.4	$\frac{MJ}{m^3K}$
Undist. ground temp.	10.0	$^\circ C$
Grout conductivity	1.0	$\frac{W}{mK}$
Contact resist. pipe/filling	0	$\frac{mK}{W}$
Type	Single U-tube	
Inner pipe radius	13	mm
Outer pipe radius	16.7	mm
Pipe conductivity	0.4	$\frac{W}{mK}$
Pipe spacing	62	mm
Equivalent borehole resist.	0.2	$\frac{mK}{W}$
Fluid	Water[3]	
Mass flow rate (case 1)	20	$\frac{kg}{s}$
Mass flow rate (case 2)	12	$\frac{kg}{s}$

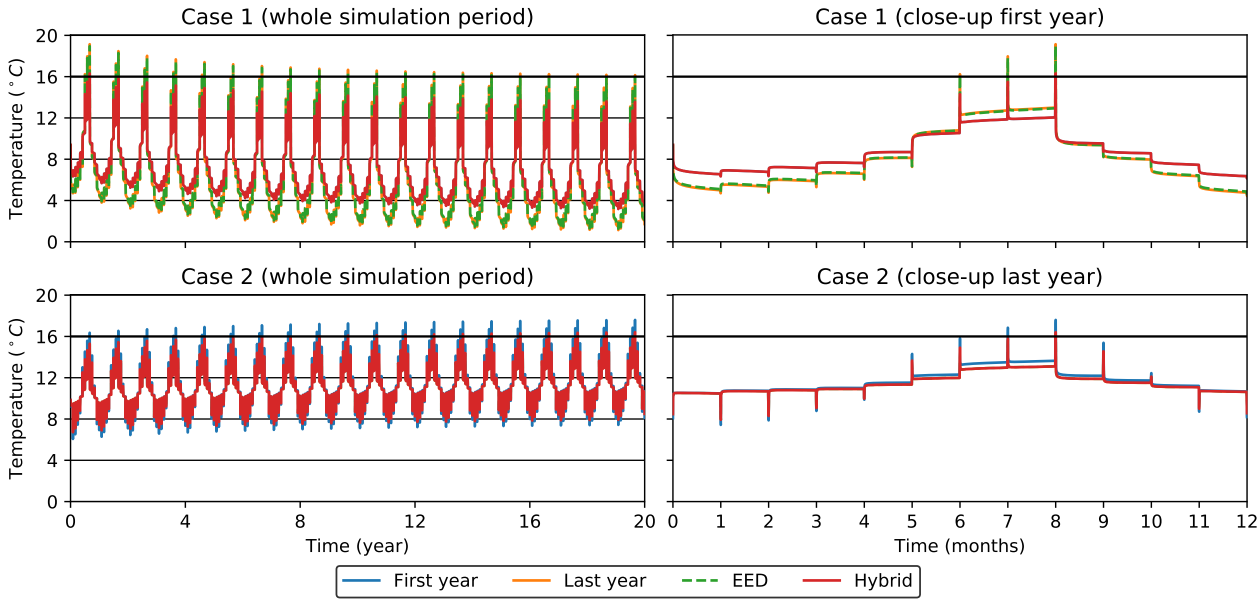

Figure 6: Dynamically simulated temperature profiles based on the borefield lengths derived from EED, FY, LY and the Hybrid method for Case 1 and 2.

Conclusion

In this paper it was shown that the rather easy to use methods that do exist for borefield sizing are not universally applicable and do sometimes lead to underestimations. Therefore it was proposed to come up with a new level 2 sizing method by reasoning about the four categories a borefield can be in. This method is the combination of two existing methods that do size the borefield in the last and the first year of the study period, with a small modification to the first year sizing method making it a level 2 method instead of a level 3 one.

It was shown by comparison with Earth Energy Designer and using dynamic simulations that this novel method gives an overall better result than the two existing methods individually. Furthermore, it has been shown that the tool EED provides the wrong automatic sizing when the field is limited in the first year of operation. Because this hybrid method is equally complicated as the existing ones it is composed of (and even simpler than the sizing in the first year) and gives more robust results, this method is preferable over both the existing ones. The code for this method is open source and can be found on: `https://github.com/wouterpeere/GHEtool`.

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Nomenclature

$g(t)$	g-function at time t
k_s	Thermal ground conductivity
L	Total length of the borefield
L_i	Total length of the borefield based on sizing in month i
t_s	Normalised time
t_r	A reference time
T_b	Borehole wall temperature
T_f	Temperature of the fluid
T_g	The undisturbed ground temperature
T_m	Temperature limit (minimum or maximum)
T_p	Temperature penalty
R_b^*	Equivalent borehole resistance
R_i	Thermal resistance for pulse i
$R_{i,g}$	Thermal resistance for pulse i based on the g-function
q_{cm}	Thermal load in the current month
$\bar{q}_{pm}$	Accumulated thermal load of the previous months
q_h	Thermal peak pulse
q_i	Thermal pulse i

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