INTERNATIONAL SUMMER SCHOOL on Direct Application of Geothermal Energy

Under the auspice of:
Division of Earth Sciences

Chapter 2.5

DESIGN OF CLOSED LOOP HEAT EXCHANGERS

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1 Introduction

The European market for geothermal heat pumps as well as for underground thermal energy storage for heating, cooling or combined heating/cooling is growing significantly. Positive environmental impact by reduction of CO_2 emission and other harmful effluents as well as the uncertain availability of fossil energies influenced this development. In Germany increase of oil and gas prices in 1999 and 2000 combined with special electricity rates for heat pumps have improved the economy of these systems considerably.

Correct design and proper construction of the system decides for technical and economical success or failure. A undersized ground loop system will show severe operational problems reaching from high operational costs to system damage and environmental impact. This can even result in shutting down of the plant. Oversized ground loops require high investment and the installation will be uneconomic and hinders the dissemination of the technology.

Therefore the design has to be done thoroughly. The VDI 4640 guideline – thermal use of the underground – gives support for the design procedure for small systems up to 30 kW. Bigger installations as well as underground thermal energy storage are typically more complex and require more sophisticated methods like computer simulation.

This exposition follows closely the VDI 4640 Guidelines and is therefore officially valid in Germany but also accepted in other European countries like Switzerland and Austria which have also contributed to it.

2 General Considerations

During the design phase the most favourable ground heat source of the site has to be identified and the heating system as well as the other components have to be adjusted to it. Heat can be extracted from the ground by

- pumping of ground water (open loop)
- via horizontal ground loops (horizontal closed loop)

- via borehole heat exchangers (vertical closed loop in boreholes)

The selection of either a vertical or a horizontal system is done according to geology, demand of space and the structural conditions at site. The correct design of the ground loop requires the time dependent profile of the heat (energy) demand and the heating power. From this results the

- design power of the ground source
- evaporation power of the heat pump
- annual operation hours
- peak load of the ground source

Proper knowledge of the geological and hydro-geological conditions allow conclusions about the thermal and hydraulic properties of the underground. Thus the appropriate ground source can be selected.

2.1 Heat Source – Ground Water

The design of open loop ground water heat pumps is fairly simple. The water is pumped from the ground through a production well. The well capacity has to meet the required permanent pumping rate of the heat pump. Typically the flow-rate amounts to 0.25 – 0.30 m_/h per 1 kW evaporation power at a DT = 3 K. The has to be re-injected downstream through an injection well into the same aquifer at an appropriate distance to avoid short-circuit.

Additionally to the pumping capacity water quality is an important issue. Besides the mineral content, temperature, ph-value, electric conductivity and the redox-potential allow conclusions about the danger of clogging and corrosion of materials used.

2.2 Heat Source – Horizontal Ground Loop

Horizontal ground loops (see fig. 1) are typically made of plastic pipes installed horizontally in the ground at a depth of 1.2 – 1.5 m. Cold heat transfer fluid is circulated through the pipes and thus extracting the heat. This type of system uses the heat flux coming from the top which results from direct or indirect solar energy (solar radiation, rain, etc.). The geothermal heat flux of 0.1 W/m_ is neglectable. The design is not only influenced by the thermal properties of the underground but also by the exposition of the plot of land where the system is installed and the surrounding area. The surface of the ground loop must neither be build over nor be sealed from rain. Depending on the type of underground the heat extraction rate varies from 10 – 40 W/m_.

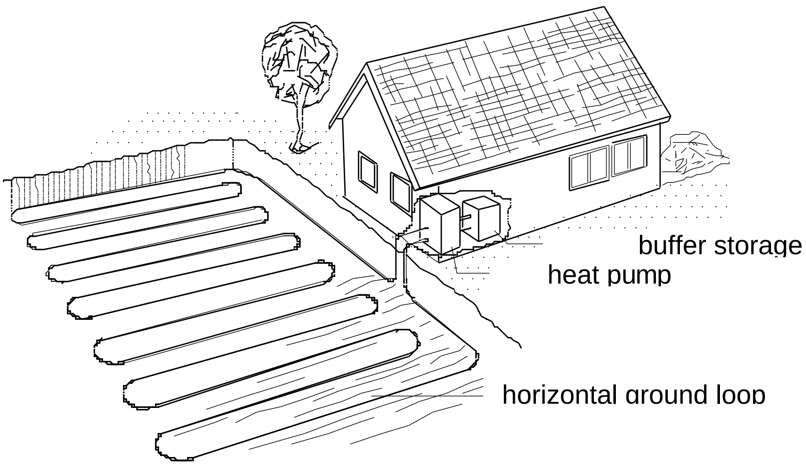

Fig. 1: Horizontal closed ground loop (/2/)

Reference /2/ gives a simple method for sizing by a nomogram (see fig. 2). The underground is characterized as follows:

- Regular conditions: Humid, silty-sandy ground with regular solar radiation exposure; specific extraction rate 20 – 30 W/m_ (ground class 2 and 3 in fig. 2).
- Unfavourable conditions: Stony ground, dry and shady; specific extraction rate 8 – 12 W/m_ (ground class 4 in fig. 2).
- Favourable conditions: Sandy ground, water saturated with high solar radiation; specific extraction rate 35 – 40 W/m_ (ground class 1 in fig. 2).

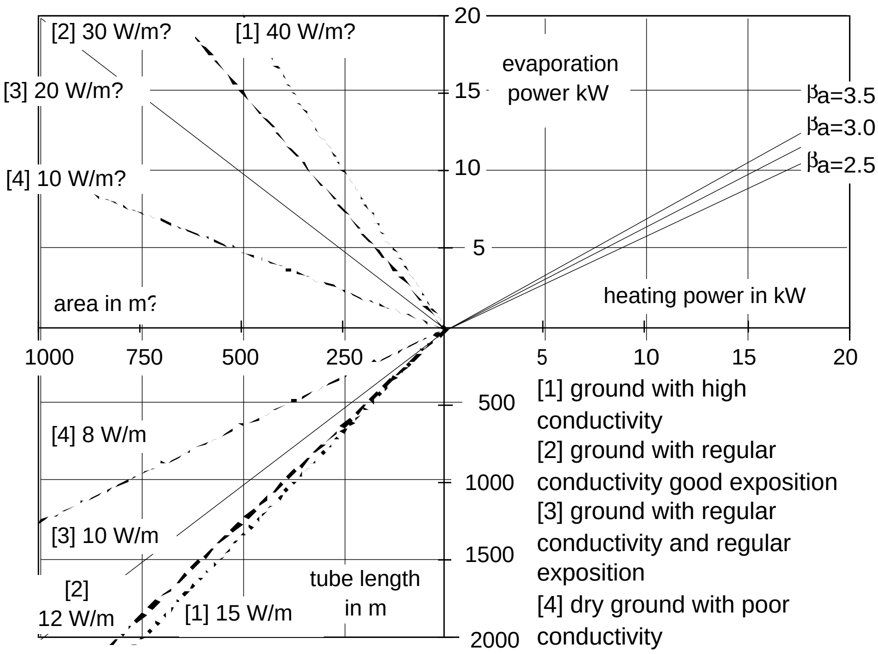

Fig. 2: Nomogram for sizing of horizontal ground loops (/2/)

Example:

For 15 kW heating power and a seasonal performance factor SPF = 3.5 the evaporation power is 10.7 kW. For a ground class 2 soil with 30 W/m_ extraction rate an area of 360 m_ with a total pipe length of 895 m is determined.

In order to extract also during longer cold periods enough energy the specific annual energy extraction rate should not exceed 50 – 70 kWh/m_/a. Thus the area of the ground loop is approximately 1.5 – 2.0 - times the heated space. For low energy or passive houses this value can fall below this limit. The difference between the fluid inlet and the ground temperature should not exceed ±12 K for base load and ±18 K for peak load conditions respectively.

2.3 Heat Source – Borehole Heat Exchangers

Borehole heat exchangers (BHE) are typically made of plastic tubes inserted in vertical or inclined boreholes (see fig. 3). For good thermal contact between the tube and the ground the borehole is grouted with a special material which additionally tightens it. In Germany borehole heat exchangers are typically less than 100 m because of the additional permit of deeper ones according to the mining law. This requires also a thorough design as under-sizing leads to too strong sub-cooling and probably freezing. This reduces the performance of the heat pump and the deeper part of the BHE keeps frozen as there is not enough heat delivery from the surrounding for recovering totally. According to /1/ the temperature difference of the fluid in the BHE and the undisturbed ground must not exceed ±10 K under base load and ±15 K under peak load conditions.

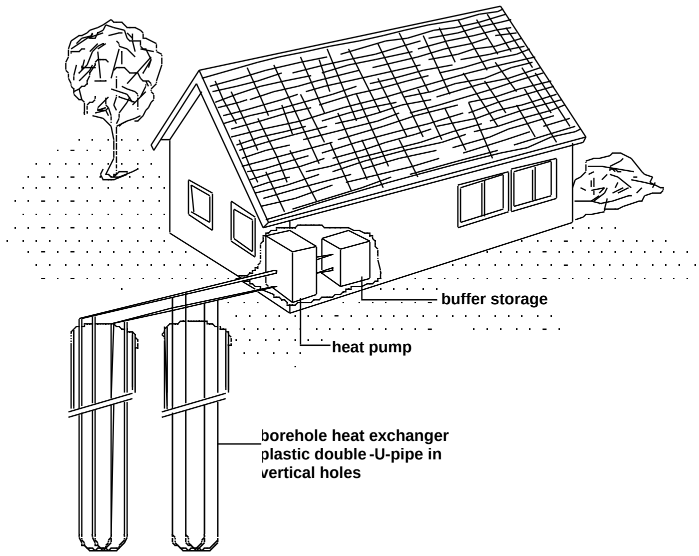

Fig. 3: Borehole heat exchangers in vertical holes (/2/)

In general the design is depending on the type of underground. Influencing factors are thermal conductivity and humidity of the ground especially ground water flow. Meanwhile a method – the Thermal Response Test – is available for determining in-situ the thermal properties of the underground and the BHE.

The VDI 4640 Guideline /1/ distinguishes between small system up to 30 kW heating power and bigger ones. Below 30 kW a table of values and a nomogram is proposed, whereas for bigger systems computer simulation is strictly recommended. In most cases the Thermal Response Test is not economic for small systems but it is highly recommended for bigger plants.

Table 1 gives specific heat extraction rates for different geological conditions. It is only applicable if the following requirements are met:

- length of BHE 40 – 100 m
- min. distance of BHE: 5 m for 40 – 50 m and 6 m for 50 –100 m long BHEs
- only heat extraction
- double – U – pipes DN20, DN25 or DN32 or coaxial BHE with more than 60 mm diameter

If there are more independent installations close together at one location the extraction power has to be reduced by 10 – 20 % because of the influence on each other. For less than 1000 hours of operation per year the length of the BHEs can be reduced by 10 %.

Table 1: Specific extraction rate of BHEs for a heating power < 30 kW (/1/)

underground	spec. extraction rate	
	for 1800 h	for 2400 h
general figures:		
bad underground (λ <1,5 W/m/K)	25W/m	20 W/m
regular rock and water saturated sediments (λ =1,5 - 3,0 W/m/K)	65 W/m	50 W/m
rock λ > 3,0 W/m/K	84 W/m	70 W/m
different underground:		
gravel, sand dry	<25 W/m	<20 W/m
gravel, sand water-saturated	65 – 80 W/m	55 – 65 W/m
clay, loam humid	35 – 50 W/m	30 – 40 W/m
limestone (massive)	55 – 70 W/m	45 – 60 W/m
sandstone	65 – 80 W/m	55 – 65 W/m
acid magmatites (e.g. granite)	65 – 85 W/m	55 – 70 W/m
basic magmatites (e.g. basalt)	40 – 65 W/m	35 – 55 W/m
gneiss	70 – 85 W/m	60 – 70 W/m
high groundwater-flow in gravel/sand for single systems		80 – 100 W/m

Additionally to the specific extraction power the annual amount of heat discharged has to be considered which is determining the long-term influence. This value should be in the order of 100 – 150 kWh/m/a. In case of re-injection of heat deviation of this interval is allowed. This will be discussed in more detail.

Allow specific extraction rates a proper design of BHEs?

The main influencing factor is the underground itself with it's specific thermal conductivity. High groundwater flow in unconsolidated ground will affect the extraction rate considerably. The

annual time of operation which is resulting in the total amount of heat discharged (in kWh/m/a) is another important influence /3/. This depends also on the type of system (e.g. bivalent, geothermal for base load) and thus on the climate at site /4/. Specific extraction rates (power) are responsible for the short-term effects, while the heat (energy) discharged is determining the long-term performance. As shown with a plant in Switzerland /5/ only with a correct designed system, the heat can be considered as renewable energy.

Fig. 4 shows the specific extraction rate as a function of the annual full load operation hours. This was calculated with the program EED for a building of 10 kW heating power and a heat pump SPF = 3.5. Ground thermal conductivity was assumed to be 2.0 W/m/K without groundwater flow.

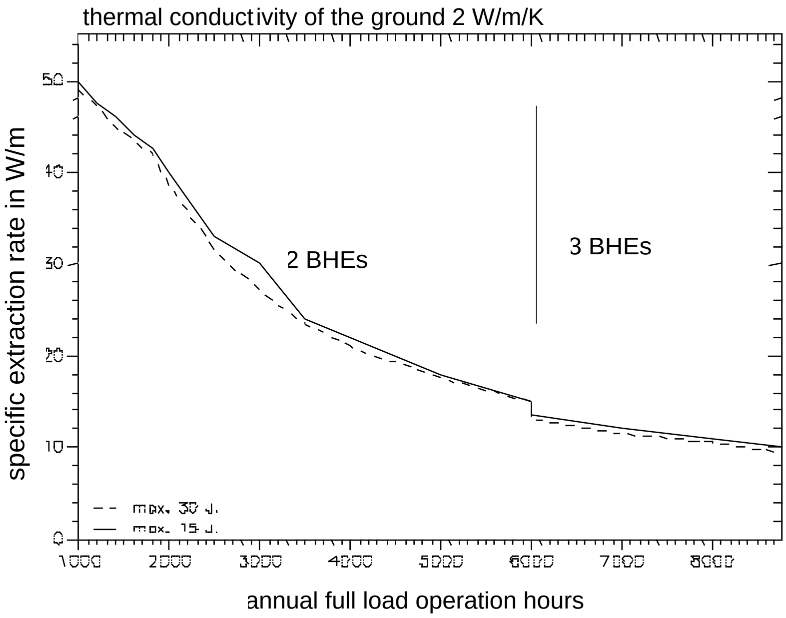

Fig. 4: Specific extraction rate as a function of the annual full load operation hours (heating power 10 kW, SPF = 3.5, l = 2.0 W/m/K, without groundwater flow)

For a typical residential building (1800 h/a) the extraction rate for two BHEs is determined to 42.6 W/m/K. With increasing annual full load operation hours to 3000 – 5000 h/a the extraction rate is reduced to values below 20 W/m/K, above 6000 h/a three BHEs have to be used as the length of each would exceed 200 m for 10 kW heating power. On permanent operation the extraction rate is about 10 W/m/K.

The mutual influence of BHEs is remarkable. For permanent heating the length of BHEs has to be increased, in case of borehole storages like in Neckarsulm-Amorbach /6/ this is a big advantage.

In Fig. 5 this mutual influence is illustrated with an example of 60 buildings with individual geothermal heat pumps with BHEs. A reduction of distance between the boreholes results in an increase of required BHE length.

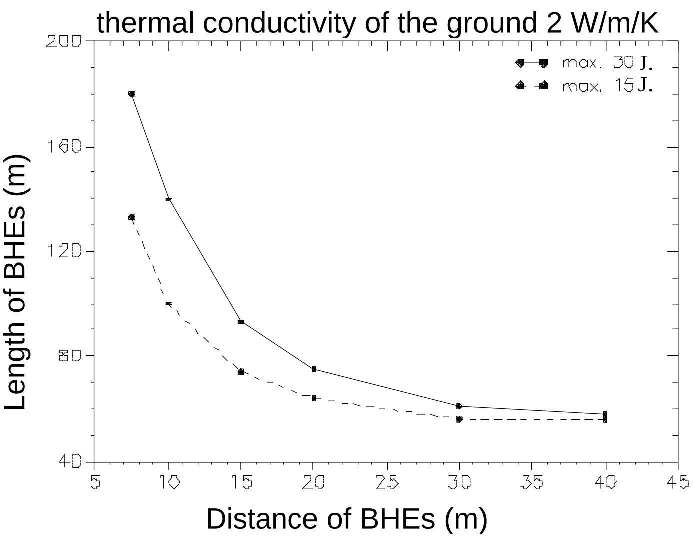

Fig. 5: Influence of distance on the length of BHEs (e.g.: 60 buildings, 7 kW heat demand each, 2 BHEs/house, no groundwater, no recharging, ground property l = 2 W/m/K, calculation period 15 a, 30 a)

It can be concluded that only for small and simple application, the extraction rate can be used for designing. Therefore the VDI 4640 Guideline gives restrictions for the use of table 1. It is only valid for small systems without influence on each other, bigger installation and especially those for heating and cooling require more detailed calculations.

For such small systems the Swiss Bundesamt fuer Energiewirtschaft initiated the development of a nomogram /7/ for Swiss conditions but it could also be used in Austria and Germany. This nomogram (see fig. 6) is based on computer simulations but not validated by field monitoring.

From the annual heating energy and heating power considering the climatic conditions by the altitude of the location and the nomogram-factor (eq. (1)) the length of the BHE is determined. For more plants close together the extraction power has to be reduced by 10 – 20 % because of mutual influence

$$a = \frac{Q_{Ha}}{Q_{Ha} / \beta_a - Q_{pa}} \quad (1)$$

a	nomogram - factor
Q_{Ha}	annual heating energy in kWh/a
βa	seasonal performance factor
Qpa	annual energy demand of peripheral components (circulation pump) in kWh/a

The validity of the nomogram is defined as follows:

Heating energy		4 – 16 MWh/a
Heating power		3 – 10 kW
Altitude of site		200 – 1400 m
Thermal conductivity		1,2 – 4,0 W/m/K
Length of BHE	(1 BHE)	60 – 160 m
	(2 BHEs)	60 – 100 m
Nomogram – factor		3,8 – 4,6

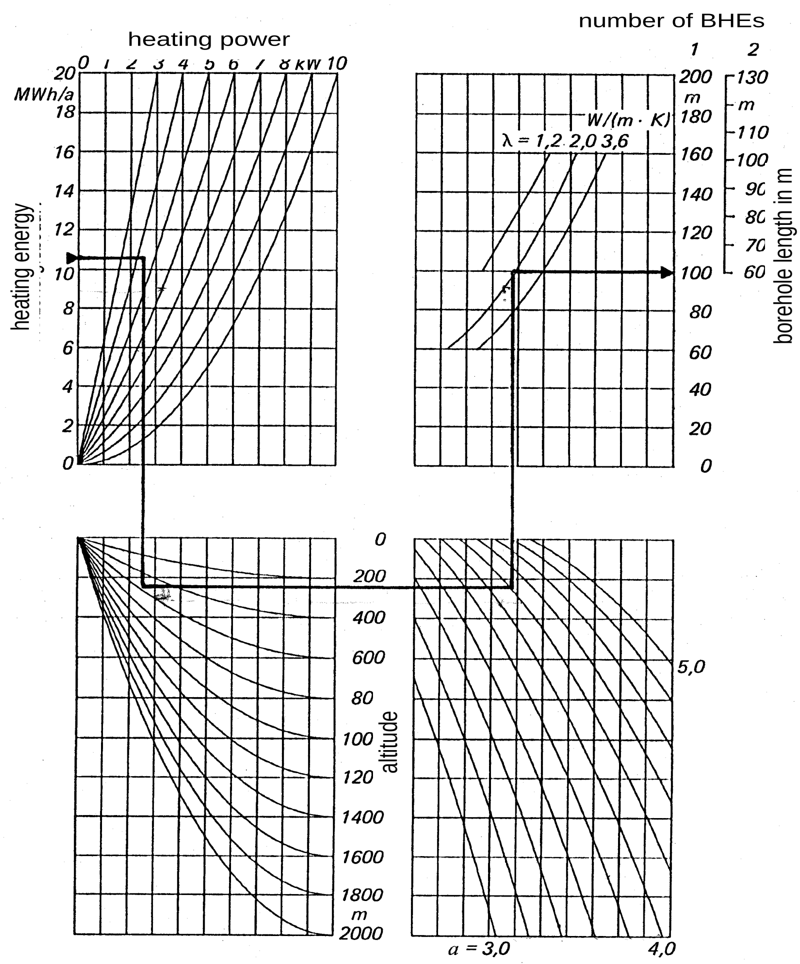

Fig. 6: Nomogram for design of BHEs (/7/, /1/)

3 Design Examples

The following examples should demonstrate the different design procedures for a single family house located in the eastern part of the Odenwald (300 m above sea level) with specifications given in table 2.

Table 2: Border conditions for the example

heat demand acc. DIN 4701	$\dot{Q}_H$ = 12 kW	annual full load operation hours	t_a = 1500 h/a
inlet-temp. to heating system	T_v = 30 - 35°C	SPF	β_a = 3,5
extracted power ($\dot{Q}_{EWS} = \dot{Q}_H * (\beta_a-1)/\beta_a$)			$\dot{Q}_{EWS,2}$ = 8,6 kW
underground: sandstone; thermal conductivity			λ = 2,3 W/m/K

Case 1: Design according to table 1 – general values

Ground - regular rock (1,5 W/m/K < λ < 3,0 W/m/K) with $\dot{q}_{EWS}$ = 50 W/m results for β_a = 3,5 per 1 kW heating power 14 m BHE:

Two BHEs of 84 m each should be installed.

Case 2: Design according to table 1 – different minerals

Specific extraction rate sandstone Q_{BHE} = 55 - 65 W/m, for β_a = 3.5 per 1 kW heating power results 11 - 13 m BHE:

=> L_{BHE} = 132 - 156 m

Two BHEs of 66 - 78 m each should be installed.

Case 3: Nomogram (fig. 6)

Annual heating energy $Q_{Ha} = Q_H * t_a$ peripheral energy $Q_{pa} = Q_p * t_a$ with Q_p = 0.4 kW

Q_{Ha} = 18 MWh/a

Q_{pa} = 0.6 MWh/a

Heating power and energy are at the border of validity of the nomogram, therefore the design is made for _ of the system (6 kW heating power, 9000 kWh heating energy with a = 3,96).

Two BHEs of 65 m each should be installed.

Case 4: Design with EED (Earth Energy Designer)

In comparison to the already described methods this system was also designed with EED. Additionally to the assumptions above EED takes the distribution of the base and peak load as well as the minimum fluid temperature into account. According to VDI 4640 /1/ this temperature was set to +1 °C for permanent operation and –5 °C for peak load conditions. The borehole diameter is 115 mm and their distance 6 m. Furthermore the physical properties of the heat exchanger pipe and the grouting material are used.

Two BHEs of 88 m each should be installed.

Because of the more accurate calculation the result with EED is a more reliable one. The results of all cases are summarised in table 3. The deviation of the different methods are up to 25 %, modifications of borehole diameter, distance of tubes and grouting show an influence less than 10 %. Therefore it is recommended to use more sophisticated design methods even for small systems.

Table 3: Summary of the different design results

method	spec. extraction rate	borehole heat exchangers		
		number	length of BHE	total length
case 1: table 1 general figures	50 W/m	2	84 m	168 m
case 2: table 1 different rocks	55-65 W/m	2	66-78 m	132-156 m
case 3: nomogram		2	65 m	130 m
case 4: design by EED		2	88 m	176 m

Finally the design of a horizontal ground loop should be given for this example. According to VDI 4640 /1/ for humid sandy ground which is expected at this site the specific extraction rate is 15 – 20 W/m_ and thus for b_a = 3.5 an area of 36 – 48 m_/kW_{th} is required. For 12 kW Heat demand 432 – 576 m_ of ground loop has to be built.

4 Conclusions

The design of the ground source has an significant influence on the performance of geothermal heat pumps for space heating. Mistakes in design will not only be uneconomic because of high operational costs, but can also cause damages at buildings and the environment.

In the past the discussions about design was mainly about specific extraction rates. Very often the assumed values vary from 55 W/m/K to 100 W/m/K. As shown, these values are very much depending on the regional geological situation and cannot be used at other locations or climatic conditions. With respect to the long-term performance the values proposed in the VDI 4640 and those from monitored systems are close together.

The VDI Guideline gives design values and procedures for:

- ground water wells
- horizontal ground loops
- vertical borehole heat exchangers

The design of water wells is fairly easy, approximately 0.25 m_/kW-evaporation power is required. Important is to consider hydro-chemical parameters, correct construction and proper operation.

Horizontal ground loops can be designed by a nomogram or values listed in the VDI Guideline. Experiences are required for the assessment of the location with respect to exposition and underground. Computer programs are hardly available.

For the design of vertical borehole heat exchangers, values from tables and a nomogram exist which are valid for small systems (<30 kW) only. Available computer programs allow a more reliable design as they take more parameters into account. For bigger systems detailed simulation is necessary.

In general good knowledge of the underground and its thermal properties is an important requirement for a well designed plant. Only such systems have a high life expectancy, are economic from the point of view of investment and operational costs and are environmentally beneficial.

5 References

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