A THERMO-ECONOMIC ANALYSIS OF A RESIDENTIAL GROUND-SOURCE HEAT PUMP SYSTEM: ONE DEEPER VS. TWO SHALLOWER BOREHOLES

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Abstract: The preferred case when designing a ground-source heat pump (GSHP) system for a single-family house in Sweden is to drill a single borehole to the depth required for the desired energy extraction. There are however situations when the local geological, hydrological or other conditions prohibit drilling to the required depth, and therefore two shorter boreholes are drilled. This paper analyses the thermal and economic consequences of drilling two shorter boreholes instead of one deeper borehole for a typical Swedish single family house. A series of simulation-based analyses are presented; the first accounts only for the first order effects - the shorter borehole length and thermal interaction between the two boreholes. Then, second order effects – the geothermal gradient, extra horizontal piping in the case of two vertical boreholes, and different hydraulic resistances – are analyzed. The analyses look at the thermal performance of the ground heat exchangers, the resulting heat pump and circulating pump energy consumption, electrical energy costs, and different first costs due to differences in material usage, upper casing requirements and costs required for drilling and installation.

Key Words: GSHP, ground heat exchanger, borehole depth, economics

1 INTRODUCTION

About a fifth of all single-family houses in Sweden use ground source heat pumps (GSHP) for space heating and domestic hot water (DHW) production. The preferred case when designing a ground-source heat pump (GSHP) system for a single-family house in Sweden is to drill one single borehole to the depth required for the desired energy extraction. However, situations occur when the local geological, hydrological or other conditions prohibit drilling to the required depth, and therefore two shorter boreholes are drilled. Examples of such situations are fractured rock with groundwater flow, or layered hard rock and porous ground material with groundwater flow.

The performance of a borehole heat exchanger (BHEX) depends on a number of factors, of which some are affected by borehole depth, spacing and number of boreholes:

- The geothermal gradient increases the ground temperature with increasing depth, hence two shorter boreholes will have a lower average borehole temperature than one deep borehole
- The distance between two boreholes affects the amount of energy that can be extracted, due to thermal interaction between the boreholes
- Flow conditions in the collector pipes
- Pumping energy losses

The economics are affected by several factors:

- Total drilled borehole meters
- Total meters of cased borehole
- Number of well tops and bottom weights
- Trench and piping between boreholes

This paper presents an investigation of the effects on performance and economics of drilling two shorter boreholes compared to one deeper borehole for a Swedish type GSHP system for a single family house.

2 METHODOLOGY

The base case is a typical Swedish house heated by a GSHP, simulated for the case of one single borehole for heat extraction. This base case is then compared to the case of two shorter boreholes with equal energy performance as the single borehole. The boreholes are simulated for connection in series and in parallel, and the borehole spacing is varied from 3 m to 20 m. The penalty in required borehole depth is compared, and the economic effect on first cost is calculated. A comparison of energy penalty is also made for the case where the active total borehole depth for one and two boreholes are set to equal.

2.1 House Description and Energy Loads

The building used in this study is a typical Swedish single family house – a renovated 1940s-era house in Stockholm. It is a 125 sqm building with hydronic radiator panel heating. The building data is taken from the TABULA database (www.building-typology.eu). The hourly building heating loads and water heating load are estimated with the building simulation program EnergyPlus. Typical daily domestic hot water data is taken from the Swedish Energy Agency (2009).

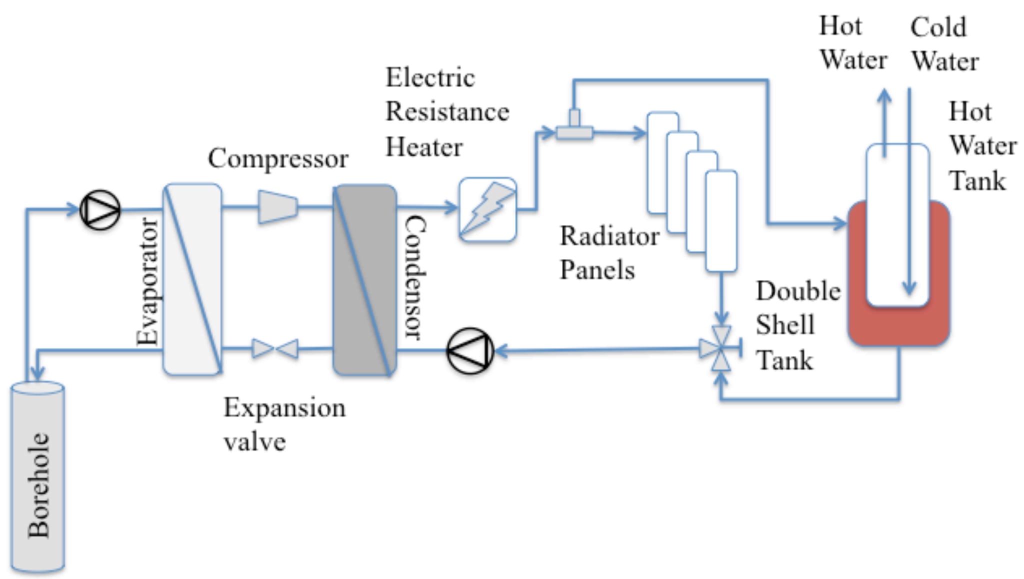

Figure 1 Ground Source Heat Pump with Integrated Hot Water Storage Tank and Electric Resistance Heater.

2.2 Heat Pump Model

The heat pump model used in this paper represents a typical Swedish residential GSHP with integrated DHW generation and storage, where there is a double walled DHW tank within the heat pump unit storing 160-200 liters of hot water. No desuperheater is used and the water is heated with hot water coming from the heat pump. The GSHP is non-reversible and provides house heating via radiators and DHW heating only. The unit gives priority to DHW heating and the control setpoint is determined by usage (i.e. house heating or DHW heating) and, for house heating, by the external air temperature. When the heat pump cannot meet the combined DHW and house heating loads, a back-up electric resistance immersion water heater is activated. The model is described in more detail by Gehlin and Spitler (2014).

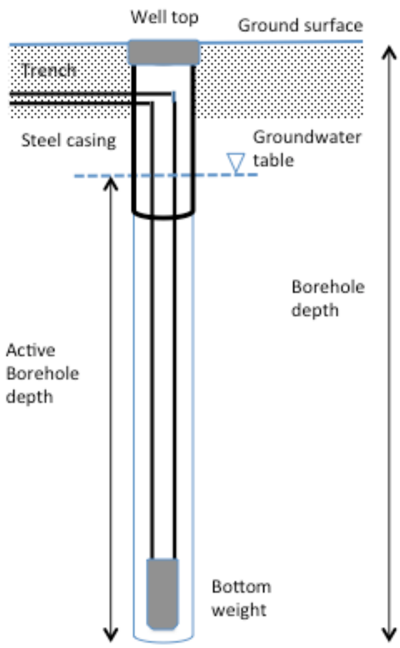

Figure 2 Ground Heat Exchanger

2.3 Ground Heat Exchanger Models

Because the study looks at the difference between a single borehole and two borehole ground heat exchangers and the amount of horizontal piping in the ground will vary between the two systems, two ground heat exchanger models – vertical and horizontal - are utilized. Both models have previously been implemented in EnergyPlus.

The vertical ground heat exchanger (Figure 2) used in this study is a typical Scandinavian un-grouted, groundwater-filled closed loop, using a single U-tube. The borehole is drilled in hard crystalline rock with high groundwater level and the U-tube is suspended in the borehole. The groundwater is protected from surface pollution by a steel casing on the upper borehole.

The vertical ground heat exchanger model used was described by Fisher, et al. (2006) and is based on the Yavuzturk and Spitler (1999) response factor model. The response factors (g-functions) were determined using the approach described by Xu and Spitler (2006). For purposes of this study, the vertical ground heat exchanger model in EnergyPlus Version 7.2 was implemented to be able to properly account for flow rates when two boreholes are connected in series; it was also modified to account for laminar flow conditions.

The thermal resistance of the groundwater filled borehole is computed by the EnergyPlus model; the grout conductance is adjusted so that under turbulent flow conditions in the U-tube the borehole resistance is 0.07 K/(W/m) (Gustafsson and Gehlin, 2008) measured in groundwater-filled boreholes. When the Reynolds number falls below 2300, a laminar convection correlation is applied. For the system in this study, this occurs when the two boreholes are connected in parallel.

The horizontal piping also serves as a small horizontal ground heat exchanger and is modeled with the Lee, et al. (2013) model originally developed and validated for foundation heat exchangers. The scheme for connecting the two models together is the same as that used by Cullin, et al. (2013) and has the same approximations: the vertical and horizontal ground heat exchangers are connected in series, but only thermally interact with each other via the fluid in the tubing.

Groundwater filled boreholes are only considered to be "active" over the length of the borehole that is below the water table; above the water table where the borehole is actually air-filled, no heat transfer is assumed to occur. For this study, we have assumed a water table depth of 5m. Therefore, there is likely to be little conductive heat transfer between the vertical and horizontal ground heat exchangers.

The ground thermal properties and undisturbed temperatures are treated separately for the two ground heat exchangers, as summarized in Table 1. The horizontal ground heat exchanger tubing is buried 0.5 m deep in the above-bedrock soil (labeled "soil" in Table 1). The horizontal ground heat exchanger model utilizes a full surface heat balance to predict ground temperatures, but the initial conditions and boundary conditions away from the tubing utilize the Kusuda and Achenbach (1965) model with the parameters determined for Stockholm using the Xing (2014) approach. The vertical ground heat exchanger uses the rock thermal properties given in Table 1. The undisturbed ground temperature is computed as the mean temperature over the active borehole length, including the effect of the geothermal gradient.

Table 1: Ground thermal properties

Rock thermal conductivity	3.5 W/m,K
Rock thermal heat capacity	2.678 MJ/m^3,K
Soil thermal conductivity	1 W/m,K
Soil thermal heat capacity	1.8 MJ/m^3,K
Ground surface temperature	8.3^{o}C
Geothermal gradient	1^{o}C/100 m

2.4 Pumping energy

The overall energy calculation is somewhat complicated by calculation of the circulating pump power. The data on which the heat pump model is based includes a nominal value for the circulating pump, which comes from the manufacturer, integrated within the heat pump cabinet. In practice, the actual flow rate would be expected to vary with the borehole depth and piping configuration (i.e. serial or parallel connection of boreholes). However, to keep the comparisons relatively simple, we have assumed that a circulating pump with 25% efficiency could be chosen for each piping configuration. We have made an estimate of the pressure losses for each configuration and the heat pump model estimates the run-time for each configuration, for each hour of the year. (The required heat pump run time varies because the capacity varies with heat pump EFT.) Taking the estimated pump power as the theoretical power divided by the efficiency, and multiplying by the total run hours for the configuration, gives the pumping energy required.

2.5 Description of Test Cases

For all test cases the first borehole is placed at 4 m distance from the building, and the trench for horizontal piping is 0.5 m deep with the pipes placed 0.5 m apart. The groundwater table, determining the inactive borehole depth, is set to 5 m, and the steel casing is 6 m, which is the minimum depth for casing according to the Swedish BHEX guidelines (SGU, 2007). The boreholes are un-grouted and groundwater filled. The horizontal piping and the BHEX piping is PEM DN32PN6 and heat carrier fluid is chosen as 30% propylene glycol mix. The simulation period is 10 years and electricity consumption is computed for the 10th year of operation.

The base case is chosen to be a single borehole with active borehole depth of 120 m, and total borehole depth of 125 m. We then investigate for the two-borehole cases firstly the energy usage if the total active borehole length is kept constant, and secondly the required depth of a two-borehole heat exchanger in order to give the same energy performance as the single borehole base case.

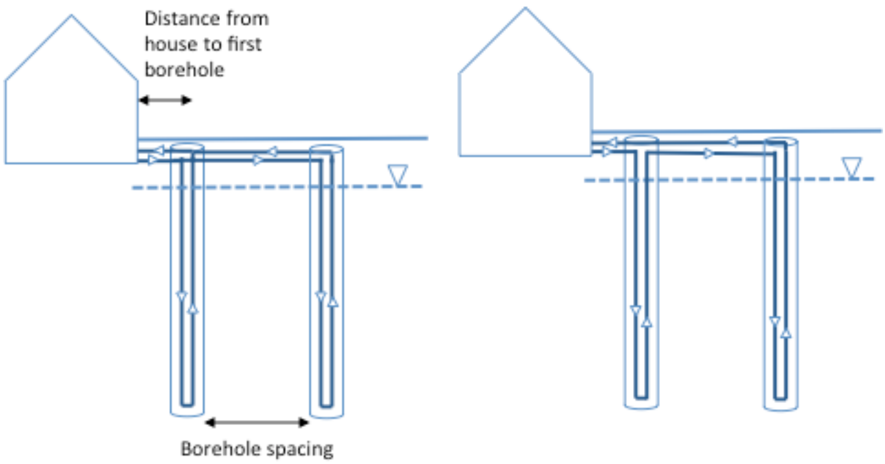

Figure 3 Parallel (left) and serial (right) borehole connection

To account for the effects of thermal interaction between the two boreholes, simulations are made for borehole spacings of 3 m, 6 m, 9 m, 12 m and 20 m. The most common design in Scandinavia when two boreholes are drilled is to connect the boreholes in series, but parallel connection may also occur. Hence simulations have been made both for serial and parallel connection. Serial connection has the advantage of maintaining turbulent flow and lower borehole thermal resistance, but has a penalty in increased pump energy losses, while parallel connection has the advantage of lower pumping energy losses but on the other hand may suffer from laminar flow and higher borehole thermal resistance.

2.6 Economic Analysis

The electricity rate is calculated as an average annual total electricity price of 0.16 USD/kWh based on data from a single-family house in the Stockholm area over a period of three years (2010-2012).
Ground heat exchanger cost is set as 33 USD/m borehole, and includes drilling and collector piping. According to Swedish guidelines for borehole heat exchangers (SGU, 2007), the uppermost part of the borehole (minimum 6 m), above hard rock must be sealed with a steel casing and secured into rock to a depth of 2 meters. The cost for drilling and casing of that part of the borehole is 121 USD/m. Each borehole is fitted with a well top and a bottom weight and the total cost of this is 314 USD/borehole. The cost for piping and digging the trench between the house and one borehole, located at a maximum of 6 meters from the building, is included in the drilling cost, but for the case of two boreholes there is an extra cost for using a caterpillar of 430 USD. This cost includes piping and digging the trench, and is not dependent on trench length. All these factors are verified by the Swedish Drillers Association as good estimates of the average costs in Sweden (Barth, 2014). The borehole

is groundwater-filled; hence there is no cost for grouting. The heat pump and installation cost for the heat pump is not included as those costs are the same for this system whether it uses one or two boreholes. Nor is the cost for installation of radiators included, as that is not specific to the ground source heat pump system.

The total cost per year over its lifetime (annualized cost) for the ground source heat pump system, c_{total}, is given by Eq. 1, where c_{el} is the electricity cost per kWh, e is the annual electrical energy used by the system, C_{syst} is the first cost of the system, a is the annuity factor, set to 5.7%:

$$c_{total} = c_{el}{}^*e + C_{first}{}^*a \quad (1)$$

3 RESULTS

Figure 4 shows the energy penalties for two boreholes with the same total active borehole length as the single-borehole base case. The energy penalty is the increase in electrical energy consumed by the two-borehole system; it depends on the borehole spacing, whether the two boreholes are connected in series or in parallel, and on whether or not the pumping energy is included in the analysis. Without including the pumping energy, the parallel connection shows significantly higher energy consumption because of the laminar flow causing higher borehole thermal resistance and, hence, lower heat pump entering fluid temperatures (EFT), leading to lower heat pump COP. However, the parallel connection also substantially reduces the pumping energy, so when that is accounted for the difference between the two options is substantially reduced. In fact, at 20 m spacing, the two systems have nearly the same small energy penalty.

The energy penalty is reduced as borehole spacing increases due to reduced thermal interaction between the boreholes and increased horizontal ground heat exchanger area. As a check of how the two influences affect the energy penalty, Table 2 shows results from three cases: the single borehole base case, the two-borehole case with 20 m spacing and 24 m of horizontal trench containing 48 meters of tubing, and a case with the horizontal trench length shortened to 0.5 m. Although easy to do in a simulation, in real life this would be equivalent to insulating the horizontal piping. But, it does allow us to see that even at 20 m spacing, the borehole thermal interaction increases the heat pump and immersion heater energy consumption by about 3.5%, while the horizontal piping reduces the energy consumption by about 2.5%.

Table 2: Effect of horizontal piping

	Single BH	**Two BH, series, 20 m spacing**	**Two BH, series, 20 m spacing**
Total horizontal trench length (m)	4	24	0.5
Total active borehole length (m)	120	120	120
Total HP + IM Htg. Elec. Energy (kWH)	11192	11585	11307
Heat pump run time hours	3804.9	3993.0	3849.4
Minimum HP EFT (°C)	-0.29	-1.71	-0.51
HP Htg. Elec. (kWh)	3672	3804	3701
HP Wtr. Htg. Elec. (kWh)	2760	2802	2774
IM Htg. Elec. (kWh)	1049	1126	1058
IM Wtr. Htg. Elec. (kWh)	3712	3853	3773

Current recommendations (SGU, 2007) in Sweden are that 20 m borehole spacing be utilized to minimize thermal interaction between two boreholes. As can be inferred from Table 2, this reduces the impact of thermal interaction to about 3.5% of the electrical energy, but also increases the favorable impact of having horizontal piping. If boreholes cannot be placed as far as 20 m apart, it is possible to drill the second borehole with an angle so that the average distance between the boreholes is increased. However, as the horizontal trench length would probably be reduced in this case, it may not have quite as significant an impact as would be expected.

It should be noted that the laminar flow in the parallel borehole connection is caused by a combination of factors that do not apply in, for example, much of North America. These factors include low ground temperatures and high heating loads leading to low fluid temperatures and high concentrations of propylene glycol; the predominance of single borehole residential systems resulting in larger diameter tubing being considered "standard". Furthermore, even the single borehole system, at low temperatures, may be in the transition region between turbulent and laminar flow. A common design strategy in Sweden since the 1980s is to size the heat pump for 55-60 % capacity coverage, which will cover 90 % of the energy demand, as introduced by (Karlsson et al. 2003). The remaining capacity demand is met by an electric resistance immersion heater. This strategy also mitigates adverse impacts of dropping into laminar flow.

Another way of looking at the impact of using two boreholes instead of one is to look at the required borehole depths that would give the same energy performance as the single borehole case. We have done that for the cases with two boreholes connected in series. Our procedure is to run simulations at several depths and to interpolate or extrapolate when we get close to the desired energy consumption. Table 3 summarizes results from the single-borehole base case and five two-borehole designs accounting for the effects of shorter borehole length and thermal interaction between the two boreholes, as well as second order effects such as the geothermal gradient, and extra horizontal piping in the case of two vertical boreholes. The table includes impact of the thermal performance of the ground heat exchangers on the resulting heat pump and immersion heater energy but excludes circulating pump energy consumption. For boreholes with short spacing the penalty in required borehole depth is considerable, but as borehole spacing approaches 20 m, required total active borehole depth converges towards the originally planned active borehole depth for a single borehole. The total drilled borehole depth, including the inactive upper borehole part above groundwater level, will however be deeper than the original single borehole.

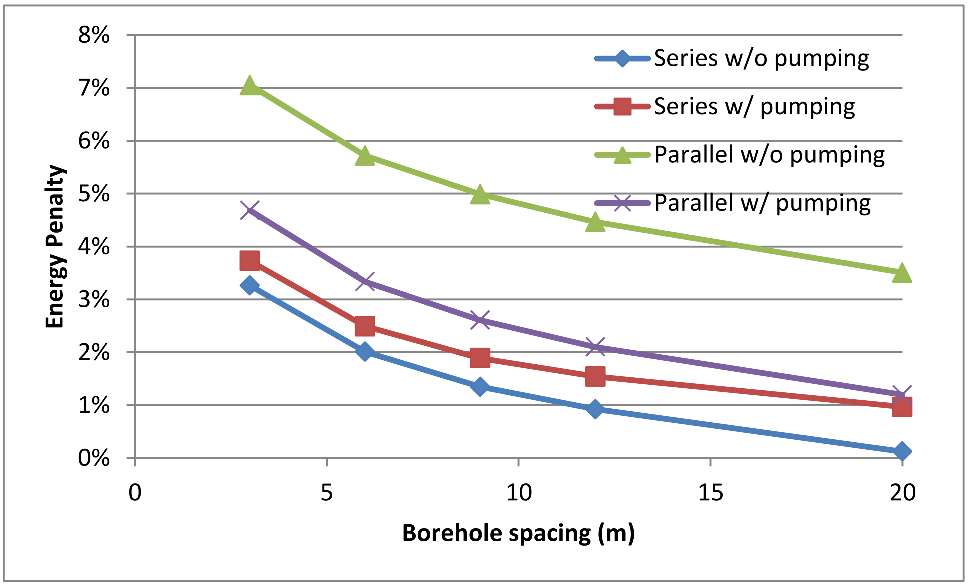

Figure 4 Energy penalty for boreholes in series and parallel

Table 3: Two borehole designs with equivalent energy performance

	Single borehole	3 m spacing	6 m spacing	9 m spacing	12 m spacing	20 m spacing
Trench Length (m)	4	7	10	13	16	24
Total borehole depth (m)	125	159.4	148	142.4	138.2	131.2
Active borehole depth (m)	120	149.4	138	132.4	128.2	121.2
Penalty Total Depth (%)	-	28	18	14	11	5
Penalty Active Depth (%)	-	25	15	10	7	0.9

Figure 5 shows annual electricity cost, well specific first cost (well tops, bottom weights, drilling and casing the first six meters, and extra costs for digging the trench for two boreholes) and first cost for drilling converted to annualized cost over the life of the system. The penalty in energy cost for not compensating for active borehole depth is relatively small compared to the penalty in first cost for extra drilling and double well specific cost. Hence, as long as the two boreholes can be placed far enough apart, the economic effect of drilling to the same total active borehole depth for two shallower boreholes instead of compensating for the loss in energy performance by drilling deeper will be small.

Figure 6 shows how the costs are impacted by using a two-borehole ground heat exchanger instead of the single borehole. The well specific component costs increase the annualized costs by about four percent. Because the well-specific costs include the first 6 m of the borehole, which are cased, the drilling costs (i.e. the costs for drilling below 6 m) are slightly lower and show up as a credit for the cases with two boreholes with 120 m of active borehole length and 130 m of total borehole length. The increase in electricity cost due to increased use of the immersion heater, as the thermal performance decreases due to thermal interaction between boreholes, is small – a mere 3% for the worst case with 3 m borehole spacing. This is to be compared with the impact on first cost for increased drilling and well specific cost for two boreholes, which is about 6.5% for the worst case.

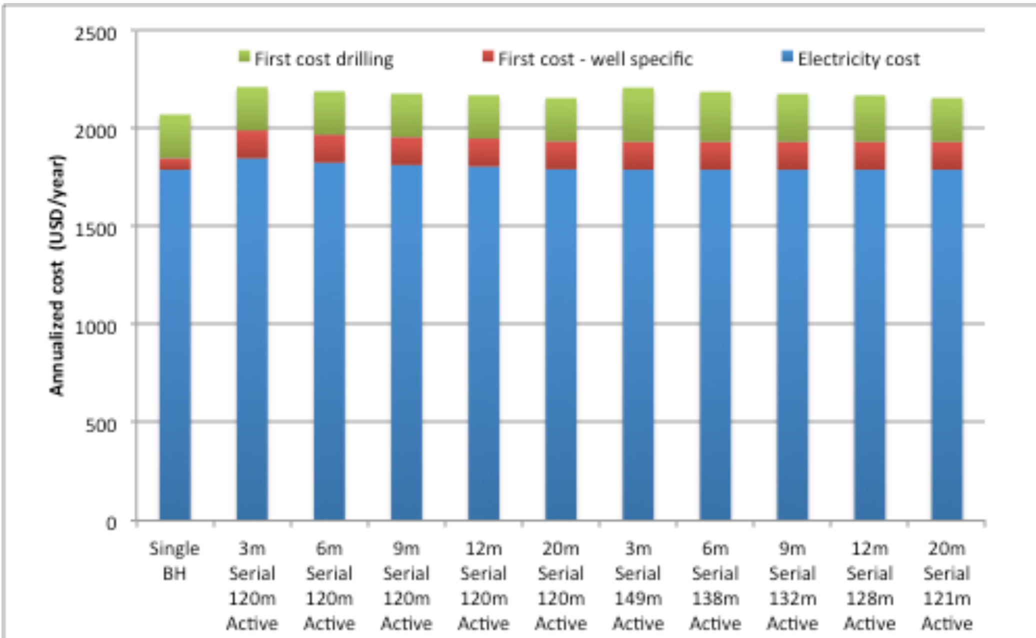

Figure 5 Cost impact of two boreholes instead of one deep (serial)

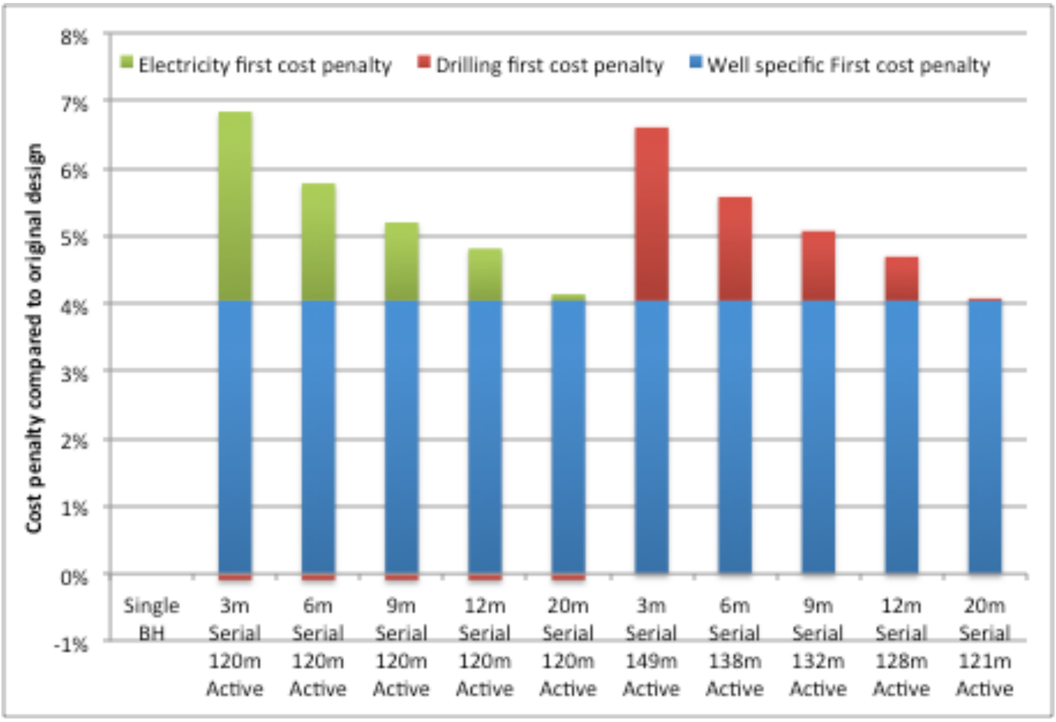

Figure 6 Cost penalty (serial)

4 CONCLUSIONS AND RECOMMENDATIONS

This paper has presented an investigation of the energy performance and cost related impacts of having to drill two shallower boreholes instead of one deep borehole to support a GSHP system for a typical 1940's era single family house in Sweden. The need to drill two shallower boreholes may arise from local geological and hydrological conditions, such as fracture zones with groundwater flow, preventing deeper drilling. From an energy performance point of view, the two boreholes should be drilled ideally 20 m apart, or at least 12 meters apart, to minimize thermal interaction, and be connected in series to prevent laminar flow. From a purely economic point of view, the boreholes could very well be drilled 3 m apart and to the same total active borehole depth as the originally planned single borehole if the available surface area precluded increased spacing. The penalty in electricity cost is insignificant in comparison to the increased first cost for drilling deeper to compensate for loss in energy performance. However, drilling two boreholes will cost at least 4% more than drilling one borehole, due to the double well-specific first costs.

In this study we have used two boreholes of equal depth; however in real life this is often not the case when the necessity of drilling two boreholes instead of one borehole occurs. We may however conclude from our results that as long as the two boreholes are placed 20 m apart, and the total active depth of the two boreholes equals the active depth of the originally planned single borehole, this will suffice.

The simulations in this study have been limited to one location in Sweden (Stockholm), typical ground thermal properties for Swedish bedrock, and a typical BHEX design for Swedish GSHPs. In fact, a number of features of this study are unique to northern Europe. Further studies for locations with other climates, ground properties, and designs, with grouted boreholes and heat injection, as well as other cost figures for electricity and drilling, would be of interest. As can be seen in this study, the results are highly dependent on pumping costs, so studies with other antifreeze mixtures and other pump sizing strategies would also be of interest.

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