ANALYSES OF GROUND-SOURCE HEAT PUMPS COMBINED WITH SOLAR COLLECTORS IN DWELLINGS

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ABSTRACT

In order to analyze different systems with combinations of solar collectors and ground source heat pumps, computer simulations have been carried out with the simulation program TRNSYS. The advantage of using solar heat was studied and compared for different systems with varied depths of the borehole for a single family dwelling in Sweden.

It was found that recharging the borehole during summertime with solar heat is not increasing the efficiency in the simulated systems, but recharging during winter time, when the load is large, is efficient for systems with undersized boreholes. For well-sized systems, the best savings of electricity is found when the solar heat is used for domestic hot water during summer and recharging the borehole during winter. Recharging of solar heat reduces the net heat extraction from the borehole, which also may be useful in areas with adjacent boreholes thermally influencing each other.

1. INTRODUCTION

A ground-source heat pump system is used in many single–family dwellings with a moderate to large heat demand and has often been installed when the old oil burner is removed. The ground-source heat pump systems save about 2/3 of the supplied energy to the building, but increase the electricity demand if the building was heated with oil before. In Sweden, the interest for the combination of ground-source heat pump and solar collectors has steadily increased in the dwelling sector during the last years. Solar heat can decrease the electricity demand and may be utilized either for heating of domestic hot water, heating the building, increasing the temperature in the evaporator in the heat pump, recharging the borehole or combinations of all. As there are many variables in these systems, the benefits of solar heat are complicated to evaluate.

In a project in Lund University, Sweden, the combination of solar collectors and ground-source heat pump has been analyzed with TRNSYS simulations in 2004 [Kjellsson 2004] and 2008 [Kjellsson et al 2008] . The aim of the simulations was to find the advantages with solar heat in these combined systems and to find the best strategies in systems design and operation. A solar collector model [Perers 2006] including condensation has been developed to cover more solar collector designs.

2. SYSTEMS AND COMPONENTS

When solar collectors are combined with a heat pump there are opportunities for improved overall efficiency. The solar collectors can produce useful energy at lower temperatures, as compared with conventional use of solar heat in dwellings, leading to better efficiency because of decreased heat losses, and increased time of operation, as the lower levels of irradiation may be utilized and the borehole can be recharged. The efficiency of the heat pump can be increased as the brine temperature to the evaporator is increased by the solar collectors. The system efficiency may be increased as the solar collectors during summertime replace the operation of the heat pump. Figure 1 shows an example of the system of solar collectors in combination with heat pump and borehole with ground heat exchanger.

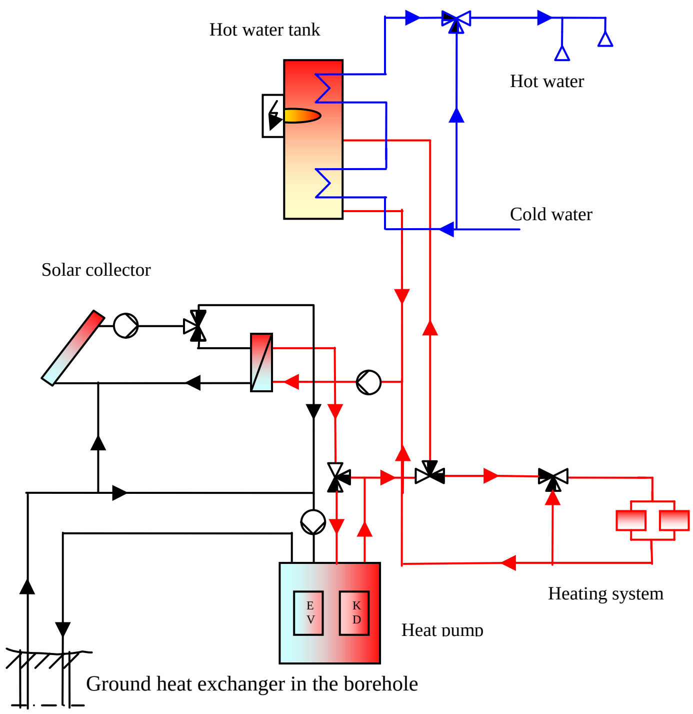

Figure 1: Example of a system with solar collectors in combination with a ground-source heat pump.

The benefits of a combination of solar collectors and ground-source heat pump are many and varied, depending on system design and system control strategy. One advantage is that the solar collectors can produce all heat to the domestic hot water during the summer, and the heat pump may be shut off. The life span of the heat pump may then be increased and the boreholes recharges naturally from the environment.

With an efficient control strategy of the solar collector system, low temperature solar heat can be used during the times when the solar collectors cannot produce sufficiently high temperature to be utilized for hot water or if there is no need for heat to the domestic hot water. The solar heat may then be used for the heating system in the building. If there is no demand in the building, or if the temperature of the solar collectors is too low even for this, the solar heat may be used to raise the temperature of the brine to the evaporator, giving the heat pump better operating conditions. Is there no heat demand in the building, or if the temperature of the solar collectors is too low, the solar heat may be used to load the borehole.

The advantages of recharging the borehole may be:

- increased fluid temperature which gives
    - possibility to use shorter boreholes or
    - possibility for a higher extraction of heat from the borehole
- reduction of the thermal influence of neighbouring boreholes with heat extraction

The reduction of the thermal influence is of special interest in densely populated dwelling areas, where a concern for long-term thermal influence between adjacent boreholes might lead to restrictions on the use of ground heat sources.

Table 1: Different possibilities of using solar heat in combination with ground-source heat pump and effects on the system.

Mode of operation	**Solar collector**	**Heat pump**	**Borehole**
1. Solar collector is used to produce or preheat domestic hot water	Heat production at “high” temperatures (>50°C), or lower for preheating	Heat pump not in operation	No heat extraction
2. Solar collector is used to produce heat for the heating system	Heat production at lower temperatures (about 20-50°C) gives increased efficiency and longer operation time	Heat pump not in operation	No heat extraction
3. Solar collector is used to increase the temperature in the brine to the evaporator in the heat pump	Heat production at lower temperatures (about 5-20°C) gives increased efficiency and longer operating time	Heat pump in operation, increased COP because of high temperature to the evaporator, which increases the heat production and decreases the operation time	Reduced heat extraction
4. Solar collector is used to produce heat for recharging of the borehole	Heat production at lower temperatures, gives increased efficiency and longer operating time	Heat pump is not in operation – no other heat demand The operation conditions for the heat pump is improved for the season	Heat injection to the borehole gives increased temperature

The solar recharge may also be used to:

- increase the evaporator temperature when the active borehole depth is undersized e.g. because of

- higher heat demand than assumed
- the ground thermal conductivity was lower than assumed
- the ground water level was lower than assumed

- counteract freezing of boreholes
- counteract thermal influence of adjacent boreholes

3. SIMULATIONS

To simulate the combined system with solar collectors and ground-source heat pump, the simulation program TRNSYS (Transient Systems Simulation Program) has been used. The first part of the simulations was performed in TRNSYS 15 during 2004 and has been reported in [Kjellsson 2004]. From these results new simulations have been conducted in TRNSYS 16.

Different systems with solar collectors were simulated and compared with a system without solar collectors and the following analyses were performed for varying depths of the borehole:

1. The coefficient of performance (COP)
2. The seasonal performance factor (SPF)
3. The monthly mean and lowest temperatures to the evaporator (including analyses of different thermal resistance in ground heat exchangers)
4. The use of electricity (including different thermal conductivity in the ground and different thermal resistance in ground heat exchangers)
5. The savings of electricity compared to without solar collectors
6. The heat extraction from the ground

The base case (system 1) is a system with a ground-source heat pump in a single family dwelling without solar collectors. The heating load was about 26 000 kWh/year and the domestic hot water demand about 3400 kWh/year, totally about 29 400 kWh/year. The parameter for the heating demand is given as the overall conductance 250 W/K.

The climate in the base case is weather data from Stockholm and a user-defined Meteonorm-file was used as the input file.

The input file for the heat pump was the data for a conventional Swedish heat pump, scaled proportionally for the different sizes. A conventional sizing should be around 7 kW (delivered heat) and simulations were conducted for 6, 7 and 8 kW respectively.

The borehole was varied between 60 and 160 m and the temperature in the borehole during operation of the heat pump was followed. In the base case no solar collector was included, and the result was compared to different systems with 10 m^2 glazed flat plate solar collectors.

In order to investigate the maximal influence of recharging the borehole, all solar heat in **system 2** was directed to the borehole by way of the heat pump..

Instead of connecting the solar collectors directly to the heat pump another possibility is to bring the solar heat directly to the borehole (**system 3**). This is often proposed by the manufacturers in order to protect the heat pump from high temperatures.

In **system 4** the solar collectors are connected to the storage tank, as a conventional solar collector system for domestic hot water. In this system the operation time of the heat pump will be reduced during summer and the borehole can be recharged naturally from the surroundings.

In **system 5** there are possibilities to use the solar heat to recharge the ground, to increase the temperature in the evaporator and for heating of the domestic hot water. The solar collector system and the borehole system are linked together in one common system. In the simulated system, the two operation modes are changed manually, so in wintertime all solar heat is used for increasing the temperature to the evaporator or recharging the borehole (operation mode 1) and in summer all solar heat is used in domestic hot water system (operation mode 2). The actual dates for changing the modes may be optimized for different systems and in the simulated cases this was found to be November to February for mode 1 and March to October for Mode 2.

In **system 6** the impact of a brine tank was studied. The solar heat was delivered to a buffer tank in order to keep up the temperature, before using it in the heat pump.

After the first simulations the result indicated that system 3 and 6 was not promising in system efficiency so the major simulations were conducted with system 1 (as base case), 2, 4 and 5 (which is the combination between 2 and 4).

4. RESULTS

The temperature from the borehole to the evaporator in the heat pump depends on the rate of extraction of heat from the borehole. The efficiency of the system is connected to the coldest monthly mean temperature to the evaporator (when the heat pump is operating) and figure 2 shows this temperature for different systems and borehole depths.

There is a minimum in the temperature depending on the depth of the borehole. When the system has a too short borehole, the auxiliary electrical heat covers the demand to a higher degree and the heat pump shuts off, which leads to increased temperatures for shorter boreholes.

System 1 - no solar heat
System 2 - all solar heat recharged to the borehole (by the heat pump)
System 4 - all solar heat to domestic hot water
System 5 – all solar heat recharging the borehole November - February, the rest of the year to the domestic hot water.

Base case: Stockholm climate, 10 m² flat plate solar collector, power of heat pump 7kW$_{th}$, about 29 400 kWh/year heat and DHW demand, result from operation year 20.

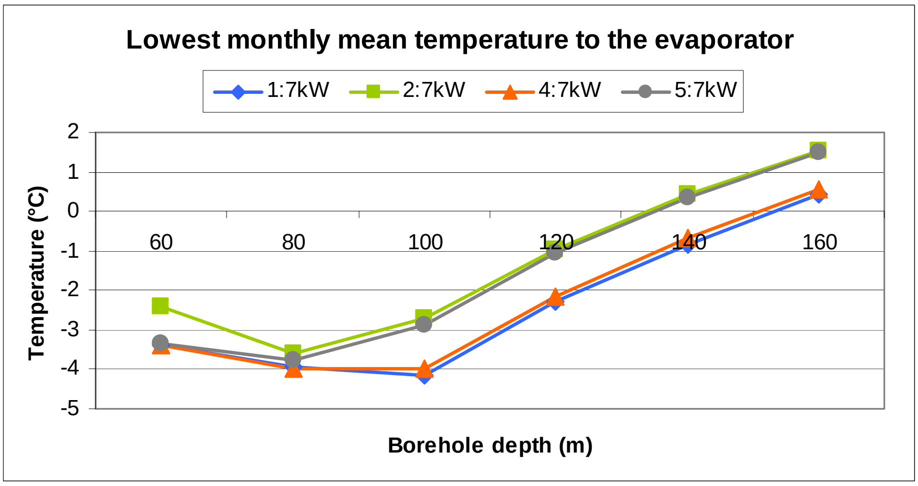

Figure 2: Lowest monthly mean temperature to the evaporator with different depth of boreholes, for four different systems for boreholes 60 – 160 m.

The highest temperatures are found in the system with all solar heat recharged, but in the system with only recharging November-February, the temperature is almost the same, except for the shortest borehole. There is hardly any difference between the systems with solar heat to the domestic hot water and no solar collectors at all.

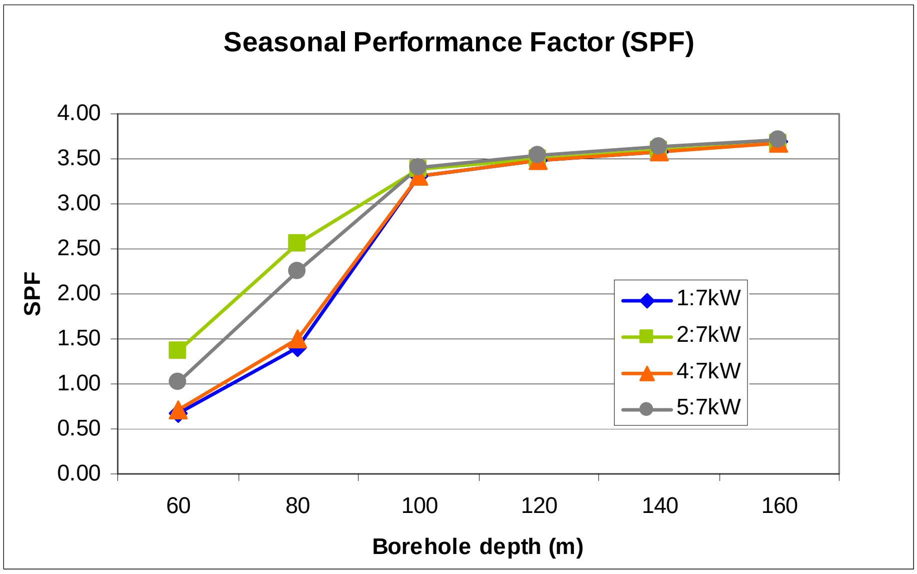

Figure 3: Seasonal performance factor (SPF) for the system including auxiliary electricity and electricity to the circulation pumps.

The Seasonal Performance Factor (SPF) for the system is defined as delivered heat from the heat pump divided by total supplied electricity (including electricity to the compressor, the auxiliary heat and to the circulation pumps), over a year. SPF is sensitive to the depth of the borehole below a critical depth, figure 3. If the borehole is too short and the auxiliary electricity is used, the SPF decreases rapidly. For a well designed system the SPF increases slightly with deeper boreholes. For the same load and solar collector area, the heat pump power is also influencing. Increased power of the heat pump gives increased demand of auxiliary heat for short boreholes compared to a heat pump with less power.

The savings of electricity with solar heat in the different systems is depending on several parameters. For system 2, with all solar heat recharging the ground, the savings are significant for shorter boreholes, but almost nothing for deeper boreholes, see figure 4. It may even be negative if the demand of electricity to the circulation pumps exceeds the benefit of the solar heat.

In system 5, with the solar heat used for domestic hot water between March and October, there are savings of electricity for all depths of the borehole. Figure 4 shows the savings for two different thermal conductivities in the ground. For short boreholes the savings are larger for a lower thermal conductivity, but for boreholes over a critical depth, the thermal conductivity does not influence the savings compared to a system without solar collectors.

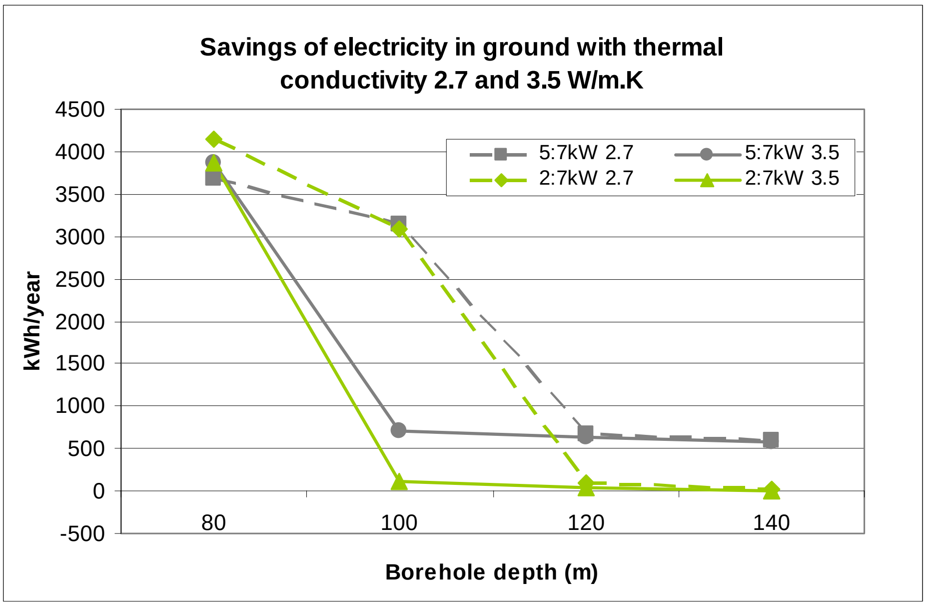

Figure 4: Savings of electricity for systems with solar heat compared to systems without solar heat for two thermal conductivities in the ground, 2.7 and 3.5 W/m,K respectively.

The net heat extracted from the borehole is defined as the extracted heat subtracted with the recharged solar heat. The net heat extracted from the borehole depends, except of the heat demand, and the performance and size of the solar collector system, also on the size of the heat pump, the borehole depth and system. It is a large difference between the systems and when all solar heat is recharged (system 2) only about half of the heat is extracted during a year, compared to the system without solar heat. This may be an important option in areas with thermal influence between adjacent boreholes. It is possible to compensate the extracted heat and the boreholes can be placed with shorter distance, see figure 5.

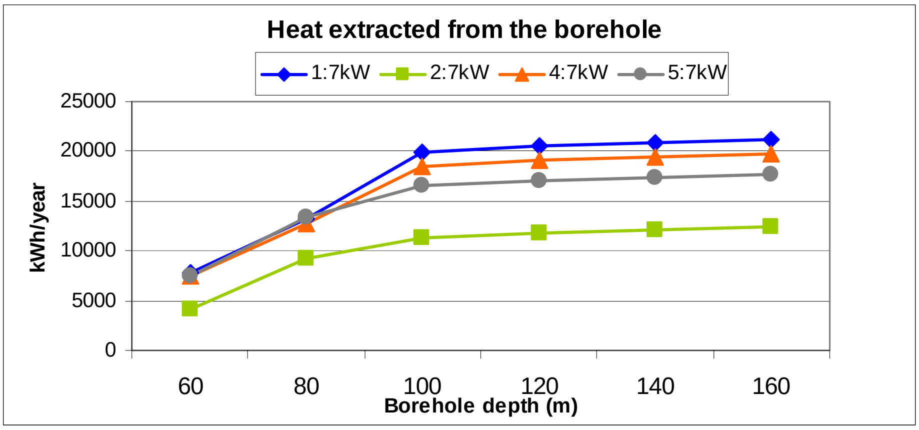

Figure 5: Heat extracted from the ground for the four systems, for boreholes depths 60 – 160 m.

5. CONCLUSIONS

The benefit of using solar heat in the system with ground-source heat pump depends on the performance of the actual system. If the boreholes are too short for the system and heat demand, the best savings of electricity is to use the solar heat during summer time for domestic hot water and during winter time for recharging the borehole. The benefit of recharging during summertime is very limited.

If the borehole is thermally influencing other boreholes and the ground is cooling down, the net heat extracted from the borehole may be reduced significantly with recharging the borehole with solar heat. It may also be possible to drill boreholes closer compared to without recharging.

The results are for single-family houses. For larger systems the value of solar heat is increased when used in seasonal storage in the ground. Investigations of larger systems were not part of the project.

ACKNOWLEDGMENT

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