

Optimization of systems with the combination of ground-source heat pump and solar collectors in dwellings

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ABSTRACT: The use of ground-source heat pumps for heating and domestic hot water in dwellings is increasing rapidly in Sweden. The heat pump extracts heat from the ground by a borehole, normally between 80-180 m deep. In order to reduce the electricity demand in the system, the combination with solar collectors is introduced. This system may be designed in many ways and the advantages differ a lot.

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.

Large differences were found between the systems. The optimal design is when the solar heat may be used directly for domestic hot water during summertime and used for recharging the borehole during wintertime. The advantage is related to the rate of heat extraction from the borehole as well as the whole design of the system. The demand of electricity may increase with solar recharging, because of the increased operating time of the circulation pumps.

Another advantage with solar heat in combination with heat pumps is when the boreholes or neighbouring installations are drilled so close that they are thermally influencing each other. This may lead to decreasing temperatures in the ground, which gives decreased performance of the heat pump and increased use of electricity. The net annual heat extraction from the ground is reduced by recharge from solar heat.

Keywords: Solar collectors, ground source heat pump, energy efficiency in buildings

1. INTRODUCTION

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 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. An example of a system is shown in figure 1. As there are many variables in these systems, they are complicated to evaluate.

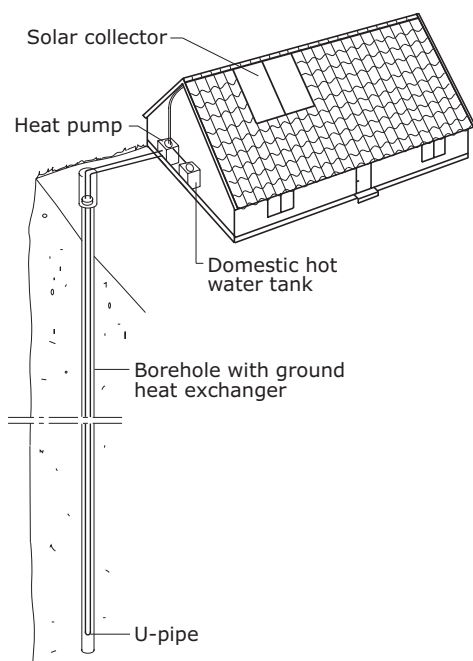


Figure 1: Single-family dwelling with solar collectors and ground-source heat pump.

In a project in Lund University, Sweden, the combination of solar collectors and ground-source heat pumps has been analyzed with TRNSYS simulations in 2004 [1] and 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 [2] including condensation has been developed to cover more solar collector designs.

2. BACKGROUND

Ground-source heat pumps, in combination with solar heat, have been tested with different system design during

the last 25 years in several countries. Experiences from 1984/85 with operation of 14 heat pump plants in Sweden, including equipment like simple solar collectors or air collectors to recharge heat into the ground, were reported. The system performance was considered to be satisfactory regarding operating time, energy performance, coefficient of performance (COP) etc. However, it was concluded to be more cost-effective to achieve a higher source temperature and thus an improvement in performance by drilling a deeper borehole. The increase of the source temperature due to recharging only reached about 2°C.

The developments since these projects were realised are that the components have improved in performance and that costs have decreased, as well as the cost for the conventional energy has increased. The control system has, by the microprocessor technique, opened new possibilities for the operation strategies and makes it possible to design and optimize systems for different applications, according to solar radiation and heat demand. The drawback is that the complexity in these systems may cause difficulties in control of the operation and optimisation.

3. COMPONENTS AND SYSTEMS

3.1 The borehole

The heat to a conventional ground-source heat pump is extracted from boreholes. For single family dwellings it is normally enough with one borehole, but for larger heat demand several boreholes can be connected. The depth of the borehole varies from 60 to 180 m. The depth depends on the heat load, the thermal conductivity and the natural temperature in the ground, the ground water level and the distance to other ground source heat pump systems etc.

In the borehole there is normally a collector consisting of a U-pipe heat exchanger with a circulating heat carrier fluid. In ground-source heat pump systems without solar collectors, the heat carrier

fluid is normally an antifreeze solution with ethanol/water. If the system is connected to solar collectors with high temperatures, this antifreeze liquid can not be used due to fire hazards and a glycol based rape oil is normally used instead. In Sweden, the borehole (outside the U-pipes) is normally filled with ground water.

3.2 The Heat Pump

The heat pump is, for single family dwellings, normally sized to cover 50-70 % of the maximum designed heat load. This means that the heat pump covers 85-95 % of the annual heat demand in the building. If the demand changes, the operation conditions for the heat pump is also changed.

Depending on the thermal characteristics of the building, auxiliary direct electric heating will normally be needed when the outdoor temperature is less than about -5°C .

The sizing of the heat pump depends on if it is included in an existing heating system or if it makes its own system. In the latter, the heat pump system also includes a hot water heater and an electric booster, which provides the auxiliary heat when the load is larger than the heat pump can provide during cold days.

3.3 The Solar Collectors

Depending on the type of solar collectors used in the system, the solar heat can be used in several ways. For unglazed solar collectors, the heat can be used either to increase the temperature to the evaporator or for recharging the borehole. The simplest way is to connect the solar collector to the return pipe from the evaporator back to the borehole.

When using glazed solar collectors, one possible system is to only use the solar collectors for domestic hot water, se figure 2. In this system, the heat pump is used for all of the heating and as auxiliary heating for the domestic hot water, when the solar collector is not able to cover the total demand. The operation time of the heat

pump decreases as the solar collector produces the hot water during the summer and the heat pump can be shut off. This gives the borehole a natural recovery and may give the heat pump a longer life time, as the summer operation with many starts and stops is reduced to a minimum.

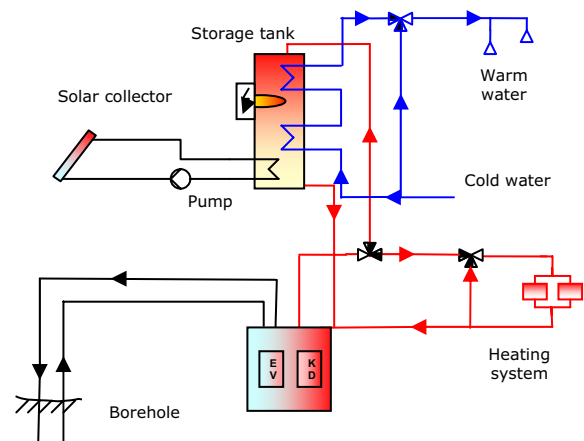


Figure 2: System with a heat pump and glazed solar collectors used for heating domestic hot water.

3.4 System with flexibility

With glazed solar collectors, the solar heat can be used also for more than heating domestic hot water. With a system as in figure 3, there are possibilities to use solar heat also to heat the building, the evaporator or the borehole.

The solar collector circuit and the borehole circuit in the system in figure 3 are linked together with an antifreeze liquid with an external heat exchanger for the water in the heating system.

The disadvantage with the combination of solar collectors and ground-source heat pump is primarily the investment costs, which increases with the complexity. Also the cost for operating the circulation pumps increases, as the operating time is extended. The conventional circulation pumps in both the solar collector circuit and the borehole circuit, have a low investment cost, but also a low efficiency. This means that the regulation of the pumps must be optimized for the overall system performance.

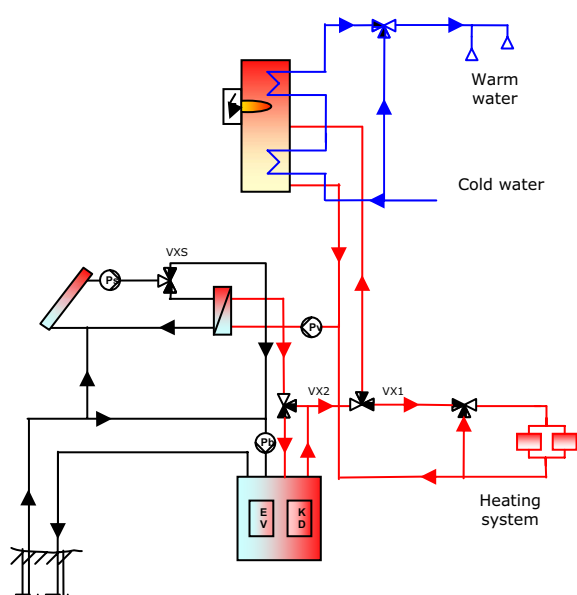


Figure 3: System with a heat pump and glazed solar collectors, with possibilities to use solar heat for heating domestic hot water, the heating system in the building, the evaporator in the heat pump or recharge the borehole.

4. 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 [1]. From these results new simulations have been conducted in TRNSYS 16 and a new report with the results will be available in 2008.

The questions at issue to analyse were for the different systems:

1. The mean and lowest temperatures to the evaporator
2. The coefficient of performance (COP) and seasonal performance factor (SPF)
3. The use of electricity
4. The savings of electricity

5. 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 area of the building is not stated – it may be a building with a high specific energy demand less than 150 m² or it may be a large, energy efficient building. 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 m² glazed 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, see also figure 2. 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 recharging the ground, to increase the temperature in the evaporator and to use it for 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 switched between 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).

5. RESULTS

5.1 Temperature to the heat pump

The temperature to the evaporator is dependent on the rate of extraction of heat from the borehole. In figure 4 shows the monthly mean temperature to the evaporator (during the time when the heat pump is in operation) for different systems, with 100 m borehole.

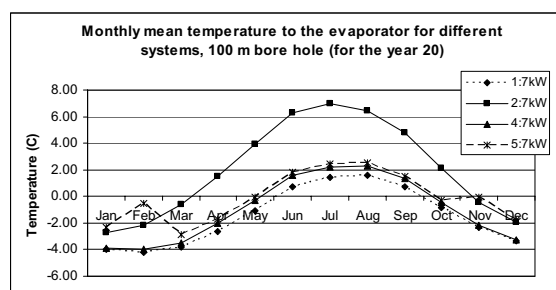


Figure 4: Monthly mean temperature to the evaporator for 100 m borehole, (heat pump power 7 kW, 10 m² solar collectors) for the operation year 20, for four different systems. System 1 - no solar heat, system 2 - all solar heat recharged to the borehole (by the heat pump), system 4 - all solar heat to domestic hot water and system 5 – all solar heat recharging the borehole November - February, the rest of the year to the domestic hot water.

The efficiency of the system is connected to the coldest temperature to the evaporator and in figure 5 the lowest monthly average temperature for different systems and borehole depths are shown.

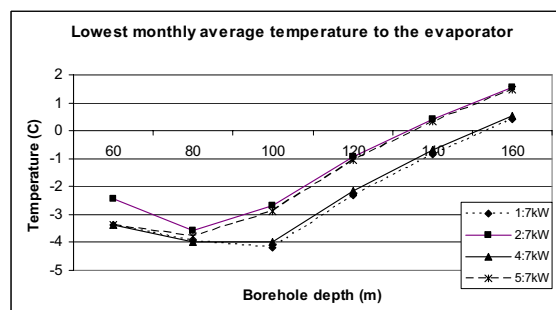


Figure 5: Lowest monthly average temperature to the evaporator with different depth of boreholes, for four different systems. System 1 - no solar heat, system 2 - all solar heat recharged to the borehole (by the heat pump), system 4 - all solar heat to domestic hot water and system 5 – all solar heat recharging the borehole November - February, the rest of the year to the domestic hot water.

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.

5.2 Coefficient of performance (COP) for the heat pump

The coefficient of performance for the heat pump (COP) is the quota between the delivered heat power from the heat pump and the supplied electricity to the heat pump compressor. In this case the COP is calculated for the whole year performance. The COP for the whole year is depending on the temperatures in the systems, the depth of the borehole and the power of the heat pump (the load and the solar collector area are fixed). All systems show the same pattern with a minimum of the COP. For shorter boreholes the COP increases when the auxiliary heater supplies energy to the system and the extraction from the boreholes decreases.

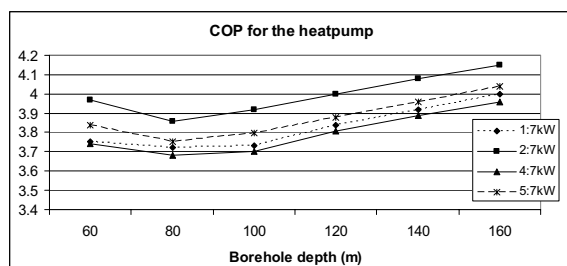


Figure 6: Coefficient of performance (COP) for the heat pump for different depth of boreholes, for four different systems. System 1 - no solar heat, system 2 - all solar heat recharged to the borehole (by the heat pump), system 4 - all solar heat to domestic hot water and system 5 - all solar heat recharging the borehole November - February, the rest of the year to the domestic hot water.

The differences between the systems are for varying depths of boreholes similar to

the differences in temperatures, in fig 5. System 2, with all solar heat to the borehole, gives the best operation condition for the heat pump and also the highest COP. Although there is only recharging of solar heat in four months during the winter, system 5 shows a higher COP compared to the other systems.

5.3 Seasonal performance factor (SPF) for the system

In the seasonal performance factor (SPF), the heat delivered from the heat pump is divided with all supplied electricity in the system. The electricity is used to the compressor in the heat pump, to the circulation pumps and to the auxiliary heat. The whole year performance is compared between the different systems.

The SPF is dependent on the use of the auxiliary heat and it decreases rapidly for short boreholes, see figure 7.

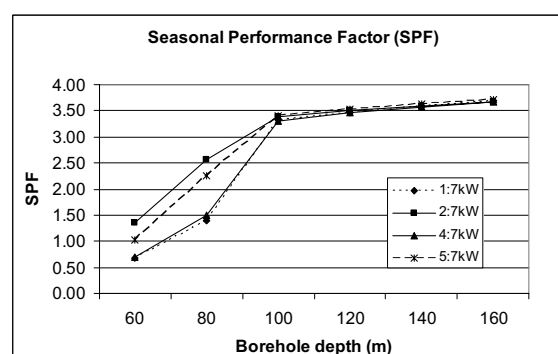


Figure 7: Seasonal performance factor (SPF) for the system including auxiliary electricity and electricity to the circulation pumps for boreholes 60 – 160 m and for the operation year 20, for four different systems with the heat load 29400 kWh/year. System 1 - no solar heat, system 2 - all solar heat recharged to the borehole (by the heat pump), system 4 - all solar heat to domestic hot water and system 5 - all solar heat recharging the borehole November - February, the rest of the year to the domestic hot water.

The seasonal performance factor (SPF) gives a better understanding for the performance of the system compared to the COP, in which the electricity to the auxiliary heat and circulation pumps is not included.

5.4 Use of electricity

Compared to a system without a heat pump, there are large savings in the use of electricity. For shorter boreholes, the savings from the solar heat are increasing, see figure 8.

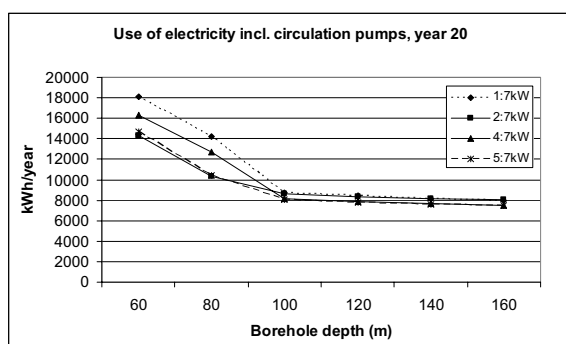


Figure 8: Use of electricity including circulation pumps for boreholes 60 – 160 m and for the operation year 20, for four different systems with the heat load 29.400 kWh/year. System 1 - no solar heat, system 2 - all solar heat recharged to the borehole (by the heat pump), system 4 - all solar heat to domestic hot water and system 5 – all solar heat recharging the borehole November - February, the rest of the year to the domestic hot water.

5.5 Savings of electricity

The savings of electricity in the different systems is depending on several parameters. The simulations are made for different systems with solar heat, different sizes of heat pumps and borehole depths and the savings are calculated as the difference for similar systems without solar heat.

For the system 2, with all solar heat to the ground by way of the heat pump, the savings are significant for shorter boreholes, but almost nothing for deeper boreholes, see figure 9.

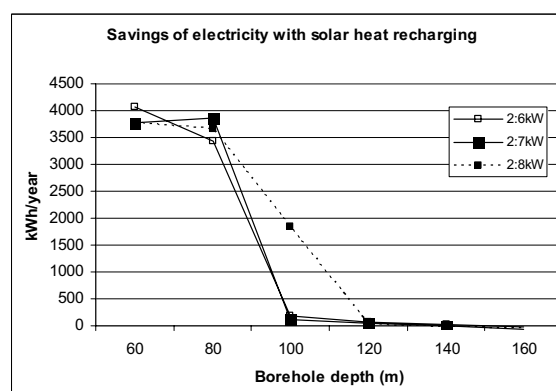


Figure 9: Savings of electricity with solar heat recharging in system 2 compared to system 1 without solar heat, for boreholes 60 – 160 m, the heat pump power 6, 7 and 8 kW and for the operation year 20. System 1 - no solar heat, system 2 - all solar heat recharged to the borehole (by the heat pump).

When comparing the savings of electricity in the system with all solar heat to the domestic hot water (system 4), with the system without solar heat, the increase for shorter boreholes is not so high, but for all boreholes there is a saving, as the solar collectors are replacing the heat pump during summertime, see figure 10.

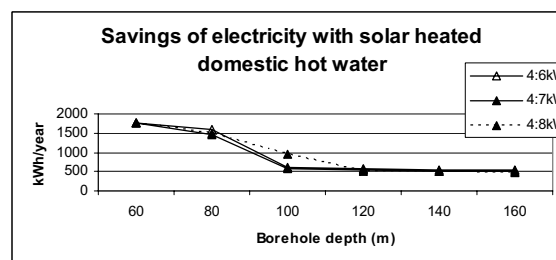


Figure 10: Savings of electricity with solar heated domestic hot water in system 4 compared to system 1 without solar heat, for boreholes 60 – 160 m, the heat pump power 6, 7 and 8 kW and for the operation year 20.

The highest savings are found in system 5, the combination of recharging and using solar heat for domestic hot water, see figure 11.

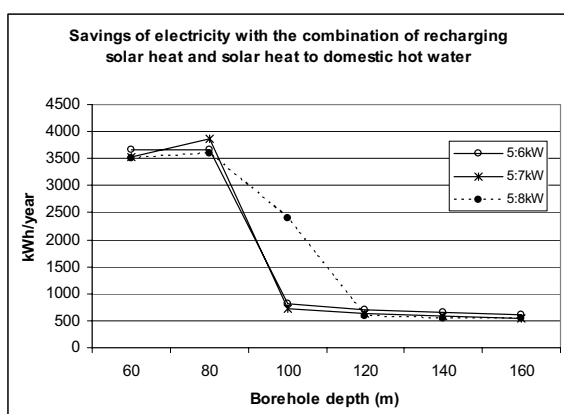


Figure 11: Savings of electricity in the combined system 5 with recharging in winter and solar heated domestic hot water in summer, compared to system 1 without solar heat, for boreholes depths 60 – 160 m, the heat pump power 6, 7 and 8 kW and for the operation year 20.

In this case the savings for system 5 for shorter boreholes are in the same order as for system 2, and for deeper boreholes like system 4.

5.6 Heat extraction from the ground

A positive effect of recharging boreholes may be utilized when neighbouring boreholes are thermally influencing. It is possible to compensate the extracted heat and the boreholes can be placed with shorter distance, see figure 12.

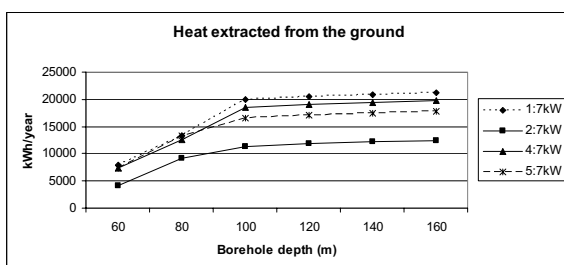


Figure 12: Heat extracted from the ground for the four systems, for boreholes depths 60 – 160 m and for the operation year 20. System 1 - no solar heat, system 2 - all solar heat recharged to the borehole (by the heat pump), system 4 - all solar heat to domestic hot water and system 5 – all solar heat

recharging the borehole November - February, the rest of the year to the domestic hot water.

6. 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 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 than without recharging.

ACKNOWLEDGMENT

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