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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 common in Sweden. The combination with solar collectors has been introduced to reduce the electricity demand in the system.

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 system alternatives. The optimal design is when solar heat produces domestic hot water during summertime and recharges the borehole during wintertime. The advantage is related to the rate of heat extraction from the borehole as well as the overall 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 thermally influence 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.

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 Fig. 1. The ground is the heat source for the heat pump and the compressor in the heat pump is using electricity to produce heat for the building and the domestic hot water. In the system the solar collectors may supply heat directly to the domestic hot water system, the building heat distribution system or supporting the heat pump in different ways. As there are many variables in these systems, they are complicated to evaluate.

In a project at 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 designs during the last 25 years in several countries. Experiences from 1984/85 with the 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 [1].

The developments since these projects were realized are that the components have improved in performance and that costs have decreased, whereas the cost for conventional energy has increased. The control system has, by the microprocessor technique, opened

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Nomenclature

COP	Coefficient of performance for the heat pump: the quota between the delivered heat power from the heat pump and the supplied electricity to the heat pump compressor (–)
Q_{auxh}	Electricity used by the auxiliary electrical heater in the heat pump (kWh)
Q_{auxs}	Electricity used by the auxiliary electrical heater in the storage tank (kWh)
Q_{gain}	Internal gains (W)
Q_{hp}	Electricity used by the compressor in the heat pump (kWh)
Q_{loss}	Conductive heat loss from the house (W)
Q_{pb}	Electricity used by the brine pump in the borehole system (kWh)
Q_{ps}	Electricity used by the circulation pump in the solar collector system (kWh)
$\sum Q_{el}$	Total use of electricity in the system (kWh)
SPF	Seasonal performance factor: the heat delivered from the heat pump divided with all supplied electricity in the system (–)
T_a	Ambient temperature (K)
T_{house}	Temperature in the house (K)
UA	Overall conductance for heat loss from the house (W/K)

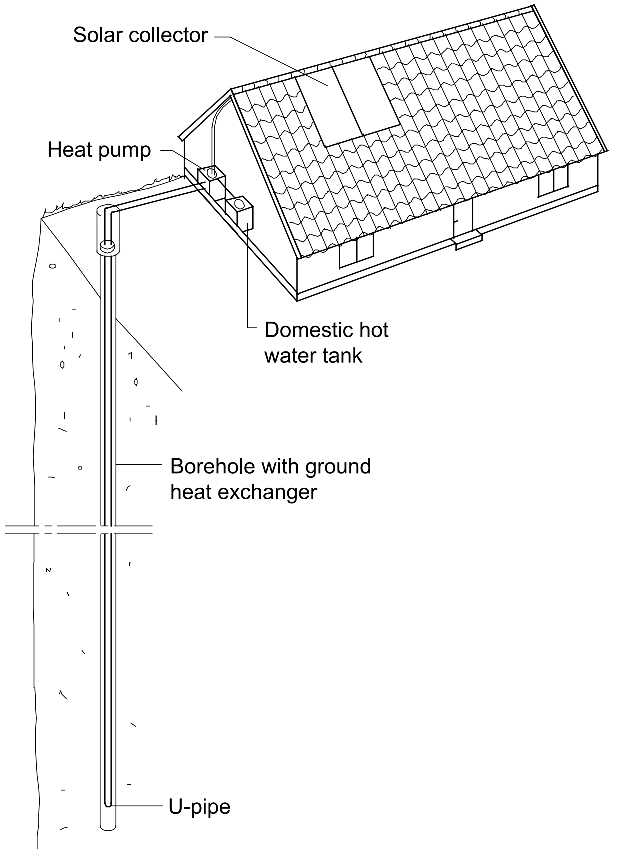

Fig. 1. Single family dwelling with solar collectors and ground-source heat pump.

new possibilities for 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 realizing optimal system design and operational control.

3. Components and systems

3.1. Borehole

Heat to a conventional ground-source heat pump is extracted from the ground via a borehole heat exchanger. For single family dwellings it is normally enough with one borehole, but for a larger heat demand several boreholes can be connected. The depth of the borehole varies from 60 to 250 m. The depth depends on the heat load, the ground thermal conductivity, 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 usually an antifreeze solution consisting of ethanol and water. If the system is connected to solar collectors with high temperatures, this antifreeze liquid cannot be used due to fire hazards and glycol based rape oil is used instead. In Sweden, the borehole (outside the U-pipes) is normally filled with ground water.

In the ground-source heat pump system, heat is removed from the ground through brine with a circulating, antifreeze solution. These closed-loop systems collect heat from the ground by horizontal or vertical piping in the ground. The antifreeze solution, which has been chilled by the heat pump's refrigeration system to a temperature below the ground-temperature, circulates through the piping, absorbing the heat from the surrounding ground.

3.2. Heat pump

The heat pump is, for single family dwellings, normally sized to cover 50–70% of the maximum designed heat load of the building. The maximum designed heat load is calculated from the mean minimum outdoor temperature at the actual place and the type of building construction (the design outdoor temperature DUT). This design 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 are also changed [1].

Depending on the thermal characteristics of the building, auxiliary direct electric heating will normally be needed during cold spells when the outdoor temperature is less than about $-5\ ^{\circ}C$.

In general, the sizing of the heat pump will depend on whether the heat pump covers part of the load (bivalent system) or the whole load (monovalent 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. 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, see Fig. 2. In

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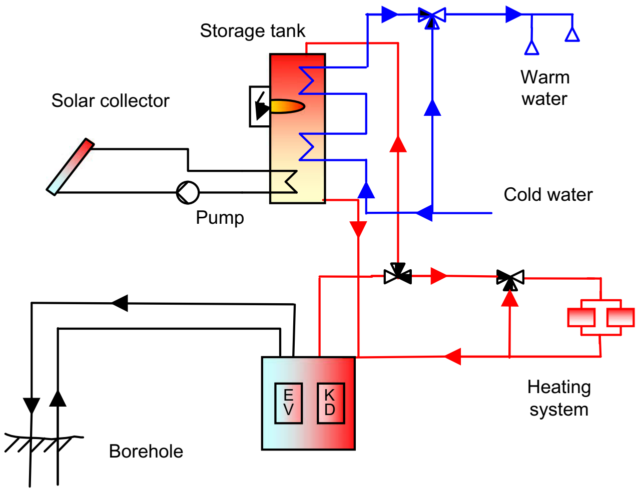

Fig. 2. System with a heat pump and glazed solar collectors used for heating domestic hot water.

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 summer and the heat pump can be shut off. This gives the borehole a natural recovery and may give the heat pump a longer lifetime, as the summer operation with many starts and stops is reduced to a minimum.

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 Fig. 3, there are possibilities to use solar heat also to heat the building, the evaporator or the borehole.

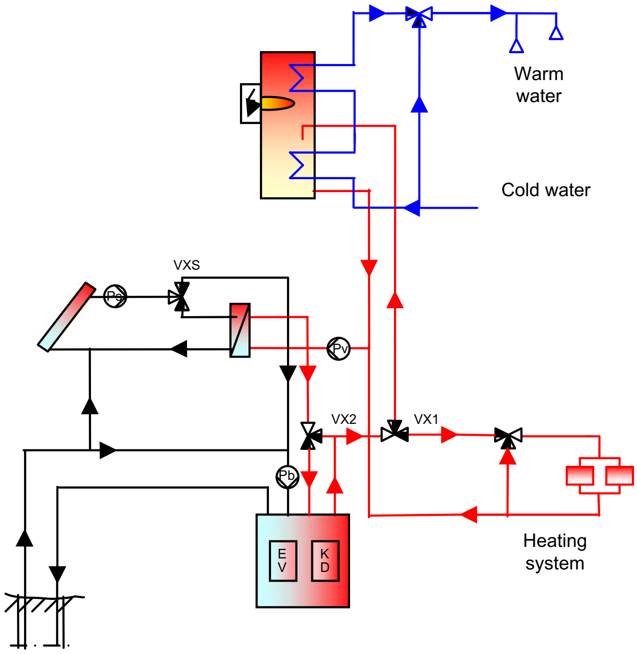

Fig. 3. System with a heat pump and solar collectors. Solar heat may be used for (1) heating of domestic hot water, (2) heating the building, (3) heating the evaporator in the heat pump or (4) to recharge the borehole.

In the heat pump, the heat from the ground is transferred to the refrigerant in the evaporator. The refrigerant boils and transfers to a low-temperature vapour, which is fed in to the compressor. Here the pressure and temperature increase. The hot vapour then passes the condenser and the heat is transferred to the heating distribution system in the building and the vapour changes to liquid phase. The pressure is still high. The liquid passes the expansion valve where the pressure and temperature are decreased. The refrigerant boils when it passes through the evaporator and the thermodynamic cycle is completed. The compressor is operated with electric energy.

The solar collector and the borehole in the system in Fig. 3 are linked together via the antifreeze liquid circuit that transfers heat to the water in the heating system via an external heat exchanger. In this system there are possibilities to use the solar heat to recharge the ground, to increase the temperature in the evaporator and to use it for domestic hot water.

In the simulated system, the two operation modes are switched manually, so in wintertime all the 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 the domestic hot water system (operation mode 2). The actual dates for changing the modes may be optimized for different systems.

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 their operating time is extended. Conventional circulation pumps used in both the solar collector circuit and the borehole circuit are relatively cheap and have a low efficiency. This means that the regulation of the pumps must be optimized for the overall system performance. When using new highly efficient circulation pumps, presently coming on the market, the conditions for this optimization will change.

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 [3]. The first part of the simulations was performed in TRNSYS 15 during 2004 and has been reported in Ref. [1]. From these results new simulations have been conducted in TRNSYS 16 and a new report with the results will be available in 2009. Theoretical analyses of the heat transfer and the heat losses in the borehole are described in Ref. [4]. The background theory is described in the referred report and the author is the same (Göran Hellström) as well as for the heart of subroutine for Type 557 as the manual “Duct ground heat storage model, Manual for computer code”.

The questions at issue to analyze 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 net 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 m^2 or it may be a large, energy efficient building. The heating demand is expressed as the overall conductance (including ventilation losses) and the value 250 W/K is used. The simulated building models a single

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lumped capacitance house compatible with temperature level control. The overall conductance for heat loss from the house is given as the input and the thermal losses are calculated by:

$$Q_{\mathrm{loss}} = \mathrm{UA} \times (T_{\mathrm{house}} - T_{\mathrm{a}}) - Q_{\mathrm{gain}} \quad [\mathrm{W}] \qquad (1)$$

Q_{loss} = conductive heat loss from the house (W),
UA = overall conductance for heat loss from the house (W/K),
T_{house} = the temperature in the house (K),
T_{a} = the ambient temperature (K),
Q_{gain} = internal gains (W).

The climate in the base case is weather data from Stockholm obtained from Meteonorm 5.0 in a user-defined format.

The input file for the heat pump is based on data for a conventional Swedish heat pump, scaled proportionally for the different sizes. Conventional sizing should be around 7 kW (delivered heat) and simulations are conducted for 6, 7 and 8 kW nominal heat output respectively.

The borehole was varied between 60 and 160 m and the temperature in the borehole during operation of the heat pump was recorded.

No solar collector was included in the base case, and the results were compared to different systems with 10 m^2 glazed solar collectors.

The flow rate in the solar collectors as well as in the borehole is 1620 kg/h in system 2. These systems are connected without a heat exchanger. In system 5, the flow rate in the solar collector system is 600 kg/h.

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 Fig. 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 recharge 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 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 the 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–February for mode 1 and March–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.

The first simulation results indicated that systems 3 and 6 were not promising in system efficiency; so further simulations were focused on system 1 (as the base case), 2, 4 and 5 (which is the combination between 2 and 4). In system 6, the configuration is fairly advanced and complicated for use in a small system, and there are no advantages compared to system 2. However, this configuration might be interesting in large systems.

5. Results

System 1 – no solar heat.
System 2 – all solar heat recharging the borehole.
System 4 – all solar heat for domestic hot water.
System 5 – all solar heat recharging the borehole in November–February, the rest of the year for domestic hot water.

Base case: Stockholm climate, 10 m^2 flat plate solar collector, power of heat pump 7 kW, about 29 400 kWh/year heat and DHW demand, result from simulation results from the 20th year of simulation.

5.1. Temperature to the heat pump

The temperature to the evaporator depends on the heat extraction rate from the borehole. Fig. 4 shows the monthly mean temperature to the evaporator (during the time when the heat pump is in operation) for different systems with a 100 m borehole.

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

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 less energy is extracted from the ground.

5.2. Coefficient of performance (COP) for the heat pump

The coefficient of performance (COP) for the heat pump 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 depends 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 extraction from the boreholes decreases.

The differences between the systems for varying depths of boreholes are similar to the differences in temperatures, in Fig. 5. System 2, with all solar heat to the borehole, gives the best

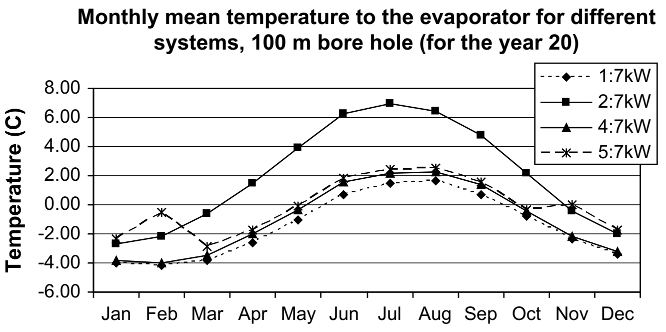

Fig. 4. Monthly mean temperature to the evaporator for a 100 m borehole (heat pump power 7 kW, 10 m^2 solar collectors).

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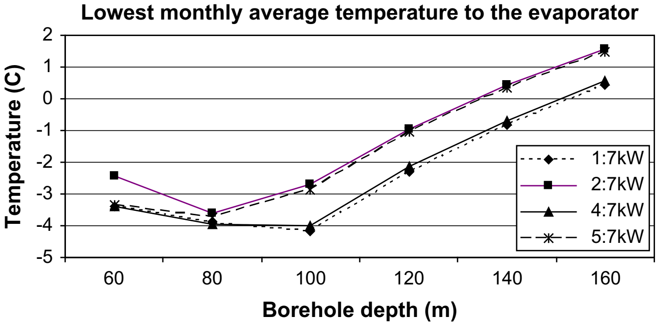

Fig. 5. Lowest monthly average temperature to the evaporator with different depths of boreholes.

operation condition for the heat pump and also the highest COP. Although there is only recharging of solar heat in four months during winter, system 5 shows a higher COP compared to the other systems without recharging (system 1 and 4) (Fig. 6).

5.3. *Seasonal performance factor (SPF) for the system*

The seasonal performance factor (SPF) is defined as the heat delivered from the heat pump divided by *all* supplied electricity in the system. The electricity is used by the compressor, the heat pump, the circulation pumps, and the auxiliary heat. The annual performance is compared between the different systems.

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

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

5.4. *Use of electricity*

The electricity used in the system is calculated in the following way:

$$\sum Q_{el} = Q_{hp} + Q_{auxh} + Q_{auxs} + Q_{pb} + Q_{ps} \quad [\text{kWh}] \tag{2}$$

$\sum Q_{el}$ = total use of electricity in the system (kWh),
Q_{hp} = electricity used by the compressor in the heat pump (kWh),
Q_{auxh} = electricity used by the auxiliary electrical heater in the heat pump (kWh),
Q_{auxs} = electricity used by the auxiliary electrical heater in the storage tank (kWh),
Q_{pb} = electricity used by the brine pump in the borehole system (kWh),
Q_{ps} = electricity used by the circulation pump in the solar collector system (kWh).

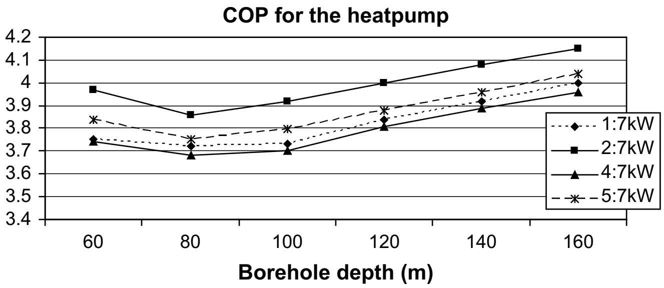

Fig. 6. Coefficient of performance (COP) for the heat pump for different depths of boreholes.

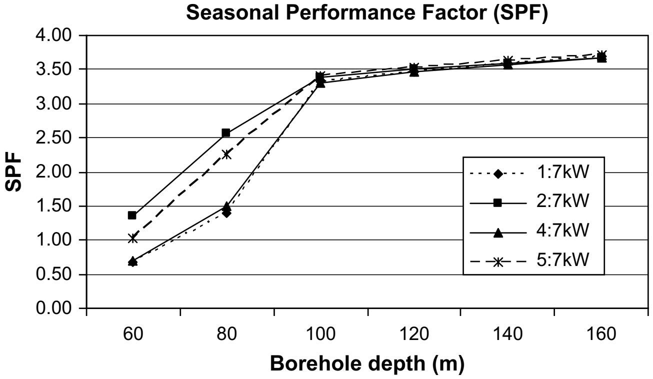

Fig. 7. Seasonal performance factor (SPF) for the system including auxiliary electricity and electricity to the circulation pumps for 60–160 m boreholes.

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

5.5. *Savings of electricity*

Savings of electricity in the different systems depend on several parameters. The simulations are performed for different systems with solar heat, different sizes of heat pumps and borehole depths. The savings are calculated as the difference in relation to similar systems without solar heat.

For system 2, with all solar heat to the ground by way of the heat pump, the savings are significant for shorter boreholes, but almost negligible for deeper boreholes, see Fig. 9.

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 (system 1), the increase for shorter boreholes is not so high. However, there are savings for all boreholes, as the solar collectors substitute the heat pump operation during summertime, see Fig. 10.

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

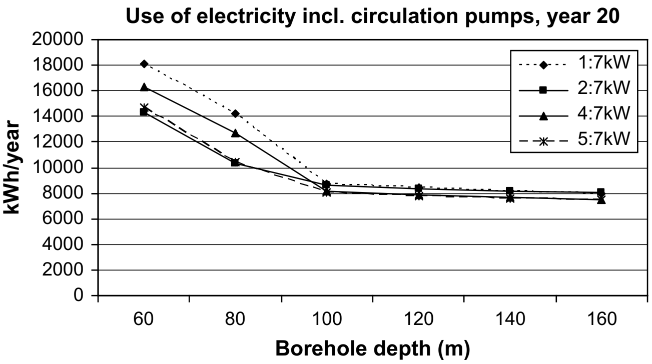

Fig. 8. Use of electricity including circulation pumps for 60–160 m boreholes.

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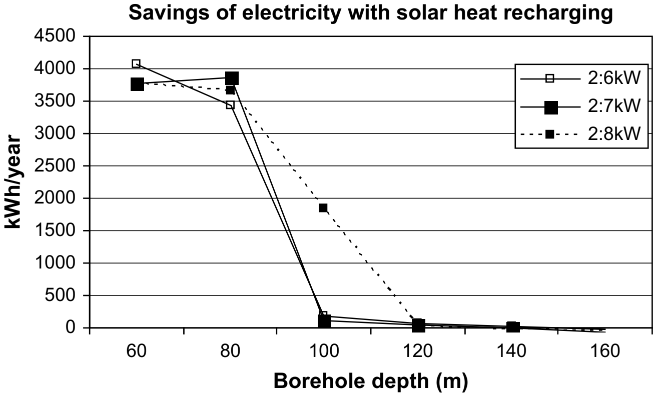

Fig. 9. Savings of electricity with solar recharging in system 2 compared to system 1 without solar heat, for 60–160 m boreholes, heat pump power 6, 7 and 8 kW.

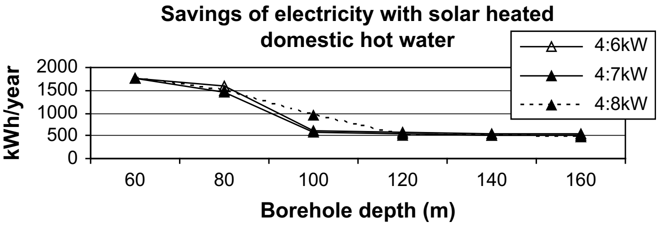

Fig. 10. Savings of electricity with solar heated domestic hot water in system 4 compared to system 1 without solar heat, for 60–160 m boreholes, heat pump power 6, 7 and 8 kW.

In this case the savings for system 5 for shorter boreholes are in the same order as for system 2. For deeper boreholes it performs similar to system 4.

5.6. Heat extraction from the ground

Recharging the boreholes may have a positive value when neighbouring boreholes are thermally influencing each other. Long-term cooling of the ground and mutual thermal influence depend only on the net heat extraction. It is possible to compensate the extracted heat and the boreholes may be placed with a closer spacing, see Fig. 12.

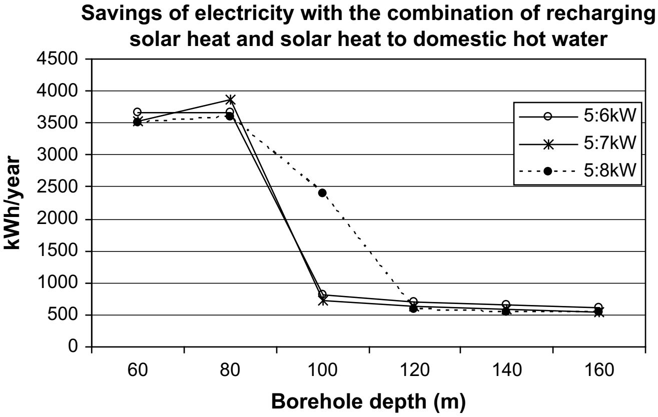

Fig. 11. Savings of electricity in the combined system 5 with recharging in winter and solar heated domestic hot water in summer, compared to system 1 without solar heat, for borehole depths 60–160 m, heat pump power 6, 7 and 8 kW.

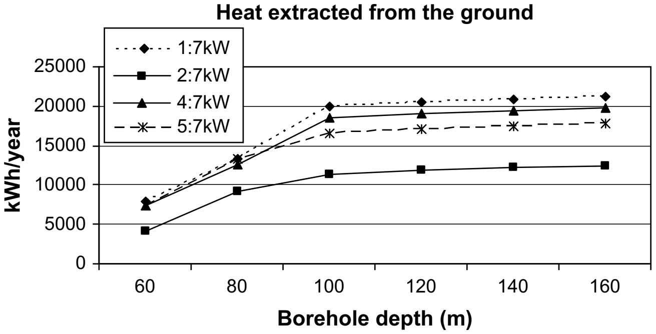

Fig. 12. Heat extracted from the ground for the four systems, for borehole depths 60–160 m.

5.7. Discussion of errors

Results from the simulations of the combined systems are dependant on a large variety of parameters. The used models of the simulated types in TRNSYS are validated and the accepted tolerance for the integration and the convergence in the simulations were both set to 0.001. In order to get comparable results between the systems, only a minimum numbers of parameters was changed between the simulations. This means that there are excellent possibilities to investigate a large number of different parameters, but when comparing with other systems, e.g. realized projects, there are uncertainties such as control systems etc., that will influence the result. However it is not possible to change the parameter of major interest, the depth of the borehole, in a realized system, but in the simulations the sensitivity to this parameter can be compared in all systems.

6. Conclusions

There are three major reasons for adding solar collectors in a ground-source heat pump system; one is to decrease the use of electricity and the others are to raise the temperature in the borehole or to decrease the net heat extraction.

If the reason is to decrease the use of electricity, the best energy saving is in a system where the solar collectors produce domestic hot water during summertime and recharge the borehole during winter. Natural recharging from the surroundings is large during summertime, when the heat demand in the building is low. If the installation is not undersized, the temperature in the borehole increases naturally during summertime and this is enough. It is more energy efficient to use solar heat during summer for domestic hot water, compared to recharging the borehole during summer. Recharging during summertime gives a higher temperature in the borehole, but it gives almost no annual savings in electricity if the system is well-sized. One reason for this is that the temperature increase is soon lost in the ground and gives more or less only advantages in close timing with the extraction. The sooner the recharged heat is used – the better. Note that even without recharge there will be an increase in the borehole temperature when the heat pump is not in operation, but when it starts the temperature immediately decreases.

During wintertime, the temperature in the borehole is much lower as the heat extraction rate is large, and normally the coldest month in the borehole is February (or early March). In November–February there is low irradiation and the solar collectors normally deliver a very small part to the domestic hot water system. The actual date for shifting the operating mode of the solar collectors may differ according to the latitude, weather conditions and

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system, but for the simulated system, the best efficiency was to change between domestic hot water and recharging respectively in November 1st and February 28th. The recharging during winter has most impact, since the temperature in the borehole is low and the heat pump is working during the worst conditions. The solar collector can produce heat at a low temperature, which is more efficient compared to the high temperatures required for domestic hot water. The advantage or savings in electricity is although dependent on the sizing of the system. If there is almost no need for auxiliary electric heat, the advantage of recharging is low.

For systems with too short boreholes, the savings in electricity may be large, especially if the solar heat can replace electricity from the auxiliary electrical heater. If the boreholes are deeper than the normal sizing, there are no savings at all with recharging. However, solar heat for domestic hot water is always replacing electricity as the operating time of the heat pump decreases irrespective of the sizing of the borehole.

If the reason to introduce solar heat in the system was due to a low temperature in the borehole, the system is probably undersized and recharging with solar heat may be very efficient. Recharging will also decrease the net extraction from the ground and the problem with long-term cooling of the ground can be diminished. The sizing of the borehole depends on the actual conditions regarding heat extraction and possible thermal influence from other boreholes. The sizing can also change during lifetime due to the enlarged load from a pool or an extension of the house. In this case solar collectors can be interesting.

One disadvantage of recharging solar heat with long operating times is the increased demand of electricity to the circulation pumps. Longer operation time may be accepted with high-efficiency pumps. The advantage is dependent on the sizing of the system, especially if the recharged heat is replacing auxiliary heat. The use of electricity to the circulation pumps can easily exceed the decreased use of electricity in the heat pump, if the circulation in the solar collector system and the borehole system is allowed to run whenever there is possible solar heat to charge in the borehole.

In single family dwellings in Sweden, the bulk of the heat demand occurs during wintertime and the performance of the system during this time is of decisive importance for the seasonal performance. When evaluating the merits of different system alternatives, it is important to compare the whole year performance and to include all the demands of electricity, especially to all circulation pumps.

The coefficient of performance (COP) for the heat pump can momentarily be very high in systems with solar heat, when the temperature to the evaporator is elevated. However, the seasonal performance factor (SPF) for the system (on an annual basis) was low in systems with undersized boreholes. Reporting COP values obtained during periods with favourable operational conditions is misleading if the overall annual system performance (SPF) is not mentioned in the same context.

As systems with ground-source coupled heat pumps and solar collectors are very complex, it is hard to give general results or design rules. If the system is well-designed regarding heat pump capacity, borehole depth, and building load and presuming all subsystems are working well, the best use of solar heat is for producing domestic hot water during summer (March–October) and recharging the borehole during winter (November–February). The optimum periods for this control strategy depend on the size of the heat load and domestic hot water.

A careful design of the system is important in order to minimize the use of electricity.

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References

[1] Kjellsson E. Solar heating in dwellings with analysis of combined solar collectors and ground-source heat pump. Report TVBH 3047, Dept. of Building Physics, Lund University, Sweden; 2004 (licentiate thesis in Swedish). Available at <www.byfy.lth.se/Publikationer/3000.htm>.

[2] Perers B. A dynamic collector model for simulation of the operation below the dewpoint in heat pump systems. Proceedings of the International Conference EuroSun 2006, Glasgow, 27–30 June 2006.

[3] Klein SA, Beckman WA, Mitchell JW, Duffie JA, Duffie NA, Freeman TL, et al. TRNSYS 16 – a transient system simulation program. Madison, USA: Solar Energy Laboratory, University of Wisconsin; June 2006.

[4] Hellström G. Ground heat storage, thermal analyses of duct storage systems, part I: theory (thesis). Dept. of Mathematical Physics, University of Lund, Box 118, S-221 00 Lund, Sweden; 1991.

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