RESIDENTIAL GROUND-SOURCE HEAT PUMP SYSTEMS –RESULTS FROM A FIELD STUDY IN SWEDEN

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ABSTRACT

The situation on the Swedish market for ground-source heat pumps is characterized by high and increasing energy prices, high sales volumes, relatively high initial costs (purchase and installation, etc.) and low life cycle cost. In order to maintain the public acceptance for the technology and to ensure a continuous positive development of the market, efficient and reliable systems are of great importance.

The main objectives of this study were to evaluate the efficiency of the GSHP systems and to record the experiences of the end users. Questionnaires were sent to 450 domestic end users who had installed GSHP-systems during the period 1996-2003. The study focused on systems designed for single family houses, reflecting the current market in Sweden and the vast majority were retrofits, where the heat pump system replaced old boilers or the similar, with vertical ground-source heat exchangers. From the questionnaire, 25 systems were inspected more in detail by means of interviews and ocular inspections. The study was concluded with measurements during 12 months, in five selected systems of different designs, age and size. The measurements incorporated data necessary to evaluate the system performance factor.

The study showed that a great majority (98 %) of the end-users were satisfied with their systems and that a relatively low number of serious malfunctions (such as compressor failures) occur. Dissatisfaction was often the result of mistakes relating to the installation rather than the system itself, or its operation. The measurements revealed an average system performance factor of 2.6 including auxiliary heating.

INTRODUCTION

Sweden has a long tradition of utilizing heat pumping technology for heating purposes, and the acceptance and interest for the technology is high in relation to most other countries as illustrated in Figure 1, showing the sales for residential Ground-Source Heat Pumps (GSHP) in Sweden during the period 1994-2009 (SVEP 2010).

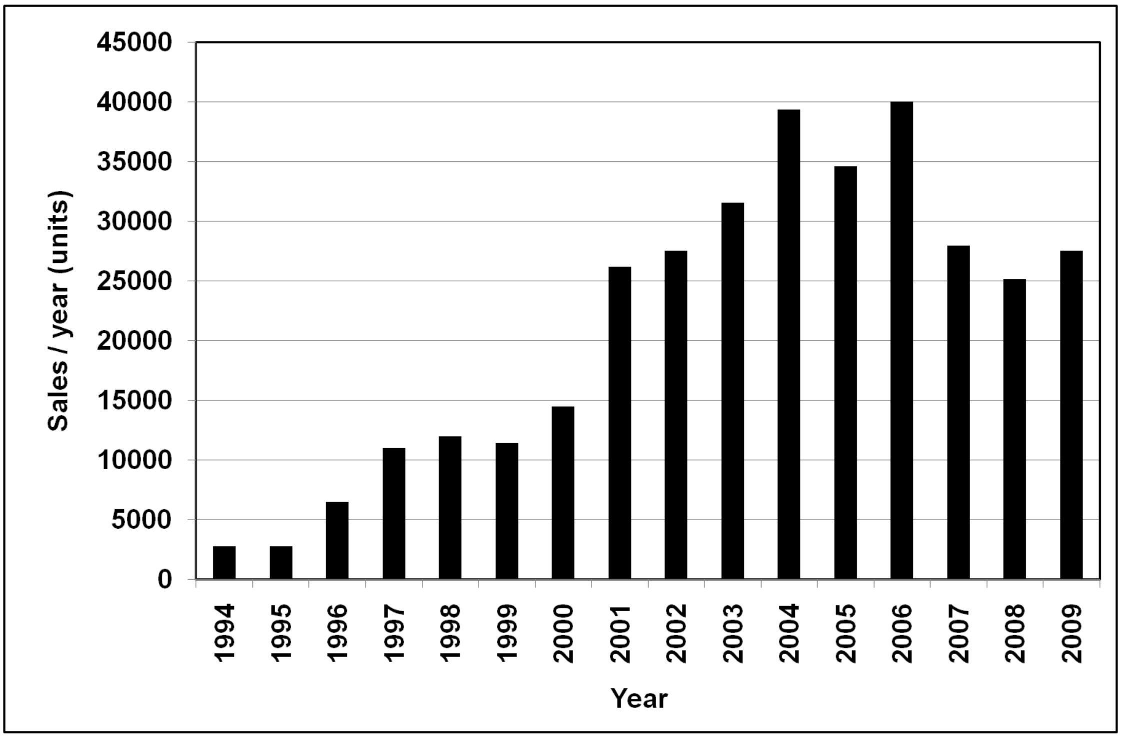

Figure 1. Sales statistics for Ground-Source Heat Pump systems in Sweden

Before the first oil-crisis in 1973, many new dwellings were equipped with oil-fuelled boilers or electrical heating systems. Since then the situation has changed. The cost of oil has increased drastically. Also the awareness amongst the public regarding the environmental issues of using oil as a heat source has increased. This has more or less deleted oil-fuelled boilers from the Swedish residential heating market. In addition, the electricity price has steadily increased, almost doubled during the period 1996-2007, according to the branch- and interest organisation of electrical producers etc. “Svensk energi” (Home Page). Thus, although the heat pump business in Sweden has had some seasonal ups and downs, an increase of sales numbers is clearly visible during the period 1998 – 2006 as shown in Figure 1, due to retrofitting, replacing oil-fuelled boilers. The decrease in sales numbers during 2005 was partly due to the fact that a new governmental subsidy, for conversion from direct-electric heating systems to hydronic distribution systems connected to heat pumps, was announced to come into force in 2006, why a large number of consumers chose to wait with their investment. During the year 2006 alone, about 40 000 new residential ground-source heat pumps were installed in Sweden. The means for the subsidy were available during 2006 and part of 2007. After 2006, the sales have returned to more “normal” numbers, taking into account that a large share of the old oil-fuelled boilers by that time had been replaced, and also bearing in mind the economic world situation since late 2008. According to the Swedish Heat Pump Association more than 85 % of oil-fuelled boilers are replaced. On the whole, the heat pump market in Sweden can be regarded as a mature market and the Swedish manufacturers of GSHP are successful.

At the same time, there is a serious lack in objective knowledge and information regarding the efficiency, experience of end users, etc., of GSHP-systems in “real” applications on a long term basis. Due to this, SP was requested by the Swedish consumer Agency and the Swedish Energy Agency to perform a field study with focus on residential GSHP-systems. The study was initiated in 2003 and ended two years later.

The study included an enquiry to 450 end-users of GSHP as well as a field study in which 25 systems were studied and their owners interviewed more in detail. The main objectives were to record experiences of the end-users, to identify problems in order to enable future improvements to GSHP systems and to gather reliable information about present systems. The investigation was concluded with measurements during twelve months on five selected systems. The main objective of the measurements was to determine the seasonal efficiency of the systems.

ENQUIRY AND FIELD STUDY

1.1 Participants

The send-out included randomly selected systems spread across Sweden, from the far north to the most southern parts. The geographical location was important since climatic and geological conditions vary substantially across Sweden. The undisturbed ground temperature, as an example, varies between 2°C and 8°C, according to Rosén et al. (2001), between different areas, which naturally may influence the system, depending on the adaptation of the system to the differing boundary conditions. Further, in order to avoid systems not reflecting the current technological situation, the years of installation was mainly selected to be later than 1998, since Sweden enforced stricter regulations regarding refrigerants, i.e., a refill stop of CFC's was enforced during 1998 (Axell et al. 2005). In addition, other prerequisites with possible relation to the selection of send-out addressees were carefully evaluated in order to gain an overview perspective of the viability of the technology. About 251 end-users, corresponding to 56 % of the sendout, decided to participate in the enquiry. The questionnaire dealt with questions such as system design, experience from the operation and the purchasing process, etc.

Not surprisingly, the main market for residential GSHP was found to be the retrofit buildings, often constructed before 1980 and equipped with old boilers in need of refurbishing or change, reflecting the current market in Sweden. About 98 % of the participants belonged to this category. The motives for the choice of GSHP varied, but the two most common motives were a desire to lower the energy cost and to increase the comfort, besides the need to exchange a malfunctioning or ineffective boiler.

The vast majority of the small residential GSHP-systems in Sweden were found to be alternating heat pumps for the production of space heating and domestic hot water heating. The distribution systems were, most often, hydronic radiator systems. Before 1980, Swedish radiator systems used high temperatures, typically 80/60, which means that the supply- and return temperatures were 80°C and 60°C, respectively, at the Design Outdoor Temperature (DOT). In 1984, new building regulations were issued by the former governmental department "Statens planverk" (1980) where, in order to decrease the energy use, it was prescribed that hydronic heating systems must not be designed such that the supply temperature at the DOT exceeds 55°C. However, since the old radiator systems built before the new regulations most often were quite over-sized they could generally easily be converted for use at lower supply temperatures, without any problems occurring regarding heating capacity.

The heat source was generally a single closed-loop vertical Geothermal Heat Exchanger (GHX) constructed in crystalline bed-rock, with a single plastics U-type GHX with ground water as heat transfer medium between the bedrock and the collector. Back-filling with grout or the similar is almost nonexistent in Sweden.

1.2 Experiences of end-users

Overall, the study showed that the end-users were satisfied with their systems, in the sense that their expectations and motives for the investment had been fulfilled. About 9 out of 10 participants claimed that they were satisfied and that they had noticed decrease in energy costs, and/or that the comfort had been improved. The minority that was not satisfied motivated this with reasons that in most cases could be traced back to the installation process, and especially to the dimensioning of the system. One example was unsatisfactory savings in relation to what was estimated before the installation, usually depending on mistakes during the dimensioning. The most common mistake was underestimation of the heating demand of the house. Another complaint was poor service during installation and/or service. The complaints on the heat pump itself, however, were very few among the unsatisfied participants.

In Sweden, the most common way to purchase a GSHP system is to make an all-in contract with a company that takes care of all necessary actions to get the system running, according to the study. These contractors are often collaborate with certain heat pump retailers of certain heat pump brands. In this respect neighbours, friends and working colleagues ,together with personal experience of the consumers, play an important role in the choice of contractor, and thus to the choice of heat pump system. Also the price matters, but not at all to the same extent.

The number of serious malfunctions (such as compressor failures) was relatively low. Only 2 % of the participants reported this. Somewhat more often occurring problems were failures of circulation pumps, electronic circuit boards, etc. About 4 % of the participants claimed that the number of repairs and/or the service in conjunction with these were unacceptable. However, the major problem was disturbing noise from the heat pump and/or from the heating system. Among the participants, 18 % claimed that they were disturbed by this, while the percentage of those who claimed any problems at all were about 30 %. Due to the subjective nature of the problem it is hard to distinguish common distinctive features of the systems causing the problem. However, noise emission from a compressor driven heat pump can never be deleted completely, since it contains moving parts. But there are means of reducing the magnitude of the noise: sufficient acoustic insulation in the heat pump; correct location of the heat pump in the facility; flexible connections between the heat pump and the distribution system; shunted temperature control of the supply to the distribution system to avoid thermal tensions, etc.

Another issue that was indicated by the study was leakage of antifreeze heat carrier fluid (i.e., brine) after the installation. However, the question in the enquiry regarding this matter was somewhat ambiguous, why the actual magnitude of the possible problem could not be defined, since leakage can be indicated in this manner only by the necessity of repetitive refilling, since release of air trapped in the brine circuit, etc., often necessitates a refill after start-up. However, refilling of the systems on a repetitive basis occurred in a few cases, as shown by the interviews, but to which extent and where in the system leakage occurred (from the underground collector pipe, from the connections or the tubes between the house and the bore, or from the piping indoors) could not be established by the investigation. The most commonly used brine for residential GSHP-systems is denaturised ethyl alcohol solutions. These are not poisonous, except in high concentrations, and they are biodegradable, but the denaturisation-agent might, if introduced to a ground-water aquifer and during certain conditions and ways, render a freshwater source unusable. However, further research into the issue of brine-leakage is necessary in order to give definitive answers.

SEASONAL MEASUREMENTS

The measurements were initiated in November 2003 and ended the same month in 2004. The system boundaries used during the measurements are schematically described in Figure 2.

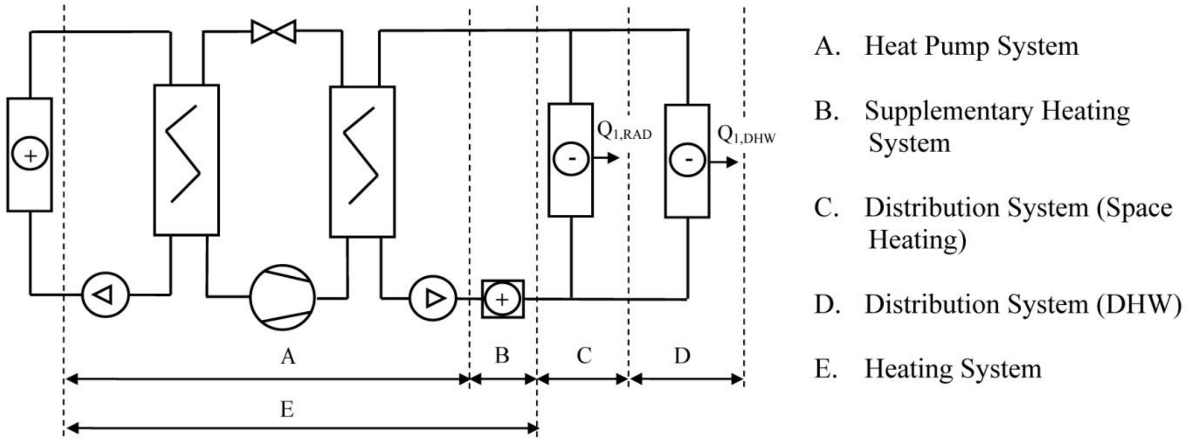

Figure 2. Definitions of system boundaries used during the measurements

The measured quantities were primarily

- Supplied electric energy to the heating system (W_{hs}).
- Supplied electric energy to the supplementary heating system (W_{sh}).
- Delivered thermal energy to the distribution system ($Q_{1,rad}$).
- Domestic hot water use in the form of thermal energy ($Q_{1,dhw}$).

The measuring equipment was monitored by the system owners on a weekly basis and reported to SP every month. The collected data were mainly used to determine the seasonal efficiency of the systems. In this respect, the Seasonal Performance Factor (SPF_{hs}), defined as in eq. (1), and the Seasonal Performance Factor, (SPF_{hps}) defined as in eq. (2), was calculated. The latter is an indicator of the performance of the heat pump system (see Figure 2) whilst the System Factor (SPF_{hs}) describes the efficiencyof the entire system.

However, the main bulk of the Swedish GSHP's are not dimensioned to cover the entire heat power demand of the building at DOT, why a supplementary heater is necessary. The amount of supplementary heating will affect the System Factor drastically. In order to visualize the effect from supplementary heating, the Energy Coverage Factor (ECF), defined as in eq. (3), was calculated.

$$SPF_{hs} = \frac{Q_{1,rad} + Q_{1,dhw}}{W_{hs}} = \frac{Q_{1,hps} + Q_{1,sh}}{W_{hps} + W_{sh}} = \frac{Q_{1,hps} + W_{sh}\,\eta_{sh}}{W_{hps} + W_{sh}} \qquad (1)$$

$$SPF_{hps} = \frac{Q_{1,rad} + Q_{1,dhw} - Q_{1,sh}}{W_{hs} - W_{sh}} \qquad (2)$$

$$ECF = \frac{Q_{1,rad} + Q_{1,dhw} - Q_{1,sh}}{Q_{1,rad} + Q_{1,dhw}} \qquad (3)$$

1.3 Systems

Table 1 gives a short description of the systems and houses incorporated in the measurements.

Table 1. Data of the systems included in the measurements

System	Units	A	B	C	D	E
Construction year of the building	---	1971	1972	1969/1970	~1950-1960	1955
Estimated energy demand[1]	MWh	29.4	36.5	20.3	40.6	32.5
Year of installation	---	2003	1999[2]	1998	2003	2002
Approx. first cost of inst.	€	14 400	18 700	10 200	18 900	15 400
Type of distribution system	---	Radiators	Radiators	Radiators	Radiators	Radiators
Nominal Capacity of Heat Pump[3]	kW	6.6	10.9[4]	6.6	10.5	7.1
Nominal Capacity (supplementary heater)	kW	6 (Electrical)	23.3 (Oil boiler)	6 (Electrical)	9 (Electrical)	9 (Electrical)
Total bore depth of GHX	m	n. d.	181	100	200	141
Active bore depth of GHXv	m	130	168	92	170	139
Type of DHW-heater	---	Separate unit, double cased storage tank	Electrical heater, cold water preheated in boiler	Double cased storage tank	Separate unit, double cased storage tank	Double cased storage tank

1. Used as input to the dimensioning calculation
2. The heat pump system was replaced in 2002
3. Operating condition: Brine inlet 0°C; Heating water outlet 50°C
4. Operating condition: Brine inlet 0°C; Heating water outlet 45°C

The systems were of different brands, system designs, ages and sizes. All the systems produced both domestic hot water and space heating, and were installed during the period 1998-2003. The heat source was single closed-loop vertical heat exchangers. The heat pumps operated with curve control where the return or supply temperature from/to the distribution system correlated to the actual outdoor temperature. The heat pumps altered between domestic hot water heating and space heating by reversing valves that shifted the flow such that it flowed through the domestic hot water heaters only (double-cased storage heaters) or through the distribution system only (radiator systems). The heat pumps operated with floating condensation, meaning that the condensation temperature followed the changes in heat demand due to differing operation modes and heat loads. One exception from the general design was system “B” in which all heat was delivered to a tank, i.e., an old oil-boiler, in which the entering fresh water was pre-heated before entering an electrical water heater in which the temperature was boosted to desired levels. DHW and space heating was thus produced simultaneously by the heat pump to a certain extent. The boiler also acted as supplementary heater for space heating.

1.4 Results

Table 2 presents a summary of measured and calculated results.

Table 2. Measured and calculated results

System	A	B	C	D	E
$Q_{1,hs}$	23.4	28.2	17.5	42.3	37.2
$Q_{1,dhw}$	4.01	1.92	1.05	1.38	1.77
$Q_{1,sh}$	1.69	1.26	0.04	1.48	4.12
W_{hs}	10.1	11.9	7.3	15.3	16.0
W_{sh}	1.78	1.33	0.04	1.55	4.34
SPF_{hs}	2.7	2.5	2.5	2.9	2.4
SPF_{hps}	3.1	2.7	2.5	3.1	3.0
$SPF_{hs,summer}$	2.2	1.6	2.3	2.7	3.0
$SPF_{hs,winter}$	2.8	2.6	2.6	2.9	2.4
ECF	94	96	100	97	90

The results revealed an average SPF_{hs} of 2.6, ranging between 2.4 - 2.9 for the five systems A-E. The corresponding SPF_{hps} was found to end up in the range of 2.5 - 3.1.

The results clearly visualized the effect from supplementary heating, although this was not the only influencing factor, but probably the most important. Thus, the results were also to a large extent due to the dimensioning values. Systems C and E serve as good examples to that even small change in ECF will render noticeable improvements in SPF_{hs}. Even though the ECF was 90 % for system E the decline in SPF_{hs} was 20 %, which should be compared to the case if no supplementary heating would have been used. System C had a poor SPF_{hps}, but since almost no supplementary heat was used the SPF_{hs} was not bad in relation to the other systems.

Besides the obvious factors affecting the performance and efficiency of the systems, such as efficiency of the heat pump, dimensioning etc. also the “nature” of the heating demand, i.e., the relative proportion between the space heating and the domestic hot water demand, will influence SPF_{hs}. To illustrate the difference in SPF_{hs} due to the nature of the heating demand, the SPF_{hs} was calculated during the heating season (September-April) and during the summer season (May-August) respectively.

DISCUSSION

The heat pump efficiency, the Coefficient of Performance (COP), is often stated at a certain operating condition (often the most beneficial condition for the heat pump) in advertisements and similar, which often is understood as synonymous to the efficiency of the complete heating system on a seasonal basis by the consumers, and, in some cases, unfortunately also by the contractors. In addition, the definition of the used COP, i.e., how the COP is defined and under which operating condition the COP is valid, varies between manufacturers. This is quite confusing for consumers, but sometimes also for contractors performing the dimensioning calculation, which was revealed by the study.

The interpretation that the seasonal performance of a heat pump on a seasonal basis may be evaluated at one (or two) operating conditions is, however, quite far from the truth. The performance of a heat pump during a season will vary significantly, since the operating conditions, such as heat source temperature, supply temperature to the space heating distribution system, etc., varies during the year, which in turn affects the heat pump. For the Heating System the difference would be even greater, mainly due to use of supplementary heating. To make a successful dimensioning it is therefore necessary for the contractor performing the calculations to have access to reliable data of the performance at a number of different operating conditions, in order to make an accurate calculation. Such calculations should be conducted by use of test results measured by accredited laboratories in order to obtain as reliable results as possible, and therefore as good performance as possible of the heating plant.

Also it is necessary to evaluate GSHP systems using a “system approach “and not to focus on the key component only, in this case the heat pump. No heat pump, regardless of how well it performs, will be effective when operating in a system for which it is not suited. The optimisation of the heat pump with respect to the heat source, the type of distribution system for space heating, the heating demand, etc., is the most influencing factor on the performance of the heating system. However, it is naturally also very important to use the best technology, i.e., the most efficient heat pump/heating system/distribution system, etc., in order to achieve high efficiency of the system. The “best technology”, in this respect, means the most suited system for each specific application to gain as high energy savings as possible to as low cost as possible.

The traditional Swedish ground-source heat pump design is generally not as efficient at heating and storing domestic hot water as it is during space heating operation, since the domestic hot water demand, in the traditional market, is quite small relative to the heating demand for space heating. This can be seen by comparing $SPF_{hs,summer}$ to $SPF_{hs,winter}$ for systems A-D (Table 2). System E is an exception, resulting from a much lower ECF and thus higher amount of supplementary heating than the other systems during the heating season, due to an undersized heat pump system relative to the heating demand. The $SPF_{hs,summer}$ for system B is not completely comparable to the others, since the heat pump was turned off during parts of the summer, why the full heating demand was covered by the electrical DHW heater. A general trend, however, is that the domestic hot water demand in newer buildings will correspond to a much larger proportion than traditionally, why the domestic hot water heating performance of the heating system will gain in importance for the efficiency of the heating systems in the future.

CONCLUSIONS

In Sweden the market for GSHP’s, which at present almost exclusively is the retrofit market, has had a relatively long period to develop and to improve. This was clearly depicted by the results, since about 90 % of the participants were satisfied with their heating system. Very few complaints were aimed at the heat pump itself, but rather at issues that could be traced back to the installation process, such as unrealistic dimensioning and insufficient service during installation. Disturbing noise, however, was an exception reported by about 18 % of the participants in the enquiry, and 30 % of the participants who had claimed any problems at all. In the future, however, a higher focus on the performance of the DHW heater should be necessary, in order to maintain the success.

According to this study, a typical SPF_{hs} in the middle parts of Sweden should lie somewhere around 2.4-2.9 for a GSHP. The SPF_{hps} should end up in the range 2.5-3.1, which on average corresponds to a decrease in seasonal performance by approximately 11 % due to the supplementary heating system. When installing a GSHP system the main issue to consider is the dimensioning of the system (i.e., optimisation between the heat pump and the application, heating demand, heat source etc) since this will have a main influence on the end result. Necessary prerequisites in order to obtain this is reliable input data from the consumer for the calculations, and reliable data regarding the heat pump performance. The contractor performing the dimensioning, and often also the installation and start-up of the system, therefore has a great responsibility for the end result, which naturally requires competence. The study has revealed some deficits regarding competence.

NOMENCLATURE

COP	Coefficient of Performance	(-)
DHW	Domestic Hot Water	---
ECF	Energy Coverage Factor	(%)
GHX	Ground Source Heat Exchanger	(-)
GSHP	Ground Source Heat Pump	(-)
SPF_{hps}	System Performance Factor	(-)
SPF_{hs}	System Factor	(-)
$Q_{1,dhw}$	Domestic hot water energy supply	(MWh/year)
$Q_{1,hps}$	Thermal energy supplied to the space heating distribution system by the heat pump system	(MWh/year)
$Q_{1,hs}$	Thermal energy supplied by the heating system to the space heating distribution system.	(MWh/year)
$Q_{1,rad}$	Thermal energy supplied to the radiator system	(MWh/year)
$Q_{1,sh}$	Thermal energy supplied system by the supplementary heater	(MWh/year)
W_{hps}	Electrical energy input to the heat pump system	(MWh/year)
W_{hs}	Electrical energy input to the heating system	(MWh/year)
W_{sh}	Electrical energy input to the supplementary heating system	(MWh/year)

Subscripts

Summer	Summer season
Winter	Heating season

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