FIELD MEASUREMENTS OF GROUND SOURCE HEAT PUMP SYSTEMS INSTALLED IN EXISTING SINGLE FAMILY HOUSES

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Abstract:
Field measurements are ongoing, for a period of two years, of the performance of twenty heat pump systems used for space heating and tap water heating in single-family houses. The heat pumps were installed during 2003 - 2007, replacing either oil or electrical heating in houses built between 1940 and 1980. The primary objective is to obtain knowledge about the heat pump efficiency, SPF, energy savings and CO_2 reductions. It is also interesting to elucidate the difference in efficiency between the old heat pumps in this study and those modern heat pumps of best available technique measured in the Swedish contribution to IEA HPP Annex 37. The results in this field study correspond well to results from SCOP-calculations based on laboratory tests performed 2005 in SP's laboratory according to EN14511. The results from Annex 37 and laboratory tests performed 2012 show an evolution forward and modern heat pumps are more energy efficient. The total heat supplied differs considerably between households. The heat pump technology saves purchased energy and reduces CO_2 emissions compared with the replaced heating system. In most cases, the energy savings are between 60 and 70%, and in a few cases between 50 and 60%. The corresponding figures for the good examples in Annex 37 are 67-75%.

Key Words: heat pumps, field measurements, SPF, compressor, efficiency

1 INTRODUCTION

European Parliament and European Council Directive 2009/28/EC (the RES Directive) on the increased use of renewable energy aims at increasing the use of renewable energy within the European Union in a resource-efficient manner. This implies advancing the development of new energy and cost-effective technologies. As a result of the RES Directive, the use of heat pumps (HP) to provide space and water heating has increased, and it has also become increasingly common to combine heat pumps with solar heating (IEA HPP Annex 38/SHC Task44). According to IEA HPP, heat pumps can reduce global CO_2 emissions by almost 8 % by using renewable energy as a source for heating (IEA 2008). Heat pumps have also a huge potential for energy savings but, in order to raise their acceptance, there is a need to be able to demonstrate this potential for energy savings and CO_2 reduction with heat pump technology. There is also a need for greater knowledge of the efficiency of heat pumps in real installations, especially concerning heat pump systems for combined operation, including heating and domestic hot water production. The operational performance of heat pumps (COP) is often given as that measured under steady-state operating conditions and at full capacity (i.e. as defined in EN 14511 1-4 (EN 14511 2008). These conditions do not always reflect the performance of heat pumps operating in real heating systems, where they often operate at part load in different climate conditions. The efficiency of a heat pump system is influenced by how the heat pump is connected to the system, by the system design and by the operating temperature of the heating system. This means that the design of the heat pump system, and the quality of the installation, will influence the final efficiency of the system. When evaluating field measurements, it is therefore relevant to quantify heat pump performance in terms of its seasonal performance factor (SPF). It is most important to provide information on which electrical components, and what other forms of useful energy were supplied to the building that are included when calculating SPF. This field study includes measurements of twenty heat pump systems used for space heating (SH) and domestic hot water (DHW) heating in single-family houses. The measurements are on-going and the monitoring period will be two years. The primary objective is to obtain knowledge about the heat pump efficiency, SPF, electricity consumption, energy savings and CO2 reductions. A further objective is to explain why the efficiency differs between different heat pump systems, and to find the reason for variations between different months. It is also interesting to elucidate the difference in efficiency between the heat pumps in this study and those measured in the Swedish contribution to IEA HPP Annex 37, where good examples are demonstrated (Tiljander et al. 2011). On behalf of the Swedish Energy Agency, SP performed SCOP-calculations according to EN14825 based on laboratory tests according to EN14511 during 2005, and these test results can be compared with the results in this field study since the heat pumps in this field test are produced at the same year or some years earlier.

2 IMPLEMENTATION

The field study includes ground source heat pumps from manufacturers in Sweden, of different brands and sizes. All heat pump systems are used for space heating and domestic hot water. The heat pumps were installed during 2003 - 2007, replacing either oil or electrical heating in houses built between 1940 and 1980. All the houses have different size and construction. There are houses with one or two levels in this study and some houses have basement. The heated area varies between 90 and 310 m^2. The capacity of the heat pumps varies between 7 and 12 kW. Half of the households containing two persons and half contains more than two persons. The field measurements started in May 2012 and will be finished in June 2014. The collected data are used to determine the seasonal efficiency of the systems.
All sites are located in the south of Sweden, at 15 different places in an area extending 60 kilometres west and 40 kilometres north from Borås. Table 1 shows monthly and yearly average ambient air temperatures for some representative locations. The temperatures in table 1 are based on measurements during the period 1996-2006 (Meteonorm).

Table 1: Average outdoor temperatures (^oC) for five locations in the field study (Meteonorm)

	Skepplanda	Gothenburg	Alingsås	Herrljunga	Borås
Jan	0,2	0,0	-0,2	-0,8	-1,1
Feb	0,2	0,1	-0,1	-0,6	-0,9
Mar	1,5	1,5	1,3	1,0	0,8
Apr	6,2	6,3	6,1	5,7	5,7
May	10,7	10,7	10,6	10,4	10,3
June	14,1	14,1	14,0	13,9	13,6
July	16,6	16,5	16,5	16,3	16,0
Aug	16,8	16,8	16,7	16,4	16,2
Sep	13,1	12,9	12,8	12,3	11,9
Oct	8,4	8,1	8,0	7,4	7,0
Nov	4,2	3,9	3,8	3,2	2,8
Dec	0,9	0,4	0,5	-0,2	-0,5
Year	**7,7**	**7,6**	**7,5**	**7,1**	**6,8**

2.1 Measurements

The measurements were started on the 1st of May 2012 and will be concluded on the 30st of June 2014. The measured quantities were:

- Heat for space heating (kWh).
- Heat for domestic hot water measured before DHW tank (i.e. including standby losses) (kWh).
- Total electrical energy supplied to the HP-system (kWh). All electrical components (compressor, control system, heat source circulation pump, heat sink circulation pump and back-up heater) are included.
- Indoor and outdoor temperatures (^oC).

On the 1st of June 2013, additional meters for separately measuring of the electric energy supplied to the back-up heater (kWh) were installed.

The measurements were carried out as equally as possible at the different sites, but the location of measuring points differed somewhat due to different system designs. The heat meters were installed in the liquid circuits and their temperature sensors were placed in thermowells. The measured values were logged twice an hour, and the logged data were manually collected every fourth month.

2.1.1 Measurement equipment

Table 2 is a compilation of the measurement equipment used in the study.

Table 2: Measurement equipment used in the field study

Quantity	Type of meter	Product	Measurement uncertainty[1]	Resolution display	Resolution logger
Heat	Ultrsonic energy meter with two Pt100 sensors	Kamstrup Multical 402	±2% at normal conditions	0,01 kWh	0,1 kwh
Electric energy	Electricity meter 3-phase	ABB ODIN 4165	±2%	1 kWh	0,01kWh
Indoor temperature (alternative 1)	Internally mounted thermistor	INTAB Tinytag Ultra2	±0.45 K	--	0.01^oC
Indoor temperature (alternative 2)	Internally mounted thermistor	Testo 174T	±0,5 K	0.1 ^oC	0.01 ^oC
Outdoor temperature	Internally mounted thermistor	INTAB Tinytag Ultra2	±0.7 K	--	0.01 ^oC
Logging of pulses (heat meter)	Pulse counter for external circuit	INTAB Tinytag Plus Re-ed G-75	Lowest pulselength 150 s	--	0-255 pulses per interval (1s-240h)
Logging of pulses (electric energy meter)	Pulse counter for external circuit	Comet S7021	Lowest pulselength 1ms	1 pulse	0-61695 pulses per interval (1s-24h)

2.1.2 Measurement uncertainty

The uncertainty of the measured values has been estimated at better than the following (with a 95% confidence interval:

Heat for DHW (including stand by power)	± 10%
Heat to space heating	± 9% but not better than 43 kWh / week
Indoor temperature	± 0.5^{o}C
Outdoor temperature	± 1.0^{o}C
Electric Energy	± 2%
SPF	± 11%

Small temperature differences contribute largely to the high uncertainty of the heat measurements. The heat sink pump is on all time, even when there is no need for space heating. At these operating conditions, the temperature difference in the water system for space heat is near 0 and a small error in temperature measurements implies a relatively high error in heat measurements. Heat for DHW is complicated to measure since the temperature increase rapidly and the temperature meters have longer response time. In some sites there is a flow in the domestic hot water circuit when the compressor is off and in these cases the measurement uncertainty is due to a small temperature difference.

2.2 Evaluation

In this work, measured data from the first year of the field study have been evaluated by calculations of both monthly and seasonal performance factors (SPF). Specific heating demand and specific electric energy demand were calculated on yearly basis. Also energy savings compared to heating with electric boiler and reduction of CO_2 emissions compared to oil heating and electric heating have been calculated.

The amount of renewable energy is estimated as the difference between the heat supplied for space heating and domestic hot water production, and the total electrical energy used.

2.2.1 Performance factor

The performance factor is influenced by the definition of system boundaries. It is most important to describe what electrical equipment is included and what is not included within these boundaries. When calculating performance factors in this study, system boundary 4 as defined in the EU – project SEPEMO-build (2010) was used. I.e. all electrical components in the heat pump system are included and SPF is calculated according to Equation 1.

$$\mathrm{SPF} = \frac{Q_{H\_hp} + Q_{W\_hp} + Q_{HW\_bu}}{E_{S_{pump}} + E_{HW\_hp} + E_{HW\_bu} + E_{B_{pump}}} = \frac{Q_{Tot}}{E_{Tot}} \quad (1)$$

2.2.2 Specific energy demand

The specific energy demands for heating and for operating the system are calculated according to SEPEMO (2012) with Equatuion 2 and Equation 3.

$$\mathrm{SHD} = \text{specific heating demand} = \frac{\text{usable energy}}{\text{heated area}} = \frac{Q_{Tot}}{\text{heated area}} \quad (2)$$

$$\mathrm{SEED} = \text{specific electric energy demand} = \frac{\text{Final energy}}{\text{heataed area}} = \frac{E_{Tot}}{\text{heated area}} \quad (3)$$

2.2.3 Energy savings

The energy saving (ES) when using a heat pump compared with using an electric boiler is defined as the difference between the heat supplied for space and domestic hot water heating, and the electrical energy used (Equation 4).

$$\mathrm{ES} = \mathrm{Q_{Tot}} - \mathrm{E_{Tot}} \tag{4}$$

2.2.4 Reduction of carbon dioxide emissions

The reduction of CO_2-emissions has been calculated by using the CO_2 – coefficient, K, according to Equation 5 (SEPEMO build 2011). The CO_2 – coefficient includes also the equivalent emissions from other greenhouse gas emissions.

$$COR = \text{Final energy x K} \tag{5}$$

Reduction of CO_2 emissions was evaluated by comparing the heat pump systems with electric boiler and oil heating. These two conventional heating systems were chosen for comparison since the heat pumps in this study replaced either electrical boilers or oil heating. They used to be the most common heating systems in Sweden before pellets and heat pumps where implemented on the market. Gas heating is not common in Sweden.

Comparison with electric boiler: The reduction in CO_2 emissions is assumed to correspond to the energy savings between heating with electric boiler and heating by heat pump, for which the savings can be calculated with Equation 4. Two different types of electricity production have been compared: the Swedish mix and coal condensing power The CO_2 – emission coefficients are assumed to be 36,4 g /kWh), and 968 g /kWh (Gode et.al. 2011).

Comparison with oil heating: The reduction in CO_2-emissions is assumed to correspond to the difference in emissions from oil heating and the emissions due to electrical energy production. Here, too, the Swedish mix and coal-fired cold condensing power have been used in the calculations. The reduction of greenhouse emissions can be calculated with Equation 6. K for oil heating is assumed to be 288 g /kWh (Gode et.al. 2011) and the annual efficiency is 0.86. It is worth noting that this figure is only taking the emissions from combustion in account. The emissions due to production of electric energy for heat carrier circulation pump are not included. This implies that the comparison will not be quite accurate since the circulation pump energy is included in the heat pump system.

$$COR_{oil} = \left(\mathrm{Q_{H_{hp}}} + \mathrm{Q_{W_{hp}}}\right) \mathrm{x\ xAE_{oil}} - \mathrm{E_{Tot}\ x\ K_{el}} \tag{6}$$

3 RESULTS

In this paper results from the period the 1th of May 2012 to the 30st of April 2013 are presented. System boundary 4 according to the SEPEMO-project (2010) is used for the evaluation.

All sites, in this study delivered an even, comfortable indoor temperature that, with one exception, is between 20,5 ^{o}C and 23,5 ^{o}C for the different households. The need for space heating starts at outdoor temperatures between 15 ^{o}C and 17 ^{o}C, depending on the construction of the building. There is one exception, a household that prefer an indoor temperature of 19 ^{o}C and in this case the need for space heating starts at an outdoor temperature of 12 ^{o}C. This study shows that a low indoor temperature reduce the need of space heat. Site d is an example where the weekly average indoor temperature was changed during the measuring period. Table 3 shows the average indoor temperature and the need of space heat during five different weeks when the average outdoor temperature was near 0 ^{o}C.

Table 3: Average out- and indoor temperatures and need of space heat for five different weeks

Outdoor temperature (^{o}C)	Indoor temperature (^{0}C)	Space Heat (kWh)
0,3	12,8	562
-0,9	12,8	857
0,4	13,6	747
-0,6	16,5	1119
-0,1	17,8	1114

3.1 Supplied Heat, electric energy demand and performance factor

Figure 1 presents the total supplied heat and the purchased electrical energy together with SPF. The chart shows results from the first year for the different sites. The need of supplied heat varies considerably and some households need twice as much heat as the household with the lowest heat demand. The differences are due to building construction, user behavior, installation of heat pump etc. Generally, small buildings have a larger specific heating demand than large buildings. Table 4 shows the specific heating demand (SHD) and the specific electric energy demand (SEED) for both the smallest and the largest buildings in the study (three of each).

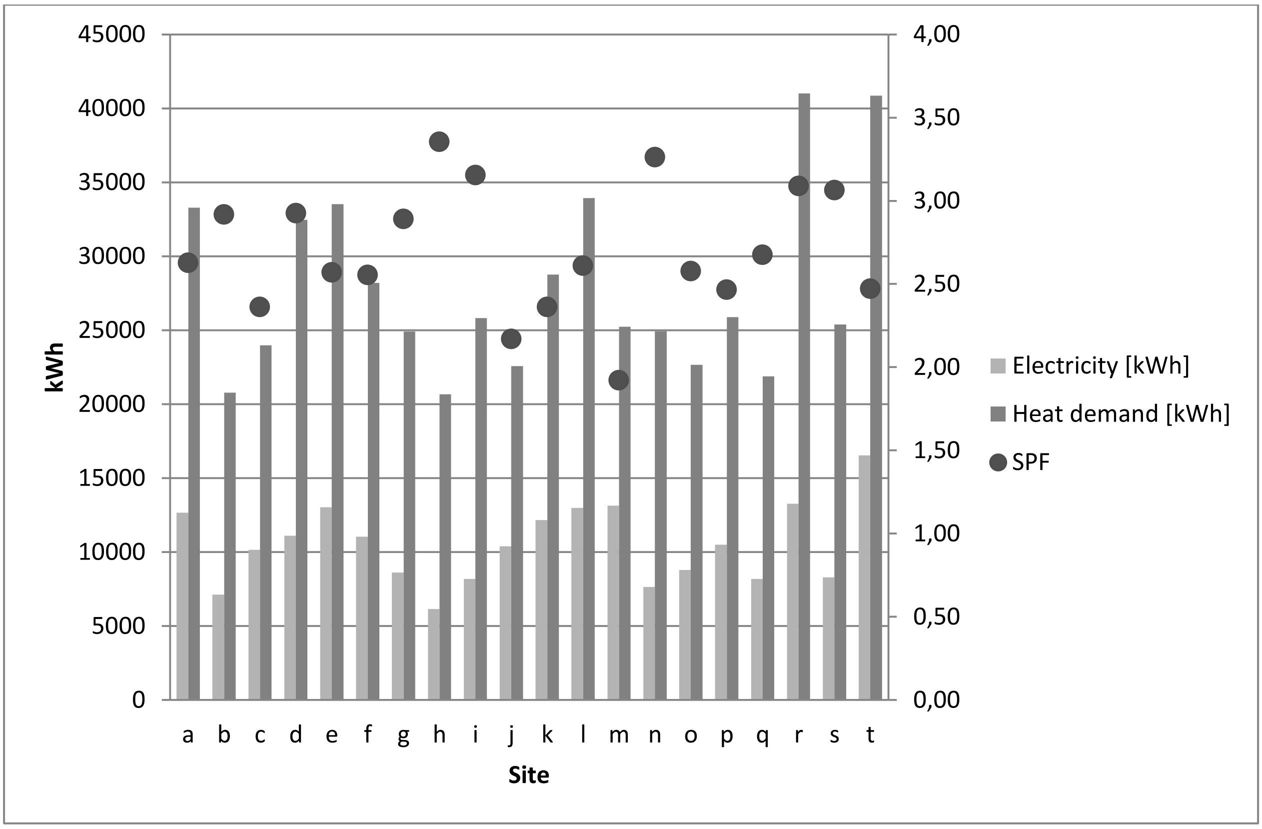

Figure 1: Total supplied heat, purchased electric energy and SPF. Yearly values for all sites.

There are also great differences in domestic hot water production. The heat demand for heating of DHW varies between 1026 and 9817 kWh. The proportion of heat that provides hot water varies between 5% and 24% of total heat demand. The big difference is due to user behavior and building construction.

Table 4: SPF, SHD and SEED for six sites

Site	SPF	Area (m^2)	SHD (kWh/m^2)	SEED (kWh/m^2)
f	2,6	90	313	123
i	3,2	100	258	82
a	2,6	106	314	120
t	2,6	246	92	36
o	2,5	260	157	64
d	2,9	310	105	36

Figure 2 shows the supplied heat distributed over the year for site g. Site g is chosen as example since it has a total heat demand that is near the mean value for all sites. Furthermore, the proportion of heat for each month is considered to be more or less valid for all sites. Space heating is not required during the summer, which means that the heat supplied is used for heating domestic hot water.

The purchased electric energy varies between 6000 kWh (site h) and 16000 kWh (site t) for the different sites.

The highest SPF in this study is 3.4 and the lowest is 1.9, average 2.7. The difference in SPF is mainly due to the difference in building constructions and heat pump installations.

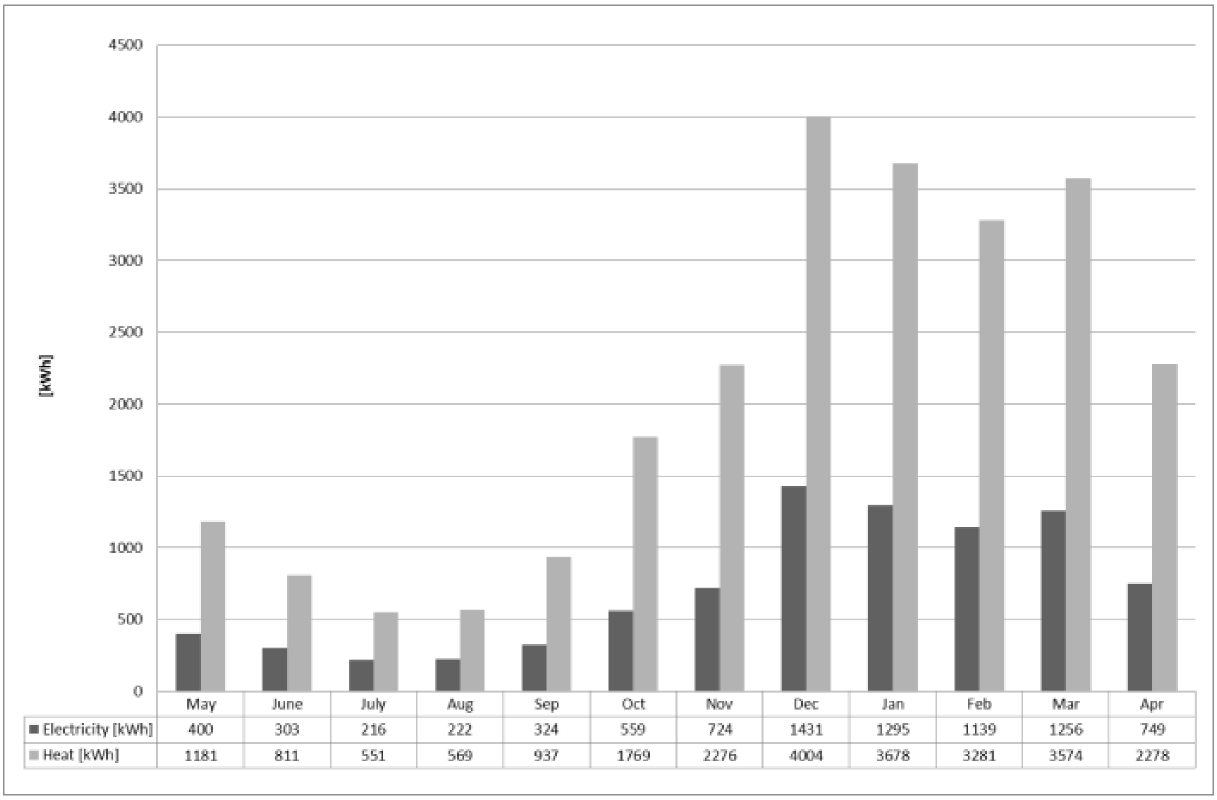

Figure 2: Total supplied heat and purchased electric energy. Monthly values for site g.

Figure 3 shows the monthly performance factor for site g. The performance factor is low during the summer month when there only is need for domestic hot water. The chart also shows a small decrease in performance factor during the cold winter months.

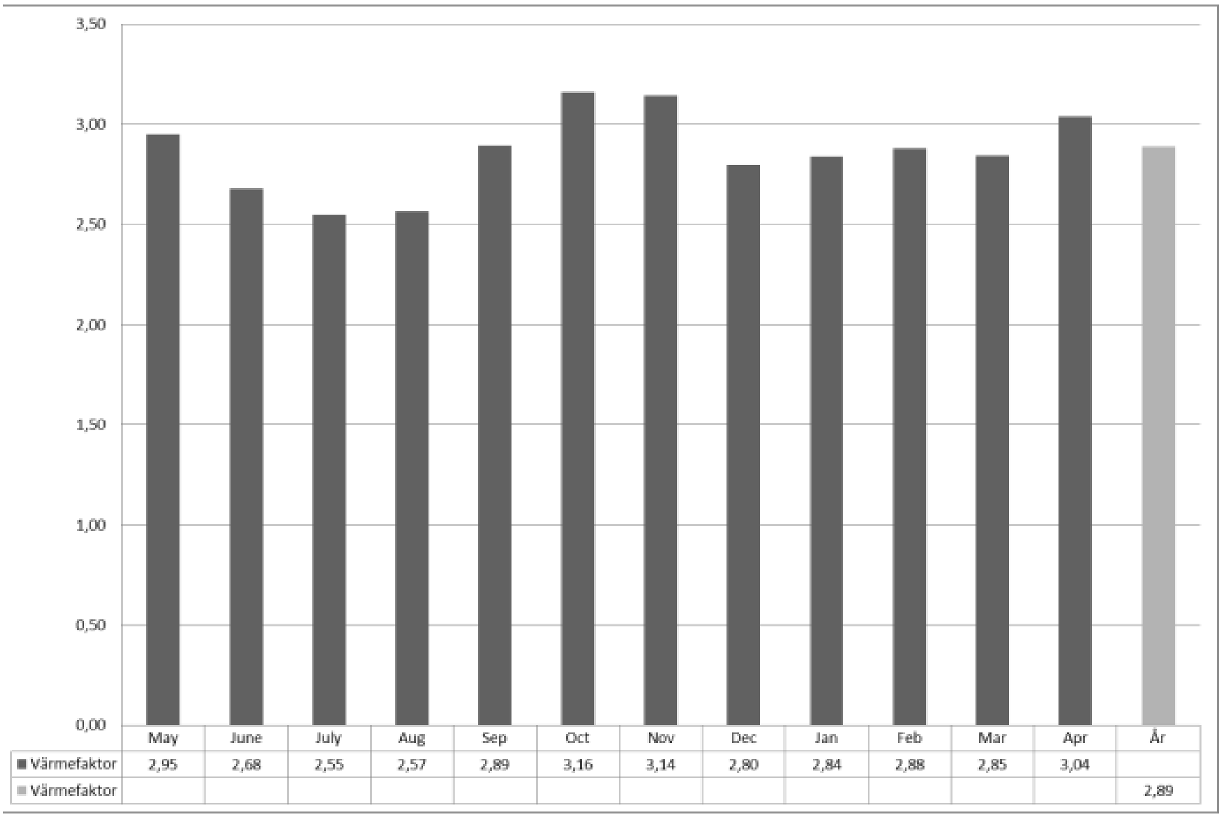

Figure 3: Performance factor distributed for each month for site g.

3.2 Energy savings and reductions of CO_2 emissions

The saving of energy purchased is on average 62% of total heat demand for the facilities in the study. Site m has the lowest saving with 48% and site h has the highest with 70%.

Table 5 is a summary of yearly results from six selected sites. Table 3 presents supplied heat, used electric energy, energy savings compared to heating with electric boiler and reduction of CO_2 emissions compared to heating with electricity (COR_{el}) and oil (COR_{oil}). The electrical production is assumed to be either Swedish mix (SM) or coal condensing (CC) power production. The sites in Table 5 are examples that reflect the results from the study and they are selected from the following criteria:

a	average SPF, average ES (%)
g	average Q_{Tot}
h	highest SPF, highest ES (%), lowest E_{Tot}
m	lowest SPF, lowest ES (kWh and %)
s	average ES (kWh)
t	highest Q_{Tot}, highest E_{Tot}

Table 5 shows that CO_2 emissions are mostly influenced of the type of electric energy production. There is a considerably difference between SM and CC power production.

Table 5: Summary of yearly results for six different sites in the study

Site	Q_{Tot} (kWh)	E_{Tot} (kWh)	ES (kWh)	ES (%)	SPF	COR_{el} CC ($kgCO_2$-eq)	COR_{el} SM ($kgCO_2$-eq)	COR_{oil} CC ($kgCO_2$-eq)	COR_{oil} SM ($kgCO_2$-eq)
a	33279	12671	20608	62	2,6	19949	750	-1121	10683
g	24910	8619	16291	65	2.9	15770	593	-1	8028
h	20667	6160	14507	70	3.4	14043	528	958	6697
m	25242	13135	12107	48	1.9	11720	441	-4262	7975
s	**25391**	**8291**	**17100**	**67**	**3.1**	**16553**	**622**	**477**	**8201**
t	**40848**	**16532**	**24316**	**60**	**2.5**	**23538**	**885**	**-2324**	**13078**

4 DISCUSSION

It is necessary to consider the whole heat pump system (not only the heat pump itself) when evaluating the results from field measurements. No heat pump, regardless of how well it performs, will be efficient when operating in a system where its properties do not match or complement those of other systems with which it is intended to work. The efficiency of the system is affected by the structure and design of the building, type of auxiliary systems and heating demand. It is important to define system boundaries and state which electrical components that are included in the analyses of the heat pump system. In this work all electrical equipment are included when evaluating the equipment. The measurements in the Swedish contribution to IEA HPP Annex 37 (Tiljander *et al*. 2011) show that if only the electrical equipment in the heat pump unit itself (compressor and control system) are included, SPF increases at least with 0.5 compared with all equipment included (heat pump unit, brine pump, back up heater and all auxiliary drivers, including circulation pump for heat carrier). One of the goal of the present work is to compare heat pump systems with electrical and/or oil heating. The comparison with oil heating is not quite fair since all electric equipment are included in the measurements and the figures for oil heating do not include electric energy for heat carrier circulation pump.

The winter of 2012-2013 was very cold in Sweden. The heat pump systems worked well without problems. In the summer, almost all the supplied heat was used for DHW-heating. Heat pumps are generally not as efficient at heating DHW as they are at space heating. This is due to a higher condensing temperature when heating DHW. Consequently, performance factors are lower during the summer month and increase during spring and autumn (Figure 3). The decrease in SPF during winter month is probably due to need of additional electrical back up heat, maybe in combination with high leaving water temperatures to the radiators. Another reason can be decreasing heat source temperature in winter time.

The heat pumps in this study are from 2001 to 2007, when electricity prices were relatively low compared to today. In order to reduce investment costs the heat pumps were sized to cover approximately 50% of the heating demand the coldest day, which often resulted in that they covered 90% of the heat demand over the year. This implies that the remaining heat demand, in cold days, will be supplied with electrical back up heater. I.e. old heat pumps were often sized for an energy cover ratio at around 90%. The corresponding figures for on-off controlled heat pumps installed today are that the shall cover 70-75% of the heating demand the coldest day which results in that they cover 97% or more of the energy demand over the year. This is probably one major reason why modern heat pump systems probably are more energy efficient than the ones evaluated in this study.

The results in this study correspond well with results from earlier field measurements performed by SP. Stenlund *et al*. (2007) performed measurements on five ground sorurce heat pumps installed 1998 to 2003. SPF varied between 2.4 and 2.9 with an average of 2.6 which is slightly lower than SPF in this study. Results from field measurements on modern heat pumps (Tiljander 2012) confirms that modern heat pump systems can be more energy efficient than the old ones in this study. For example the energy savings are between 50 and

70% in this study and the corresponding figures for the modern heat pump systems are 67-75%. One of the ground source heat pump evaluated in the Swedish contribution to Annex 37, where different heat pump systems on the Swedish market were investigated, had SPF of 4.0 when all electrical equipment were included in the evaluation. Tests made in SP's laboratory on behalf of the Swedish Energy Agency and the Swedish Consumer Agency during a period from 1998 to year 2012 (Lindqvist *et al.* 2014) also confirmed that ground source heat pumps on the Swedish market have increased their efficiency over the years.

When evaluating heat pump systems it is important, together with the SPF value, to consider other performance indicators. Table 5 shows that the heat demand and used electric energy differ considerably between the sites. The heat demand is due to building construction and user behaviour. The amount electric energy used is beyond this also due to the size of the heat pump in relation to the heating demand and the installation. Site h is an example of a good installation of a well sized heat pump and moreover, the household is very conscious regarding their energy consumption.

Table 5 shows that there is a potential for reduction of greenhouse gas emissions by using heat pump technology, but the reduction is influenced by the type of electricity production. When oil heating is compared with heat pump systems, and the electricity is produced from coal condensing power, there is a break point between heat demand and electric energy used where CO_2 emissions become larger for heat pump systems than for oil heating. If the Swedish power mix is used instead; the reduction of CO_2 emissions is significant.

The efficiency of a heat pump system is dependent on the design and installation. To obtain the best possible results, the heat pump system must be "tailored" to each individual building. This may be difficult in old buildings where the heat pump is replacing an old heating system that has an existing distribution system. A few guidelines, confirmed by this or earlier studies, to keep in mind during installation are:

- Size the heat pump by heat demand.
- Install variable speed circulators that are controlled by heat demand.
- Standby losses in the DHW heater should be minimized.
- Insulate pipes and components.

The study also shows that building owners can reduce their heating demand by lowering indoor temperatures and domestic hot water use.

5 CONCLUSIONS

Field measurements are useful to enhance knowledge about the efficiency energy consumption of installed heat pumps. Demonstration is an effective way to communicate a message about what factors that influence the differences in efficiency between seemingly equivalent systems. Another advantage with field measurements is that the obtained knowledge can be used to get the heat pump systems more energy efficient by different measures.

When evaluating heat pump systems, it is important to consider not only the SPF value, but also other performance indicators, such as energy demand, specific energy demand, energy coverage ratio, CO_2 emissions, availability etc.

The results of this field study show that there is a great potential for energy savings by using heat pump technology. Comparison with direct electricity, the energy savings are between 48 and 70 % of total heat demand. The savings depend on system solution, the heat pump capacity and heat pump settings. The saving of energy purchased is on average 62% of total heat demand for the facilities in the study. The difference between heat and electrical energy use can be considered renewable.

There is a good potential for CO_2 reduction by using heat pump technology. CO_2 emissions are affected by which type of heating system the heat pump system is compared to, and how the electricity is produced. In this project, the heat pump system has been compared to electrical boiler and oil-fired heating. Two different types of electrical energy, Sweden mix and coal condensing power production, have been considered in the calculations. There is a considerably difference between Swedish mix and coal condense power production.

SPF for the 20 heat pump systems was determined to be between 1.9 and 3.4. The average SPF for the 20 systems in this study is 2.7. SPF in this study are generally lower compared to the SCOP-values calculated based on comparative laboratory tests SP performed during 2012, but at the same level as the SCOP-values based on lab tests from 2005. Differences are partly due to that the heat pumps in this study are from 2001 to 2007, when electricity prices were lower and in order to reduce investment costs the heat pumps were sized not to cover as much heat as they are installed to cover today. At the same time the heat pumps today are more efficient which both results from laboratory tests and the results from field measurements in the Swedish contribution to IEA HPP Annex 37 show.

6 ACKNOWLEDGEMENT

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7 NOMENCLATURE

AE = Annual Efficiency
CC = Coal Condense power
COR = Reduction of greenhouse gas emissions
DHW = Domestic hot water
E = Used electrical energy (kWh)
ES = Energy savings (kWh)
K = CO_2-emission coefficient (g/kWh)
Q = Supplied heat (kWh)
SH = Space heating
SCOP = Seasonal Coefficient of Performance
SEED = Specific electric energy demand (kWh/m^2)
SHD = Specific heating demand (kWh/m^2)
SM = Swedish Mix
SPF = Seasonal performance factor

7.1 Subscripts

B_pump = heat sink: pumps for SH or DHW
el = electrical energy
H_hp = HP in SH operation
HW_bu = Back-up heater for SH and DHW
HW_ebu = Electrical back-up heater for SH and DHW
HW_hp = HP for SH and DHW

oil = oil heating
W_hp = HP in DHW operation
S_pump = HP source: brine pump
Tot = Total

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