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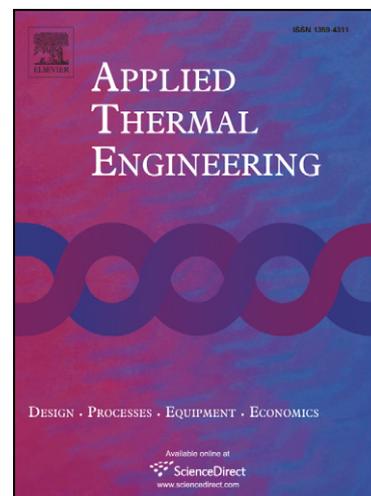
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**Build-up and long-term performance test of a full-scale solar-assisted heat pump system
for residential heating in Nordic climatic conditions**

(Test of a solar-assisted heat pump system)

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Abstract

This paper presents the build-up and long-term performance test of a full-scale Solar-Assisted Heat Pump System (SAHPS) for residential heating in Nordic climatic conditions. This particular SAHPS was developed within the EU project ENDOHOUSING, by predominantly using components and techniques that are available on the market. The analysis primarily focuses on system performance, with emphasis on Heat Pump (HP) and total system Seasonal Performance Factor (SPF), based on long-term and full-scale operation. Analysis shows that despite unfavourable building conditions, for low energy use and utilisation of a SAHPS, the system was successfully in full operation (for about two years) fulfilling heating requirements. Data processing of the series representing the full year period of 2007(feb)-2008(feb), presented a HP and total SAHPS performance of: $SPF_{HP}=2.85$ and $SPF_{SAHPS}=2.09$. The authors argue that with an optimised SAHPS control and operation strategy, additional use of circulation pumps and energy (electricity) could be vastly reduced, hence attaining a SPF_{SAHPS} value that is in parity with the SPF_{HP} . As the Nordic (Swedish) Endohousing SAHPS has not yet been properly optimised/designed and installed in an appropriate house, the $SPF_{HP}=2.85$ is considered satisfactory.

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Keywords: Solar-assisted heat pump system; roof integrated unglazed solar collector; ground heat storage/source; long-term; full-scale; test

Nomenclature

E	electrical energy	(J)
\dot{E}	electrical power	(W)
c_p	specific heat capacity	(J/kg·K)
COP	Coefficient of Performance	(-)
Q	thermal energy	(J)
\dot{Q}	thermal energy per unit time	(W)
T	temperature	(K)
\dot{m}	mass flow	(kg/s)
SPF	Seasonal Performance Factor	(-)

Greek symbols

τ	sampling interval	(s)
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Subscripts

AH	Auxiliary Heat
comp	compressor
CP	Circulation Pump
DCW	Domestic Cold Water
DHW	Domestic Hot Water
evap	evaporator
GHE	Ground Heat Exchanger
HP	Heat Pump

HS	Hot Store
SAHPS	Solar-Assisted Heat Pump System
tot	total
trad	traditional
USC	Unglazed Solar Collector

1. Introduction

The possibilities, benefits and build-up of Solar-Assisted Heat pump Systems (SAHPS), for heating or cooling purposes, has been studied in various projects since the 1970s; e.g. see [1-3]. These projects display a variety of system designs in various climates. These also present a range of performance results and advice/suggestions on system design, control strategy and performance. Due to differences in system complexity and application, it becomes difficult to formulate any general conclusions concerning system design, usefulness and performance [3]. The fundamental aim with a SAHPS is to attain higher heating or cooling Coefficient of Performance (COP) values in comparison to regular Heat Pump (HP) systems [3]. SAHPS have a variety of system build-up and control strategy complexity (depending on design), due to a combination of various components, temperature levels, thermal requirement (storage vs. usage), climate and system output (amount and duration of heating or cooling use); making the task of designing and optimising these dynamic systems in terms of performance and cost demanding. The assessment of system performance from various designs and operations has in previous studies been made by computational simulations or experimental tests [1-3, 5-13], Inalli and Esen [13] present a study similar to this paper. System simulations and analysis specifically focusing on Nordic system design (residential heating) is presented by [3, 14, 15]. Kjellsson [3] discussed and concluded the importance of optimising (hence reducing) the use and running time of Circulation Pumps (CPs) and other energy consuming auxiliary components, in a SAHPS (for heating) coupled to a borehole. The energy consumption by these components may reduce the efficiency and overall system performance, to an extent that the benefit of this particular system solution is jeopardised.

1.1 The EU project ENDOHOUSING

The EU project Endothermic Technology for Energy Efficient Housing in the EU (ENDOHOUSING) Project No: NNE5-2001-00565 was launched June 2003 and officially ran to May 2006 [16]. ENDOHOUSING was a demonstration project for exploring the potentials of a particular SAHPS design, that combines components available on the market, for providing thermal energy to meet full space heating/cooling and hot water requirements for domestic houses in different regions of the EU throughout the year; thereby assessing the feasibility of designing and realising a full-scale and almost commercially available SAHPS. The only component that's not commercially available is the solar collector. It was developed and designed as a roof-integrated Unglazed Solar Collector (USC) named the Endopanel. The objective was to accomplish USC's that propitiously blend into their surroundings thus preventing an 'add on' appearance and having a dual and symbiotic function (heat absorption and roofing). The USC consists of an extruded aluminium profile (see Fig. 1) with sealed ends and welded in-/outlet pipes underneath. Feet enable fixation onto the roof and folds allow interlocking. From a thermal perspective, the choice of using an USC is based on its varying working abilities. Despite that an USC produces lower fluid temperatures than a glazed collector [4], it can absorb and emit heat from and to the ambient via convection, moisture condensation and long wave (IR) radiation - widening and prolonging its thermal use and being able to emit excess heat produced by the HP if the system is in cooling mode [16].

Five demonstration sites (Endosites) were established between latitudes 35°-62°. Systems were installed in houses situated in Cyprus, southern and northern Italy, in central Germany and Sweden (Sandviken, see Fig. 1). The systems are based on the same concept [16], with modifications made to improve performance in the prevailing local climatic conditions.

Fig. 1 (a) and (b)

The basic concept of the ENDOHOUSING SAHPS is to have two thermal storages with different temperatures, named cold and hot store, consisting of storage vessels [16]. These storages are intermittently charged and discharged with heat (on daily basis) by the USC, HP or space heating/cooling circuit (see Fig. 2). The HP is a

commercial product for domestic heating purposes, normally coupled to a borehole or Ground Heat Exchanger (GHE). This particular HP has a built-in tank for DHW generation, CPs (cold and hot side) and Auxiliary Heat (AH) (electricity backup), commonly used in Sweden [3, 17].

1.2 Objectives

This paper presents the build-up and long-term performance test of a full-scale SAHPS for residential heating in Nordic climatic conditions. The design and operation of the specific SAHPS is presented in order to give a technical description of the system, the project background and to illustrate a system that uses components and techniques which predominantly are available on the market. Performance is an important aspect of system design and operation, as it shows the system efficiency, usefulness and potential improvements in the future. The SAHPS analysis performed in this paper primarily focuses on system performance, with emphasis on HP and total system Seasonal Performance Factor (SPF) (see section 3), based on long-term and full-scale operation. No detailed component analysis is performed within the scope of the paper.

2. The Swedish Endosite in Sandviken

The Swedish demonstration site is located in Sandviken. The house, from the 1920's (see Fig. 1), does not provide favourable conditions for low energy use nor utilisation of a SAHPS because:

- The house is poorly thermally insulated, leading to large heat losses, power requirement and high supply temperatures. The ventilation rate corresponds to 0,6 ACH without heat recovery.
- The heat distribution system has few radiators; hence the supply temperature must be high in order to emit the required heat (not optimal for HP COP [18]).
- The roof is oriented to the east and west (the USC's are placed eastward). No roof surface is exposed to substantial direct solar radiation during the day, limiting the potential of absorbing global solar

radiation. Southward surfaces have the highest exposure of direct solar radiation [3, 4] in the northern hemisphere.

The system was installed during the autumn to winter in 2005-2006. The main parts are:

- USC's: 39 Endopanel covering $\sim 42.5 \text{ m}^2$.
- Heat pump: IVT Greenline HT Plus 9C, thermal output 8.4 kW [19].
- Energy storage: IVT compact Ground Heat Exchanger (GHE) [19], 18 modules in two circuits, $\sim 52 \text{ m}^2$ effective module area, placed horizontally at a depth of $\sim 1.5 \text{ m}$ in the ground.
- Valves, CPs, monitoring and control equipment (see Fig. 2). Electrical power use for CPs: GHE circuit 250 W, USC circuit 100 W.

Fig. 2

In comparison to the original ENDOHOUSING system concept, this system was adapted for Nordic climatic conditions, since heating is the predominant requirement. Intermittent operation on daily basis for recharging the cold store is not possible when the heating requirement is considerably higher than the heat input, if any. The adaptation consisted of replacing the cold store vessel with a seasonal heat storage, a GHE. It actively charges the ground with thermal energy during late spring, summer and early autumn months. Thermal energy is extracted during the heating season, though intermittent recharging may occur upon the presence of warm winter periods. Besides recharging, the fluid temperature to the HP evaporator may directly be raised, hence increasing COP in comparison to a traditional non charged ground collector or borehole [20]. Having the pipe spacing 0.15 m, the GHE is a compact type and is usually vertically installed in the ground. It is often used in combination with exhaust ventilation heat pumps for heat recharging, since it is too small for natural heat recharging, using solar heat and outdoor temperatures from the summer season. Normally, the pipe spacing is 1 m for horizontal installations, almost requiring a 10 times larger ground surface but no active recharging.

This design is based on the roof circuit (USC) charging the ground or directly raising HP evaporator temperatures (see Fig. 2). There is neither direct heating nor preheating of the DHW or space heating, as it was anticipated that the 'useful' heat or temperature level obtained from the USC is insufficient most part of the year.

During the summer season, there will be occasions when the heat and temperature level from the USC is sufficient for preheating DHW. But, the energy savings, compared to only running the HP, is low (within this project) in view of a more complex and costly system design. Normal energy use for DHW during the summer is for an average Swedish family about 2000 kWh [3]. At this Endosite, DHW consumption was scheduled to simulate 'normal' residential behaviour, since there were no occupants at the time of system installation. DHW was drained twice per day (morning and evening) to resemble daily energy usage, ~14 kWh [3]. The SAHPS was set to deliver space heating for obtaining an indoor temperature of +20°C. Internal heat sources, such as electric appliances and human beings, were not simulated.

Fig. 3

The system consists of three main circuits: the GHE, the roof (USC's) and the radiators (space heating), see Fig. 2. The HP is a market product which is designed for domestic heating purposes using a borehole or GHE as energy source. This particular HP has a built-in tank for DHW production, CPs (cold and hot side) and Auxiliary Heat (AH) (electricity), as customary in Swedish installations. The sole component controlling the evaporator inlet temperature and routing of thermal energy to and from the GHE is a 4-way-valve. The valve bypasses the flow, carrying heat from the USC's, directly to the GHE when the HP is not in operation. When the HP is running, the valve mixes, if necessary, the fluid entering the HP evaporator to the maximum temperature of +15°C: Nordic ground-coupled HP's are optimised for borehole and ground collector installations (temperatures) having the maximum inlet evaporation temperature of +20°C, but recommended to be no more than +15°C [22].

The USC roof is in operation while the USC's outlet temperature is higher than the outlet temperature from the GHE. There is an exception; if the USC's inlet temperature is $< \pm 0$ °C while the outdoor air temperature $\leq \pm 0$ °C and relative humidity ≥ 70 %, heat absorption is prohibited to avoid moisture condensation and freezing on the USC surface. The control of CPs running time was not optimised within the scope of the Swedish ENDOHOUSING project. The CPs for the roof (USC), ground (heat exchanger) and heating (radiator) circuit (see Fig. 2) were set to run continuously. On / off flow in the roof circuit was controlled by a magnetic valve. The HP has two built-in CPs which are entirely controlled by the HP.

3. System performance evaluation methodology

Efficiencies are defined in various ways, though the main purpose is to establish the net useful energy (upgraded energy) delivered from the process, in relation to purchased energy supplied to the system. Two efficiencies are commonly used to quantify and evaluate performance, e.g. see [3, 15]. These are: Coefficient of Performance (COP) and Seasonal Performance Factor (SPF). COP is a momentary entity, defined as:

$$COP_{HP\ trad} = \frac{\dot{Q}_{evap}}{\dot{E}_{comp}} \quad (1)$$

COP only takes into account electricity supplied to and heat delivered from the HP unit whereas SPF involves other energy that is actively supplied to and delivered from the system, such as energy (electricity) to CPs and control units. A vital difference is also that SPF considers energy (electricity) supplied to the system, though the heat pump unit is in stand-by mode. SPF may give values which are lower than those of COP. For example, electricity for running CPs in order to maintain system fluids flows, e.g.: roof (USC), GHE and radiator circuit, will appear in SPF whether or not the HP unit is running, thus reducing the value of SPF. However, SPF may also give higher values than COP during favourable conditions. If the temperature from the USC is sufficiently high, then the thermal energy can directly be used for heating or preheating DHW or space heating, thus increasing the value of SPF as the HP is not in operation although heat is delivered. Note, this operation scenario is not relevant for this SAHPS. This paper primarily focuses on performance of the HP and total system within heating applications; see Eq. (2-4). The SPF_{HP} can be seen as the upper limit of performance of this SAHPS.

$$SPF_{HP} = \frac{\sum Q_{HP\ tot\ output}}{\sum E_{HP\ tot}} = \frac{\sum (Q_{space\ heating} + Q_{DHW})}{\sum (E_{comp} + E_{HP\ CPs} + E_{AH})} \quad (2)$$

Eq. (2) can be rewritten and expressed in terms of monitored variables such that

$$SPF_{HP} = \frac{\sum [\dot{m}_{HP \rightarrow HS} \cdot \tau \cdot c_p \cdot (T_{HP \rightarrow HS} - T_{HS \rightarrow HP}) + \dot{m}_{DHW} \cdot \tau \cdot c_p \cdot (T_{DHW} - T_{DCW})]}{\sum (E_{comp} + E_{HP\ CPs} + E_{AH})} \quad (3)$$

SPF for the system is in energy form described by Eq. (4), where

$$SPF_{SAHPS} = \frac{\sum Q_{SAHPS\ tot\ output}}{\sum E_{SAHPS\ tot}} = \frac{\sum (Q_{space\ heating} + Q_{DHW})}{\sum (E_{HP\ tot} + E_{CP\ USC} + E_{CP\ GHE})} \quad (4)$$

4. Long-term and full-scale test results from the Swedish Endosite

System operation, monitoring and data logging (the sampling rate is 1 minute) commenced in February 2006. Data from all Endosites was collected and stored at a central server in Germany until ~October 2006. Local data storage was not established until February 2007, explaining the absence of data during the period of transition. Sporadic data glitches appear throughout the entire monitoring campaign. Data storage at the central server proved to be somewhat unreliable, rendering missing samplings. Local data logging was more dependable, but failures in sensors, power and data communication are occasional. Due to incomplete data series, data processing and system performance analysis done in this paper consists of various performance ratios as expressed in section 3, instead of accumulated system energy performances in terms of e.g. kWh per month or year.

In November 2007, the USC fluid froze causing the panels to burst. Due to previous leakage in the coupling between the manifold and the Endopanel, the USC circuit was continuously refilled with water during the spring and summer, to the extent that the antifreeze protection was inadequate. A planned refill was delayed, resulting in damage. In order to obtain annual series, the analysis was extended until February 2008 despite that the USC circuit was not in operation. The expected impact this has on the system performance during November to February, is minute since it is too cold for the USC's to harvest heat.

Fig. 4 (a-f) and Fig. 5 show the relative system performance and absolute temperature variations of the fluid to/from the GHE on monthly basis. A number of exemplifying snapshots of monthly conditions are also presented, in order to give a better insight to the system conditions and behaviour that imply its performance.

Fig. 4 (a) to (f)

Fig. 5 (a) and (b)

4.1 Snapshots of monthly system performances and conditions

Temperatures from three months, with significant variations in system operation due to different seasons, are presented in this section. The months chosen to represent these snapshots are: March 2006, May 2007 and July 2007.

Fig.6 (a) to (f)

5. Discussion

The long-term and full-scale tests present a variety of results. First, note that the low value (about 1) in Fig.4 (a - b), in Feb 2006 is due to running the AH prior to using HP operation when monitoring commenced. The total heating requirement results from both space heating and DHW, so the share of total heating that each represent will vary throughout the year. Since the DHW heating requirement is minutely affected by outdoor temperature variations, the change in total heating requirement/output is thereby due to space heating; see Fig. 4 (c). These variations will affect both SPF_{HP} and SPF_{SAHPS} , since a change in total heating requirement shifts system heat output temperature levels (DHW vs. space heating). The HP condensers temperature is for DHW significantly higher than for space heating. Whilst the HP has a compressor that has a fixed rpm (hence heat output in time), the HP running time plays a dominating role in the accumulated heat output. This is evident when comparing figures Fig. 6 (e), with the total running time 40 hours, with e.g. Fig. 6 (a) having some 500 hours and Fig. 6 (c) about 120 hours. Short compressor running time and more start-ups, reduces the compressor efficiency as the HP heat output will be more affected by mechanical losses (e.g. friction and vibration) and thermal HP cycles start-ups (the compressor is not optimised for these operational conditions); as also discussed by Karlsson and Fahlén

[23], that these factors are of significance for HP performance. It is judged that the combination of these above discussed aspects result in reduced SPF during summer months, compared to the rest of the year. Despite that the incoming fluid temperature to the HP evaporator is relatively high - as opposed to the heating season - performance is low, see Fig. 4 (a - b) and Fig. 6 (a, c and e); keeping in mind the high temperatures required for DHW generation. When analysing series presented in Fig. 4 (a) and (c), the reduction in SPF_{HP} for the 2006 series is larger than for 2007-2008 since the share of DHW use is larger. The difference in DHW use is due to problems with the scheduled DHW-usage procedure. At the same time, space heating during the 2007 summer period is somewhat higher, which additionally reduced the share of DHW energy in comparison to total HP heat output.

When comparing Fig. 4 (a) and (b), there is evidently a significant difference between SPF_{HP} and SPF_{SAHPS} . The overall reduction in SPF_{SAHPS} is primarily due to the power (electrical) use of CPs (see Fig. 4 (d)); showing the importance of reducing the power and running time of system CPs and other energy consuming auxiliary components (as also concluded by Kjellsson [3]). The characteristics of the SPF_{SAHPS} series presented in Fig. 4 (b) closely resembles the SPF_{HP} variations (Fig. 4 (a)), although there are monthly discrepancies. As an example of such discrepancy, a comparison between March and May in the 2006 and 2007-2008 series is made, see Fig. 4 (a - b). May is distinguished as having the highest SPF_{HP} . Comparing the same months for 2006 and 2007-2008 in Fig. 4 (a - b), SPF_{SAHPS} shows that May no longer displays the highest performance. The explanation is found in Fig. 4 (d). It presents the relative use of electricity by CPs (for the GHE and USC) in comparison to electricity used by the HP (primarily for the compressor). The ratio is higher for May than for March, which has a direct impact on the SPF_{SAHPS} . This means that the HP running time is lower in May than in March (compare also Fig. 6 (c) with Fig. 6 (a)). As the HP is in standby mode, the CPs are still running, hence reducing the SPF_{SAHPS} . By comparing Fig. 4 (d) and (e), it becomes graphically evident that the normalised reduction from SPF_{HP} to SPF_{SAHPS} is strongly correlated with the relative increase in CPs energy (electricity) usage. The energy consumption by the CPs, for running the GHE and USC at this Endosite, can considerably be reduced. It would be possible to attain a SPF_{SAHPS} that is in parity with the SPF_{HP} , since the HP used in the ENDOHOUSING project already has built in CPs. With a demand-controlled strategy, energy for the additional CPs could vastly be reduced. However this analysis is beyond the scope of the presented system tests and this paper. The overall annual SPF results of the Swedish ENDOHOUSING SAHPS, is presented in Fig. 4 (f). The most representative result is for 2007(feb)-2008(feb) since it contains a full year of data.

Besides the actual system performance, one of the main interests was the use of the GHE as seasonal heat storage, see Fig. 5 (a - b). As seen in Fig. 5 (b) for the 2007 series, the GHE is intensively being charged during the spring via the USC circuit. During this period, the system is simultaneously producing DHW and space heating, showing its intermittent operation, for example as shown for May 2007 (Fig. 6 (c)). Peaks in the graphs represent incoming GHE fluid that has been heated by the USC circuit and routed into the HP evaporator by the 4-way-valve. Dips display the inability of the 4-way-valve to mix the incoming fluid temperature sufficiently fast. After the USC roof froze in November 2007, the GHE could no longer actively be charged. This was unfortunate for the SAHPS, but an opportunity to compare the behaviour of the ground heat storage since the system was still running. The 2006 and 2007 series in Fig. 5 show a similar thermal behaviour. The 2008 series displays a considerable temperature reduction during the period ~March to ~October. Although the 2006 and 2007 series display a significantly higher temperature during the summer periods, the temperature rapidly declines during the autumn to the same level as for the uncharged 2008 series, corresponding to the beginning of November. This indicates that the present GHE design (at this Endosite) e.g. concerning ground depth, soil type, surface area and GHE configuration, is not capable of extensive seasonal heat storage though the ground temperature reaches equilibrium with its surroundings, ~ 20 °C, during summer. In order to make a general analysis on improved thermal storage capacity, a relevant model of the GHE and its surroundings has to be developed. At present time, such a model is not readily available. As the GHE is located in soil, the thermal storage process is not only described by ordinary heat transfer, but is also significantly dependent of moisture transfer (precipitation, water tables, surrounding soil, snow layers, etc. affecting thermal parameters) and phase change (vapour/water/ice). The influence of moisture is noticed when the fluid temperature in the ground is below zero, but quite constant for about four to five months. In order to perform a reliable system optimisation of the Swedish Endosite SAHPS, a suitable GHE model has to be developed and used in system simulations. The effects of moisture will make this GHE model complex.

6. Conclusions

This paper presents the build-up and long-term performance test of a full-scale SAHPS for residential heating in Nordic climatic conditions. The design is based on components and techniques which predominantly are available on the market. This paper primarily focuses on system performance, with emphasis on HP unit and total system SPF, based on long-term and full-scale operation. Despite unfavourable building conditions in terms of energy use and utilisation of a SAHPS, the Swedish ENDOHOUSING SAHPS succeeded in full operation (for about two years) and in fulfilling heating requirements. The major encountered technical problems during the test period was some missing monitored data and leakage in the USC/manifold couplings, the latter eventually leading to frost shattering of the USC since fluid losses were replaced with water and not corrected in time. Concerning system performance, data processing of the series representing the full year period of 2007(feb)-2008(feb), presented a HP and total SAHPS performance of: $SPF_{HP}=2.85$ and $SPF_{SAHPS}=2.09$. The authors argue that it would be possible to attain an SPF_{SAHPS} value that is almost equivalent to the SPF_{HP} , since the HP used in the ENDOHOUSING project has built-in CPs. Low energy use by auxiliary components is vital for good system performance, as concluded by Kjellsson [3]. With an optimised SAHPS control and operation strategy, additional use of CPs and energy (electricity) could be vastly reduced. Regular ground-coupled HP systems display an annual mean value of $COP \approx 3$ for residential heating in Swedish (Nordic) conditions [22]. Having this in mind and also considering that the Swedish Endohousing SAHPS has not yet been properly optimised nor installed in an appropriate house, the $SPF_{HP}=2.85$ is considered being a success. In order to additionally increase the overall SPF of the Swedish ENDOHOUSING SAHPS, an extensive system analysis/simulation including a relevant thermal model of the GHE and its surroundings, which considers moisture transfer and phase change, has to be performed. Only then is it possible to assess the full potential of this particular system design. Such thermal model was not prevalently available. Regarding the ground heat storage at the Swedish Endosite, the data showed that the present design e.g. concerning: ground depth, soil type, surface area and GHE configuration is not capable of extensive seasonal heat storage – it requires intermittent recharging.

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References

- [1] O. Ozgener, A. Hepbasli, A review on the energy and exergy analysis of solar assisted heat pump systems, *Renewable and Sustainable Energy Reviews* 11 (2007) 482-496.
- [2] A. Hepbasli, K. Yildiz, A review of heat pump water heating systems, *Renewable and Sustainable Energy Reviews*, article in press, (2008).
- [3] E. Kjellsson, Solvärme i bostäder med analys av kombinationen solfångare och bergvärmepump, (in Swedish), Licentiate Thesis, Division of Building Physics, Lund Institute of Technology, Lund, Sweden, 2004.
- [4] J.A. Duffie, W.A. Beckman, *Solar Engineering of Thermal Processes*, third ed. Wiley, New Jersey, 2006.
- [5] H. Wang, C. Qi, E. Wang, J. Zhao, A case study of underground thermal storage in a solar-ground coupled heat pump system for residential buildings, *Renewable Energy* 34 (2009) 307-314.
- [6] H. Wang, C. Qi, E. Wang, Performance study of underground thermal storage in a solar-ground coupled heat pump system for residential buildings, *Energy and Buildings* 40 (2008) 1278-1286.
- [7] A. Ucar, M. Inalli, Thermal and economic comparisons of solar heating systems with seasonal storage used in building heating, *Renewable Energy* 33 (2008) 2532-2539.
- [8] A. Ucar, M. Inalli, Exergoeconomic analysis and optimization of a solar-assisted heating system for residential buildings, *Building and Environment* 41 (2006) 1551-1556.
- [9] V. Trillat-Berdal, B. Souyri, G. Achard, Coupling of geothermal heat pumps with thermal solar collectors, *Applied Thermal Engineering* 27 (2007) 1750-1755.
- [10] V. Trillat-Berdal, B. Souyri, G. Fraise, Experimental study of a ground-coupled heat pump combined with

- thermal solar collectors, *Energy and Buildings* 38 (2006) 1477-1484.
- [11] H.-F. Zhang, X.-S. Ge, H. Ye, Modelling of a space heating and cooling system with seasonal energy storage, *Energy* 32 (2007) 51-58.
- [12] W.B. Yang, M.H. Shi, H. Dong, Numerical simulation of the performance of a solar-earth source heat pump system, *Applied Thermal Engineering* 26 (2006) 2367-2376.
- [13] M. Inalli, H. Esen, Experimental thermal performance evaluation of a horizontal ground-source heat pump system, *Applied Thermal Engineering* 24 (2004) 2219-2232.
- [14] R. Tepe, M. Rönnelid, Solfångare och värmepump - Marknadsöversikt och preliminära simuleringsresultat, (in Swedish), Internal report at SERC, University of Dalarna, Borlänge, Sweden, 2002.
- [15] R. Tepe, M. Rönnelid, B. Perers, Swedish solar system in combinations with heat pumps, ISES Solar World Congress, Gothenburg, Sweden, Jun 15-19 2005.
- [16] G.S Virk, Final Technical Report – Publishable, Deliverable D9c, EU project: Endothermic Technology for Energy Efficient Housing in the EU (ENDOHOUSING) Project no: NNE5-2001-00565, 2008.
- [17] L. Eriksson, Boom för värmepumpar när oljepriset rusar i höjden, (in Swedish), *Ny Teknik*, 2004.
- [18] M. Moran, H. Shapiro, *Fundamentals of engineering thermo dynamics*, second ed. Wiley, New York, 1993.
- [19] IVT, Swedish heat pump and related products manufacturer, <http://www.ivt.se>, accessed 2009-02-03.
- [20] SVEP, The Swedish heat pump society, <http://www.svepinfo.se>, accessed 2009-02-03.
- [21] U. Kronström, Personal communication. IVT (Swedish heat pump manufacturer), Technical manager, <http://www.ivt.se>, accessed 2009-02-03, 2009.
- [22] Swedish Energy Agency, Bra att veta om bergvärme (Good to know about ground coupled heat pump systems), (in Swedish), <http://www.energimyndigheten.se>, accessed 2009-02-03.
- [23] F. Karlsson, P. Fahlén, Impact of design and thermal inertia on the energy saving potential of capacity controlled heat pump heating systems, *International Journal of Refrigeration* 31 (2008) 1094-1103.

Figure captions

Fig. 1. A drawing showing the ENDOHOUSING flat panel USC (a) and a picture of the roof-integrated flat panel USC, installed at the Swedish demonstration site in Sandviken (b).

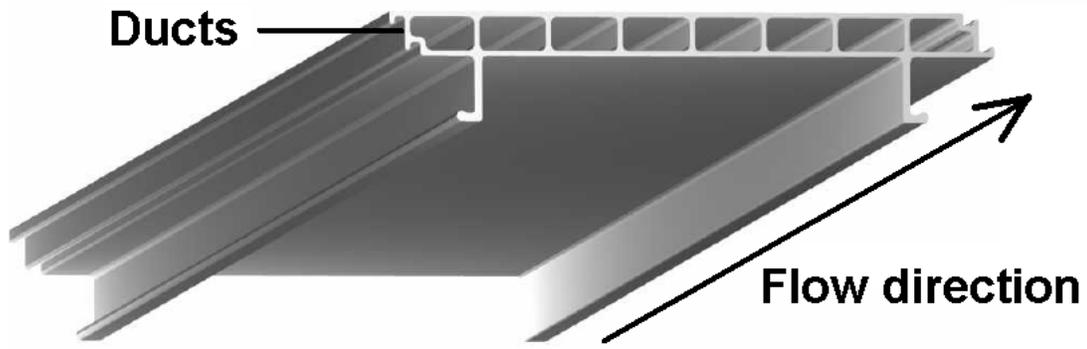
Fig. 2. A system drawing of the Swedish Endosite which schematically presents the flows and system components and operation. The CP's next to the HP are actually built in the HP. System (temperatures and flows), outdoor climate (temperature, solar radiation, relative humidity and wind speed), indoor climate (temperature) and HP (electrical power use) parameters were/are measured.

Fig. 3. The GHE installed for thermal storage in the ground (via the USC) and to be used as an HP energy source (see also Fig. 2).

Fig. 4. (a) Annual variation in SPF_{HP} per month. (b) Annual variation in SPF_{SAHPS} per month. (c) Annual variation in DHW to total HP thermal output ratio per month. (d) Annual variation in CPs (GHE and USC) to HP power input ratio per month. (e) Annual variation in normalised difference in SPF_{HP} to SPF_{SAHPS} per month. (f) Annual SPF_{HP} and SPF_{SAHPS} .

Fig. 5. (a) Incoming and outgoing GHE fluid temperatures in 2006. (b) Incoming and outgoing GHE fluid temperatures in 2007–2008.

Fig. 6. March 2006: (a) Evaporator inlet temperature when the HP is running. (b) Condenser outlet temperature. May 2007: (c) Evaporator inlet temperature when the HP is running. (d) Condenser outlet temperature. July 2007: (e) Evaporator inlet temperature when the HP is running. (f) Condenser outlet temperature.

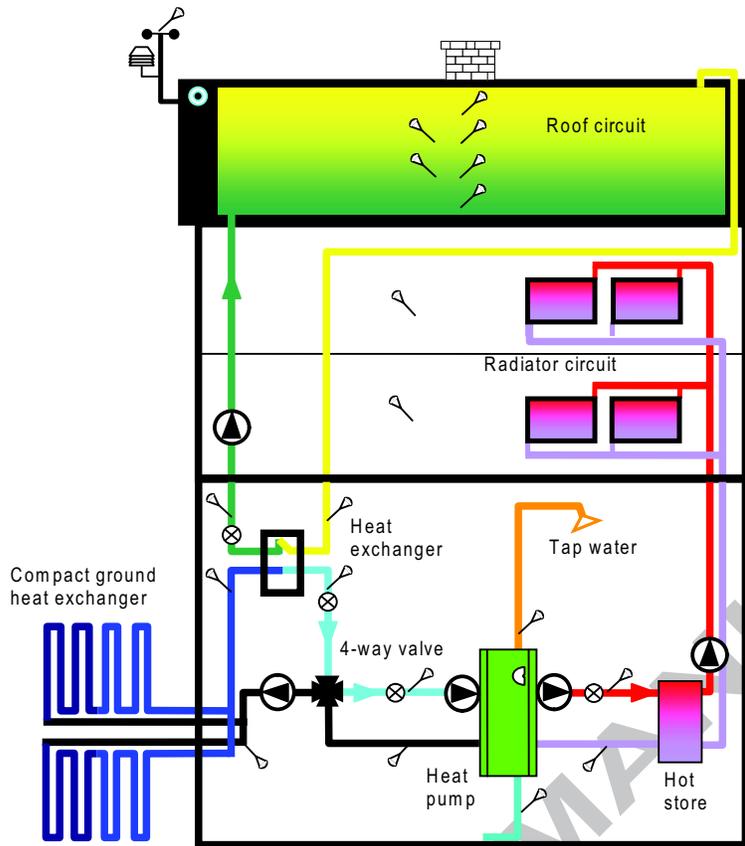


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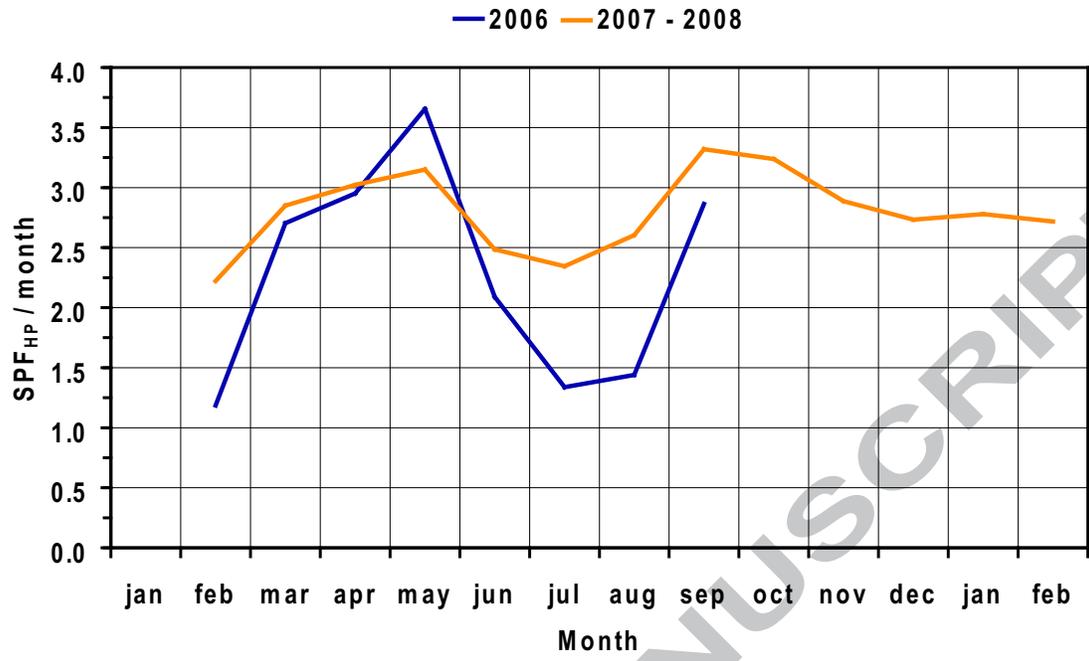


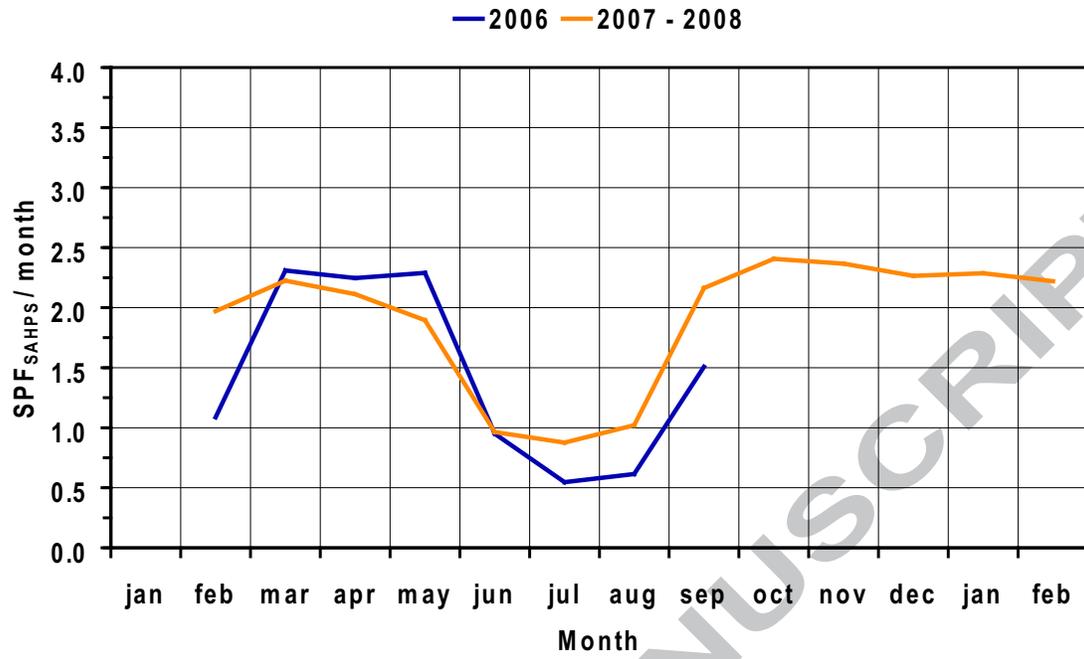
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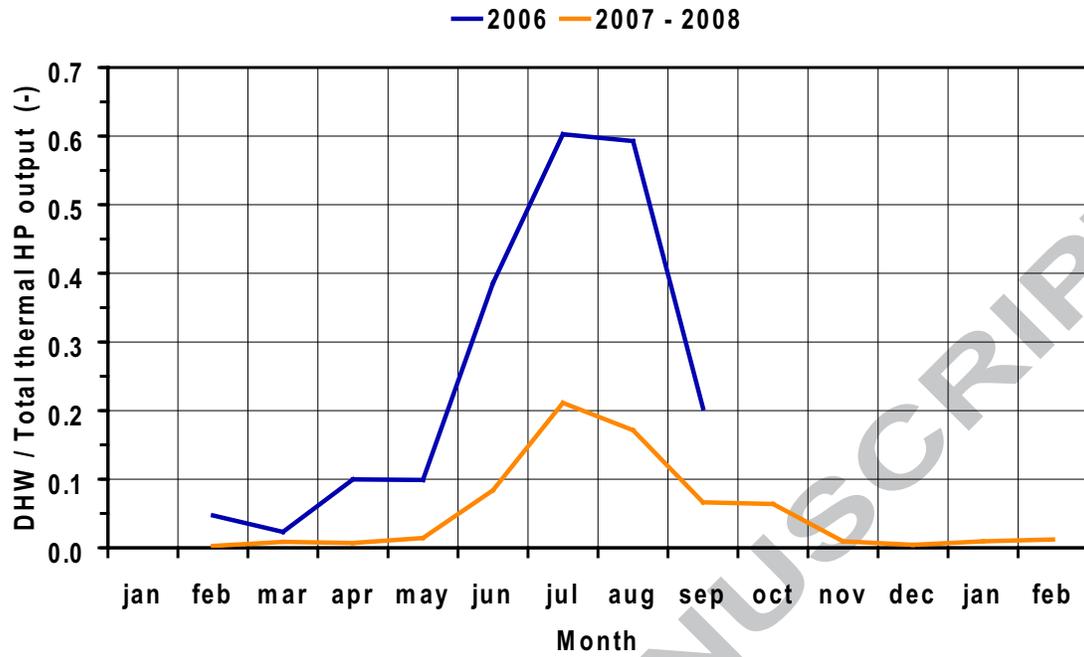
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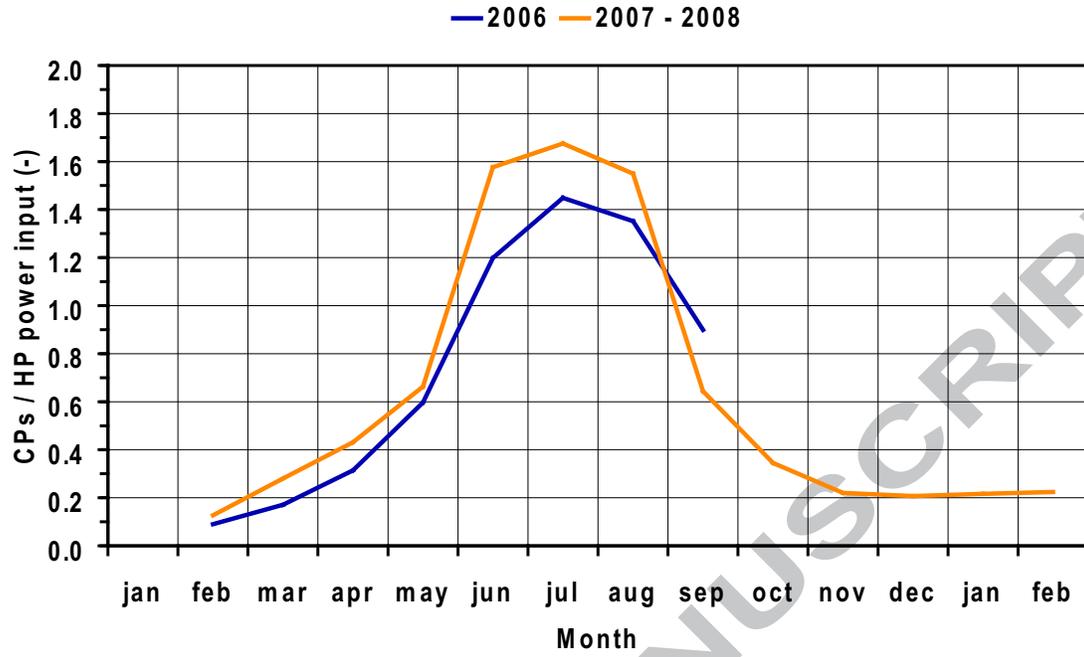


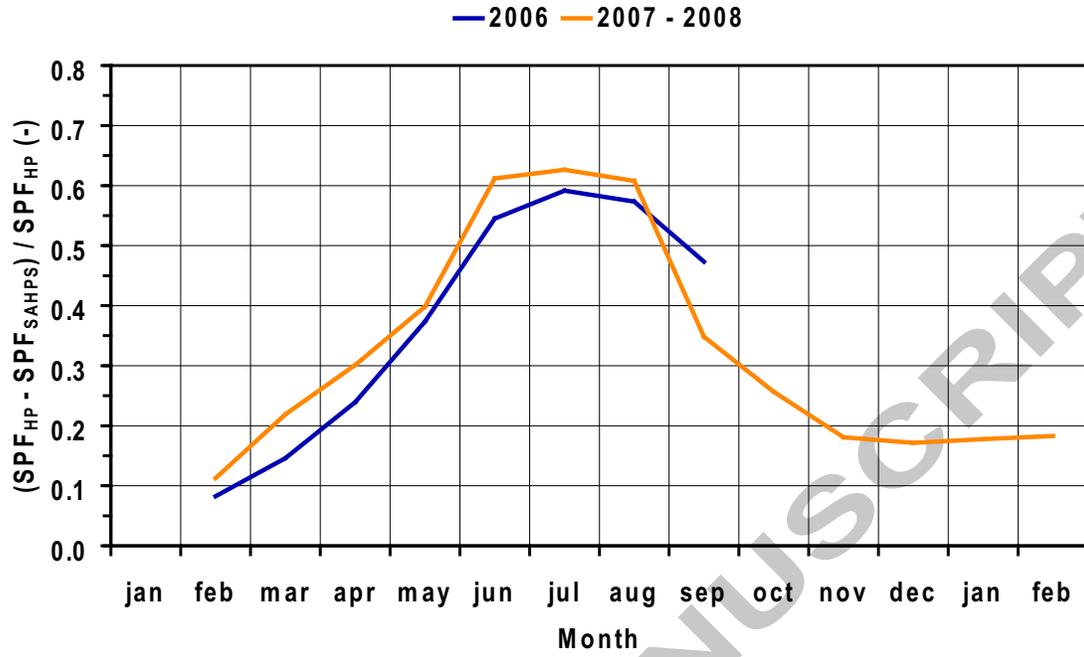


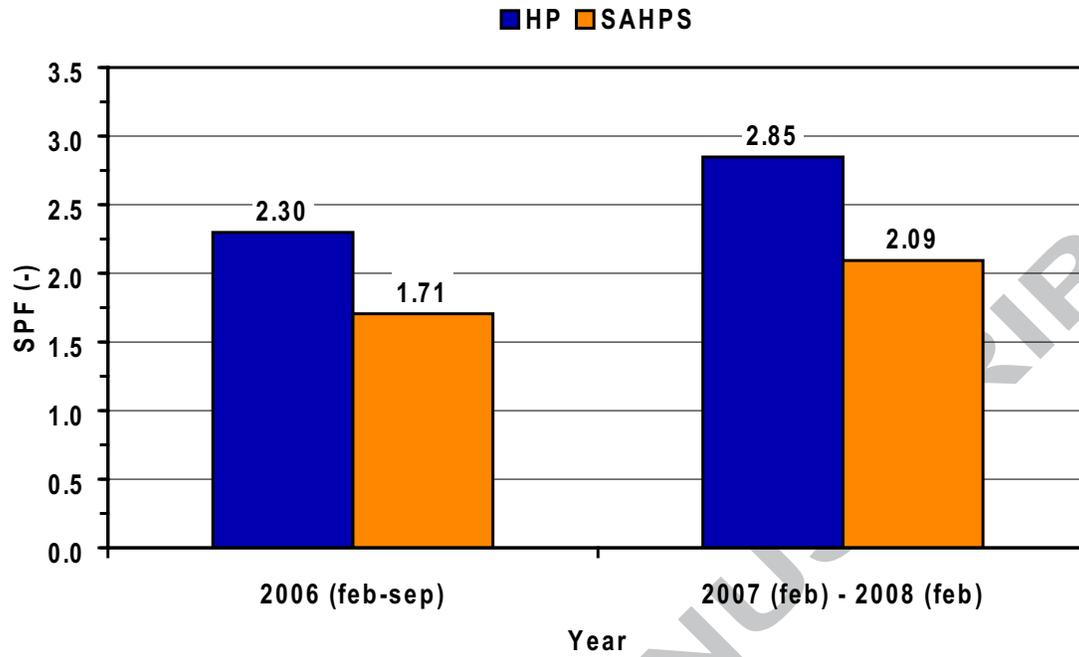




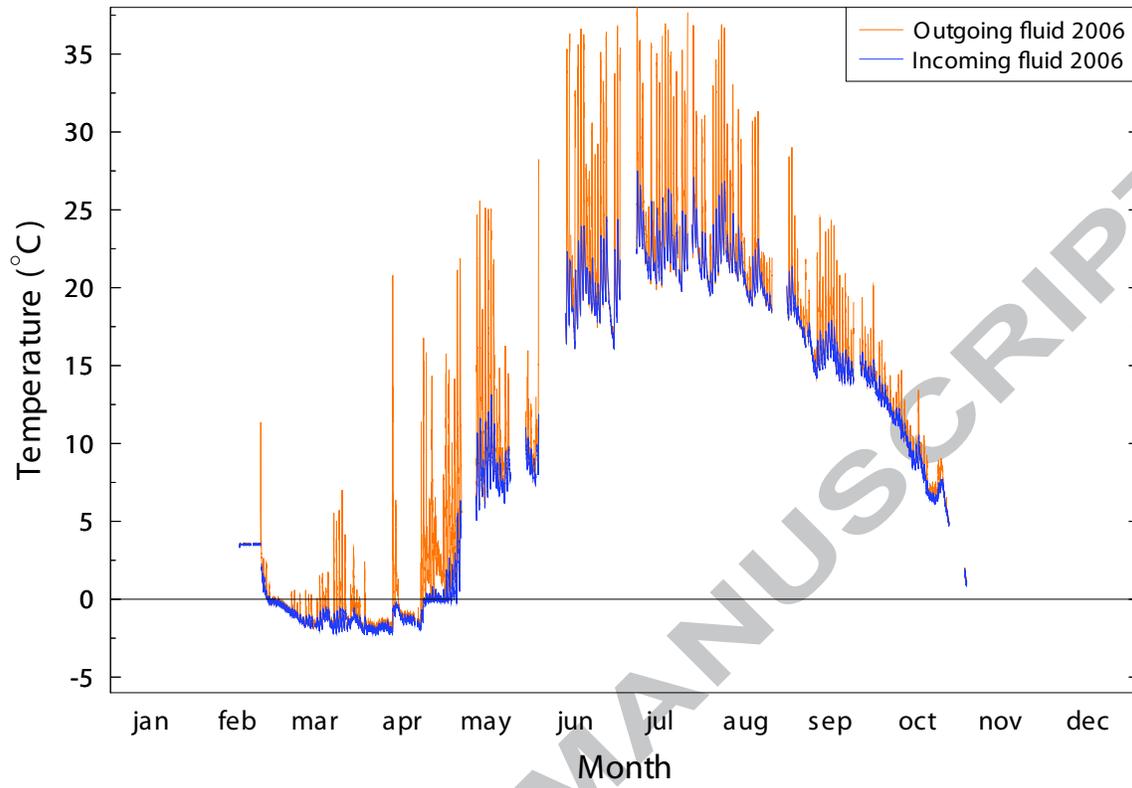








GHE temperatures at endosite Sandviken, Sweden



GHE temperatures at endosite Sandviken, Sweden

