EVALUATING ENVIRONMENTAL BENEFITS OF GROUND SOURCE HEAT PUMPS: THE STRENGTHS AND WEAKNESSES OF COP AND SCOP[i]

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Abstract : In North America, many governments and utilities base their grants and financial assistance program on the theoretical coefficient of performance (COP) of heat pumps at a fixed temperature as determined by test carried under CAN/CSA-C13256 or CSA C748-94(2005). In Canada a thorough analysis of ground source heat pump (GSHP) design also indicates that many designers tend to undersize their systems, relying on back-up energy systems for part of the annual heating loads. This tendency to undersize systems reflects C-448 Standard's recommendations to design at between 70% and 105% of design heating load. Independent studies conducted on Canadian residential GSHP systems concluded that the seasonal coefficient of performance (SCOP) show total-system performances on average, 15% below the laboratory tested applicance COP. We conclude that simple claimed energy efficiency and environmental advantages reflect wishful thinking based on faulty logic about COP. This paper presents technical analysis between the theoretical COP of the heat pumps and the SCOP of installed systems under real life operating conditions.

Key Words: COP, Seasonal COP, optimization, geothermal heat pump, design

1 INTRODUCTION

The Canadian GeoExchange Coalition (CGC) has certified more than 14,000 residential ground source heat pump (GSHP) systems during 2007 - 2010, collecting technical information which allows the CGC to better characterize markets. As importantly as better understanding markets, this unique technical knowledge greatly helped CGC develop more accurate computer assisted design & analysis tools. Four years into the process, the CGC is now in a position to challenge some market restrictions caused by existing standards, and to recommend government and utility program improvements.

This paper focuses on the difference between the reported coefficient of performance (COP) of a GSHP unit as established, under laboratory controlled conditions, by standard *CAN/CSA-C13256-1-01 Water-source heat pumps – Testing and rating for performance – Part 1: Water-to-air and brine-to-air heat pumps* (hereafter C13256) and the real field system performance measured by the seasonal COP (SCOP). We will first talk briefly about GSHP design practices in Canada as prescribed by existing standards and discuss GSHP performance under varying entering water temperatures (EWT). We will then present estimated SCOP calculations produced by a new innovative computer assisted system design and analysis tool. Finally, we will present a comparative analysis of estimated SCOP using the CGC tool with real SCOP measured on existing systems.

2 REGULATED DESIGN REQUIREMENTS

Design and installation of residential GSHP systems in Canada are governed by *CAN/CSA C448.2-02 – Design and Installation of Earth Energy Systems for Residential and Other Small Buildings* (hereafter C448). Article 10.3.1 of this standard specifies that:

> The heat pump(s) shall be sized in such a way that their rated heating capacity, at the minimum entering liquid temperature (0^{o}C (32^{o}F for closed-loop systems and 10^{o}C (50^{o}F) for open systems), is not less than 70% of the building's design heat load. The combined output of the heat pump and any supplementary heat shall be equal to or greater than 100 % design, but the heat pump shall not exceed 105% of the design heat loss.
> ***Note:*** *The intent of this clause is to ensure that the heat pump supplies more than 90% of the building's annual space heating energy load.*

The standard thereby requires a minimum heating capacity for the heat pump appliance, relative to a building's heating need. However, there is nothing that will guarantee that the unit will be able to provide the full range of this heating capacity, because the system is not referred to as a whole: standard C448 is silent about the minimum entering water temperature of the loop in heating mode, for example. According to C13256, the GSHP unit EWT for a closed loop is 0^{o}C and 10^{o}C for an open loop. In applications, there is no way to guarantee this temperature. Standard C448 does not require any minimal water temperature for system design, and rightly so. (No minimum EWT can be required since EWT is actually dictated by a variety of factors including financial parameters).

As stated above, the minimum heat pump capacity of 70% in standard C448 aims at ensuring that the unit will provide 90% of the building's annual space heating energy load. Figure 1 illustrates the concept. The reader will note that this 70% rule overestimates the minimum capacity required to provide 90% of the building's annual space heating energy load. We will discuss this issue in further detail in the next section of this paper.

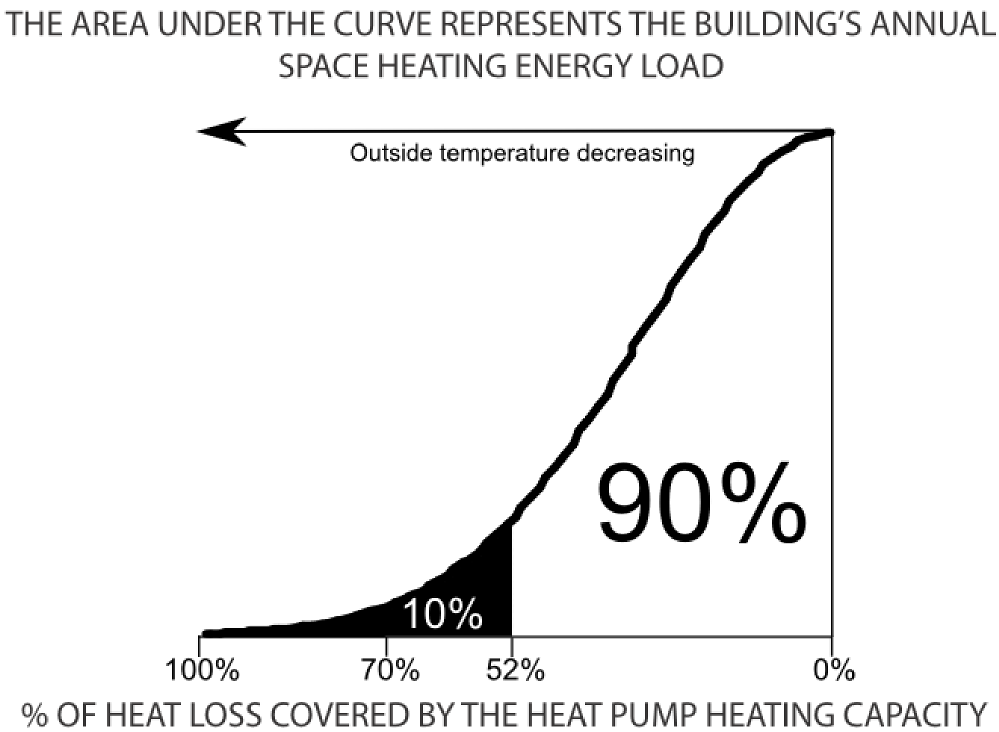

Figure 1 – Illustration of clause 10.3.1 of CAN/CSA C448.2-02

Standard C448 does refer to standard C13256, which mandates a specific minimum COP for the heat pump unit, according to the type of GSHP system installed. Minimum COP stated in C13256 includes:

- Ground water heat pump (EWT = 10°C), minimum COP = 3.6
- Ground loop heat pump (EWT = 0°C), minimum COP = 3.1
- Water loop heat pump (EWT = 10°C), minimum COP = 3.6

Here again, there is nothing to guarantee that the heat pump unit will not have a lower field performance since the EWT can be below those established in C13256.

In reality, perhaps as many as 75% of GSHP systems in Canada will function with EWT below 0°C in times of intense atmospheric cold. The heat pump unit ratings established at 0°C are therefore not actually representative of the operating conditions for GSHP systems in Canada. From industry discussion, we believe that current heat pump ratings are based of theoretical EWT originally set for average climatic conditions, where ground temperatures are higher than in Canada. As an adjustment based on ISO 13256, C13256 was never appropriately adapted or adjusted for Canadian climatic conditions.

3 HEAT PUMP PERFORMANCE: COP VS SCOP

Many factors will affect the performance of a GSHP unit but the most important are water flow, air flow, and heat pump EWT. Comparing two GSHP systems where one heat pump appliance tests at a higher COP, assuming a fixed EWT, this will not necessarily be more efficient than a system equipped with a heat pump with a lower COP over a full year of operation.

In reviewing systems for CGC Certification, we have found that design EWT is not the same for all systems installed in Canada. The design EWT is the minimum water/brine temperature at the entry of the heat pump during the year. The system performance will depend on the design EWT as set by the designer, as well as the seasonal temperature fluctuations where the system is installed. In heating mode, this temperature will increase when the system operates at only a portion of its full load, which in turns increases the performance of the unit.

The system COP will fluctuate throughout the year and over time, hence the importance to look at the SCOP rather than the rated COP of the heat pump unit or any instantaneous COP of the system. For this reason it will eventually become very important to use a transitory mathematical model when trying to estimate the impact multiple variables have on a GSHP system. The SCOP is much more representative of real life system performance because also it takes into consideration all the parameters of a GSHP system as well as all the site specific conditions.

Our experience' demonstrates that problematic systems rarely show fluid temperature which fall bellow design EWT. However, designers or equipment actually installed regularly reflect equipment selection and design choices made at room temperature. Additionally, it is common for a residential project to get its flow balanced at start-up only, when EWT is around 12ºC. When this temperature falls, viscosity increases greatly and we see an adverse effect of both: 1) higher pressure drop (per the standard Darcy-Weisebach equation) and 2- a lesser Reynolds number, meaning less heat exchange within the pipe. Both phenomena combine and can easily denigrate system performance, to a point where the total system will simply fail. We have concluded that for this reason among others, sizing a pump equipment choice at room temperature, with a rule of thumb guide for antifreeze, is a serious and somewhat common mistake.

Figure 2 shows the relationship between the COP and the EWT of four GSHP units available on the market. These heat pump units all have the same nominal heating capacity and their performance ratings were all set according to C13256. The reader will note that Model No. 4 has the lowest efficiency on the first EWT temperature range (below 4°C) but then has the second best efficiency in the second EWT temperature range. On the other hand, Model No. 1 is the most efficient over the first temperature range but past 4°C, on the second temperature range, it becomes the less efficient. In other words, comparing GSHP unit performances calculated at a fixed EWT (for a COP) will provide inaccurate results for entering water temperatures other than 4.0 degrees, as ratings do not reflect actual system performances in real life working conditions over time (SCOP).

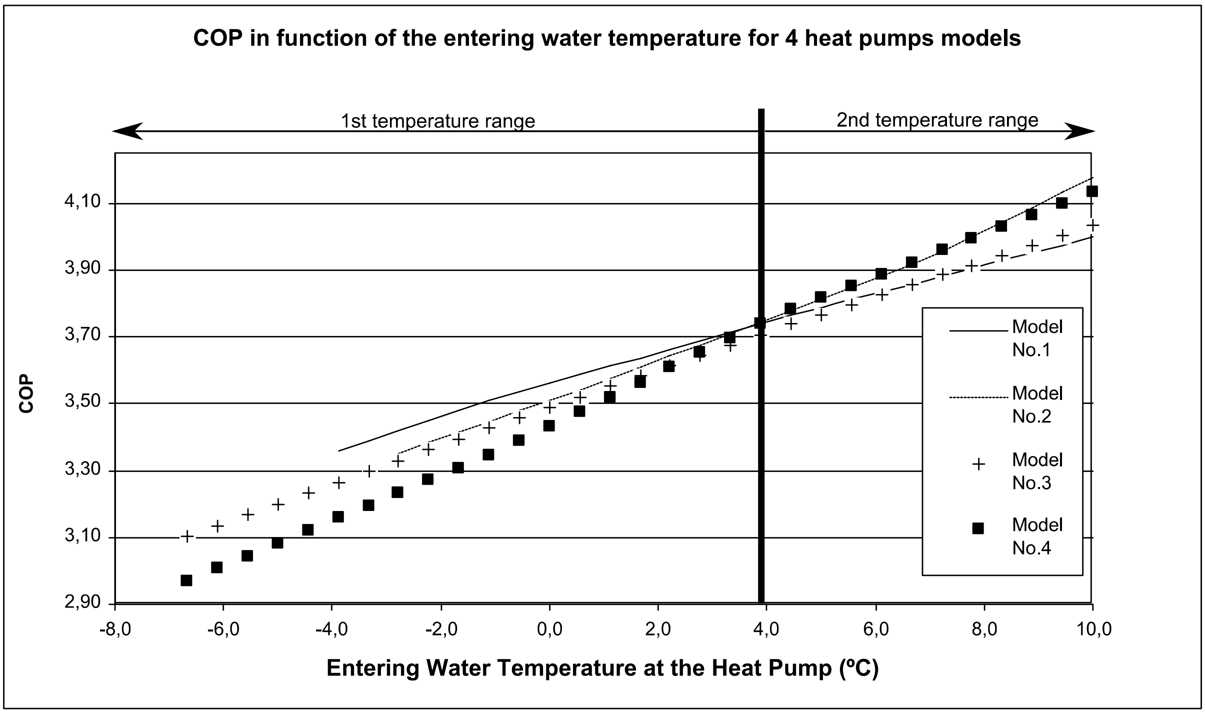

Figure 2 – Four heat pumps models showing their COP in function of the entering water temperarture (EWT)

4 ADVANCED GSHP SYSTEM PERFORMANCE SIMULATION TOOL

Unfortunately for our purposes, a GSHP system is constantly in a transitory regime where variables affecting the operation of the system are not constant. For example, heat extraction or rejection to the ground will vary on a daily basis and affect the ground temperature over time. This temperature variation over time can have a beneficial or and adverse effect on the system as a whole. As far as possible, the system designer will attempt to optimize the ground temperature in the first years of operation and stabilize it over time. For vertical boreholes, CGC training specifies a design horizon of ten years for system designers.

Most residential design software on the market is not able to address minimum requirements set in standard C448. In CGC's staff and member-reported experience, current design tools are often too simplistic, are not all user friendly and most do not consider important design parameters such as grout properties, borehole diameters as well as thermal interference between boreholes. In addition, the choice of meteorological regions is limited to a few cities per province. This is too little for a country the size of Canada where climatic conditions are often quite different a few km apart.

To address these weaknesses, CGC staff engaged in R&D activities over 2010 and developed an innovative and more advanced computer assisted design and analysis tool. For closed vertical GSHP systems, this CGC tool uses the commercial system design method proposed by Kavanaugh and Rafferty (1997). The software produces an estimated SCOP based on the BIN method, and the BIN calculation is based on the SCOP estimation method presented in ASHRAE (2005).

To the best of our knowledge, this is the only design tool available in Canada that produces a BIN table based on accurate municipal meteorological data as well as other design parameters not considered by other software. For residential applications, the CGC tool is also more accurate as it considers the overall system performance based on all system components, not only the rated performance of a heat pump unit. When used in conjunction with C448 requirements, the CGC tool provides a much better estimation of the 70% / 90 % design requirement and also produces a more credible SCOP.

5 CONTRASTING COP AND SCOP THROUGH FIELD MONITORING

The technical observations in this section of the paper are based on CGC's staff technical knowledge acquired through the CGC market transformation initiative. Modeled data presented in the various figures are based on scenarios run using the CGC design and analysis tool.

It is current practice for system designers to "play" with the maximum heat pump unit capacity at 0^oC to attempt to reduce the cost of a GSHP system. Many designers have understood that a design under the 70% minimum requirement of C448 (see Figure 1) will nevertheless result in an outcome where the GSHP system will deliver more than 90% of the annual energy load of the heat pump unit. For example, many decide on a 15 kW heat pump rather than a 20 kW unit because instead of designing at 85% of rated capacity, they can design at 60% and still provide more than 90% of the annual space heating energy load.

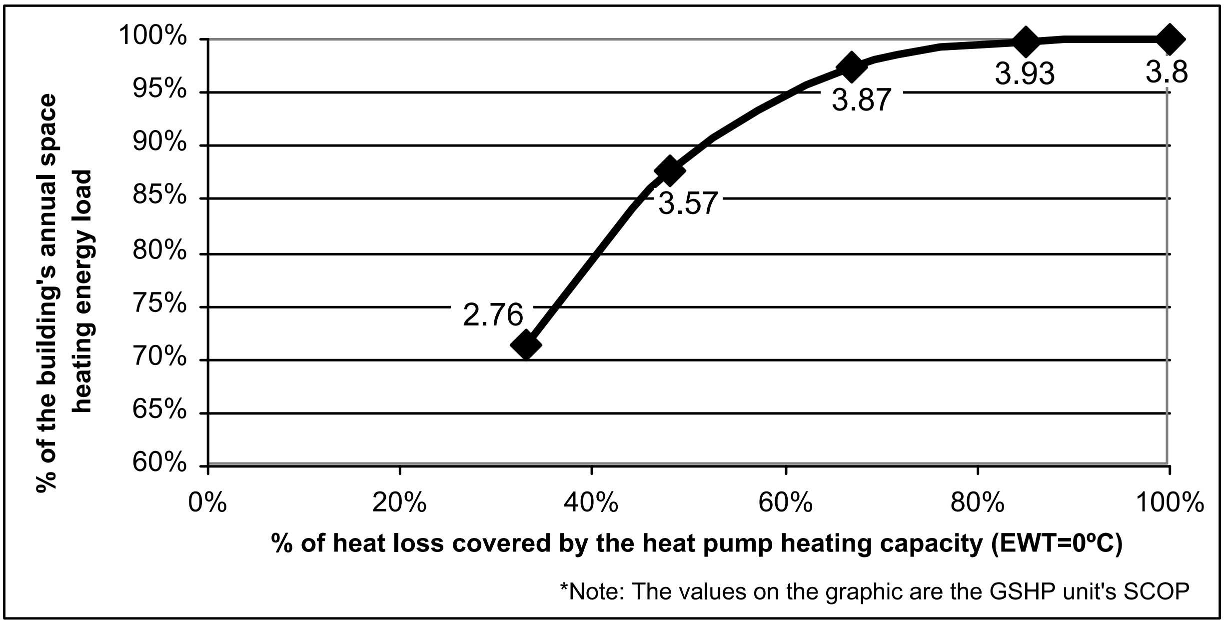

Figure 3 – Percentage of annual energy contribution in function of the percentage of heat loss covered by the heat pump (EWT=0ºC)

Figure 3 above presents the annual percentage of energy delivered for five different heat pump unit sizes, of the same model from the same manufacturer and for the same building.

We can clearly see that the slope of the curve decreases rapidly when the heat pump unit heating capacity, at a fixed EWT of 0°C, falls under 70 % of the building's design heat loss. However, we note that three of the heat pumps nevertheless deliver more than 90% of the annual energy load when the heat pump unit heating capacity, again at the fixed EWT, is higher than 52 %.

As observed by the CGC, Canadian designers often choose a design EWT of less than 0°C, depending on their location. Where this happens, the heat pump unit's coefficient of performance will be lower than its estimated performance at 0°C, and a heat pump with a yet higher capacity may be required to provide 90% of the annual energy load (Figure 2).

Let's take an example. In Figure 4, we illustrate results with the same heat pump Model No. 1 and Model No. 4 as was presented in Figure 1. The SCOPs are calculated for different EWT. The operating simulations for the two heat pump models are simulated for two different buildings. The first simulation is for a building where the GSHP system provides 70 % of the nominal heating load and the second for a building where the GSHP system provides 50 % of the nominal heating load.

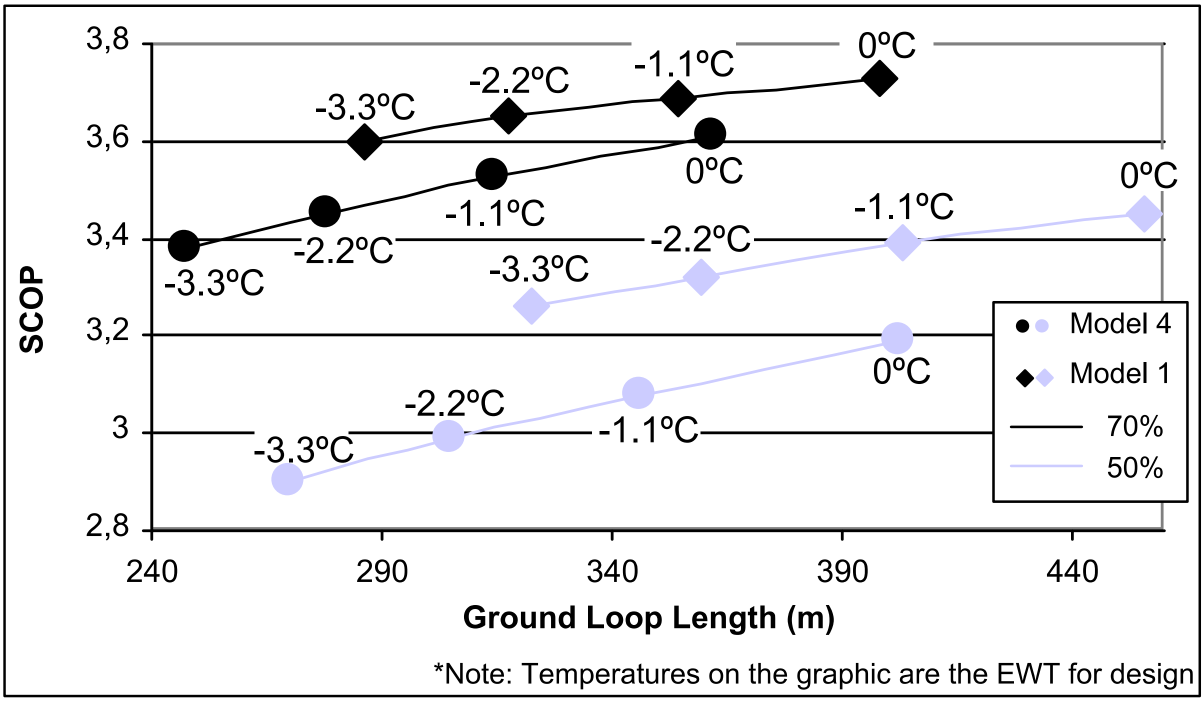

Figure 4 – SCOP of two different heat pumps with the same nominal heating capacity in function of the ground loop length (% of heat loss covered at 70% and 50%)

Some conclusions follow from examination of Figure 4:

1) For the same loop length, the heat pump unit with the highest rated COP (Model No. 1) produces the largest SCOP even when the design EWT is decreased.
2) For a load of 70%, the heat pump unit with the smallest COP (Model No. 4) may have the same SCOP as Model No. 1 (with the higher COP) but the loop length will be higher for Model No.1.
3) Designing at 50% rather than 70% for the same loop length considerably affects the overall system performance for both heat pump models.

4) The size of the ground loop for the heat pump unit with the smallest COP (Model No. 4) is smaller than for the heat pump unit with the higher COP (Model No. 1) for the same minimum EWT (-3,3ºC). The SCOP will also be lower.

If the customers were to understand these hypotheses, there could be a major impact on GSHP market penetration. This means that the design of a GSHP system includes a more detailed economic analysis - essentially the consumer's financial and cash capacity - before finalising the residential design. For example, the less efficient heat pump (Model No. 1) will likely be less expensive than Model No. 4, but will also require a smaller loop. For an EWT of -3.3^{o}C, the customer will lose the benefits of some SCOP units (0.2) but will save about 45 meters in drilling and loop costs. With a relatively high drilling cost of $20 per foot, this amounts to approximately $2,800 or approximately a 10% cost reduction for the average Canadian closed vertical loop system (CGC 2010).

For the end-user, this difference in GHSP system price may make a real difference in the purchase decision. By designing in this manner, and assuming elastic GSHP demand (Kantrowitz and Tanguay, 2011), a contractor would be in a position to compete very efficiently in the market place and increase his overall revenues thanks to higher sales volume.

While this may be counter-intuitive to many, efforts to increase the performance requirement for heat pump appliances may well produce unexpected results by putting pressure on the overall system price. All things considered, the overall economic efficiency of a GSHP system could be better with a less efficient heat pump unit. This is an illustration of the economist's iron law of diminishing returns.

Andrushuk (2009) showed that GSHP system SCOP for a sample of ten homes in Manitoba were often lower than the heat pump unit COP provided by the manufacturers. (One house had an open loop system and was excluded from our analysis). In the study, the average system SCOP was found to be 2.8 while the average heat pump appliance COP was 3.6.

Though the sample size of this monitoring project is small, we do not assert statistical significance for the system or unit performance, only that the case is illustrative of methodological processes. In fact Andrushuk (2009) has executed outstanding work relative to the general lack of monitoring and field studies done in Canada to date. CGC has engaged in bursaries to encourage university and college students to increase academic attention on the field for this reason among many others.

One significant aspect of this monitoring project is the fact that in their field calculations of SCOP, Andrushuk (2009) considered the energy used to circulate the heat transfer fluid in the GHSP systems. According to C13256 however, the energy spent on pumping is practically not included in the heat pump unit COP calculation. They only consider the energy used to overcome the internal resistance (pressure drop) of the heat pump. This represents approximately 7% of the circulating energy for a horizontal loop and 15% for a vertical loop. This means it will affect about 1.5% to 3% the heat pump performance. Assuming a tolerance variation of the coefficient of performance for each different heat pump going out of a manufacture, this portion of energy can be neglected.

To isolate a proper comparison of heat pump unit COP and heat pump unit SCOP only, the energy used for pumping is not included in the present paper. By doing so, we are reducing the influence of variables such as the type of heat exchanger (vertical, horizontal, open loop), the type of antifreeze in the heat transfer fluid, the flow rate, the pipe diameter, and ground loop configuration. We then recalculate the field-monitored results obtained in Andrushuk (2009), using CGC's design and analysis tool. The results are presented in Figure 5.

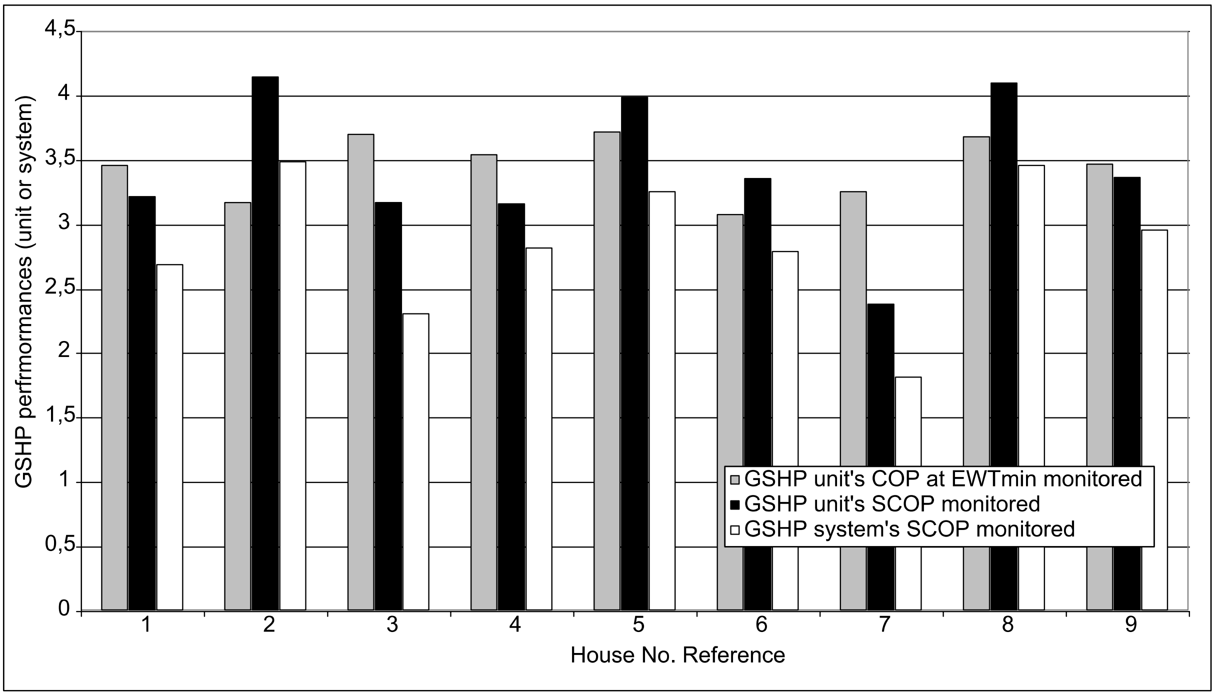

Figure 5 – Nine geothermal systems with their different performances (unit's COP/SCOP, system's SCOP)

The various COPs shown (taken from manufacturers specifications catalogues) are associated with the minimum EWT measured during the year. In theory, the heat pump unit COP must be lower than the system SCOP since, by definition, the loop temperature is never under the measured minimum EWT.

In the context of this paper, and considering the results presented in Figure 5, houses 1, 3, 4, 7 and 9 will be excluded from our analysis. Many factors could explain why the adjusted SCOP is lower than the COP at the measured minimum EWT:

- The heat pump unit could be at the end of its life cycle;
- The heat pump was too large for the building needs and cycles too much;
- An inadequate commissioning (flushing and purging);
- System repairs done with non-original manufacturers components;
- An under-designed air or water distribution system;
- A poorly calibrated heat transfer fluid flow at the heat pump entrance;
- Poorly calibrated monitoring equipment;
- Controls that are not well adapted to the system or poorly programmed;
- Other factors.

When simulated with the CGC design and analysis tool, we found that the estimated SCOP for the four remaining houses matched almost perfectly the real monitored SCOP with a deviation of less than 2%. The results are presented in Figure 6.

Puttagunta (2010) performed a similar analysis with GSHP systems installed three homes in Connecticut, Virginia and Wisconsin. Using residential energy modelling tools which account for real-world fan and pump energy, they obtained estimated results which were relatively close to the monitored SCOP.

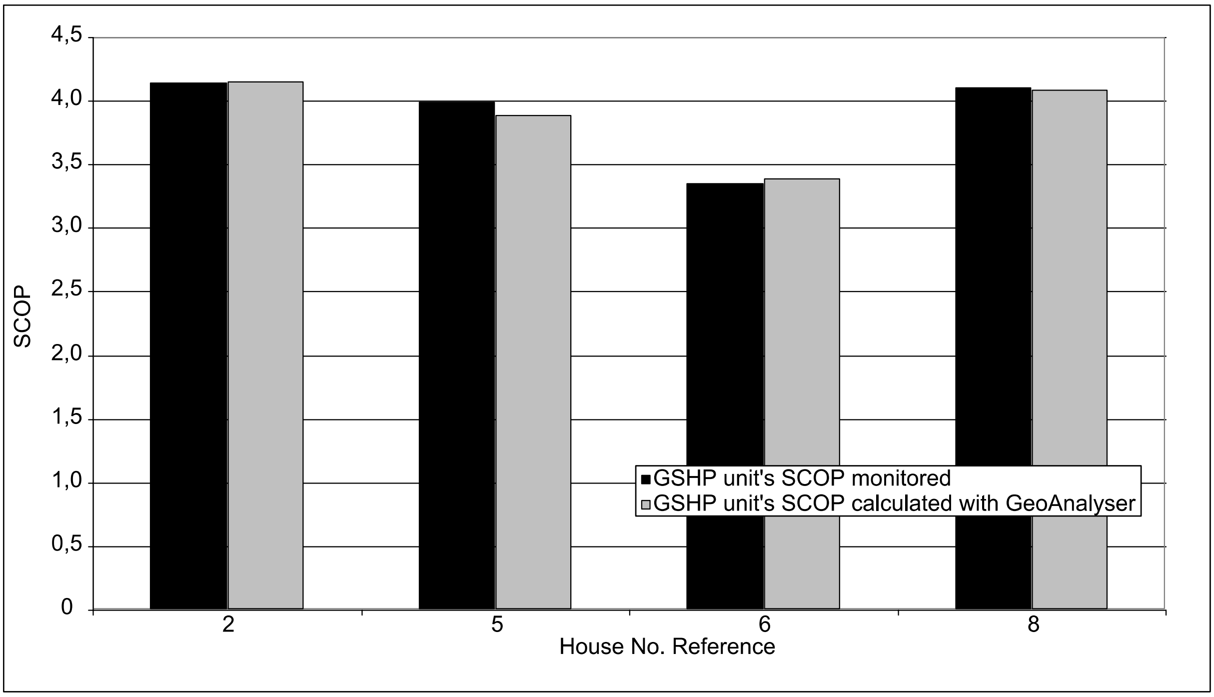

Figure 6 – Comparison of four GSHP systems SCOP-monitored in real field applications versus calculated SCOP with the CGC design and analysis tool

Our analysis also shows it is possible to accurately estimate the GSHP system SCOP using the CGC computer assisted design and analysis tool. Further R&D presently conducted by CGC staff will lead to the addition of new design parameters, including consideration for the energy used for pumping. This is a key element in improving the software's estimation of SCOP. While researching this paper, we found that a system's seasonal performance is directly affected by the energy used for pumping in an amount ranging from 10 to 20%.

6 CONCLUSION

The requirements of standard C448 regarding the minimum system sizing are inadequate as they fail to reflect the GSHP system capacity to deliver at least 90% of the building's annual space heating energy load with heat pump capacity much lower than the minimum set by the standard at 70%.

Heat pump unit ratings also do not adequately reflect the true performance of a GSHP system. A heat pump unit X, with a higher rated COP than a heat pump unit Y, at a fixed EWT does not imply that the GSHP system equipped with unit X will have a better performance than the GSHP system equipped with unit Y. In fact it seems that a higher unit COP may be correlated with lower system SCOPs – this is a key area for further research. Many variables will influence EWT variability over time: heat exchanger configuration, the type and concentration of the antifreeze solution, geology, hydrogeology, pipe diameters, flow speed, ground temperature variations, changing energy needs of the building served, overall building characteristics, an inadequate commissioning, and so on.

The CGC has developed a unique computer assisted design and analysis tool. This tool has the capacity to accurately estimate the real GSHP system SCOP. Using this software, it is now possible to optimize GSHP designs to the point where a contractor could guarantee the efficiency and energy savings of their installations.

CGC concludes that the estimated GSHP system SCOP should be used for future financial assistance programs rather than the heat pump unit COP. The former metric, though more complex, reflects the real potential energy costs and savings, and therefore energy and climate impacts, of GSHP systems.

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