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Long-term GSHP system performance measurement in the USA and Europe

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ABSTRACT

This paper presents an overview of the International Energy Agency (IEA) technology collaboration program Heat Pumping Technologies (HPT) Annex 52, "Long term performance measurement of ground source heat pump (GSHP) systems serving commercial, institutional and multi-family buildings." This project, which ran from 2018 through 2021, focused on measuring the performance of larger GSHP systems, going beyond energy use intensities which commingle the performance of the building envelope, occupancy effects and the system performance. Instead, performance factors were calculated, similar to coefficients of performance, but measured over various time intervals and system boundaries. The primary objectives of the Annex were refining and extending methodologies to better characterize system performance in larger buildings, creating a library of quality long-term measurements in the form of case studies, and providing guidelines for instrumentation, uncertainty analysis, key performance indicators, data management and quality assurance.

This paper summarizes the Annex outcome and illustrates use of the Annex boundary levels with a comparison between typical European and US GSHP systems. It is anticipated that this experience and the guidelines produced as a result of this experience will lower the cost and improve consistency and quality for future performance measurements.

INTRODUCTION

The energy consumption of building heating and cooling systems often exceeds design expectations. This difference is often referred to as the "building energy performance gap." (de Wilde 2014, Scofield 2009, Spitler 2020). Reasons for the gap include errors in design and installation, as well as non-optimal operating and control settings. Problems that don't lead to occupant discomfort may neither be detected nor mitigated for months or years unless performance measurements are made. Despite the need for such measurements, published results from long-term performance monitoring of building energy systems are scarce. Instead of long-term measurements, energy use intensity (EUI) is a widely used indicator of building energy consumption, usually given as annual energy consumption per square meter or square foot of building floor area. As a minimum, EUI calculation requires only building utility bills and floor area. However, analyses of EUI have limitations in the difficulty to differentiate between the effects of the building envelope loads and occupants and the performance of the HVAC system. A high energy use in a building may be caused by e.g., a poor building envelope, high internal heat gains or other occupant effects, or by poor HVAC system performance. The EUI does not identify the cause(s) for the high energy use. For that we need more detailed performance measurements.

Also, in buildings that utilize ground-source heat pump (GSHP) systems the actual performance may vary widely. Gleeson and Lowe (2013) reviewed field measurements of heat pump systems for residential buildings, mainly single-family buildings, comprising 600 heat pump systems in six European countries. For larger non-residential ground-source heat pump (GSHP) systems. Spitler and Gehlin (2019) give an overview of published long-term (>1 year) measured

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seasonal performance factor (SPF) and coefficient of performance (COP) values reported in the literature for 55 systems worldwide. Such systems are necessarily more complex than GSHP systems for small residential buildings, and often include both heating and cooling as well as supplementary heating and cooling sources and heat recovery. For larger GSHP systems in particular, owners have made significant investments with expectations of high performance, hence it is important that high performance be achieved. The literature review showed that there is little or no consistency in how to measure the performance and report the results. Cost-effective measurement programs are hindered by this lack of consistency and a lack of guidance regarding measurement system design. This was the starting point of a new international collaboration project – Annex 52.

IEA HPT Annex 52

IEA HPT Annex 52 - *Long-term performance monitoring of GSHP systems for commercial, institutional and multi-family buildings* was carried out during 2018-2021 by seven participating countries: Sweden, the USA, the UK, the Netherlands, Germany, Norway and Finland. The aims of Annex 52 were to (1) survey and create a library of quality long-term measurements of GSHP system performance for commercial, institutional, and multi-family buildings, (2) refine and extend current methodology to better characterize performance of such systems with the full range of features shown on the market, and (3) provide a set of benchmarks for comparisons of GSHP systems in the participating countries.

The main publications from Annex 52 are summarized in Table 1. These publications comprise more than 1000 pages in total and are available on the Annex 52 webpage[1]. In addition, three sets of open-source measurement data from two GSHP systems have been made available. These outcomes from Annex 52 help building owners, designers and technicians evaluate, compare, and optimize GSHP systems, and provides useful guidance to manufacturers of instrumentation and GSHP system components, as well as to developers of tools for monitoring, controlling and fault detection/diagnosis. In the long run, this will lead to energy and cost savings.

Table 1. Overview of Annex 52 Guidelines and Reports

Report	Main content	Reference
Instrumentation Guideline	Overview of instrumentation that is typically required to measure the long-term performance of GSHP systems. Information about the use of heat meters and distributed temperature sensing in GSHP studies. Discusses challenges of data management and some methods to address these challenges.	Davis et al, 2021
Uncertainty Calculation Guideline	Practical introduction to calculation of uncertainties in measured performance factors for GSHP systems with the goal of helping practitioners estimate the uncertainty in performance factors.	Spitler et al, 2021a
Key Performance Indicator Guideline	Lists and defines recommended key performance indicators for larger GSHP systems. Defines and explains a new system boundary schema suitable for describing larger GSHP systems.	Gehlin et al, 2022
Annotated Bibliography	82 publications reporting at least one full season of measured data performance values (SPF, COP) for larger GSHP systems	Gehlin and Spitler, 2022a
Case Study Summary Report	2-page summaries of 29 GSHP system case studies	Gehlin and Spitler, 2022b
Annex 52 Final Report	Umbrella report summarizing the main work and results	Gehlin and Spitler, 2022c
Individual case study reports	27 individual case study reports for 29 larger GSHP systems in multiple countries.	

[1] https://heatpumpingtechnologies.org/annex52/

SYSTEM BOUNDARY SCHEMA AND KEY PERFORMANCE INDICATORS

A main contribution from Annex 52 is the development of a system boundary schema that, unlike most of the previously published system boundary schemas, is detailed and flexible enough to handle the complexity of larger GSHP systems. The starting point was the SEPEMO system boundary schema (Nordman et al. 2012), developed mainly for small heat pump systems in single family buildings, and which is widely used within the EU. The four boundaries allow analysis of the performance of different parts of the system – (1) heat pump, (2 & 4) circulating pumps on both sides of heat pump, and (3) auxiliary heating. Spitler and Gehlin (2019) evaluated six similar schemas, including the SEPEMO schema. These schemas have limitations when accounting for the complexity of larger GSHP systems, which led to the development of a new boundary schema. The Annex 52 boundary schema (Gehlin and Spitler 2021a) includes six boundaries and an indicator for use of supplemental heating or cooling (Figure 1). Every SEPEMO boundary matches one of the Annex 52 boundaries, but there is also a system boundary for the ground heat exchanger circuit (boundary 0), and one boundary that helps identifying the effect on the performance by buffer tanks (boundary 3). For boundary 1 (heat pump unit only and the electricity used for the compressor), none of the Annex 52 monitoring projects found it practical to exclude parasitic losses within the heat pump from the electricity measurement. An asterisk in the boundary level (e.g. HC5*) denotes an approximation was made – in this case including parasitic losses in the measured performance factor.

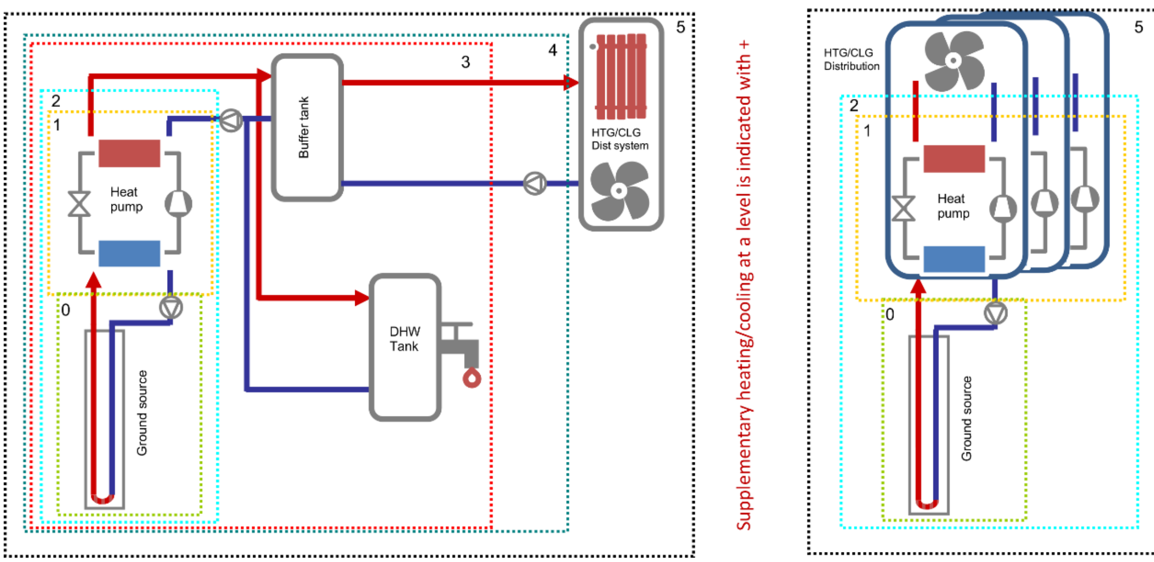

Figure 1 The Annex 52 system boundary schema applied for a centralized (left) and a distributed (right) GSHP system. Supplementary heating/cooling at a boundary level is indicated with +. (Gehlin and Spitler 2021)

A consistent and well-defined system boundary schema is paramount when analyzing the performance of a GSHP system. The performance differs depending on how the boundaries are defined. However, in the literature there has unfortunately been little consistency in the use of system boundaries. In fact, system boundaries are often not clearly defined at all, which makes it difficult to compare and evaluate the reported performance.

The Annex 52 key performance indicator guidelines (Gehlin et al. 2022) list and define a number of key performance indicators (KPIs) suitable to characterize performance of GSHP systems at various system boundaries. These include KPIs for the ground source, for the system components, and for the overall GSHP system level, as well as some KPIs for the overall building level to give an understanding for the loads on the GSHP system. While the Annex 52 scope didn't include financial indicators, several of the KPI could be extended to give financial indicators. Among other performance indicators, the guideline explains the terms COP, SCOP[2], EER and SEER, commonly used by the heat

[2] SCOP = Seasonal coefficient of performance; EER = Energy efficiency ratio; SEER = Seasonal energy efficiency ratio

pump industry to refer to KPI based on laboratory testing of a heat pump unit under one or more conditions. These KPI often have implications for codes and regulations. To distinguish between laboratory measurements and field measurements, Annex 52 promotes using the term "performance factor" when referring to field measurements, such as in the Annex 52 case study reports. The performance factor (PF) should be used with an indicator of the time period (Seasonal, Monthly, Weekly, Daily, or Binned – SPF, MPF, WPF, DPF, BPF), and with subscripts that correspond to the defined boundary conditions, e.g. H1 for heating at boundary level 1, C2 for cooling at boundary level 2 and HC4 for combined heating and cooling at boundary level 4.

All six system boundaries in the Annex 52 system boundary schema do not necessarily appear in every GSHP system. If, for example, there is no buffer tank installed in the system, the boundary level 3 does not exist, and for ground source systems with direct heating and/or cooling and no heat pump, boundary 1 does not exist and system boundary 0 and 2 become the same. For a distributed heat pump system, where there is no central heat pump, but multiple heat pump units are installed in the building, system boundaries 3 and 4 do not exist.

IEA HPT Annex 52 case studies

Annex 52 resulted in long-term measurement programs for more than 30 larger GSHP systems in seven countries (Figure 2). These GSHP systems cover a range of different building types and system applications and features. All but one of the GSHP projects have central heat pumps, as is common in Europe. The GSHP system located in the USA has distributed heat pumps in the building. As for ground sources, most of the monitored buildings use boreholes as the source for heating and cooling; four use energy piles, of which one combines energy piles with boreholes; and five use groundwater. 29 of these GSHP systems are described in individual detailed case study reports, available for download on the Annex 52 website[3].

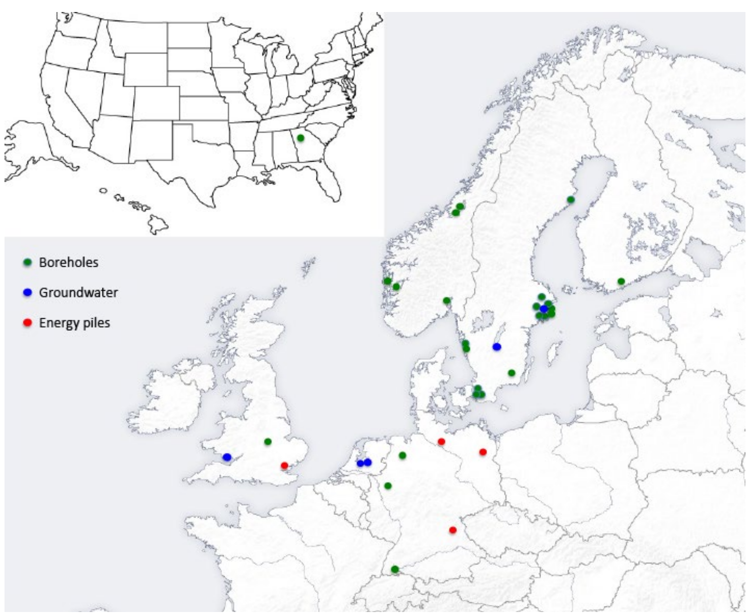

Figure 2 Monitored GSHP systems in the IEA HPT Annex 52 international collaboration project 2018-2021.

[3] https://heatpumpingtechnologies.org/annex52/documents/

A TALE OF TWO BUILDINGS

To illustrate the use of the boundary levels developed in Annex 52, we consider two of the GSHP systems – a central system and a distributed system.

The Studenthuset building

Studenthuset ("The Student Building") is a 6300 m² general purpose building used for student activities at the University of Stockholm (left in Figure 3). It was completed in 2013. The four-story building contains offices, small meeting rooms, study-booths for students and a café. Space heating and domestic hot water (DHW) are provided by a ground source heat pump (GSHP) system consisting of five water-to-water ground-source heat pumps, of nominal heating capacity 40 kW each when providing 40°C hot water for building heating. For DHW, the heat pump provides 55°C hot water, and its temperature is further increased by a Legionella protection system consisting of an electric resistance heater that raises the hot water temperature from 55°C to 60°C and a continuously-operating hot water recirculation pump. "Free cooling" is provided by circulating fluid from the ground loop to fan coil units in the building.

The bore field consists of 20 groundwater-filled boreholes in hard rock, drilled to a depth of 200 m, and fitted with single U-tubes filled with an ethanol/water mixture. The bore field is located below a landscaped courtyard, and the boreholes are drilled at an angle so that they reach under the surrounding building. Further details of the building, GSHP system and system performance are given in Spitler and Gehlin (2019, 2021b).

Figure 3 Studenthuset (left) and ASHRAE Headquarters building (right)

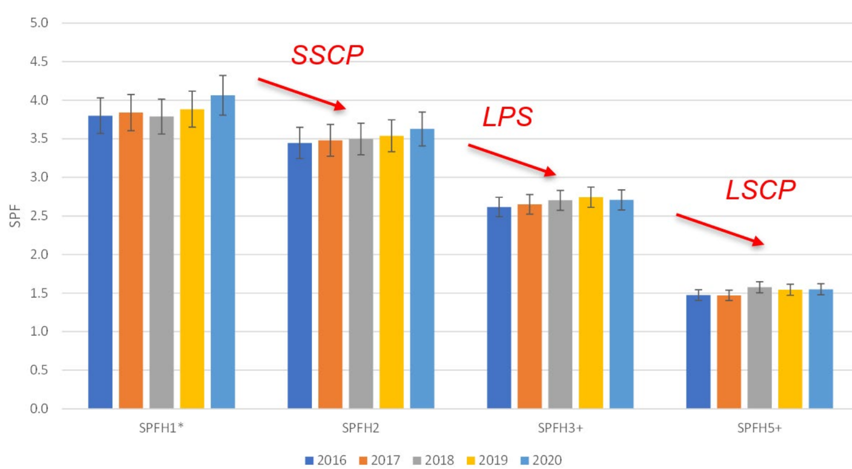

Figure 4 Studenthuset Heating SPF

Year-by-year seasonal performance factors at four boundary levels are shown in Figure 4. Although there is some year-to-year variation, the largest difference occurs as the boundary level is changed. The change in performance from boundary H1* to boundary H2 reflects the energy usage of the source-side circulating pump (SSCP). The Legionella protection system (LPS) causes the decrease from boundary level H2 to H3+. Finally, the load side circulating pumps (LSCP) consume a considerable amount of energy and significantly reduce the performance between boundary levels H3+ and H5+. Taking the year 2020 as an example, the SPF decreases from 4.1 to 3.6 to 2.7 to 1.6 underlines the importance of distribution energy in overall system performance.

Likewise, for cooling, the SPF is quite high when only considering the source-side circulating pump for the "free" cooling. However, accounting for the internal distribution energy lowers the SPF from about 35 to 3. Another ramification related to the distribution energy is that system performance can be quite good when the load is high but suffers under low load conditions. This is discussed below in the Comparison section.

The ASHRAE Headquarters building

The former ASHRAE headquarters building (right in Figure 3) was renovated in 2007-2008, and part of the renovation included installation of a GSHP system serving the 2nd floor of the building. Further details of the renovation and system performance are given by Spitler, et al. (2021b); see also references cited there. The GSHP system is configured as a distributed system with 14 water-to-air heat pumps with a total nominal capacity of 111 kW (31 ½ tons).

The closed-loop vertical borehole heat exchanger field lies under the parking lot and consists of twelve 122-m deep vertical boreholes containing single U-tube 1 ¼" nominal diameter HDPE pipes, grouted with thermally-enhanced grout. Water is circulated from the field to the 14 heat pumps with a central variable-speed pump, controlled to maintain the loop differential pressure set point. Individual heat pumps have solenoid valves that shut off the loop flow to the heat pump when it is off. Combined with the pump speed control, this has the effect of keeping flow rate to each heat pump approximately constant when the heat pump is on. SPFs for the entire system are shown in Figure 5 for a two-year period where data were available. The increase in SPF from the 1st year to the 2nd year is largely due to changing the differential pressure set point, which was found to be too high in April of 2012.

Comparison

Comparison of central and distributed ground source heat pump systems in two climates with different load profiles and different ground temperatures is difficult at best. Figure 6 is an attempt at making such a comparison. The daily overall (heating+cooling) performance factors (Boundary level 5) for the two systems are plotted against daily heating and cooling loads normalized by the maximum daily heating and cooling loads for each system. For Studenthuset, since free cooling is used, it is helpful to distinguish whether heating or cooling dominates; the days have been color-coded accordingly. This is not done for the ASHRAE HQ building since heat pumps are used for both heating and cooling.

For both systems, the performance increases as the load increases. For the Studenthuset building, this is true for all three modes, with the highest performance factors for cooling-dominated days. Even though the ground temperature is considerably cooler in Stockholm than in Atlanta, and the Stockholm system uses "free cooling" while the Atlanta system uses a compressor for both heating and cooling, the performance factors at boundary level 5 are higher for the distributed GSHP system in Atlanta than the central GSHP system in Stockholm. While this finding can't be generalized, it is a reminder that the distribution energy is quite important to the overall system performance.

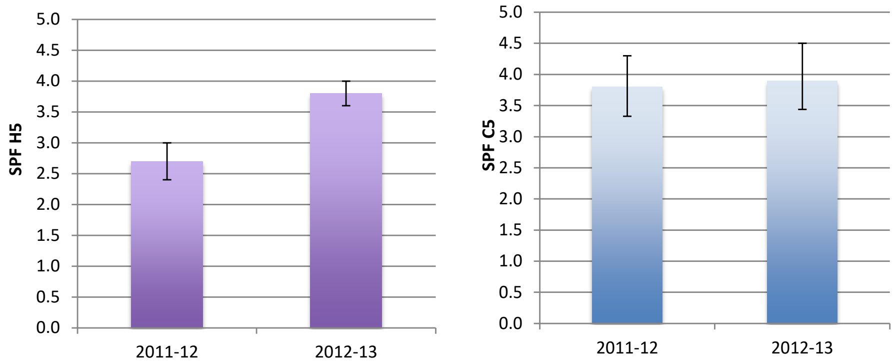

Figure 5 ASHRAE Headquarters Heating and Cooling SPF

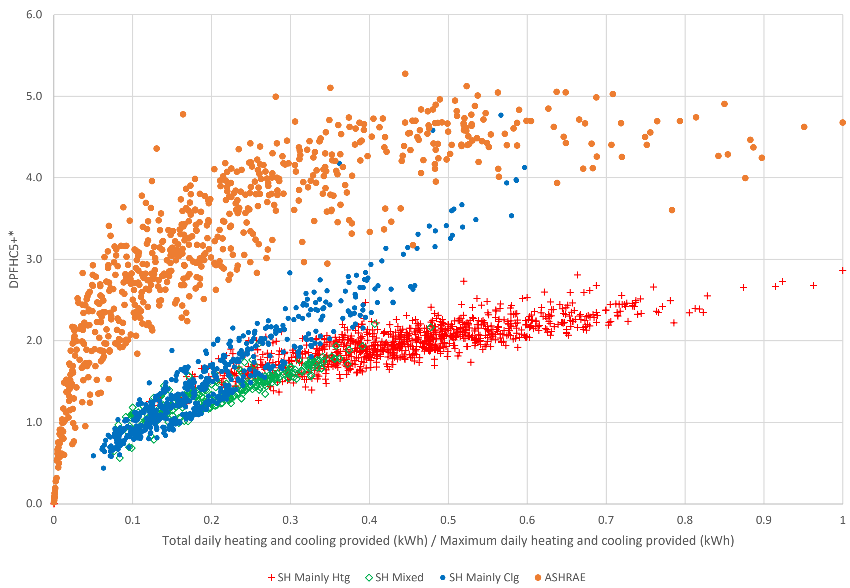

Figure 6 Daily heating and cooling performance factor for system boundary 5 (DPFHC5+) against daily heating and cooling loads normalized by the maximum daily heating and cooling loads for each system.

CONCLUSIONS

Annex 52 has provided useful methodologies and guidelines to support performance measurements of GSHP systems, availability of which should lower the cost of measurement programs, as it allows more informed selection of instrumentation and reduced analysis effort later. Annex 52 has provided benchmarking data for 29 GSHP systems, but the real value will increase as performance measurement becomes ubiquitous. As performance data for more systems and more system types over a wider geographical distribution become available, the usefulness for benchmarking will increase. The availability of widespread high-quality performance measurement will facilitate better design and operation of GSHP systems.

Systems serving two buildings – a central GSHP system with water-to-water heat pumps and a distributed GSHP system with water-to-air heat pumps, typical of Scandinavian and North American practice, respectively - were compared. Although the results from two buildings can't be generalized, they certainly provide incentive for further investigation. The central GSHP system used significantly more energy for distribution, lowering the overall SPF considerably. We hope that these results spur increased attention to the role of distribution systems in GSHP system performance. Though this study has focused on GSHP systems, distribution energy also plays a significant role in the performance of other HVAC systems. System performance measurement using well-defined boundary levels and KPI is a useful tool in all HVAC systems.

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