14th IEA Heat Pump Conference
15-18 May 2023, Chicago, Illinois

Heat pump system performance measurement in Annex 52

Signhild Gehlin[a*] Jeffrey D Spitler[b]

[a]The Swedish Geoenergy Center, Box 1127, 22104 Lund, Sweden
[b]School of Mechanical and Aerospace Engineering, Oklahoma State University, Stillwater, Oklahoma, USA

Abstract

This paper presents an overview of the IEA HPT Annex 52, "Long term performance measurement of ground-source heat pump (GSHP) systems serving commercial, institutional and multi-family buildings." Energy use intensities are a common system metric, but comingle the performance of the building envelope, occupancy effects and the system performance. The annex utilizes performance factors and a new boundary schema which facilitates characterizing the performance of different parts of the system. The annex delivered a library of quality long-term system performance measurements in the form of case studies, improved methodologies to better characterize system performance in larger buildings, and guidelines for instrumentation, uncertainty analysis, key performance indicators, data management and quality assurance. This paper focuses on performance measurements of the heat pumps, covering both internal and external approaches, instrumentation and uncertainty guidelines. Though aimed at water-source heat pumps, the annex schema and guidelines are applicable to air-source heat pumps (ASHP) and air-conditioning systems also.

Keywords: Ground source heat pumps;GSHP;performance measurement;SPF;HPT Annex 52;

1. Introduction

Field measurements of building heating and cooling system performance are rarely made but are essential to ensure that performance expectations are actually met. For GSHP systems, owners have made significant investments with expectations of high performance. Hence, it is particularly important that high performance is achieved. Though some field measurements have been reported in the literature, there is little or no consistency on how to measure the performance or how to report the results. Cost-effective measurement programs are hindered by this lack of consistency and a lack of guidance regarding measurement system design.

The four-year international collaboration project IEA HPT Annex 52 - Long-term performance monitoring of GSHP systems for commercial, institutional and multi-family buildings - was carried out by seven countries: Sweden, the USA, the UK, the Netherlands, Germany, Norway and Finland. The Annex was initiated to improve the state-of-the-art in GSHP system performance measurement, going beyond energy use intensity (EUI) measurements that comingle the performance of the building envelope, occupancy effects and the system performance. Instead, performance factors are used to characterize the system performance. As introduced by a 1948 Edison Electric Institute report [1], a performance factor (PF) is similar to a coefficient of performance (COP) except the COP is an instantaneous value and the PF covers a specified time period. Performance factors are field measured; COPs may be field measured, but most commonly COP measurements are made in a laboratory. Performance factors are commonly defined for different system boundaries (e.g. the heat pump, the heat pump & source-side circulating pump) and different time periods (e.g. daily, weekly, monthly,

* Corresponding author. Tel.: +46 75 700 88 23
E-mail address: signhild.gehlin@geoenergicentrum.se

seasonal). Performance factors depend on system design and operational parameters such as setpoints, part-load conditions, source- and sink temperatures. The high degree of granularity with five system boundaries aids in analysis of the system performance. The specific objectives of Annex 52 were to:

- Create a library of quality long-term measurements of GSHP system performance for commercial, institutional, and multi-family buildings served by any type of ground source (e.g. vertical boreholes in rock, pile heat exchangers in soil, open-loop groundwater wells.)
- Refine and extend current methodology to better characterize large-scale GSHP system performance and to provide a set of benchmarks for comparisons of such systems. The improved methodology will be beneficial for the IEA and will facilitate collection of more accurate and uniform statistics, and thus help in estimating, with less uncertainty, how much energy we can produce and how much CO2 emissions we can reduce with GSHP systems.
- Provide guidance for instrumentation, uncertainty calculation, key performance indicators and system boundaries that cover as many GSHP system features as possible.

Outcomes from the Annex include new boundary schema and guidelines for instrumentation, uncertainty, key performance indicators, data management, and quality assurance. In addition to the final report [2], four subtask reports [3-6] and 27 case study reports [7,8] containing 29 monitoring projects have been published, comprising more than 1000 pages in total. These reports are published on the Annex 52 webpage https://heatpumpingtechnologies.org/annex52/documents/. In addition, the Annex has so far resulted in three sets of open-source measurement data from two GSHP systems, seven published peer reviewed scientific journal papers and 14 peer reviewed conference papers.

Prior to the Annex, there have been relatively few long-term performance measurements of ground-source heat pump systems serving larger commercial buildings. Gleeson and Lowe [9] reported a meta-analysis of field measurements for residential buildings in Europe in which 216 ground-source heat pumps were included, but the analysis was complicated by inconsistent boundary schemas. Spitler and Gehlin [10] reported on 55 GSHP systems serving commercial and multifamily residential buildings. Both references [9,10] noted a significant range in SPF values that cannot be explained solely by different equipment or different climatic conditions.

This paper gives an overview of the boundary schema, then focuses on methods and results for the heat pump boundary (Level 1). Measured SPF for the heat pump only are summarized for 20 systems with a total of 78 years of measurements.

2. Boundary Schema

The overall performance of a GSHP system is affected by the performance of the source side ground circuit, as well as the heat pump (HP) unit performance and the load side circuit performance, including supplementary heating and cooling. Hence, performance factors are necessarily defined for a specific set of boundaries. However, in the literature, there is little consistency in the use of system boundaries, and, in many cases, the system boundaries are not clearly defined. This makes it difficult to compare published performance factors for GSHP systems. The SEPEMO system boundary schema [11] was initially used for calculation of performance factors within Annex 52. However, the SEPEMO system boundary schema has limitations when accounting for the complexity of larger GSHP systems used in commercial, institutional, and multi-family residential buildings.

Annex 52 has sought to harmonize system boundary definitions and identify and recommend performance indicators that will allow evaluation at multiple clearly stated system boundaries. A new system boundary schema consisting of six defined boundaries and an indicator for use of supplemental heating or cooling was defined within Annex 52 [2]. It is based on the SEPEMO schema but is revised and extended, such that every SEPEMO boundary matches one of the Annex 52 boundaries (see Figure 1 and Table 1). This improves the applicability to larger and more complex GSHP systems of various types. The Annex 52 system boundary schema has been applied on all case studies within Annex 52.

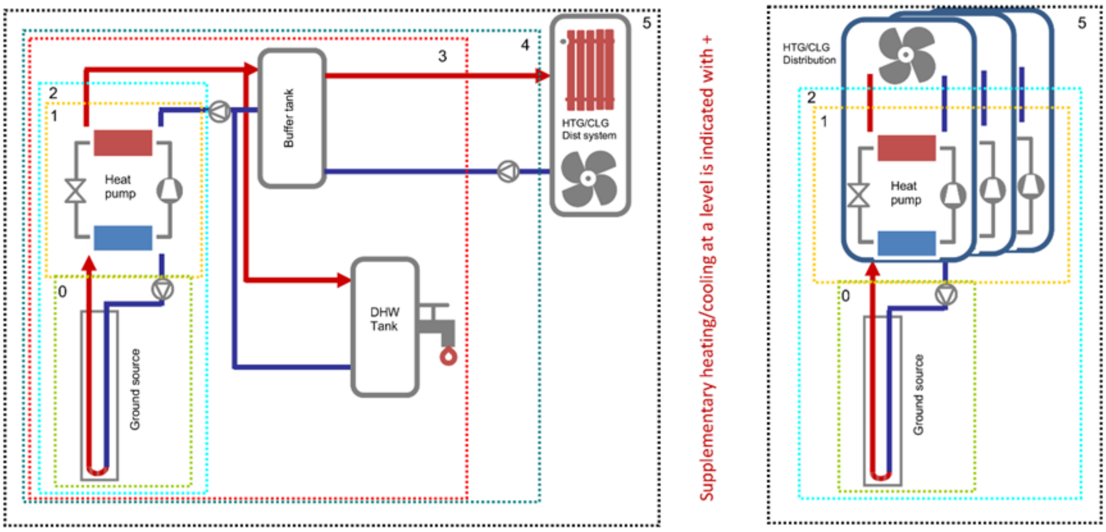

Fig. 1 Annex 52 system boundary schema for centralized systems (left) and distributed systems (right).

Table 1: Annex 52 system boundary schema and its relation to the SEPEMO boundary schema. [2]

	Boundary Levels											
Boundary description	0	0+	1	1+	2	2+	3	3+	4	4+	5	5+
Ground Source (circ. pump + ground heat exchanger)	x	x			x	x	x	x	x	x	x	x
Heat pump unit incl. internal energy use, excluding internal circ. pump.			x	x	x	x	x	x	x	x	x	x
Buffer tank (incl. circ. pump between heat pump and buffer tank)							x	x	x	x	x	x
Circ. pump on load side (between buffer tank & building heating/cooling distribution system)									x	x	x	x
Building heating/cooling distribution system											x	x
Auxiliary heating or cooling		x		x		x		x		x		x
Corresponding SEPEMO boundary level			H1/C1		H2/C2	H3			C3		H4	C4

3. Heat Pump Boundary (Level 1) Methods

There are two approaches for determining heat pump performance factors – the so-called external and internal approaches [12]. Further diagrams illustrating these two approaches are found in the Annex 52 instrumentation guideline [4].

3.1. External Approach

The external approach makes use of measurements that are made external to the vapor compression cycle of the ground-source heat pump:

- Power measurements of the compressor, and other devices if needed to establish performance factors at different boundaries.
- Entering and exiting temperature measurements of the secondary refrigerant or air on the load side of the heat pump.
- Mass flow measurements made of the secondary refrigerant (heat transfer fluid) or air on the load side of the heat pump.
- For measurement of cooling performance factors with water-to-air heat pumps, humidity measurements of the air entering and exiting the evaporator are also needed.
- Thermodynamic properties or thermodynamic property routines for the secondary refrigerant or air.

The cooling or heating capacity is determined calorimetrically – by multiplying the measured mass flow rate by the difference in enthalpy. For flows without phase change, the enthalpy difference would usually be estimated as the product of the specific heat and the temperature difference. Uncertainty calculations are illustrated for this method in [5].

3.2. Internal Approach

The internal approach [13] makes use of:

- Pressure and temperature measurements of the refrigerant at the compressor suction and discharge.
- Temperature measurement of the refrigerant at the condenser discharge.
- Power measurements of the compressor, and other devices if needed to establish performance factors at different boundaries.
- An estimate of the compressor heat loss.
- Thermodynamic property routines for the refrigerant.
- Temperature measurements of the entering and exiting temperatures of the condenser and evaporator on the secondary refrigerant or air side.

The pressure and temperature measurements at the compressor suction and discharge and the temperature measurement at the condenser discharge are used, with the aid of the refrigerant property routines, to determine the enthalpies at all state points in the cycle. Coupled with the compressor power measurement and the estimate of the compressor heat loss, the refrigerant mass flow rate can be determined. With this information, instantaneous values of COP, cooling capacity, heating capacity, and isentropic efficiency can be determined. By making enough time series measurements, the performance factor for the heat pump can be determined by integrating the instantaneous values of the cooling or heating provided and the electrical power input. The temperature measurements of the secondary refrigerant and/or air are used to determine 2^{nd} law efficiencies of the individual components. This capability allows better diagnosis of internal heat pump problems, compared to the external approach. Further refinements and uncertainty analysis are discussed in references [5,12,13].

3.3. Discussion

Both approaches may be used to determine performance factors and both approaches require careful attention to propagation of uncertainties. Each approach has its own advantages and disadvantages, which may be summarized as follows:

- The internal approach uses more sensors but can provide additional information about the performance of the individual components in the heat pump. This information is very useful for diagnosing problems.
- In some systems, the secondary refrigerant may be “over-pumped”, that is, the pump has been conservatively selected and delivers high flow rates and low temperature differences. If insufficient care has been taken in specifying the sensors, the low temperature differences may lead to low accuracy with the external approach.
- The external approach does not require making connections (pressure measurements) to the refrigerant, and, so, is less invasive. On the other hand, heat pumps increasingly have more and more internal measurement points, decreasing the required additional instrumentation and connections.

As internal heat pump controls and monitoring become more sophisticated with additional sensors, it seems likely that the internal approach or a variation on it could be implemented by the manufacturer, if desired. This would further lower the cost of monitoring and fault detection and diagnosis.

4. Heat Pump Boundary (Level 1) Results

In this section, we present seasonal performance factor results based on measurements made in the Annex 52 case studies. 20 systems that provided building heating and cooling (in some cases) were monitored that could provide SPF at boundary level 1; a total of 78 years of SPFs were measured. The measured values are summarized in Table 2. With three exceptions (IKEA Uppsala, Backadalen and Rosenborg), the external method has been used for these case studies. Unfortunately, there were no case studies within Annex 52 comparing the internal and external approaches.

For heat pumps operating in heating mode, the average SPF_{H1} is 3.9, whether taken as the simple average of 12 systems, or the average of 78 years of operation. For cooling operation, the average SPF_{C1} is 3.9 taken as the average of 8 systems or 3.7 as the average for all years. For heat pumps that provide both heating and cooling, the combined SPF_{HC1} is 3.7 as the average for 6 systems, or 3.5 taken as the average for all years. For comparison purposes, Spitler and Gehlin [9] found an average SPF_{H1} of 4.0 for 39 systems and an SPFC1 of 5.5 for 12 systems reported in the literature.

Table 2. Annex 52 case studies presenting SPF1 results

Building name	Country	Years	HC1 Min	***HC1 Avg.***	HC1 Max	H1 Min	***H1 Avg.***	H1 Max	C1 Min	***C1 Avg.***	C1 Max	UGT [°C]
Aalto University [14]	Finland	*1*		***3.7***								8.6
Hugh Aston Building [15]	UK	*2*	3.3	***3.5***	3.7	2.9	***3.2***	3.6	3.9	***3.9***	4.0	12.3
The Crystal [16]	UK	*8*	1.5	***2.5***	3.3	2.3	***3.0***	3.7	1.1	***2.2***	2.9	13.1
Kalnes [17]	Norway	*5*	4.3	***4.6***	4.8							8.1
KIWI Dalgård [18]	Norway	*1*					***2.9***					5.0*
Sweco building [18]	Norway	*1*					***3.4***			***3.5***		8.0*
Moholt 50/50 [18]	Norway	*1*					***3.2***					5.0*
Frescati [19]	Sweden	*3*				5.6	***6.2***	6.5	4.7	***5.2***	5.6	9.0
Forskningen [20]	Sweden	*1*					***3.6***					9.8
Rosenborg [21]	Sweden	*1*		***4.9***			***5.0***			***4.4***		10.0
Frölunda Club house [22]	Sweden	*3*				3.6	***3.8***	3.9				8.0*
Studenthuset [23]	Sweden	*5*				3.8	***3.9***	4.1				9.2
Traktorn [24]	Sweden	*2*				3.9	***4.0***	4.0				11.1
Briljanten [25]	Sweden	*4*				3.1	***3.2***	3.4				11.1
IKEA Uppsala [26]	Sweden	*3*	3.6	***3.7***	3.9	3.6	***3.8***	4.0	3.6	***3.7***	3.9	6.8
Backadalen [27]	Sweden	*1*					***3.9***					7.8
AOV [28]	Germany	*9*	3.0	***3.4***	4.3	2.9	***3.4***	4.5	1.8	***4.0***	5.1	11.3
GEW [29]	Germany	*11*	2.0	***3.6***	4.6	1.7	***2.5***	2.8	1.6	***4.1***	6.8	12.0
EFB [30]	Germany	*14*				5.1	***5.7***	7.2				10.6
WGG [31]	Germany	*2*				4.8	***5.1***	5.3				11.7

*Estimated undisturbed ground temperatures (UGT) based on local annual mean air temperature.

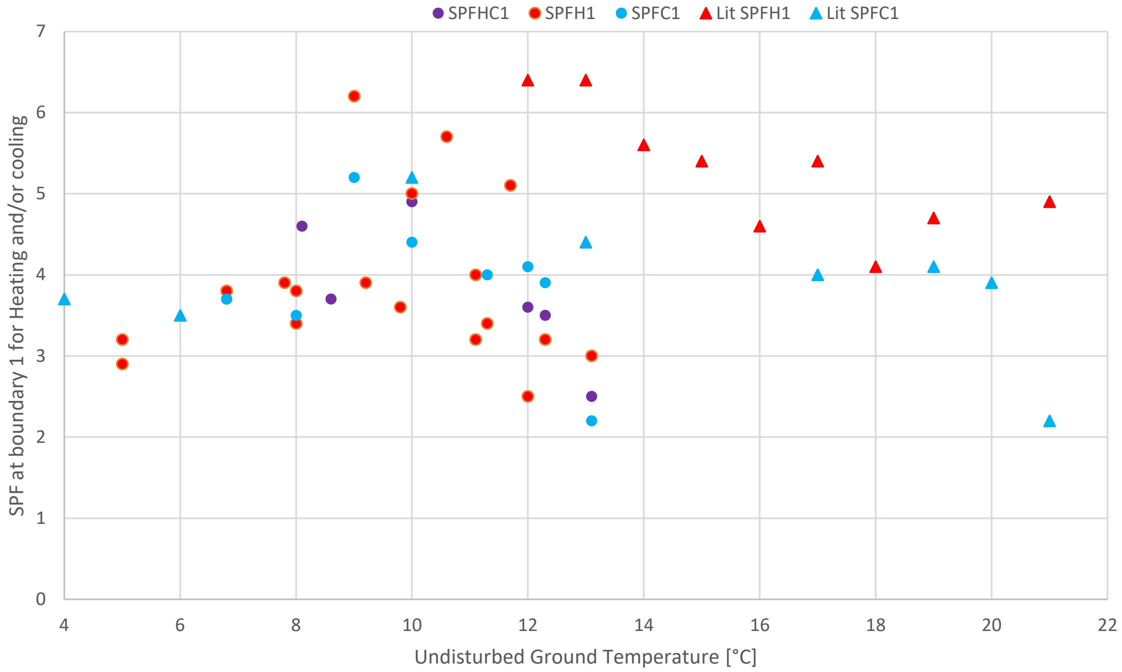

Fig. 2 SPF for level 1 vs Undisturbed Ground Temperature (UGT) -Values from Annex 52 Case Studies and Literature Review [10]

One finding of multiple studies, e.g. [9,10] is, that there is no clear relationship between ground temperature, system type, or other variables and the reported SPF. Figure 2 illustrates this, showing average SPF_{H1}, SPF_{C1} and SPF_{HC1} for (1) the 20 Annex 52 case studies and (2) 55 systems reviewed in [10] versus undisturbed ground temperature (UGT) at the locations. Not all systems reported all measures; SPFH1 is reported by 8 of the Annex 52 studies and 39 of the literature review studies; SPFC1 is reported by 8 of the Annex 52 studies and 12 of the literature review studies. SPFHC1 is reported by 8 of the Annex 52 studies and none of the literature review studies. All but four of the Annex 52 locations have measured UGT and the remaining values were estimated by the case study authors based on the annual mean air temperature at the locations. UGT values for the literature review cases have been estimated with a model [32-34] based on weather data.

Some of the systems in Table 2 show marked variation in year-to-year values of SPF. For some systems, these changes in SPF are connected to changes in load or equipment. The Crystal Building in London undergoes some abrupt changes in SPF_{C1} due to apparent control and operation issues. In the system serving the AOV building [28] a modest decline in the ground temperatures occurs over nine years of operation, as evidenced by the heat pump entering and exiting fluid temperatures shown in Figure 3. The SPF_{H1} values in Figure 4 show a corresponding decline in performance associated with the heat pump entering fluid temperatures. However, with the limited sample size, it seems year-to-year variations are more likely to be caused by other factors than changes in the ground temperatures.

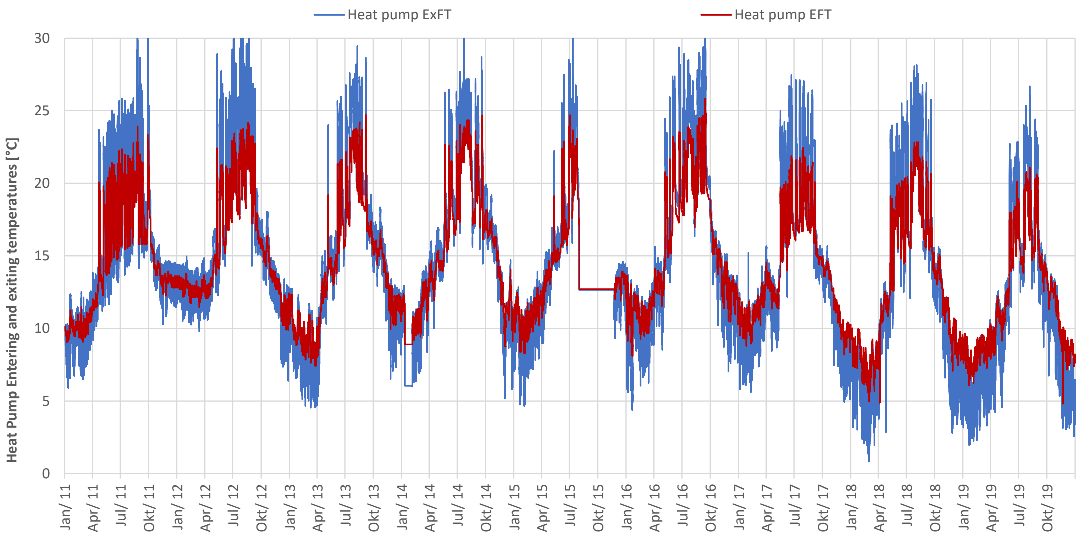

Fig. 3 Heat pump entering and exiting fluid temperatures for AOV building [28] Adapted from original figure; used by permission.

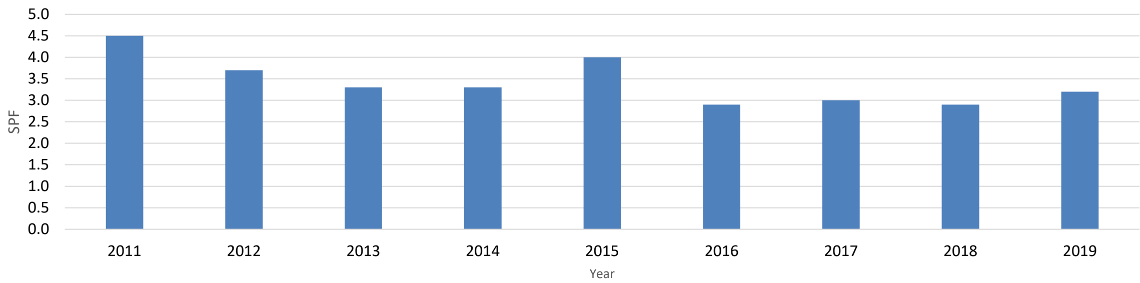

Fig. 4 SPF_{H1} for AOV building [28]

The Frescati building [19] has exceptionally high SPF_{H1} and SPF_{HC1}. The borehole system is connected to a local thermal network and operates with three parallel heat pumps of which the two larger heat pumps are frequency regulated and deliver heat at 30°C while the third heat pump is a smaller on-off regulated heat pump delivering heat at 40°C. The small heat pump has lower performance but is used less frequently than the other two heat pumps, so has little influence on the combined SPF_{H1} for all three heat pumps. The system uses district heating to meet peak loads. This allows the lower supply temperature and higher performance.

The EFB building [30] is another building with very high performance at system level 1. The heat pumps are connected to a large number of energy piles below the building and provide heating via concrete core activation, with a very low distribution temperature (22°C). Significant supplementary heating is provided from a district heating system via radiators and ventilation. The heat pumps are operated in this way to cool the ground surrounding the pile heat exchangers so that free cooling can be provided in the summer. This combined with the very low distribution temperatures leads to high values of SPF_{H1}. The system has been monitored over 14 years and although SPF_{H1} has been above 5 all the measured years, the performance has increased significantly to values around 7 in the later three years (2017-2019) after refining the operating strategy.

Apart from the 20 buildings listed in Table 2, the Emmaboda case study [35] also reported SPF for system level 1. The Emmaboda system is, however, an industrial system, originally a high-temperature borehole thermal energy storage (HT-BTES) without heat pumps, used to store waste heat from the foundry. After several years in operation, the system design and operation were altered by installing heat pumps and decreasing the average storage temperature from ~45°C to ~30°C. The system now serves as a high-temperature process cooling with very high performance at system level 1. The measured SPF_{C1} over the three measured years after the heat pumps were installed reach 13.1 on average but can't really be compared with the performance of ordinary building heat pump systems.

5. Discussion, Conclusions and Recommendations

Some of the main findings of Annex 52 include the following:

- Annex 52 has contributed to systematization of field measurements by introducing a new boundary schema that accounts for a wide range of system features that go beyond typical residential systems.
- Annex 52 has developed guidelines for key performance indicators, instrumentation, measurement, and uncertainty analysis. These guidelines will allow better planning of field measurements at lower costs and facilitate fault detection/diagnosis and optimization of system design and operation.
- While field measurements of ground-source heat pump system performance factors are still relatively rare and uncertainty analysis of performance measurements is even rarer, the Annex has contributed a significant increase in the number of published field measurements of larger GSHP systems. The Annex sought to collect data for benchmarking, but this is only provided to a limited degree. Most of the systems are located in northern Europe. Further studies covering a larger geographic area would be welcome.
- This paper has only presented SPF for the heat pumps, but the Annex is much broader, covering SPF for a range of boundaries. A general trend is that SPF decreases as the boundary is extended to include the source-side distribution system and some or all of the load-side distribution system. In fact, even systems with "free cooling" via use of ground loop fluid to provide cooling may have SPF_{C5} that is not markedly different from GSHP systems that use the heat pump to provide cooling. It should also be noted that, though often ignored, the energy used by distribution systems is not unique to GSHP systems or ASHP systems. Field measurements of energy at all boundaries used by other competing heating and cooling systems would be a welcome contribution to the field, as this would shed light on the need for increased efficiency in heating and cooling distribution systems.
- System SPFs at all boundary levels are highly variable from system to system, with, for the most part, no clear relationship between SPF and other factors. This was illustrated in this paper for the heat pumps, but similar disparities were found at other boundary levels.
- A number of the case studies found that short-term performance factors (e.g. hourly and daily) were generally higher during periods of higher load, even though source temperatures were less favorable.

With regards to seasonal performance of the heat pumps:

- The measured system average heat pump SPFs (Level 1) presented in this paper range between 2.2-4.9 for SPF_{HC1}, 2.5-6.2 for SPF_{H1}, and 2.2-5.2 for SPF_{C1}, with overall average values for all systems being 3.9 for SPF_{HC1}, 3.9 for SPF_{H1}, and 3.7 for SPF_{C1}. These are in line with results from systems previously reported in the literature.
- Two systems with very high SPF_{H1} had significant supplementary heating and were designed so that the heat pumps used a very low distribution temperature allowing excellent heat pump performance.

The Internet of Things (IoT) is rapidly developing. Many of the measurements needed to calculate seasonal and other performance factors are already internally measured within currently available heat pumps, though this information is often not available to end users. It seems likely to us that making this information available and lowering the cost of field measurement combined with a higher degree of automated evaluation would lead to wider use of field measurements and much better understanding of real-world performance. This in turn will lead to improved system performance and a higher degree of renewable energy in our heating and cooling systems. Finally, we note that though the focus of the annex and this paper is ground-source heat pump systems, much of the work on field measurements can be and should be directly applied to air-source heat pump systems and air-conditioning systems also.

Acknowledgements

The support from the authors' employers and the Swedish Energy Agency (TERMO research program Grant 45979-1) is gratefully acknowledged. The second author's work was supported by the OG&E Energy

Technology Chair. This work is part of the IEA HPT Annex 52, *Long-term performance measurement of GSHP systems serving commercial, institutional and multi-family buildings*.

References

[1] Edison Electric Institute. 1948. Suggested Field Test Procedure for Determination of Coefficient of Performance and Performance Factor of an Electric Heat Pump While Operating on the Heating Cycle, New York City, Edison Electric Institute. Report No. Q-11.
[2] Gehlin, S. and J.D. Spitler. 2022. Final report. IEA HPT Annex 52 – Long-term performance monitoring of GSHP systems serving commercial, institutional and multi-family buildings. https://doi.org/10.23697/xsbr-xn83
[3] Gehlin, S., Spitler, J.D. 2022. Subtask 1 Report – Annotated Bibliography – Final Document. IEA HPT Annex 52 – Long-term performance monitoring of GSHP systems serving commercial, institutional and multi-family buildings. https://doi.org/10.23697/dzpy-yp81
[4] Davis, M.J., Martinkauppi, I., Witte, H., Berglöf, K., Vallin, S. 2021. Guideline for Instrumentation and Data – Final Document. IEA HPT Annex 52 – Long-term performance monitoring of GSHP systems serving commercial, institutional and multi-family buildings. https://doi.org/10.23697/tgr4-qn89
[5] Spitler, J.D., Berglöf, K., Mazzotti-Pallard, W., Witte, H. 2021. Guideline for Calculation of Uncertainties – Final Document. IEA HPT Annex 52 – Long-term performance monitoring of GSHP systems serving commercial, institutional, and multi-family buildings. https://doi.org/10.23697/m2em-xq83
[6] Gehlin, S., Spitler, J.D. Witte, H., Andersson, O., Berglöf, K., Davis,M., Javed, S., Bockelmann, F., Turner, J., Clauss, J. 2022. Subtask 3 Report – Guide for analysis and reporting of GSHP system performance – system boundaries and key performance indicators (KPI) – Final Document. IEA HPT Annex 52 – Long-term performance monitoring of GSHP systems serving commercial, institutional and multi-family buildings. https://doi.org/10.23697/xa7z-vd92
[7] Gehlin, S., Spitler, J.D. 2022. Case Study Summary Report. IEA HPT Annex 52 – Long-term performance monitoring of GSHP systems serving commercial, institutional and multi-family buildings. https://doi.org/10.23697/qfnt-rb80
[8] https://heatpumpingtechnologies.org/annex52/documents/
[9] Gleeson, C. P. and R. Lowe. 2013. Meta-analysis of European heat pump field trial efficiencies. Energy and Buildings 66(0): 637-647. https://doi.org/10.1016/j.enbuild.2013.07.064
[10] Spitler, J. D. and S. Gehlin. 2019. Measured Performance of a Mixed-Use Commercial-Building Ground Source Heat Pump System in Sweden. Energies 12(10): 2020. https://doi.org/10.3390/en12102020
[11] Nordman, R., O. Kleefkens, P. Riviere, T. Nowak, A. Zottl, C. Arzano-Daurelle, A. Lehmann, O. Polyzou, K. Karytsas, P. Riederer, M. Miara, M. Lindahl, K. Andersson and M. Olsson. 2012. SEPEMO - Seasonal performance factor and monitoring for heat pump systems in the building sector., SP Technical Research Institute of Sweden.
[12] Fahlén, P. 2005. Performance audits of heat pumps - procedures and uncertainties. 8th International Energy Agency Heat Pump Conference. Las Vegas, International Energy Agency.
[13] Berglöf, K. 2005. Methods and potential for on-sire performance validation of air conditioning, refrigeration, and hat pump systems. 8th International Energy Agency Heat Pump Conference. Las Vegas.
[14] Todorov, O., Vallin, S., Virtanen, M., Leppäharju, N. (2021). Case study report for monitoring project – Aalto University New Campus Complex, Otaniemi (Espoo). Finland. IEA HPT Annex 52 – Long-term performance monitoring of GSHP systems serving commercial, institutional and multi-family buildings. https://doi.org/10.23697/cm70-g204
[15] Rees, S.J. 2021. Case study report for a large university building, UK. The Hugh Aston Building at De Montfort University. IEA HPT Annex 52 – Long-term performance monitoring of GSHP systems serving commercial, institutional and multi-family buildings. https://doi.org/10.23697/qwab-0818
[16] Turner, J., Loveridge, F. Rees, S.J. 2021. Case study report for the Crystal Building, United Kingdom. IEA HPT Annex 52 – Long-term performance monitoring of GSHP systems serving commercial, institutional and multi-family buildings. https://doi.org/10.23697/kmxr-hw82
[17] Clauß, J., Taveres-Cachat, E., Erstad, E. 2021. Case study report for Kalnes energy central, Sarpsborg, Norway. IEA HPT Annex 52 – Long-term performance monitoring of GSHP systems serving commercial, institutional and multi-family buildings. https://doi.org/10.23697/jh1q-4k55
[18] Stene, J. 2021. Case Study report for 1) KIWI Dalgård, 2) The SWECO Building and 3) Moholt 50|50 – Norway. IEA HPT Annex 52 – Long-term performance monitoring of GSHP systems serving commercial, institutional and multi-family buildings. https://doi.org/10.23697/wa60-2121
[19] Lazzarotto, A. 2021. Case study report for Frescati NPQ, Sweden. IEA HPT Annex 52 – Long-term performance monitoring of GSHP systems serving commercial, institutional and multi-family buildings. https://doi.org/10.23697/emqr-m785
[20] Mazzotti-Pallard, W. 2021. Case study report for Forskningen, Stockholm, Sweden. Three plus energy buildings (by design) with GSHPs, variable-length boreholes, ventilation recovery and pre-heating, wastewater recovery & PV panels. IEA HPT Annex 52 – Long-term performance monitoring of

GSHP systems serving commercial, institutional and multi-family buildings. https://doi.org/10.23697/dfs2-v474
[21] Abuasbeh, M. 2021. Case study report for Rosenborg, Sweden. GSHP installation coupled with aquifer thermal energy storage ATES supplying heating and cooling for two commercial buildings. IEA HPT Annex 52 – Long-term performance monitoring of GSHP systems serving commercial, institutional and multi-family buildings. https://doi.org/10.23697/6h7v-bt33
[22] Javed, S., Zhang, H., Liu, H. 2021. Case study report for a small Clubhouse building in Gothenburg, Sweden. IEA HPT Annex 52 – Long-term performance monitoring of GSHP systems serving commercial, institutional and multi-family buildings. https://doi.org/10.23697/8n0p-3n24
[23] Gehlin, S., Spitler, J.D. 2021. Case study report for Studenthuset, Stockholm, Sweden. Long-term performance analysis of the GSHP system for a student union building. IEA HPT Annex 52 – Long-term performance monitoring of GSHP systems serving commercial, institutional and multi-family buildings. https://doi.org/10.23697/pmr0-0778
[24] Ekestubbe, J. 2021. Case study report for Kv Traktorn, Lund, Sweden. Long-term performance analysis of the GSHP system for an office building. IEA HPT Annex 52 – Long-term performance monitoring of GSHP systems serving commercial, institutional and multi-family buildings. https://doi.org/10.23697/92qm-rr10
[25] Ekestubbe, J. 2021. Case study report for Brf Briljanten, Lund, Sweden. Long-term performance analysis of the GSHP system for a multi-family building. IEA HPT Annex 52 – Long-term performance monitoring of GSHP systems serving commercial, institutional and multi-family buildings. https://doi.org/10.23697/te3s-cb70
[26] Walfridson, T. 2021. Case study report for IKEA Uppsala, Sweden. IEA HPT Annex 52 – Long-term performance monitoring of GSHP systems serving commercial, institutional and multi-family buildings. https://doi.org/10.23697/vda5-8s77
[27] Walfridson, T. 2021. Case study report for Backadalen, Göteborg, Sweden. IEA HPT Annex 52 – Long-term performance monitoring of GSHP systems serving commercial, institutional and multi-family buildings. https://doi.org/10.23697/r7zd-s388
[28] Bockelmann, F. 2021. Case study report for AOV, Germany. Office building with borehole heat exchanger. IEA HPT Annex 52 – Long-term performance monitoring of GSHP systems serving commercial, institutional and multi-family buildings. https://doi.org/10.23697/s338-wf13
[29] Bockelmann, F. 2021. Case study report for EFB, Germany. Office building with energy piles. IEA HPT Annex 52 – Long-term performance monitoring of GSHP systems serving commercial, institutional and multi-family buildings. https://doi.org/10.23697/2hb1-h641
[30] Bockelmann, F. 2021. Case study report for GEW, Germany. Office building with borehole heat exchanger. IEA HPT Annex 52 – Long-term performance monitoring of GSHP systems serving commercial, institutional and multi-family buildings. https://doi.org/10.23697/0cfw-xw78
[31] Bockelmann, F. 2021. Case study report for WGG, Germany. School with gym and energy piles as well as agrothermal field. IEA HPT Annex 52 – Long-term performance monitoring of GSHP systems serving commercial, institutional and multi-family buildings. https://doi.org/10.23697/ek2v-c43
[32] Xing, L. and J. D. Spitler. 2017. Prediction of undisturbed ground temperature using analytical and numerical modeling. Part I: Model development and experimental validation. Science and Technology for the Built Environment 23(5): 787-808. https://doi.org/10.1080/23744731.2016.1258371
[33] Xing, L. and J. D. Spitler. 2017. Prediction of undisturbed ground temperature using analytical and numerical modeling. Part II: Methodology for developing a world-wide dataset. Science and Technology for the Built Environment 23(5): 809-825. https://doi.org/10.1080/23744731.2016.1262705
[34] Xing, L., J. D. Spitler and A. Bandyopadhyay. 2017. Prediction of undisturbed ground temperature using analytical and numerical modeling. Part III: Experimental validation of a world-wide dataset. Science and Technology for the Built Environment 23(5): 826-842. https://doi.org/10.1080/23744731.2016.1253978
[35] Andersson, O., Rydell, L., Håkansson, N. 2021. Case study report for the Xylem HT-BTES plant in Emmaboda, Sweden. Efficiency by using heat pumps for extraction of stored heat. IEA HPT Annex 52 – Long-term performance monitoring of GSHP systems serving commercial, institutional and multi-family buildings. https://doi.org/10.23697/j2hk-4×61