

IEA HPT Annex 52 – Measuring GSHP system long-term performance

Signhild Gehlin¹, Jeffrey D. Spitler²

¹ Swedish Center for Geoenergy, P.O. Box 1127, SE-22104 Lund, Sweden

² School of Mechanical and Aerospace Engineering, Oklahoma State University, USA

signhild@geoenergicentrum.se

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ABSTRACT

In January 2018, the International Energy Agency (IEA) and its technical collaboration program (TCP) Heat Pumping Technologies (HPT) launched the new international collaboration project *Annex 52 - Long-term performance measurement of GSHP systems serving commercial, institutional and multi-family buildings*. The aim of this IEA Annex is to monitor and analyze a large number of ground source heat pump (GSHP) systems in several countries from a long-term performance perspective. At the beginning of 2019, more than 30 GSHP performance-monitoring case studies, located in Sweden, the Netherlands, UK, Finland, Germany and the USA, form part of the Annex 52 work. These case studies cover a range of building types, system applications and ground sources. With all these different system applications included, Annex 52 will offer unique experience and information on GSHP system performance, and give guidance on instrumentation, monitoring, data analytics, performance analysis and suitable performance indices based on international experience. This paper gives an overview of Annex 52, including the active monitoring projects and the work and findings so far.

1. INTRODUCTION

Carefully instrumented and analyzed long-term measurements of system performance data from large ground source heat pump (GSHP) systems are rare but highly valuable tools for researchers, practitioners and buildings owners. Such measurements help to show how the various system components and control strategies affect the overall performance; to identify best practices, design and installation issues that lead to poor performance; and to give guidance on how unanticipated consequences of the design may be partially or totally ameliorated. In the literature, analyses of good quality long-term performance monitoring data from GSHP systems are sparse, and there is no consensus on key figures for performance evaluation and comparison. Performance monitoring results that report uncertainty are even rarer.

In January 2018, a new international collaboration project on long-term performance of larger GSHP systems was initiated through the International Energy Agency (IEA) and its technical collaboration program (TCP) Heat Pumping Technologies (HPT). The project, Annex 52, has the name “Long-term performance measurement of GSHP systems serving commercial, institutional and multi-family buildings.” The duration is four years, finishing in December 2021. The aim of this IEA Annex is to monitor and analyze a large number of ground source heat pump systems in several countries from a long-term performance perspective. The emphasis is on heat pump and system performance, e.g. determining coefficients of performance, seasonal performance factors and system efficiency indices. The results and experience from the many monitoring projects will be used in the three annex subtasks. Within the first subtask, an annotated bibliography of previously published long-term monitoring projects reported will be compiled, together with a case study report summarizing all the included Annex 52 monitoring projects. The second and third subtasks will provide guideline documents on instrumentation, monitoring, analysis and key metrics for long-term performance of large GSHP systems.

2. PERFORMANCE INDICATORS

The most common performance indicator for building heating and cooling systems is likely energy use intensity (EUI), typically expressed as annual energy usage of the building per unit area, e.g. kWh/m². Yet, this indicator cannot differentiate between the effects of the building envelope, its usage, and the performance of the heating and cooling system.

For GSHP systems, system coefficients of performance (COP) and seasonal performance factors (SPF) with various boundaries (see Section 4 below) have occasionally been reported in the literature. (See Section 5 below.) Such measurements, whether termed COP or SPF, have the advantage of being able to focus solely on the actual system performance without comingling the effects of the building envelope and usage.

Usage of the terms COP, SPF, EER, etc. is often confusing. Regrettably, Thomson (1853) did not give a name to the ratio of heating provided to energy input

when he described the use of heat engines to heat and cool buildings. In what was probably the first reference in the literature to a residential heat pump application, Haldane (1930) used only the term “efficiency”, giving values in the hundreds of percent.

Less than 20 years later, the term “coefficient of performance” had come to be used in such a variety of ways that an industry committee (Joint AEIC-EEI Heat Pump Committee 1948) declared “The term cp [coefficient of performance] has been rather loosely used in the past, resulting in misunderstanding and confusion.” For field measurements, the committee defined COP as applying to a single operating condition, and the term performance factor to refer to a “value based on an extended period of time, stating the period of time covered.”

In Great Britain, Griffith (1957) introduced a new term “performance energy ratio” to characterize daily performance of a custom-built experimental heat pump. One of the audience, Mr. F. Mather, responded “It is unfortunate that, having become accustomed to the term ‘coefficient of performance’, we now have to think of ‘performance energy ratio’.” See Rees (2016).

In the present day, within the heat pump industry, certain terms (COP, SCOP, EER, SEER) are commonly used to refer to indices that are calculated based on physical testing of a heat pump unit under one or more conditions in a laboratory. These indices often have implications for codes and regulations. Nevertheless, some researchers (Zhai and Yang 2011, Southard, et al. 2014b; Liu, et al. 2017) have used “COP” or “SCOP” to refer to field measurements.

The term “performance factor” is used more widely when referring to field measurements, but it has also been used (IEA HPT TCP 2016) to refer to calculated values based on testing of heat pumps under multiple conditions in a laboratory. SPF (Seasonal Performance Factor) has also been used to refer to periods shorter than a year, e.g. Wemhoener et al. (2017) present a graph with monthly SPF.

Given the confusing situation, we plan to use the term “performance factor” with an indicator of the time period (seasonal, monthly, weekly, daily, or binned – SPF, MPF, WPF, DPF, BPF) with subscripts that correspond to the boundary conditions, e.g. H1, C4, as discussed in Section 4.

3. MOTIVATION

Why measure system performance? A first answer may be the maxim “You can’t improve what you don’t measure.” Indeed, many building heating and cooling systems consume excess energy due to problems that are only discovered after months or years. Many design decisions and control settings can have significant deleterious impacts on energy efficiency, yet are poorly understood. If performance measurements are not made, these problems may never be detected.

Table 1: Possible questions to be answered by performance monitoring

Possible users	Questions to be answered
Prospective building owners	Is a GSHP system worth the extra investment?
Building owners	Is my system saving me the money that I expected?
Building owners	How does my system compare to other systems in the area serving similar buildings?
Building owners	How well does my system meet environmental criteria and building certification requirements?
Code-writing and regulatory bodies	How can we make informed decisions for energy policy, codes, and regulations?
Consulting (HVAC design) engineers	Do the systems I designed work as well as I expected? What should I do differently next time?
Consulting (HVAC design) engineers	How have other GSHP systems for similar applications in my area worked?
Building maintenance staff	Does my system need attention? Are there any failing components? Has the performance increased or decreased since last year? Is it likely to fail in the coming year?
Building energy managers	Is there room for further improvement in the system, or do we need to address other areas?
Controls engineers	How can setpoints be optimized? What are optimal setpoint values?
Commissioning agents	How does the system work compared to the intended design? Is the system constructed according to design documents?
Equipment manufacturers	How well do my products perform in the field? What market opportunities are there for new products and new features on existing projects?
Environmental Certification and Building Performance Certification Authorities	How can certification programs reward real energy efficient systems and not just planned efficiency or low building energy consumption, which may be due to low occupancy?
Handbook authors	What are best practices leading to highly efficient systems?
Researchers	How can simulation models be validated?

One anecdote from a well-designed, well-maintained, commissioned GSHP system in the USA with a highly knowledgeable owner (Southard, et al. 2014b) illustrates this point. Changing a single setpoint in the pump speed control changed the heating SPF from 3 to 4 from one heating season to the next. The high degree of sensitivity could not be understood without performance monitoring.

More specifically, Table 1 gives possible questions that may be answered by performance monitoring. To be clear, some of these questions will not be answerable until performance monitoring is spread widely enough that meaningful comparisons can be made, both with other GSHP systems and other types of heating and cooling systems. So, it may take some time before the value of performance monitoring will be fully realized. However, with the rise of the internet of things (IOT), we expect that that day is coming. This Annex is taking steps to standardize methods and analyses that will support widespread performance monitoring of ground-source heat pump systems.

What about other types of heating and cooling systems, besides GSHP systems? Long-term field measurements of the performance of other types of heating and cooling systems are vanishingly rare in the literature. The authors strongly believe that these types of measurements are needed for other systems – looking at Table 1, many of the questions can only be answered when performance monitoring is commonly performed for a variety of heating and cooling system types. This Annex, however, focuses on GSHP systems for several reasons. First, GSHP systems are often a more expensive first-cost option, so there is an extra premium on knowing the performance. Second, the annex participants' experience in monitoring system performance of a number of GSHP systems revealed that even though the systems were often energy efficient, there was room for improvement. Furthermore, system performance trends often deviated significantly from what might be expected based on theory and simulation, suggesting that a better understanding of how real-world performance varies would be useful to improve future design and operation practice.

4. BOUNDARY SYSTEM SCHEMA

Performance factors are necessarily defined for specific sets of boundaries. E.g., boundaries may be drawn around the heat pump only, on the heat pump and source-side circulating pump, or on the entire system including the distribution pumps and fans. There is little consistency in the use of system boundaries in literature, and in many cases the used system boundaries are not clearly defined. This makes it difficult to compare published performance factors for GSHP systems.

An attempt to harmonize heat pump system boundary schema was made within the EU project SEPEMO (Nordman 2012). The SEPEMO system boundary

schema were primarily defined for small residential heat pump systems in Europe, and thus do not reflect the complexity of larger GSHP systems that often provide both heating and cooling, sometimes simultaneously. Worth noting is the fact that the SEPEMO system boundaries for SPF_{H1} and SPF_{H2} correspond to SPF_{C1} and SPF_{C2} , while the boundaries for SPF_{H3} do not correspond directly to those for SPF_{C3} . SPF_{H3} includes auxiliary heating but not distribution pumps/fans, whereas SPF_{C3} includes distribution pumps/fans, but not supplementary cooling units. Hence if there is no auxiliary heating in the heating system, $SPF_{H2} = SPF_{H3}$, while $SPF_{C3} = SPF_{C4}$ for systems without supplementary cooling. When comparing the performance of centralized and distributed GSHP systems, the overall (H4 or C3) boundaries must be used, because the distributed GSHP energy necessarily includes fan power (Figure 1).

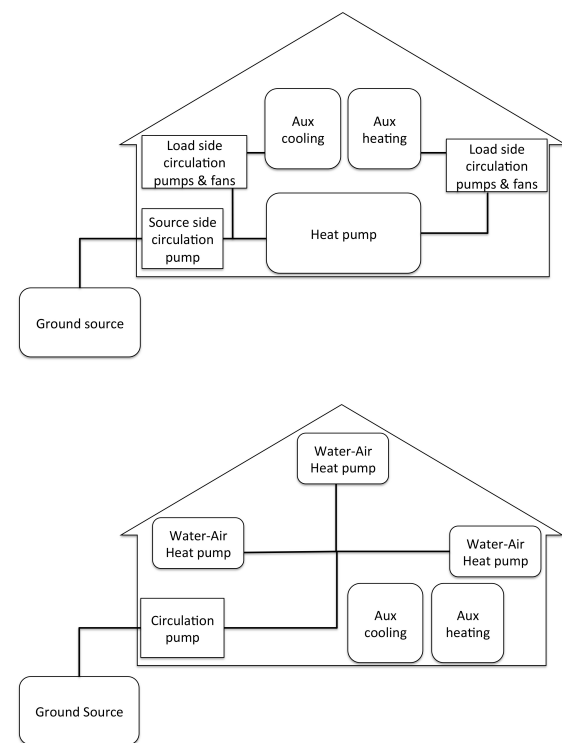


Figure 1: Schematic of a centralized (top) and a distributed (bottom) GSHP system.

Within the EU project GroundMed (Mendrinou and Karytas 2016) another boundary schema was used for evaluation of several large-scale GSHP systems in the Mediterranean area. The schema is similar to that defined by SEPEMO, but supplementary heating and cooling are not included, and the heating and cooling boundaries use the same scheme. In a German study of ten non-residential GSHP systems by Winiger et al. (2013), a boundary schema was used which includes one boundary that included the ground-source and source side circulation pumps only, and no boundaries were defined that included the heat pump only. Boundaries apply for both heating and cooling, however while auxiliary heating is included,

supplementary cooling is not. The three schema are compared in Table 2.

Within Annex 52, the SEPEMO schema will be used on a preliminary basis for all case studies, and its applicability will be evaluated and compared with other possible schema. The aim is to find consensus on suitable and comparable boundary schema for large and complex GSHP systems.

5. PUBLISHED GSHP SYSTEM PERFORMANCE MEASUREMENTS

As a first step within Annex 52, a literature review of previously published long-term performance monitoring of GSHP systems was undertaken. In this literature review, 32 GSHP systems serving commercial, institutional and multi-family buildings with reported SPF and seasonal COP values were identified. 20 of these buildings are located in European countries, 11 in the USA and one in China. The majority of the GSHP systems use vertical borehole heat exchangers in rock or soil, while a handful of the systems use groundwater, municipal wastewater or mine water as their source. Five of the 32 buildings have distributed GSHP systems, delivering heating and cooling with fans integrated in the heat pump units, while the others have centralized GSHP systems. In the reviewed literature, there is little consistency in the use of system boundaries for calculating SPF and COP values. In several cases, the system boundaries used are not clearly defined.

Naicker and Rees (2018) present seasonal system performance factors for a GSHP system serving a university building in Leicester, England. Heat pump seasonal performance factors are presented as well as combined cooling and heating SPF for the system. Hourly and daily combined performance factors are calculated. Wemhoener et al. (2017) report monthly and annual performance factors for a net zero energy building that utilized ground-source heat pumps in Uster, Switzerland. Urchueguía et al. (2008) compared an air-source heat pump system and a ground-source heat pump system serving portions of a university building in Valencia, Spain. Daily and seasonal performance factors corresponding to the SEPEMO H2 and C2 boundaries were reported. Montagud et al. (2011) present additional data for this system after five years of operation. Mermoud et al. (2014) used the SEPEMO (Nordman 2012) boundary conditions to analyze a GSHP system serving an office building in Geneva, Switzerland. Vanhoudt et al. (2011) describe three years of performance monitoring results of a groundwater based GSHP system in Brasschaat, Belgium. Heat pump seasonal performance factors as well as seasonal system performance factors are reported, though the boundaries are unclear. Michopoulos et al. (2013) monitored a ground-source heat pump system serving an office building in Pylaia, Greece. Weekly and seasonal heat pump performance factors were presented. Mendrinou and Karytas (2016) report on annual heating and cooling SPF for eight

GSHP systems in southern Europe (Padova, Athens, Barcelona, Valencia, Coimbra, Benedict, Septèmes-les-vallons and Oradea) monitored as part of the EU Ground-Med project. Four levels of system boundaries are defined (See Table 2). Heating and cooling SPFs for all buildings for all four levels are reported graphically. Winiger et al. (2013) report on analysis of ten ground-source heat pump systems serving non-residential buildings in Germany. One of the case studies makes use of waste heating, allowing heating without heat pump operation. Four system boundaries were evaluated, none of them with only the heat pump included (See Table 2).

Liu et al. (2017) summarize annual performance measurements of 10 ground-source heat pump systems serving commercial buildings in nine US states (Montana, Arizona, North Carolina, New York, Michigan, South Carolina, Colorado, Nebraska and Indiana). The ground-sources include both open loop and closed loop borehole systems, as well as a mine water system and a system utilizing municipal wastewater as the source. Most of the systems use distributed water-to-air heat pumps to provide both heating and cooling. Annual heating and cooling system coefficients of performance (SCOP) were determined for eight of the ten buildings. For the other two, difficulties in differentiating between energy used to provide heating and energy used to provide cooling led the authors to define an effective overall SCOP that combined heating and cooling.

Southard et al. (2014a, 2014b) and Spitler et al. (2017) present monitoring studies of two distributed heat pump systems at the ASHRAE Headquarters building in Atlanta in the USA. The two systems were an air-source variable-refrigerant flow heat pump system and a ground-source heat pump system. Seasonal heating and cooling system coefficients of performance were calculated for the two systems. Because the systems were distributed and delivered heating and cooling with fans integrated in the heat pump units, and the electrical energy was measured for all heat pumps and the source-side circulating pump together, the coefficients of performance correspond to SEPEMO levels H4 and C4.

Zhai and Yang (2011) describe a GSHP system with 280 boreholes in Shanghai, China. System boundaries are not explicitly stated, but the average COPs of the heat pumps are given for summer and winter respectively.

SPF and COP values for the 32 GSHP systems in the literature review were compared using the system boundary schema defined by the EU project SEPEMO (Nordman 2012). Only about half of the 32 cases give the overall system SPF. The comparison of the buildings give an SPF_{H4} range between 2.5 and 4.7, while the range for SPF_{C4} is 2.7-7.0. Uncertainty is analyzed for only two of the systems (Southard et al. 2014a, 2014b, Spitler et al. 2017, Urchueguía et al. 2008).

Table 2: System boundary schema for SPF and COP

		Heat pump	CP & fans on source-side	Auxiliary heating	CP & fans on load-side (between HP & BT)	CP & fans on load-side (between BT & building heat distribution system)	Fan coil unit fans	Supplementary Cooling	Notes
SEPEMO (Nordman 2012)	H1	X							No boundary at the buffer tank.
	H2	X	X						
	H3	X	X	X					
	H4	X	X	X	X	X			
	C1	X							
	C2	X	X						
	C3	X	X		X	X			
	C4	X	X		X	X		X	
Winiger, er al. (2013)	I		X						Applies to both heating and cooling; supplementary cooling not accounted for.
	II	X	X						
	III	X	X	X					
	IV	X	X	X	X	X			
GroundMed (Mendrinis & Karytas 2016)	I	X							Heating, cooling defined with same scheme. Supplementary heating, cooling are not treated.
	II	X	X						
	III	X	X		X	X			
	IV	X	X		X	X	X		

A plot of system SPFs for the four SEPEMO boundaries versus undisturbed ground temperature (Figure 2) shows that there is no strong correlation between these two factors. Up to a point, system design, installation and operation have a stronger impact on the system performance than the geographic location. Further investigation of this is part of the coming Annex work.

6. ANNEX 52 CASE STUDIES

A year after the start of Annex 52, at the beginning of 2019, six countries have joined the Annex; Sweden, the Netherlands, the UK, Finland, Germany and the USA. Altogether, these countries are measuring long-term performance of 31 GSHP systems (Figure 3 and Table 3). Seven of the GSHP systems (Beckomberga, Domstolen, Polishuset, Klipporna, ASHRAE HQ, De Aston House, and VGH) have already-complete

monitoring data sets. Southard et al. (2014a and 2014b) and Spitler et al. (2017) report SPF for the GSHP system in the ASHRAE HQ building in Atlanta. The ground-source heat pump system had SEPEMO scheme SPF_{H4} of 3.3 ± 0.2 and SPF_{C4} of 4.3 ± 0.6 . Naicker and Rees (2018) presented SPFs for the Aston House for SEPEMO levels C1 and H1, (3.19 and 4.06, respectively). Combined cooling and heating SPF are also defined corresponding to SEPEMO levels H1, H2 and H4 boundary conditions and are referred to as SPF_1 , SPF_2 , and SPF_4 with values of 3.54, 2.97, 2.49, respectively. Data for the other systems are currently being analyzed. Three systems (Aalto University, Backadalen and KTH Rocks) are new-built systems that are just starting their monitoring programs and data collection. The remaining systems have on-going monitoring data collection, with at least one year of data already collected.

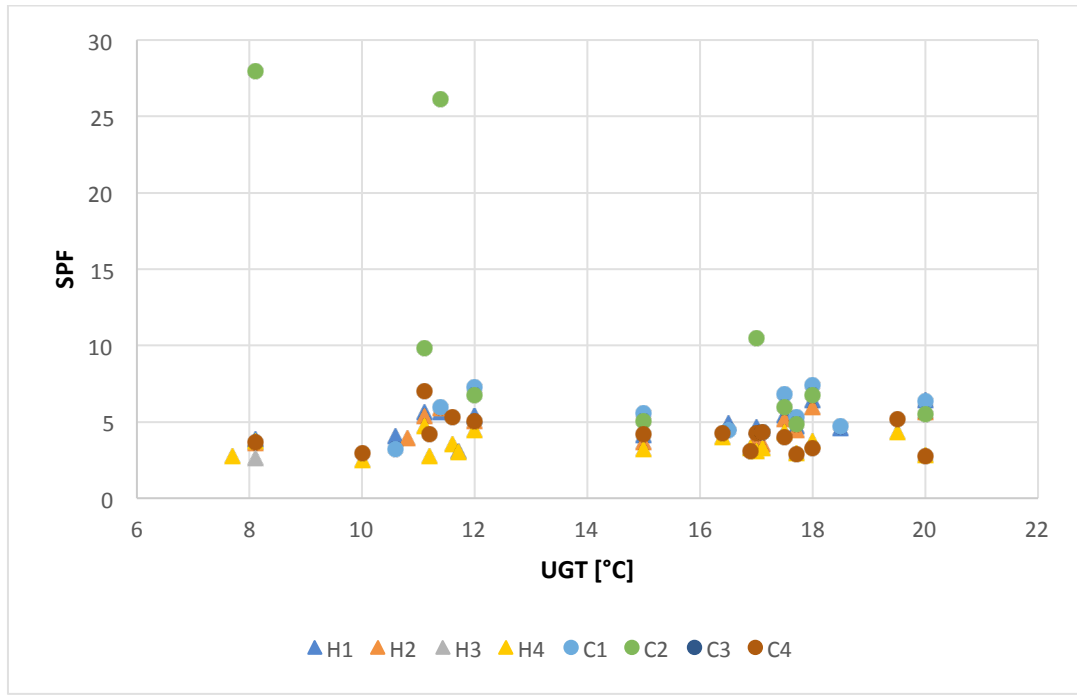


Figure 2: Seasonal performance factor vs undisturbed ground temperature (UGT) for 32 GSHP systems.

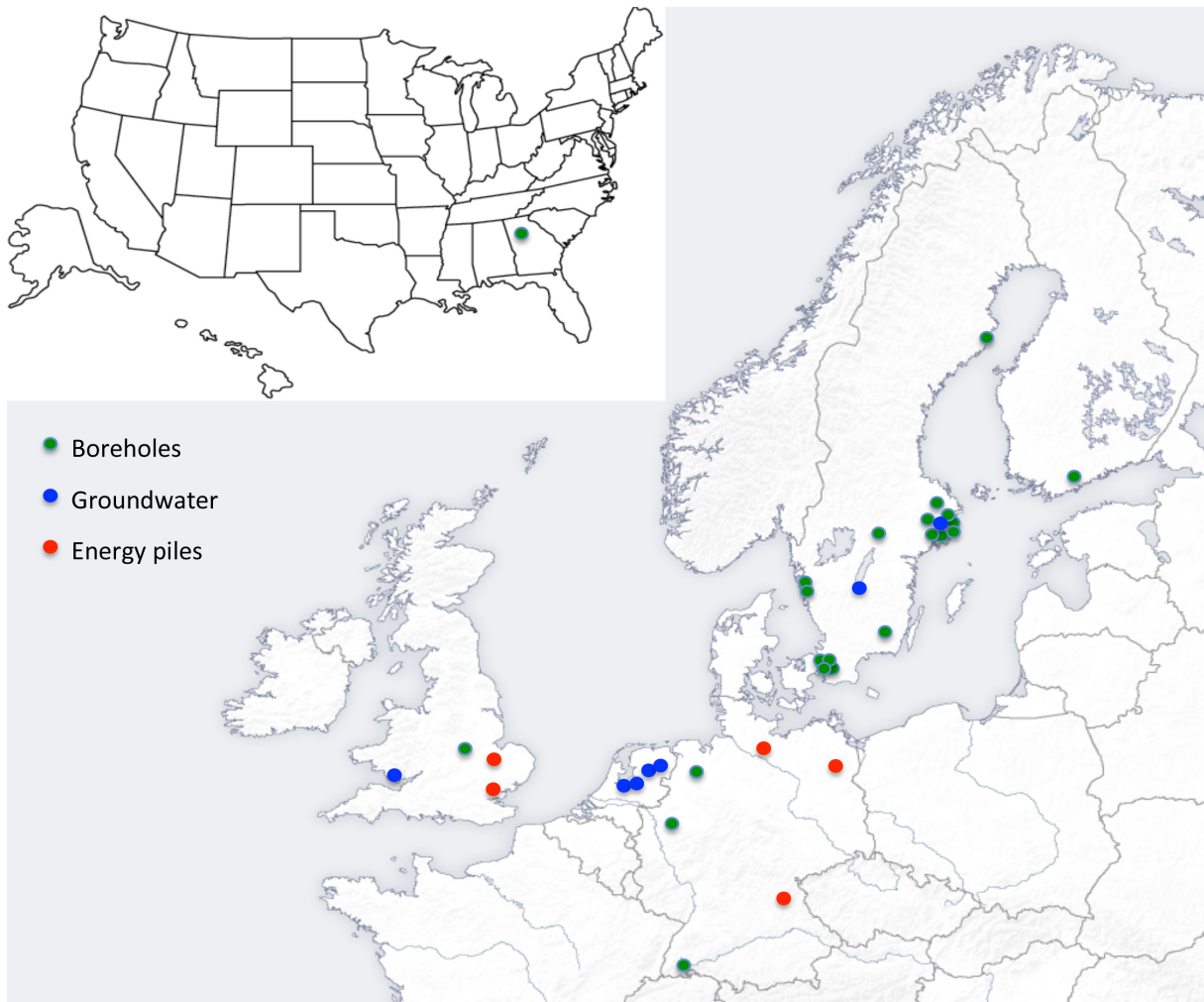


Figure 3: Location of the IEA HPT Annex 52 GSHP monitoring projects listed in Table 2.

Table 3: The GSHP monitoring projects included in IEA HPT Annex 52 as of February 2019.

#	Country	Location	Building name	Building type	Ground source
1	Finland	Espoo	Aalto University	University	Boreholes
2	Germany	Vechta	AOV	Office	Boreholes
3	Germany	Geisenkirchen	GEW	Office	Boreholes
4	Germany	Konstanz	KON	Residential	Boreholes
5	Germany	Berlin	EFB	Office	Energy Piles
6	Germany	Lüneburg	VGH	Office	Energy Piles
7	Germany	Neumarkt	WGG	School	Energy Piles
8	Netherlands	Utrecht	SKU OVT	Office/train station	Aquifer
9	Netherlands	Drente	Provinciehuis	Office	Aquifer
10	Netherlands	Amsterdam	DeLaMar Theatre	Theatre	Aquifer
11	Netherlands	Meppel	The Schiphorst	Care home	Aquifer
12	Sweden	Stockholm	Studenthuset	Office	Boreholes
13	Sweden	Emmaboda	Xylem	Industry	High temperature Boreholes
14	Sweden	Lund	Traktorn	Residential	Boreholes + District heating
15	Sweden	Lund	Briljanten	Residential	Boreholes + District heating
16	Sweden	Jönköping	Domstolen	Office	Aquifer
17	Sweden	Göteborg	Backadalen	Residential	Boreholes + District heating
18	Sweden	Uppsala	IKEA	Warehouse	Boreholes
19	Sweden	Umeå	NUS	Hospital campus	Boreholes in thermal grid
20	Sweden	Stockholm	KTH Rocks	Residential	Boreholes
21	Sweden	Stockholm	NPQ	University campus	Boreholes in thermal grid
22	Sweden	Stockholm	Rosenborg	Office	Aquifer
23	Sweden	Malmö	Polishuset	Office	DGC Boreholes
24	Sweden	Malmö	Klipporna	Office	Boreholes
25	Sweden	Göteborg	Frölunda Club	Club house	Boreholes
26	Sweden	Stockholm	Lindhagen	Office	DGC Boreholes
27	Sweden	Stockholm	Beckomberga	Residential	Boreholes + Sewage
28	UK	Leicester	Aston House	University	Boreholes
29	UK	Cardiff	Grangetown	Nursery school	Aquifer
30	UK	London	The Crystal	Office	Boreholes/Energy piles
31	UK	Cambridge	22 Station Road	Office	Energy Piles
32	USA	Atlanta	ASHRAE HQ	Office	Boreholes

Gehlin et al. (2018) report on one year of performance monitoring data for the student union building Studenthuset in Stockholm, Sweden. SEPEMO scheme SPF_{H_2} of 3.72 and SPF_{C_2} of 28.95 are presented. The Studenthuset building uses direct cooling from the ground, hence the high SPF for cooling.

The main focus of the Annex is on non-residential buildings, or rather buildings with GSHP systems more complex than that of a single-family house. Six of the case studies cover GSHP systems serving multi-family residential buildings, and one serves a residential care home for elderly people. The majority of the included case studies make use of boreholes in rock or un-consolidated ground layers as their ground-source. Among these systems, various combinations of boreholes and other sources are seen. Two of the borehole systems belong to office type buildings with a low-temperature direct-use application for heating and cooling, combined with district heating. Two other borehole systems are part of local thermal networks that connect several buildings within a university campus, or a hospital campus. One of the borehole systems is an industrial high-temperature borehole storage application, which has operated without heat pumps over several years (Nordell et al. 2016), and where recently heat pumps have been installed. Performance before and after heat pump installation will now be compared.

Seven of the case studies use aquifer thermal energy storage (ATES), where groundwater is the source for heating and cooling. Four of these ATES systems are located in the Netherlands, where ATES is a common application. The others are located in Sweden (2) and in the UK (1). A first performance evaluation of the early operation of the ATES system Rosenborg in Stockholm is presented by Abuasbeh and Acuña (2018). Focus is mostly on the ground source performance. Five case studies (two in the UK and three in Germany) make use of energy piles, in one case in combination with boreholes. Energy piles are building foundation piles that are equipped with plastic piping as heat exchangers. The sizing of an energy pile system is made primarily for the foundation requirements and not for energy sufficiency.

At the time of this paper being written, SEPEMO system boundaries are being identified for all of the 32 case studies, and performance factors are being calculated based on the SEPEMO scheme, or as near as possible on the SEPEMO scheme. Based on experience from these case studies, as well as from other GSHP systems in literature, guidelines for instrumentation, monitoring, data collection, and analysis of performance data will be compiled within Annex 52 and made available to the public. A first draft of guidelines for instrumentation is under preparation and is expected to be finished by the end of 2019.

7. CONCLUSIONS

As non-residential GSHP systems and large GSHP systems for multi-family buildings become increasingly common as an alternative to conventional heating and cooling systems, the need for benchmarking and uniform performance indicators increases. Annex 52, which will run from 2018 through 2021, commenced with a literature review that shows a lack of published high-quality long-term performance monitoring of large GSHP systems. Published performance measurements are geographically sparse and the uncertainty is seldom quantified. The nomenclature for performance indicators used by different authors is inconsistent, reflecting a lack of consensus on how to evaluate, express and present performance for complex large-scale GSHP systems. Though performance evaluation for most of the case studies is still in the beginning stages, it is already evident that the SEPEMO boundary scheme used for SPF calculation is insufficient for covering the complex nature of large-scale GSHP systems.

Annex 52 aims to provide tools to improve the state of the art, based on wide international experience from the more than 30 case studies that are currently included in the Annex. These tools include an improved boundary scheme with complementary performance indicators, guidelines on instrumentation and monitoring, guidelines on analysis and key metrics, a thorough bibliography and a unique case study report with long-term performance evaluation of more than 30 GSHP systems worldwide, using a harmonized evaluation scheme.

The results from Annex 52 will contribute significantly to harmonization and system development of such tools. With these new tools, we hope to prepare the way for widespread long-term performance monitoring to become a useful tool for a variety of end users in the GSHP market (see Table 1).

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