Annex 52

Long-term performance monitoring of GSHP systems for commercial, institutional, and multi-family buildings

Final Report

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May 2022
Report no. HPT-AN52-1

Published by Heat Pump Centre
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Production Heat Pump Centre, Borås, Sweden

ISBN: 978-91-89711-89-1
Report No. HPT-AN52-1

DOI: 10.23697/xsbr-xn83

Preface

This project was carried out within the Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP), which is a Technology Collaboration Programme within the International Energy Agency, IEA.

The IEA
The IEA was established in 1974 within the framework of the Organization for Economic Cooperation and Development (OECD) to implement an International Energy Programme. A basic aim of the IEA is to foster cooperation among the IEA participating countries to increase energy security through energy conservation, development of alternative energy sources, new energy technology and research and development (R&D). This is achieved, in part, through a programme of energy technology and R&D collaboration, currently within the framework of nearly 40 Technology Collaboration Programmes.

The Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP)
The Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP) forms the legal basis for the implementing agreement for a programme of research, development, demonstration, and promotion of heat pumping technologies. Signatories of the TCP are either governments or organizations designated by their respective governments to conduct programmes in the field of energy conservation.

Under the TCP, collaborative tasks, or "Annexes", in the field of heat pumps are undertaken. These tasks are conducted on a cost-sharing and/or task-sharing basis by the participating countries. An Annex is in general coordinated by one country which acts as the Operating Agent (manager). Annexes have specific topics and work plans and operate for a specified period, usually several years. The objectives vary from information exchange to the development and implementation of technology. This report presents the results of one Annex.

The Programme is governed by an Executive Committee, which monitors existing projects and identifies new areas where collaborative effort may be beneficial.

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The Heat Pump Centre
A central role within the HPT TCP is played by the Heat Pump Centre (HPC).

Consistent with the overall objective of the HPT TCP, the HPC seeks to accelerate the implementation of heat pump technologies and thereby optimize the use of energy resources for the benefit of the environment. This is achieved by offering a worldwide information service to support all those who can play a part in the implementation of heat pumping technology including researchers, engineers, manufacturers, installers, equipment users, and energy policy makers in utilities, government offices and other organizations. Activities of the HPC include the production of a Magazine with an additional newsletter 3 times per year, the HPT TCP webpage, the organization of workshops, an inquiry service and a promotion programme. The HPC also publishes selected results from other Annexes, and this publication is one result of this activity.

For further information about the Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP) and for inquiries on heat pump issues in general contact the Heat Pump Centre at the following address:

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1 Executive summary

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 be 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 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 (rock, soil, groundwater, surface water).
- 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 CO_2 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 this document, this report is comprised of four subtask reports and 27 case study reports containing 29 monitoring projects. These publications comprise 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 ten peer reviewed conference papers. Additional publications are in progress.

Key findings from the work within Annex 52 can be summarized as follows:

- The previously defined SEPEMO system boundary schema is insufficient for treating the complexity of large-scale GSHP systems. The Annex 52 system boundary schema, with six defined boundaries and an indicator for use of supplemental heating or cooling, better captures the complex nature of large GSHP systems. Unlike the SEPEMO boundary schema, the Annex 52 schema are consistent between heating and cooling, also allowing performance factors to be defined for combined heating and cooling.
- Performance indicators for GSHP systems require clearly stated system boundaries as well as the time frame at which the performance is evaluated. Seasonal performance factors (SPF) should be used only for measured performance over a full year. (This is worth emphasizing, since the definition is sometimes misused in the literature.) Measured performance over shorter time intervals - daily (DPF), monthly (MPF) or binned performance factors (BPF) - are also valuable performance indicators.
- Uncertainty analysis of performance data is rarely reported, despite being an important tool to help design the measurement program and understand the significance of its results. Annex 52 provides guidelines aimed at the application of uncertainty analysis to measurements made to monitor performance of GSHP systems.
- The monitoring projects report a combined total of 119 years of data, with SPFHC1, the combined heating and cooling seasonal performance factor at boundary 1 (heat pump only) in the range 1.5-7.2 with an average of 4. 88% of the measured years have SPFHC1 of 3 or higher. SPFHC2, the combined heating and cooling seasonal performance factor at boundary 2 (heat pump and source-side circulating pump) are in the range 1.4-13 with an average of 4.7. Values at the high end of the range represent systems dominated by free cooling. 80% of the project-years have SPFHC2 of 3 or higher.
- The projects carried out within Annex 52 show that most systems work satisfactorily although there is room for further improvement and optimization. The distribution system on the load side of the heat pump has a detrimental effect on the system performance at system boundaries 3-5. Energy use for hot water, distribution pumps and fans account for this detrimental effect.

The outcomes of Annex 52 will be useful for lowering the cost of obtaining robust, accurate, and consistent measurements of performance. This helps building owners, designers and technicians evaluate, compare, and optimize GSHP systems. It also provides useful guidance to manufacturers of instrumentation and GSHP system components, and developers of tools for monitoring, controlling and fault detection/ diagnosis. Lowering the cost will in turn lead to wider adoption of performance measurement schemes, increased energy and cost savings, and increased benchmarking leading to better understanding of system design and performance expectations.

Annex 52 relates to the overall strategy of IEA and HPT by providing multinational consensus on how to instrument, measure, analyse and evaluate long-term performance of GSHP systems. This advances the energy technology within this field by facilitating further improvement of components, systems, and operational strategies of GSHP systems. The annex work fills an important gap in research and practice. Although Annex 52 was focused on ground-source heat pump systems, much of the work is directly relevant to air-source heat pump systems and air-conditioning systems, particularly the guidelines on instrumentation and uncertainty analysis. The boundary schema and many of the key performance indicators could readily be used or adapted for use with air-source heat pump systems and air-conditioning systems.

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2 Foreword

This report concludes the four-year international collaboration project IEA HPT Annex 52 - *Long-term performance monitoring of GSHP systems for commercial, institutional and multi-family buildings*. The project was led by Sweden, with the Swedish Geoenergy Center as the Operating agent, and ran from January 2018 to December 31, 2021. Seven countries participated in Annex 52; Sweden, the USA, the UK, the Netherlands, Germany, Norway and Finland.

Annex 52 has aimed to survey and create a library of quality long-term measurements of GSHP system performance for commercial, institutional, and multi-family buildings and to refine and extend current methodology to better characterize performance of GSHP systems serving commercial, institutional and multi-family buildings with the full range of features shown on the market, as well as to provide a set of benchmarks for comparisons of such GSHP systems around the world. This helps building owners, designers and technicians evaluate, compare, and optimize GSHP systems. It also provides useful guidance to manufacturers of instrumentation and GSHP system components, and developers of tools for monitoring, controlling and fault detection/ diagnosis. In the long run, this will lead to energy and cost savings.

Annex 52 has engaged a large group of international experts and organizations. The 9 national and 16 international experts' meetings and workshops that have been arranged within Annex 52 have attracted over a hundred experts, of which about a quarter are women, from nearly 60 companies and organisations. The hard work and contributions from all these experts are most gratefully acknowledged. I especially thank Dr. Jeffrey D. Spitler from Oklahoma State University and Dr. Matthew Davis from University of New Hampshire, who have been the editors of the uncertainty calculation guideline and the instrumentation guideline. Their invaluable support and major work efforts have been paramount for the compilation of these two Annex deliverables.

The Swedish work that has led to this report has been partially funded by the Swedish Energy Agency (TERMO research program Grant 45979-1). The UK work has been funded by the Engineering and Physical Sciences Research Council (UK), the UK Department for Business, Energy and Industrial Strategy, and the Royal Academy of Engineering (UK). The Norwegian work has been funded by ENOVA Grant 18/3576. The German work that has led to this report has been funded by the German Federal Ministry for Economic Affairs and Energy (BMWi). The US work was partly funded by the OG&E Energy Technology Chair at Oklahoma State University. The Finnish work that has led to this report has been partially funded by Business Finland and Aalto University Campus and Real Estate. The Dutch work has been funded by RVO Netherlands.

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3 Annex 52 objectives and scope

Annex 52 aimed to survey and create a library of quality long-term performance measurements of GSHP systems, serving commercial, institutional and multi-family buildings. All types of ground sources (rock, soil, groundwater, surface water) were included in the scope. Previous work was surveyed within the annex but the emphasis of the annex has been on long-term measurements performed within the project time frame. The annex also aimed to refine and extend current methodology to better characterize GSHP system performance serving commercial, institutional and multi-family buildings with the full range of features shown on the market, and to provide a set of benchmarks for comparisons of such GSHP systems around the world.

In order to better characterize performance of GSHP systems serving commercial and institutional buildings, the guidelines provided by the SEPEMO project were refined, extended to cover as many features as possible, and formalized in guidelines documents. This has been done in concert with measurement projects in the seven participating countries. Additional analysis procedures that help diagnose poor performance and opportunities for system performance improvements have also been investigated. Over 30 case studies featuring GSHP system performance measurements for systems in the participating countries have been included and these case studies now serve as reference sets for future benchmarking.

Annex 52 has been organized into three subtasks:

Subtask 1 "Long-term measurement case studies – new and previous" includes two parts. The initial part is an annotated bibliography covering past GSHP system performance studies. The second part consist of long-term measurement case studies of GSHP performance that have been performed and analysed within the Annex timeframe.

Subtask 2 "Guide for instrumentation and measurement of GSHP systems" was aimed at finding consensus on necessary instrumentation and monitoring practices for larger GSHP systems, including relevant parameters, frequency, instrument quality, etc. This work has resulted in two guideline documents on instrumentation and measurement and on uncertainty calculation for GSHP system performance.

Subtask 3 "Guide for analysis and reporting of GSHP system performance data" was aimed at finding consensus on suitable key performance indicators and analysis procedures for GSHP system performance monitoring, with a resulting guideline document.

The Annex will benefit researchers, building owners, installers, and manufacturers by providing high quality measured performance data that can be used for further research, validation of simulation models, and testing of control strategies. It provides useful guidelines for instrumentation, data logging, and analysis of results. These results can be used to optimize the system performance, detect faults, assure quality, and give feedback on system components which may lead to further product development. The collection of results from the measurement projects also serves as a useful set of benchmarks for comparisons of other systems in the future. Society will benefit from the Annex work as optimized GSHP performance minimizes CO_2-emissions and increases the utilization of local and renewable energy resources.

The improved and verified methods for collecting operational data and determining performance of GSHP systems 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 CO_2 emissions we can reduce with GSHP systems.

The technical sector targeted in this Annex is primarily the commercial and institutional building sector, typically where both heating and cooling are needed, but other sectors such as the large residential building sector and the industrial building sector may also benefit from the outcomes of the Annex. Improved model validation, component development and improvements in control- and monitoring systems will provide improvement on large GSHP systems in general.

The cooling and free-cooling aspects are increasingly important as building envelopes become better insulated and efficient. Instrumentation, monitoring and evaluation of the heat pumps and both the source and distribution sides of the GSHP system are included in the Annex scope.

4 Background

Field measurements of building heating and cooling system performance are rarely made but essential to ensure that performance expectations are actually met. For GSHP systems, owners have made significant investments with expectations of high performance, so it is particularly important that high performance be achieved. Field measurements have been reported in the literature (Gehlin and Spitler 2022a), however, as Spitler and Gehlin (2019) concluded in their performance monitoring literature review, 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 focus of Annex 52 is performance measurement of GSHP systems serving commercial, institutional, and multi-family buildings. These buildings may, for example, have:

- Multiple heat pumps, which may be part of a central heating and cooling plant or be distributed throughout the building(s).
- Water-to-water (brine-to-brine), or water-to-air heat pumps.
- Depending on the above two items, a separate distribution system for heating and cooling may be needed, or the distribution system may only involve attaching ductwork to the distributed water-to-air heat pumps.
- Heating and cooling, with the cooling often being predominant for commercial and institutional buildings. Furthermore, heating and cooling may be provided simultaneously to different parts of the building, either by using both sides of the heat pump, or with some heat pumps providing heating and others cooling. In some cases, cooling or pre-heating may be provided directly by the boreholes without the aid of heat pumps (so-called free-cooling).
- In addition to the ground heat exchanger made up of multiple boreholes or doublets etc., complementary heat sinks or sources (e.g. cooling towers, fluid coolers, solar collectors) may be utilized, forming what is sometimes called a hybrid GSHP system.
- A range of pumping/piping system designs using variable speed central circulation pumps, distributed circulation pumps, primary/secondary pumping, and two-pipe or one-pipe configurations.
- Control systems that affect flow rates in part-load conditions, operation of the auxiliary heat sink or source, and other aspects of the system operation.
- Standby electrical losses from control boards in the heat pumps, circulation pump variable-speed drives, Legionella protection and other components.
- Heat pumps sometimes operating with only the fan running to assist in distribution of outdoor air.

This diversity in the system configuration adds several degrees of complexity to analyses of seasonal performance factors, e.g., when the heat pumps are providing both heating (which could include building heating and domestic hot water heating), and cooling, how is the electrical energy used by the central circulation pump allocated? How should the free-cooling amount be quantified? How do heat pump stand-by losses affect seasonal performance factors?

The EU project SEPEMO (Nordman 2012) defined heating and cooling seasonal performance factors (SPF) for residential heat pump systems with a range of boundary conditions. The final report noted that heat pump system performance depends not only on the heat pump, but also on the climate and quality of installation. While the SEPEMO project guidelines served as an excellent starting point for the analysis of GSHP systems serving commercial, institutional, and multi-family buildings, they do not fully address all of the features that may be found in these larger systems. The results from Annex 52 make possible both improvements to GSHP system performance and direct comparisons with other heating/cooling systems installed in similar buildings.

5 Structure of this document

This document is the final summary of all the work that has been done within the Annex 52 project over the four-years project period 2018-2021. It presents published results, gathered experience and conclusions from measured long-term performance studies of ground-source heat pump systems serving commercial, institutional, and multi-family buildings. These studies include both previously published studies as well as those performed within the Annex.

The Annex 52 subtasks are covered in this report as follows:

- A literature survey (Chapter 6) and a number of international monitoring projects on long-term performance measurements of larger GSHP systems (Chapter 8)
- Guidelines for instrumentation (Chapter 9), uncertainty calculation (Chapter 10)
- Guidelines for analysis and reporting of GSHP system key performance indicators (Chapter 7)

Three appendices are included. Appendix A contains a list of the core participants within Annex 52; Appendix B is a glossary of used terms and abbreviations in this report. Appendix C contains links to the four Annex 52 subtask reports: The annotated bibliography and the three guideline documents on instrumentation, uncertainty calculation and key performance indicators. Also provided is a link to a compilation of two-page summaries of each of the completed Annex 52 monitoring projects.

All deliverables, including the full case-study reports, from Annex 52 are made available from the Annex 52 official webpage at the HPT platform: **https://heatpumpingtechnologies.org/annex52/documents/**

6 Annotated bibliography

As part of the fulfilment of the Annex 52 Subtask 1, an annotated bibliography was compiled (Gehlin and Spitler 2022a). The bibliography includes a total of 82 publications and gives an overview of published literature reporting on long-term measured (at least one full season of measured data) performance values (seasonal performance factors, SPF, and coefficients of performance, COP) for ground source heat pump (GSHP) systems used in commercial, institutional, or multifamily residential buildings. The bibliography is divided into two parts. The first part includes 64 publications reporting on long-term performance monitoring of larger GSHP systems for commercial, institutional, and multi-family buildings, providing measured seasonal performance factors, SPF, published between 2002-2021. The second part contains an additional 18 publications published between 1995-2020, and reporting on larger GSHP systems that present measured performance other than SPF.

6.1 Literature survey

The initial basis for the annotated bibliography was the literature reviewed by Spitler and Gehlin (2019). 17 of the papers that appear in the annotated bibliography were reviewed and summarized in the Spitler and Gehlin (2019) journal paper. The literature review by Spitler and Gehlin comprises 55 GSHP systems used in commercial or multi-family residential buildings, and the features of these GSHP systems are summarized in tabular format, with SPF values based on the SEPEMO definitions. For three of the GSHP systems a combined cooling and heating SPF (HC4) is given. In cases where values were given for multiple years, they have been averaged. The 55 systems are sparsely located on three continents. About half the cases give the overall (H4 or C4) system SPF. Median values of annual SPF for heating are 4.1, 3.6, 3.1, and 2.9 for SEPEMO boundaries H1, H2, H3, and H4, respectively. Median values of SPF for cooling are 5.5, 6.4, and 4.2 for SEPEMO boundaries C1, C2, and C4, respectively.

After the initial literature review in 2019 of the 55 GSHP systems in 14 countries, the bibliography was significantly expanded. Several of the 82 publications report data from the same GSHP systems, and some publications report data from more than one GSHP system, e.g. Hughes (2018) provides a systematic analysis of 19 larger GSHP systems in the UK, Liu et al (2017) present performance data from ten GSHP systems in the USA, and Mendrinos and Karytas (2016) report long-term performance of eight European GSHP systems analysed within the European GroundMed project.

6.2 Bibliography selection criteria

The publications in the annotated bibliography were selected based on relevance to the Annex 52 scope, specifically the type of building, ground source type and presented performance indicators. These criteria are described as follows. First, the publications must contain measured data from at least one full season of operation. Simulated or calculated performance would not fit the scope. Second, the buildings served by the GSHP systems described in the publications should be larger than single-family houses. We included systems serving a variety of commercial and institutional buildings, such as shopping malls, offices, university or hospital buildings, and factory buildings. In addition, systems serving multi-family buildings were included. Third, the scope was restricted to systems with a ground source, though any type of ground source was considered acceptable. The ground sources considered included boreholes in rock, clay or unconsolidated formations, horizontal ground-loops, groundwater wells, surface water systems, energy piles and caverns or pit storage. Inclusion of a heat pump was not a required criterion - the ground-source system could serve a heat pump or cooling machine or provide direct heating or cooling. High-temperature ground storage also met the criteria for the selection.

6.3 Contents of the bibliography

The publications were found through earlier literature reviews, searches in publication databases and from references in other publications. They were collected by the Annex 52 participants at large over the course of the Annex. For each reference, we attempted to summarize the following information:

- Full reference
- Building type and size
- Geographic location
- Description of the ground source system
- Description of the installed equipment

- Building Energy Use Intensity (EUI)
- Heat pump COP
- SPF
- Duration of measured data
- Used system boundary scheme (e.g. SEPEMO)
- Central or distributed heat pump system
- Inclusion of uncertainty analysis
- Undisturbed ground temperature
- Description of level of detail
- Additional comments or notes

Each publication in the bibliography does not necessarily include information on all of the above points.

The reported building types include universities, hospitals, office buildings, multi-family buildings, museums and archives, schools and nursery schools, warehouses and a detention facility. They are located in 17 countries: Belgium, China, Finland, France, Germany, Greece, Italy, Poland, Portugal, Romania, Slovenia, South Korea, Spain, Sweden, Switzerland, UK and the USA. The vast majority of the ground sources are boreholes, but the bibliography also contains buildings served by energy piles, groundwater systems, surface water and horizontal ground loops. Several of the publications present data from the same buildings, but there are also publications that contain data from multiple buildings. The majority of the GSHP systems in the bibliography are located in Europe.

6.4 Findings

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. Uncertainty analyses of the reported performance factors are extremely rare. Only a handful of publications include uncertainty analyses. Another conclusion is that the availability of measured performance data is yet far too limited to be useful in setting performance expectations. It is hoped that the standardization of nomenclature, guidelines for instrumentation and analysis, and examples provided by the Annex will aid in significantly increasing the availability of measured performance data.

7 Guide for analysis and reporting of GSHP system performance

The "Guide for analysis and reporting of GSHP system performance – system boundaries and key performance indicators (KPI)" (Gehlin et al. 2022) provides guidance about system boundaries and useful key performance indicators for evaluating the operation and efficiency of larger GSHP systems. The guideline gives a brief introduction to performance monitoring and its importance and usefulness (Chapters 1 and 2) and defines a set of system boundaries for consistent performance analysis (Chapter 3). In Chapter 4, the KPIs suitable for performance evaluation of larger GSHP systems are described, and Chapter 5 gives examples of how KPIs have been used for performance analysis and fault detection in some of the Annex 52 monitoring projects.

The overall performance of any GSHP system is affected by the performance of the source side ground circuit and the heat pump (HP) unit performance, as well as the load side circuit performance. This also includes supplementary heating and cooling. The experts within Annex 52 have identified performance indicators that will allow evaluation on all three levels – source side, heat pump unit and load side. These performance indicators could be used for commissioning, fault detection, system optimization and future system development, and may help answer a multitude of questions from relevant target groups, as listed in Table 7.1.

Table 7.1. Target groups and why performance monitoring is useful (from Gehlin and Spitler 2019)

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? How does my system compare to other systems in the area serving similar buildings? 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? 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 compare 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 cetrification 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?

The guideline gives directions on how and why to measure, analyze and present long-term performance data with emphasis on heat pump and system performance. Examples of performance indicators are heat pump coefficient of performance, performance factors, load factors and various energy use ratios and efficiency indices. The report is based on the results from the many monitoring projects carried out within Annex 52 and provides guidance on system boundaries, key metrics, and examples from some of the Annex 52 case studies. The work summarized in the Key performance indicator guideline is a step towards standardized methods and analyses that will support widespread performance monitoring of GSHP systems. Many of the KPI are also applicable to air-source heat pump systems and air-conditioning systems.

7.1 System boundaries

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, when calculating a performance factor, it must necessarily be defined for a specific set of boundaries. As an example, 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. 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. 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.

As a starting point for Annex 52, the SEPEMO system boundary schema (Nordman 2012) was used for calculation of performance factors. 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. Therefore, 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 (Gehlin and Spitler 2021a). 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 7.1 and Table 7.2). 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.

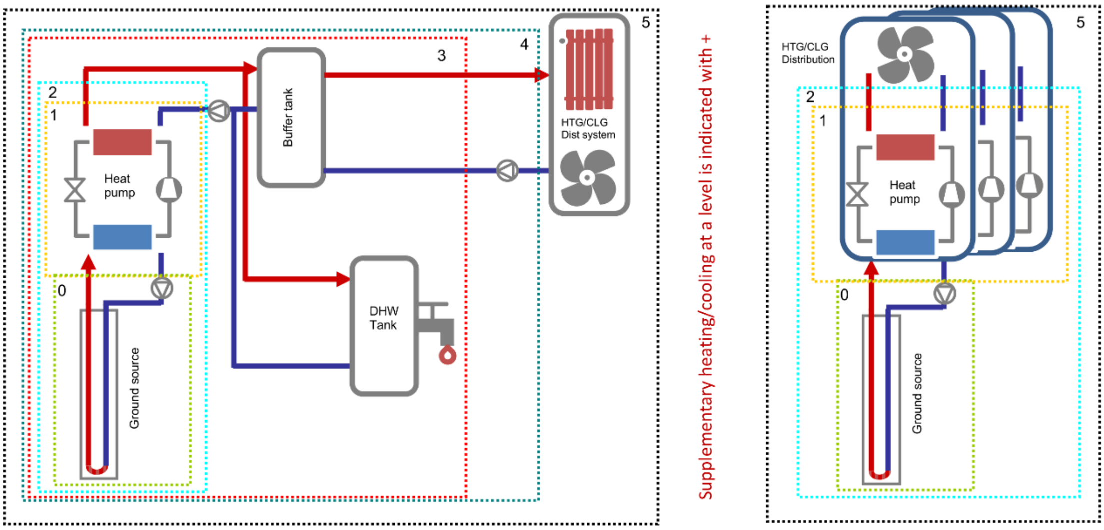

Figure 7.1 The Annex 52 system boundary schema applied for a centralized (left) and a distributed (right) GSHP system. Supplementary heating/cooling at a boundary level is indicated with +.

Figure 7.1 shows the Annex 52 system boundaries for a centralised (to the left) and a distributed (to the right) heat pump system. The typical European GSHP system is a centralized heat pump system where the ground source is connected to one or multiple heat pumps placed in a machine room, sometimes but not always connected to a buffer tank. From this central machine room, the heating and/or cooling is distributed through piping systems to heat distribution components in the many rooms in the building. In a distributed GSHP system, the ground source is connected to multiple smaller heat pump units distributed in the building's rooms. When comparing the performance of centralized and distributed GSHP systems the overall boundary (system boundary 5) must be used, because, without submetering within the heat pump unit, the distributed GSHP energy necessarily includes fan power.

Table 7.2. The Annex 52 system boundary schema and its relation to the SEPEMO boundary schema (from Gehlin and Spitler 2021a). CP =circulation pump, GHE = ground heat exchanger, HP = heat pump, BT = buffer tank, H/C = heating/cooling.

Boundary description	Boundary Levels											
	0	0^+	1	1^+	2	2^+	3	3^+	4	4^+	5	5^+
Ground Source (CP + GHE)	X	X			X	X	X	X	X	X	X	X
Heat pump unit including internal energy use, excluding internal CP			X	X	X	X	X	X	X	X	X	X
Buffer tank (including CPs between HP and BT)							X	X	X	X	X	X
CP[1] on load-side (between BT & building H/C distribution system)									X	X	X	X
Building H/C distribution system											X	X
Auxiliary heating or cooling		X		X		X		X		X		X

SEPEMO: H1/C1 H2/C2 H3 C3 H4 C4

(Mapping corresponds with having auxiliary H/C only at the same levels as SEPEMO. For the proposed scheme, the "+" superscript indicates auxiliary heating/cooling within the boundary.)

From a European perspective, it is tempting to suggest that only system boundary 2, which includes the ground source and heat pump unit, be used for performance evaluation, since the distribution on the load side of the building would be mostly the same regardless of the heating or cooling source. However, ignoring the distribution system may give a somewhat optimistic picture of the efficiency. The Annex 52 case studies show that distribution losses often cause significant decrease in performance. Centralized GSHP systems tend to have higher losses on the load side, whereas distributed GSHP systems tend to have higher losses on the source side. There is high potential for improvement of distribution losses, whether they mainly occur on the load side or source side. The six system boundaries of the Annex 52 system boundary schema highlight the effect of the heating and cooling distribution on the system performance, which provides valuable information for system optimization.

All but one of the GSHP systems included in the Annex 52 project are such centralized GSHP systems. The remaining GSHP system is a distributed heat pump system, which is a common heat pump system design in the USA.

7.2 Key performance indicators

Chapter 4 of the KPI guideline list and define KPIs for GSHP systems on an overall building level as well as for the ground source, system components, and overall GSHP system level. The guideline explains how these KPIs are obtained and used. Financial indicators are not within the Annex 52 scope, but several of the performance indicators identified and recommended by Annex 52 provide the material for financial indicators and evaluation. An overview of the included KPIs are shown in Table 7.3.

Table 7.3. Key Performance Indicators (KPI) for GSHP systems at four system levels

Overall building KPIs	Ground source KPIs
Building energy use intensity (EUI) Building energy signature Temperature signature Energy load fractions	Annual heat extraction and rejection Specific heat extraction rate Specific energy extraction Ground Thermal Imbalance Ratio (IR) Storage efficiency ATES well productivity
System level KPIs	**Component level KPIs**
Coefficient of Performance (COP and SCOP) Energy Efficiency Ratio (EER and SEER) Performance Factors (SPF, MPF, DPF, HPF, BPF) System Efficiency Index (SEI) Load factor average/peak per month	Compressor KPI – Compressor isentropic efficiency Condenser KPI – Condenser efficiency Evaporator KPI Cycle efficiency Heat pump cycling

Not all of the listed KPIs have been used in the Annex 52 monitoring projects, as not all indicators are relevant to every GSHP system. Combined with the Instrumentation guideline (Davis et al 2021), the KPI guideline offers help to building owners in setting up cost-effective monitoring programs and instrumentation for their GSHP systems.

8 Performance monitoring projects

As part of Annex 52 subtask 1, 32 GSHP monitoring case studies completed their long-term monitoring programs, and 29 are presented in individual reports. These GSHP systems, located in seven countries, cover a range of applications (Figure 8.1 and Table 8.1 and Table 8.2). The case study reports are published on the Annex 52 website (**https://heatpumpingtechnologies.org/annex52/documents/**), and short 2-page summaries are compiled in Appendix C.

A majority of the GSHP systems use boreholes in the ground as the heat source and sink. Five of the GSHP systems use groundwater as the source for heating and cooling and four of the GSHP systems use energy piles, of which one combines energy piles with boreholes.

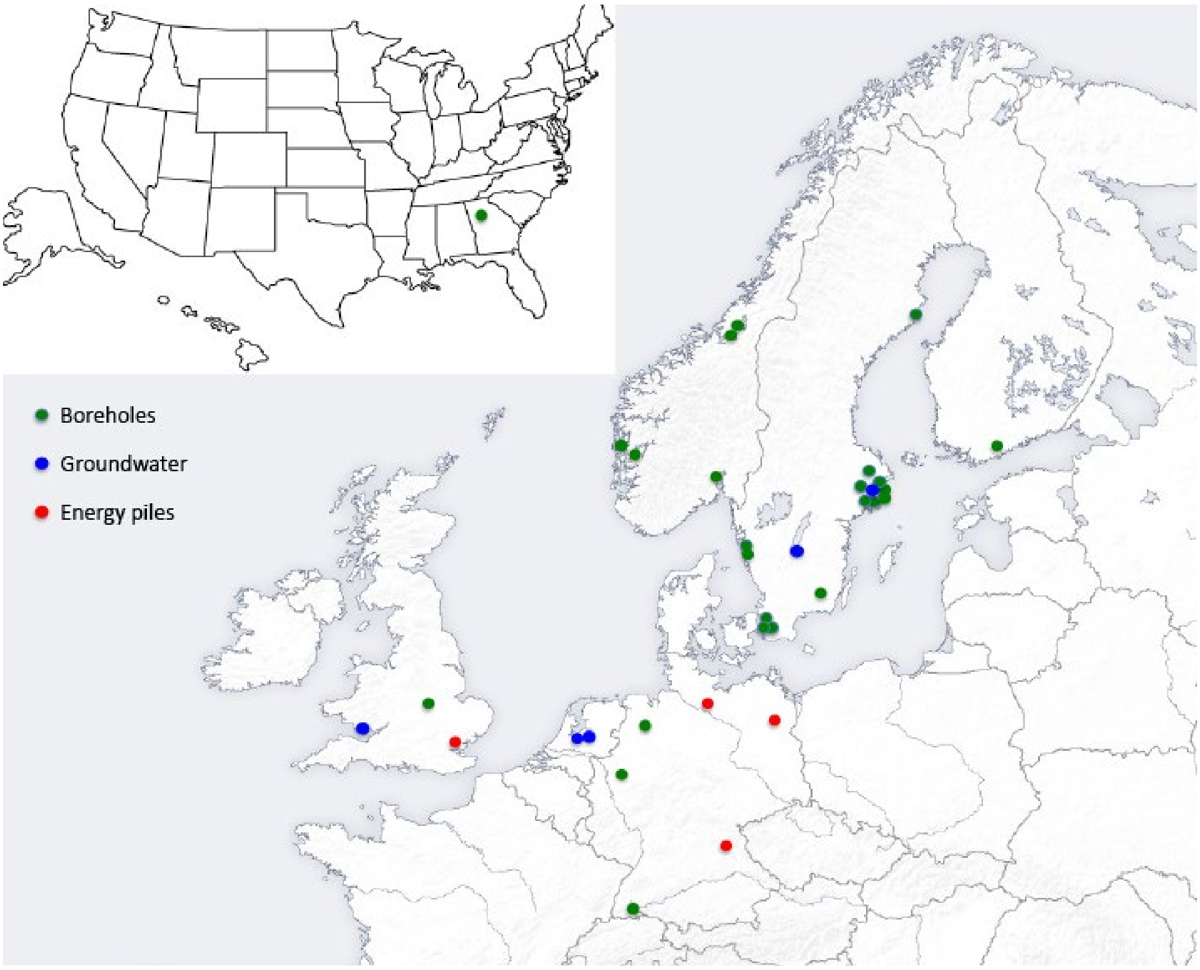

Figure 8.1: Map showing the monitored GSHP systems within Annex 52

Table 8.1: Building type and ground sources of the monitored case studies in the seven countries in Annex 52

	Sweden	Germany	Norway	UK	Finland	USA	Netherlands
Residential	4	1	1	-	-	-	-
Commercial	9	5	4	3	1	1	2
Industrial	1	-	-	-	-	-	-
Boreholes	12	3	5	1	1	1	-
Groundwater	2	-	-	1	-	-	2
Energy Piles	-	3	-	1	-	-	-

Table 8.2: Overview of monitored GSHP systems within Annex 52

#	Country	Location	Building name	Building type	Ground source	Reference
1	Finland	Espoo	Aalto University	University	Boreholes	Todorov et al (2021)
2	Germany	Vechta	AOV	Office	Boreholes	Bockelmann (2021a)
3	Germany	Gelsenkirchen	GEW	Office	Boreholes	Bockelmann (2021b)
4	Germany	Konstanz	KON	Residential	Boreholes	Bockelmann (2021c)
5	Germany	Berlin	EFB	Office	Energy piles	Bockelmann (2021d)
6	Germany	Lüneburg	VGH	Office	Energy piles	Bockelmann (2021e)
7	Germany	Neumarkt	WGG	School	Energy piles	Bockelmann (2021f)
8	Netherlands	Utrecht	SKU OVT	Office/train station	Aquifer	
9	Netherlands	Amsterdam	DeLaMar Theatre	Theatre	Aquifer	
10	Norway	Bergen	Scandic Flesland	Conference hotel	Boreholes	Midttømme et al (2021)
11	Norway	Sarpsborg	Kalnes energy central	Hospital campus	Boreholes	Clauss et al (2021)
12	Norway	Trondheim	KIWI Dalgård	Supermarket	Boreholes	Stene (2021)
13	Norway	Trondheim	Moholt 50/50	Residential/Office	Boreholes	Stene (2021)
14	Norway	Bergen	Sweco office building	Office	Boreholes	Stene (2021)
15	Sweden	Stockholm	Studenthuset	Office	Boreholes	Gehlin and Spitler (2021b)
16	Sweden	Emmaboda	Xylem	Industry	Boreholes	Andersson et al (2021)
17	Sweden	Lund	Traktorn	Residential	Boreholes	Ekestubbe (2021a)
18	Sweden	Lund	Briljanten	Residential	Boreholes	Ekestubbe (2021b)
19	Sweden	Jönköping	Domstolen	Office	Aquifer	Walfridson (2021a)
20	Sweden	Göteborg	Backadalen	Residential	Boreholes	Walfridson (2021b)
21	Sweden	Uppsala	IKEA	Warehouse	Boreholes	Walfridson (2021c)
22	Sweden	Umeå	NUS	Hospital campus	Boreholes	Walfridson (2021d)
23	Sweden	Stockholm	Forskningen	Residential	Boreholes	Mazzotti-Pallard (2021)
24	Sweden	Stockholm	Frescati NPQ	University campus	Boreholes	Lazzarotto (2021)
25	Sweden	Stockholm	Rosenborg	Office	Aquifer	Abuasbeh (2021)
26	Sweden	Malmö	Polishuset	Office	Boreholes	Javed, Liu, Zhang, (2021)
27	Sweden	Göteborg	Frölunda Club house	Club house	Boreholes	Javed, Zhang, Liu (2021)
28	Sweden	Stockholm	Lindhagen	Office	Boreholes	Javed et al (2021)
29	UK	Leicester	Hugh Aston Building	University	Boreholes	Rees (2021)
30	UK	Cardiff	Grangetown	Nursery school	Aquifer	
31	UK	London	The Crystal	Office	Boreholes/ Energy piles	Turner et al (2021)
32	USA	Atlanta	ASHRAE HQ	Office	Boreholes	Spitler et al (2021b)

8.1 Results from the Annex 52 monitoring projects

Data from 119 measured years have been collected from the reported case studies and used for calculation of monthly and seasonal energy loads and performance factors based on the Annex 52 system boundary schema. Only one of the many monitoring projects had instrumentation allowing for reporting of performance factors for all six Annex 52 system boundaries; the other projects have reported performance for fewer system boundaries. Several of the monitored GSHP systems do not provide cooling, but only heating, and for some systems not all system boundaries in the Annex 52 schema exist.

Table 8.4 gives an overview of the reported seasonal performance factors from the Annex 52 case studies. SPF values within each system boundary vary significantly, which is expected since the GSHP applications in the reporting case studies include high-temperature storage and residential buildings as well as offices, warehouses

and hospitals, all with their own system features and thermal load profiles. Direct cooling (also called free cooling) applications tend to result in high SPFs for cooling.
Table 8.4 also shows the percentage of measured years that report an SPF value of at least 3. At system level 1 (heat pump only) 88% of the measured years had a seasonal performance factor for combined heating and cooling (SPFHC1) of 3 or higher, and at system level 2 (ground circuit and heat pump) 80% of the measured years had a seasonal performance factor for combined heating and cooling (SPFHC2) of 3 or higher. At system boundaries 3-5 this percentage drops significantly. This shows that the energy used for distribution of heating and cooling in the buildings has a detrimental effect on the overall system performance. Figure 8.2 illustrates the spread of the SPF for combined heating and cooling (SPFHC) at boundary levels 1-5 for the measured years. High values of SPF0, SPF2, and SPF5 (marked with *) correspond to free-cooling and free-heating systems, including the HT-BTES. The high value of SPFC1 (marked with **) is for the HT-BTES system.

Table 8.4: Overview of SPF for the monitored GSHP systems included in Annex 52. System boundaries according to Annex 52. (H = heating, C = cooling, HC = heating & cooling)

System boundary	*Number of reporting projects*	*Measured years*	*SPF range*	*Measured years with SPF 3 or more*	*Average*	*Median*
SPFHC0	6	39	10.9-65*	100%	33*	33.9*
SPFHC1	14	66	1.5-7.2	88%	4	3.8
SPFHC2	11	62	1.4-13	80%	4.7	3.5
SPFHC3	3	26	0.8-12	62%	5	5.5
SPFHC4	12	57	1.2-8.8	44%	3.3	2.7
SPFHC5	4	21	1.1-3.7	10%	1.9	1.8
SPFH0	9	50	3.1-171*	100%	37*	32*
SPFH1	18	71	1.7-7.2	72%	4	3.8
SPFH2	15	71	1.5-6	72%	3.7	3.6
SPFH3	8	41	0.4-5.5	53%	3.3	3
SPFH4	12	55	1-4.4	49%	2.8	2.9
SPFH5	6	27	1-136*	30%	21*	2.4
SPFC0	8	45	13.5-173*	100%	60*	51*
SPFC1	9	41	1.1-13.2**	76%	4.4	3.9
SPFC2	11	58	1.6-128*	89%	22*	5.2
SPFC3	2	12	0.6-4.3	67%	2.9	3.2
SPFC4	5	27	0.6-5.8	28%	2.5	2.5
SPFC5	5	26	0.5-145*	35%	23.6*	2.4

Monthly performance factors (MPF) for heating and cooling have been reported at various system boundaries for most of the Annex 52 case studies. MPFs typically vary over the year due to changes in monthly energy loads and return temperatures. Overall MPFs and MPFs for heating tend to be higher in the winter and lower in the summer, although the ground heat exchanger return temperatures are more favorable in the summer. The explanation is that under low-load conditions, cycling losses and electricity used for control boards and energized solenoid valves decrease the performance as they become a larger portion of the total electricity use. For cooling, MPF tend to be higher during the winter months, when return fluid temperatures from the ground are lower. This is as expected.

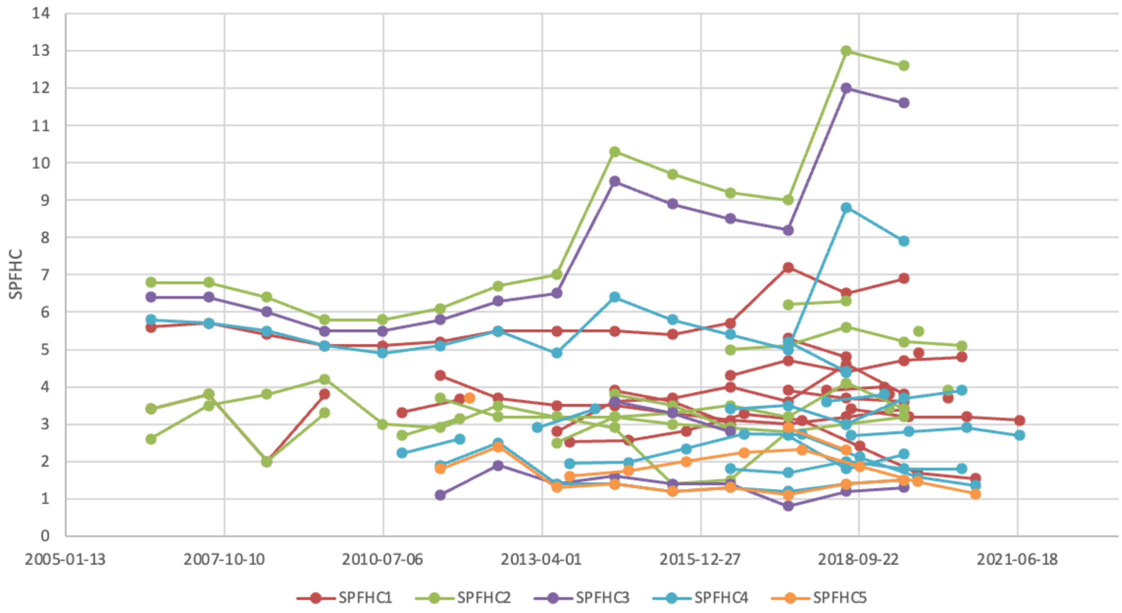

Figure 8.2: Overall seasonal performance factors for heating and cooling combined (SPFHC) at system boundaries 1-5 from all the reported monitoring projects in Annex 52.

8.2 Conclusions

The projects carried out within Annex 52 show that most of the GSHP systems work satisfactorily from a performance point of view, although there is room for further improvement and optimization. The dominant factor for the overall system performance is the amount of heating and cooling provided by the GSHP system. Performance factors tend to be highest when the building is used heavily, and the lowest performance factors appear when the building is little used. The reason for this is that the proportion of electrical energy used for circulation pumps, fans and "parasitic" uses such as control boards and solenoid valves decrease when energy provided increases. The system performance typically drops significantly at system boundaries 3-5 as the distribution system on the load side of the heat pump has a detrimental effect on the system performance. Energy use for hot water, Legionella protection, distribution pumps and fans are common causes. There is room for further system improvement and component development to minimize the energy use for load side distribution.

9 Instrumentation Guideline

Ground source heat pump (GSHP) systems in large buildings are often complex, consisting of many components and serving an array of heating and cooling needs. The complexity of the system poses challenges in determining the most appropriate boundaries and calculations to document the system performance. The use of a heterogeneous mixture of instruments that are often serving dual functions to both control system operation and monitor the system state at a given time require that accuracy and sampling rates are selected with understanding of the requirement for both purposes. A proper commissioning, including on-site verification of sensors, is important.

GSHP systems require significant investments from the building owners, and with that comes expectations of high system performance. To verify that high performance is achieved, field measurements are necessary. However, cost-effective measurement programs are hindered by a lack of consistency and a lack of guidance regarding measurement system design and instrumentation. Adding missing instrumentation to a GSHP system once it is operational is significantly more costly than including it in the original system layout. An important goal of Annex 52 was therefore to compile a guideline for instrumentation of GSHP systems larger and more complex than the typical small residential GSHP system. Combined with the Annex 52 recommendations on system boundaries and key performance indicators, the instrumentation guideline will help lower the cost for obtaining robust, accurate, and consistent measurements of performance. Lowering the cost will in turn lead to wider adoption of performance measurement schemes, increased energy and cost savings, and increased benchmarking leading to better understanding of system design and performance expectations.

Most of the case studies in Annex 52 focus on an integrated metric of installed performance. The performance factor (PF) is the ratio of the measured thermal energy delivered to the building to the measured electricity consumed by the system components over a specified time-period. Annex 52 has established a set of nested boundaries to provide context for reporting performance factor values and improve the ability to compare values between studies. While the PF provides a consistent integrated measure of system performance, additional analyses are necessary to understand the factors that may be impacting system performance, which are critically important to optimize system design and operation, and to identify issues that can be addressed to improve performance.

The Annex 52 instrumentation guideline (Davis et al 2021) presents an overview of instrumentation that is typically required to measure the long-term performance of GSHP systems. GSHP performance studies can be conducted to meet a variety of monitoring and verification (M&V) objectives and they also provide data that can be used to improve system performance. The instrumentation guideline also provides additional information regarding the use of the heat meters and distributed temperature sensing in GSHP studies. Finally, the challenges of data management are discussed as well as some methods to address these challenges.

The Annex 52 instrumentation guideline focuses on the instrumentation needed to measure the performance of a GSHP system, rather than the methods of analysis, and includes a wide range of potential measurements that can be used for a variety of purposes. In some cases, there is opportunity to design a monitoring and verification program at the beginning of a project and specify the types, accuracies, and placement of sensors as well as the characteristics of the sensor network. In other cases, the analyst may be using existing sensors that are part of an existing building management system. The Annex 52 instrumentation guideline aims to inform practitioners about the wide range of possibilities that may be encountered but does not prescribe the methods of instrumentation or data analysis, which will vary from site to site and depend on many factors.

It is recommended that each M&V study set clear objectives and methods of analysis from the outset. These will then guide the selection of the types and locations of measurement points and will inform the required accuracy of the measurements. The selection, installation, and commissioning of measurement systems is complex and will differ from site to site. Data may be collected by interfacing with a building management system or use of a separate network of sensors – either approach has its own set of challenges.

When fault detection and diagnosis are part of the M&V objectives, it is recommended that measurements are taken at consistent intervals of approximately one minute. Even when seasonal performance factors are the primary interest and energy meters that record cumulatively over coarser sampling intervals may suffice, interpreting the underlying factors that affect performance will often require minute-resolution data.

It is also critically important that building owners and operators and the contractors that install and maintain the equipment plan for the use of data early in the process. M&V plans should include the methods that will be used to document sensor accuracy and verify that sensors are operating correctly once installed and configured, including the on-site calibration when appropriate. Sensors should be tagged in a manner that includes sensor metadata as well as the placement of sensor relative to system components.

Chapter 5 in the Instrumentation guideline discusses distributed temperature sensing (DTS). When a ground heat exchanger (GHE) is part of the GSHP system, it may be useful to also conduct detailed measurements of temperatures within the GHE. The relatively new technology of DTS using fiber optic cables may provide important insights into the performance of the GHE and inform strategies to improve system efficiency. As with other measurements, DTS require careful planning, both in the design of the DTS system and its components as well as calibration of the installed fiber optic cable.

The monitoring and verification of GSHP systems is essential to document the operating efficiency of GSHP systems and, when sufficient data are collected, can help to identify components of the system design and operation that may be adjusted to provide greater efficiency. Consistent and well-documented case studies will also ensure that efforts to electrify the heating of buildings meet the stated goals. These will often include the reduction of operating costs and greenhouse gas emissions.

With the increasing quantities of data in buildings comes a need to clarify access to data early in a project. If GSHP system monitoring data is collected by and stored in a BMS, it may be intermingled with sensitive information, such as building alarms and occupancy. Methods should be developed early to partition the data for use by different groups, each with different data needs and objectives. This may lead to slight modifications in the design of the sensor network or the software that is used but will help to ensure that M&V objectives can be met.

Finally, though Annex 52 treats GSHP systems, the instrumentation guidelines are also directly applicable to air-source heat pump systems and air-conditioning systems.

10 Uncertainty Calculation Guideline

When reporting the performance of GSHP systems, it is highly desirable to estimate the uncertainty of performance factors (PF) and other quantities of interest, for several reasons. These include understanding the significance of the results – e.g. are the results meaningful; are trends in the results meaningful? For example, in one of the Annex case study reports (Spitler, et al. 2021b), the measured seasonal performance factor for heating at boundary 5 (the entire system) increased from 2.7±0.2 one winter to 3.8±0.2 the next winter. This was caused by a change in the differential pressure setpoint controlling the pump speed. There is no overlap between the two values, accounting for uncertainty – hence, it is a true increase in the performance. On the contrary, if the change in values had been from 2.9±0.4 one winter to 3.2±0.5 the next winter, it would not have been possible to draw a conclusion.

The uncertainty analysis can also shed light on design and specification of instrumentation for future monitoring projects. Uncertainty analysis is an important tool to help understand the significance of results not only for GSHP systems, but from any measurement program. However, despite its usefulness, as discussed by Spitler and Gehlin (2019), prior to 2019, there were very few reported performance factors in the literature that were accompanied by uncertainty measurements.

The Annex 52 uncertainty calculation guidelines (Spitler et al. 2021a) are specifically aimed at the application of uncertainty analysis to measurements made to monitor performance of ground-source heat pump systems. The guideline document provides a practical introduction to calculation of uncertainties in measured performance factors for ground-source heat pump systems with the goal of helping practitioners estimate the uncertainty in performance factors. The methods described are the same for calculation of uncertainties for measured performance factors over shorter and longer periods of time.

The uncertainty guideline gives a brief introduction to and overview of uncertainty analysis (Chapters 1 and 2) and defines terminology used in uncertainty analysis. The propagation of uncertainty from sensor to derived quantity is based on the relatively simple approach described by Taylor (1997), though more specialized methods are described in the guideline appendices. As in Taylor (1997), the words “error” and “uncertainty” are used interchangeably in the guideline document. The main emphasis in the guidelines has been the uncertainty in calorimetric measurements of heating and cooling provided, as this is often where the most difficulty lies.

Chapter 3 discusses sensor errors and the forms of typical specifications for sensor uncertainty. Chapter 4 covers uncertainty analysis in calorimetric measurements of heat transfer rates. Chapter 5 covers the internal method, which uses measurements of refrigerant pressure and temperature to calculate performance.

Chapter 6 covers uncertainty in calculated performance factors. Chapter 7 covers a few special cases, and Chapter 8 concludes the guidelines.

To set the context, the final quantities of interest are primarily SPFs (annual), monthly or daily performance factors, or performance factors over all times in a specific outdoor air temperature bin or entering fluid temperature bin. So, while random errors exist, they are usually mitigated by a large number of measurements over which a specific COP value is computed. One exception is SPF computed for bins with very few hours, e.g. less than 10 measured hours. Accordingly, systematic errors are of more concern and random errors are, for the most part, neglected in this uncertainty analysis. Appendix A covers a few cases where random errors may be important. Appendix B contains some discussion of sampling error, a form of random error which may become important when estimating uncertainty in energy from discrete power or heat transfer rate measurements.

Though the Annex 52 work is focused on calculating performance factors over long time periods, the same types of measurements can be used to detect a range of problems which can then be corrected; these measurements might typically be made on short intervals and used to detect control/stability problems and check the vapor compression cycle performance against expectations. The theory of uncertainty analysis is the same for both applications.

Again, though Annex 52 treats GSHP systems, most of the uncertainty analysis is directly applicable to air-source heat pump systems and air-conditioning systems.

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Walfridson, T. (2021d). Case study report for Norrlands Universitetssjukhus, Umeå, Sweden. IEA HPT Annex 52 – Long-term performance monitoring of GSHP systems serving commercial, institutional and multi-family buildings.

Appendix A List of participants

Table 1 – Participants in the Annex 52 core working group

Country	*Organisation*	*Organisation type*	*Name*
SE	The Swedish Geoenergy Center	*Operating agent*	Signhild Gehlin
USA	Oklahoma State University	Co-operating agent	Jeffrey D Spitler
SE	KTH	University	José Acuña
SE	KTH	University	Alberto Lazzarotto
SE	KTH	University	Willem Mazzotti-Pallard
SE	KTH	University	Mohammad Abuasbeh
SE	Lund University	University	Saqib Javed
SE	RISE	Research institution	Tommy Walfridson
SE	Geostrata	Engineering company	Olof Andersson
SE	Xylem	Industry partner	Leif Rydell
SE	EON	Energy provider	Jonas Ekestubbe
SE	SWECO	Engineering company	Iuliia Svyrydonova
SE	ClimaCheck	Cleantech company	Klas Berglöf
N	NORCE	Research institution	Kirsti Midttømme
N	Sintef	Research institution	John Clauss
SF	Aalto University	University	Markku Virttanen
SF	Aalto University	University	Oleg Todorov
SF	GTK	Geological Survey	Ilkka Martinkauppi
SF	GTK	Geological Survey	Nina Leppäharju
SF	GTK	Geological Survey	Sami Vallin
USA	University of New Hampshire	University	Mathew Davis
UK	University of Leeds	University	Simon Rees
UK	University of Leeds	University	Fleur Loveridge
UK	University of Leeds	University	Josh Turner
UK	British Geological Survey	Geological Survey	David Boon
NL	GroenHolland	Engineering company	Henk Witte
D	Steinbeis-Innovationszentrum energie	Research institution	Franziska Bockelmann

Appendix B Glossary

Table 2 – Commonly used abbreviations

Abbreviation	*Definition*
AF	Antifreeze
ATES	Aquifer Thermal Energy Storage
BPF	Binned performance Factor
BTES	Borehole Thermal Energy Storage
COP	Coefficient of Performance (of a HP)
CP	Circulation pump
DH	District Heating
DHW	Domestic Hot Water
DPF	Daily performance factor
EER	Energy efficiency ratio
EM	Energy meter
EUI	Energy use intensity
GHE	Ground heat exchanger
GSHP	Ground Source Heat pump
H/C	Heating/cooling
HEX	Heat exchanger
HP	Heat pump
HPF	Hourly performance factor
HPT	Heat Pumping Technologies
HT-BTES	High Temperature Borehole Thermal Energy Storage
HVAC	Heating, Ventilation and Air Conditioning
IEA	International Energy Agency
IR	Imbalance ratio
KPI	Key performance indicator
MPF	Monthly Performance Factor
PF	Performance Factor
SCOP	Seasonal coefficient of performance
SEER	Seasonal energy efficiency
SEI	System efficiency index
SEPEMO	Seasonal Performance Monitoring (EU project name)
SPF	Seasonal Performance Factor
TCP	Technology collaboration program
WPF	Weekly performance factor

Appendix C Links to additional Annex 52 reports

1. Subtask 1 report – Annotated Bibliography - 62 pages - **https://doi.org/10.23697/dzpy-yp81**
2. Case study summary report - 62 pages - **https://doi.org/10.23697/qfnt-rb80**
3. Guidelines for instrumentation and data - 62 pages - **https://doi.org/10.23697/tgr4-qn89**
4. Guidelines for calculation of uncertainties - 54 pages - **https://doi.org/10.23697/m2em-xq83**
5. Guide for analysis and reporting of GSHP system performance – system boundaries and key performance indicators (KPI) - 38 pages - **https://doi.org/10.23697/xa7z-vd92**

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Report no. HPT-AN52-1