IEA HPT Annex 52 - Long-term performance monitoring of GSHP systems for commercial, institutional, and multi-family buildings

Guidelines for Instrumentation and Data

Final Document

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Preface

This report is part of the work within IEA HPT Annex 52 - *IEA HPT Annex 52 - Long-term performance monitoring of GSHP systems for commercial, institutional and multi-family buildings*, with project period January 2018 to December 31 2021. The Annex 52 Operating Agent is Sweden.

Annex 52 aims to survey and create a library of quality long-term measurements of GSHP system performance for commercial, institutional, and multi-family buildings. While previous work will be surveyed, the emphasis of the annex is on recent and current measurements. The Annex also aims 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 GSHP systems around the world.

The results from the Annex will help building owners, designers and technicians evaluate, compare, and optimize GSHP systems. It will also provide useful guidance to manufacturers of instrumentation and GSHP system components, and developers of tools for monitoring, controls, and fault detection/ diagnosis.

This document provides guidance on instrumentation and data management. The primary objective is to provide guidance on measurements that are necessary to quantify the Seasonal Performance Factors described in the accompanying Annex documents. We also provide guidance on other measurements that, in the experience of Annex participants, have proven useful in the assessment of the performance of the individual components of a GSHP system, such as the heat pump equipment, ground loop, building envelope, and occupancy usage.

Summary

This document presents an overview the 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 also provide data that can be used to improve system performance. Additional information is provided regarding the use the heat meters and distributed temperature sensing in GSHP studies. Challenges of data management are discussed as well as some methods to address these challenges.

Contents

1 Introduction

This guide complements the other Annex 52 documents: Guidelines for Calculation of Uncertainties and Guide for Analysis and Reporting of GSHP System Performance and aims to provide guidance to researchers, building owners, and system designers on instrumentation and data management that will improve the ability to perform long-term performance monitoring of a ground source heat pump system in commercial, industrial, and multi-family buildings. We do not endorse a specific approach or technology but rather provide guidance, based on the experiences of the Annex 52 participants, on options that are available and best practices. This document is not intended to serve as a definitive guide to metrology or cover all aspects of the technologies discussed. As technologies continue to evolve, this document should be updated accordingly.

One of the main objectives of the Annex is to provide guidance to building owners and researchers on best practices to measure and document the benefits of GSHP systems at the scale of an individual building. To the extent that best practices become commonplace, they will provide the basis for aggregating benefits of the technology in portfolios of buildings, enabling an assessment and benchmarking of various design and intervention strategies.

Generally, collection of building energy data aims to fulfill two complementary objectives. On the one hand, measuring the state of system variables is necessary as part of an operations and control program. For example, when a measured room temperature falls outside of the desired set point range, a system component is activated to provide heating or cooling. A record of the measured set point and actual room temperatures provide useful information when assessing the performance of the system components involved. To the extent practicable, it is desirable to use individual measurements for both control and evaluation objectives. However, some measurements that are for control may not be essential for performance assessment, such as data from space-specific occupancy sensors or building alarms. Similarly, some measurements will be necessary only for performance assessment. The emphasis here will be on measurements that can serve the role of assessing GSHP system performance. Another challenge that arises in the use of single measurements for dual purposes is that the accuracy that is acceptable for one purpose may not be suitable for the other. For selection specification, the accuracy should be specified based on the use that has the tightest requirements. Commissioning should always include verification of all sensors, as data collection can be rendered useless if accurate sensors are not correctly applied.

Performance assessment of a GSHP system can fall into several broad categories, each with different requirements for data and data accuracy. Monitoring and verification (M&V) focuses on the retrospective verification that one or more efficiency measures meet the stated energy savings objectives. The data requirements for M&V studies will often focus on time-integrated measures of energy flows (production and consumption) to calculate seasonal performance factors (SPFs) as one type of Key Performance Index. The second category of performance assessment focuses on real time measurement for system optimization and the detection and diagnosis of system faults. The data requirements for system optimization and fault detection require measurements on individual system components.

1.1 Monitoring & Verification (M&V)

The Efficiency Verification Organization (EVO) is a leading international authority on M&V. In 2002, the EVO established the International Performance Measurement and Verification Protocol (EVO, 2002), commonly referred to as the IPMVP. EVO has since published a number of supplemental volumes to address renewable energy systems (EVO, 2017), uncertainty analysis (EVO, 2019a), and summaries of notable issues and examples (EVO, 2019b).

M&V activities generally consist of some or all of the following[1]:

- meter installation, calibration, and maintenance
- data collection and screening,
- a standardized computational approach,
- computations with measured data, and
- reporting, quality assurance, and verification of results

The IPMVP framework is generally applicable to all energy efficiency measures and emphasizes comparing actual performance to a baseline (either measured or modeled) to quantify financial and environmental benefits of the energy efficiency measure. The EVO documents are not prescriptive but rather provide recommendations for building owners and practitioners developing a M&V plan.

One common and particularly complex objective is to meter the thermal energy moving through a building system. Sometimes this is done for financial purposes (billing or energy savings contract); other times, as in this Annex, it is used to quantify system performance.

One aim of the Annex 52 project is to provide specific recommendations to develop an M&V plan for large GSHP systems. These recommendations build upon those of the of IPMVP framework and other relevant M&V best practices. Like the IPMVP, the recommendations herein are based on past experience of the Annex 52 participants and are not prescriptive. M&V plans should be developed in consideration of specific objectives and cost constraints.

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[1] https://evo-world.org/en/m-v/what-is-m-v

1.2 System Optimization

While quantitative methods for fault detection and diagnostics in HVAC system have been known for several decades (e.g., International Energy Agency 1999; Katipamula and Brambley, 2005), the increased availability of internet-connected devices that enable real-time data collection utilizing cloud-based storage capabilities has reduced costs and accelerated development. Ideally, these devices can also leverage existing measurements that are part of the Building Management System as well as sensing devices that are increasingly common within heat pumps. While these systems help to alleviate some issues regarding sampling frequency and data storage, they are not always available. Strategies for dealing with the practical limitations encountered are also presented.

1.3 GSHP System Performance

In general, M&V plans for GSHP systems involve quantification of useful energy produced relative to energy consumed. Compared with other systems, M&V of GSHP systems tend to be more complex as they involve electrical energy usage and thermal energy flows. In addition, large systems often involve thermal energy storage and so-called 'free cooling' or 'direct cooling' for cooling mode heat rejection.

1.3.1 M&V Studies

Between 2009 and 2012, several European countries collaborated in an extensive survey of heat pump performance (air source and ground source) spanning more than seven countries and involving more than 50 systems (mostly residential). The project was entitled: *SEasonal PErformance factor and MOnitoring for heat pump systems in the building sector (SEPEMO-Build)* and is commonly referred to simply as SEPEMO. The work products and reports are archived at http://sepemo.ehpa.org/info/home/. As part of that effort, the SEPEMO project developed some novel approaches to standardize both data collection and methods of analysis. The SEPEMO project focused on residential buildings with relatively simple GSHP systems. Efforts were made to standardize data collection using data loggers with attention to minimize measurement error (Zottl and Nordman 2011). Like the SEPEMO project, the compilation in HPT Annex 37 takes an M&V approach advocating the heat and electricity meters with pulse output with sample intervals up to one week (HPTannex37).

Jurisdictions aiming to stimulate the adoption of heat pumps as part of a broader renewable energy strategy have produced a number of heat pump performance studies. While most rely on heat and electricity meters, some extend the data collection to include other measures, such as ground loop temperature, internal and external temperatures, and system configuration and sizing data that can provide insight into under-performing systems (Rees and Curis 2014).

1.3.2 Fault Detection and Diagnostics

In the past decade there has been growing interest in monitoring individual components of an HVAC system to detect and fix problems that may arise from equipment malfunction, installation error, or operator error. Rapid identification and rectification help to ensure system efficiency, reduce down-time and improve customer satisfaction. Heat pump manufacturers are increasingly building web-enabled energy monitoring systems into the heat pumps that collect tens of data points at minute and sub-minute intervals. While the primary purpose of these systems is to assist installers and manage warranty issues, these data are also beginning to be used to assess system performance (CDH Energy 2018).

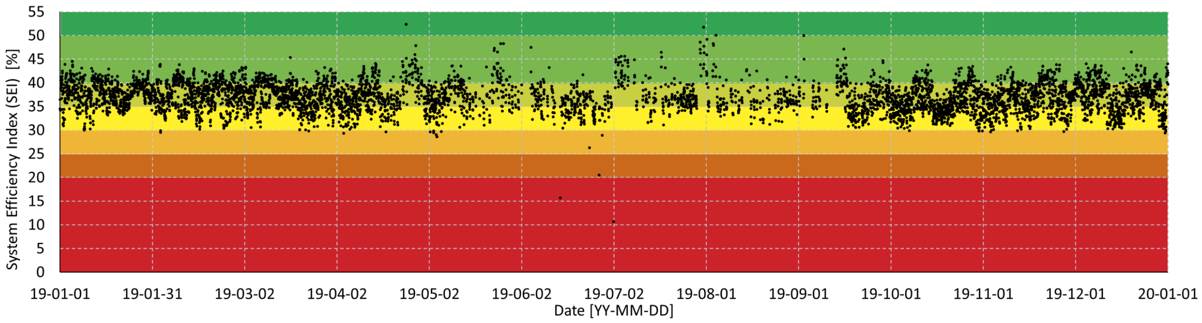

Figure 1-1 System Efficiency Index of the IKEA Uppsala heat pump monitoring project. Diagram colored according to the colors used in the ClimaCheck Online software.

Using the data provided with the so-called internal method (Lane et al., 2014) will give much higher possibility to find errors. For example, Figure 1-1 shows the System Efficiency Index calculated using the internal method varying from low (orange) or even very low (red zones) up to expected performance (green). Further analysis of the sub-efficiencies revealed that the compressor was managed poorly, most likely due to the configuration of the controls, and could easily be corrected. Other errors found using the internal method as part of this Annex involved the occasional flooding of the compressors with liquid refrigerant, likely causing the faulty compressors of the NUS project in Umeå, Sweden.

1.4 GSHP Monitoring Program Design

In developing a GSHP monitoring program, the objective should be determined at the outset. If the primary objective is to calculate the SPF, measures of the thermal and electric energy flows are essential. Selection of the meter types and placement of the sensors will affect the accuracy of the measures and should be considered carefully.

If the sensors and data collection are part of a BMS, it is important to begin discussing meters and sensor specifications as well as the data management plan early with building owners and BMS contractors. In some cases, meters may require higher accuracy sensors and/or output options than those that are typically specified.

The frequency of measurements and data storage requirements for GSHP system performance may differ from typical BMS specifications. When there is an opportunity to operate a data collection system separate from the BMS, there is more flexibility in the selection of meters, sensors, and measurement frequency, though in most cases this is cost prohibitive.

Managing data from a BMS can also present challenges as the primary purpose of the BMS is for building controls and security, potentially limiting access to data for purposes of performance analysis. Methods and protocols to access system operating data should be specified in the monitoring program design.

Another important component of a monitoring program is the specification of the methods for ensuring data quality and completeness. All monitoring programs should document sensor accuracies and specify that on-site inspection to ensure that sensors are installed according to the manufacturer specifications and that sensors are properly calibrated for installed conditions and are reporting the correct values to the data collection system.

The GSHP monitoring program should be developed by parties that will be responsible for the procurement and installation of sensors as well as those that will be responsible for data collection and analysis. A well-documented monitoring program will help to ensure that the objectives can be effectively and efficiently accomplished.

2 Measurement Locations and Frequency

This chapter focuses on recommended point measurements for calculation of performance metrics described in the accompanying document: *Guide for Analysis and Reporting of GSHP System Performance*.

The types of GSHP systems covered in this Annex tend to be complex and consist of many different components. These components may include the ground-source heat pump(s), the ground heat exchanger, thermal storage components, and equipment necessary to circulate the thermal energy throughout the system. Furthermore, analyses are often conducted with a variety of system boundaries and for a wide range of purposes. While not required, it is convenient to envision measurement locations as being associated with an individual system component so that energy flows associated with the component can be quantified independently and then integrated with other components for a system-wide analysis. This chapter is organized around the measurements necessary to assess performance metrics of different components of a GSHP system.

The measurement technologies that are commonly used to obtain the measurements are discussed in Chapter 3 and a framework for organizing the measurement data is presented in Chapter 6.

2.1 GSHP System Components

2.1.1 Ground source heat pump

It is expected that most systems covered by this guideline will have one or more ground source heat pumps as a key piece of equipment. However, there are also ground source systems that do not use heat pumps, such as direct cooling systems and high-temperature borehole storage.

External method

The performance of a GSHP is often described by the coefficient of performance (COP) which represents the ratio of energy output to energy input and is established under constant and steady state conditions. For installed systems, it is common to measure the field analog to the COP, the seasonal performance factor (SPF). For SPF calculations, the energy inputs include electric energy used to power the equipment, including the compressor and circulating pump, and any auxiliary sources of thermal energy. The energy outputs include the useful thermal energy generated by the equipment and may include the thermal energy from the ground loop or other thermal sources.

To quantify the thermal energy flows, it is necessary to measure the difference in fluid temperature as it passes through the heat pump and the mass flow rate of the heat conveying fluid. The electric energy required is measured by an electric meter. Figure 2-1 illustrates the measurement points necessary when using the traditional external method for a ground-source heat pump. These are also summarized in Table 2-1.

Table 2-1. Recommended measurement points for a ground-source heat pump (see Figure 2-1).

Description	Fig. 2-1	Comments
Heat pump compressor electrical input	E1	Depending on location of measurement, may include circulating pump and controls.
Source-side supply and return temperatures	Tc1, Tc2	May be calibrated as pair sensors for measures of ΔT
Supply (thermal source) fluid flow rate	F1	Single measurement per thermal source. Same meter may be used for more than one heat pump.
Supply side circulating pump(s) electrical input	E2	May be combined with and inseperable from E1 for a given heat pump. A single circulating pump may serve more than one system component.
Load side flow rate	F2	Load-side heat conveying fluid may be air or water.
Load side supply and return temperatures	Th1, Th2	May be paired for calibration of ΔT
Load side circulating pump(s), fan(s)	E3	May consist of multiple pumps and/or fans

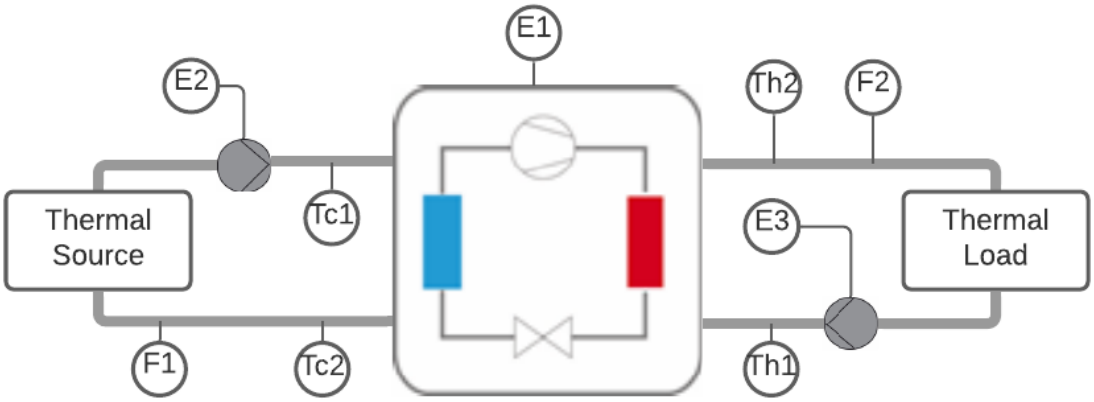

Figure 2-1. Recommended measurement points associated with a ground source heat pump. The thermal load is illustrated as hydronic but same measurements generally apply to a water-to-air heat pump.

Internal method

In addition to the traditional external method for quantifying heat pump performance, Lane et al. (2014) describe a method for assessing the operation and efficiency of the refrigeration cycle within the heat pump. The so-called internal method requires measurements of refrigerant pressure and temperature and, provided these are sufficiently accurate, the flow can be inferred from the enthalpy characteristics of the refrigerant and the electric power supplied to the compressor motor. While the accuracy of the temperature difference in water/brine on the source and load side may be improved by pairing sensors, refrigerant temperatures are absolute. The reader is referred to Lane et al. (2014) for details on the application of this method and the specific requirements for sensor placements and accuracies.

In modern heat pumps and chillers, most sensors required are already installed from the factory and submetering of power is common, potentially reducing the installation cost significantly. The internal method will establish the following:

- Cooling/heating COP
- Total System Efficiency (SEI)
- Sub-efficiencies of components
    - Compressor isentropic efficiency
    - Evaporator efficiency
    - Condenser Efficiency

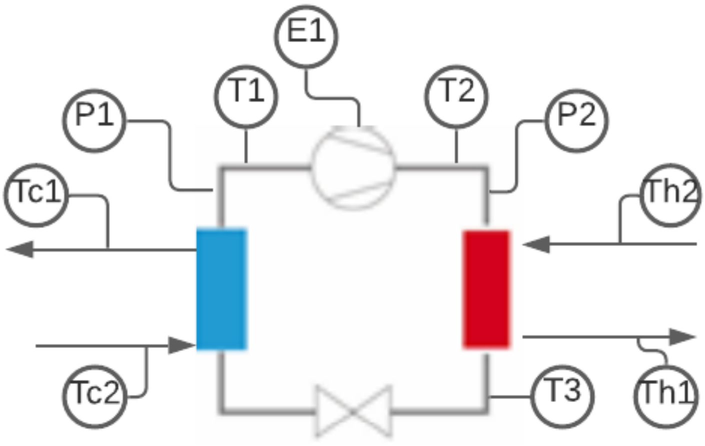

Figure 2-2. Measurement locations for the internal method of a heat pump as described in Lane et al (2014).

Table 2-2. Recommended measurement points for a basic ground-source heat pump using the internal method (see Figure 2-2).

Description	**Fig. 2-2**	**Comments**
Heat pump compressor electrical input	E1	Electric power of compressor
Source-side supply and return temperatures	Tc1, Tc2	May be paired for calibration of ΔT
Load side supply and return temperatures	Th1, Th2	May be paired for calibration of ΔT
Pressure and temperature of refrigerant	T1, P1	Before compressor
Pressure and temperature of refrigerant	T2, P2	After compressor
Liquid temperature of refrigerant	T3	After condenser and before expansion device

2.1.2 Thermal Sources and Sinks

A GSHP system can utilize a variety of thermal energy sources and sinks to meet the heating and cooling demand of a building. A ground heat exchanger is typically the main source (heating) and sink (cooling) and may be one of many configurations. Additional sources may include solar thermal arrays and supplemental sources of heat (electric, oil, gas) and cooling (e.g., cooling towers).

2.1.2.1 Ground heat exchanger

The ground heat exchanger (GHE) is a key element of any GSHP system and the performance of the GHE plays an integral role in the overall system performance. The source circuit has the system boundary 0 in the Annex 52 system boundary schema, while the SEPEMO boundary schema does not include a boundary for the ground circuit alone. Characterization of the GHE performance can consider a number of metrics. Key to the SPF approach is the measurement of the thermal energy provided by the GHE as a function of energy inputs, such as circulating pump power. In addition to assessing the energy performance of a GHE, it may also be of interest to evaluate the sizing of the GHE in relation to the design and usage. This involves measuring the long-term trends that may exhibit warming or cooling, due to unbalanced cooling or heating loads, respectively. While some long-term trending may be expected and part of the design, excessive trending can have adverse impacts on the long-term performance.

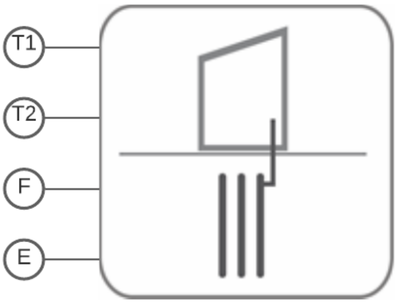

Figure 2-3. Measurement points associated with a closed-loop ground heat exchanger.

Table 2-3. Recommended measurement points for SPF calculations in a closed-loop ground heat exchanger, shown schematically in Figure (see Figure 2-3).

Description	**Fig. 2-3**	**Comments**
Supply and return temperatures	T1, T2	May be paired for calibration of ∆T
Electricity usage of the circulating pump(s)	E	Include electricity usage of any auxiliary heating/cooling, if present.
Flow rate of the heat conveying fluid	F	Should include documentation of fluid thermal properties.

To quantify the energy flows necessary to compute SPF metrics, it is necessary to measure the temperatures (supply and return), the flow rate of the heat conveying fluid, and the electricity consumption of the circulating pumps. The effectiveness of the GLE to extract thermal energy from the ground can be impacted by thermal resistance of the pipe and grout (borehole thermal resistance) which can be inferred from the measurements.

Open loop ground heat exchanger

Open loop ground heat exchangers can take many different forms. In open loop systems, the supply and return flow rates may be in different locations or differ from one another

In traditional open systems that have two groundwater wells, the supply and return flows are occurring at different locations which may necessitate separate flow meters (or a bi-directional flow meter). In doublet configurations, the wells that serve as supply and return flows may alternate seasonally, while others (recirculation) may remain fixed throughout the year. It is recommended that the supply and return flows are treated independently though, in some cases, they may be equal and allow for the use of a single meter.

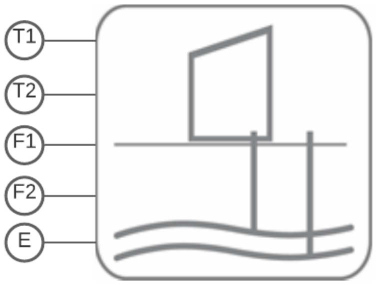

Figure 2-4. Measurement points associated with an open-loop ground heat exchanger.

Table 2-4. Recommended measurement points for SPF calculations in an open-loop ground heat exchanger, shown schematically in Figure (see Figure 3-4).

Description	**Fig. 2-4**	**Comments**
Supply and return temperatures	T1, T2	May be paired for calibration of ΔT
Electricity usage of the circulating pump(s)	E	Include electricity usage of any auxiliary heating/cooling, if present.
Flow rate of the heat conveying fluid on the supply side	F1	For a two-well system, the ’supply’ and ’return’ designations may change depending on heat or cooling mode.
Flow rate of the heat conveying fluid on the return side, or bleed flow rate for standing column wells.	F2	For a standing column well, the return flow may measured by subtracting any system bleed that may be present.

Monitoring the water level in the supply and return wells is also important to ensure that the hydraulic connection with the aquifer remains adequate and the groundwater pump remains with the range of specified distances below the water table.

Another type of open-loop configuration is the standing column well in which a single well serves as both supply and return. Standing column well systems often contain a flow circuit that reduces the return flow rate (system bleed), which should be measured separately. For simple bleed systems, the return flow can be calculated as the supply flow minus the bleed flow.

2.1.2.2 Supplemental sources and sinks

While the core components of GSHP systems consist of ground source heat pumps and some form of ground heat exchanger, there can also be other thermal energy sources and sinks that supplement the primary sources. It is important to account for any supplemental source or sinks of thermal energy in assessing the performance of GSHP systems.

As a general guideline, it is recommended that both the thermal energy produced/rejected (kWh) and associated energy inputs be measured directly for supplemental sources and sinks. For example, elements like solar thermal arrays and cooling towers may be treated much like a ground heat exchanger in that heat is transferred via a circulating fluid and the energy transfer can be calculated from measurements of the supply and return temperatures and the flow rate through the supplemental system. As with a GHE, the electricity consumption of the circulating pumps should also be measured.

For supplemental sources that convert electricity or fossil fuel to thermal energy, such as an electric heating element in a tank or an oil-fired furnace delivering hot water or steam, the input fuel source can be measured and, if the efficiency of the heating equipment is known, the thermal energy input into the GSHP system can be quantified.

2.1.3 Thermal storage assets

In addition to supplemental thermal sources and sinks, a GSHP system may also utilize thermal storage assets as a means to utilize waste heat, store excess cold, and/or efficiently manage the load on the system. The most commonly used storage asset is a buffer tank that helps to optimize the operation of a water-to-water heat pump. Measurements on a buffer tank typically consist of a representative tank temperature as well as supply and return temperatures on both the source and load sides. If the buffer tank is fitted with an electric heating element, it too should be monitored as a supplemental heat source.

Thermal energy can also be stored in the ground, using either aquifer or borehole thermal energy storage, ATES or BTES, respectively. There are also other possibilities of underground storage, such as buried tanks, caves and pits (CTES). These systems are often complex and designed specifically for the site conditions. When including ground thermal storage in the assessment of GSHP system performance, the energy inputs and outputs must be measured as with other system components. As these methods are continuing to be developed and tested, the measurement protocols will often focus on answering specific questions about the storage asset performance. For example, continuous measurement of temperature profiles through a system may be conducted using distributed temperature sensing with fiber optic cables, as described in more detail in Chapter 5.

2.2 Combined Measurements

While each sensor should be associated with a piece of equipment, it is common in practice to have measurement locations that are redundant and can be served by a single sensor.

For example, the temperature of the return flow from a ground heat exchanger is, assuming negligible pipe losses or mixing with other sources, the same as the supply temperature to a heat pump. One sensor may be used to serve this dual purpose, provided the database schema allows for one(sensor)-to-many(purposes) relations. In systems with multiple heat pumps, the temperatures entering and leaving individual heat pumps may not be good indicators for the return and supply temperatures of the ground heat exchanger, as temperatures may be affected by mixing and thermal storage components.

Another example, but with different implications, is when a single variable-speed pump on the ground loop serves multiple heat pumps. While the electricity consumed by the circulating pump would be measured with a single meter, post processing of the data would require dividing the total power consumption between the heat pumps being served. Such post-processing should consider piping configurations and the synoptic power consumption of the heat pumps being served.

2.3 Sampling Frequency

Sampling of GSHP operating conditions represents a discrete sampling of continuously varying conditions. In determining the optimal sampling frequency, a number of factors must be considered. While high frequency sampling may ensure a more accurate representation of the conditions, it may not be practical if data storage or processing capabilities are limited[2]. When data processing and storage are limited, more care needs to be taken in developing sampling strategies that can still meet specific project objectives that may involve time scales ranging from minutes to many years.

When data storage is not a limitation, the upper limit of the sampling rate should be small enough to capture the short-duration events. For example, if it is desired to detect heat pump duty cycles that are as short as 2 minutes in duration, the sampling rate should be no greater than 1 minute. Generally, the sampling rate should be one-half of the duration of the shortest event to be captured. If the signal being sampled has strong periodicity, the sampling interval may need to be as short as 1/4th of the period[3]. However, most GSHP systems do not exhibit strong periodic signals. The lower limit of the sampling rate should avoid transient effects that may

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[2] For reference, storing a set of 40 measurement points at one-minute intervals for five years requires approximately 1 GB of disk space (either in a SQL database or a comma separated value text file).

[3] The reader is referred to literature on the Nyquist-Shannon sampling theorem that addresses the aliasing that can result when the sample frequency is either too low or is at the same frequency as the signal.

arise from network latency (asynchronous measurements), transient conditions of the equipment state, and use of pulse output energy meters. These issues typically occur at time scales of several seconds. Based on the experience of the Annex 52 participants, a sampling interval of 1 minute is recommended, when data storage is not a limiting factor.

Apart from the total storage capacity, which can usually be augmented by periodically archiving data to an external system, determining the proper frequency is important. The frequency of data collection should be tailored to the goal of the monitoring and the characteristics of the process. Table 3-5 summarizes a variety of time varying process that may be part of the GSHP monitoring program.

Table 2-5. Time varying process that may be part of GSHP monitoring program.

System	Sampling rate	duration
Borehole heat exchanger field temperature evolution	1 - 30 min	Months
Borehole thermal resistance	1 - 10 min	Hours
Energy balance open and closed loop systems	5 - 30 min	Years
PID control on pumps and valves	0.5 – 2 min	Hours
Energy monitoring building	0.5 - 10 min	Years
Heat pump refrigerant cycle operation	0.1 – 1 min	Hours

2.4 Pulse Output Meters

When using meters that record discrete pulses for integrated measures of electricity, flow, or thermal energy, the resolution of the measurement depends on the pulse rate of the meter (number of pulses per unit energy) and the sampling interval. For example, if measuring electric power (W) with a pulse electric meter that records one pulse per Watt-hour, the lower bound of a discrete measurement recorded by 1 pulse over 1 minute would be 60 W. Similarly, if the pulse counter has a frequency limit 4 Hz, the maximum recorded power over a one-minute interval would be approximately 14 kW.

2.5 Environmental conditions

When evaluating the performance of a GSHP system, the environmental conditions in which the system is operating provides important context. As part of a GSHP M&V program, a method for obtaining a sufficient record of outdoor weather conditions should be specified.

In some cases, it may be necessary to establish a dedicated weather station at or near the building of interest. While temperature is the most critical measurement, humidity is also helpful. For on-site weather measurements, care should be taken to ensure that measurements are representative of conditions. Temperature sensors should be at least 2 meters from any surface, open to free movement of air, and shielded from radiation in all directions. In cases where a nearby web-accessible weather data can be obtained from a reliable source, such as a government agency, measurements should be retrieved at no more than hourly intervals. To assist in the interpretation of GSHP system performance relative to building design, the solar insolation and wind speed may also be useful.

3 Measurement technologies

This chapter provides an overview of technologies available to make the measurements described in Chapter 2. The most common types of measurements for a GSHP system are flow, temperature, and electricity. This guideline document is not intended to provide an exhaustive overview of each technology nor a comprehensive review of all technologies available but rather an overview of technologies that are suitable for GSHP systems.

3.1 Flow

This section deals primarily with measuring the flow of heat conveying liquids that are either on the source side (GHE) or load side (building) of the ground source heat pump(s). The final subsection provides a brief overview of air flow measurements that are necessary for measuring performance of a GSHP system with water-to-air heat pumps. In this section, reference to ‘air flow’ will be explicit, while ‘flow’ implies a heat conveying liquid.

Flow metering technologies that are used in GSHP systems generally fall into one of three categories: (1) differential pressure, (2) positive displacement, and (3) velocity. Some studies have used mass flow meters (Coriolis meters), such as Ruiz-Calvo et al. (2016). However, these are expensive and, at present, fairly uncommon and will not be covered here.

Each metering technology has distinct advantages and disadvantages and care should be taken in choosing the optimal technology for the metering objective. For GSHP applications, factors can be broken down into (1) the characteristics of the fluids and flow rates to be measured and (2) the cost of equipment, ease of installation, and ongoing maintenance requirements. GSHP systems that have an open source (e.g. groundwater) tend to have more particulates in the heat conveying fluid than closed systems. However, if antifreeze is used in a closed loop system, its viscosity will be higher than water, particularly at and below 0 °C.

The range of flow rates is another important criteria as some flow meters can provide accurate measurements over a wide range of flows while others are limited to a smaller range of flows. The ratio of the highest flow to lowest flow for which the meter retains its accuracy is referred as the turn-down ratio and is dicussed more in Chapter 4 (Heat Meters). It is not uncommon for a GSHP system that serves a highly variable load with variable speed pumps to have a turn-down ratio of 20:1.

3.1.1 Differential Pressure

Differential pressure meters operate on the premise that the flow rate in a filled pipe is proportional to the change in fluid pressure along the length of the pipe. These meters create a pressure drop which, in some cases, can be significant. Differential pressure devices include the orifice device (Figure 3-1) and the Venturi and Pitot tubes. Any pressure losses due to metering must be accounted for in pumping specifications and may have adverse effects on the system flow.

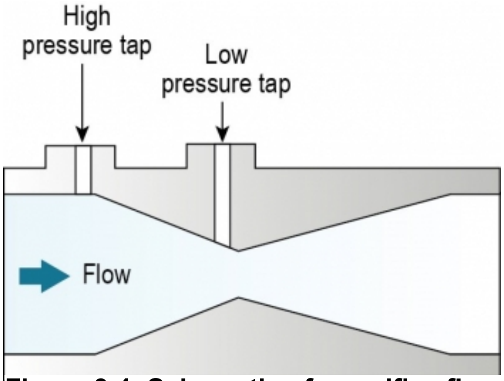

Figure 3-1. Schematic of an orifice flow meter (source: US Department of Energy)

3.1.2 Positive Displacement

Positive displacement flow meters sample the entire volume of fluid. The most common are the nutating disk and multi-jet flow meters.

Nutating Disk

A nutating disk meter is the most commonly used water meter in the US (US DoE). As water flows through the meter, it forces a disc to rotate about an inclined spindle. Each rotation is recorded and represents a known volume of fluid. The benefit of these devices is that they sample the entire volume of flow rather than measure a velocity and calculate the flow based on assumed velocity profile. They are reported to provide accurate and highly repeatable measurements.

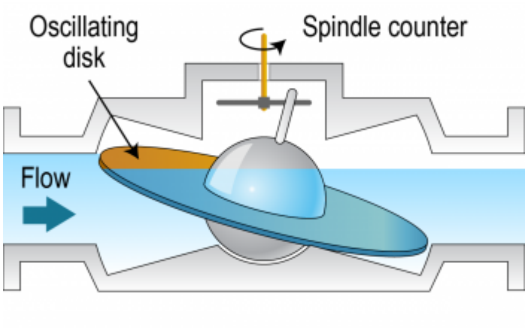

Figure 3-2. Schematic illustration of a nutating disk flow meter (source: US Department of Energy)

Multi-jet

Multi-jet meters divert the flow into multiple jets at equal angles that turn an impeller mounted on a horizontal axis. Multi-jet meters are often rated to have higher accuracies and are manufactured for both cold and hot water applications. Stafford (2011) reported the use of JS-NK 20 pulse output flow meter with one pulse per liter.

3.1.3 Velocity

Velocity meters measure either the average velocity of the fluid in the pipe or a velocity at a known distance from the pipe boundary and then calculate the average velocity from the single point measurement.

Paddle (turbine)

Paddle meters, sometime referred to as turbine meters, have a small rotating blade that samples part of the flow field. These meters are commonly used with heat meters in the United States and are inserted into an existing pipe. Using a hot-tap, insertion flow meters can be installed post installation and provide very accurate measurements over a wide range of flows.

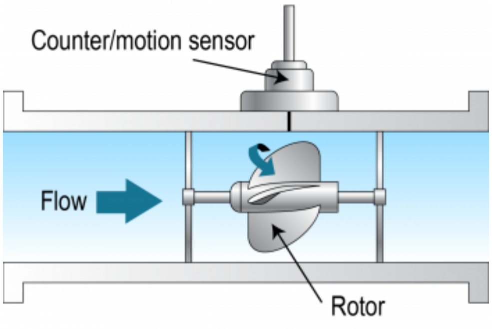

Figure 3-3. Schematic illustration of a turbine flow meter (source: US Department of Energy)

Generally, the fluid should be clean and free of debris, such as in a closed loop GHE. However, even in closed loop systems small debris, such as shavings from ground loop fusing, can damage the paddle, particularly in some of the more sensitive instruments.

Vortex

Vortex shedding flow sensors measure the vortices that result from the fluid passing a finned obstruction (shedder bar) and correlating the vortices to flow rate for a given pipe size. These are installed as inline flow meters and have a small pressure drop. This technology is commonly used in heat pumps that have embedded sensors. The practitioner should note the potential limitation to low viscosity fluids, particularly when antifreeze solutions operating at low temperatures may increase the fluid viscosity. It is common for different models from a single manufacturer to have different viscosity limits and accuracy.

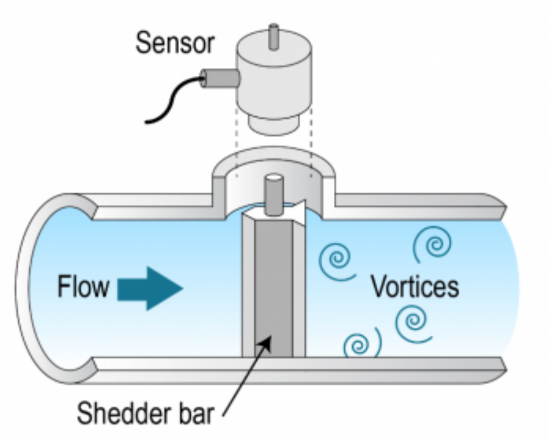

Figure 3-4. Schematic illustration of a vortex shedding flow meter (source: US Department of Energy)

Electromagnetic

Electromagnetic flow meters (sometimes referred to as simply as ‘mag meters’) use Faraday’s law of induction that states that when a conductive fluid moves through a magnetic field, an electric flux is created. The magnitude of the electric flux is proportional the volumetric flow rate and the magnitude of the magnetic field (Beck at al., 2019). Vanhoudt et al. (2011) used electromagnetic flow meters in the long-term evaluation of an aquifer thermal energy storage system in Belgium.

Ultrasonic

Ultrasonic meters are non-invasive devices and send ultrasonic pulses into the flowing medium. Some GSHP studies that have used ultrasonic flow meters include: Zhai and Yang (2011), Yu et al. (2011), and Naicker and Rees (2018).

When using the Doppler method, the signal sent from the transmitting element into the fluid interacts with particles in the fluid (bubbles or other particles) and the frequency shift of the signal is detected by the receiving element to determine the fluid velocity. When using meters that rely on Doppler method, the fluid should have some bubbles or other particulate matter in suspension.

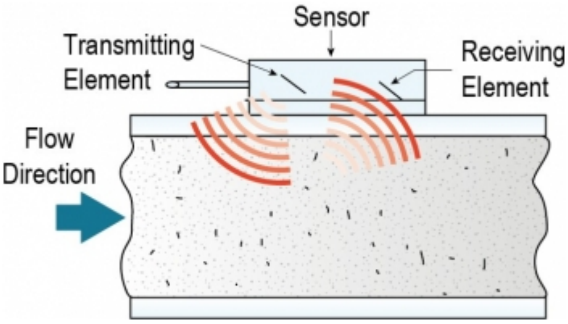

Figure 3-5. Schematic illustration of a Doppler ultrasonic flow meter (source: US Department of Energy)

Unlike the Doppler-based ultrasonic meters, those that use the travel time method require clean and viscous fluids for best accuracy. The travel time method uses a pair of transceivers that both send and receive ultrasonic signals. The transceivers are placed so that one signal is moving downstream and the other upstream. The difference in the travel time measurements between transceivers is used to calculate the fluid velocity.

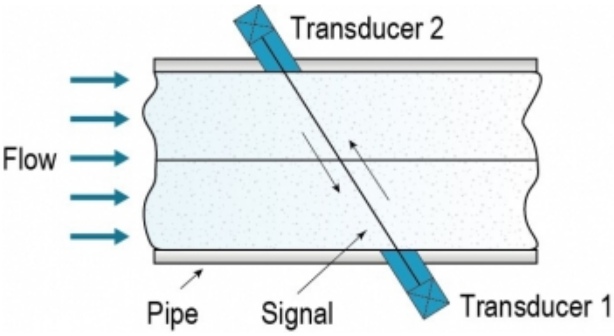

Figure 3-6. Schematic illustration of a travel time ultrasonic flow meter (source: US Department of Energy)

Some potential sources of error include cavitation and/or fouling in the pipes, transient flow, and differences between actual and assumed pipe diameters. Sanderson and Yeung (2002) provide a detailed set of guidelines and recommendations for non-invasive travel time ultrasonic flowmeters and discuss a number of common errors that arise when deploying this technology.

3.1.4 Flow meter selection

In the selection of flow meters for the heat conveying fluid, it is important to determine the range of flows that are expected to be measured accurately. While for GSHP systems, small flow rates make only minor contributions to the total heat transfer measured, the meter selected should have an acceptable accuracy at the smallest flows of significance. Flow meters will also have a maximum flow rate at which the accuracy is rated, and the ratio of the maximum and minimum flow rates is the turndown ratio. As discussed more in the Heat Meters chapter, flow meter accuracies are often grouped into classes based on the turndown ratio and the accuracies at the minimum and maximum value.

Another consideration in the selection of a flow meter is the compatibility with the heat conveying liquid. For example, if the liquid is expected to have particulate matter, an ultrasonic Doppler meter may be preferred over a mechanical turbine meter.

The pressure drop across a flow meter may also be important as the circulating pumps are sized to overcome the resistance of the piping and fittings but may also need to account for pressure drop through flow meters. Positive displacement and differential pressure meters tend to have higher pressure losses than velocity meters.

Configuration of the piping and availability of straight pipe runs may also be a factor in flow meter selection. Other than mechanical displacement meters, flow meters that measure characteristics of the fluid velocity in a pipe require quieting sections above and below the meter. These distances typically require sections of straight pipe with no fittings that are 10 pipe diameters upstream of the meter and 5 pipe diameters downstream of the meter. For mechanical meters, those relying on moving parts to measure flow, the orientation of the flow meter is important as changes in orientation can result in changes in the characteristic rotation of parts.

For installation and maintenance, it is important to always follow the manufacturer's installation instructions closely and ensure that meter calibrations continue as recommended by the manufacturer. One useful guide for calibration of flow meters is the Good Practice Guide: The Calibration of Flow Meters (TUV NEL, N.D.).

In addition to insuring laboratory calibration, it is also important to verify the operation of the flow meter during commissioning. Ideally, a meter with greater accuracy would be installed, at least temporarily, to confirm the installed meter is reporting accurately. Installed accuracies can be affected by fluid properties, actual dimensions of pipe for methods that rely on velocity measurements, electrical interference in the vicinity of the meter, and errors in meter installation.

Choi et al. (2011) evaluated three types of flow meters as deployed in heat meter assemblies. They evaluated a total of 24 heat meters representing three flow meter technologies (turbine, ultrasonic, and electromagnetic). They calibrated the meters in the lab and then deployed for field testing. They found good accuracies (+/- 2.5%) for the turbine and ultrasonic meters but significant deviation (underreporting) for the electromagnetic meters at lower flow rates.

3.1.5 Air Flow Measurements

Ideally, quantifying the thermal load in a brine-to-air GSHP system would involve direct measurements of air flow and humidity. However, these measurements are complex and not typically made. In the Annex 52 Case Study on the ASHRAE headquarters, Spitler and others use a combination of commissioning data, real time data on some heat pumps, and humidity measurements to develop proxy methods for heat pumps without direct measurements. Each case will be unique and EN 12599 provides detailed procedures that can be tailored to the specific use case.

3.2 Temperature

Temperature measurements are important for a number of purposes in GSHP systems. Measurements of in-pipe fluid temperature help to quantify operating conditions and rates of heat transfer. Measurements of air temperatures help to understand building conditions and equipment operation relative to local weather conditions and system controls. Distributed temperature sensing of ground loops helps to inform the analysis of ground loop performance – in terms of both temperatures within the pipes and heat exchange with the ground.

3.2.1 Varying Resistance Devices

Thermo-resistance devices rely on the temperature dependence of electrical resistance of some metals. The two most common classes are resistance temperature devices (RTDs), in which the resistance increases with temperature, and NTC thermistors, in which the resistance decreases with increasing temperature. Both classes of sensors come in a variety of configurations.

3.2.1.1 Resistance Temperature Device (RTD)

Resistance temperature devices (RTDs) rely on the sensitivity of electrical resistance to changes in temperature. RTDs use thin strands of wire, typically platinum or nickel, with a known resistance at 0 °C and the resistance increases linearly with temperature. For example, a Pt100 RTD sensor uses platinum and has a resistance of 100 ohms at 0 °C. RTD sensors can cover a wide range of temperatures and it is important to select a sensor with a range that is closest to the temperature range of interest. Typically, the larger the resistance value, the more sensitive the RTD is to change in temperature.

The temperature sensors are typically embedded in a probe and potted with a waterproof material to prevent damage from moisture. The sensors inside the probe are connected to an interface with a 2, 3, or 4-wire configuration. In the 3 and 4-wire configurations, internal bridge circuits are used to offset some of the effects of lead wire length. It is important to consult manufacturer specifications for any additional corrections needed for longer lead lengths, and it is important that the sensors selected are compatible with the interface. Accuracy of platinum RTDs is defined by the standard IEC 60751 which breaks down sensor accuracies into Classes. When selected and used properly, RTD sensors can have high accuracy over temperature ranges typical of HVAC systems and Class A sensors are strongly recommended.

3.2.1.2 Thermistor

Thermistors are similar to RTDs in that they rely on an element with a temperature dependent resistance and are typical housed in a small ceramic electrical component. Unlike RTDs, the change in resistance may be represented by either a positive temperature coefficient (PTC) or a negative temperature coefficient (NTC).

For NTC devices, the non-linear relationship can be beneficial for measuring small changes in temperature. However, the signal must be linearized, typically through a separate circuit, and then converted to temperature. While the use of NTC thermistors is relatively uncommon in heat meters, they are commonly used in HVAC equipment and controls. NTC devices are sometimes described with a parameter (beta) that is used for the linearization and the accuracy is reported as an interchangeability of devices. A more accurate calibration technique uses the Steinhart-Hart equation (Steinhart and Hart, 1968).

These varying resistance devices should not be confused with thermocouples that rely on a temperature-dependent voltage that is induced at the junction between two different metals. Thermocouples can measure very high temperatures and are commonly used in furnaces but are generally not applicable in GSHP systems.

3.2.2 Integrated circuits

Digital temperature sensors offer an alternative to the resistance temperature devices. These are commonly used in electronic devices and rely on the temperature sensitivity of the bandgap voltage of a transistor in an integrated circuit. In GSHP systems, a commonly used digital temperature sensor is the DS18B20. Like thermistors and RTDs, the integrated circuit device can be potted into a stainless-steel probe and waterproofed. The main advantages of these digital sensors are that they are low-cost and data can be transmitted on a single (2-wire) bus without loss of signal. Each sensor has a unique internal fixed identifier that is transmitted with the temperature data. Some low-cost controllers can interface with up to 20 devices. In GSHP systems, it is often necessary to measure temperatures at multiple locations that may be separated by 10s of meters. As the number of sensors and distances increase, it is important to design the network topology in accordance with manufacturers recommendations. The DS18B20 sensor noted above has a factory calibration of 0.5 °C, though it can be calibrated for greater accuracy. The integrated circuit temperature sensors are reported to have very good long-term stability.

3.2.3Temperature sensor selection

When selecting temperature sensors for GSHP system monitoring and verification, there are four primary considerations: accuracy, durability, communications, and cost. When evaluating accuracy of temperature sensors, consider whether the application will be for measuring the absolute temperature (e.g., borehole temperature, air temperature, etc.) or whether the sensor will be part of a pair used to measure a temperature difference. When measuring long-term trends of absolute temperature, such as the evolution of a GLHE, an accuracy of ±1 °C may suffice. However, when measuring temperature differences in GSHP systems, the error should be less than 0.25°C. These smaller errors of temperature difference can be potentially obtained by pairing sensors of lower accuracy and using a fixed offset to adjust measurements. Care should be taken that the offset is not itself temperature dependent. It is recommended that Pt1000 Class A sensors, or those with equal or better accuracy, are used for all temperature measurements associated with the GSHP system.

In addition to accuracy, sensors should be durable so that they can be left in place for many years without failing from exposure to environmental conditions. The sensor probe may be submersed in a liquid or thermal grease. Most temperature sensing technologies are available in stainless steel probes with waterproof enclosures. The connecting cable must be suitable for conditions that will likely experience condensation.

The size of the sensor probe should also be compatible with the sensor location. Some sensors are mounted to the exterior of a metal pipe, others might be installed in a thermal well (socket), while smaller diameter sensors (3mm) may be inserted into the heat conveying fluid though a rubber membrane test plug (also called ‘binder plug’ or ‘Pete’s port’).

When sensors are mounted on the outside of a pipe it is important to use heat transfer paste, aluminum tape and insulation adapted to the application. Higher temperature difference relative to surroundings, thicker tube walls, and risk for condensation increase need for closed-cell insulation. It is important to ensure that the long axis of the sensor is aligned with the pipe to ensure good contact. Surface mounted sensors should be mounted sufficiently away from components that act as flanges. Also, while insulation will help to reduce sensor bias towards room temperature, it will not eliminate it. With that said, if sensors are used to measure a temperature difference, the bias of a sensor pair will be similar, reducing its impact.

It is important that temperature sensors are compatible with the instruments reading the signal. The benefits of a 4-wire RTD will not be realized if it is interfaced with a 2-wire RTD interface. Likewise, OneWire temperature sensors require a OneWire controller and proper design of the sensor network bus.

3.3 Electricity

Electric usage is important in determining the performance of a GSHP system, particularly with respect to the power consumption of the heat pumps, circulating pumps, and any electric auxiliary heating/cooling.

The measurement of power in an AC circuit involves the measurement of current, voltage, and power factor, with the electric power being the product of the three. For a completely efficient split-phase motor, the power factor is 1.0. Values less than 1 result from the alternating voltage and current being slightly out of phase with one another. Most electric meters will measure the real power (watts); however, some applications rely on calculation of the apparent power using independent measures of voltage and current (volts-amps).

In most GSHP studies that are part of this Annex, electricity usage is measured with one or more electric meters that are part of a BMS and measure the power continuously and record the cumulative over a period of time. The average power over the interval can be determined by dividing the cumulative energy (watt-hours) over the interval by the duration of the interval (hours). When electric meters are part of a BMS, periods between readings can be 15 minutes, an hour, or more. While the cumulative power measurement will be very accurate, any variations in power during the period between samples is not recorded. To capture equipment operating patterns, such as duty cycles, it is preferable to obtain power readings at 1-minute intervals.

In addition to issues with averaging power over long time intervals, electric meters will typically measure multiple system components and thus limit the options for the system performance factor (SPF) boundaries described in the accompanying Annex 52 report. For example, an analysis of SPF0 requires an isolated measure of the ground loop circulating pump in a BMS, the circulating pump power may be combined with other system components. Similarly, the difference between SPF2 and SPF3 is the exclusion or inclusion of load-side circulating pumps. Again, the placement of the electricity meters may dictate the performance boundary. If measurements of electrical components are measured individually during on site verification, it may be possible to estimate electricity usage of individual components using other information from the BMS (such as pump speed).

If resources permit, it is recommended to use electric meters that can be polled at 1-minute intervals and provide both cumulative (watt-hour) and instantaneous measures (watts). As noted in Section 2.4, if relying on pulse output meters it is important to select meter components so that the desired resolution can be obtained. An alternative approach that allows for greater granularity at the expense of some accuracy is to measure amperage of (using current transducers) delivered to individual components and multiply the current by the circuit voltage that can be measured at one location.

3.4 Pressure

Measurements of liquid and gas pressures are often necessary when assessing the performance of GSHP systems, such as with flow sensors that use differential pressure. Quantifying the pressure losses in pipes and pipe networks is important for ensuring that pump sizes are correct and design flow rates are maintained.

Pressure sensors operate on the principle that the applied force deforms a diaphragm in a manner that can be sensed by a mechanical spring or a piezoelectric transducer. One side of the diaphragm is maintained at a reference pressure so that pressure measurements are relative to the reference pressure. Pressure sensors fall into four categories, based on the reference pressure: absolute pressure is measured relative to a true vacuum; gauge pressure is measured relative to atmospheric pressure; differential pressure is measured pairwise, and sealed pressure sensors measure pressure relative to a fixed value.

When measuring liquid flow in pipes, it is important to note that a measurement of pressure is just one component of the total mechanical energy of the fluid and the ‘pressure drop’ in pipe flow also includes the changes in gravitational static pressure that result from changes in elevation. It is therefore critical that the relative elevations of pressure measurements are also known. For placement of pressure sensors relative to pipe orientation, pipe fittings, and fluid characteristics, the reader is referred to Lane et al. (2014).

In the selection of pressure measurement sensors, the accuracy is typically reported as a percent of full scale (maximum pressure reading) and this accuracy should be considered relative to the lowest anticipated pressure measurement. Also, because of the mechanical nature of the measurement, sensors will have a burst pressure that is typically reported as a multiple of the maximum rated pressure reading.

For measuring in refrigeration systems, it is important to use sensors adapted to the pressure to be measured. A sensor selected for a high-pressure refrigerant discharge pressure will have poor accuracy and resolution for a low-pressure refrigerant. Pressure range should be adapted to pressure range of the system measured.

Accuracy for pressure sensors are often given as percent of Full Scale FS and thus it is not recommended to use a wide range and measure at the lower end. For measurements in refrigeration system with selection of suitable range for the refrigerant 1.0% accuracy is recommended/typically used and for high accuracy requirements 0.1% are commonly available.

4 Heat meters

Several heat meter standards have been developed over the past two decades, each is primarily aimed at providing specifications for the quantification of meter accuracy, manufacturing, and testing. This guideline aims to describe the portions of the heat meter standards that are relevant to the user to select an appropriate meter for a GSHP system and correctly interpret the readings provided. While sometimes referred to as thermal energy meters, the term heat meter is commonly used in the standards that define the accuracy classes and will be used herein.

4.1 Heat Meter Standards

Four main heat meter standards have been developed to serve different markets and legal jurisdictions. Each of the standards follows a similar approach for quantifying and classifying errors.

The International Organization of Legal Metrology (Organisation Internationale de Métrologie Légale, OIML) released a three-part recommendation to its Member States for heat meters in 2002. The OIML R75 Part 1 provides the General Requirements, including the means by which errors should be quantified and classified, Part 2 provides guidance on the manufacturing and testing requirements, and Part 3 provides guidance of the format of the Test Reports. Following the development of OIML R75, the European Union, Canada, and the United States have developed additional standards, (EN1434, C900.1, and ASTM 2017, respectively) that are available for purchase. Review of the other standards suggests that they largely follow the same accuracy classes for accuracy as OIML R75 (OIML, 2002). The international standard (OIML, 2002) is referenced here as it is in the public domain, though when required for compliance, the practitioner should refer to the appropriate standard.

4.2 Meter Accuracy

The accuracy of a heat meter is governed by the maximum permissible errors of the heat meter components, which include a measure of the temperature difference and flow rate of the heat-conveying fluid and the calculator that computes the thermal energy from the measurements and the thermal properties of the heat conveying fluid. It is important to recognize that the accuracy of a heat meter is a combination of three components and the magnitude of each error component can depend on the magnitude of the quantity being measured. Unfortunately, heat meter errors cannot be determined as simply a percent of reading or percent of full scale like many other measurement devices.

4.2.1 Differential temperature classes

The heat meter accuracy classes for temperature difference (Table 4-1) refer to the smallest temperature difference (ΔT_{min}) that can be measured while maintaining the Maximum Permissible Error (MPE) of 3.5%. For example, to satisfy an MPE of 3.5% for a temperature difference of 1 degree Celsius, it is necessary for the temperature sensor pair to have an accuracy of 0.035 degrees Celsius. The greater the accuracy of the temperature difference measurement (lower Class number), the smaller the minimum temperature difference that can be accurately measured. This does not mean that temperature differences less than the ΔT_{min} cannot be measured and reported, only that temperature differences below the minimum have an error greater than 3.5%. Because GSHP systems often have small temperature differences, it is important to quantify the accuracy of the temperature difference measurements.

Table 4-1. Temperature difference accuracy class used in common heat meter standards.

ΔT Class	ΔT_{error} [°C]	ΔT_{min} [°C]	ΔT_{error} [°F]	ΔT_{min} [°F]
1K	0.035	1.0	0.063	1.8
2K	0.070	2.0	0.126	3.6
3K	0.105	3.0	0.189	5.4
5K	0.175	5.0	0.315	9.0
10K	0.350	10.0	0.630	18.0

For temperature differences that are computed from individual point measurements, the accuracy of the temperature difference can also use same accuracy scheme. For example, for a pair of sensors that are calibrated to within 0.1 ºC of a common standard, the measurement error for the temperature difference measured by the pair would be 0.14 ºC ($\sqrt{0.1^2 + 0.1^2}$) and reported as Class 5K accuracy. For comparison, heat meters designed for high-temperature hot water systems may be equipped with RTD temperature sensors that meet the IEC751 Class B accuracy (±0.3 ºC at 0 ºC) resulting in a temperature difference accuracy of 0.42 ºC, exceeding the Class 10K limit, suggesting that, in order to have an error less than 3.5%, a minimum temperature difference must be greater than 10 °C, a condition rarely met in GSHP applications. Heat meter product literature commonly report the accuracy of the flow sensor as the accuracy of the meter, rather than the total error. The total heat meter error is the sum of the errors attributed to the three contributing sources: flow, temperature difference, and computation. The temperature difference error, in percent, is expressed according to the temperature sensor Class (ΔT_{min}) in units of degrees Celsius (or Kelvin). Larger temperature differences result in smaller relative error.

$$E_t = \pm(0.5 + 3\,\Delta T_{min}/\Delta T)$$

4.2.2 Flow sensor classes

In addition to the temperature difference of the heat conveying fluid, a measure of flow rate is essential. The Maximum Permissible Error for flow sensors depends on the ratio of the permanent flow rate (q_p) to actual operating flow rate (q)[4]. Table 2 shows the range of allowable MPE for flow sensors by Class and turndown according to the following equations (OIML R75-1:2002).

Class 1 $E_f = \pm (1 + 0.01\ q_p/q)$, but not more than ± 3.5 %

Class 2 $E_f = \pm (2 + 0.02\ q_p/q)$, but not more than ± 5 %

Class 3 $E_f = \pm (3 + 0.05\ q_p/q)$, but not more than ± 5 %

Turndown is defined as the ratio of the maximum flow rate (q_p) to minimum flow rate (q_i) expressed as a ratio.

Table 4-2. Flow meter accuracy classes as a function of turndown and accuracies at minimum and maximum flow rates.

Class	Turndown	E_f at minimum flow ($q=q_i$)	E_f at maximum flow ($q=q_p$)
Class 1	10:1	1.10%	1.01%
	25:1	1.25%	1.01%
	50:1	1.50%	1.01%
	100:1	2.00%	1.01%
	250:1	3.50%	1.01%
Class 2	10:1	2.20%	2.02%
	25:1	2.50%	2.02%
	50:1	3.00%	2.02%
	100:1	4.00%	2.02%
Class 3	10:1	3.50%	3.05%
	25:1	4.25%	3.05%

Flow meter methods include (but are not limited to): vortex shedding sensors (e.g., Grundfos VFS series), multi-jet water meters, turbine meters, ultrasonic, and induction meters. The metering technology is important when interpreting flow data as the accuracy of different metering technologies may depend on the fluid characteristics, particularly when the fluid is an aqueous mixture with an antifreeze.

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[4] "The permanent flow rate is the highest flow rate at which the heat meter shall function continuously without the permissible errors being exceeded.", OIML R-75:2002

4.3 Meter Error

While heat meter standards use the flow meter accuracy class (1, 2, or 3) to define the heat meter class, the flow meter error is just one component of the total error. The total meter error is the sum of the errors in the temperature difference (E_t), the flow sensor error (E_f) and the error introduced by the calculator (E_c) which is assumed to be a function of both the temperature and temperature difference, $E_c = \pm(0.5 + \Delta T_{min}/T)$. Heat meter standards focus on the maximum permissible error (MPE) that may occur, from all sources, when measuring heat transfer and use the sum the individual MPEs in (1) measured temperature difference ($E_{\Delta T}$), the flow measurement (E_f), and the calculator error (E_c) as the MPE of the meter.

Because the actual errors that arise through the measurement of thermal energy depend on the temperature differences and flowrates at the time the measurements are made, and these conditions can vary considerably over time, the actual error should be calculated according to the accompanying Guidelines for Calculation of Uncertainties and use the applicable errors defined in the heat meter classes to quantify individual error components. The heat meter classifications of temperature difference and flow meter errors are also useful in reviewing manufacturer specifications when selecting the proper flow meter.

In addition to sensor errors in the measurement of temperature difference and flow rate, heat meters are also susceptible to errors in installation. For example, in a study contracted by the UK Department of Energy and Climate Change, AECOM (2013) report on several installation and maintenance issues that can significantly increase heat meter errors. They found that in some installations, the heat meter was installed in the wrong location. When a heat meter is produced with paired sensors, the sensor offset is programmed into the calculator and the temperatures sensors are not interchangeable between the supply and return pipes. They also report errors that arise from using water-glycol mixtures as the heat conveying fluid when the flow sensors and calculators assume water only.

Butler et al. (2016) conducted a comprehensive study of heat meter errors that result from manufacturer calibration inaccuracies, incorrect meter installation, and effects of installation conditions. They found that the combination of these errors can be expected to result in an overall uncertainty between -5.9 and 2.5%, with a 95% confidence interval. To achieve desired accuracy, they recommend that temperature sensor be installed in the fluid flow rather than on the pipe surface.

4.4 Meter Selection

4.4.1 Heat Meter Components

As noted above, it is important to document the accuracy of the flow and temperature difference measurements and the calculator. Heat meter literature will tend to focus on accuracy classification of the flow sensor (as it defines the meter class) and the accuracy of the calculator. Knowing the temperature difference class is important to quantify meter errors. For GSHP systems, the accuracy class should be 5K or lower.

4.4.2 Heat Transfer Fluid

Heat meters are typically tested with water as the heat transfer fluid. However, GSHP systems often use a brine (water-antifreeze mixture) as a heat transfer solution, requiring customization of the energy calculations to account for fluid properties. While thermal properties of fluids are temperature dependent, the variation within the temperature ranges often encountered in GSHP systems is small. For a more detailed discussion of the thermal properties of fluids commonly used in GSHP systems and their impact on errors in heat flow calculations see Witte (2013).

In addition to a modification of the heat flow calculations relative to water, some antifreeze solutions, such as propylene glycol and ethanol, exhibit significantly higher viscosities at low temperatures. These increased viscosities may violate assumptions commonly used for measurement devices. For example, flow sensors that rely on vortex shedding technologies have an upper viscosity limit that may be too low, under very cold conditions. In addition, as noted above, flow sensors in meters are typically calibrated to the fluid properties of water only and use of a brine can affect both the calculation of heat transfer that include thermal properties of fluid as well as the flow sensor reading used in the calculation.

4.4.3 Registers for heating and cooling

When a component in a GSHP system can provide both heating and cooling, it is important that these be quantified separately, requiring two registers in the heat meter. Some heat meters can be configured to record heating and cooling separately but many use the absolute value of the temperature difference and record both heating and cooling in the same register. In these cases, it is necessary to use measured temperature to parse the heat meter totals into separate components. If the temperature data is not recorded separately (and only the cumulative heat transfer), this will not be possible.

4.4.4 Meter output options

Heat meters that meet international standards are required, at a minimum, to output a pulse signal (e.g., pulses per $\text{kWh}_{\text{thermal}}$). Similarly, the availability of accumulated energy may only be available at discrete time intervals (e.g., hourly, daily, monthly). However, in assessing performance of GSHP systems, it is often desirable to have recorded measures of the fluid flow rate and both the supply and return temperatures at a resolution that can provide insights into system operation and performance (e.g., one-minute samples). Some custom configurations of heat meters, such as those that have interfaces for building management systems or an optional analog-output board, may provide instantaneous measures to flow rate and temperature in addition to the metered thermal energy.

4.4.5 Approved Lists

Some jurisdictions have published lists of approved meters to assist consumers in selecting meters that meet the prevailing standards, in terms of testing, manufacturing, and providing rating classes. Meters on these approved lists may or may not meet the specific objectives of evaluating the long-term performance of a GSHP system. As noted above, according to international standards, heat meters are designated a Class (1, 2, or 3) based on the accuracy of the flow sensor. However, this classification does not stipulate any accuracy requirements on the measure of temperature difference. In GSHP systems, the temperature difference can be small and warrant better accuracy than may be provided with a Class 2 heat meter.

4.5 Summary

The measurement of heat absorption from or loss to a heat conveying liquid is complex and relies on multiple measurements (fluid flow and temperature difference) under conditions that vary over time. Measurement of the liquid flow rate and temperature in a pipe are, in themselves complex, and can be accomplished with a wide range of instruments.

The heat meter standards have been developed for different regions and jurisdictions follow similar definitions of accuracy classes for the measurement of temperature difference and flow rate as well as the definition of the Maximum Permissible Error for each class.

When applying the heat meter standards to a GSHP system, the accuracy class of the temperature difference (1K, 2K, 3K, 5K, or 10K) is of particular importance. Because the meter accuracy class is defined as the flow sensor class (1, 2, or 3), the accuracy of the temperature difference is often not disclosed. For example, if a jurisdiction mandates the use of a Class 2 heat meter, the only accuracy requirement is that the flow sensor meets the Class 2 definition (Table 4-2).

While sometimes required for certain programs, heat meters can also provide useful data for quantifying the performance of GSHP systems, but only if the care is taken to select the meter so that all accuracy classes are appropriate for the conditions and the meter allows for access to the individual flow and temperature readings at a useful time interval. If an integrated meter is not required, researchers may choose to install dedicated sensors and perform the calculations of heat transfer separately.

5 Distributed Temperature Sensing

5.1 Introduction

Distributed temperature sensing (DTS) technology is an emerging technology that can be used to measure temperature along a continuous path with an acceptable accuracy over tens of kilometers. The technology is typically used to monitor high-temperatures or rapid temperature changes in order to operate components safely or detect fires or leakages (Ukil et al., 2012). Another common use of the technology is to monitor temperature profiles for scientific studies (Ukil et al., 2012).

Recently, DTS has become a method for monitoring temperatures in boreholes in various environments (Freifeld et al., 2008; Monzó, 2018; Saar, 2011; Somma et al., 2019). A DTS system can provide dense temperature measurements along a borehole heat exchanger (BHE). Monitoring temperatures in a BHE can provide valuable information on heat transfer between the BHE and the surrounding bedrock or soil. These data can then yield estimates of thermal properties of the underground materials. Further, the data may help for optimizing and planning boreholes in terms of efficiency and cost.

The DTS technology described here is based on Raman scattering (Hausner et al., 2011), which is described as inelastic scattering of photons (Vandenabeele, 2013). In this physical phenomenon, incident light pulses interact with vibrating molecules and shift the frequency of photons (Schenato, 2017). If a vibrating molecule emits a photon with lower energy and frequency than incident light, the phenomena is called Stokes Raman scattering. On the other hand, a molecule emitting photon with higher energy and frequency than light is called the anti-Stokes Raman scattering (Vandenabeele, 2013).

A DTS system includes optoelectronic device called optical time-domain reflectometer (OTDR) connected with fiber optics made from silica glass (Schenato, 2017). The DTS-device emits a short laser pulse and measures backscattered photon intensities of the Stokes and anti-Stokes scattering along the optical fiber (Hausner et al., 2011). The ratio between the intensities of the Stokes and the anti-Stokes can be converted directly to temperature values as the intensity of the anti-Stokes is temperature-dependent while the intensity of the Stokes is very weakly dependent on temperature changes (Schenato, 2017). The derivation of the relationship between Raman scattering and temperature is presented thoroughly by Farahani and Gogolla (1999).

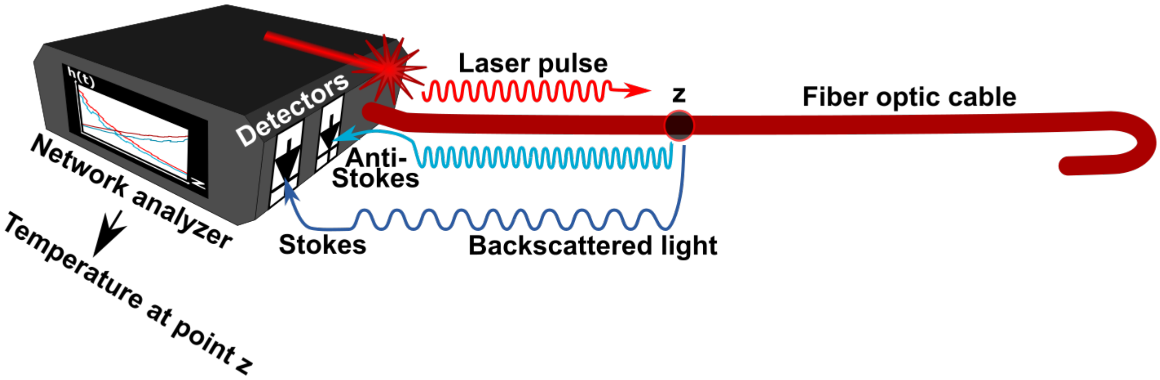

Figure 5-1. Schematic picture of distributed temperature system where a laser pulse propagates through a fiber optic cable.

5.2 Instruments and cables

There are various DTS instruments and cables available in the market and they must be selected based on the expected measurement condition, required spatial and temperature resolution, measurement range, number of measurement channels and measurement configuration. Different DTS instrument models are manufactured to withstand different measurements conditions. Some can withstand temperatures from 40 °C to -40 °C and wide range of humidity, but others are manufactured only for inside conditions. Therefore, one criterion for selecting DTS instrument must be based on the conditions where the unit is used or/and stored.

Sampling interval, spatial resolution, temperature resolution and time required for a single measurement are also important factors for the selection of DTS instrument. Sampling interval determines how densely DTS instrument detects temperature values along the cable and each instrument has minimum and maximum setting for sampling interval. It can vary from tens of centimetres to a few metres. However, individual temperatures are spatially averaged, and this is described as spatial resolution. Therefore, DTS instruments provides weighted average temperature values along a specific length of fiber, meaning that adjacent samples are dependent on each other. Usually, spatial resolution of the instrument is from one to several meters, and it is always higher than the sampling interval. The reader is referred to Tyler et al. (2009) and Selker et al. (2014) for more detailed discussion of sampling interval and spatial resolution. Improved instruments can provide temperature values at similar temperature resolution but with shorter sampling interval, spatial resolution, and measurement time. Temperature resolution refers to the uncertainty of measured temperature values, or how much measurements vary between consecutive measurements or adjacent points along the cable that are at the same temperature (Silva et al. 2017). Note that the temperature resolution is different than absolute accuracy for individual temperature values. If the detectors of the DTS instrument detects less backscattered light, temperature resolution gets worse and thus signal noise is higher meaning weaker signal to noise ratio. Therefore, longer single measurements can provide more accurate temperature values, but improved detectors can integrate temperature over the time as reliably in the shorter measurement time. Nonetheless, measurement times are usually from minutes to tens of minutes for a single measurement with the DTS instrument.

The fiber optic cable is made from doped silica glass which are designed to minimize error caused by fiber. Cables can be installed using optic connectors to the measurement channels of the DTS. The number of the channels can vary from 2 to 16 and the maximum allowable measuring distances can vary from four to tens of kilometres.

A DTS unit can only measure one measurement channel at time; therefore, it is only possible to measure one measurement channel at time. Increased measurement distance decreases measurement accuracy, therefore, it is preferred to use shorter cables and multiple measurement channels rather than a long cable and one channel. However, if multiple boreholes need to be measured simultaneously; long cables with long measurement distances must be used and accuracy slightly compromised. With that said, high quality cables can provide better temperature resolution over long measurement distances as there is less dispersion of the travelling light. Additionally, improved DTS instruments detect backscattered light from greater distances. For the above-mentioned reasons, it is important to consider measurement distances, sampling interval, spatial resolution, temperature resolution and required time for single measurement based on accuracy required in the research or commercial project, as DTS instruments are optimized based on these parameters.

There are different fiber types in the market such as single-mode and multimode fibers. The single-mode is 9µm/125µm diameter and the inner core where the laser pulse propagates is 9µm. However, most DTS devices uses multimode fibers: 50µm/125µm or 62,5µm/125µm, and from these the 50µm is the most common. When choosing the 50µm multimode fiber, the glass core type (graded index or step index) must be chosen. The DTS devices use graded index multimode fibers. In the graded index core the laser pulses propagates smoothly and increase the refractive index.

There are also differences in how protection of the fibers and the outer shell of the cable are made; therefore, there are differences with stiffnesses of the cables. The appropriate cable stiffness should be chosen based on installation purpose. The most robust cables and fibers are armoured with layers of steel. A fiber optic cable should be selected based on the installation environment. For example, deep geothermal installations require differently protected cables than shallow geothermal installations due to high pressure at deep depths. When measuring temperatures inside the pipe and in the flow, make sure that the cable properties are suitable to use in the flow and the cable keeps its shape in a line and is not twisted by the flow.

The DTS instrument can be operated either on a site or remotely. Some of the DTS instruments allow remote access; therefore, the hardware of the DTS unit can be managed and data transferred using remote connection. It is important to keep in mind that safety issues arise with DTS systems due to the laser propagating in the fiber. The DTS device use a Class 1 laser and it will be harmful when pointed straight in the eye. It is important to be sure that the laser is always off when attaching the connectors to the device or when fusion splicing the fibers.

5.3 Designing DTS monitoring systems

DTS monitoring systems are designed on a case-by-case basis for each borehole heat exchange (BHE) field. Defining a clear objective of the DTS monitoring is important as it affects the design of the system. Therefore, it is important to consider whether the DTS monitoring system is being used to optimize the operation of the BHEs or provide results for scientific research. The DTS monitoring could be done by a single case basis or as a permanent fixture. Single measurements are suitable when the monitoring is done only few times in the year for system evaluation and optimization. In these cases, the DTS instrument does not need to be installed at the site permanently though the cable could be installed permanently in the borehole(s). For scientific research, it is common to have a dedicated DTS instrument at the site for the duration of the research.

In the DTS monitoring system, the fiber optic cable(s) are installed to monitor temperatures in one or multiple boreholes. Recommended guideline is to install cables in at least 10% of the boreholes. As the bedrock or soil is heterogeneous, distributing the monitoring of boreholes evenly will help to observe differences between boreholes when optimizing the operation of the BHE.

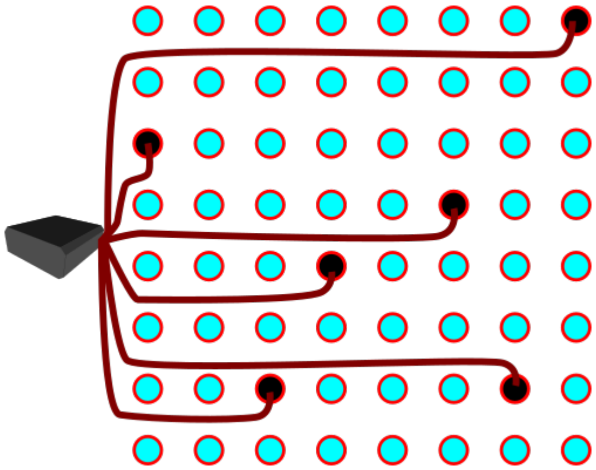

Figure 5-2. DTS monitoring systems in multiple boreholes in BHE field

DTS can also be used to monitor so called passive boreholes, which are not used for heat injection or extraction. Passive boreholes are used to monitor temperature changes of the underground material that results from heat injection or extraction. In addition, these boreholes may provide details on thermal conductivity of underground materials, groundwater flow directions, or detect subsurface geologic features. For passive boreholes, the exact location and borehole orientation must be known in order to interpret the data correctly.

5.4 Cable installation methods and calibration

Fiber optic cable installation depends on the heat exchanger configuration and cable type used, as illustrated in Figure 5-3. In a BHE with a U-tube pipe, the cable can either be installed inside of the pipe (Figure 5-3a) or in the annular space around the pipe that may be filled with grout or groundwater (Figure 5-3b). If the target is to monitor temperature of the grout or groundwater, then cables can be installed outside of the pipes. One drawback in installing cable in the grout or groundwater is that the location of the cable relative to the pipes is difficult to determine. At some points, the cable may be in contact with the borehole wall and at other points with collector pipe; therefore, data may be difficult to interpret. When cables are installed in both legs of the pipe, temperature development of heat exchanger fluid in the inlet and outlet legs can be monitored simultaneously. However, cable type must be stiff when installing it inside the collector legs as heat exchanger fluid flow may push the cable in the outlet leg upwards; therefore, cable may deform and cause problems for data interpretation. In BHE with coaxial pipe, cables can be installed in the center pipe, the annulus, or both (Figure 5-3c). Monitoring temperatures in the center pipe reveals quality of the pipe wall insulation. A cable installed in annulus can provide temperature data about heat exchange process between the fluid and bedrock.

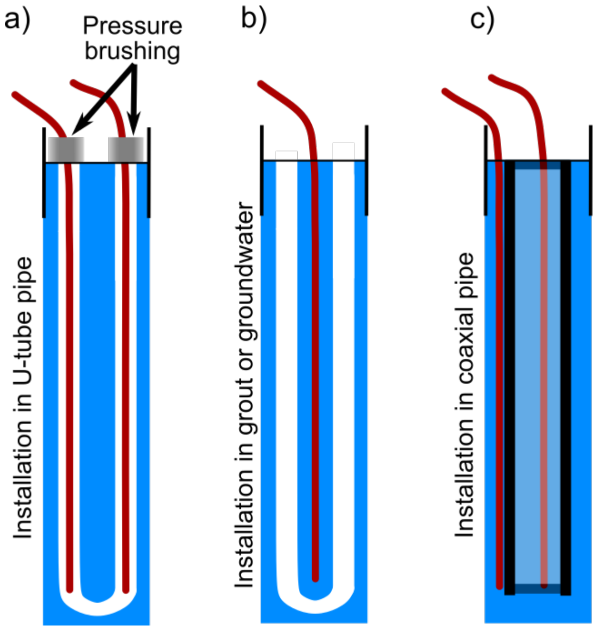

Figure 5-3. Cable installation locations for single U-tube and coaxial BHE.

Figure 5-4 illustrates installation of the cables in one borehole using double-ended configuration. The termination of each cable is installed in the bottom of each U-tube leg, and they are terminated by spliced connection, which enables temperature measurements in loop. Therefore, two fibers in the same cable measure parallel temperature readings along each of the U-tube legs. Also, the cables installed in inlet and outlet leg are connected by spliced connection in order to measure one borehole simultaneously.

Calibration procedures for the different configurations are presented by Tyler (2009), Hausner et al. (2011), van de Giesen et al. (2012), and des Tombe et al. (2020). Usually, internal calibration procedure of DTS instrument provides absolute temperature values with poor accuracy; therefore, reliable temperature measurements require appropriate calibration procedures. In DTS measurements, there are two configurations: single-ended and double-ended measurements, which require slightly different calibration approaches (see Figure 5-5). The cable terminations can be made by simply cutting the cable or by fusion splicing two fibers to each other. Cutting the cable for termination results in single-ended cable where only one end is connected to the DTS instrument; therefore, laser pulse is emitted in one direction during the measurement. This measurement configuration (see Figure 5-5a) will require several calibration points, with at least two known temperatures from both ends of the cable to correct temperature offset and the slope of the error function. Creating duplexed single-ended measurement (Figure 5-5b) is done by installing one cable into the borehole that goes to the bottom and comes back to the surface and by fusion splicing two fibers to each other in the termination point. The main advantage of the duplexed single-ended configuration is that both calibration points can be placed near the DTS instrument.

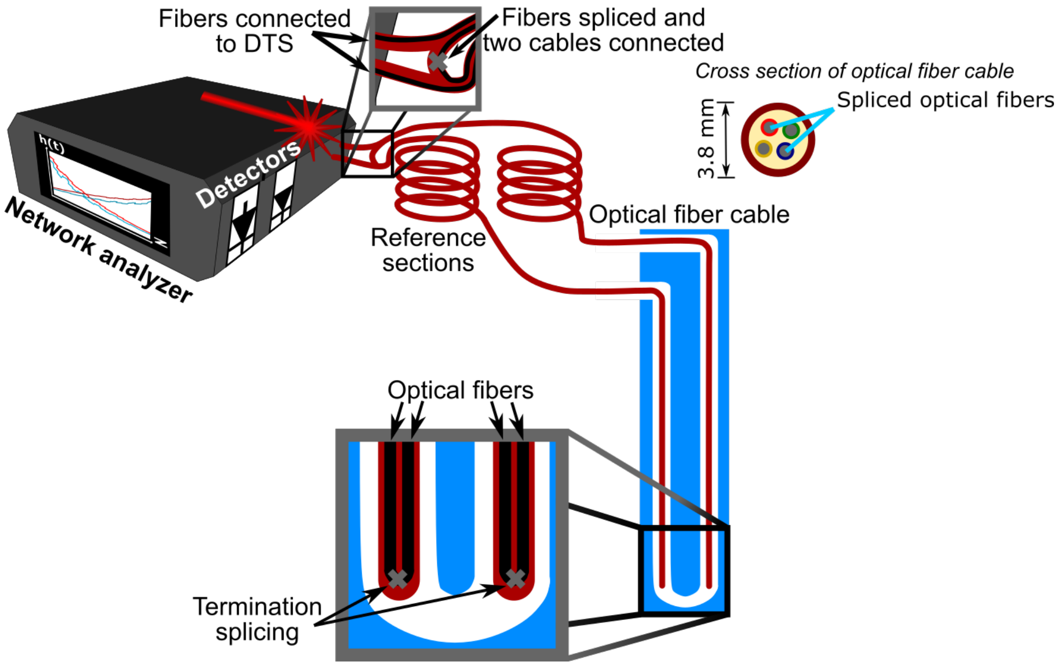

Figure 5-4. DTS at Aalto New Campus Complex. The system is double-ended configuration, where two fiber optic cables are connected by splicing near the DTS device so that the laser can be emitted both directions and one BHE can be measured with single measurement. Inset shows cross section of cable.

To make more precise measurements, use double-ended measurements (Figure 5-5c). The difference between duplexed single-ended and double-ended measurement is that in the latter both ends of the fiber are connected to the two channel slots of the DTS instrument. Then the laser signal goes straight to the bottom of the borehole and back to surface and the DTS instrument. In this type of measurement, the DTS instrument uses both channels to make measurements in both directions in the cable. These measurements need only one calibration point for sufficient accuracy as shown by Tyler et al. (2009). Therefore, every DTS measurement needs to be calibrated to at least one known reference temperature. Precise measurements require at least two calibration points with different known reference temperatures. According to van de Giesen et al. (2012), the recommended length of the reference sections should be more than 10 times greater than spatial resolution of the DTS instrument.

Measurement data may be processed by relying on manufacturer’s software or the user’s programming software. Manufacturer’s software usually provides temperature data along the entire length of the fiber optic cable and uses internal calibration procedures. The user’s programming allows more freedom for data processing as temperature data can be provided as a function of borehole depth and the data can be calibrated using specific methods selected by the user. For calibration purposes, there are scripts developed to calibrate DTS data as described by des Tombe et al. (2020).

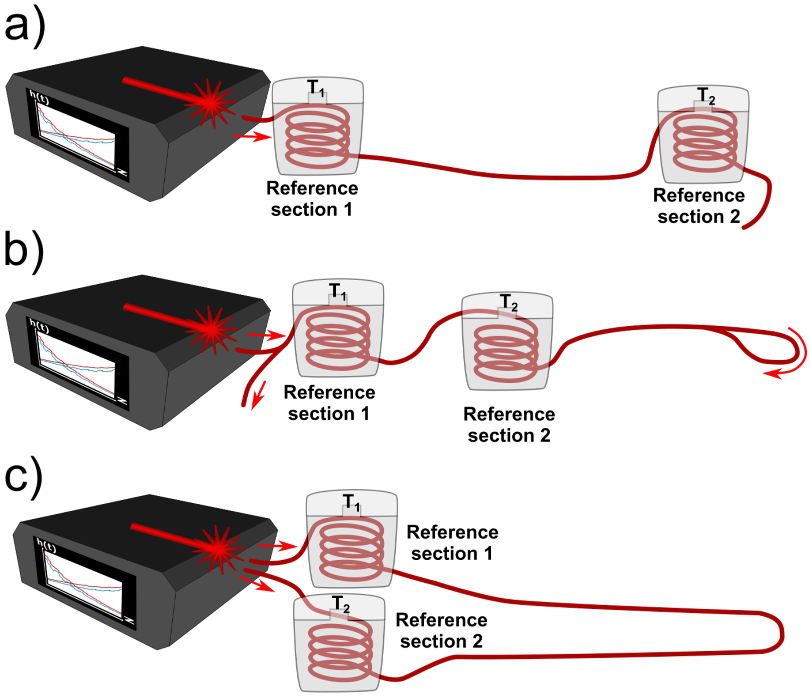

Figure 5-5. Each DTS measurement needs to have at least one reference temperature for sufficient calibration. Precise calibration requires two reference temperatures.

Figure 5-6 shows an example of DTS data results. Temperatures are measured from both the inlet and outlet of the U-pipe during active heat exchange. Measuring with DTS provides an advantage in measuring temperatures all the way down and up the pipe. The temperatures measured with the DTS method provide an opportunity to study the borehole and the ground properties, and, for large BHE fields, optimize the heat exchange in the field. For example, note the outlet temperature in Figure 5-6b. The temperatures are slightly warming when coming back to surface and this suggests a change in the flow rate may improve performance.

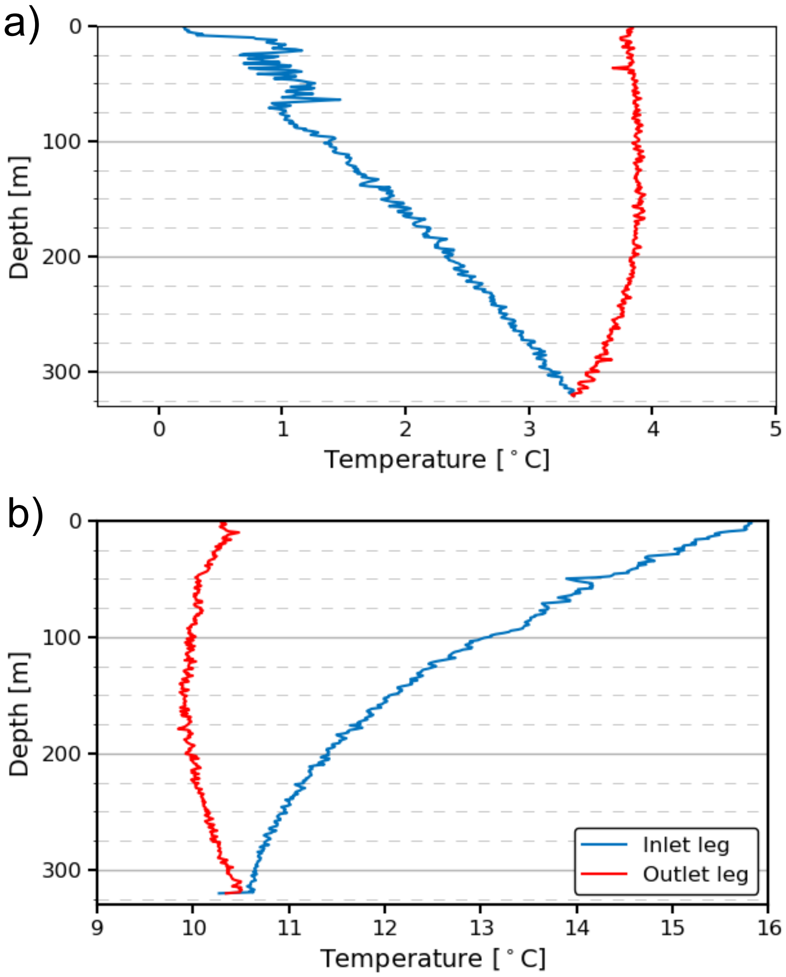

Figure 5-6. DTS data example from a borehole with normal U-pipe collector during a heat exchanging. Cables are installed inside both tubes: inlet and outlet. a) Wintertime - Heat extraction b) Summertime - Cooling mode

5.5 Error sources

5.5.1 Error caused by DTS sensor

According to Hausner et al. (2011) and Van de Giesen et al. (2012), wavelength and frequency of the laser pulse and shifted backscattered Raman photons are mainly dependent on design of the laser pulse. However, the laser pulse may be slightly affected by operation conditions of the DTS instrument such as temperature, humidity, and fluctuations in power supply. These changes in operation conditions cause minor variation in the operation of laser, prism, gratings and laser detector. In addition, Stokes and Anti-Stokes detectors are slightly affected by thermal changes in the system. Therefore, the components of the DTS instrument may cause some error because of changing operating conditions.

5.5.2 Error caused by fiber optic

In the DTS system, differential attenuation of the Raman backscattering occurs (unit: db km^{-1}) along the fiber optic cable. Stokes and anti-Stokes signals attenuate with different rates; therefore, the Stokes and anti-Stokes ratio measured by DTS instrument is not the same as the true ratio at the point of interest. For that reason, the Stokes and anti-Stokes ratio must be calibrated in order to obtain accurate temperature. Differential attenuation changes along the fiber optics due to bends, strains, splices, and other distortions. Error caused by the fiber optic is cumulative; therefore, differential attenuation must be calibrated by integrating the effect between the DTS unit and point of interest (Hausner et al., 2011; van de Giesen et al., 2012).

5.5.3 Calibration error

The optical time-domain reflectometer detects intensities of the Stokes and anti-Stokes along the fiber and automatically derives temperature profiles at different positions from their ratio based on the internal reference temperature of the device (van de Giesen et al., 2012). However, the relationship between temperature and the ratio of the Stokes and the anti-Stokes is complex as it depends on the operating conditions of the device (e.g. quality of power supply and operating temperature of the device) and the optical fiber, such as bends and strains along the fiber (Hausner et al., 2011). Because the installation conditions contribute to variations in the measured values, preinstalled calibration of the commercially available DTS devices may underestimate the errors of the system once installed. Hausner et al. (2012) show poorer accuracy (± 1 - 2 °C) when calibration is based on stationary internal reference temperature. Therefore, relying only on preinstalled calibration may yield inaccurate temperature values in BHE applications. However, with careful calibration procedure, a DTS system can provide accuracy of 0.1 °C (van de Giesen et al., 2012).

Additionally, using single-ended measurements have some drawbacks as their calibration procedure neglects differential attenuation, step losses due to fiber splices, sharp bends or pressure brushings, and fiber sections with a different differential attenuation such as coiled sections or different fiber types (des Tombe et al., 2020). For example, bias caused by step losses may require manual calibration in single-ended configuration. Also, the cutting point of the single-ended usually introduces remarkable change in differential attenuation and the effect could be seen already in temperatures before (e.g., 100m) the termination; therefore, data close to the termination is difficult to calibrate correctly. However, double-ended measurements provide the method to minimize the effect of step losses and can estimate integrated differential attenuation with its calibration algorithms.

6 Data Management

When collecting data to assess the performance of a ground source heat pump system, it is important to define a clear data management strategy. The data management strategy will depend on many factors including the objectives of the performance analysis and the resources available. The objective of this chapter is to provide an overview of the main elements of a data management plan but not prescribe any particular approach.

Most studies that are part of this Annex rely on sensors connected to a building management system (BMS) and the sharing of those data outside of the BMS scope. The main benefit of this approach is that it leverages data collection that may already be part of the system equipment and controls and the BMS provides a network backbone for additional supplementary sensors. However, there are several challenges that arise when relying on a BMS for data.

First, the primary objective of a BMS is to operate multiple systems effectively and securely within a building. The emphasis is on real time observations rather than storing long records for historical analysis. A BMS will typically have hundreds to thousands of sensors measuring equipment states, environmental conditions, alarms, and occupancy at a granular level. When data points for continuous measures are stored, such as temperature and energy, it is typically at 15-minutes intervals, rather than the 1-minute interval recommended here, and the duration of stored data may be on the order of weeks to months rather than years.

A second challenge is mapping of BMS datapoints onto a data model that is suited for efficient analysis. While not yet widely adopted, efforts like Project Haystack aim to standardize the tagging of data points in a BMS so that data can be used my multiple analysts to meet a wide range of analysis objectives.

Retrieving data from a BMS raises several issues. One is access as data will need to be shared with the analyst outside the internet firewall. This can be accomplished manually where the BMS administrator downloads files and sends them to the analyst, or it can be automated using software on the BMS server. The second major issue is interpreting the BMS data. It is essential that a reading from a given sensor has the necessary metadata so that sensor data can be analyzed correctly. For example, a numeric value from a flow sensor is of no use unless the location of that flow sensor is known as well as the units of the measurement.

With increasing efforts to electrify buildings, there is an opportunity to leverage the Internet of Things (IoT) in buildings, additional resources are being developed to facilitate the integration of devices, data, and systems. One example is the VOLTTRON platform developed by the US DoE (Katipamula et al., 2016) that can act as an independent data acquisition platform and enable the use of customized data tagging and storage.

6.1 Sensor Networks

Sensors described in Chapter 3 are typically connected to a network that serves to monitor and potentially control system operation. Some common sensor network protocols used in GSHP systems include Modbus, BACnet, LonWorks, and OneWire. For each network protocol, there are commercially available sensing devices and controllers. In some cases, the controllers are connected to a local computer that serves as a local data warehouse. In other cases, the controllers report data to a web-hosted server so that the data can be more readily accessible for analysis and reporting.

Building energy equipment is increasingly equipped with embedded sensors. In most cases, these are compatible with the common network protocols so that the equipment can be connected to a BMS without additional sensors.

The design, installation, and operation of a sensor network is complex and well beyond the scope of this document. However, some fundamental characteristics of each type of network are discussed in the context of measuring GSHP system performance.

The Modbus protocol was developed in 1979 and is a widely accepted, open-source protocol. While it does require a license, the license is royalty free. The Modbus protocol defines a message structure that controllers use to request access to a device, specify how it will respond to requests from other devices, and how errors will be detected and reported[5]. Modbus can be communicated through serial networks (RS485) or through Ethernet. Ethernet has the advantage of enabling multiple controllers and being much faster. Serial communication is done through daisy-chaining devices together and, for measurements that are needed on 1-minute intervals, network latency may be an issue to consider.

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[5] Modicon Modbus Protocol Reference Guide, PI-MBUS-200 Rev J, 1996

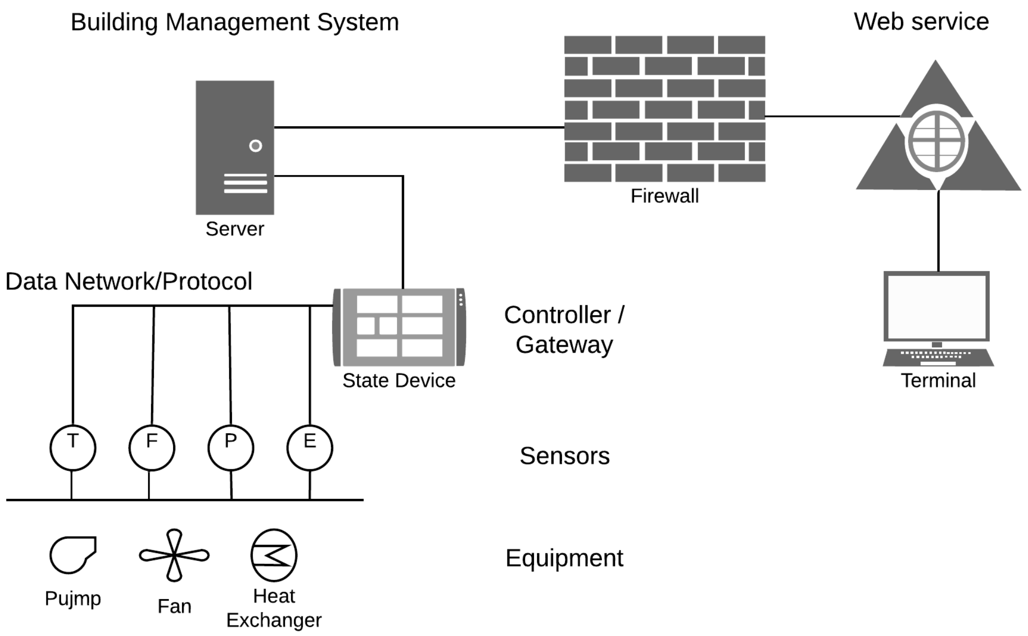

Figure 6-1. Schematic illustration of data measurements in relation to sensor network and data sharing.

The Building Automation and Control Network (BACnet) standard was developed by ASHRAE in the 1990s with the specific objective for building automation and control. In 2003, BACnet became an international standard (ISO-16484-5). Like Modbus, BACnet is an open protocol and can be applied to a wide range of systems including lighting, access control, HVAC, and maintenance. Like Modbus, BACnet can be communicated over the internet (BACnet IP) or through a token-passing protocol (BACnet MS/TP) through serial ports.

Unlike devices that operate on a Modbus or BACnet network in which users define addresses for different devices, the One-Wire® protocol uses a specific set of solid-state devices that have internal, fixed, and unique 16-bit identification addresses. One-wire devices can serve a variety of needs including measuring temperature, providing analog-to-digital conversions (e.g., 4-20mA and 0-10VDC) and counting of open-closed contacts common in electric, flow, and heat meters. Like the other serial networks, signals from One-Wire devices are transmitted on a single two-wire bus (one data wire, one ground wire) but communications are digital rather than analog. Like the other networks, the devices communicate with a controller that polls the sensors and translates the digital signal, often into an XML text object, for communication with other devices and other the internet. One advantage of the One-Wire network and One-Wire devices is that, in many cases, the devices can be powered by parasite power from the One-Wire controller, and do not require a separate power supply. While some of the sensors provide a specific measurement need (e.g., the DS18B20 is a digital temperature sensor), others can be used to convert an analog device into a digital signal as part of the network (e.g., using the DS2438 to digitize a voltage signal from an analog thermistor circuit). The main disadvantage of One-Wire networks is network stability which requires careful design of the network and a robust One-Wire controller and gateway.

6.2 Data Models

One of the main challenges in quantifying performance of GSHP systems is the ability to effectively use the data collected by the sensors and sensor networks. When specifying data points, measurement sensors, and communication protocols to collect data, it is important to also develop a process for managing the metadata – the data about the data. A data model for a GSHP system should include both static information about the system, such as equipment, design specifications, sensor characteristics, as well as the time series data of observations, such as flow, temperature, and power.

In a GSHP system, it is common to have multiple components (e.g., heat pumps, a ground loop, circulating pumps, and thermal storage tanks) and each of these requires a different suite of measurements, each with potentially different technologies, accuracies, and locations. In addition, the entities will have specific relations to one another, such as a circulating pump that may be serving a specific heat pump.

The most common approach is to simply tag each sensor with an ad hoc character string. When data is needed for analysis, the BMS is queried for the history values of specific sensors according to their ad hoc tag. The values are then returned as comma separated variables. However, this approach lacks the necessary metadata, such as units, sensor type, and sensor location, that are essential for interpretation. The ad hoc tagging of sensors will most often lead to confusion when analyzing the data and, in some cases, prevent any meaningful analysis.

It is strongly recommended that when setting up a BMS system, sensors are tagged according to an industry standard that includes metadata and relations to other entities. One increasingly popular approach for tagging assets in buildings the Project Haystack (commonly referred to simply as Haystack). Haystack is an open-source suite of technologies that provide a standardized approach for modeling building data. In addition to a standardized set of tags, Haystack also provides a means to exchange data using a set of different formats (e.g., JSON, CSV, and RDF). Haystack also defines relationships between building entities (e.g., site, equipment, sensor, etc.) by using dictionaries of tag value pairs. In the most recent release, Haystack has added tags for ground source systems[6].

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[6] https://project-haystack.org/doc/docHaystack/ATES

Another open-source effort, called Brick[7], formalizes the relationships presented in Haystack dictionaries using the Resource Description Framework (RDF). The RDF representation can encompass more complex relations between entities within a building (Fierro et al., 2020) and by using the RDF representations, the interoperability of the data is improved and provides an opportunity to improve fidelity and streamline data access and analysis. Projects that use the Haystack tagging can be converted to a Brick data model. We recommend that when using a BMS for data collection, the relations between measurement points, locations, and equipment are captured with a data ontology such as Haystack that can then be upgraded to an RDF representation using Brick.

For systems that rely on large number of individual monitoring systems and do not use a single BMS system, such as when heat pumps are distributed throughout a building and each have their own internet enabled monitoring system, a more traditional relational databases (e.g., PostgreSQL) combined with a time series database (e.g., InfuxDB) provide a powerful tool for managing the data. The metadata can be stored in a set of tables connected by primary and foreign keys and a unique identifier for each piece of equipment (e.g., heat pump, borehole heat exchanger, storage tank, etc.). The operating data for each piece of equipment can be efficiently stored in and retrieved from a time series database.

6.3 Quality Assurance

The quality and completeness of the operating data is critical to the successful use of measurements for fault detection, diagnostics, and calculation of key performance indices.

6.3.1 Calibration, Commissioning, and Verification

A monitoring program plan should always include explicit specifications for the methods to document sensor calibration as well as those used for commissioning and verification of all sensors. Sensor calibration refers to the specification from the manufacture, including any calibration certificates, of the rated accuracy of the sensors and whether the accuracies are absolute, a percentage of the measured value, or percentage of the full-scale value. Commissioning of sensors is accomplished by on-site inspection to ensure that sensors are installed in accordance with manufacturer and project specifications and are installed in the correct locations. For example, for temperature sensors, ensure that supply and return temperature sensors are on the correct pipes, for flow sensors, ensure that meter placement meets the minimum upstream and downstream distances to fittings. Verification refers the systematic process of verifying (a) that each sensor is connected and reporting through the sensor network, (b) that each observation is consistent with the known operation of the equipment, and (c) that sensor

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[7] https://docs.brickschema.org/intro.html

measurements are consistent with handheld measures. The latter is particularly important for sensor readings that may be affected by the length of connecting wire, such as resistance-dependent temperature measurements. This is best accomplished by cycling the equipment through a sequence of operations and recording parameters with handheld meters then comparing handheld readings with recorded data.

Methods for continuous commissioning should also be explored. For example, to ensure the accuracy of measured temperature difference across a heat pump, the value can be evaluated when flow is circulating but the heat pump is off. Under these conditions, the inlet and outlet water temperatures should be within the measurement error of the temperature difference. Calibration of sensors should be conducted on a regular basis and in accordance with manufacturers recommendations.

6.3.2 Filtering for spurious data

Spurious data refers to data points that do not represent the measured quantity and can arise through errors in the sensor and/or communications network. If undetected, they can cause adverse effects in the data analysis. Perhaps more importantly, if the measurements are part of a control logic, spurious readings can cause the system controls to send spurious signals to equipment.

Thresholding can be effective and predicable but should be used with caution. If the thresholds are set to the calibrated range of the sensor, useful measurements may be lost. Without a priori values of the thresholds, these can be difficult to set. It also requires setting thresholds for all sensors. Because thresholding does not require a sample of measurements to evaluate a point in question, it is most appropriate for controls.

When integrating energy fluxes over time or conducting other types of analysis, a population of measurements is available to characterize the distribution of values which can then be used to detect spurious measurements during data analysis. One common approach is to consider the entire distribution of measurements and then flag and/or exclude measurements that fall some distance from the median value. For example, one may decide that samples that exceed three times the standard deviation are to be flagged and excluded from the analysis. This works well for measurements that have a symmetric distribution. However, consider a sampling of flow rates in a variable flow system. If much of the system operating time is at a relatively low level, meeting only a small part of the total system capacity, the population of measured flows may follow a normal distribution with a small coefficient of variation. Under peak demand conditions, which occur over a relatively short period of time, the flow rates may be several standard deviations higher than the previously recorded mean, and mistakenly treated as spurious. A non-parametric alternative is to use a multiple of a percentile of the distribution. For example, measurements that are greater than three times the upper 5th percentile would be considered spurious. Similarly, measurements that are less than 1/3rd the lower 5th percentile, would be considered spurious. Other more sophisticated methods utilize artificial intelligence and machine learning algorithms, such as cluster analysis and maximum likelihood estimators (Zucker et al., 2015). When removing outliers, it is prudent to preserve the original data for further analysis.

Another approach is to look for anomalous correlations between measurements. For example, if high electrical consumption of the heat pumps is correlated with high flow rates in the GHE, this indicates variable speed pump is properly serving a variable stage (or multi-compressor) heat pump system. On the other hand, if measured flow rates are consistently high, regardless of heat pump operation, this may suggest a problem with the variable speed pump or the controls.

6.3.3 Synchronization

Two separate issues arise when analyzing time series data for GSHP systems. The first is the synchronization of the individual measurements and the second is the whether the measurements are representative of the true value at the time of recording.

When measurements are used from different sensor networks, the timestamps for each sensor network may not be synchronized. This is particularly true when controllers recording the timestamp are not connected to the internet and are unable to use internet clock time. Clocks in controllers that are not connected to the internet may differ and drift over time, particularly in how they adjust for time changes. For example, if a controller uses the coordinated universal time (UTC) it will not adjust for daylight savings while controllers that use local time may or may not automatically adjust timestamps. When possible, UTC is highly recommended.

Another issue with synchronization is, even when the timestamps in the controller are correct, measurements stamped with the same time may not be made at the same time. This may be due to different sensors being polled at different intervals (e.g., 1-minute, 5-minute, 15-minute, etc.) or, if the network uses serial communications, network latency may result in an incorrect timestamp being assigned measured values. Timestamp errors from network latency is typically limited to seconds to one or two minutes. A further complication may result if some sensors report at uneven intervals, reporting on a change-of-value, or from a pulse counter.

Many synchronization errors can often be detected through careful analysis of the data. Several scripting languages used for data analysis, such as Python and R, have methods to correct for clock and synchronization errors. For example, if two time series are out of phase, one of the time-series can be shifted to adjust for the time offset. Similarly, for time series at different intervals, each time series can be resampled onto a common time frame with different options for assigning interpolated values.

The other main issue that arises when analyzing time series data for GSHP systems is that instantaneous measurements may not be representative of the process of interest at the recorded time. This can result from the response time of individual sensors and the dynamic nature of a GSHP system. Temperature sensors used in a heat transfer calculation take time to respond to changes in the fluid temperature, and this lag depends on the placement of sensors and the thermal mass of a thermal well, if used. In addition, because GSHP are dynamic and the heat transfer process is transient, the residence time of the heat conveying fluids in the pipes may impact the analysis and interpretation of the measurements.   For example, when calculating heat exchange from measurements of temperature and flow rate, the measurement is relative to the location of the temperature measurement pair and will be influenced by the initial temperatures of the fluid in the pipes. By using measurements at a fixed locations some distance from the heat pump, the calculation may result in apparent heating or cooling that differs from the heat pump operation and can be misleading. When measurements near the heat pump equipment, the lag effect should be small (1 minute or less) while the lag effect will be larger for the entire GHE. An alternative method of analysis would be to consider the change in temperature of a given parcel of fluid moving through system. Further research is needed to assess the errors when calculating heat exchange for a fixed (Eulerian) reference frame rather than a moving (Lagrangian) reference frame.

7 Summary

The electrification of building thermal systems is essential in current strategies to reduce greenhouse gas emissions. As buildings and transportation are electrified, it is critically important that the most efficient methods – those that use the least electricity – are deployed at scale.

Heat pumps are a proven technology that can meet this need with great efficiency as the electricity is used to capture thermal energy from the environment (ground, water, air). While heat pump technology has been rapidly improving, with rated heat pump coefficient of performances of up to 5, the actual efficiency of a heat pump system deployed in a building can vary significantly. In some cases, this variation is due to system design such as when excessive pumping power is deployed, reducing the overall system efficiency. In other cases, the performance may be higher if the thermal energy in the environment is more plentiful (at higher temperatures) than expected or when the desired heating and cooling can be achieved through simple circulation of fluids without the need for a heat pump compressor. Efficiencies are also affected by a suite of field condition, such as installation errors, inadequate refrigerant charge, improperly set or faulty controls, poor equipment performance, to name a few.

Ground source heat pump 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.

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

This 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. This guideline aims to inform 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. In the collection of data, working with and managing a network of sensors, or interfacing with a building management system, is essential and presents its own set of challenges.

When fault detection and diagnosis is one 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.

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.

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 distributed temperature sensing (DTS) using fiber optic cables may provide important insights into the performance of the GHE and inform strategies to improve system efficiency. As with the point 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 is 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 is meeting the stated goals, that will often include the reduction of operating costs and greenhouse gas emissions.

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