oTherm: Best Practices for Data Users

GSHP Technology

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oTherm Project Tasks:

- MS 2.4: Best Practices for GSHP technology for oTherm
- MS 2.4a: Documentation of Case Study Examples for GSHP systems
- MS 3.3: oTherm Performance Data Specification for GSHP

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Introduction

The collection and analysis of data from building systems using renewable heating and cooling (RH&C) systems has been recognized as high priority in addressing a number of market barriers (e.g., NYSERDA, 2017). As society strives to transition off of fossil fuels towards more sustainable heating and cooling technologies, there is a growing need to document the performance of these technologies.

The oTherm framework envisions meeting that need by leveraging readily available operating data from individual pieces of RH&C equipment to address a variety of needs related to the monitoring and verification (M&V) of RH&C technologies (Figure 1). Some of the potential use cases for oTherm data include:

- Lowering barriers to market penetration, such as
    - consumer confidence,
    - access to financing,
    - Insurability of assets
- Documenting environmental benefits of RH&C technologies
- Evaluating efficacy of policies

The oTherm project documentation consists of a set of three Best Practices documents and documentation of the data dictionaries (see inset box). The Best Practices documents provide guidance for both data providers and end users. Best Practices typically have two characteristics – first they are based on evidence that they lead to an optimal outcome and second, they are amenable to widespread adoption. Here the focus is specifically on developing best practices for analyzing data that can be used to efficiently assess performance of ground source heat pump (GSHP) installations. The optimal outcome is to provide data for streamlined and efficient M&V of

oTherm Documents

- Best Practices for Data Providers, Part 1 – Monitoring System Providers
- Best Practices for Data Providers, Part 2 – M&V Program Managers
- **Best Practices for Data Users – GSHP Technology**
- Device-level Data Dictionary
- Facility-level Data Dictionary

many GSHP installations. To attain widespread adoption of best practices, affordability and flexibility are favored over accuracy and rigid standardization.

The Best Practices for data providers are split into two parts. The first part focuses on the compatibility of a monitoring system with the oTherm framework while the second part aims to inform both M&V Program Managers and oTherm data analysts about the potential application of oTherm data to address a wide range of performance assessment objectives (Figure 1). The third Best Practices document (this document) is a guide to the implementation of the oTherm framework as part of a M&V program for GSHP systems.

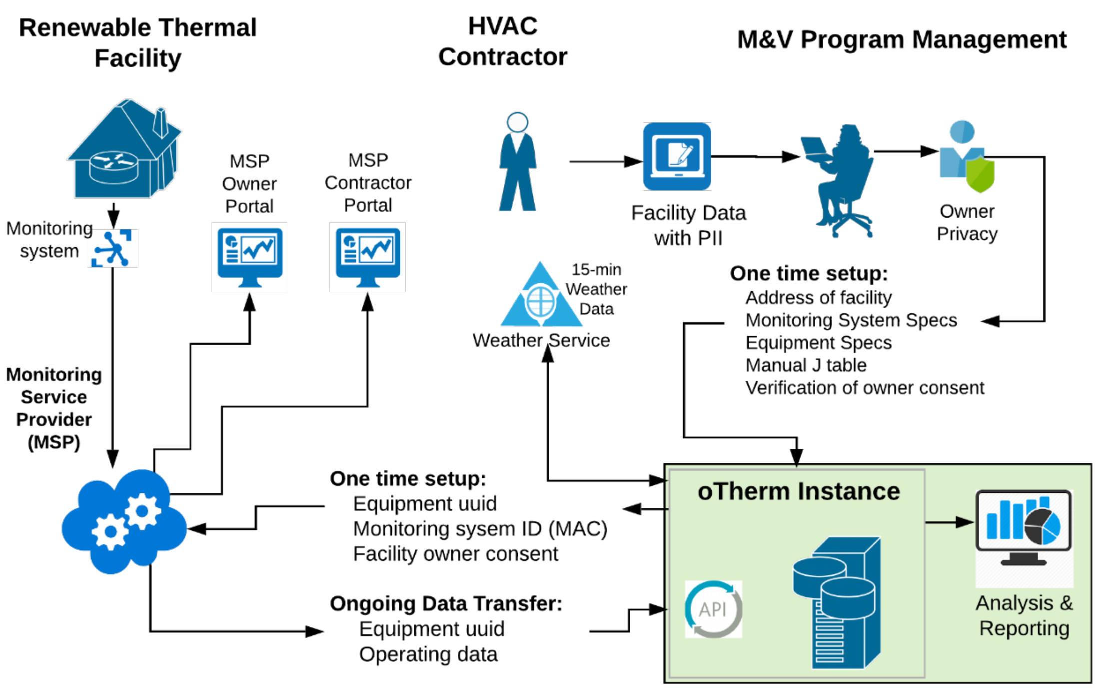

Figure 1. Illustration of oTherm data flow. This Best Practices document focuses on the use of oTherm data for GSHP systems.

Several GSHP performance studies help to inform the best practices for oTherm. This is not an exhaustive list of performance studies conducted nor is it a critique of individual studies. Rather we look to draw key lessons that will inform future studies. The main guiding documents used to develop these Best Practices include:

(1) The SEPEMO project (Nordman and others, 2012) measured heat pump performance in 52 sites in several European countries over a one-year period. While they note the importance of detailed site specifications and they typically report the type of heat pump, conditioned floor area, and climate, they did not use a standardized approach to the data elements or the data organization, making it more difficult to assess performance of the portfolio of sites in the context of site characteristics.

(2) In 2016, the Minnesota Department of Commerce published the results of a detailed study of ground source heat pumps in 37 residential buildings (Huelman et al, 2016). In their study, they collected information about the heat pump (capacity), ground loop orientation (horizonal vs. vertical), and ground loop size (number of circuits and length of each circuit).
(3) The NYSERDA study of over 50 systems in upstate New York (CDH, 2018) provided one of the more systematic cataloging of site data and has proven to be very useful in interpreting performance data. In addition to conditioned area, heat pump capacity, and type of ground loop, CDH (2018) also included details on pipe sizes, number of pipes in circuit, antifreeze types, freeze protection levels, and design heating and cooling loads. This level of detail provides much greater fidelity in the analysis of operating data.

Many other relevant studies have been done and are cited herein.

oTherm Data

The oTherm data schema is designed to accommodate a wide range of programmatic needs and data collection methods. The general design of the schema is illustrated in Figure 2 and Appendix A provides a detailed description of the tables for GSHP systems. A 'Site' is associated with three main elements: one or more thermal sources, a thermal load, and one or more pieces of thermal equipment. The thermal equipment is then associated with a monitoring system and corresponding the time-series operating data. Weather data is polled on a 30-minute interval from a nearby National Weather Service station and stored in a separate time-series database.

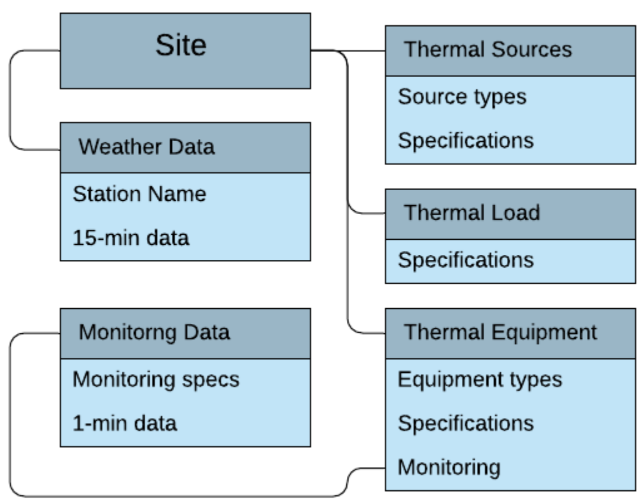

Figure 2. Schematic of main oTherm data elements

Data Models

For GSHP systems, the minimum data requirements include a measure of heat pump compressor operation, such as a current switch to denote on/off, or a current transducer to measure power. While thermostat data can also be helpful, direct measures of the heat pump are recommended. In addition to heat pump operation, it is important to be able to differentiate between heating and cooling. As such, measures of the heat pump entering and leaving water temperatures can be used to infer whether the heat pump is extracting heat from the ground loop (heating) or rejecting heat to the ground loop (cooling). For heat pumps in general, the operating status (on/off, heating/cooling) are the recommended minimum data requirements.

In addition to time series heat pump operating data, performance analysis of GSHP systems should also include enough metadata regarding thermal sources, loads, and equipment so that interpretation of the operating data can meet the stated M&V objectives.

It is assumed here that the data being analyzed is compatible with the oTherm Device- and Facility-level data models. While this document focuses on the GSHP technology, the same principles apply to other RH&C technologies, such as air source heat pumps, solar thermal, and biomass boilers and furnaces.

RECOMMENDED BEST PRACTICE (CONSISTENT DATA SCHEMA):

- An analysis of oTherm data should capitalize on the underlying data schema and specifications of the monitoring system as well as characteristics of the site, thermal equipment, and thermal sources.

Data Limitations

Measuring the energy production and energy usage of GSHP systems is difficult as it involves measuring flow rate and temperatures of heat conveying liquids in pipes and electricity measurements on components of a GSHP system (e.g., compressor, fan, circulating pump(s)). This document focuses on analysis of data rather than methods of data collection. While some discussion of measurement techniques provides context for analyses, the reader is referred to Annex 52 documents (Davis and others, in prep) for more detailed coverage. Detailed instructions on how to retrieve data from an oTherm instance is included in the oTherm Technical Documentation [under development]

Monitoring equipment

The analyst should be aware of the methods used by a monitoring system, the locations of the measurements, and their reported instrumental accuracies, that are stored as monitoring system specifications in the oTherm database. While each monitoring system represents an optimal combination of accuracy and cost, the optimum differs for each monitoring system. Monitoring system that are lower cost and easier to install provide more opportunities for data collection but may lack highly accurate sensors. On the other hand, research-grade instrumentation provides high quality data but is more costly and difficult to install, resulting in fewer opportunities. Monitoring data in an oTherm instance will usually be a collection of sites utilizing different monitoring systems, each with differing data points and accuracies.

Measurement Error and Bias

Measurement error generally consists of two components, (1) a sensor bias of a measurement made with an individual device relative a true value, and (2) random error due to fluctuations in electronics and sensor communications. The sensor bias is attributed to variations in the manufacturing process where each sensor deviates from the ideal by a small amount. Because the operating data for a GSHP system usually consists of thousands of individual measurements from the same sensor, the random error cancels out and is assumed negligible.

Here, measurement bias is different than sensor bias in that measurement bias refers to a systematic difference in the measured value to the true value due to installation or calibration of the measurement device. One example of measurement bias includes the measurement of the temperature of a heat conveying fluid with a sensor that is affixed to the exterior of the pipe. Even if the pipe is metal, the sensor has a good thermal connection to the pipe, and is well insulated from the environment, if the temperature of the fluid in the pipe is significantly different than the temperature of the environment, a measurement bias will result. Another example is an apparent bias in monitoring data when compared to manual measurements made in the field (e.g. CDH Energy, 2018). Some of these biases can be quantified and the magnitude reduced through data processing while others contribute to the overall measurement error. In many cases, GSHP measurements can be compared with manufacturer performance data to assess and correct for monitoring system bias.

RECOMMENDED BEST PRACTICE (DATA QUALITY):

- An analysis of oTherm data should be accompanied by an assessment of monitoring system methods including sensor accuracy and bias.

Monitoring Objectives

While M&V program development is addressed in more detail in Best Practices for Data Providers Part 2, it is helpful to consider some different potential M&V objectives when developing a plan for data analysis. For example, in some instances, a research-grade assessment of a few installations (e.g. less than 10) may be of interest with the intent of quantifying the seasonal performance factors (SPFs) to determine overall performance and observe any differences in design or installation. At the other end of the spectrum, a utility incentive program may wish to collect just a few data points with relatively low accuracy to ensure that ground loop temperatures remain within the operating window of the design. Other examples might be to satisfy a billing or contractual agreement regarding energy usage of heat pump system or to report the production of thermal energy production to the regional REC database (i.e., NEPOOL, GAT/PJM, etc.).

Data collected in programs with different objectives will have varying degrees of completeness and accuracy. The methods used to collect data and the respective sensor accuracies should be documented in the oTherm database. When interpreting oTherm data for a specific type of analysis, such as seasonal performance factor, it is important to consider the suitability of using data collected for other purposes and the impact that measurement error may have on the interpretation. Each objective will require different methods of analysis with differing uncertainty tolerances.

RECOMMENDED BEST PRACTICE (SUITABILITY OF DATA TO MEET OBJECTIVES):

- Each oTherm database instance will have a different set of data points recorded, both in terms of the time-series data of heat pump operation and the level of detail captured about the facility. In assessing the suitability of an oTherm instance for analysis, the analyst should review the availability of data for the specific database instance being use.
- Clearly define the objective of the analysis and the suitability of individual oTherm data streams with respect to data quality and frequency. Down-select data to include only the monitoring systems that meet the accuracy requirements of the analysis.
- Check monitoring system documentation for information on location of sensors as these may result in measurement bias and affect the interpretation of data.

Data Analysis

The main goal of the oTherm data framework is to increase the availability of data so that analyses can be conducted for a wide range of use cases. While developing comprehensive data analyses is beyond the scope of the project, it is important to illustrate how oTherm data can potentially meet different M&V objectives. This document summarizes some commonly used performance metrics for GSHP systems, along with some case study examples for illustration (Appendix C).

Thermal Energy Production

Thermal energy production is a key metric when assessing the performance of a GSHP system. Because measuring thermal energy exchange is comparatively easier for hydronic systems, the measurements are usually made on the source (ground loop) side of a water-to-air heat pump, rather than the load side (air ducts). The useful energy provided can then be calculated from the measured geoexchange rate and the electricity consumption of the heat pump that is converted to thermal energy.

The thermal energy production from the ground loop (geoexchange) is often considered the renewable energy portion of the system and can be obtained in a several ways.

Metered

A heat meter is a device consisting of two temperature sensors (supply and return), a flow meter, and a calculator. Most heat meters output the thermal energy that passes by the meter with a pulse output signal. Some meters with more sophisticated communications modules (e.g., Modbus) can be polled to also provide the values of fluid temperatures and the fluid flow rate. Heat meters, particularly those in the US market, will generally use the absolute value of the temperature difference to compute the heat flow rate (Btu/hr) and/or cumulative amount of thermal energy (Btu) passing the meter. As a result, heating and cooling are not differentiated into separate registers. To make use of heat meter data for GSHP performance analysis, it is often necessary to post process heat meter data into separate registers, depending on the sign of the difference between the supply and return fluid temperatures, though with pulse output meters, temperature data may not be available.

Calculated

The energy produced from the ground loop can also be computed by measuring the thermal exchange on the source side of the heat pump (s).

$$Q_{heat} = \int_0^t c_p \dot{m}\,(T_i - T_o)dt$$

$$Q_{heat} = \sum_{i=0}^{n} c_p \dot{m}_i\,(T_{in_i} - T_{out_i})\Delta t_i$$

Where c_p is the heat capacity, $\dot{m}$ is the mass flow rate, and T_{in} and T_{out} are the source and return temperatures of the heat conveying fluid, respectively. If Q_{heat} is negative, it is considered ‘cooling’ as heat is being rejected to the source side.

When the monitoring system uses on-pipe temperature sensors, there is a lag in the temperature reading that can result in erroneous calculations of Q_{heat}. It is recommended to lag on-pipe temperature measurements by 1 minute to correct for this measurement bias. As noted above, on-pipe temperature sensors can also result in a bias of the measured temperature towards the room temperature. However, because both fluid temperature measurements are biased in the same way, the effect on measures of the temperature difference is minimal.

Note that with on-pipe temperature sensors it may be necessary to offset or lag temperature measurements relative to other recorded values. This is because there is a time delay between a temperature change in the heat transfer fluid and a temperature change on the surface of the pipe. Failure to do this may result in the appearance of false heating or cooling cycles that occur immediately before and have the opposite sign of the actual heating or cooling cycle. An example of this is a short (1-min) cooling cycle that occurs immediately before a longer heating cycle on a cold day. Lagging temperature measurements when using on-pipe temperature sensors should remove these erroneous cycles.

RECOMMENDED BEST PRACTICE (PARTITION HEAT FLOW FOR HEATING FROM COOLING):

- Whether using heat meter data or computing the heat flow rates from individual sensors, GSHP performance analysis requires that the geoexchange for heating be separated from the geoexchange rejected for cooling.
- Consider methods to reduce the impact of measurement biases on calculated heat flow rate. Some monitoring systems may account for these in the reported data, consult the monitoring system documentation.

Proxy methods

Two states in the Northeast US, New Hampshire and Massachusetts, have developed rules for reporting the thermal energy production for ground source heat pumps.   Both methods use a combination of the heat pump performance data and operating data to measure the thermal energy production. These methods are provided here as examples, and other similar methods can be developed, depending on the objective of analysis.

The New Hampshire method uses the AHRI rated heat pump heating capacity and coefficient of performance to compute the thermal energy production from a measured runtime in heating mode.

$$Q_{heat}[BTU] = HC \cdot \left(\frac{COP - 1}{COP}\right) t_{heat}$$

Where HC and COP are the AHRI heating capacity for the heat pump, respectively, and t_{heat} is the time spent in heating mode in hours, regardless of the stage or actual power consumption.

The Massachusetts method also uses the manufacturer heat pump performance data. Both the measured fluid temperature and power consumption of the GSHP equipment are used to compute the renewable heat production.   Neglecting the emissions factor and multiplier used in the actual AEC calculation, the Massachusetts method for calculated renewable thermal energy can be expressed as:

$$Q_{heat}[W \cdot hr] = \sum_{i=0}^{n} (COP_{EWT} - 1) \cdot Watts_i \cdot \Delta t_{heat_i}$$

Where COP_{EWT} is the temperature-dependent coefficient of performance as determined from manufacturer heat pump performance data. *Watts* is the measured power consumption of the heat pump and Δt_{heat} is the i^{th} increment of time over which successive measurements are made, typically one minute.

Both the proxy methods require continuous monitoring to track the heat pump operating runtimes in heating mode as determined by (1) the conditions that the heat pump is running and (2) the fluid temperature entering the heat pump is greater than the fluid temperature leaving the heat pump.

The proxy methods for energy production here focus on thermal energy produced from the ground loop and not the total heat delivered to the load side. Furthermore, some parameters are not unique. For example, for water-to-air heat pumps, COP_{EWT} depends on flow rates on both the source and load sides.

It is also important to note that methods based on the manufacturer heat pump performance data assume that the actual heat pump operation is close to the laboratory operation. These proxy methods can be useful as a baseline to compare measured production and potentially identify biases in monitoring data or problems with heat pump operation.

Energy Consumption

In addition to quantifying the energy production of a ground source heat pump system, the electrical energy consumed is also important to quantify overall system performance. The oTherm data model includes fields for documenting the method of electrical consumption of different components of the GSHP system. These can include measuring power with a revenue-grade energy meter or calculating power with measured amperage and either measured or assumed voltage.

In some monitoring system configurations, the power measurement is made in the electric service panel and will often include power to operate the ground loop circulating pump and possibly the load-side circulators -- blowers or hydronic pumps, depending on type of heat pump. Check the monitoring system specification description for details.

Metered

Watt meters that measure current, voltage, and power factor provide the most accurate measures of power usage. One potential drawback is that while power meters accurately measure watts, they often use pulse output to report energy (watt·hours). If the meter is not configured to accumulate pulses between measurement times, the readings will be irregular. For example, for a watt meter configured to output one pulse per kilowatt·hour, a heat pump operating at 4 kilowatts, will only output one pulse over a 15 minute interval, making it difficult to interpret data. Because of the need to measure line voltage, watt meters are most often installed in the electric service panel. As with heat meters, some electricity meters have the ability to report more granular data (amperage, voltage, and power factor) at regular intervals.

Calculated

Another method for measuring power is to measure electric current with a transducer and multiply the current by an assumed or measured line voltage. While this method lacks the accuracy of a watt meter, it may provide more granularity in that individual components (heat pump compressor, circulating pumps, fans, etc.) can be measured separately. The monitoring system specifications should include details of these measures.

Proxy methods

The manufacturer performance data tables provide a resource for estimating power consumption if other measures of heat pump activity are recorded to indicate both operating status and the stage of operation. For example, a simple current switch device that detects on-off status of the heat pump can be combined with data from a thermostat to determine heat pump operating conditions that can then be applied to the performance data tables to estimate electricity consumption. This method assumes that the heat pump is operating according to the thermostat.

RECOMMENDED BEST PRACTICE (CHECK DATA FOR MEASUREMENT BIAS):

- Both the measured heat of extraction/rejection and electric power can be compared with expected values for the heat pump equipment, as determined from the manufacturer performance data tables. When measurement bias (different than sensor bias) is identified, the monitoring system specifications should be updated accordingly.

Seasonal Performance Factors (SPFs)

The seasonal performance factor (SPF) is a metric used to evaluate the performance of installed heat pumps. SPF values are sometimes separated into monthly values or values binned on ranges of entering water temperatures.

In heating mode, the SPF is calculated similarly to the COP. The difference is that COP values are determined under laboratory conditions while the SPF values are calculated using real-world operational data. Further, while COPs are measured with laboratory-grade equipment, calculation of SPFs may use estimated or proxy values in lieu of measured values, depending on the availability and quality of data. The heating SPF is calculated as the ratio of the heating or cooling provided and the electricity used to generate the heating or cooling:

$$SPF = \frac{Heating\ or\ Cooling\ Provided\ [kWh]}{Electricity\ Used\ [kWh]}$$

When calculating SPF values, it is important to note the boundaries of the analysis. Spitler and Gehlin (2020) build upon the SEPEMO boundaries defined by Nordman and others (2012) to delineate a set of nested boundaries the include successively more components of the system.

Uncertainty Analysis

One of the primary challenges in analyzing SPF values and comparing them between systems or with laboratory-rate COP values is the uncertainty associated with measurements used to calculate the SPF values. All measurements have some degree of associated uncertainty, but field measurements used to calculate SPF values generally are obtained with lower quality sensors than those used the laboratory to calculate COP values. As a result, they have a larger uncertainty due to sensor bias. Most studies that report measured performance (COP or SPF) do not quantify uncertainty (e.g., Puttagunta et al., 2010; Huelman et al., 2016) even though it can be significant.

Uncertainty due to sensor bias can be absolute or fractional. Absolute uncertainty has the same units as the value being measured. Fractional uncertainty is a fraction of the measured value. While the sensor bias for a given sensor will be constant, the impact on the uncertainty of the calculated SPF depends on the measured value, which changes in time. This is of particular concern with the uncertainty of a measure of temperature difference.

Calculating the SPF of GSHP systems relies on quantifying the geoexchange (thermal energy exchanged with the subsurface) and the electricity used by the GSHP system. Quantifying the geoexchange requires taking the product of density and specific heat capacity of the heat transfer fluid, the mass flow rate of the heat transfer fluid, and the temperature change of the heat transfer fluid across the heat pump. The uncertainties in the density and specific heat capacity values are very small relative to the other uncertainties and are typically ignored (Spitler et al., in prep). The temperature change of the heat transfer fluid has a constant absolute uncertainty, meaning that the true temperature change is within a fixed number of degrees from the measured value. Electricity usage measurements can have a fractional or absolute uncertainty, depending on the measurement method.

Because the uncertainty of geoexchange and the electrical consumption of the GSHP system (E_Q and E_w, respectively) can change depending on the actual conditions, the uncertainty must be calculated separately for each timestep in the period of interest. Following Taylor (1997), the fractional uncertainty for thermal energy exchanged with the subsurface and the electrical consumption (e_Q and e_W, respectively) can then be calculated as:

$$e_{Q,n} = \frac{\sum_{i=1}^{n} E_{Q,n}}{\sum_{i=1}^{n} Q_i}$$

$$e_{W,n} = \frac{\sum_{i=1}^{n} E_{W,n}}{\sum_{i=1}^{n} W_i}$$

Where Q_i and W_i are the measured values of the geoexchange and electrical consumption, respectively. The quantities are summed over n time intervals, typically each 1-minute in duration.

The fractional uncertainty of the SPF value can then be obtained by adding the fractional uncertainties of the thermal energy exchanged with the subsurface and the electrical consumption of the GSHP system in quadrature:

$$e_{SPF,n} = \sqrt{(e_{Q,n}^2 + e_{W,n}^2\,)}$$

While this description of uncertainty analysis focuses on SPF calculations, as they involve multiple types of measurements, uncertainty analysis should also be performed when calculating and reporting other key performance indicators.

RECOMMENDED BEST PRACTICE (UNCERTAINTY ANALYSIS):

- When reporting integrated performance metrics, the uncertainty analysis should be conducted to determine the impact of measurement errors.

- Because measurement errors can depend on the conditions at a given moment in time (such as ΔT), uncertainty analysis for integrated metrics should be calculated from integrated values of the incremental uncertainty.

Energy Usage Patterns

There are several use cases that involve an analysis of energy usage patterns. These can often be done with only heat pump power measurements though some type of ancillary data, such as outdoor air temperature and information about the equipment and building, is often useful for context.

Energy Use Intensity

One particularly helpful analysis that can be accomplished with very simple monitoring equipment is the energy usage as a function of conditioned area and outdoor air temperature. One application of this analysis offers an opportunity to compare the efficiency of different technologies, such as air-source and ground-source heat pumps over a wide range of outdoor weather conditions (e.g., Ueno and Loomis, 2015).

Time-of-Day Usage

There is a growing interest in quantifying hourly demand profiles for building heat and cooling to manage generation assets and explore models for demand-response programs (e.g., National Academies, 2021). While heat pump usage patterns tend to vary with season – with winters having higher demand in morning and summer a higher demand in the afternoon – specific usage patterns depend on preferences of building occupants and individual usage patterns. Quantifying patterns of usage across a large number of heat pumps in a given regions will help to inform utilities in forecasting weather-dependent generation patterns and identify opportunities for demand response measures.

Load Factor

Because adoption of GSHP systems will often replace fossil-fuel fired systems and represent more energy intensive appliances in a home, electric utilities are also interested in the load factors for typical residential GSHP systems and the month-to-month variation in load factors over the course of a year. For the purposes here, the load factor is defined as the ratio of the electricity consumed over a period of time, such as one month, to the consumption that would have occurred if the peak demand operated over the entire month. The load factor ranges from 0 to 1, with higher values representing more uniform and predictable demand.

$$\text{Load Factor} = \frac{\text{kWh used in period}}{\text{kW}_{\text{peak}} \cdot \text{hours in period}}$$

Use of Auxiliary Heat

Energy use intensity and load factor calculations can be significantly impacted by the use of auxiliary heat. Here auxiliary heat refers to the electric resistance heat that can either supplement the heat capacity of a heat pump or serve as a substitute if the heat pump is not operational. Because this is usually installed on a separate electrical circuit, it can be easily isolated during monitoring. When analyzing auxiliary heat usage, it is recommended to consider the condition under which it is operating, which will generally fall into two general categories: (1) supplemental heat necessary to meet demand or (2) emergency backup heat due to heat pump fault. For the former, the demand may be due to outdoor temperatures near or below the design temperature, which will typically be extended periods of usage, or the demand may be due to a thermostat set point not being met, requiring additional heat.

RECOMMENDED BEST PRACTICE (ENERGY USE PATTERNS):

- Some M&V objectives may benefit from analyses of patterns in energy usage to compare systems with the same technology or across technologies.
- When analyzing use of auxiliary heat, it is recommended that the usage is associated with the prevailing conditions.

GSHP System Diagnostics

In addition to a variety of performance and energy use pattern analyses, data in an oTherm instance may also be useful to identify and diagnose variations between the actual system operation and the expected operation.

Ground Loop Temperature

One important parameter in the design of GSHP systems is the minimum entering water temperature (EWT). Lower than expected EWTs might have an adverse impact on system performance, particularly if the temperature approaches the freeze protection limit. Long-term degradation of system performance may result from a large difference in the annual energy budget – the so-called net annual ground load. When observed minimum EWTs remain well within the design values, it may indicate that the loop was oversized, which could be helpful to system designers.

One way to analyze ground loop temperatures is to construct histograms of the observed EWT. As with many other analyses, it is important to work with a subset of observations so that only values when the heat pump is in operation are considered. It is helpful to partition the observations into two registers, one for heating and one for cooling. In addition to the visual representation with histograms, quantitative metrics can be produced, such as minimum and maximum EWTs over a period time.

While analysis of ground loop performance often focuses on EWT, the leaving water temperature (LWT) is also important to monitor system operation relative to freeze protection levels. When using the measured temperatures to assess thermal exchange processes in the ground loop, the average of measure EWT and LWT is a reasonable representation. For more detailed discussion and alternative weightings, see Marcotte and Pasquier (2008).

Ground Load

Another analysis that can provide insights into the system performance is a comparison of the of measured geoexchange with the design values. The expected design value can be represented as straight lines connecting the maximum heat of extraction/rejection for the heat pump (at the design EWTs) and the design outdoor air temperatures with the outdoor air temperature for heating and cooling with the balance point temperature that requires no geoexchange. Because of thermal energy storage and latency in monitoring and weather data, it is recommended to use daily average values.

It is expected that the average daily geoexchange will be at or slightly below the design value. When significant departures are present, it may suggest that the system is either not operating as designed or the estimate of the load used in the design was incorrect.

Duty Cycle Patterns

Duty cycles represent the portion of a period that a system is active. Puttagunta and Shapiro (2012) suggest that rapid cycling can be detrimental to system performance, particularly in cooling mode and diminished latent heat capacity. Because of the modes of operation (heating and cooling) have different energy flows, analysis of duty cycles should be split into separate registers for heating mode and cooling mode. GSHP duty cycles can be used as a check to ensure that the system heating and cooling operation are consistent with the outdoor air temperature. For example, problems with reversing valves can be detected by observing significant heat pump duty cycles that are opposite of the expected condition.

GSHP duty cycles can be further analyzed to consider the length of individual heating or cooling cycles. In general, as the outdoor air temperature decreases the length on individual heating cycles should increase and vice-versa for cooling. Analysis of the length and distribution of individual heating or cooling cycles may provide insight into poorly preforming systems. An example of this, a system where individual heating cycles are much shorter and more frequent than expected may be due to issues with a control board to the placement of thermostat relative to supply ducts.

Summary

Ground source heat pump operating data can be used to assess system operation relative to design and assist in identifying underlying causes for under-performing systems. These analyses can also inform GSHP system designers about installed patterns that may indicate opportunities for modification of design practices, and potentially lowering the cost of installations.

RECOMMENDED BEST PRACTICE (DIVERSE MEASURES OF SYSTEM PERFORMANCE):

- Use operating data to compare installed system operation relative to design. In many cases, these measures are impacted less by measurement errors than traditional SPF measures.

Economic and Environmental Benefits

In cases where the economic and environmental benefits are of interest, the cost of electricity to provide the measured heating/cooling benefit can be readily obtained from the measured electric energy consumption and the cost per unit (kWh). Given the measured heating/cooling benefit, the cost of alternative fuel sources can be calculated as well. The difference between the actual cost and alternative fuel cost represents the cost savings (Nakagawa et al., 2011). The system payback can then be determined by subtracting the operating cost savings from the project capital cost.

The economic analysis can be extended to also calculate carbon offsets. The carbon intensity of the delivered electricity (kg CO_2/kWh) is available through the US EPA eGRID project (US EPA, 2021) and can be used to calculate the carbon emissions from a GSHP system. These emissions can then be compared to the emissions that would have resulted from delivering the same heating/cooling benefit from an alternative fuel (or traditional air conditioner).

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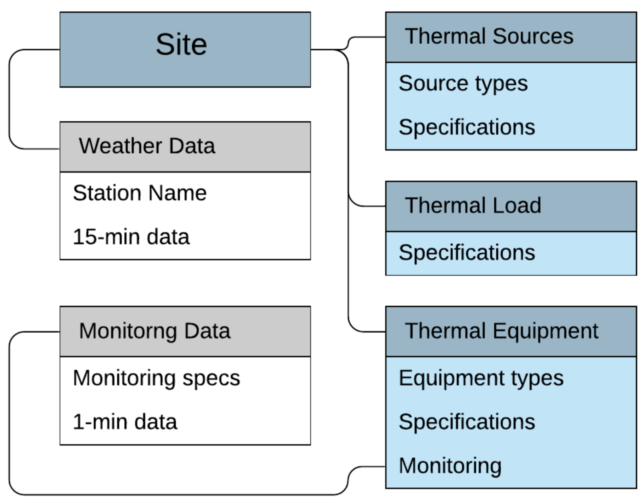
Appendix A: GSHP Performance Data Specification

The oTherm framework consists of a backend web application written in Python (Django platform) with two databases (SQL and Time Series) that is 'containerized' using Docker for efficient deployment. The front end and APIs supports efficient data entry and retrieval.

The oTherm data models are generally divided into the Device-Level Data Model and the Facility-Level Data Model. The rationale for the tables and relationship are covered in some detail in other project documents. Generally, the Device-Level Data Model focuses on monitoring systems and monitoring data while the Facility-Level Data Model focuses on information about the site, the thermal sources, and the thermal load. This Data Specification provides a comprehensive description of each of the tables and their relationships.

Static Data (SQL)

The static data is stored in a PostgreSQL database and the tables can be split into two general groups. The first group of tables are those that likely contain new and site-specific information. The second group of tables contain information that can likely be utilized by multiple sites. For example, a monitoring system may be defined once and then an instance of that monitoring system may be deployed at multiple sites. Tables with site data can be configured to be accessible to oTherm users while tables that can be used between sites can be restricted to those with administrative privileges.



Tables with Site Data

Site

Attribute	Format	Comments
name	**Required** **Unique** **Syntax** Max 50 characters	Recommended to be the M&V Program Management Identifier without personally identifiable information
city	**Required** **Syntax** Max 60 characters	The name of the city or town in which the site is located.
state	**Required** **ForeignKey** State.name	The two-character state abbreviation in which the site is located.
description	Optional **Syntax** Text field	An optional field for additional information and/or comments.
application	**Required** **Syntax** Max 60 characters	Typically used to denote whether renewable thermal system is for new construction or retrofit.
uuid	**Required** **Syntax** RFC 4122 uuid4() automatically generated	Automatically generated universal unique identifier for the site.
thermal_load	**Optional** **ForeignKey** thermal_load.name	Reference to entry in thermal_load table describing the overall heating and cooling loads for the site.
weather_station	**Required** **ForeignKey** weather_station.nws_id	Four-character code for National Weather Service station to be used for site weather data.

Equipment

Attribute	Format	Comments
name	**Required** **Unique** **Recommended format** [site.name]_thermal-load **Syntax** Max 40 characters	Name for the thermal load table entry. This is useful when assigning a thermal load to a site. In the initial release, a site can only have one thermal load table entry
description	**Optional** **Syntax** Text field	An optional field for additional information and/or comments.
conditioned_area	**Required** **Syntax** Float field Units = 'Sq Ft'	The total floor area of the conditioned space served by the renewable thermal system. Future releases may include zones.
heating_design_load	**Required** **Syntax** Float field Units = 'MBtuH'	The peak heating load required to meet the indoor design temperature when the outdoor temperature is the heating_design_oat. Typically determined from an ACCA Manual J analysis.
cooling_design_load	**Required** **Syntax** Float field, Units: 'MBtuH'	The peak cooling load required to meet the indoor design temperature when the outdoor temperature is the cooling_design_oat. Typically determined from an ACCA Manual J analysis.
heating_design_oat	**Required** **Syntax** Float field Units: 'Degrees F'	The outdoor air temperature for which the peak heating load is designed. Typically determined for the location from ASHRAE table.
cooling_design_oat	**Required** **Syntax** Float field Units: 'Degrees F'	The outdoor air temperature for which the peak cooling load is designed. Typically determined for the location from ASHRAE table.
uuid	**Required** **Syntax** RFC 4122 uuid4() automatically generated	Automatically generated universal unique identifier for the thermal load table entry.

Equipment Monitoring System Specification

Maps a pre-defined monitoring system to an existing piece of renewable thermal equipment.

Attribute	Format	Comments
equip_id	**Required** **ForeignKey** equipment.id	ID for the equipment that has a monitoring system attached.
monitoring_system_spec	**Required** **ForeignKey** monitoring_system_spec	id for the monitoring system that is attached to equipment. More than one monitoring system may be associated with a piece of equipment
start_date	**Optional** **Syntax** DateField	date that the monitoring system went into operation
end_date	**Optional** **Syntax** DateField	date that the monitoring system was no longer installed or operating. If a change is made to a monitoring system, the change would be recorded with a new monitoring system with a new start date.

Equipment Maintenance History

Attribute	Format	Comments
equip_id	**Required** **ForeignKey** equipment.id	ID for the equipment that is serviced
description	**Required** **Syntax** Text field	description of service done
service_date	**Required** **Syntax** DateField	date that the equipment was serviced
contractor	**Optional** **Syntax** Max 50 characters	The name of the contracting company that performed the service.
technician	**Optional** **Syntax** Max 50 characters	The name or initials of the technician(s) that performed the service.

Source

Attribute	Format	Comments
name	**Required** **Unique** **Recommended format** [site.name]_[source.type] **Syntax** Max 50 characters	Name for a thermal source located at a site and associated with one or more pieces of equipment. A site must have at least one thermal source and can have more than one.
description	**Optional** **Syntax** Text field	An optional field for additional information and/or comments.
type	**Required** **ForeignKey** source.type	The type of thermal source, e.g. vertical borehole heat exchanger.
spec	**Required** **ForeignKey** source.spec	The specifications of the thermal source, based on type.

Source Specification

Attribute	Format	Comments
uuid	**Required** **Syntax** RFC 4122 uuid4() automatically generated	Automatically generated universal unique identifier for the site.
name	**Required** **Unique** **Syntax** Max 50 characters	The name of the source specification for the site. While a source spec can be used for multiple site, it is most often specific to a site.
description	**Optional** **Syntax** Text field	An optional field for additional information and/or comments.
type	**Required** **ForeignKey** source.type	The type of thermal source, e.g. vertical borehole heat exchanger.

Vertical Loop Specification (Source subclass)

Attribute	Format	Comments
formation_conductivity	Optional **Syntax** Float field	The formation thermal conductivity in units of Btu/hr-ft-F.
grout_conductivity	Optional **Syntax** Float field	The grout thermal conductivity in units of Btu/hr-ft-F.
grout_type	Optional **Syntax** Max 50 characters	The of grout used in the borehole heat exchanger
freeze_protection	Optional **Syntax** Float	The lowest temperature at which antifreeze will prevent freezing. Report in degrees F.
formation_type	Optional **Syntax** Max 50 characters	The type of geologic material in which the heat exchanger is installed.
ghex_pipe_spec	Optional **Foreign Key** ghex_pipe_specification	Mapping to the table with the ground heat exchanger pipe specification.

Air Source Spec

Attribute	Format	Comments
compressor_location	Optional **Syntax** Max 25 characters	An optional field to describe the location of the air-source heat pump compressor. For example, ground-mount, wall-mount, roof, etc.
duct_configuration	Optional **Syntax** Max 35 characters	An optional field to describe the duct configuration of the air-source heat pump. For example., 'single-zone ducted', etc.

Thermal Load

Attribute	Format	Comments
name	**Required** **Unique** **Recommended format** [site.name]_thermal-load **Syntax** Max 40 characters	Name for the thermal load table entry. This is useful when assigning a thermal load to a site. In the initial release, a site can only have one thermal load table entry
description	**Optional** **Syntax** Text field	An optional field for additional information and/or comments.
conditioned_area	**Required** **Syntax** Float field Units = 'Sq Ft'	The total floor area of the conditioned space served by the renewable thermal system. Future releases may include zones.
heating_design_load	**Required** **Syntax** Float field Units = 'MBtuH'	The peak heating load required to meet the indoor design temperature when the outdoor temperature is the heating_design_oat. Typically determined from an ACCA Manual J analysis.
cooling_design_load	**Required** **Syntax** Float field, Units: 'MBtuH'	The peak cooling load required to meet the indoor design temperature when the outdoor temperature is the cooling_design_oat. Typically determined from an ACCA Manual J analysis.
heating_design_oat	**Required** **Syntax** Float field Units: 'Degrees F'	The outdoor air temperature for which the peak heating load is designed. Typically determined for the location from ASHRAE table.
cooling_design_oat	**Required** **Syntax** Float field Units: 'Degrees F'	The outdoor air temperature for which the peak cooling load is designed. Typically determined for the location from ASHRAE table.
uuid	**Required** **Syntax** RFC 4122 uuid4() automatically generated	Automatically generated universal unique identifier for the thermal load table entry.

Multiple Site Tables

Equipment Type

Attribute	Format	Comments
name	**Required** **Unique** **Syntax** Max 20 characters	The type of equipment provided by manufacturer. These are general classes of equipment, such as ASHP, GSHP, etc.
description	**Optional** **Syntax** Text field	An optional field for additional information and/or comments.

GHEX Pipe Specification

Attribute	Format	Comments
uuid	**Required** **Syntax** RFC 4122 uuid4() automatically generated	Automatically generated universal unique identifier for the thermal load table entry.
name	**Required** **Unique** **Syntax** Max 50 characters	A descriptive name of the GHEX pipe specification so that it may be reused on multiple sites.
dimension_ratio	**Optional** **Syntax** Max 50 characters	The of ratio of the outer pipe diameter to the minimum wall thickness. For example, DR11.
no_flowmeter_flowrate	**Optional** **Syntax** Float field	The ground loop flow rate (in gallons per minute) for fixed flow systems without an installed flowmeter.
n_pipes_in_circuit	**Optional** **Syntax** Integer field	The number of pipes in individual circuits. For a single u-tube, the value is 1.
n_circuits	**Optional** **Syntax** Integer field	The number of circuits in the ground loop. For example, for 2 boreholes with split flow, enter 2.
total_pipe_length	**Optional** **Syntax** Float	Enter value in units of feet. For a single u-tube in a 200 foot bore, the total pipe length would be 400 feet.

Manufacturer

Attribute	Format	Comments
name	**Required** **Unique** **Syntax** Max 20 characters	Name of the equipment manufacturer. This will typically include manufacturers of renewable thermal equipment and associated monitoring systems. For manufacturers that provide both heat pumps and monitoring systems, enter a separate record for each (e.g. Waterfurnace_hp and Waterfurnace_ms)
description	**Optional** **Syntax** Text field	An optional field for additional information and/or comments.
equipment_type	**Required** **Foreign Key** equipment_type	The type of equipment provided by manufacturer. Separate records are required for manufacturers that provide multiple types of equipment

Measurement Location

Attribute	Format	Comments
name	**Required** **Unique** **Syntax** Max 20 characters **Examples** ▪ 'in-pipe' ▪ 'heat pump' ▪ 'service panel'	Name of the measurement location for a specific sensor of a montirong system. For example, an electrical measurement may be made in the electrical panel or in the heat pump. Temperature measurements may be made with in-pipe sensors or on-pipe sensor affixed the exterior of a pipe. equipment manufacturer.
Description	**Optional** **Syntax** Text field	An optional field for additional information and/or comments.

Measurement Specification

Attribute	Format	Comments
name	**Required** **Unique** **Syntax** Max 30 characters **Examples** See comments	Name of the measurement for a specific sensor of a monitoring system. This name should be informative so that when a measurement specification is added to a monitoring system, the correct measurement specification can be identified from a list of options. For example, a measure of leaving water temperature made on metal pipe in units of Celsius with an accuracy of 0.1C may be 'LWT OMP 0.1 C'
description	**Optional** **Syntax** Text field	An optional field for additional information and/or comments.
type	**Required** **Foreign Key** measurement_type	Mapping of measurement spec to obtain oTherm name, possible MSP names, units.
accuracy	**Recommended** **Syntax** Decimal Field 10 digits, 5 decimal	When available, numeric accuracy should be reported. If a % of reading value, the accuracy_pct attribute should be set to TRUE. Otherwise, accuracy will be interpreted as sensor error in units of measurement_type.
accuracy_pct	**Recommended** **Syntax** Boolean	Denotes whether accuracy is reported as a percent of reading (TRUE) or in units of measurement_type (FALSE)
meas_bias_abs	**Required** **Syntax** Float field	Measurement bias, other than sensor bias. This may due to an incorrect monitoring system setting. Default = 0.0 Reported as absolute or percent.
meas_bias_pct	**Required** **Syntax** Float field	Measurement bias, other than sensor bias. This may due to an incorrect monitoring system setting. Default = 0.0 Reported as absolute or percent.
location	**Optional** **Foreign Key** measurement_location.location	Th location of a measurement.

Measurement Type

Attribute	Format	Comments
name	**Required** **Unique** **Syntax** Max 20 characters **Examples** ▪ 'heatpump_power' ▪ 'heatpump_aux' ▪ 'source_supplytemp'	oTherm measurement type name for a specific sensor of a monitoring system. These should coincide with names in Table 3 of the Device Level Data Dictionary.
description	**Optional** **Syntax** Text field	An optional field for additional information and/or comments.
msp_colunns	**Optional** **Syntax** Array field	An optional list of coinciding column names for data provided by monitoring system provider (msp).
unit	**Required** **Foreign Key** Measurement_unit.name	The abbreviation of measurement unit, such as "C" for Celsius, "W" for Watts, etc.

Measurement Unit

Attribute	Format	Comments
name	**Required** **Unique** **Syntax** Max 10 characters **Examples** ▪ 'C', 'F', 'W', 'gpm', etc.'	Measurement unit abbreviation
description	**Optional** **Syntax** Text field	An optional field for additional information and/or comments.

Model

Attribute	Format	Comments
name	**Required** **Unique** **Syntax** Max 20 characters	Name of the equipment manufacturer. This will typically include manufacturers of renewable thermal equipment and associated monitoring systems. For manufacturers that provide both heat pumps and monitoring systems, enter a separate record for each (e.g. Waterfurnace_hp and Waterfurnace_ms)
description	**Optional** **Syntax** Text field	An optional field for additional information and/or comments.
equipment_type	**Required** **Foreign Key** equipment_type	The type of equipment provided by manufacturer. Separate records are required for manufacturers that provide multiple types of equipment

Monitoring System

Attribute	Format	Comments
name	**Required** **Unique** **Syntax** Max 40 characters	Name of the monitoring system should be sufficient so that user can select correct one when associating a monitoring system with a piece of equipment.
description	**Optional** **Syntax** Text field	An optional field for additional information and/or comments. Notes on known measurement bias should be included here.
manufacturer	**Required** **Foreign Key** manufacturer	The manufacturer of the monitoring system.

Source Type

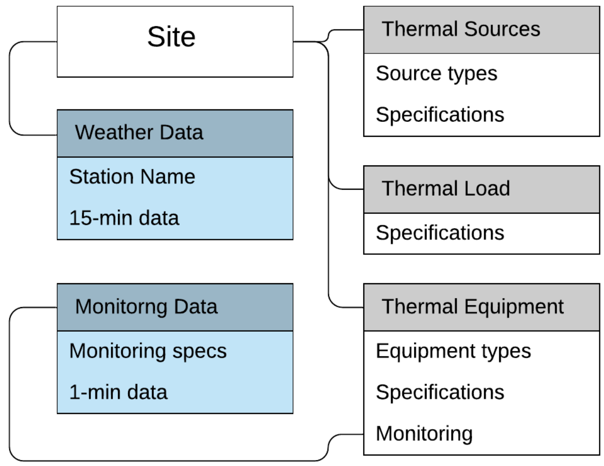
Attribute	Format	Comments
name	**Required** **Unique** **Syntax** Max 50 characters	The name of the general type of thermal source, for example, air source, ground source, district, etc.
description	**Optional** **Syntax** Text field	An optional field for additional information and/or comments.

Weather Station

Attribute	Format	Comments
nws_id	**Required** **Unique** **Syntax** Max 30 characters **Example** 'KPSM' for Portsmouth NH	The National Weather Service station identifier that is most representative of weather conditions at the site.
description	**Optional** **Syntax** Text field	An optional field for additional information and/or comments.
lat	**Required** **Syntax** Float field Units: Decimal Degrees	The latitude of the NWS station.
lon	**Required** **Syntax** Float field Units: Decimal Degrees	The longitude of the NWS station. For North America, typically reported in negative degrees relative to the prime meridian.

Time Series Data (No-SQL)

While we often associate the term 'measurement' with a single instance. In the context of time series data, a measurement is a collection of tags, fields, and timestamps.



In oTherm, the heat pump operating data for all heat pumps and all times is considered a measurement 'monitoring-data' and the weather data is considered a separate measurement ('weather-data'). The elements for each of these measurements are described in the tables below.

Monitoring Data

Data Element	Format	Comments

timestamp	**Required**
	
	Format on input
	epoch (unix timestamp)
	Example:
	`1577836800`
	
	Format on output
	RFC3339
	Example:
	`2020-01-01T00:00:00.00Z`
	
	Precision
	seconds
		When inputting time series data with a text file, the line protocol format requires that time is entered in epoch time. In oTherm, the precision is defined as 'seconds'

tag	**Required**
	
	tag key:
	`'equipment-uuid'`
	
	tag value:
	`equipment.uuid`
		Each time series record for heat pump operating is tagged with the equipment uuid.

field	**Required** **field key:** name of measurement type Example: 'source_supplytemp' **field value:** `float`	Name of measurement type for monitoring system. MeasurementType.name Each record must have least one field and most records will have multiple fields constituting a 'field set'.

Weather Data

Data Element	Format	Comments

timestamp	**Required**
	
	Format on input
	epoch (unix timestamp)
	Example:
	`1577836800`
	
	Format on output
	RFC3339
	Example:
	`2020-01-01T00:00:00.00Z`
	
	Precision
	seconds
		When inputting time series data with a text file, the line protocol format requires that time is entered in epoch time. In oTherm, the precision is defined as 'seconds'

tag	**Required** **tag key:** National Weather Service Station ID (e.g, 'KPSM') **tag value:** `weather_station.name`	Each time series record for weather data is tagged with the weather station name.
field	**Required** **field key:** name of weather measurement Example: 'temperature_c' **field value:** `float`	Name of weather measurement type Each record must have least one field and most records will have multiple fields constituting a 'field set'.

Line Protocol Input

In some cases, it may be necessary to upload time series data into the database. This can be done using text files with data in a 'line protocol' format. Each line represents a collection of (1) measurement name, (2) tag key:value pair, (3) a set of field key:value pairs, and (4) a time stamp in epoch time Single spaces delimit each of these elements. Key value pairs in a field set are delimited by commas. It is important that spaces are not included after commas.

Appendix B: Case Studies of GSHP Systems

Introduction

To illustrate some of the potential uses of oTherm GSHP data, we provide examples of some of the analyses discussed for GSHP systems. The python routines used for the analyses presented here are (will be) available at https://github.com/otherm/gshp-analysis. We use a collection of four sites to illustrate these methods of analysis.

The analyses use one year of operating data collected at approximately 1-minute intervals. Measurements that coincide with gaps in the data of more than 5 minutes have been removed. All four sites are single family residences with a single dual-stage water-to-air heat pump utilizing closed-loop vertical ground heat exchangers.

The measurement accuracies include those for calibrated and uncalibrated temperature sensors, inline flow meters (2% accuracy), and assigned design flow rate when flow is constant. The electricity measurements include systems with pulse output watt meters and systems with just current transducers where the line voltage is assumed. These four sites were selected because of the variety of measurement accuracies as well as interesting patterns of system operation.

Table B-1. Heat pump and monitoring system characteristics.

oTherm ID	State	Nominal capacity [tons] and (rated COP)	Measurement Accuracies (±		
			Temperature	Flow rate	Electricity
97b7	CT	3 (4.8)	0.2 °F	2%	1%
f006	MA	3 (4.9)	0.2 °F	20%	20%
bcb7	NH	4 (4.3)	0.9 °F	2%	1%
6ee0	NH	6 (3.9)	0.2 °F	20%	20%

Heat Pump Operating Data

As a check on the monitoring system and potential measurement bias, it can be helpful to plot the observations against the expected heat pump operation, as provided by the manufacturers performance data tables. Here, we compare the measured electricity consumption and the measured geoexchange rate against relationships inferred for both part- and full-load in heating (orange and red lines, respectively) and cooling (cyan and blue lines, respectively) (Figures B-1 to B4). In these plots, the data are filtered to include only records where the absolute value of the measured geoexchange is greater than 500 Btu/hr to ensure that they represent measures when the heat pump is running. The manufacturer performance data for heat rejected to the ground accounts for the sensible heat component, which is assumed to be 70% of the total cooling.

We present the results here in graphical form, but the deviation of heat pump operating data relative to manufacturer performance data can also be done numerically by calculating a deviation metric, such as the root mean square error of the observations relative to the expected values.

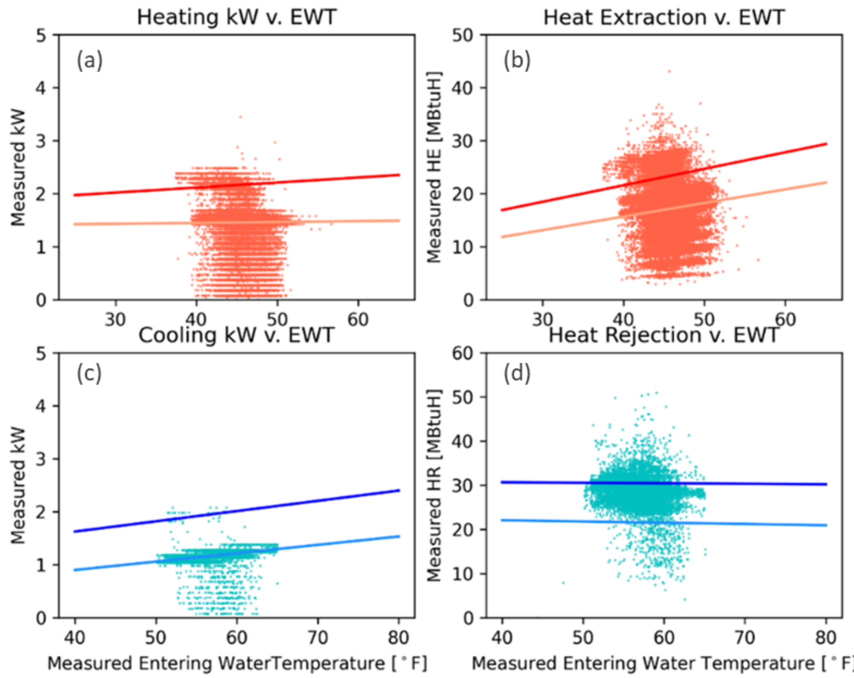


Figure B-0-1. Measured and computed values compared to expected values from manufacturer heat pump performance data for site 97b7. Note the multiple clusters below the part load line in the HE vs EWT plot. The expected heat of rejection (HR) shown in (d) is only for sensible heat component.

The data in Figure B-1 suggest that the heat pump operates in both part and full load for heating with the measured power slightly greater than the expected. The monitoring system at this site (97b7) is high accuracy and the departure is attributed to the ground loop pumping power that is included in the power measurements but not in the manufacturer performance data. One of the more notable features of site 97b7 is the dispersion of heat of extraction (HE) measures while heating (Figure B-1b). As will be noted below, this is due to an unusual pattern of heat pump duty cycles when heating. The HE measures for full load also appear to be greater than expected which may be due to measurement error, which is estimated to be ±15% for geoexchange for this site.

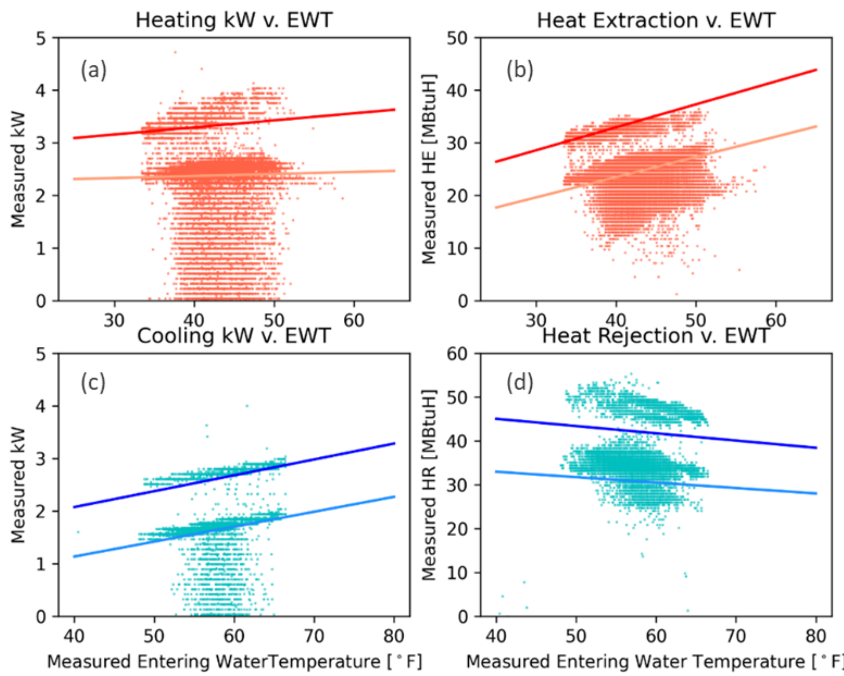


Figure B-2. Measured and computed values compared to expected values from manufacturer heat pump performance data for site bcb7. For the power data, note the clustering just above part- and full-load lines. These power data include the ground loop circulating pump which is estimated to be 400W. The expected heat of rejection (HR) shown in (d) is only for sensible heat component.

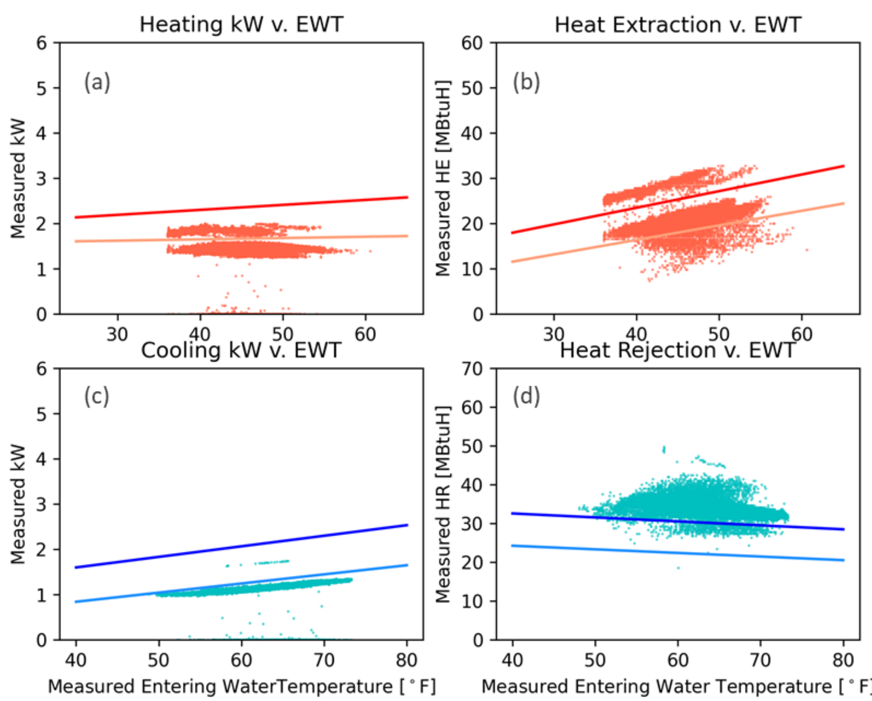


Figure B-3. Measured and computed values compared to expected values from manufacturer heat pump performance data for site f006. For the power data, note the clustering below the part- and full-load lines. These power data include the ground loop circulating and a measurement bias.

Sites f006 (Figure B-3) and 6ee0 (Figure B-4) are good examples of measurement bias. In both cases the measured power for the heat pump falls below the expected values for the respective heat pumps. Upon further inspection of the monitoring system settings, it was found that all power measurements were reduced with a multiplier of 0.8 to account for an unmeasured and estimated power factor. Based on the year-long record of observations, it appears that the power factor correction was ill-advised and the bias that was introduced should be removed when assessing performance metrics that rely on power consumption measurements. Because the data in oTherm are not corrected for measurement bias, all corrections and adjustments are left to the analyst. If a measurement bias is detected, the bias should be entered as an attribute of the monitoring system.

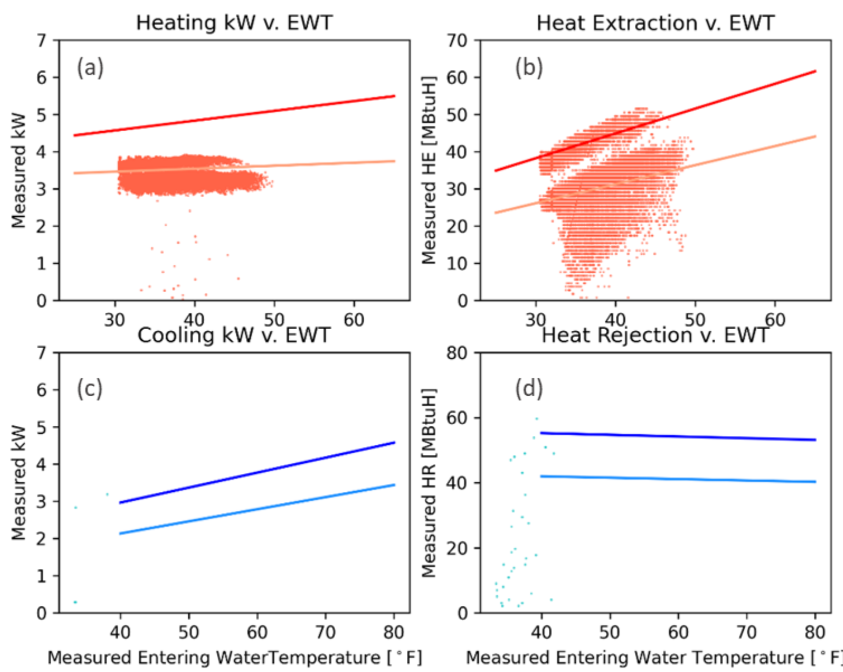


Figure B-4. Measured and computed values compared to expected values from manufacturer heat pump performance data for site 6ee0. Note the under-measurement of kilowatts (a) due to measurement bias. The expected heat of rejection (HR) shown in (d) is only for sensible heat component.

Measured heat of extraction (panels c) aligns well with expected values, with the exception of site f006 where the heat of extraction is slightly higher than expected. This site has a large uncertainty in the ground loop flow rate (Table B-1) which is the most likely cause of the difference.

Energy Production

The data allow for calculation and comparison of different energy production measures. Here we compare the measured geoexchange during heating with proxy methods developed for renewable thermal energy credits in New Hampshire and Massachusetts.

The New Hampshire method uses the heating capacity for the heat pump. Here we use the part-load capacity as the majority of runtime is in part load. The New Hampshire method does not consider actual power consumption but uses only the heat pump COP and runtimes in heating mode.

The Massachusetts method uses measured power consumption. In the analysis here, where some sites include the circulating pump power in the measurement (sites 97b7, f006, and bcb7), we deduct an estimate the fixed flow pumping power in the calculation Likewise, corrections were made for the measurement bias discussed above for an erroneous power factor in the monitoring data.

The proxy methods compare favorably to the measured values. Except for f006, they all fall within the range of uncertainty and f006 is just slightly below the standard error of the measured value. As noted above and in Figure 5-3b, the measured heat of extraction for this site is higher than expected resulting in a higher value of measured geoexchange.

Table B-2. Comparison of measured geoexchange during heating and values calculated with proxy methods

oTherm site ID	Measured Heating Geoexchange [MWh]	Proxy Methods	
		NH RE [MWh]	MA RE [MWh]
97b7	5.77 ± 0.77	5.53	5.00
f006	10.73 ± 2.23	9.16	8.28
bcb7	15.72 ± 4.75	13.79	14.81
6ee0	21.65 ± 4.65	23.41	25.11

While the number of sites is small, proxy methods appear to provide reasonable measures of the geoexchange in heating mode.

Seasonal Performance Factors

One of the most commonly used metrics to quantify GSHP system performance is the seasonal performance factor (SPF). Here, we adjust for measurement bias and apply estimates for the ground loop pumping power so that thermal energy delivered excludes pumping power (numerator) while the energy consumed (denominator) includes pumping power. This analysis coincides with an SPF1 boundary of Spitler and Gehlin (2019). Given that pumping power through the ground loop is not part of the AHRI-ISO heat pump rating, the calculated SPFs are expected to be slightly lower than the rated COP values. This is generally true (except for 97b7), though there is a large degree of uncertainty in the calculated SPF.

Table B-3. Comparison of calculated annul SPF in heating mode, with heat pump rated COPs.

oTherm site ID	Rated COP (part load heating)	Calculated SPF (heating)
97b7	4.8	5.0 ± 0.6
f006	4.9	4.4 ± 1.1
bcb7	4.3	3.7 ± 0.9
6ee0	3.9	3.1 ± 0.8

Table B-3 shows heating SPF a full year of data. SPF can also be calculated over shorter time intervals. For example, Figure B-5 shows monthly heating SPF values and uncertainty for site f006. It appears that the SPF is higher in the spring and early fall, possibly due to higher EWT, though uncertainty in calculated values is larger than month-to-month differences.

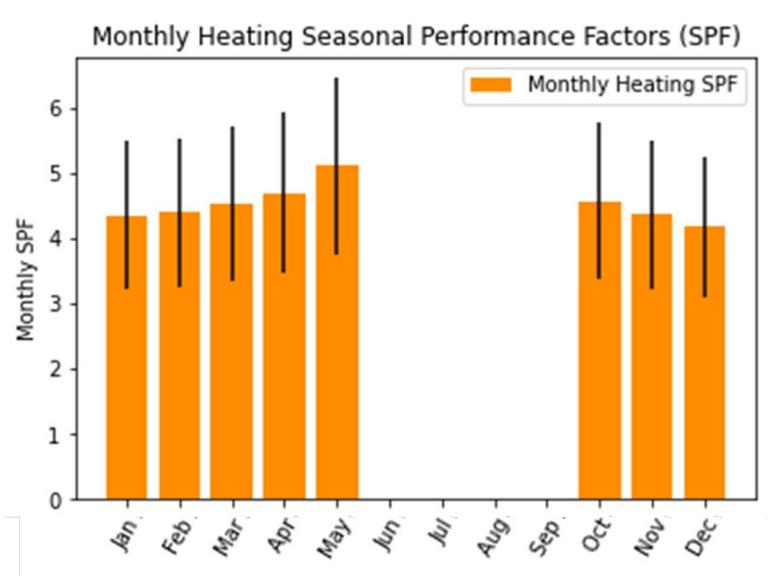


Figure B-5. Monthly SPF values for f006. Error bars shown represent one standard error on computed values.

Energy Usage Patterns

Energy usage of a heat pump system can be quantified in several different ways. Because these analyses focus only on energy usage, they are quite useful for comparing different technologies. For example, measuring thermal energy flows ASHP systems to calculate an SPF is very costly while measures of energy usage are straightforward and directly comparable with GSHP systems.

Figure B-6 quantifies the daily energy consumption (kWh) standardized to conditioned area (SF) as a function of average outdoor air temperature. This analysis also illustrates differences in building envelop efficiency. For example, the retrofit site bcb7 requires more energy per square foot than site f006, which is constructed to have a very low thermal load.

At a more granular level, we can look at the time of use on an hourly basis. For example, Figures B-7 and B-8 illustrate time of use patterns for two GSHP systems. Both systems show higher loads in the morning during winter and higher loads in the afternoon during summer. In the winter, site bcb7 (Figure B-7) has a more pronounced usage in the 06:00 hour with a 90th percentile exceeding 4 kW, suggesting both full load and some use of auxiliary heat during the 06:00 hour. This is likely due to the use of a programmable thermostat that has a rapid increase in thermostat set point. The hourly load profile for site 97b7 is more uniform with both the hourly loads and the 90th percentile during winter.

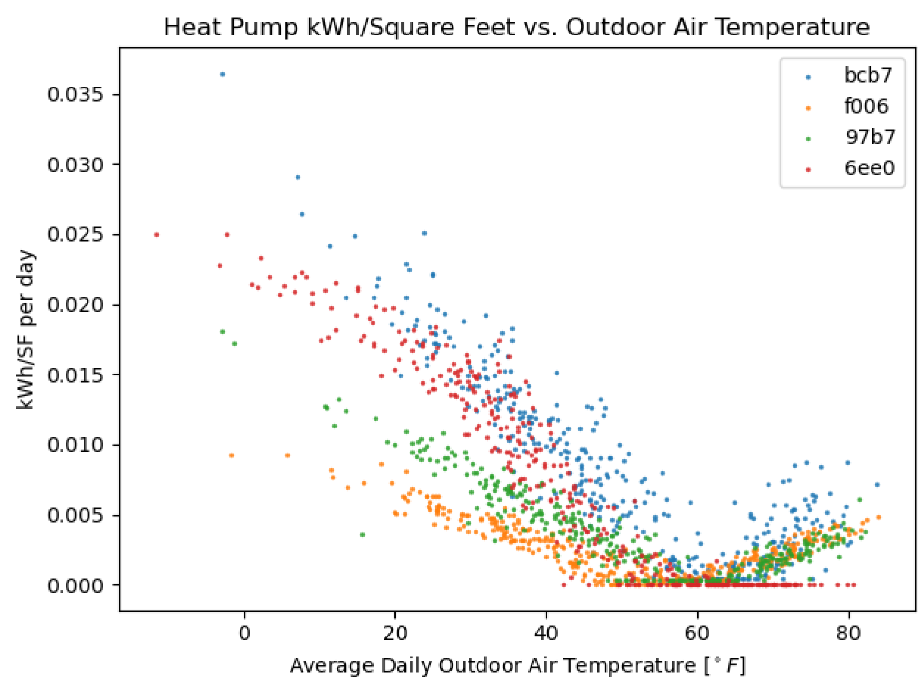


Figure B-6. Energy use intensity over a full year for four GSHP systems in New England.

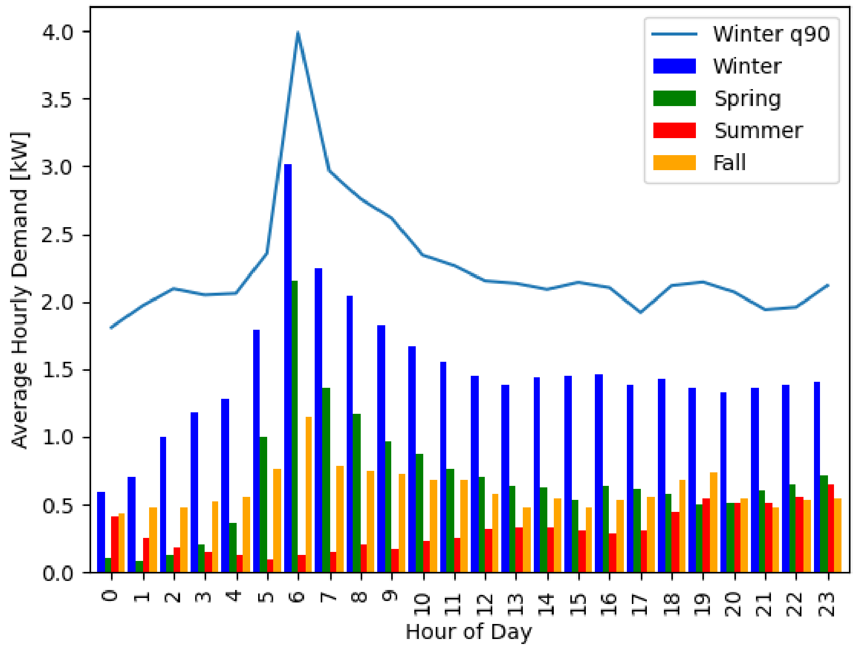


Figure B-7. GSHP average hourly power usage for site bcb7 for different seasons.

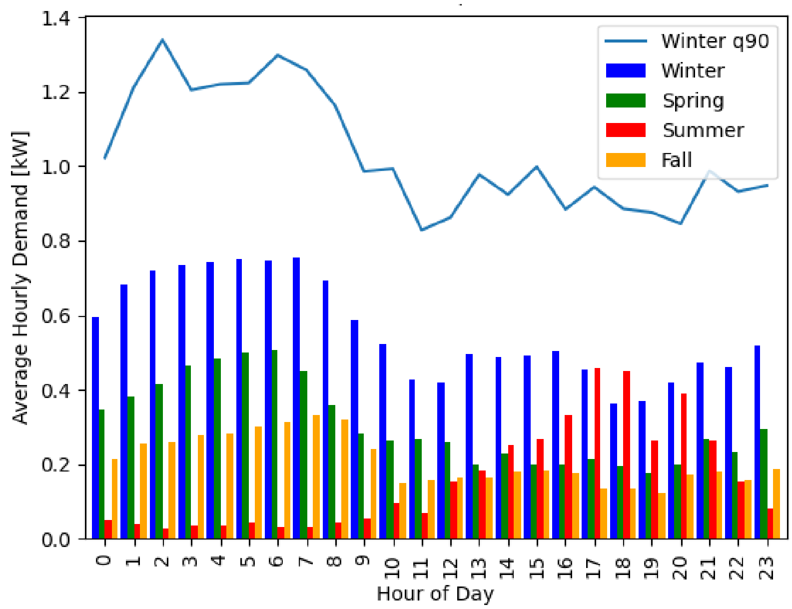


Figure B-8. GSHP average hourly power usage for site 97b7 for different seasons.

The load factor is another energy usage metric that is of interest to utilities. Figure B-9 shows monthly load factors for the four sites analyzed here as a function of total monthly usage. As monthly usages increase, so too does the load factor because the system is operating more hours during the month. Site bcb7 has the lowest load factor as it will occasionally use auxiliary heat to meet thermostat settings.

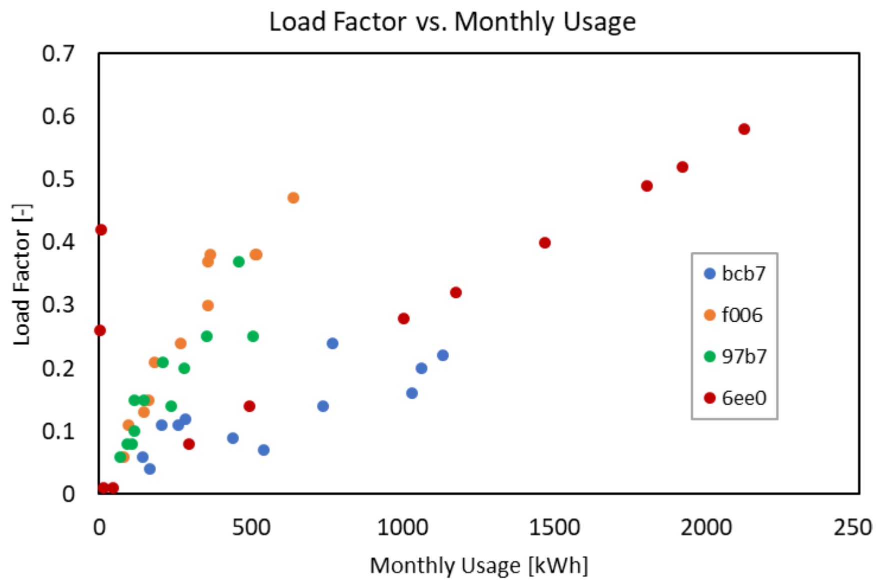


Figure B-9. Dimensionless monthly load factor for four GSHP sites in New England.

System Diagnostics

GSHP operating data can be used for a number of diagnostic analyses. Here we illustrate the daily demand on the ground loop heat exchanger (GLHE), statistics of hourly averaged entering water temperature, and heat pump duty cycles.

GLHE Demand

Figure B-10 illustrates the average daily demand on the GLHE as a function of average daily temperature. Some interesting observations include the lack of cooling at site 6ee0, which is partly responsible for lower-than expected GLHE temperatures (Figure B-11). It is interesting that the balance point for site f006 appears to be closer to 55 °F rather than 65 °F, which results in a more balanced annual ground load, and slightly higher GLHE temperatures (Figure B-11).

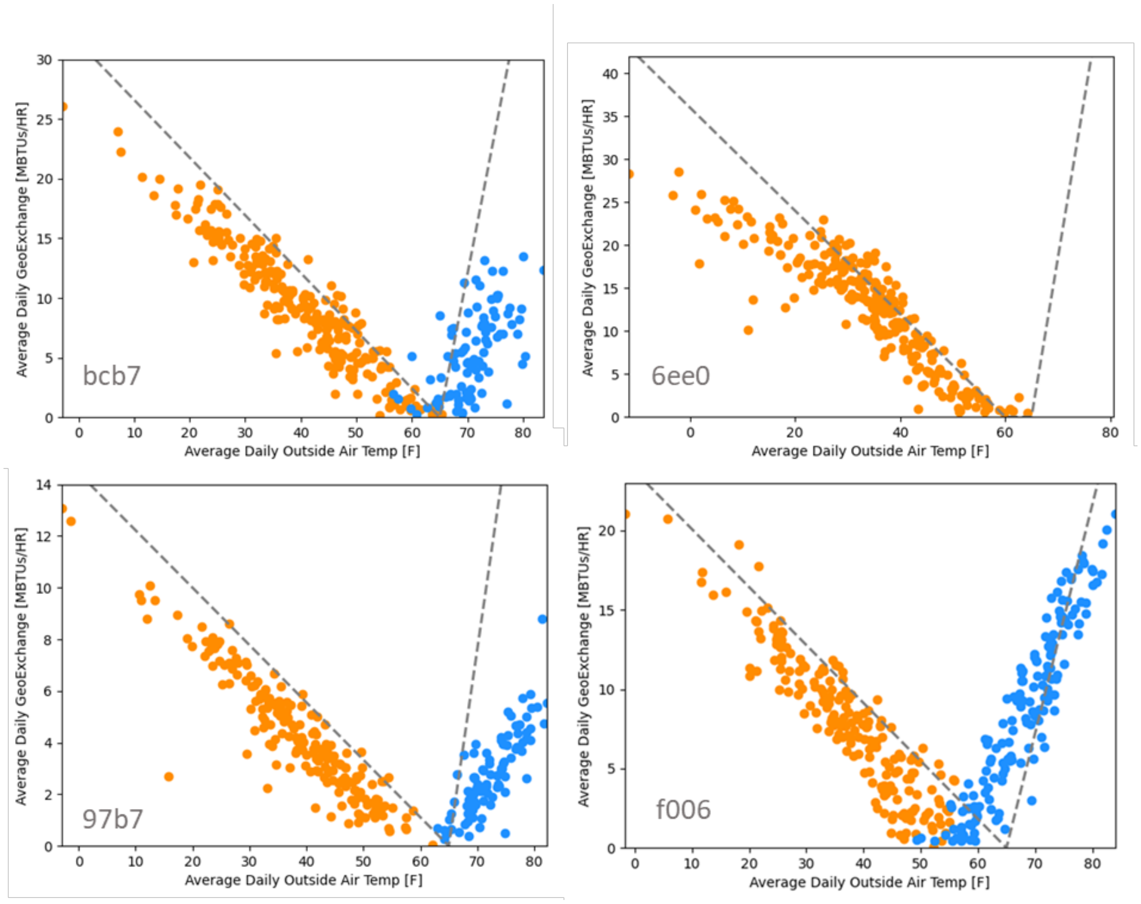


Figure B-10. Ground loop heat exchanger demand averaged over one day (MBtu/hr) as a function of outdoor air temperature. Orange symbols indicate heat of extraction (heating mode) and blue symbols indicate heat of rejection (cooling mode). Green dashed lines connect the peak ground loads with the heat pump design temperatures and balance points (typically 65F)

Entering water temperature

Ground loop temperatures can also provide insight into system performance and system design. Figure B-11 shows violin plots for hourly-averaged entering water temperatures. Only value when the heat pump is on are included in the average. The values are divided into separate sub-populations for heating and cooling mode. Each violin plot is a pair of histograms rotated 90 degrees, one for each sub-population (heating and cooling). As expected, site 6ee0 has the lowest ground loop temperatures as it only operates in heating mode while site f006 has the highest average ground loop temperature as it is the most balanced system with regards to heat of extraction and rejection. Site 97b7 has the smallest range of values indicating that the ground loop may be oversized for the actual system load.

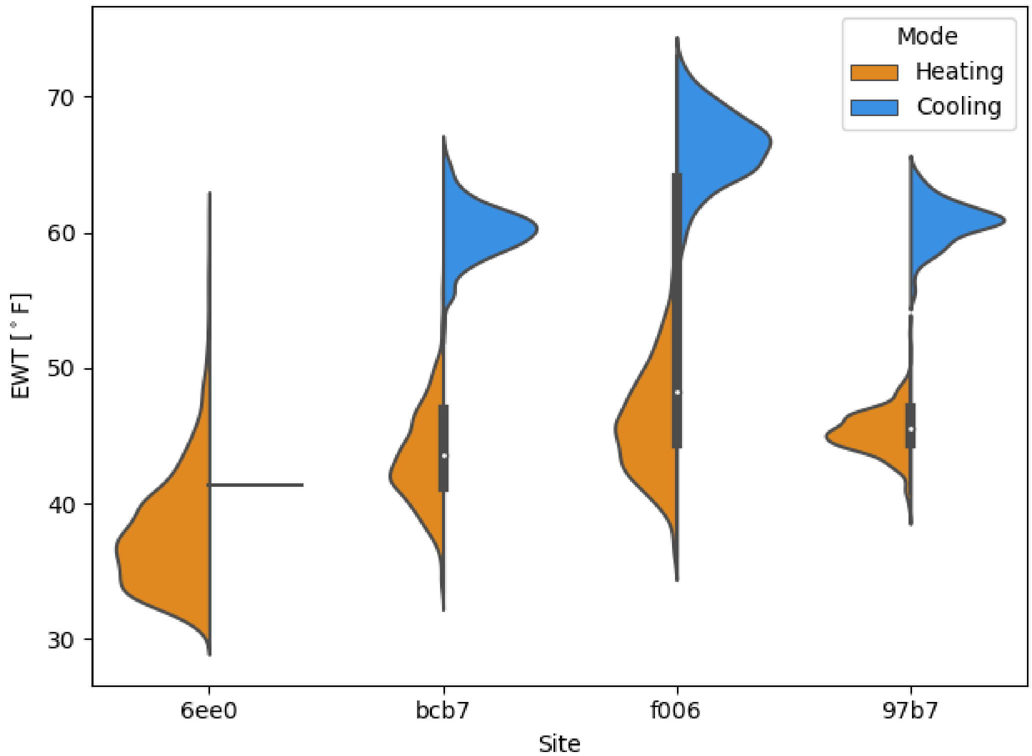


Figure B-11. Violin plots of hourly averaged entering water temperature for four sites.

Heat Pump Duty Cycles

Quantifying the durations of heat pump duty cycles and the conditions under which different heat pump modes (heating and cooling) are operating can provide further insights into system performance. It is generally expected that a heat pump will operate under heating mode when the outdoor air temperature is less than the building balance point and cooling when the outdoor temperature is greater than the balance point. Identifying significant durations of operating modes that differ from the expected may indicate a mechanical problem, such as a faulty reversing valve, or a problem with system controls.

It is also expected that the heat pump will operate for longer durations of time when the heating or cooling demand is higher (cold and hot outdoor air temperatures, respectively). Short duty cycles are generally viewed as unfavorable as they may reduce efficiency of the system, increase mechanical wear on the heat pump equipment, and indicate poor comfort issues for the homeowner. Duty cycles for site f006 follow the expected patterns with heat pump cycles generally greater than 20 minutes in duration with longer durations being correlated with more extreme weather conditions (Figure B-12). Duty cycles for site 97b7 are generally less than 10 minutes in duration for heating but follow the expected pattern for cooling (Figure B-13). While it is expected that short duty cycles might reduce system performance, the calculated SPF for heating is 5.0 ±0.6. Based on Figure B-10 there is no evidence that the system is oversized.

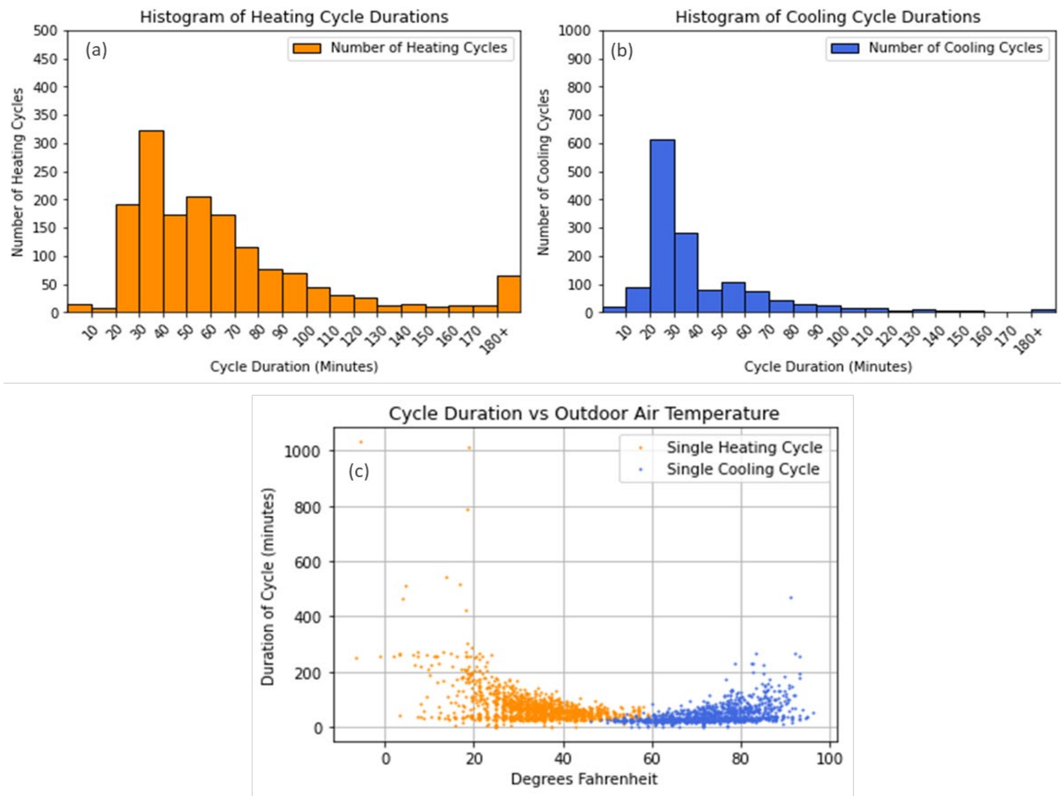


Figure B-12. Duty cycles for site f006 showing expected patterns for heating and cooling.

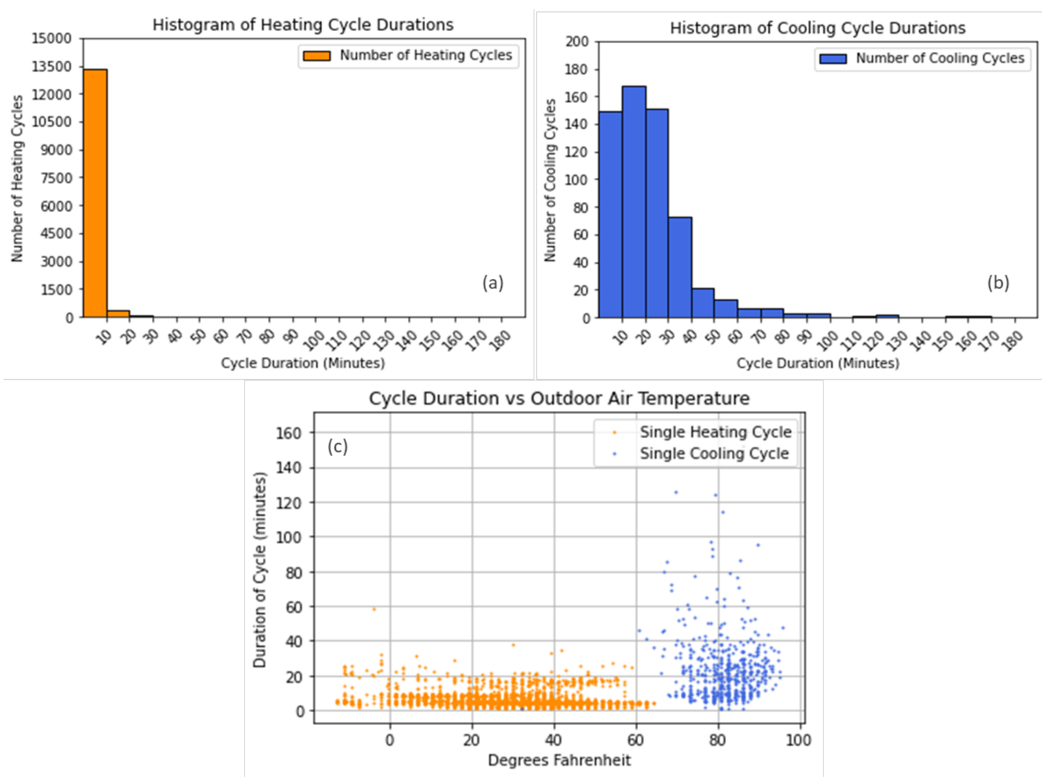


Figure B-13. Duty cycles for site 97b7 showing anomamous cycles for heating.