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December 2015

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Definitions of Acronyms and Terms

AC	alternating current
CAC	central air conditioner
FPM	feet per minute
g/m^3	grams per cubic meter
HVAC	heating, ventilation, and air conditioning
kW	kilowatt
kWh	kilowatt-hour
inch WC	inch water column
LBNL	Lawrence Berkeley National Laboratory
RH	relative humidity
VDC	voltage direct current
WHD	whole-home dehumidifier

1 INTRODUCTION

Maintaining an appropriate level of humidity in a residential building is key to ensuring occupants' health and comfort, and the structural integrity of the home. Excess humidity can impair indoor air quality, result in adverse health effects, and contribute to structural deterioration. Homeowners can take various steps to control and reduce excess humidity level in their homes, but a more precise means of control can be achieved using a whole-home dehumidifier (WHD).

The advantage of a WHD over a portable dehumidifier is that it is typically operated in conjunction with the home's air-handling system. Rather than just drawing humidity from a single area of the home, it works throughout the home by increasing the dehumidifying capability of the home's air handler. To remove excess humidity without a WHD, a homeowner must either lower the thermostat setting to prompt a dehumidification effect; or (less commonly) raise the thermostat setting until the heating turns on to provide sensible heating without increasing the humidity ratio.

Currently, WHDs represent only a fraction of the dehumidifier market, which consists mostly of portable units. However, recent years have seen an increase in WHD use across the United States; mostly in homes in humid areas of the East, Midwest, and South. As homeowners consider the dehumidification advantages of WHDs, they also question whether this equipment might increase their home's energy use. Of course, WHD energy consumption can differ greatly among households; frequency and duration of use, the configuration of the installation, user-selected settings, and exterior environmental conditions all come into play. Unfortunately, little data on the energy consumption of WHDs in actual use have been available to inform potential WHD users.

To fill this gap, Lawrence Berkeley National Laboratory (LBNL) initiated a WHD field-metering study to obtain data on WHD operation and energy consumption in real-world applications. Researchers collected real-time data on WHD energy consumption, along with associated information on housing characteristics and outdoor conditions that might affect WHD performance and efficiency. The field-metering study also collected similar data regarding air conditioner operation; however, this report discusses only the WHD portion of the project. The study activities reported here were conducted from June 2014 to January of 2015 in three Florida homes.

The field-metering study had two primary objectives:

1. To expand knowledge of WHD configurations, energy consumption profiles, consumer patterns of use, such as relative humidity (RH) settings, and environmental parameters

2. To develop distributions of hours of dehumidifier operation in three operating modes: *off, standby,* and *compressor*[a]

The energy consumption profiles provide a more detailed understanding of WHD operation and its complexities. These main profiles generated from this study are as follows:

- power consumption and its duration and frequency in different modes,
- condensate generation,
- properties of output air of an installed system under field conditions of varying inlet air temperature and RH.

Section 2 of this report highlights major problems caused by excess humidity in homes and how WHDs can be utilized to resolve those issues. Section 3 describes how test sites were selected and the characteristics of the selected sites. Section 4 outlines the data collection methods used. Section 5 describes the data handling. Section 6 presents the analysis results in the form of profile graphs and summary statistics. Section 7 provides general conclusions regarding what the results suggest in terms of usage and energy consumption of WHDs.

2 PURPOSE AND OPERATION OF WHOLE-HOME DEHUMIDIFIERS

Most homes, whether energy efficient or not, are susceptible to excessive humidity. In energy-efficient homes, homeowners control air leakage through enhanced insulation, windows, and other building components. While these measures create tight, more-efficient buildings, such design can also increase moisture buildup because a tight housing envelope can make it more difficult for moisture to escape. For different reasons, less energy-efficient (often poorly insulated) homes located in areas with warm, damp seasons also can experience high levels of indoor humidity. Regardless of the cause, the moist air that builds up in a home contributes to the growth of mold, mildew, bacteria, and dust mites; reducing indoor air quality; causing adverse health effects; and, in the long term, potentially damaging the building.

Humidity is measured in different ways for different purposes. *Absolute humidity,* also known as *vapor density,* is a measure of water vapor per unit of air volume in grams per cubic meter (g/m^3). *Relative humidity,* on the other hand, is a function of not only the water content, but also the temperature and pressure of the ambient air. It is the amount of water vapor in the air at a given temperature and pressure compared to the maximum amount of water vapor the air can hold at that particular temperature and pressure. This study measured relative humidity.

Much research has been conducted over the years to determine the optimal RH level for buildings. The optimal range generally is considered to be between 30 percent and 60 percent.[1] However, optimal RH range can change due to climate-specific factors. For example, during the

[a] Compressor mode is also referred to as dehumidification mode in the literature.

heating season in colder climates, recommended RH levels are 30 percent to 40 percent—humidity levels that help to prevent window condensation.

In regards to health impacts, Figure 2-1 shows the RH ranges related to indoor air quality and the various adverse issues that can accompany excess humidity. The red areas indicate the extent of the effects of a humidity level on the specified issues. The figure shows that the ideal RH range for human health generally lies between 45 percent and 55 percent—a range that enables the human body to avoid excessive moisture while maintaining enough humidity to avoid dry or irritated skin and lungs.

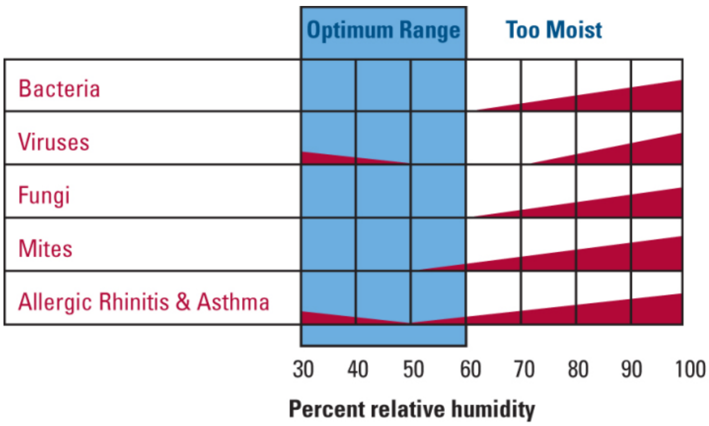

Figure 2-1 Relative humidity ranges based indoor air quality parameters

2.1 Whole-home Dehumidifier Components and Operation Modes

Whole-home dehumidifiers are typically operated as secondary system to a central air conditioner (CAC) to help achieve and maintain the home's desired humidity range. Most WHDs use mechanical/refrigeration components that include a compressor, an evaporator, condenser coils, a fan, a humidistat, duct connections, and a condensate pump with drain connection.

WHDs provide dehumidification by pulling return air from the home and passing it over the cooling coils. The wet surface of the coils traps the moisture in the air stream and the resulting condensates drip into a collector or a drain line. Drier air is then passed over a set of heating coils (the condenser) before it is returned to the home. The homeowner uses the humidistat control system to determine the preferred RH level. When the preferred level is reached, the WHD would automatically turn off and vice versa.

The system operates in one of three different modes:

- *Off:* System is off; the WHD consumes zero Watts of power
- *Standby:* System is on standby; the fan and the compressor are off
- *Compressor:* Both the fan and compressor are on

3 SITE SELECTION AND CHARACTERISTICS

We focused on selecting a group of test sites in a geographical area that is most likely to use or need WHDs. For this reason, we focused our test site recruitment in Florida. One main criterion in the selection of test site is that the WHDs should be installed and operated according manufacturer's recommendation or guidelines. The study protocol has been reviewed and approved by the Institutional Review Board at LBNL prior to the start of the study.

3.1 Site Recruitment

Prior to selecting Florida as the geographical location, we contacted a number of heating, ventilation, and air conditioning (HVAC) dealers, distributors, and contractors across the country in effort to identify regions where a relatively high number of WHDs are used. Through cooperation with the HVAC companies in Florida, we contacted interested homeowners to introduce the study and obtain their consent to install monitoring instrument on their WHDs and CACs.

3.2 Screening Criteria

To be considered as a potential test site, the home had to be occupied by the homeowner and the installed WHD had to be used continuously in conjunction with the home's air-handling system.

Among the potential test sites, some were rejected for at least one of the following reasons:

- It was not a typical WHD installation because it had been significantly customized to meet homeowner's requirements.
- There was no direct connection between the WHD and the house ducting system.
- It would be too difficult to install and access the monitoring equipment.

Candidate sites that met the minimum criteria were listed as potential participants. We then contacted the homeowners, to learn more about their WHD systems, house characteristics, CAC systems, other mechanical ventilation and air distribution systems in their home. Table 1 lists the questions.

Table 1 Site survey questions

1	Date of contact	11	Location of dehumidifier in home?
2	How did you learn about study?	12	Brand/model?
3	Homeowner on site?	13	Connected to ducting?
4	Plans to move?	14	When installed?
5	Own whole-home dehumidifier?	15	Type and placement of controls?
6	Type of home?	16	Moisture problems?
7	Year built?	17	Able to reduce moisture?
8	Square feet?	18	What led you to install a WHD?
9	Number of people living in home?		
10	Number of rooms in home?		

We shortlisted the test sites based on homeowner responses to the survey questions. After making the selections, we visited the sites to check the configuration and performance of the WHD in each home. These visits enabled us to finalize monitoring plans for each site and to gather information on the configuration of the WHD in connection with the home's air-handling system, the characteristics and controls of each home's WHD operation, and potential locations to place sensors and other metering equipment.

3.3 WHD Site Characteristics

All selected test sites have WHDs located in the attics. In this report, these test sites are referred to as WHD1, WHD2, and WHD3. Table 2 through Table 4 present details about each study home. The homeowners reported the dehumidifier control settings, and these were confirmed by observations while installing monitoring equipment.

3.3.1 Test Sites

The three sites chosen were all in Florida. The WHDs at these sites were set to run throughout the year, and each had a humidistat, which was located in a common area of the house. Air was drawn from the home's common return and supplied through a duct to the WHD air intake. Dehumidified air was supplied back to the house through the main supply duct of the central air-handling unit.

Table 2 through Table 4 provide more information about each of the three sites.

Table 2 Test site and whole-home dehumidifier information at site WHD1

Feature	Description
Type of home	Ranch style
Year built	1950
Size of home	No information provided
Construction type	Frame, brick, and T-1/11 siding
Number of occupants	1
Furnace model	Trane heat pump
CAC model	Trane heat pump
Whole-home dehumidifier info	Brand B*
Dehumidifier model	Model 1
Energy recovery ventilator	Not present
Location of mechanical equipment	Attic—insulated above, under roof deck
Air distribution zoning	2
Ducting	In attic
Controls	Humidistat in hallway
Typical control settings	RH set to 45%–50%
Laundry location and venting	Far end of house, past the kitchen
Moisture problems	No
Unusual moisture sources	No

*Brand A units were not included in this study

Table 3 Test site and whole-home dehumidifier at site WHD2

Feature	Description
Type of home	Colonial style
Year built	1950
Size of home	No information provided
Construction type	Frame, brick face
Number of occupants	4
Furnace model	Trane
CAC model	Trane
Whole-home dehumidifier info	Brand B
Dehumidifier model	Model 1
Energy recovery ventilator	Not present
Location of mechanical equipment	Insulated attic
Air distribution zoning	2
Ducting	In attic
Controls	Humidistat in hallway
Typical control settings	RH set to ~50%
Laundry location and venting	Next to back door, off kitchen
Moisture problems	No
Unusual moisture sources	No

Table 4 Test site and whole-home dehumidifier at site WHD3

Feature	Description
Type of home	1-story Cape style
Year built	2012
Size of home	No information provided
Construction type	Frame, brick facade
Number of occupants	3
Furnace model	Trane heat pump
CAC model	Trane heat pump
Whole-home dehumidifier info	Brand B
Dehumidifier model	Model 2
Energy recovery ventilator	One unit; no dehumidification
Location of mechanical equipment	Insulated attic
Air distribution zoning	2 zones
Ducting	In attic
Controls	Humidistat in master bedroom
Typical control settings	RH set to ~50%
Laundry location and venting	Side entrance / mudroom
Moisture problems	No
Unusual moisture sources	None inside; wetland behind house

3.4 Whole-home Dehumidifier Configurations

Each test site had a gas furnace, a CAC, and a WHD. Although the equipment was installed according to manufacturer's recommendations, the system configurations, duct layouts, and equipment locations differed slightly at each site. Figure 3-1 shows a typical WHD installation in relation to the air-handling equipment, direction of airflow, damper position, and placement of monitoring equipment and sensors. The sensors were primarily installed at four main locations within the system configuration: (1) the air coming into the WHD, drawn from the basement zone and the air handler return air; (2) the exit air to the basement and house; (3) the supply air to the house; and (4) the return air from the house to the air handler.

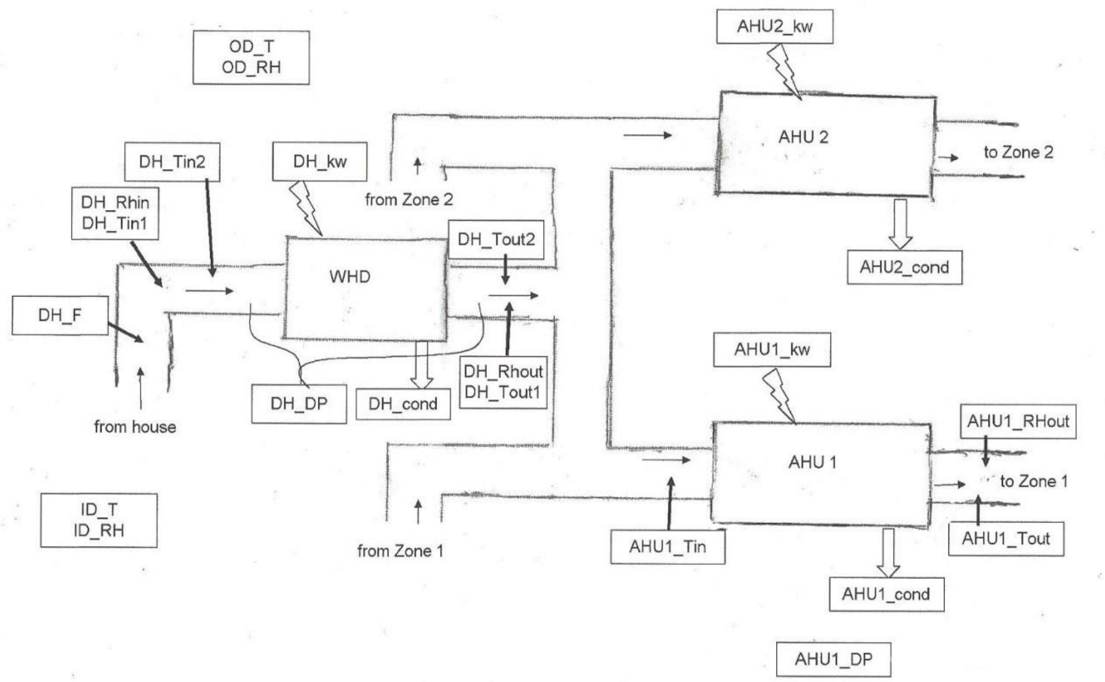

Figure 3-1 Typical WHD and CAC systems configuration and monitoring locations

4 DATA COLLECTION

Energy-metering devices recorded data on WHD energy consumption, while thermal sensors collected data on air temperature and RH. All data were recorded at one-minute intervals from July 2014 through January 2015. All measurements were conducted continuously under normal operating conditions. We did not alter airflow, adjust control settings, or modify the operation of the WHDs and CACs in the homes. The following parameters were recorded at each test site:

- Power consumption of the WHD
- Temperature and RH of air entering and leaving the WHD
- Pressure differential across the WHD
- Condensate volume
- Outdoor air temperature and RH
- Indoor air temperature and RH

4.1 Data logging system

Monitoring systems were installed at the three test sites between June 8 and June 15, 2014. Data were collected and stored by Campbell CR1000 data loggers at one-minute intervals. Each logger is installed in a NEMA-4X enclosure along with a DC power supply and a cellular modem. The modem was powered by the Campbell power supply and was connected to an external magnet-base whip antenna. Surge protection for the loggers was provided by Tripp-Lite Isotel devices. This is necessary because the area has a high frequency of lightning storms.

Data was automatically retrieved daily and archived on a secure storage site. Raw data was entered weekly into spreadsheets for review to ensure that there were no faulty data channels or misbehaving dehumidifiers.

4.2 Instrumentation

Each WHD operated on 120 volts AC through a power cord. Power consumed by each WHD was measured using a Continental Controls WattNode watt transducer with a current transformer. The WattNode and current transformer are enclosed in a wiring box with a cord passing through the box (as if it were an extension cord).

Whole-home power and power consumed by each air conditioner's outdoor unit was also measured with WattNode power meters and current transformers. These were installed directly inside each home's main circuit breaker panel. The pulse output of those power meters was recorded by an Onset HOBO UX-120 4-channel pulse recorder within the panel at 1-minute intervals. The HOBO recorders were purchased with the maximum possible memory capacity. This data was not recorded in the Campbell logger due to the separation between the main breaker panels and the attics, and the impossibility of running wires between the panel and the attic. Data was read-out from the HOBO recorders during decommissioning.

Air temperature and %RH into and out of each WHD were measured with sensors installed in the ducts immediately into and out of the WHDs. Temperature measurements in ducts, aside from those made by the Omega combined temperature and humidity sensor, were made with multiple thermistors. These are 10,000 ohm sensors with a very small (~2mm) sensing bead for fastest response in air. Indoor and outdoor temperature and relative humidity measurements were made with Omega wireless transmitters. The signal was received by an Omega receiver that fed the signals into the Campbell logger. The indoor sensors were generally placed on a shelf in living rooms. The outdoor sensors were placed, when possible, in a shady location on the north side of the house. Each outdoor sensor was protected from direct sunlight in a Dwyer RHRS weather-head (radiation shield).Outdoor measurements were quite similar between the three sites. Weather conditions caused occasionally intermittent wireless signals.

Condensate from each WHD and air handler unit was measured using a tip-bucket rain gage from Texas Electronics, as is typically used in weather stations. The rain gages were installed in each condensate line just after the line exited the WHD or air handling unit. The rain gages create a pulse for every 0.075 ounces of condensate. These rain gages have proven somewhat unreliable at one site (Site WHD2), where the magnetic pickups (that senses tips of the rain "bucket") have occasionally failed. Condensate data was lost for about a month at Site WHD2.

Static differential pressure across the WHD and one of the air handling units at each site was made with a differential pressure transducer. Pressure taps were installed in the ducts immediately entering and exiting the WHDs.

5 DATA PROCESSING

This section describes LBNL's methods for aggregating, cleaning, and analyzing the WHD data obtained from the three study sites.

5.1 Data Aggregation

The three sites data were combined into a database table where they were screened for errors and missing data. Table 5 summarizes the number of records used for each metered site.

Table 5 Site Records

Site	**Number of Records in Database (Minutes)**
WHD1	309,599
WHD2	297,645
WHD3	301,672

5.2 Data Cleaning

5.2.1 Missing records

Table 6 summarizes missing or invalid data for the three sites. Data for site WHD1 was missing only one minute in the entire duration of metering. Data from site WHD2 had one day with almost one-third missing and two days both with 7 minutes missing each. Site WHD3 had a 6 day gap in August due to a power failure.

Table 6 Summary of Missing Data

Site	**Start date**	**End Date**	**Days with Missing data**
WHD1	July 1, 2014	January 31, 2015	6/9/2014 (1 record missing)
WHD2	July 9, 2014	January 31, 2015	6/9/2014 (29% missing) 8/21/2014 (7 records missing) 9/3/2014 (7 records missing)
WHD3	July 1, 2014	January 31, 2015	8/1/2014 (59% missing) 8/2/2014 – 8/5/2014 (100% missing) 8/6/2014 (92% missing)

5.2.2 Indoor/outdoor sensor data errors

Data from the two Omega wireless RH and temperature sensors (UWRH-2-NEMA and UWRH-2A-NEMA-M12) occasionally reported data spikes as a result of transmitter/receiver systems signal attenuation. These sensors were used to measure the indoor and outdoor temperature and humidity. The error spikes are identified by sharp simultaneous spikes in both the temperature and humidity readings. Figure 5-1 demonstrates the data with the error spikes and the data after their removal.

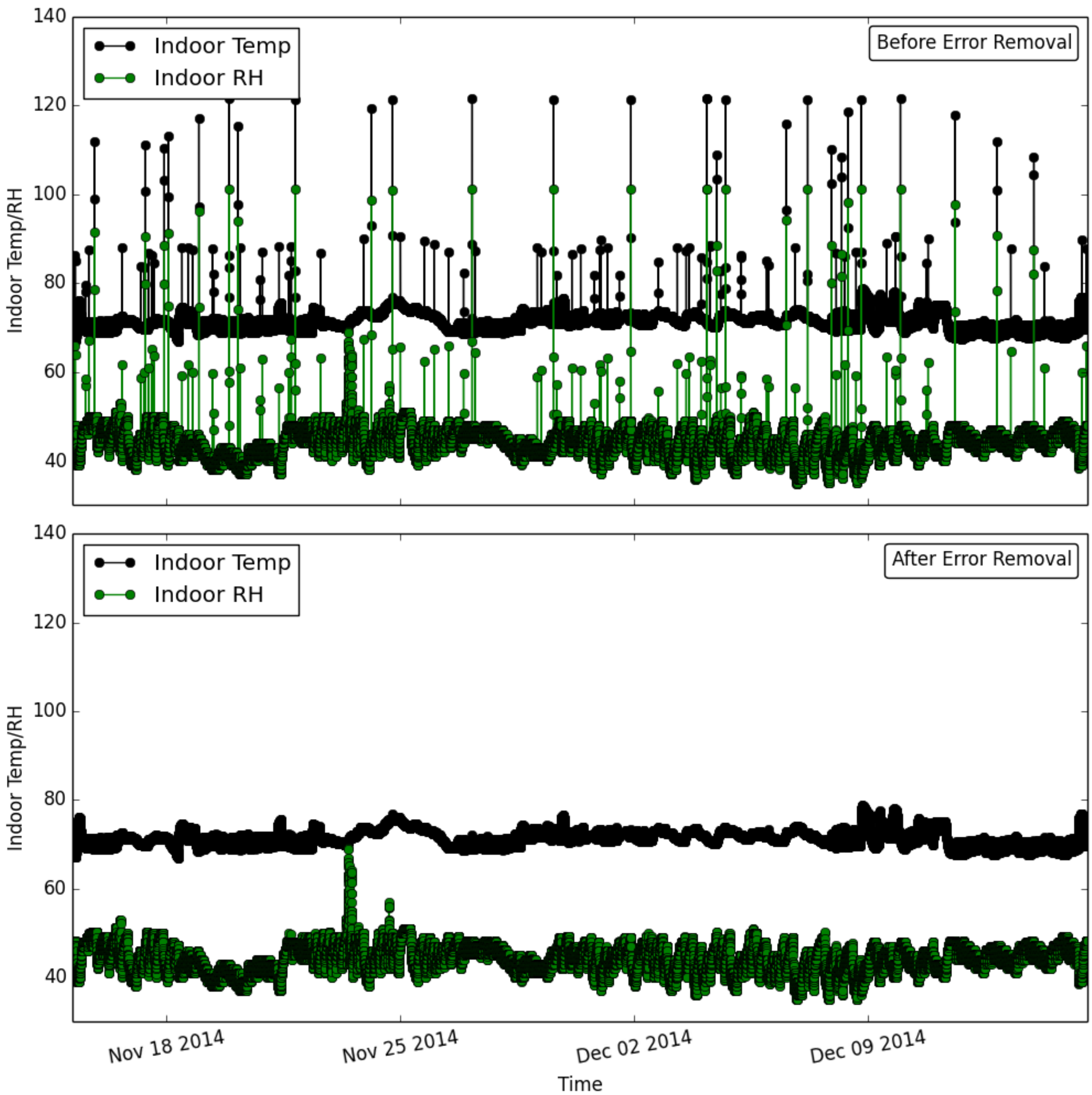

Figure 5-1 Example Error Removal for Indoor/Outdoor Sensors

Table 7 presents the percentage of error spike records that were removed for each sensor. The outdoor sensor for WHD2 contained the most data spikes, with 14.32% removed and not included in the analysis. Table 8 and Table 9 contain the average values of indoor/outdoor temperature/humidity both before and after error removal. Most of the sensor averages did not change significantly with the exception of the WHD2 outdoor sensor data.

Table 7 Percent of Error Records Removed

Site	% of Records Removed	
	Outdoor Sensor	Indoor Sensor
WHD1	0.26%	0.35%
WHD2	14.32%	2.22%
WHD3	2.03%	2.16%

Table 8 Differences in Indoor Averages Before and After Error Removal

Site	Average Indoor Humidity (%)		Difference (%)	Average Indoor Temperature (°F)		Difference (°F)
	Before	After		Before	After	
WHD1	47.54	47.47	0.07	72.49	72.42	0.07
WHD2	49.40	48.34	1.06	74.84	73.89	0.96
WHD3	51.21	50.17	1.05	72.79	71.77	1.02

Table 9 Differences in Outdoor Averages Before and After Error Removal

Site	Average Outdoor Humidity (%)		Difference (%)	Average Outdoor Temperature (°F)		Difference (°F)
	Before	After		Before	After	
WHD1	79.91	79.86	0.05	69.52	69.41	0.11
WHD2	81.75	78.77	2.98	78.23	71.69	6.54
WHD3	83.37	83.08	0.30	68.81	67.96	0.85

5.3 Data Analysis

Several columns of data were calculated based on metered data. These columns included columns for mode, vapor densities, total condensate, condensate removal rate, and condensate removal per unit energy.

5.3.1 Mode determination

The mode was determined by examining the power distribution for each site. This figure is shown below.

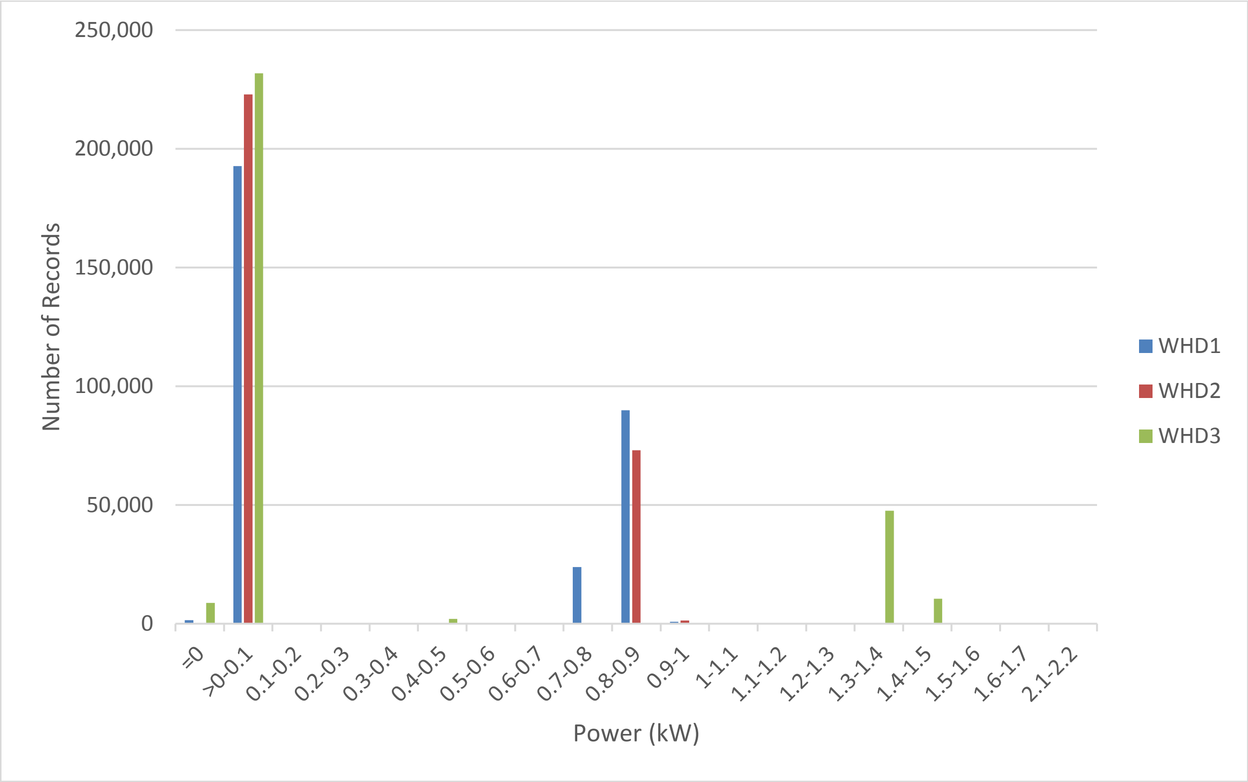

Figure 5-2 Power Distribution by Site

Site WHD1 and WHD3 had off mode peaks at 0 kilowatts (kW) and all sites had standby mode peaks between >0 kW and 0.1 kW. Each site has different peak position in the distribution while the compressor is operating. The records in-between the standby mode and compressor peak for each site are considered transitional points meaning that they are typically points measured during a transition period between standby or off mode and compressor mode, as a result of aggregation of data points within the one-minute measurement interval. These transitional points represent a relatively small portion of the data and are demonstrated in Figure 5-3 as the blue points between the upper and lower range of points (between 0.01 and 1.2kW).

A fan only mode is not clearly observed in the data collected for this study. It is possible that the transitional points included a brief fan only mode before and after compressor cycles but the metering interval of one minute may not have provided enough granularity to clearly distinguish these periods. The compressor mode results presented in this section accounts for simultaneous operation of compressor and fan and their combined energy consumption.

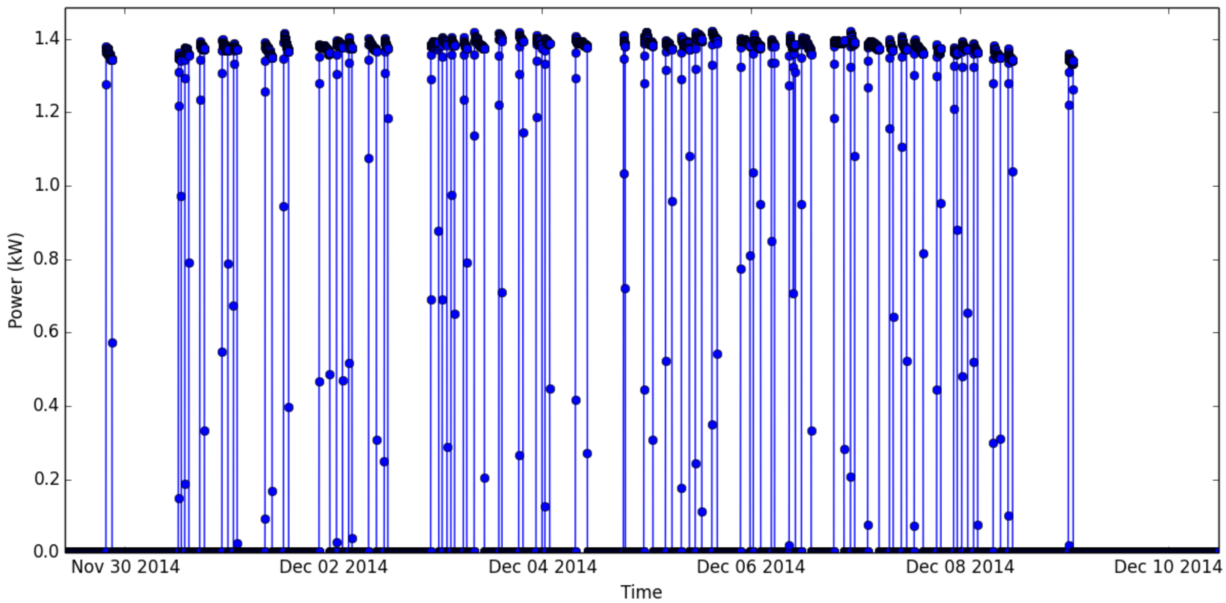

Figure 5-3 Example of Transitional Points in Power Consumption

After the power distribution examination, the following power values were used to determine the dehumidifier modes.

Table 10 Mode Power Range

Mode Name	Mode Power Range (kW)		
	WHD1	**WHD2**	**WHD3**
Off Mode	Off = 0	Off = 0	Off = 0
Standby Mode	0 < Standby < 0.01	0 < Standby < 0.01	0 < Standby < 0.01
Compressor Mode	0.7 ≤ Compressor	0.8 ≤ Compressor	1.2 ≤ Compressor
Transition[b]	0.01 ≤ Transition < 0.7	0.01 ≤ Transition < 0.8	0.01 ≤ Transition < 1.2

5.3.2 Water vapor density

Water vapor density was calculated for the outdoor air, indoor air, and air flow into and out of the dehumidifier.

5.3.3 Condensate calculations

The metered condensate data provided a specific volume of water per pulse which enabled the calculation of total condensate removed (liters), condensate removal rate (liters/hr, pints/day), and condensate removed per unit power (liters/kWh).

[b] Transition represents power consumption records with values between off/standby mode and compressor mode. The transitional points are not considered an operation mode of the system.

6 RESULTS

This section presents the results of analyzing the data collected from the three WHD systems in our field study. We first present time series profiles of power consumption, then examine the percent of time each WHD spent in each operational mode and the associated energy use. We examined how exterior ambient conditions relate to system operation and present some plausible correlations between outside conditions and each system's operating time and energy use. Finally, dehumidifier condensate removal profiles and average removal is reviewed as well as inlet and outlet WHD conditions during compressor mode.

6.1 Time Series of Power Consumption

The power data for each site was plotted as a time series. Each of the following sections contains a figure consisting of three time series plots. The top plot is of the full metering period. The middle plot is a sample representation of 14 days of data while the bottom plot is a 48 hour sample of the 14 day period.

6.1.1 *WHD1*

Figure 6-1 is the time series power consumption plot for WHD1. For the 14 day period shown in the middle plot, there were about 38 compressor cycles (about 2.7 cycles per day). Some of the compressor cycles were short while others were much longer. The frequency of the cycles seems to be increasing towards the end of the year.

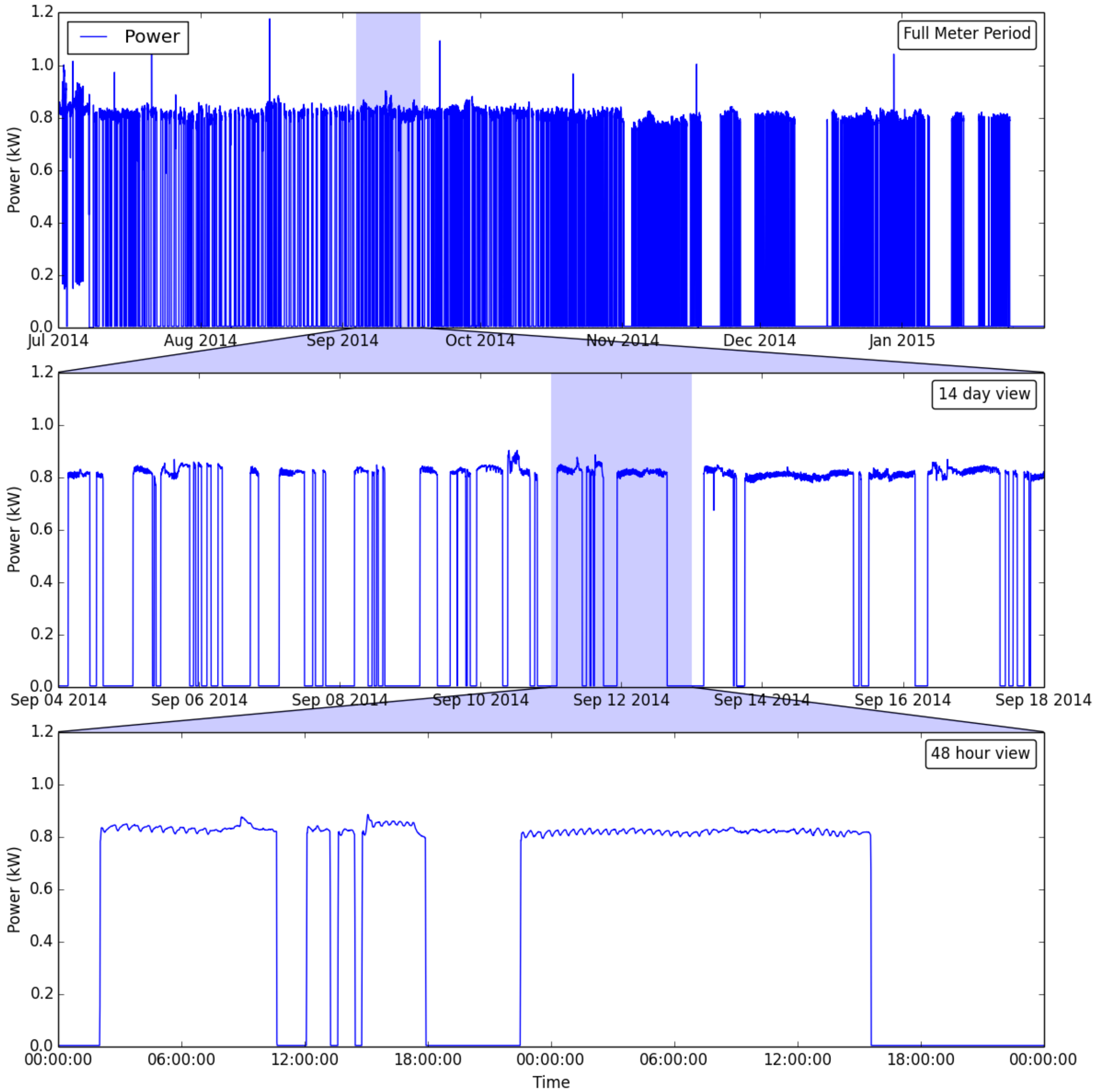

Figure 6-1 Time Series Plot of WHD1

6.1.2 WHD2

WHD2 had about 18 compressor cycles within the 14 day period shown (or about 1.3 cycles per day). The compressor cycles for WHD2 appear to be more regular than for WHD1 in that the cycle duration is more consistent as well as occurring at more regular intervals.

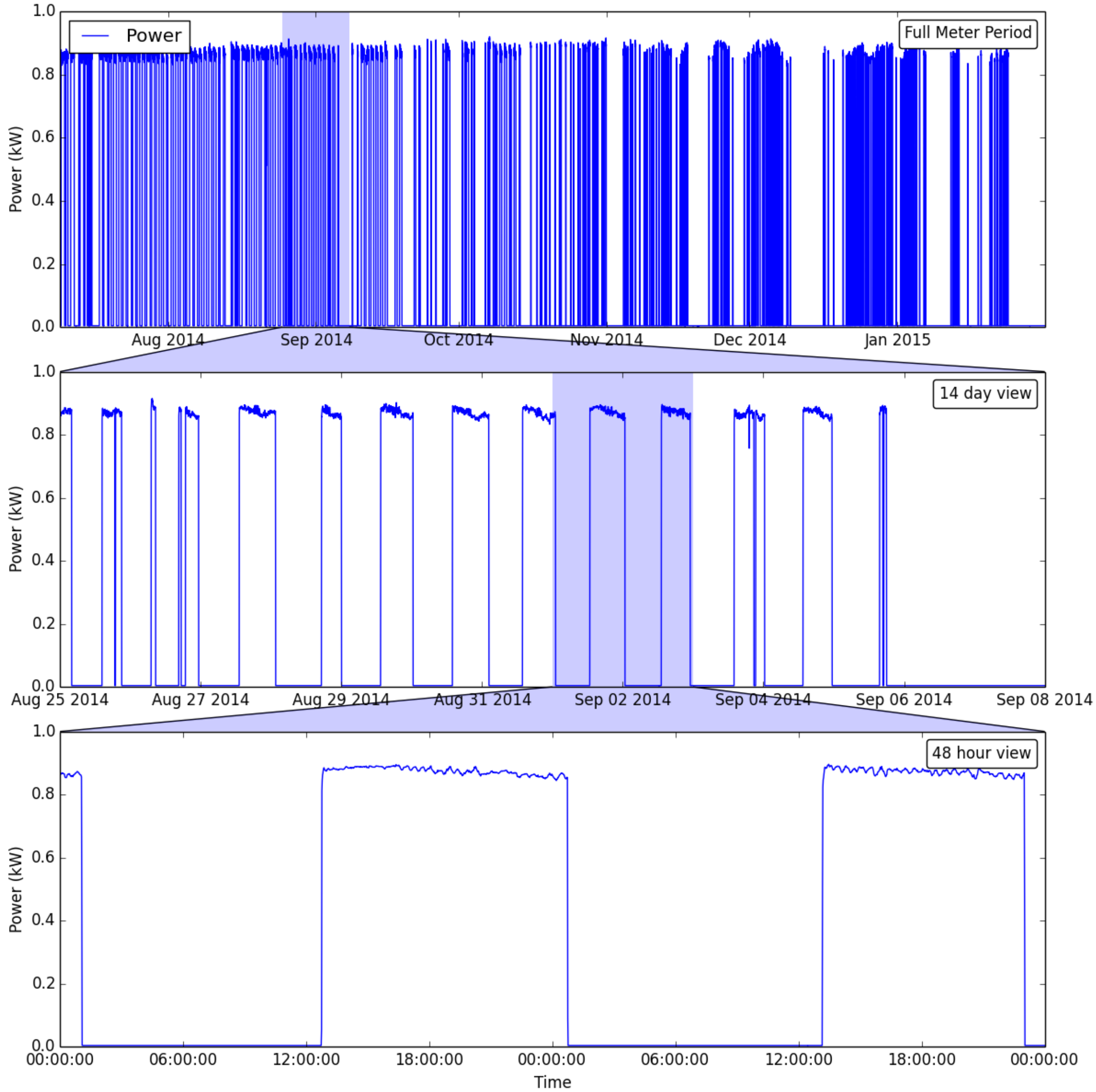

Figure 6-2 Time Series Plot of WHD2

6.1.3 WHD3

Below is the power time series for site WHD3. The compressor cycles for this site were shorter in duration than the previous two sites. In the 14 day period there were about 39 cycles, or about 2.8 cycles per day.

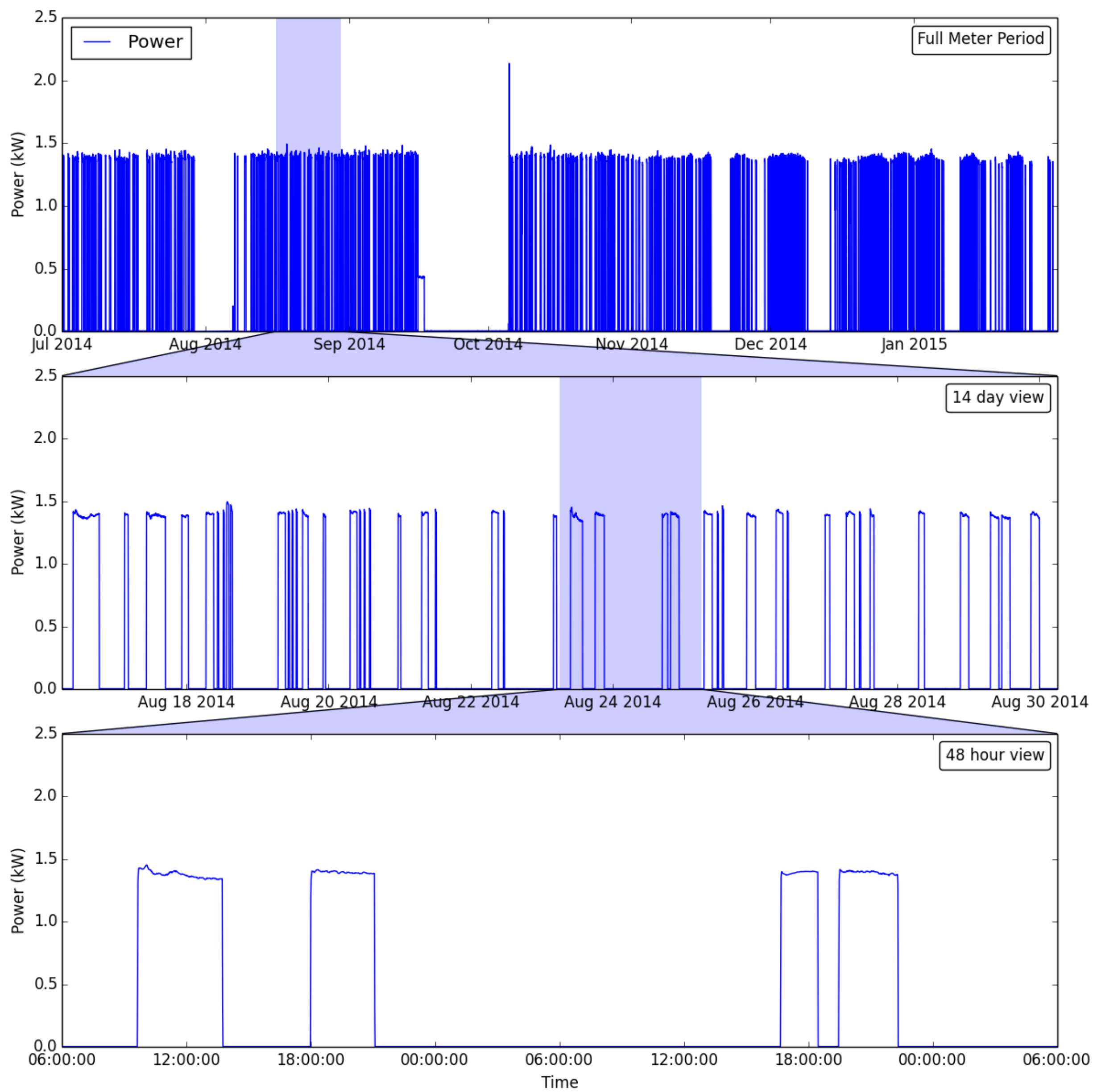

Figure 6-3 Time Series Plot of WHD3

6.2 Time Spent in Each Operational Mode

Table 11 lists the combined average time in each mode over each of the three sites by month.

Table 11 Average Time Spent in Each Operational Mode (All Sites)

Month-Year	Percent Time			
	Off Mode	Standby Mode	Compressor Mode	Transition Measurement
Jul-14	4.0	49.3	46.4	0.3
Aug-14	4.1	57.7	38.0	0.3
Sep-14	<0.05	67.4	30.9	1.7
Oct-14	0.1	72.4	27.2	0.3
Nov-14	<0.05	83.5	16.2	0.3
Dec-14	0.0	78.7	20.9	0.4
Jan-15	<0.05	86.9	12.9	0.3

The time spent in compressor mode was highest in July 2014 and declines for the rest of the year. The WHDs standby time increases as the compressor time decreases. The time spent in off mode was small throughout the year. The amount of time the transitional points take up is also very small. The following sections describe the average percent of time spent in each mode split by WHD site.

6.2.1 Time in operational mode for WHD1

Table 12 provides time in each mode for WHD1 by month. WHD1 had the most time spent in compressor mode time in July and had least compressor mode time in January 2015(where there was the most standby time). There was 3.0% of time spent in standby mode in July with only 0.1% in November. The transitional records represent about 0.4% of the total records.

Table 12 WHD1 - Average Time Spent in Each Operational Mode

Month-Year	Percent Time in Mode			
	Off Mode	Standby Mode	Compressor Mode	Transition Measurement
Jul-14	3.0	34.7	61.8	0.5
Aug-14	<0.05	62.4	37.3	0.3
Sep-14	<0.05	45.7	53.9	0.4
Oct-14	0.0	54.0	45.6	0.5
Nov-14	0.1	78.8	20.7	0.4
Dec-14	0.0	74.9	24.7	0.4
Jan-15	<0.05	84.8	15.0	0.2

6.2.2 Time in operational mode for WHD2

Table 13 provides time in each mode for WHD2 by month. Similarly with WHD1, WHD2 had the most compressor mode time in July with the least time in January 2015. The transition measurement typically represented about 0.2% of the records each month. There was less than 0.05% of time spent in off mode for WHD2.

Table 13 WHD2 - Average Time Spent in Each Operational Mode

Month-Year	Percent Time in Mode			
	Off Mode	Standby Mode	Compressor Mode	Transition Measurement
Jul-14	0.0	45.7	54.2	0.1
Aug-14	<0.05	51.6	48.2	0.2
Sep-14	0.0	74.8	25.1	0.1
Oct-14	0.0	83.6	16.2	0.2
Nov-14	0.0	88.3	11.4	0.2
Dec-14	0.0	81.5	18.2	0.3
Jan-15	0.0	91.1	8.7	0.2

6.2.3 Time in operational mode for WHD3

Table 14 provides time in each mode for WHD3 by month. The most time spent in compressor mode for WHD3 was in July and August (25.5% and 26.3% respectively). The least amount of compressor time was spent in September where there was a large gap in operation (which can be seen in Figure 6-3). Out of the three sites, WHD3 had the lowest time spent in compressor mode for the most usage months: July, August, and September. The increased time spent in transitional mode during September is due to a continuous period of WHD operation that lasted about 32 hours. After this period there was a standby period that lasted about 18 days. This behavior can be seen in Figure 6-3. It is unclear what happened during this period, although since it was only one occurrence during the entire metering duration, it was unlikely to be a fan only mode.

Table 14 WHD3 - Average Time Spent in Each Operational Mode

Month-Year	Percent Time in Mode			
	Off Mode	Standby Mode	Compressor Mode	Transition Measurement
Jul-14	7.8	66.4	25.5	0.3
Aug-14	13.9	59.4	26.3	0.4
Sep-14	0.0	81.7	13.5	4.7
Oct-14	0.3	79.6	19.7	0.4
Nov-14	0.0	83.2	16.5	0.3
Dec-14	0.0	79.7	19.9	0.5
Jan-15	0.0	84.8	14.8	0.3

6.3 Average Power Consumption by Operational Mode

The average power by mode for each site is presented in Table 15 with the standard deviations provided in Table 16. The average standby power was 5.00 Watts for site WHD1 and 4.00 Watts for sites WHD2 and WHD3. The standard deviations for standby mode are very small indicating that the standby power for each site was very steady. The average compressor mode power was about 815 Watts for site WHD1, 870 Watts for site WHD2, and 1,381 Watts for site WHD3. The standard deviations for compressor mode power indicate that while the compressor was running, the power remained at relatively at a constant level. This consistency can be seen in the 48 hour view in the time series plots. Average transition measurement power is also provided in these tables. However, transition measurement power is not particularly relevant since it is a product of the regular measurement interval (of 1 minute) of the data acquisition equipment measuring points during a mode transition. As a result, the standard deviation for transition mode power is very large.

Table 15 Average Power for Each Operational Mode by Site

Site	Average Power (Watts)		
	Standby Mode	**Transition Measurement**	**Compressor Mode**
WHD1	5.00	335.07	815.23
WHD2	4.00	406.59	870.24
WHD3	4.00	483.33	1,381.59

Table 16 Average Standard Deviation of Power for Each Operational Mode by Site

Site	Average Standard Deviation (Watts)		
	Standby Mode	**Transition Measurement**	**Compressor Mode**
WHD1	0.02	196.58	22.74
WHD2	0.02	224.80	14.42
WHD3	0.03	215.67	24.14

6.4 Average Daily Energy Use

Table 17 displays the average daily power consumption of the whole-home dehumidifier by month.

Table 17 Average kWh/day by Month and Site

Month-Year	Average kWh/day		
	WHD1	WHD2	WHD3
Jul-14	12.30	11.28	8.57
Aug-14	7.41	10.12	8.90
Sep-14	10.72	5.34	5.12
Oct-14	9.02	3.53	6.68
Nov-14	4.06	2.51	5.54
Dec-14	4.89	3.92	6.70
Jan-15	3.00	1.92	4.99

The average power consumption per day is almost entirely driven by the time spent in compressor mode with power usage from standby mode being nearly negligible. Although site WHD3 had a larger average compressor mode power than the other two sites (1,382 Watts compared to 815 and 870 Watts), it had used less energy during the large usage months of July, August, and September.

6.5 Operational Mode Related to Outdoor Conditions

Figure 6-4 demonstrates the relation of time spent in mode as a function of outdoor temperature. The time spent in compressor mode continues to rise as the outdoor temperature rises.[c] While outdoor temperatures were below 38°F, WHD sites did not spend any time in compressor mode.

As noted in section 5.2.2, some environmental data records had to be excluded. This may contribute to error in the determination of the time under each mode. An attempt was made to treat the missing data, however, because of some of the large continuous periods of missing records, these methods were unreliable and could have possibly introduced further error in the data set.

To determine the extent of the impact of the removed data on the analysis, the overall average percent time split between compressor mode and standby with all records and with error records omitted were compared. Including all records, the time split was 27.64% compressor mode and 72.36% standby mode. With omitted records the time split was 28.64% compressor mode and 71.36% standby mode, an overall change of 1.00%. This indicated that the overall average error in the following charts would be a maximum on 1.00% difference.

[c] The dehumidifier performance in these three sites may not represent installations without CACs. Determining the interaction between the CAC and WHD was outside the scope of this study.

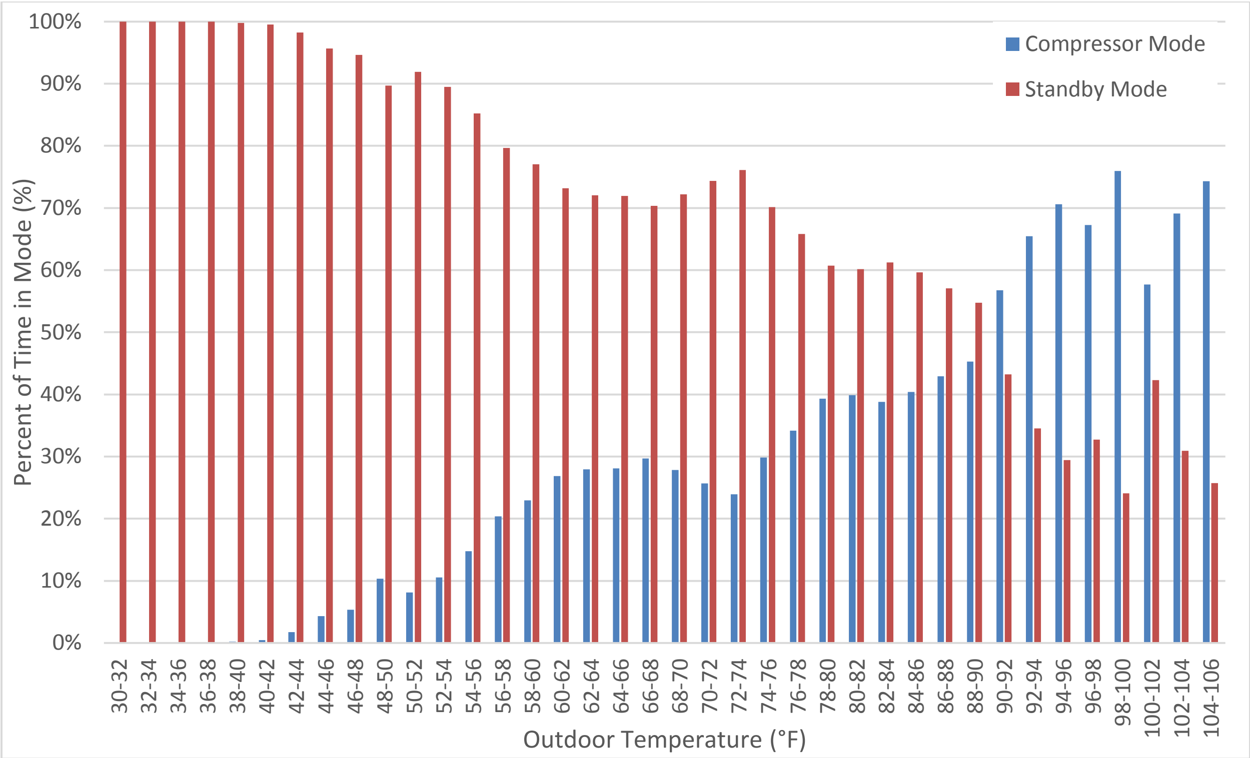

Figure 6-4 Percent of Time Spent in Mode as a Function of Outdoor Temperature

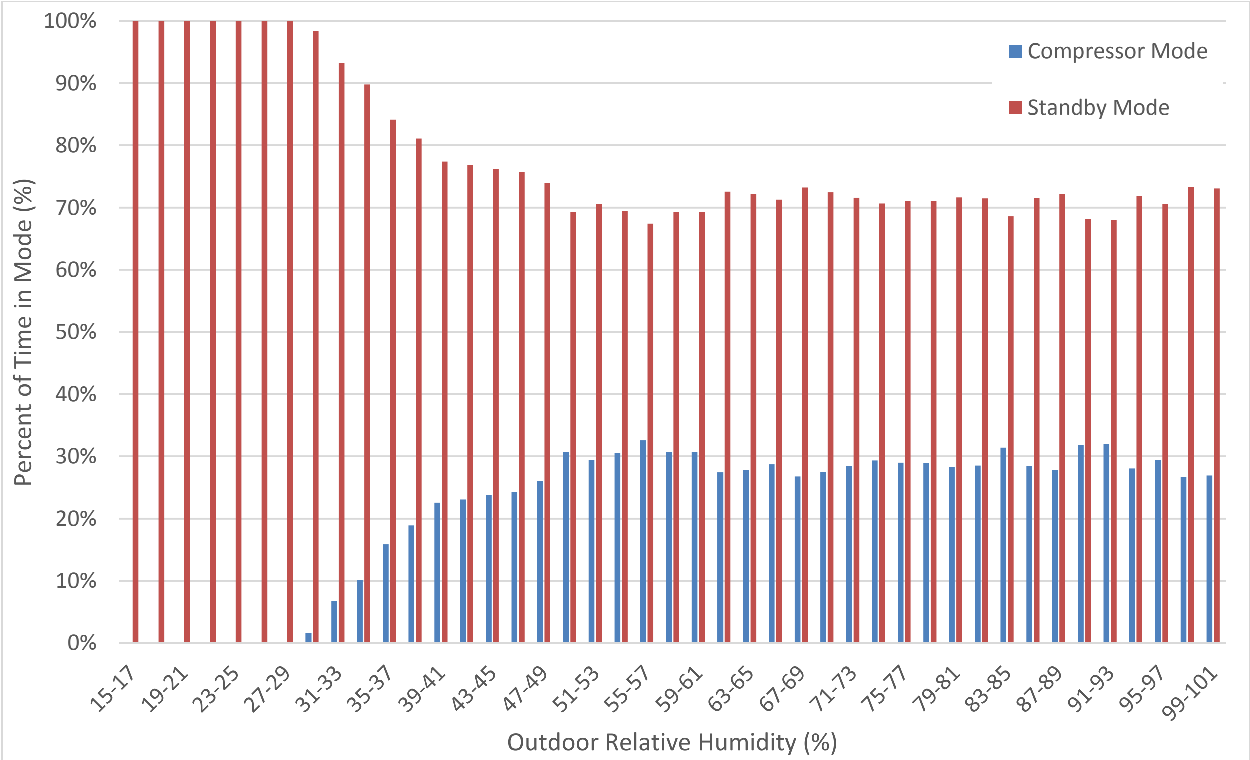

Figure 6-5 Percent of Time Spent in Mode as a Function of Outdoor Humidity

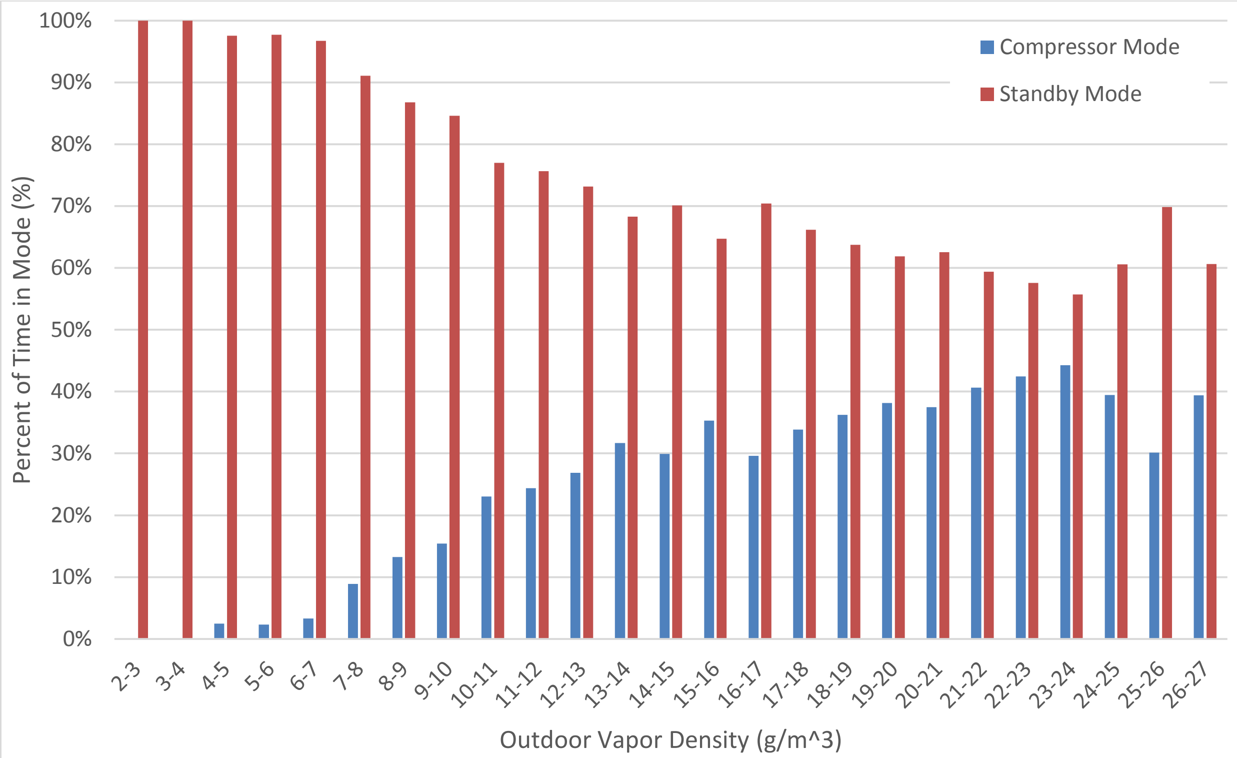

Figure 6-6 Percent of Time Spent in Mode as a Function of Outdoor Vapor Density

The WHDs were used as secondary system to keep humidity in check at these hot and humid Florida locations. To a great extent, the call for cooling would dominate the system operation, and as the RH increased, the WHD would operate more frequently. This is why for WHD used in combination with air handling units, the WHD component appeared to be driven by temperature conditions. Figure 6-5 demonstrates the relationship between outdoor humidity and time spent in mode. The trend of time spent in mode is relatively constant above outdoor humidifies of 50%. Compressor mode was not present when outdoor humidity dropped below 30%. Outdoor vapor density in Figure 6-6 displays the same trend as the Figure 6-4 in that as outdoor vapor density increases, the time spent in compressor mode also increases. Both outdoor temperature and outdoor vapor density provide reasonable metrics for describing the amount of time a WHD spends in compressor mode. This may not represent all installation conditions, for example, where a WHD is installed without a CAC.

6.6 Dehumidifier Condensate

6.6.1 Condensate Removal

Table 18 gives values for condensate removal during compressor mode. WHD2 had the highest liters/kWh out of the three sites. WHD3 had the highest measured capacity with an average condensate removal rate of about 110 pints/day. Table 19 lists the standard deviations. The standard deviations are large because of the variation of the tip bucket measurements at the minute intervals. The variation can be seen in the following section during the compressor cycles.

Table 18 Average Condensate Removal during Compressor Mode

Site	Average Condensate Removal per unit Power (liters/kWh)	Average Condensate Rate (liters/h)	Average Condensate Rate (pints/day)
WHD1	1.97	1.60	81.35
WHD2	2.05	1.78	90.30
WHD3	1.56	2.16	109.55

Table 19 Standard Deviation of Condensate Removal during Compressor Mode

Site	Standard Deviation (liters/kWh)	Standard Deviation (liters/h)	Standard Deviation (pints/day)
WHD1	0.54	0.45	22.81
WHD2	0.34	0.30	15.02
WHD3	0.39	0.55	28.02

6.6.2 Condensate Removal Profiles

The following 4 day view time series plots for each site provide an average representation of the compressor cycle and condensate removal rate associated with the cycle. The condensate collection method provided consistent results but with large variation between minute intervals. The condensate removal rate is lowest at the beginning of the compressor cycles and increases to a more stable removal rate which then generally decreases slightly over the duration of the compressor cycle. Once the WHD is out of compressor mode, the condensate removal rate sharply decreases to nearly zero. These effects can be seen by closely examining the compressor cycles and condensate removal rates (demonstrated in Figure 6-10).

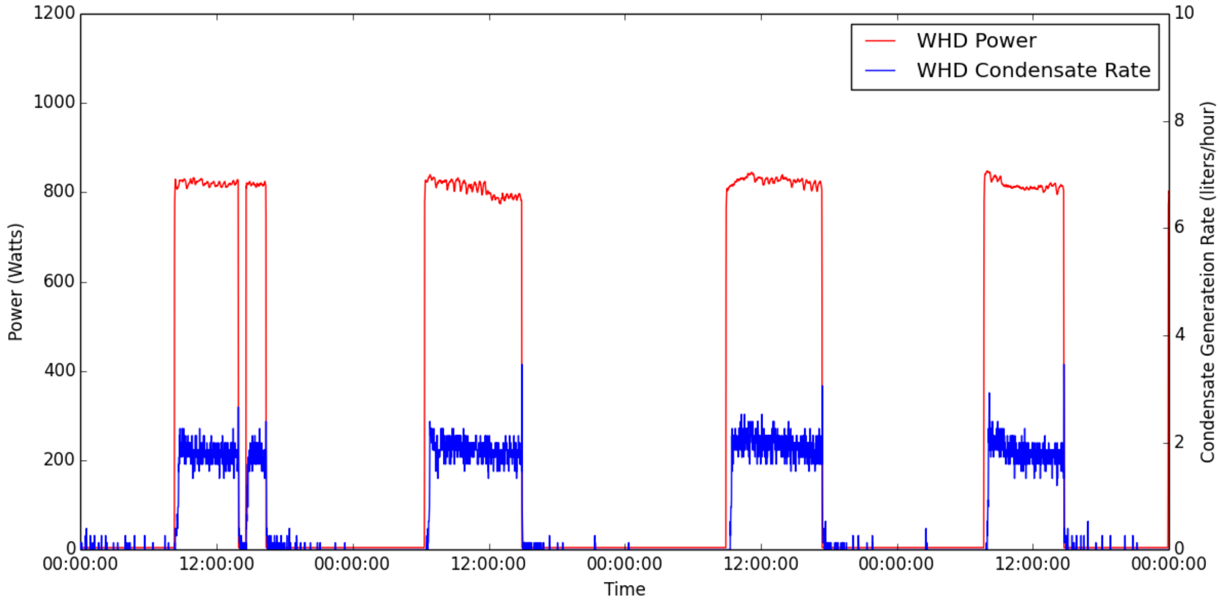

Figure 6-7 Typical WHD1 Compressor Cycle and Condensate Removal Rate (4 day view)

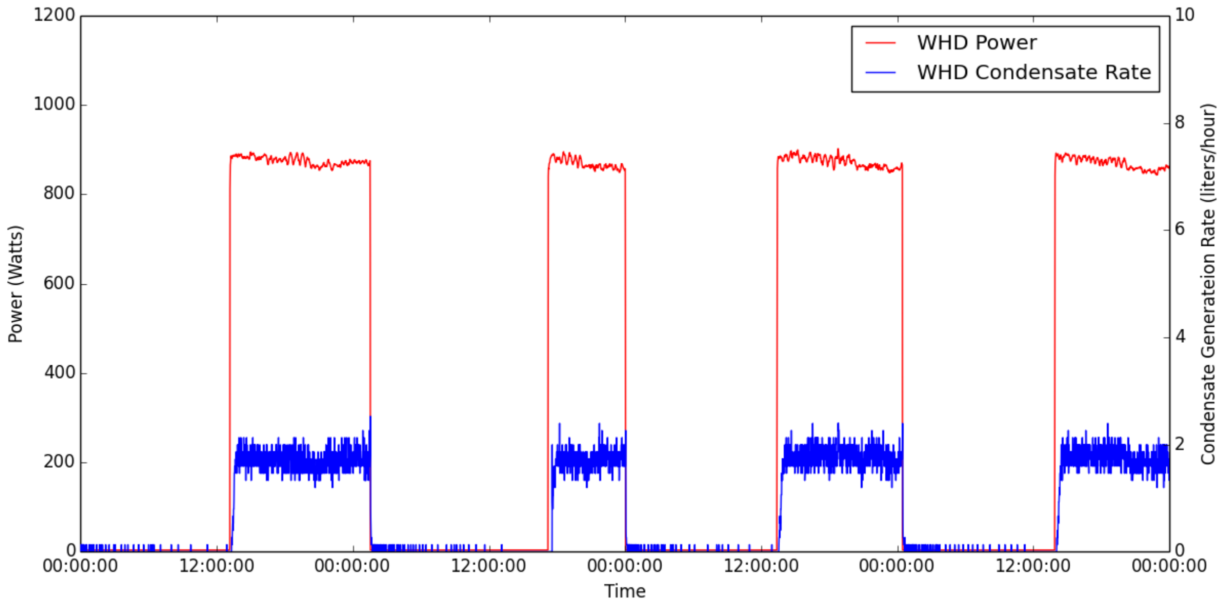

Figure 6-8 Typical WHD2 Compressor Cycle and Condensate Removal Rate (4 day view)

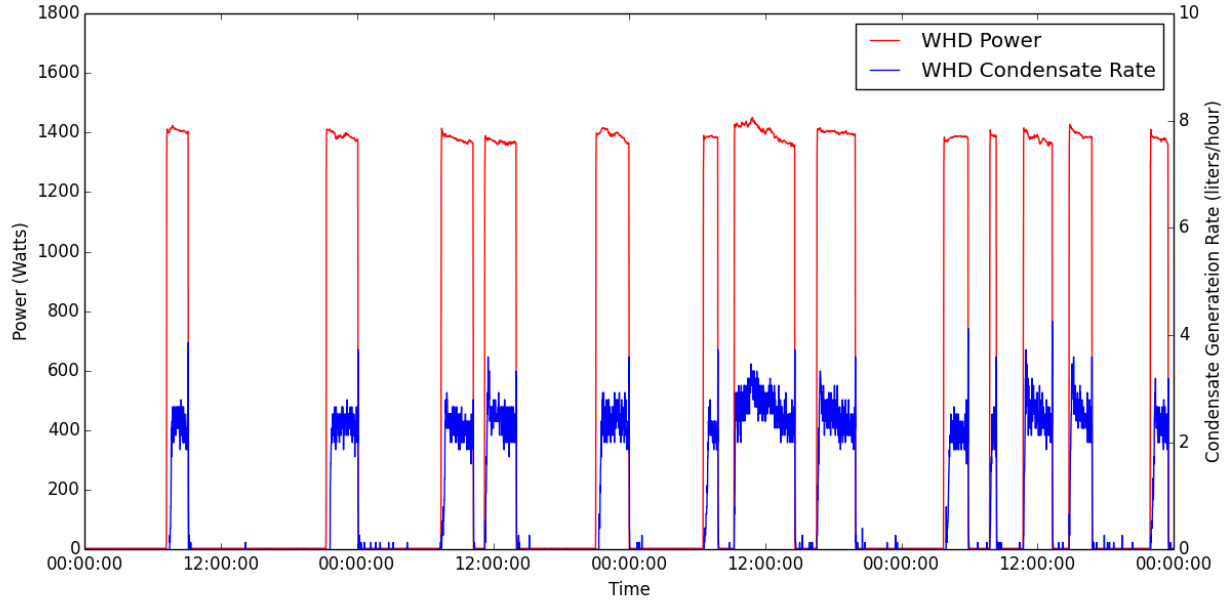

Figure 6-9 Typical WHD3 Compressor Cycle and Condensate Removal Rate (4 day view)

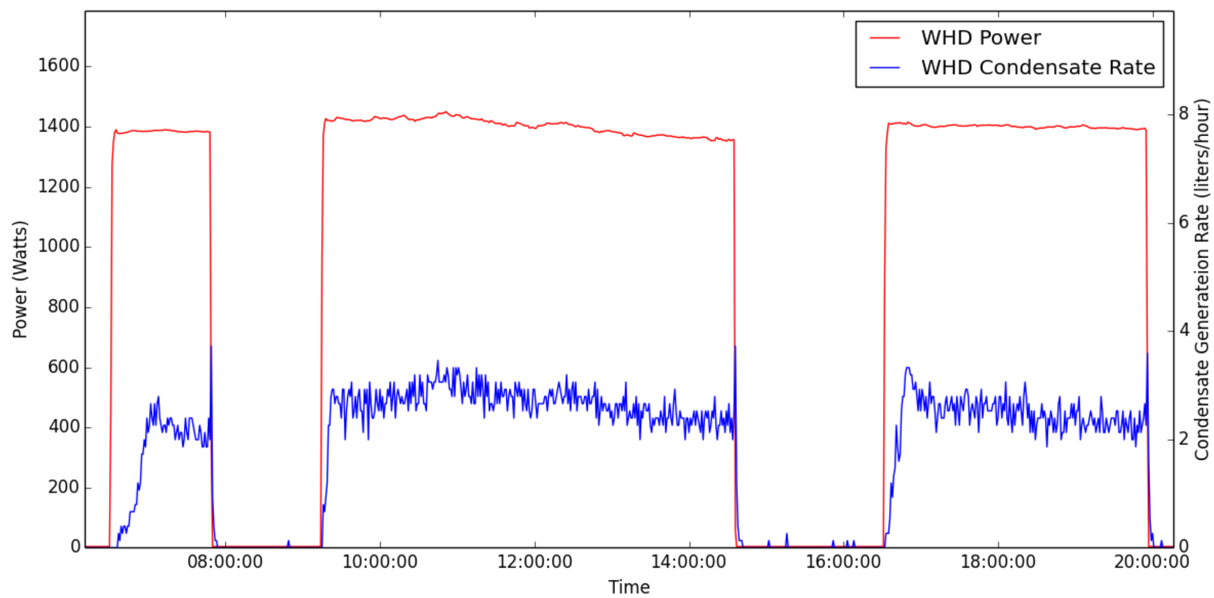

Figure 6-10 Compressor Cycle View with Condensate Removal Rate

6.7 Flow and Differential Pressure

Table 20 provides average values for the airflow through the dehumidifier while in compressor mode. The airflow had no significant trend (increase or decrease) over the metering period.

Table 20 Average Airflow during Compressor Mode by Site

Site	Airflow during Compressor Mode (CFM)	
	Average	Standard Deviation
WHD1	595.0	64.2
WHD2	343.0	6.7
WHD3	440.1	16.8

The differential pressure across the dehumidifier increased over the metering period. These effects can be seen in Figure 6-11 and in Table 21. On average, WHD1 had only a slight increasing trend (increasing from 0.11 inch WC in July 2014 to 0.15 inch WC in Jan 2015). WHD2 and WHD3 had more significant increases over the metering period with WHD2 starting at 0.28 inch WC and ending at 0.42 inch WC, and WHD3 starting at 0.22 inch WC and ending at 0.61 inch WC. Because the WHD's were part of large HVAC systems, any changes in pressure across the air distribution system could vary the pressure differential systematically. The increase could be caused by the filter, icing, and other possible issues. To confirm a cause for this observation, further investigation would be needed.

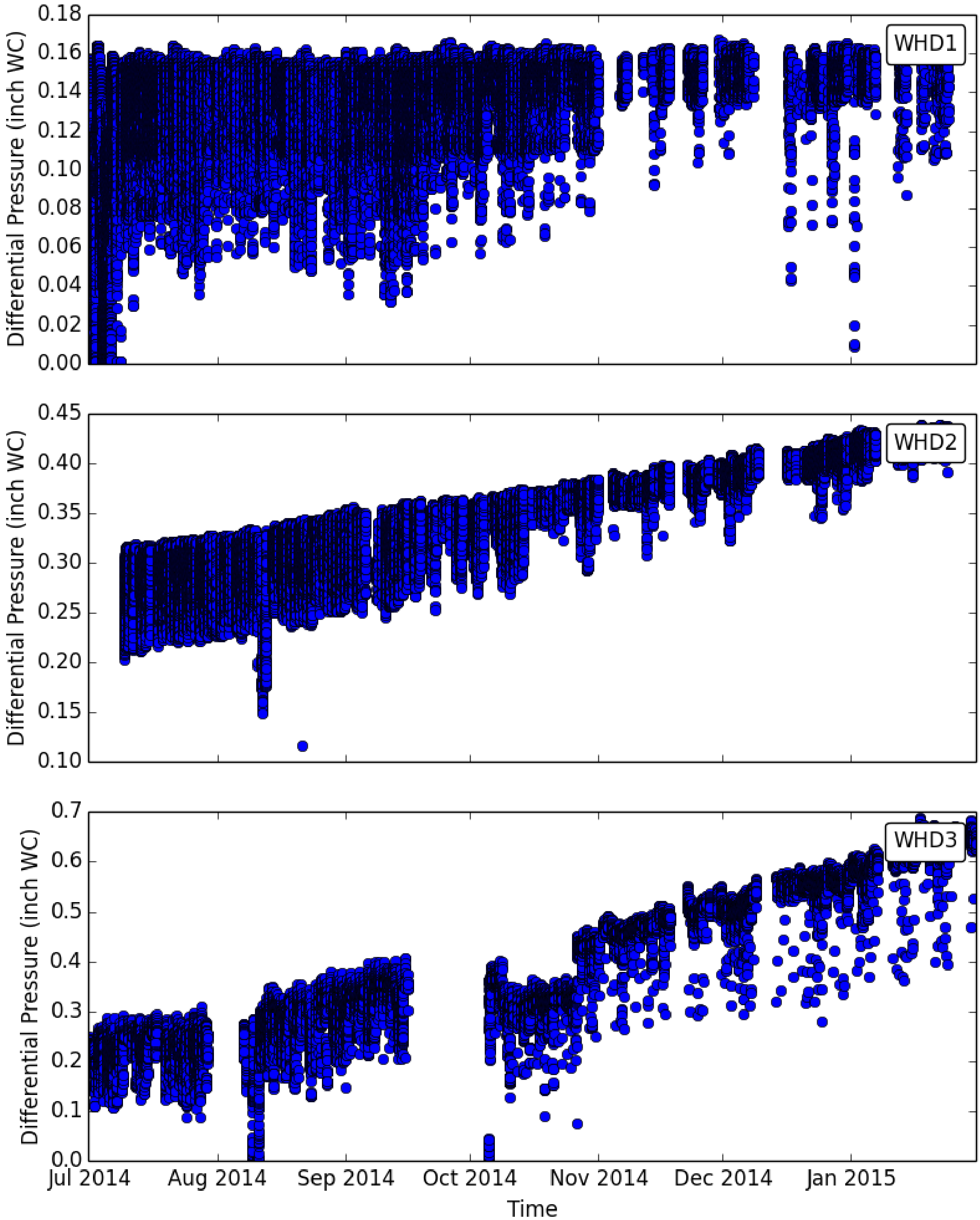

Figure 6-11 Differential Pressure during Compressor Mode Over Meter Period

Table 21 Average Differential Pressure by Site and Month

Month-Year	Average Differential Pressure (inch WC)		
	WHD1	WHD2	WHD3
Jul-14	0.11	0.28	0.22
Aug-14	0.13	0.29	0.26
Sep-14	0.13	0.32	0.32
Oct-14	0.14	0.35	0.34
Nov-14	0.15	0.38	0.47
Dec-14	0.15	0.40	0.53
Jan-15	0.15	0.42	0.61

6.8 Inlet and Outlet Conditions during Compressor Mode

The average inlet and outlet temperatures were similar for all three sites. The inlet temperature was typically between 72°F and 75°F with the outlet temperatures being between 90°F and 92.5°F. WHD3 had the largest change in relative humidity at -31.1%, however, WHD2 had on average the largest change in vapor density (at a difference of -4.3g/m^3 between inlet and outlet).

Table 22 WHD Inlet and Outlet Temperature

Site	Average Temperature (°F)		Difference (°F)	Standard Deviation (°F)	
	In	Out		In	Out
WHD1	73.2	90.0	16.8	2.3	4.0
WHD2	74.7	92.2	17.5	1.8	2.1
WHD3	72.4	92.5	20.1	1.0	2.4

Table 23 WHD Inlet and Outlet Relative Humidity

Site	Average Relative Humidity (%)		Difference (%)	Standard Deviation (%)	
	In	Out		In	Out
WHD1	46.3	18.5	-27.8	3.7	3.3
WHD2	42.2	13.0	-29.2	3.4	2.4
WHD3	47.1	16.0	-31.1	3.1	4.0

Table 24 WHD Inlet and Outlet Vapor Density

Site	Average Vapor Density (g/m^3)		Difference (g/m^3)	Standard Deviation (g/m^3)	
	In	Out		In	Out
WHD1	9.5	6.3	-3.2	1.0	1.0
WHD2	9.0	4.7	-4.3	0.6	0.7
WHD3	9.4	5.9	-3.5	0.7	1.2

6.9 Indoor Ambient Air Conditions

Table 25, Table 26, and Table 27 present the indoor data for average temperature, relative humidity, and vapor density respectively. The average indoor temperatures for the three sites was between 70°F and 76°F with minimal monthly deviation. The average indoor relative humidity was between 44% and 52% with vapor densities between 8.4 g/m^3 and 10.6 g/m^3. Indoor vapor densities tended to be higher between July and October for sites WHD1 and WHD3 whereas WHD2 was higher between September and December.

Table 25 Average Indoor Temperature by Site and Month

Month-Year	Indoor Temperature (°F)					
	WHD1		WHD2		WHD3	
	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
Jul-14	72.96	1.26	75.44	1.18	72.44	0.78
Aug-14	73.29	1.93	75.01	1.24	72.84	1.07
Sep-14	74.38	1.69	75.34	1.30	72.62	1.04
Oct-14	73.68	1.22	75.91	1.09	72.34	0.89
Nov-14	70.06	2.20	72.60	2.50	71.21	0.99
Dec-14	71.11	1.92	72.48	2.32	70.94	1.14
Jan-15	71.46	1.68	70.97	2.08	70.30	0.94

Table 26 Average Indoor Relative Humidity by Site and Month

Month-Year	Indoor Relative Humidity (%)					
	WHD1		WHD2		WHD3	
	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
Jul-14	50.15	4.10	44.68	2.67	52.97	3.08
Aug-14	51.15	4.86	45.28	2.45	51.68	2.72
Sep-14	49.01	5.35	47.17	2.98	51.97	2.57
Oct-14	47.53	4.90	49.36	2.93	50.45	1.97
Nov-14	45.53	2.99	50.25	2.85	47.81	2.60
Dec-14	44.81	3.10	50.83	2.58	48.99	2.65
Jan-15	44.08	3.29	49.78	3.37	47.75	3.00

Table 27 Average Indoor Vapor Density by Site and Month

Month-Year	Indoor Vapor Density (g/m^3)					
	WHD1		WHD2		WHD3	
	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
Jul-14	10.18	0.94	9.80	0.64	10.56	0.65
Aug-14	10.50	1.25	9.80	0.60	10.44	0.61
Sep-14	10.40	1.18	10.33	0.83	10.43	0.64
Oct-14	9.87	1.10	10.99	0.69	10.03	0.53
Nov-14	8.42	0.71	10.12	1.15	9.18	0.68
Dec-14	8.56	0.63	10.18	0.95	9.33	0.75
Jan-15	8.51	0.57	9.50	0.99	8.91	0.76

7 CONCLUSIONS

The primary goal of this study was to fill the gap of limited available energy consumption data for whole-home dehumidifiers. Although the results presented in this study are not statistically representative of whole-home dehumidifiers in the U.S., this study provided some basic knowledge and tentative conclusions about whole-home dehumidifier energy consumption, hours of use, and relation to outdoor environmental conditions.

We have learned that in a region where high humidity is prevalent, the most usage months measured were between July and September spending, on average for all three sites, between 30-46% of time in compressor mode (with site WHD1 spending about 62% of July in compressor mode). The least usage months were later in the year between November and January. Site WHD3 had a lower percent of time in compressor mode for the high usage months compared to other sites. In terms of efficiency, although site WHD3 had a higher capacity, its average condensate removal rate per unit power (1.56 liters/kWh) was lower than WHD1 and WHD2 at 1.97 and 2.05 liters/kWh respectively.

Average indoor conditions remained relatively consistent throughout the year, most likely due to the CAC. The average indoor temperature remained between 70°F and 75°F with the average indoor relative humidity remaining between 44% and 53%.

The whole-home dehumidifier's compressor operation correlated most with the outdoor temperature. The dehumidifier spent more time in compressor mode as the outdoor temperature increased. When outdoor temperature reached below 38°F, the compressor did not operate for any of the three sites. Accordingly, when outdoor temperature reached above 95°F, the dehumidifier spent between 60% and 75% of time in compressor mode. Outdoor vapor density also appeared to show a correlation with compressor operating time with higher outdoor vapor densities resulting in a higher percentage of time in compressor mode.

Additional field monitoring studies are needed to increase the data points, refine the analysis approach, and produce comparable results. A better understanding of how these systems perform in different climatic regions could only be attained by conducting similar studies in various locations. Other approach that compliments field data monitoring includes a nationwide survey to identify areas where the whole-home dehumidifiers have higher market penetration so that estimations of usage trends at national level could be made.

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