Title

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Publication Date
2014-09-23

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BERKELEY NATIONAL LABORATORY

Whole-Home Dehumidifiers: Field-Monitoring Study

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September 2014

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State, and Community Programs, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

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Definitions of Acronyms and Terms

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

1 INTRODUCTION

Excess humidity in a home is known to reduce indoor air quality, cause adverse health effects, and deteriorate structures, among other issues. To more precisely control and reduce the humidity level in their homes, occupants may choose to use either a portable unit dehumidifier or a whole-home dehumidifier (WHD). Installed in conjunction with a home's air-handling system, a WHD enables occupants to increase the dehumidifying capability of their air handler. Without a WHD, consumers must either lower the thermostat setting until the air conditioner turns on, or (less commonly) raise the thermostat setting until the heating turns on; both approaches remove moisture from the treated air. Although WHDs represent only a fraction of dehumidifier ownership, which comprises mostly portable units, in recent years there has been an increase in WHD use across the United States. WHDs most commonly are installed in homes in humid areas of the East, Midwest, and South.

The energy consumption of WHDs differs significantly among households, depending on frequency and duration of use, installation configuration, settings selected by the user, and exterior environmental conditions. Despite the observed increase in WHD use across the United States, there is little information or research focused on the energy consumption of WHDs, particularly as regards their performance in field applications (rather than laboratory analyses). Lawrence Berkeley National Laboratory (LBNL) initiated a WHD field-metering study to expand current knowledge of and obtain data on WHD operation and energy consumption in real-world applications. The field study collected real-time data on WHD energy consumption, along with information regarding housing characteristics, consumer behavior, and various outdoor conditions expected to affect WHD performance and efficiency. Although the metering study collected similar data regarding air conditioner operation, this report discusses only WHDs.

The primary objectives of the LBNL field-metering study are to (1) expand knowledge of the configurations, energy consumption profiles, consumer patterns of use (e.g., relative humidity [RH] settings), and environmental parameters of whole-home dehumidification systems; and (2) develop distributions of hours of dehumidifier operation in four operating modes: off, standby, fan-only, and compressor (also called dehumidification mode). Profiling energy consumption entails documenting the power consumption, duration of power consumption in different modes, condensate generation, and properties of output air of an installed system under field conditions of varying inlet air temperature and RH, as well as system configuration. This profiling provides a more detailed and deeper understanding of WHD operation and its complexities.

This report describes LBNL's whole-home dehumidification field-metering study conducted at four homes in Wisconsin and Florida. The initial phase of the WHD field-metering study was conducted on one home in Madison, Wisconsin, from June to December of 2013.[1] During a second phase, three Florida homes were metered from June to October of 2014. This report presents and examines data from the Wisconsin site and from the three Florida sites. We will perform additional data analysis after October 2014, when the Florida study will end.

Section 2 of this report discusses the use and operation of WHDs. Section 3 describes how sites were selected for the LBNL field study and the characteristics of the selected sites. Section 4 outlines the data-processing methods used in the study. Section 5 describes the data handling, Section 6 discusses results, and Section 7 provides conclusions regarding what the initial results suggest for energy use of WHDs.

2 PURPOSE AND OPERATION OF WHOLE-HOME DEHUMIDIFIERS

This section summarizes humidity, the means of measuring it, and the ways in which it affects occupant comfort, then explains how dehumidifiers operate to counteract excessive humidity in homes.

2.1 Humidity in Homes

Both homes that are highly energy efficient and those that are less energy efficient are prone to excessive humidity. In energy-efficient homes, air leakage is controlled through enhanced insulation, windows, and other building components. Those home improvements create tight, as opposed to leaky, buildings that can experience issues such as moisture buildup. Less energy-efficient (often poorly insulated) homes located in areas having warm, damp seasons also can experience high levels of indoor humidity. Moist air in a home contributes to the growth of mold, mildew, bacteria, and dust mites, which can reduce indoor air quality, cause adverse health effects, and, in the longer term, damage structures.

Absolute humidity, also termed vapor density, is a measure of water vapor per unit of air volume in grams per cubic meter (g/m^3). Relative humidity, a function of both the water content and temperature of ambient air, 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 temperature and pressure. The optimum RH level for a building generally is considered to be between 30 percent and 60 percent.[2] During the heating season in colder climates, however, recommended RH levels are 30 percent to 40 percent to prevent window condensation. Figure 1 shows the RH ranges related to indoor air quality and the various issues that accompany it. The red section of Figure 1 indicates the effects of humidity level on the given issues. The figure shows that the ideal range in RH for human comfort 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.

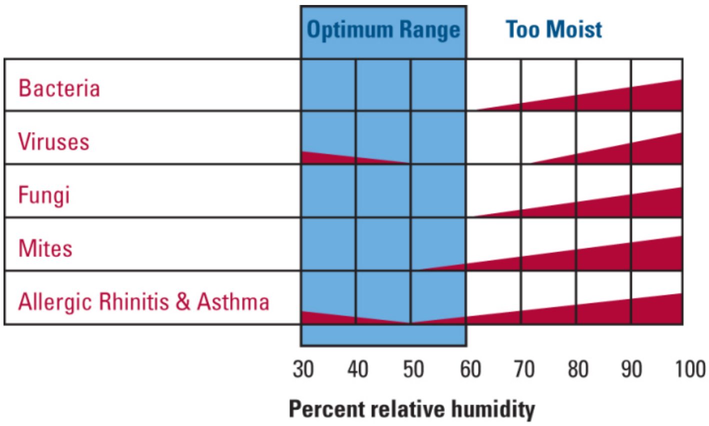


Figure 1 RH Ranges and Indoor Air Quality

2.2 Dehumidifier Components and Operation

WHDs, which operate in conjunction with a home's central air conditioner (CAC), can achieve and maintain a desired range of humidity in interior spaces. Most WHDs utilize mechanical/refrigerative technology, which comprises a compressor, cooling coils (an evaporator), heating coils, fan, humidistat, and condensate pump or drain connection.

Mechanical/refrigerative WHDs remove moisture by drawing humid air into the apparatus, passing it over the cooling coils (evaporator), where moisture condenses, and then passing it over a set of heating coils (the condenser) before returning the conditioned air to the home. The air returned to the home is drier and slightly warmer than when it entered the appliance. After the room reaches the set RH level, the WHD automatically cycles on and off to maintain that level. The moisture that condenses out of the air drips into drain line.

A WHD can operate in one of three different modes: *standby mode*, when it is ready to begin operation, but neither the fan nor compressor are running; *fan-only mode*, when the fan is running, but the compressor is not; and *compressor mode*, when both the fan and compressor are running and the dehumidifier is fully active.

3 SITE SELECTION AND CHARACTERISTICS

When selecting appropriate sites for our field study, we were careful to recruit, screen, and choose sites in an unbiased manner while also securing sites that were enough different from one another that they could provide various settings for obtaining data on WHD energy use. Obtaining energy use data that represents real-world variability in WHD system configuration and operation enabled us to be more confident that our results are representative of the larger market of WHD ownership.

3.1 Site Recruitment

To decide on the best locations to conduct our WHD field-metering study, we first contacted heating, ventilation, and air conditioning (HVAC) dealers and distributors across the country to identify regions having a (relatively) high occurrence of WHDs. To recruit potential site participants, we distributed fliers and posted advertisements about the study at selected public venues (such as stores) near Madison, Wisconsin, and Jacksonville, Florida. After receiving adequate responses, we contacted interested homeowners to further explain the study and obtain consent to collect additional information (which later was used to screen potential sites).

3.2 Screening Criteria

After launching our public search, we began to screen interested site participants. To be considered, sites had to meet the following criteria: (1) the site had and utilized a WHD, (2) the site was occupied by the homeowner, and (3) the WHD was used regularly or daily in conjunction with the home's air-handling system. Some potential study sites were rejected for at least one of the following reasons.

- The site could not be considered a typical WHD installation because the WHD had been customized significantly to fit with the air-handling system.
- There was no working connection between the WHD and the household ducting.
- The length of time the homeowner would own the home was uncertain.
- It would have been difficult to access the metering equipment after installing it.

After screening all candidate sites that met the minimum criteria, we assembled a list of potential participants. We then deployed a survey to those homeowners to collect information on their WHD system configurations, house characteristics, CAC systems, and any other mechanical ventilation and air distribution systems in their home, among other things. The site survey is outlined in Table 1.

Table 1 Site Survey for Potential Study Participants

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	Site visit scheduled
9	Number of people living in home?	19	What led you to install a whole-home dehumidifier?
10	Number of rooms in home?		

After receiving survey responses from potential study participants, we finalized our list and removed all contact information before beginning the selection process. The study sites were selected to represent a range of housing characteristics and WHD system configurations. After selecting the sites, we visited them to perform an initial check of the configuration and performance of the WHD in each home. The site visits also enabled us to finalize monitoring plans for each study site and gather information on the configuration of the WHD in connection with the home's air-handling system, the characteristics and controls of WHD operation, and potential locations for sensors and other metering equipment.

3.3 Site Characteristics

All four WHDs in the study are installed in single-family detached homes. One WHD was located in a Wisconsin basement (WHD-SiteA03), and three were installed in Florida attics (WHD-SiteB01, WHD-SiteB02, and WHD-SiteB03). Table 2 through Table 5 present basic descriptive information for each study home. Temperature set points for heating and cooling are as reported by homeowners. Dehumidifier control settings also are based on homeowner reports, which were confirmed, when feasible, by observation while installing monitoring equipment.

3.3.1 WHD-SiteA03

The WHD at WHD-SiteA03 (the Wisconsin site) was set to run throughout the year. The study site was selected because an advanced control system operated the WHD, enabling it to respond to dehumidification requirements of multiple zones.

One inlet air duct to the WHD took in air directly from the basement zone. A second duct took in air from the whole-home zone (return air) and the energy recovery ventilator (outdoor air), which was connected to the home's return air duct. A vertical duct exiting from the right side of the unit branched out to both the basement via a short duct and to the whole-home zones through connections to the supply air path of the air-handling system. Table 2 provides more information about WHD-SiteA03.

Table 2 WHD-SiteA03

Feature	Description
Type of home	Single-family detached with full basement and attached garage.
Year built	1990.
Size of home	First floor 1,496 sq ft; second floor 1,640 sq ft; basement 1,284 sq ft, of which 812 sq ft is finished space.
Construction type	Wood frame. Cast-in-place concrete with concrete-slab basement floor.
Number of occupants	2
Furnace model	American Standard AUY100R9V4W5 (natural gas forced-air furnace).
CAC model	Heil CA3036UKA1 (split-system CAC, evaporator coil in furnace plenum, condenser unit outside home).
Whole-home dehumidifier info	Brand A (installed 2005). Nominal capacity 90 pints/day, energy factor 2.2 liters/kWh. Nominal blower capacity 310 cfm at 0.4-inch water column pressure.
Central dehumidifier model	Model 2.
Energy recovery ventilator?	Yes.
Location of mechanical equipment	Basement, unfinished mechanical space.
Zoning	2
Ducting	Basement and risers to second floor. Supply and return registers in all finished spaces, including finished basement space.
Controls	Humidistat in basement for basement application and in various zones of the house for whole-home application. The energy recovery ventilator (ERV) nominally is controlled by a humidistat on the first floor.
Typical control settings	The RH set to 58%. Air conditioning set to 74 °F. Heating set to 71 °F. The humidifier control set to *off*. The ERV control set to *off* (the unit did not operate during the study).
Laundry location and venting	First floor. Dryer vented outside.
Moisture problems?	None reported.
Unusual moisture sources?	None identified.

3.3.2 WHD-SiteB01 through B03

The WHDs at all three Florida sites, WHD-SiteB01, WHD-Site B02, and WHD-Site B03, were set to run throughout the year. All the Florida units had simpler controls than did the Wisconsin site, because there was only one humidistat, which was located in a common area of the house served by the air-handling system and the WHD.

Air was drawn from the common return of the house and supplied through a duct to the inlet of the WHD. Dehumidified air was supplied back to the house through the main supply duct of the air-handling unit. Table 3 through Table 5 provide more information about each Florida site.

Table 3 WHD-SiteB01

Feature	Description
Type of home	Ranch.
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.
Central dehumidifier model	Model 1.
Energy recovery ventilator?	No.
Location of mechanical equipment	Attic—insulated above, under roof deck.
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 kitchen.
Moisture problems?	No
Unusual moisture sources?	No

Table 4 WHD-SiteB02

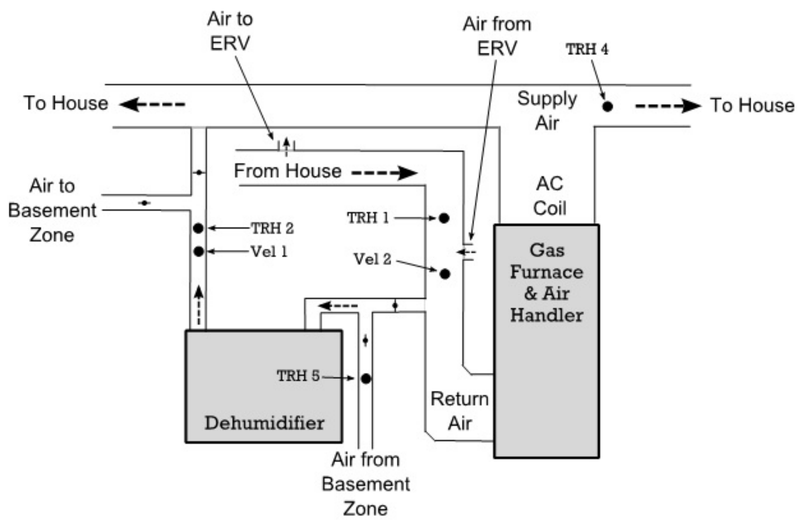
Feature	Description
Type of home	Colonial style.
Year built	1950.
Size of home	No information provided.
Construction type	Frame, brick face.
Number of occupants	4
Furnace model	Trane.
CAC model	Trane.
Whole-home dehumidifier info	Brand B.
Central dehumidifier model	Model 1.
Energy recovery ventilator?	No.
Location of mechanical equipment	Insulated attic.
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 5 WHD-SiteB03

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.
Central dehumidifier model	Model 2.
Energy recovery ventilator?	Yes.
Location of mechanical equipment	Insulated attic.
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 Dehumidifier Configurations

Each of the four study sites had a gas furnace, a CAC, and a WHD. Although installations were done according to manufacturer's recommendations, the system configurations, duct layouts, and equipment locations differed at each site. Figure 2 shows a typical WHD installation in relation to the air-handling equipment, direction of airflow, damper position, and placement of our meter and sensor. The primary sensor locations were (1) the incoming air to the WHD, which was drawn from the basement zone and the air handler return air; (2) exit air to the basement and house; (3) supply air to the house; and (4) return air from the house to the air handler.



Legend for Figure 2:

●	Sensor position
Vel 1	Pitot tube or averaging airflow station
TRH 1	Temperature & humidity sensor
-----➤	Airflow direction
⇢	Electric damper

Figure 2 Sample Ducting and Sensor Configuration

4 DATA COLLECTION

To collect data on the energy consumption and other variables related to the residential WHDs, we placed energy-metering devices and RH/temperature sensors in the four study sites. The WHD energy use data for the Wisconsin study site were recorded at one-second intervals for 7 months, from June through December 2013. The WHD energy use data for the Florida study sites were recorded at one-minute intervals from June 2014, continuing through October 2014. All measurements were carried out continuously under normal operating conditions. The LBNL team did not alter flows, suggest control settings, disable systems, or modify operation of the WHDs. Parameters recorded by the monitoring efforts included:

- temperature and RH of air entering and leaving the WHD,
- pressure differential across the WHD,
- power consumption of the WHD unit,
- outdoor air temperature and humidity,

- condensate volume, and
- indoor temperature and relative humidity.

All temperatures referred to in this study are dry-bulb temperatures.

4.6 Instrumentation

Temperature and RH were measured in the ducts connected to each WHD using analog output devices manufactured by Vaisala.[a] Airflow velocity devices (pitot tube and averaging airflow station) were connected to analog output pressure transducers manufactured by Setra.[b] Those analog signals served as inputs to a Campbell Scientific's CR1000 data acquisition system.[c] At each site, the CR1000 was installed with a battery backup power supply, a compact flash memory module having an Ethernet adaptor, and an RS 485 serial converter (for communication with electric power-monitoring devices). In addition to analog inputs, the CR1000 system monitored digital inputs from current switches, recorded pulses from condensate measurement devices, and queried power measurement devices. All inputs were recorded at one-second intervals. Onset temperature and RH sensors and loggers[d] were used to meter indoor and outdoor temperature and RH. Table 6 shows the parameters and measuring devices used in the field monitoring.

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[a] Vaisala–Energy. http://www.vaisala.com/en/energy/Pages/default.aspx. (Last accessed September 18, 2014.)

[b] Setra Sensing Solutions–Current. Energy Management: Current Switches and Transducers & Power Meter. www.setra.com/products/current/. (Last accessed September 18, 2014.)

[c] Campbell Scientific. CR1000 Measurement and Control Datalogger. www.campbellsci.com/cr1000. (Last accessed September 18, 2014.)

[d] Onset–HOBO Data Loggers. HOBO U12 Temperature/Relative Humidity Data Logger–U12-011. (Last accessed September 18, 2014.) www.onsetcomp.com/products/data-loggers/u12-011.

Table 6 Data Parameters and Measuring Devices Used for Monitoring

Data	Parameter	Measuring Device in WI	Measuring Device in FL
Energy Use	Total unit power	WattNode power meter, CR1000	WattNode WNB-3Y-208-P OptP3; Kh=0.01; CT=15 1 current transformer: CTT-0300-015
	CAC compressor, air handler power	WattNode power meter, CR1000	WattNode WNB-3Y-208-P, 100 Hz 2 CTs: ACT-075-050
	Status of compressor and fan	Veris H308, CR1000	WattNode WNB-3Y-208-P & 50-amp CTs; Onset UX-120-017M pulse recorder
System performance	Inlet and outlet temperatures and RH	Omega H94 series or similar sensor	Omega 44031-40-T thermistors & Omega HX94VW RH & temp probe
	Volumetric flow rate of blower	Pitot tube	Ebtron ELF-1000-D01 Thermal dispersion airflow measurement station, 0 to 5 VDC output, selectable input range, 0-500, to 0-3,000 FPM
	Pressure change (inlet, outlet)	Pitot tube	Omega Low Pressure Transducer PX277-05D5V
	Mass flow rate through condensate drain	Analog-output weight scale	Texas Electronics TR-4 rain gage
Environmental parameters	Indoor air temperature and RH	Onset data logger U12-011	Omega wireless RH & temp sensor UWRH-2-NEMA
	Outdoor air temperature and RH	Onset data logger U23-002 and RS3 shield	Omega wireless RH & temp sensor UWRH-2A-NEMA-M12

Section 4.2 through section 4.4 describe in greater detail how each parameter was measured. We discuss how the field equipment was used in the study, as well as, when appropriate, how equipment was set up, tested, and calibrated.

4.2 Power Measurement

Power measurements were collected using WattNode power meters[e] and Accu-CT current transformers.[f] A WattNode meter was installed in the main power distribution panel at each site, with the three channels connected to monitor power consumption of the furnace circuit (that is, the main air handler plus controls and other furnace components) and of the air conditioner condenser unit. In each case, both legs of the 240 V condenser circuit were monitored. At WHD-SiteB01, a second WattNode meter was placed in the main distribution panel to monitor energy consumption of the dehumidifier, which was located on a separate circuit. At WHD-SiteB02 and WHD-SiteB03, a second WattNode meter was placed in an enclosure near the dehumidifier, and the entire unit, the compressor, and the blower were monitored separately.

4.3 Condensate Measurement

On a WHD, a condensate pump must fill to the point of triggering a float switch before the pump cycles on to empty the condensate. The condensate pump produces a series of rapid pulses during operation. Measurements from the device are representative of total condensate production over time, but not the short-term rate of condensate production. This report presents volume per pulse, as calculated from mass per pulse based on an assumed density of water of 8.331 pounds per gallon. Tipping buckets measure water at a higher level of resolution, recording a pulse in response to just a few milliliters of condensate flow (see Table 7). However, the dynamics of condensate buildup on the dehumidifier coil and in the drain pan, surface tension, and possibly air pressure exerted by the dehumidifier blower on the condensate drain affected condensate flow from a unit, and condensate pulses often were delayed until after the start of dehumidifier operation and condensate production.

At WHD-SiteA03 there was not enough height above the floor to install a tipping bucket, and rigid ductwork connections made it impractical to lift a bucket higher. Thus it was impossible to collect condensate measurements at WHD-SiteA03.

Table 7 Condensate Pulse Factors

	WHD-SiteB01	WHD-SiteB02	WHD-SiteB03
Condensate volume per pulse	0.075 oz /pulse		
Condensate mass per pulse	0.00488 lb/pulse		

[e] Continental Control Systems LLC–WattNode® Pulse. www.ccontrolsys.com/w/WattNode_Pulse. (Last accessed September 18, 2014.)

[f] Continental Control Systems. Accu-CT®. www.ccontrolsys.com/w/News:Accu-CT_Released. (Last accessed September 18, 2014.)

4.4 Measurement of Static Pressure Across Dehumidifier

During our first visit to the three Florida sites, we measured the external static pressure across the dehumidifier (the pressure differential between the inlet and outlet ducts) while the unit was operating. The measurements were made by placing static pressure probes in the entry and exit ducts. The ducts were connected to the dehumidifier, with no more than one duct elbow between the probe and dehumidifier. The operating status of the system and the static pressures are shown in Table 8. The external and static pressures for site WHD-SiteA03 were not measured.

Table 8 Static Pressure across WHD Systems

Operating Status	WHD-SiteB01 (inch WC*)	WHD-SiteB02 (inch WC)	WHD-SiteB03 (inch WC)
Dehumidifier blower ON; air handler blower OFF	0.14–0.16	0.32	0.23
Dehumidifier blower ON; air handler blower ON	0.085–0.090 fans on low speed	0.26–0.27 fans on low speed 0.22–0.23 fans on high speed	0.18–0.19 fans on low speed 0.11 fans on high speed

* IWC = inches of water column.

5 DATA PROCESSING

This section describes LBNL's methods for cleaning, aggregating, and analyzing the WHD data obtained from the four study sites. The power consumption data were processed to develop profiles of energy use, duration of operational mode, air temperature, and RH for each of the four study sites. The methods employed are described in greater detail below. Data processing included cleaning and aggregating the data.

5.1 Data Cleaning

Table 9 summarizes missing or invalid data for the four sites. Site WHD-A03 had a 9-day gap in records from July 3 to July 12, 2013. Except for 4 other days during which a few data were missing, the rest of this site data were retrieved. Data for site WHD-B01 was missing only one minute in the 1,440-minute data set. Data from site WHD-B02 contained a 30-day gap because of a power failure. Site WHD-B03 contained a complete set of records for the entire duration of metering.

Table 9 Summary of Missing Data

Site	Start date	End Date	Days with Missing data
WHD-A03	June 26, 2013	December 12, 2013	6/26/2013 (49% missing)* 7/3/2013 (35% missing) 7/4/2013–7/11/2013 (100% missing) 7/12/2013 (46% missing) 8/1/2013 (18 records missing) 8/5/2013 (23 records missing) 8/9/2013 (5 records missing) 11/4/2013 (2 records missing) 12/12/2013 (96% missing)*
WHD-B01	June 20, 2014	July 31, 2014	6/20/2014 (28% missing)* 7/9/2014 (1 record missing)
WHD-B02	June 10, 2014	July 31, 2014	6/10/2014 (45% missing)* 6/22/2014 (93% missing) 6/23/2014–7/22/2014 (100% missing) 7/23/2014 (15% missing)
WHD-B03	June 15, 2014	July 28, 2014	6/15/2014 (53% missing)* 7/28/2014 (70% missing)*

*Indicates a start or end date for which records are complete until or after the end or start time.

5.2 Data Aggregation

Data for the Wisconsin site, WHD-A03, which were recorded at one-second intervals from June 26 to December 12, 2013, were contained in 26 separate files. After each file was processed and abridged into a one-minute (rather than one-second) interval, all the data files were combined. The Wisconsin data were aggregated into one-minute data for easier manipulation to prepare for analysis and for comparison to the three Florida sites (which were metered at one-minute intervals). The data for the three Florida sites and site WHD-A03 were combined into a single file.

After all the data from all four sites were compiled into a single data table, they were screened for errors. Efforts included filtering records that contained improperly reported or missing data. Site WHD-B02 contained 2,729 records that were missing power consumption data because of a malfunction of the metering equipment. Table 10 summarizes the number of records used for each metered site.

Table 10 Site Records

Site	Initial Number of Records (Minutes)
WHD-A03	229,993
WHD-B01	60,073
WHD-B02	29,477
WHD-B03	61,596

6 RESULTS

This section presents the results of analyzing the data collected from the four WHD systems in our field study. We first present distribution profiles of power consumption, then examine the percent of time each WDH spent in each operational mode and the associated energy use. Finally, we explore 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.

6.1 Profiles of Power Consumption

Figure 3 presents the frequency distribution of the power consumption data for all four study sites. The information was used to determine the ranges in power demand ranges for each operational mode. Four distinct ranges can be observed in Figure 3: 0 watt consumption (off mode), greater than 0 watts but less than 50 watts (standby mode), greater than 50 but less than 500 watts (fan mode), and greater than 500 watts (compressor mode). Except for WHD-SiteA03, data from the test sites demonstrate two peaks, one that indicates compressor operation, and another that indicates standby mode. At WHD-SiteA03, data for the unit seemed to show a peak for standby mode and another for fan mode, in addition to a peak for compressor operation.

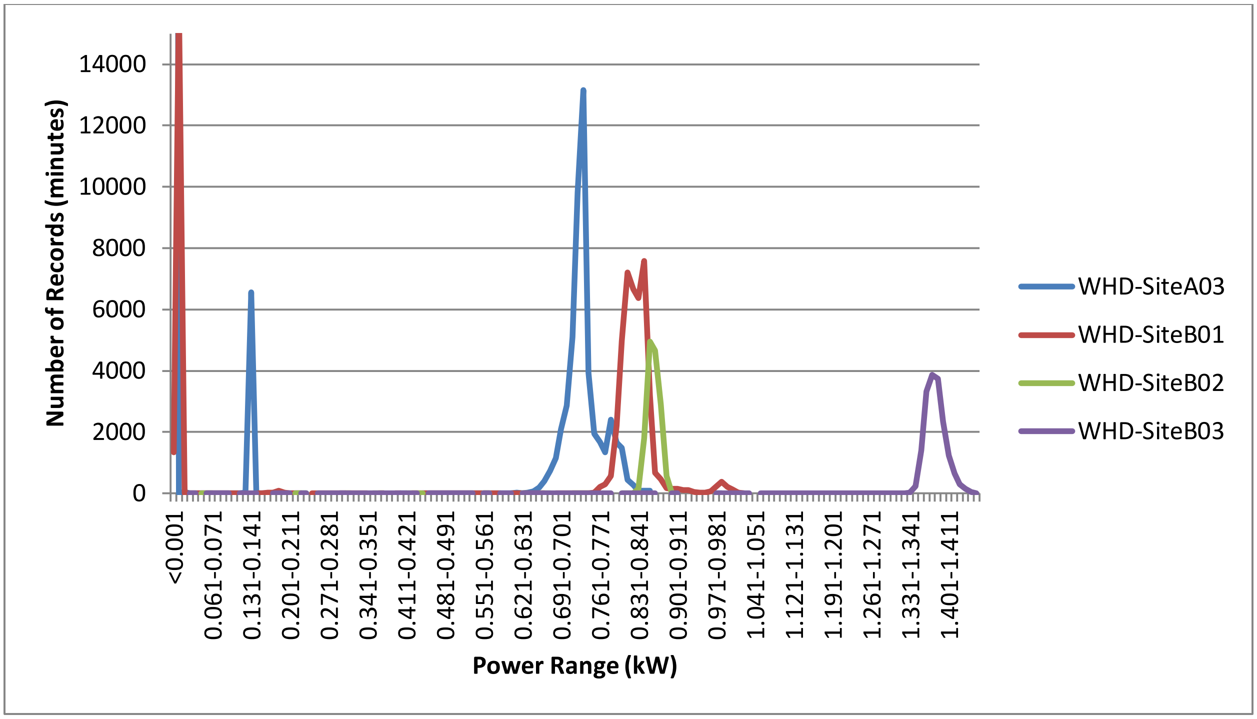


Figure 3 Ranges in Energy Use for Whole-Home Dehumidifiers

6.2 Time Series of Power Consumption

In addition to developing profiles of power consumption for the four study sites, we also used the data to develop time series of energy use for each site.

6.2.1 WHD-SiteA03

The compressor at WHD-SiteA03 cycled frequently, as shown on Figure 4 and Figure 5. On average, the number of cycles per day was about 23 (about one cycle each hour). The unit operated in compressor mode almost constantly between mid-August and mid-September. Most likely because of decreased demand for dehumidification, the frequency of compressor cycles diminished beginning in the middle of September, when the unit spent more time in fan mode.

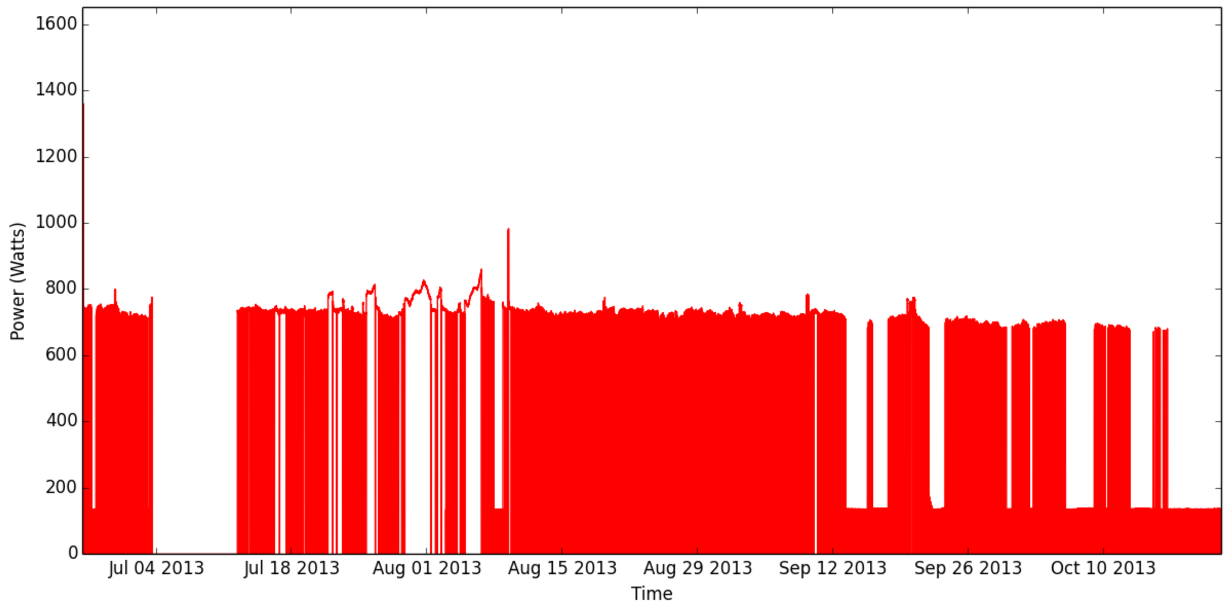


Figure 4 Plot of Power Consumption Throughout Monitoring Period for WHD-SiteA03

The 48-hour plot (Figure 5) shows that the compressor cycled less frequently, but each cycle lasted longer, between early morning and early afternoon than during late afternoon or evening hours. The compressor power consumption gradually decreased during the monitoring period (July to October). Data from late October to December (not shown in Figure 4) indicate no compressor operation.

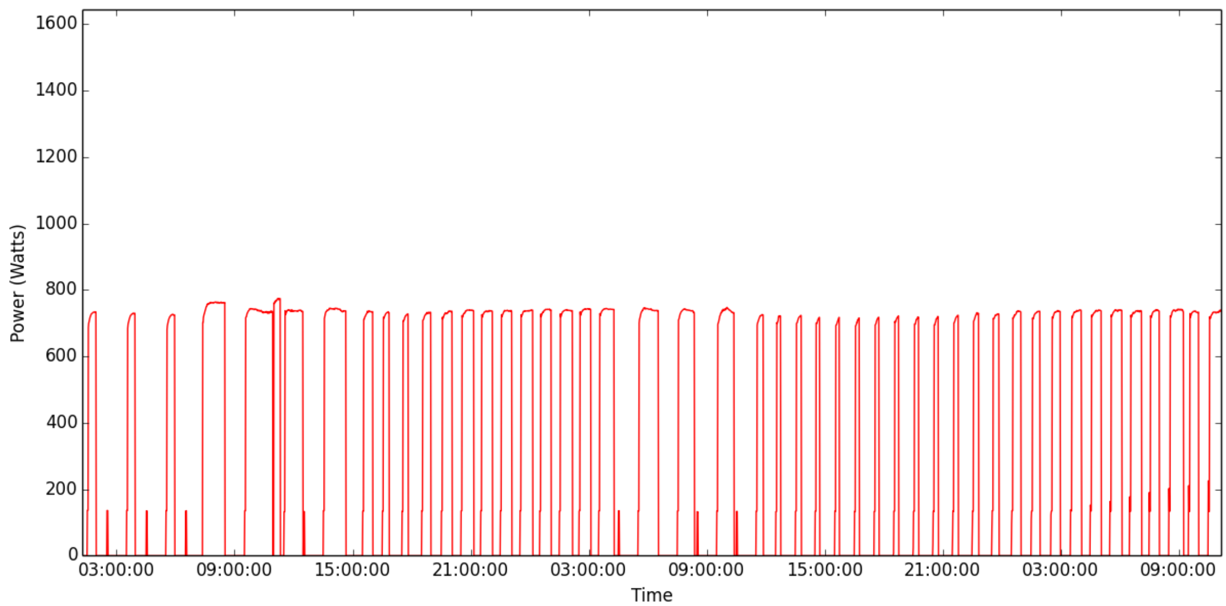


Figure 5 Typical 48-Hour Plot of Power Consumption Plot for WHD-SiteA03

6.2.2 WHD-SiteB01

Figure 6 and Figure 7 illustrate irregular compressor operation at WHD-SiteB01: long cycles occurred primarily in late June and early July, likely indicating that increased dehumidification was required for those months.

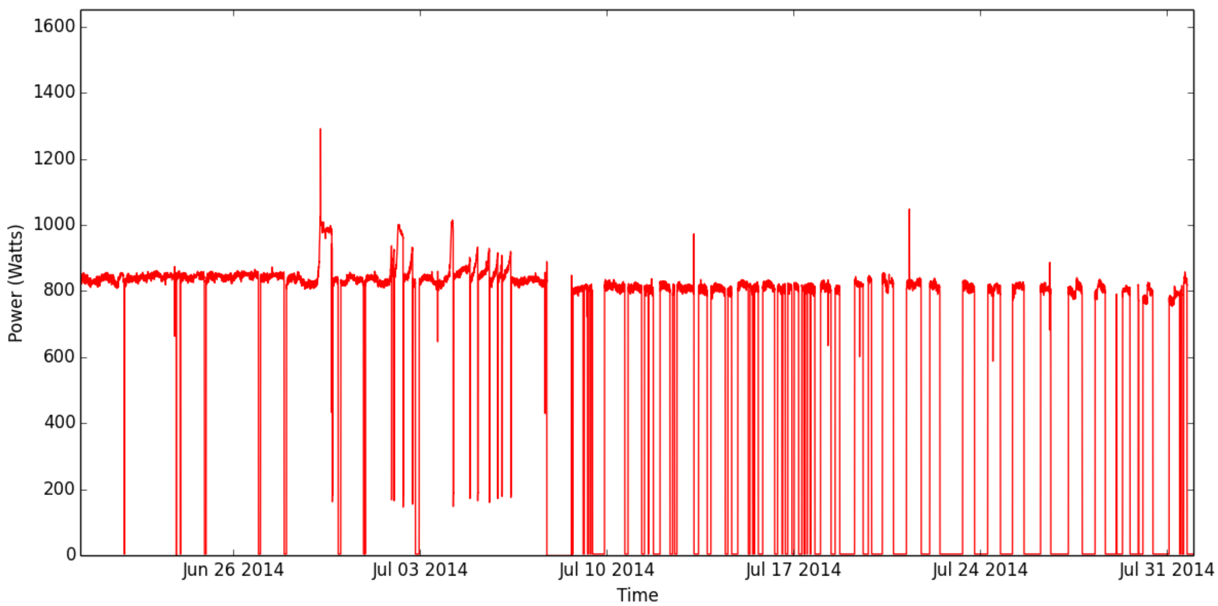


Figure 6 Plot of Energy Use for June-July for WHD-SiteB01

The 48-hour plot of typical power consumption for WHD-SiteB01 (Figure 7) shows compressor run times that ranged from 2 to 10 hours.

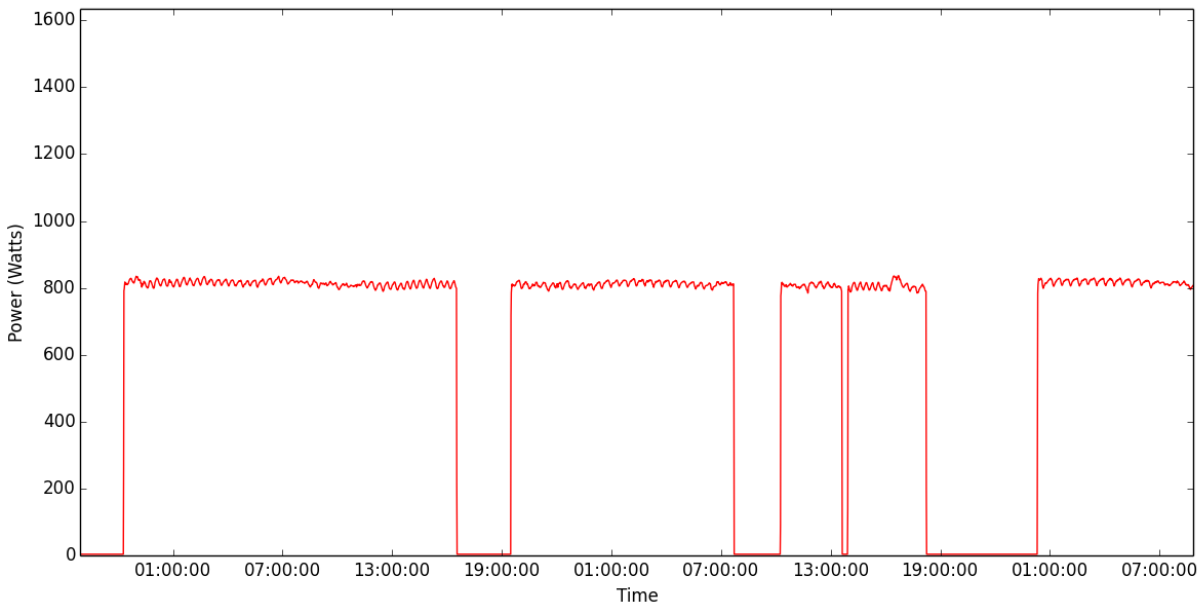


Figure 7 Typical 48-Hour Plot of Power Consumption for WHD-SiteB01

6.2.3 WHD-SiteB02

The power consumption profile for June and July for WHD-SiteB02 (Figure 8) illustrates the lack of data during about two weeks when the power supply to the unit was disrupted. The typical 48-hour profile (Figure 9) indicates that the compressor ran continuously for approximately 12 hours during each cycle.

Although the whole-home dehumidifiers at WHD-SiteB01 and WHD-SiteB02 are the same make and model, their operation and control differ. The compressor at WHD-SiteB02 demonstrated consistent periods of operation throughout the study, unlike the system at WHD-SiteB01.

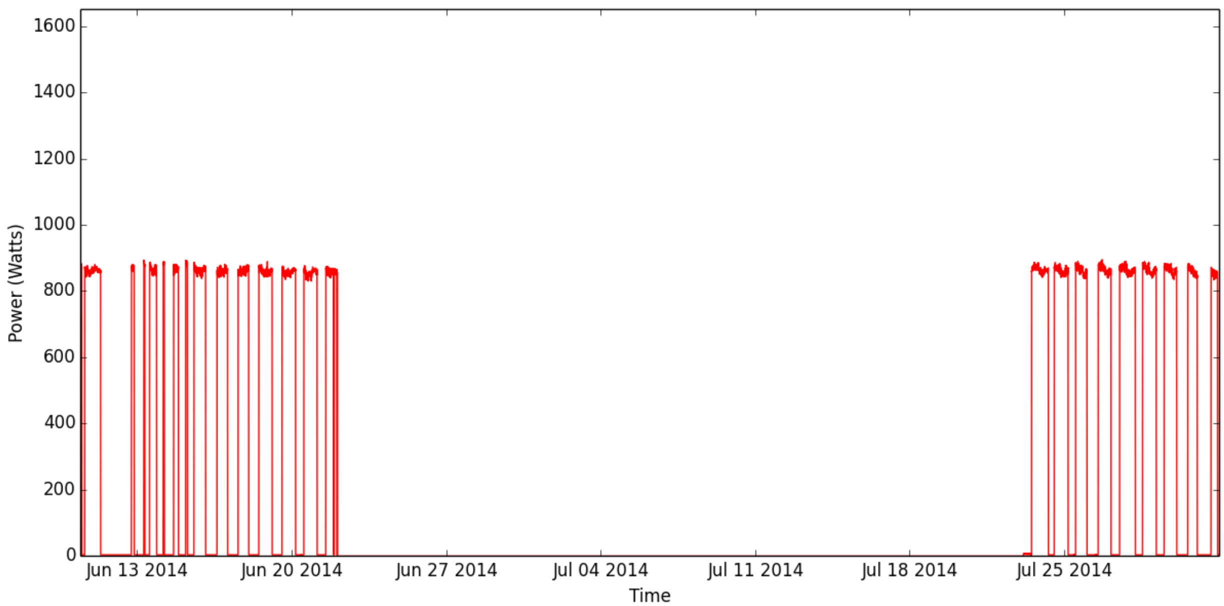


Figure 8 Plot of Power Consumption for Power Consumption June-July for WHD-SiteB02

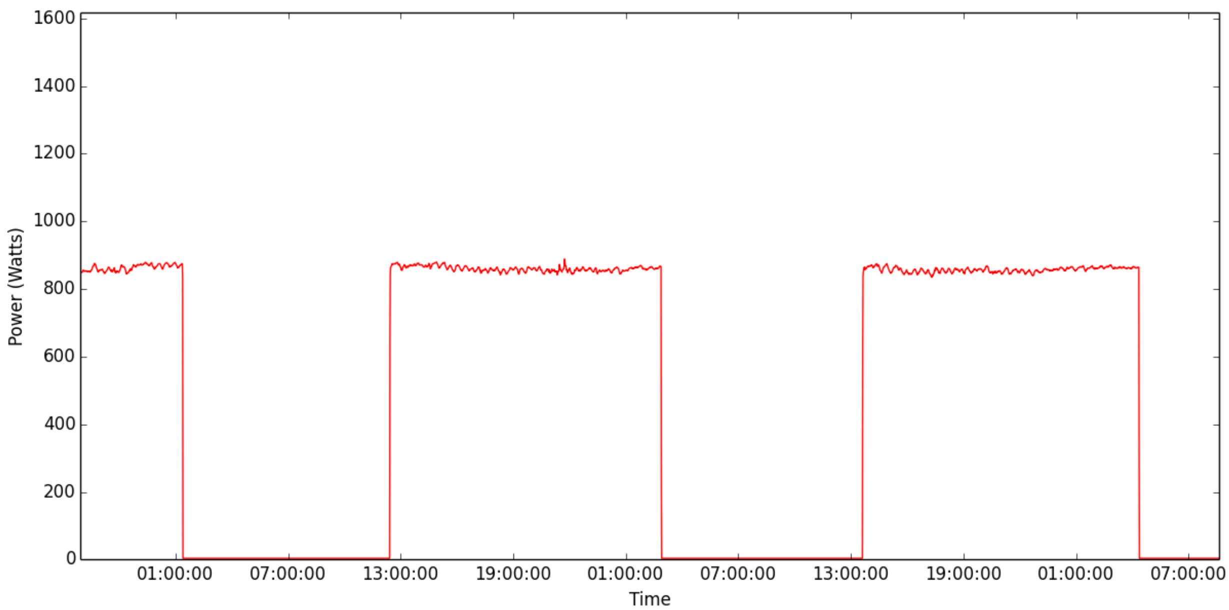


Figure 9 Typical 48-Hour Plot of Power Consumption for WHD-SiteB02

6.2.4 WHD-SiteB03

The whole-home dehumidifier at site WHD-SiteB03 is the same brand as the units at WHD-SiteB01 and WHD-SiteB02, but has a higher capacity. It operates at a higher wattage but appears to run less frequently (about 2 to 3 cycles per day). Figure 10 and Figure 11 show plots of power consumption for June-July and a typical 48-hour for WHD-SiteB03.

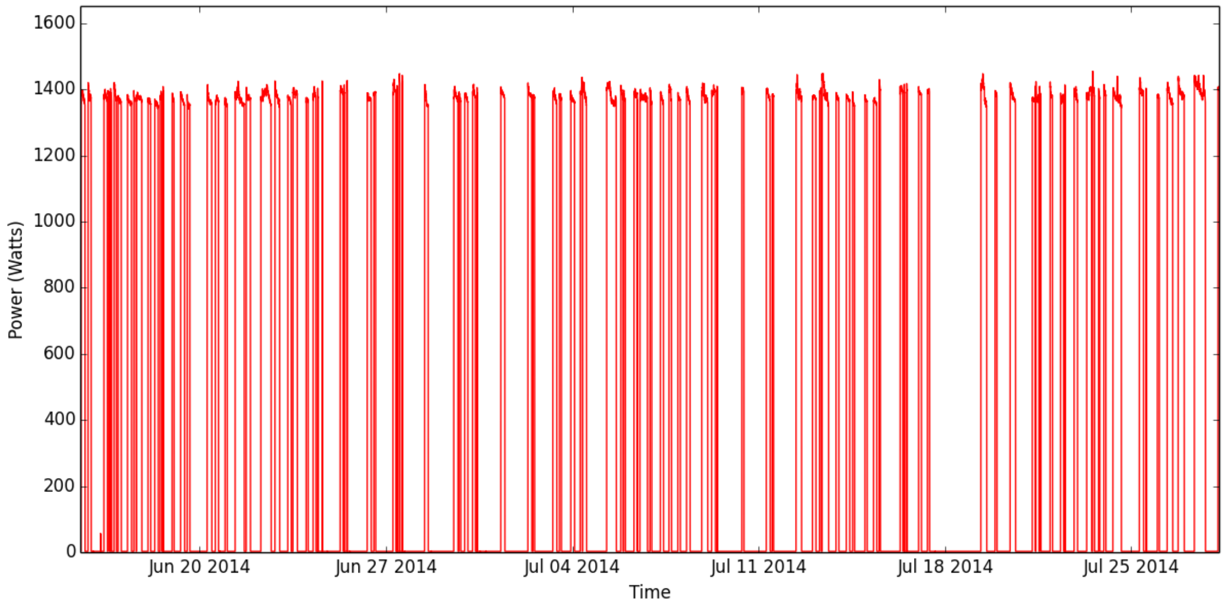


Figure 10 Plot of Power Consumption for June-July for WHD-SiteB03

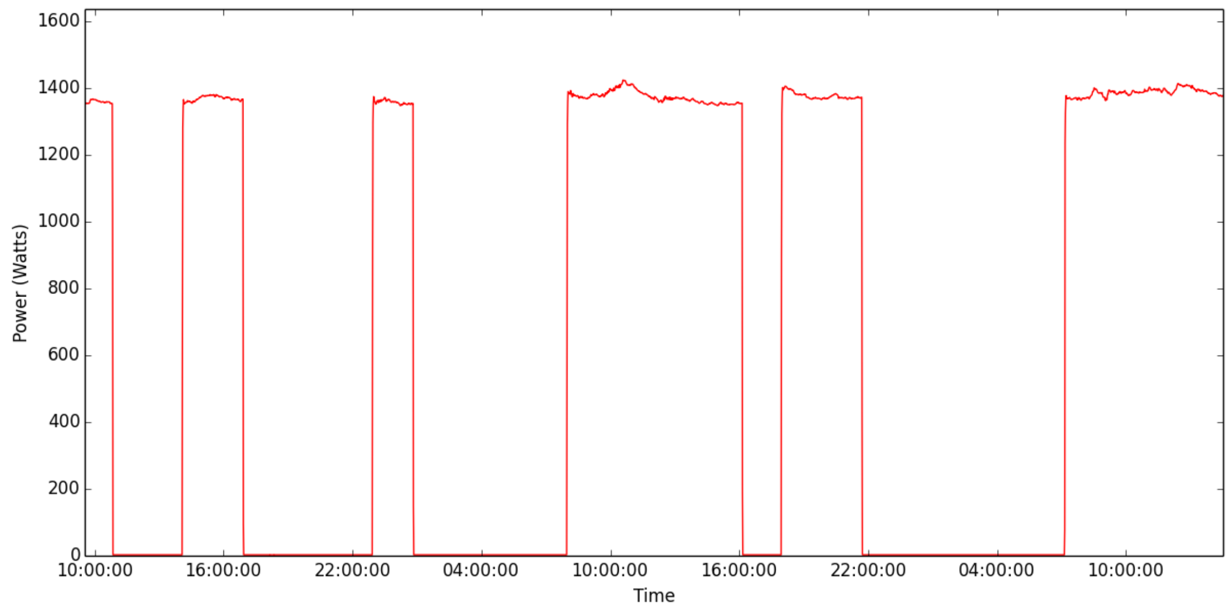


Figure 11 Typical 48-Hour Plot of Power Consumption for WHD-SiteB03

The controls for the Wisconsin site, WHD-SiteA03, differ significantly from those at the three Florida sites, which would account for the differences in cycle times. The WHD at the Wisconsin site is a different brand than those at the Florida sites. All three Florida WHDs were the same brand, so the control systems for those WHDs are similar.

6.3 Time Spent in Each Operational Mode

Table 11 lists the time the WHD spent in each operational mode for the four study sites. For the three Florida WHDs sites, most of the time was spent in either standby mode (27 percent to 71 percent of the time) or compressor mode (28 percent to 72 percent of the time). The whole-year data for the Wisconsin site (WHD-SiteA03) indicate primarily off mode (63 percent of the time), followed by compressor mode, indicating many months in which the compressor was not used much (i.e., was in off mode). The difference in time spent in off mode also may reflect the different control strategies at the Wisconsin and Florida sites and also geographical locations.

Based on our data, the WHDs spent close to zero hours in fan-only mode. Although a small percentage of time was recorded for fan-only mode at WHD-SiteA03, the other two Florida sites registered almost no fan-only operation (less than 0.5 percent of the test period). This result reflects the fact that the humidistats for the WHDs in Florida did not offer a control option of fan-only mode. The manufacturer, however, provides instructions for an option to run only the fan by modifying the connection between two wires.

Table 11 Time Spent in Each Operational Mode

Operational Mode	Range in Power Demand	WHD-SiteA03 (%)	WHD-SiteB01 (%)	WHD-SiteB02 (%)	WHD-SiteB03 (%)
Off	0 watts	63.1	2.2	0.0%	0
Standby	0 watts < demand < 50 watts	0	26.8	48.8%	71.5
Fan	50 watts ≤ demand < 500 watts	4.3	0.4	0.1%	0.1
Compressor	500 watts ≤ demand	32.7	70.5	51.1%	28.4

6.4 Average Power Consumption by Operational Mode

Data on fan power were recorded mostly at the start of a compressor cycle. Based on the very few data available for fan-only mode, fan power was between 221 and 285 watts. Site WHD-B03 consumed more power than the other two Florida sites because the dehumidifier has a larger capacity.

The average standby power for the three Florida sites ranged from 4 to 5 watts. Standby power for the Wisconsin site, at 19.5 watts, was considerably higher than that of the Florida sites. On the other hand, fan power for the Wisconsin site, at 136 watts, was considerably lower than that of the Florida sites. The average compressor power differed among the four sites. Table 12 shows the average power consumed in each operational mode for each of the four study sites.

Table 12 Average Power for Each Operational Mode

Site	Average Standby Mode Power (watts)	Average Fan Mode Power (watts)	Average Compressor Mode Power (watts)
WHD-SiteA03 (WI Site)	19.5	136.4	737.1
WHD-SiteB01	5.0	221.1	832.5
WHD-SiteB02	4.1	285.1	862.0
WHD-SiteB03	4.0	281.6	1,377.9
Average of FL Sites (B01-B03)	**4.7**	**259.2**	**1,102.3**

Table 13 lists the standard deviations for the power consumptions recorded for each mode at each of the four sites.

Table 13 Average Standard Deviation for Power Consumption by Site and Mode

Site	Standard Deviation, Standby Power (watts)	Standard Deviation, Average Fan Power (watts)	Standard Deviation, Average Compressor Power (watts)
WHD-SiteA03	8.1	18.3	32.5
WHD-SiteB01	0.5	91.4	34.2
WHD-SiteB02	0.6	122.0	12.6
WHD-SiteB03	0.3	142.4	49.7

6.5 Average Daily Energy Use

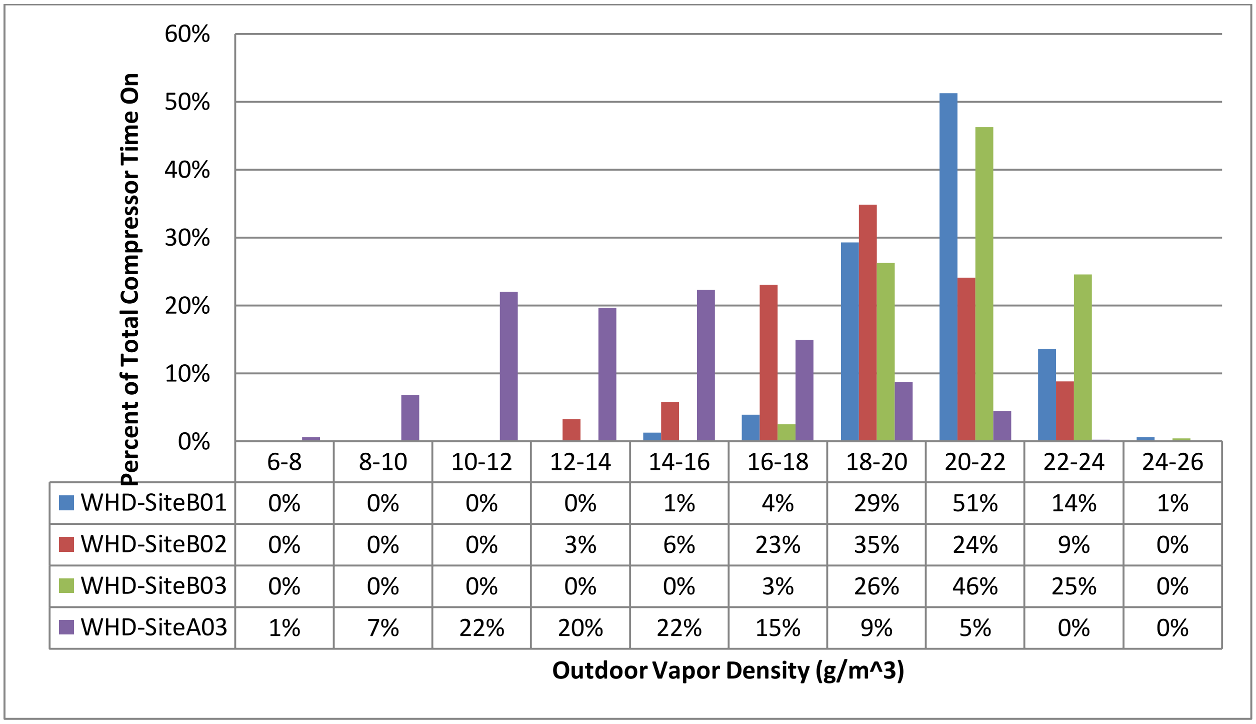
Table 14 shows the average daily energy use in kilowatt-hours (kWh) for each study site. The table also gives the standard deviations for each average. Although the WHD at WHD-SiteB03 ran at a higher overall average power (1,377 watts) than the other two Florida WHDs, the unit maintained a lower average daily energy use. Given that the three Florida sites are all located in the same relatively small area, and likely face similar dehumidification loads, the lower energy use for WHD-SiteB03 could reflect its shorter compressor run times.

Table 14 Average Daily Energy Use

Site	Average Daily Energy Use (kWh)	Standard Deviation (kWh)
WHD-SiteA03	5.65	4.85
WHD-SiteB01	14.05	5.15
WHD-SiteB02	10.41	3.19
WHD-SiteB03	9.40	4.32

6.6 Operational Mode Related to Outdoor Conditions

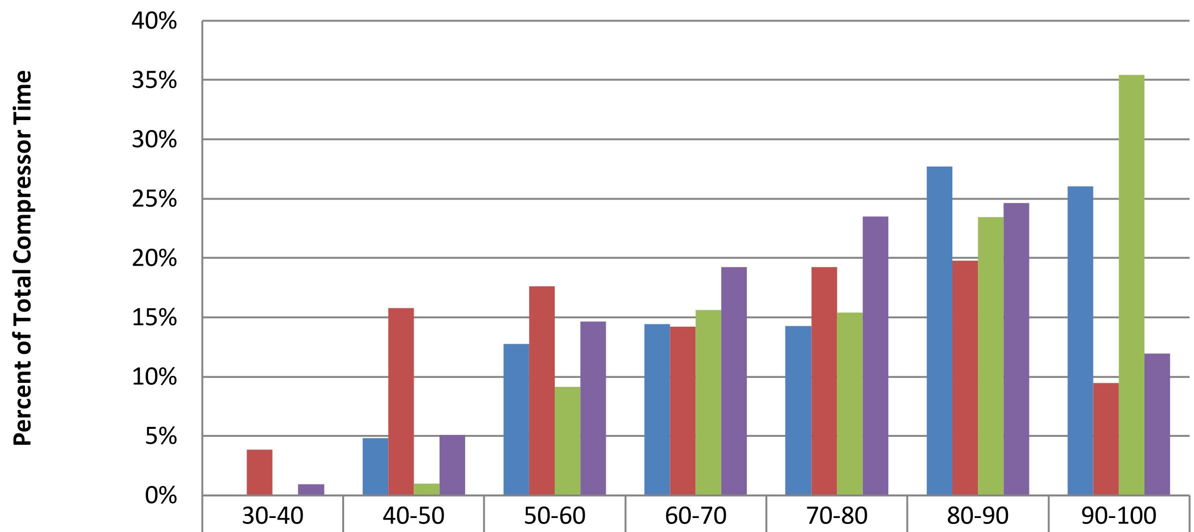
For each WHD site, we calculated the outdoor vapor density and the percent of time the unit operated in compressor mode for each range of vapor densities. Figure 12 shows for how long each range of outdoor air vapor density occurred at each site. All compressors operated longer when outdoor vapor density was higher, particularly for the units in Florida. Vapor densities between 18 and 22 g/m^3 were associated with approximately 80 percent of compressor run time at the Florida sites. At the Wisconsin site, a significantly lower range in vapor density, 10 to 16 g/m^3, accounted for about 60 percent of compressor operation.



	6-8	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24	24-26
WHD-SiteB01	0%	0%	0%	0%	1%	4%	29%	51%	14%	1%
WHD-SiteB02	0%	0%	0%	3%	6%	23%	35%	24%	9%	0%
WHD-SiteB03	0%	0%	0%	0%	0%	3%	26%	46%	25%	0%
WHD-SiteA03	1%	7%	22%	20%	22%	15%	9%	5%	0%	0%

Figure 12 Percent of Total Compressor Time Spent in Each Range of Outdoor Vapor Density

Figure 13 presents similar results for all four sites as a function of outdoor relative humidity. At all the sites, most of the time spent in compressor mode occurred when the humidity exceeded 60 percent. Figure 12 and Figure 13 appear to indicate that outdoor humidity is a better indicator of compressor run time than is outdoor vapor density. As the LBNL metering effort continues, indoor temperature, humidity, and vapor density will be examined in relation to outdoor ambient conditions.



	30-40	40-50	50-60	60-70	70-80	80-90	90-100
WHD-SiteB01	0.00%	4.83%	12.74%	14.43%	14.26%	27.71%	26.03%
WHD-SiteB02	3.87%	15.80%	17.59%	14.23%	19.24%	19.80%	9.48%
WHD-SiteB03	0.00%	0.96%	9.16%	15.59%	15.43%	23.45%	35.41%
WHD-SiteA03	0.95%	5.10%	14.64%	19.22%	23.52%	24.62%	11.95%

Figure 13 Percentage of Total Compressor Time Spent in Each Range of Outdoor Humidity

6.7 Dehumidifier Condensate

The field study used rain gauge tipping buckets to measure the amount of condensate generated at the three Florida sites. Each tip of the bucket was equal to 0.075 oz (about 2.2 milliliters) of condensate. Because the measurements were recorded at one-minute intervals, we were able to calculate the rate of condensate generation. Typical rates of condensate generation during compressor cycles for each of the three Florida sites are shown in Figure 14 through Figure 16. In the figures, compressor wattage is shown in red and read off the left vertical axis; condensate is shown in blue and read off the right vertical axis.

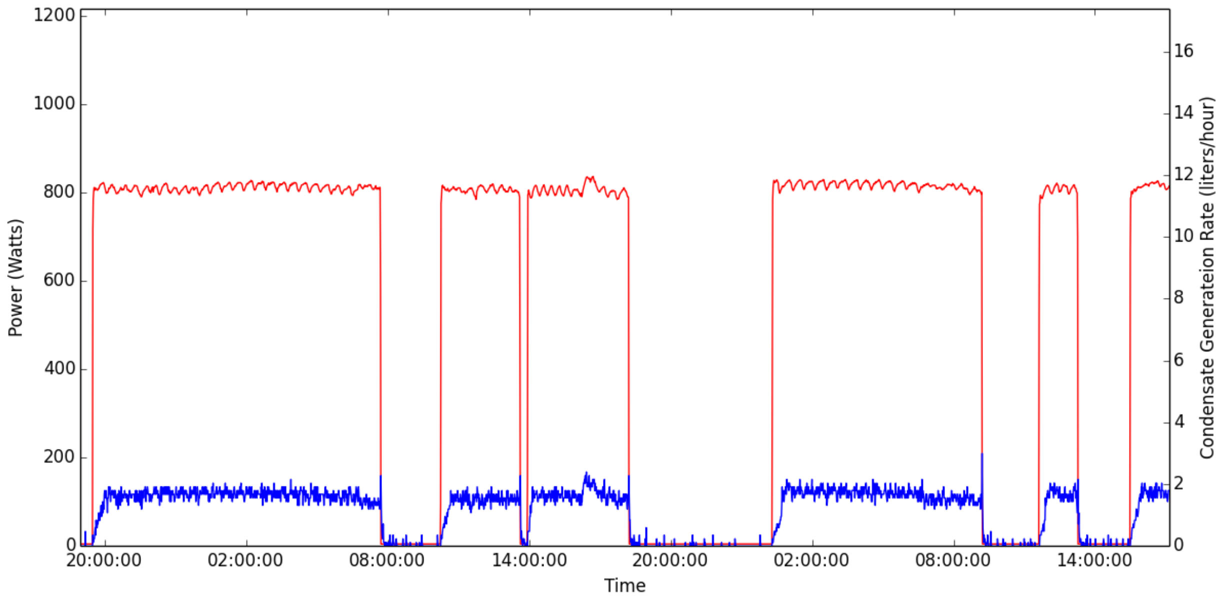


Figure 14 Typical Compressor Cycles and Condensate Removal Time Series for Site WHD-SiteB01

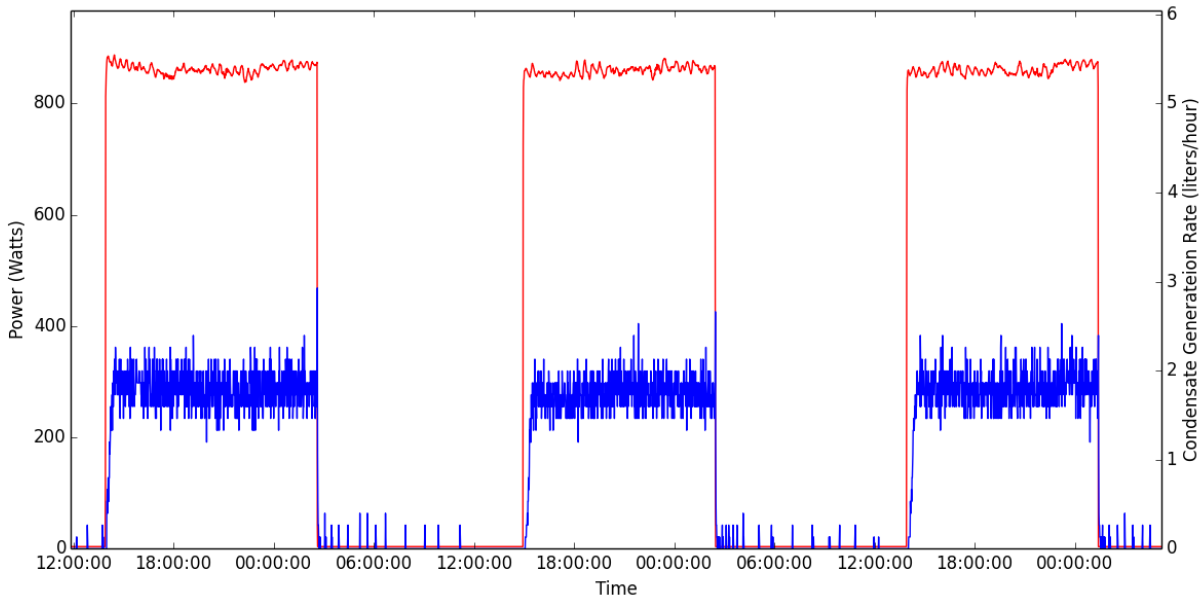


Figure 15 Typical Compressor Cycles and Condensate Removal Rate Time Series for Site WHD-SiteB02

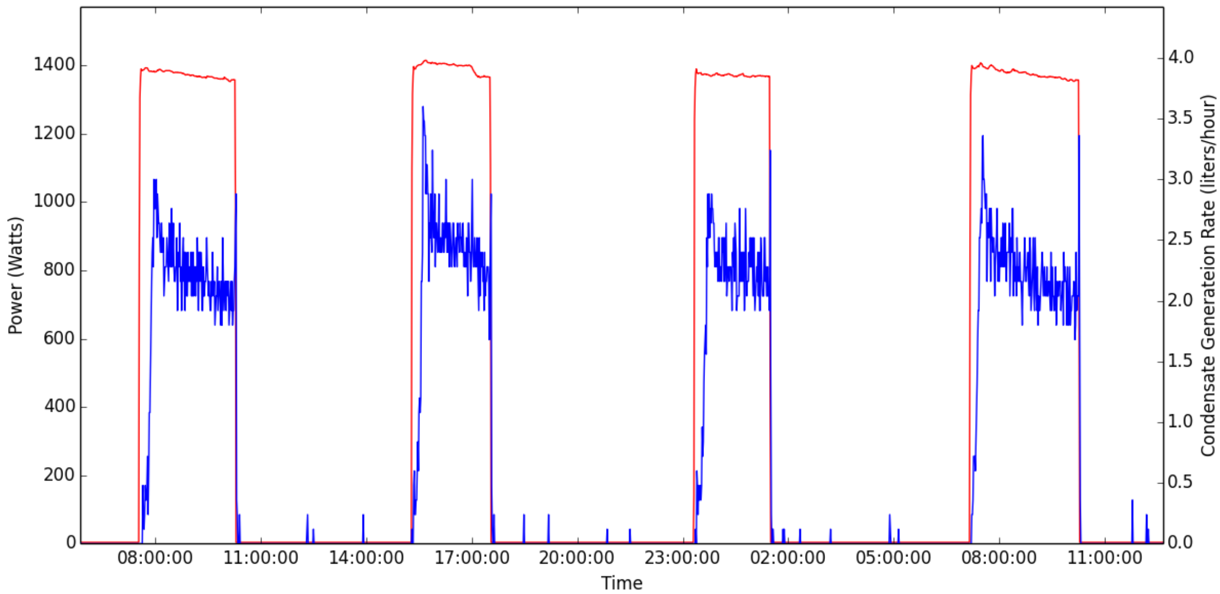


Figure 16 Typical Compressor Cycles and Condensate Removal Rate Time Series for Site WHD-SiteB03

Table 15 presents average condensate removal rates for each of the three Florida WHDs during the metering period. Because WHD-SiteB03 has the highest-capacity WHD and highest power consumption in compressor mode, the site also shows a higher condensate removal rate than either of the other two Florida sites.

Table 15 Rate of Condensate Removal in Compressor Mode (Florida Only)

Site	Removal Rate (liters/hour)		Removal Rate (pints/day)	
	Average	Standard Deviation	Average	Standard Deviation
WHD-SiteB01	1.14	0.64	57.87	32.28
WHD-SiteB02	1.54	0.33	77.99	16.73
WHD-SiteB03	2.10	0.61	106.68	30.77

Table 16 shows the average condensate removal per unit power for each of the three Florida sites. Because the average condensate removal per unit power during compressor mode for site WHD-SiteB03 is similar to the other two sites, it had roughly the same efficiency (but lower average daily energy consumption because of shorter run times). The higher standard deviation for removal rate for WHD-SiteB01 could reflect the imprecision of the meters operating at a one-minute interval at the tip bucket.

Table 16 Condensate Removal per Unit Power in Compressor Mode (Florida Only)

Site	Condensate Removal per Unit Power (liter/kWh)	Standard Deviation (liter/kWh)
WHD-SiteB01	1.54	0.87
WHD-SiteB02	1.98	0.42
WHD-SiteB03	1.69	0.51

6.8 Differential Pressure

Table 17 presents the average differential pressures across each whole-home dehumidifier during compressor mode for the three Florida sites. The pressure change in the ducts entering and exiting each unit is relatively small and comparable. When the compressor (plus fan) is operating, the variation in differential pressure is relatively small. This variation reflects the operation of the air conditioning system, which is integrated with the WHD.

Table 17 Differential Pressure during Compressor Mode (Florida Only)

Site	Differential Pressure (inch WC)	
	Average	Standard Deviation
WHD-SiteB01	0.117	0.042
WHD-SiteB02	0.283	0.025
WHD-SiteB03	0.205	0.043

6.9 Inlet Temperature

The average inlet temperatures for the WHDs at the three Florida sites are similar, about 73 °F to 75 °F. The Wisconsin WHD, Site WHD-SiteA03, had a larger standard deviation and a lower average temperature (70.4 °F) than any of the Florida sites.

Table 18 WHD Inlet Temperature during Compressor Mode

Site	WHD Inlet Temperature (°F)	
	Average	Standard Deviation
WHD-SiteA03	70.4	2.8
WHD-SiteB01	73.9	1.9
WHD-SiteB02	75.1	1.4
WHD-SiteB03	73.3	1.2

6.10 Typical Indoor Ambient Air Conditions

Figure 17 shows a typical ambient indoor temperature and humidity level while the WHDs in this study were operating in compressor mode. The temperature remained consistent while relative humidity decreased during compressor mode. All the sites exhibited similar behavior, although there sometimes was a time lag before the humidity decreased after a WHD compressor cycle.

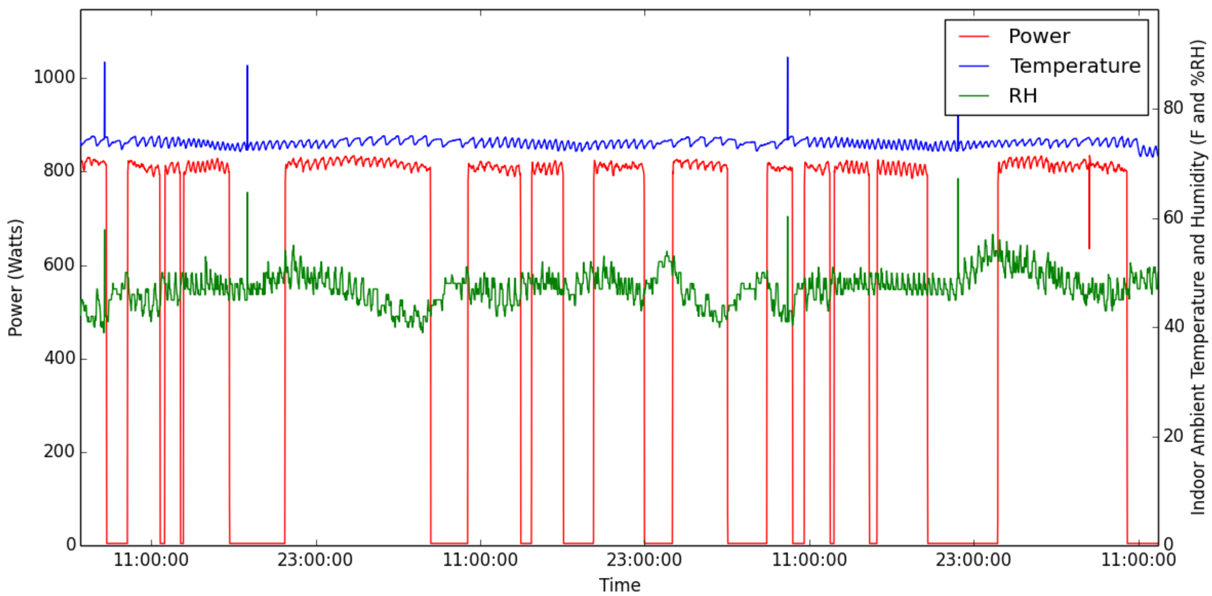


Figure 17 Typical Ambient Indoor Temperature and RH during WHD Compressor Cycles (from Site WHD-SiteB01)

7 CONCLUSIONS

LBNL used and is continuing to use a field-monitoring approach to investigate WHD energy use. The primary objectives of the study are to (1) obtain information on the applications and configurations of WHDs as used in homes, (2) understand the operational characteristics and times of use of whole-home dehumidifiers, and (3) collect data on their energy use and environmental conditions.

Four sites are insufficient to assert certainties about WHD energy use. After selecting sites and performing two phases of metering, however, we made several findings: (1) geographic locations of WHDs are primarily in the Midwest and Southeast in higher-income households, (2) larger homes having multiple climate zones might have multiple WHDs, and (3) there are some variation in the installation and configuration of WHDs. Our study metered only homes that used only one WHD that was installed in conjunction with the air-handling system. We metered WHD installations that were somewhat similar to one another so that results could be compared more easily. The RH was set to 58 percent at the Wisconsin site and between 45 percent and 50 percent at the Florida sites.

The three Florida WHDs used the same brand of appliance, and all were installed by the same technician. The Wisconsin site used a different WHD model installed by a different technician. Despite the differences in brand and installer, the percentage of time in fan-only was comparable. For the Wisconsin site, however, the dehumidifier operated in fan-only mode for longer periods because the installation allowed for selecting a fan-only mode. At the four metered sites, the WHD fan operated less frequently than did the WHD compressor. Because the air-handling system performed the function of fan-only mode by testing the humidity level of the air, the percentage of time when only the WHD fan operated was small or near zero. Length of time in compressor mode was correlated with higher outdoor vapor density; however, outdoor humidity was a better indicator of compressor operation.

ACKNOWLEDGMENTS

The authors wish to thank the following individuals for their contributions to this study: L.B. Derouches, M. Iyer, R.H. Galore, I. Galun, A.B. Lekov, M. Melody, D.H. Powers, G.J. Rosenquist, G. San, H. Stalls, and A.A. Williams.

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