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Field-Monitoring of Whole-Home Dehumidifiers: Initial Results of a Pilot Study

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Publication Date
2013-11-25

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Field-Monitoring of Whole-Home Dehumidifiers: Initial Results of a Pilot Study

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November 2013

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

AH	absolute humidity
CAC	central air conditioner
cfm	cubic feet per minute
ERV	energy recovery ventilator
P or Pa	pascals
kPa	kilopascals
L/kWh	liters per kilowatt-hour (of electricity used)
RH	relative humidity
SD	standard deviation
W	watts
WHD	whole-home dehumidifier

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1 INTRODUCTION

Since 2004, options for reducing humidity in residences have included both whole-home and portable dehumidifiers. Although shipments of whole-home dehumidifiers (WHDs) still represent a small fraction of the shipments of portable units, there has been an increase in WHDs being used in conjunction with a home's air-handling system. In the United States, WHDs are installed primarily in homes in the humid areas of the East, Midwest, and South.

Whole-home dehumidifiers are installed when homeowners want to increase the dehumidifying capability of their air handler without increasing run time. Without a WHD, homeowners must lower the thermostat setting to cause the air conditioner to turn on (or increase the temperature in the case of heating). A mechanical/refrigerative WHD, which comprises a compressor, cooling coils (an evaporator), heating coils, fan, humidistat, and condensate pump, generally is installed in parallel with the air-handling system of the central air conditioner (CAC). Some of the return air from the home is diverted to the dehumidifier. When moist air is drawn into the appliance, it passes over the cooling coils (evaporator), then over a set of heating coils (the condenser) before being returned to the home. The air returned to the home is drier and slightly warmer than when it entered the appliance. The moisture that condenses out of the air drips into a drain line.

Lawrence Berkeley National Laboratory sought to research the energy performance of WHDs. Despite the increase in use of WHDs, however, we found only one published study, in which two WHDs were evaluated in a test laboratory.[a] We found no publically available field studies of the operation and efficiency of whole-home dehumidifiers. We therefore devised a two-phase project in which Phase 1 serves as a pilot study to understand the range of configurations, operation, and energy use of WHDs. The results of the pilot study, which was performed in a single geographical area, will inform Phase 2, the primary study phase, which will be carried out in multiple geographic regions.

The primary objectives of this project are to (1) expand knowledge of the configurations, energy consumption profiles, consumer patterns of use (e.g. RH settings), and environmental parameters of whole-home dehumidification systems; and (2) develop performance maps of WHD systems. Performance mapping involves observing power consumption, condensate generation, and

[a] Winkler, J., et al. 2011. "Laboratory Test Report for Six ENERGY STAR® Dehumidifiers." National Renewable Energy Laboratory (NREL). Technical paper NREL/TP-5500-52791. December.

properties of output air of an installed system under conditions of varying inlet air temperature and relative humidity (RH), as well as different system configurations.

This report focuses on the first of the two objectives; a subsequent report will address performance mapping. This report describes results of the Phase 1 pilot study, which collected detailed data from multiple points in the air-handling systems of WHDs in three study sites in Wisconsin. This pilot field study did not alter flows, disable systems, or modify operation of the WHDs. We selected study sites having different usage patterns and system configurations. We monitored the power consumption—separately for compressor and fan, if possible—and various environmental conditions that were expected to affect the performance and efficiency of the WHDs.

The discussions in this report can be categorized into four sections which describe: (1) how we selected three sites for the pilot study, (2) the methods we used to collect and analyze data, (3) the results from the analysis, and (4) what the results indicate regarding residential energy use of the WHDs and their efficiency.

2 SITE SELECTION AND SCREENING

To select sites, we contacted dealers and distributors to identify areas where many homes have WHDs. We found a concentration of WHDs in and around Madison, WI. We distributed flyers and posted advertisements about the study at selected public venues such as stores. To interested homeowners, we explained the study and obtained their consent to collect additional screening information to help us select study sites. The screening tools included questions to characterize home configurations, air conditioning, and other mechanical ventilation and air distribution systems. This screening process was carried out through phone calls and site visits.

2.1 Screening Process

After launching the public search for study sites, we compiled a list of site survey questions used to select three study sites. The basic site selection criteria were: (1) the site has and uses a WHD, (2) the site is occupied by the homeowner, and (3) the WHD is used regularly or daily in conjunction with the air-handling system. Some potential study sites were rejected for at least one of the following reasons.

- significant customized installation of the WHD with the air-handling system so that the study site could not be considered a typical dehumidifier installation;
- no connection between the dehumidifier and the duct work within the home;
- uncertainty about the length of time the homeowner would own the home; and/or
- difficulty in accessing metering equipment after installation.

The site survey/ checklist is shown in Table 2-1. After the list of potential participants was finalized, all contact information was removed before the selection process started.

Table 2-1 Site Survey/ Checklist for Homeowners

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?		

The study sites were picked to represent different configurations to get a broad range on characterization of energy use by WHDs. After site selection, we conducted site visits to perform an initial check of the configuration and performance of the WHD in each home. The site visits enabled us to finalize monitoring plans for each study site.

2.2 Site Characteristics

All three WHDs in the pilot study are installed in the basement of a single-family detached home. In this report, the sites are identified as WHD-Site01, WHD-Site02, and WHD-Site03. Basic descriptive information for the homes is presented in the tables that follow. Temperature settings listed for heating and cooling are as reported by homeowners. Dehumidifier control settings also are based on homeowner reports, confirmed, if feasible, by observation during installation of monitoring equipment.

2.2.1 Characteristics of WHD-Site01

The residents of WHD-Site01 used their WHD throughout the year. The site was selected because it exemplifies using external[b] air to control humidity of the whole home. The WHD ran on a timer set to turn off the dehumidifier from 9 PM to 7 AM, while in other hours, the system ran continuously with the compressor cycling on and off. The outlet duct of the WHD was positioned in front of the unit, where it was attached to the supply air duct to the house. An electric damper was positioned at the bottom of the outlet duct. The condensate line exited the WHD underneath the duct connection.

[b] ‘External’ here means to the air handling system. WHD-Site01’s dehumidifier intake air is from the basement room.

Air entering the WHD was pulled from the basement (without ducting), dehumidified, and supplied to the main air stream (duct) for the whole home. This arrangement introduced negative pressure in the basement, which implies the direction of infiltration would be into the basement, either from the home or the outside, whichever was leakier. Table 2-2 gives details of WHD-Site01.

Table 2-2 Information for WHD-Site01

Parameter	Description
Type of home	Single-family detached with full basement and attached garage.
Year built	2009.
Size of home	First floor 1,500 sq ft; basement 1,500 sq ft, of which 900 is finished space. Volume of home: first floor 12,300 cu ft (8-ft ceiling height plus a vaulted area in living room); basement 11,250 cu ft (7.5-ft ceiling height).
Construction type	Wood frame. Basement is cast-in-place concrete with concrete slab floor. Finished basement space has wood furring and drywall finish over concrete walls.
Number of occupants	Three plus an additional occupant intermittently during the year.
Furnace model	Concord CG90UB075D12B (natural gas forced-air furnace).
Central AC model	Concord 4AC13L24P-1A (split-system CAC, evaporator coil in furnace plenum, condenser unit outside home).
Whole-home dehumidifier info	Unit A (installed 2009). Nominal capacity 105 pints/day, energy factor 2.9 L/kWh. Nominal blower capacity 240 cfm at 0.1-inch water column pressure. See spec sheet and manual for more information.
Central humidifier model	None.
Location of mechanical equipment	Furnace, WHD, and power-vented water heater are located in a small mechanical room (approx. 8 x 9 ft) in basement.
Zoning	Single heating and cooling zone for entire home. Dehumidifier draws air exclusively from the mechanical room, and delivers air to the main home supply ducts. Mechanical room door is kept closed; open ceiling joist framing provides an air path to rest of home.
Ducting	Sheet-metal duct system with main trunk runs in basement. Supply registers in all finished spaces including finished basement spaces. Return registers in finished first-floor and basement spaces (not including bathrooms). Return register on main return air trunk duct in mechanical room.
Controls	Dehumidifier is controlled by humidity controller mounted on mechanical room wall. Power to the dehumidifier is passed through a timer that disables operation from about 9:00 PM to 7:00 AM. Heating and cooling are controlled by a conventional thermostat in the first-floor hallway.
Typical control settings	The humidity controller typically is left at 40% RH year round. Cooling generally is set to 74 °F, and heating to 72 °F.
Laundry location and venting	Basement. Dryer vented to outdoors.
Moisture problems	None reported.
Unusual moisture sources	None identified.

2.2.2 Characteristics of WHD-Site02

The residents of WHD-Site02 operated their WHD throughout the year. This site was selected to represent the use of a WHD for basement dehumidification. The WHD was positioned next to a furnace. Connected to the WHD inlet plenum were two flex ducts, one connecting to the outdoor air, and the other to the return air duct of the home's air handler. Dehumidified air exited the WHD to the basement through a rectangular opening on the front panel of the unit. Figure 2-2 shows how the ducts are connected.

The homeowner of WHD-Site02 stored materials in the basement that required moisture protection. The WHD system pulled most of the inlet air from the return air path of the air-handling system (from the whole-home air), along with minimum amount of outdoor air. The exiting air from the WHD was supplied directly to the basement. The ducted outdoor air path to the inlet air of the unit ensured there was no negative pressure in the basement zone. However, the air flow distribution caused negative pressure to the whole-house. The make-up air could come from the outdoor or the basement zone, whichever was leakier. See Table 2-3 for more information about WHD-Site02.

Table 2-3 Information for WHD-Site02

Parameter	Description
Type of home	Single-family detached with full basement and attached garage.
Year built	1993.
Size of home	First floor 1,714 sq ft; basement 1,714 sq ft, of which about 800 sq ft is finished space. Volume of home: first floor 13,712 cu ft (8-ft ceiling height); basement 12,855 cu ft (7.5-ft ceiling height).
Construction type	Wood frame. Basement is cast-in-place concrete with concrete slab floor. Finished basement space has wood furring and drywall finish over concrete walls.
Number of occupants	Two plus an additional resident part of the year.
Furnace model	Bryant 398AAV036080 (natural gas forced-air furnace).
Central AC model	Bryant 561AJ030-B (split-system CAC, evaporator coil in furnace plenum, condenser unit outside home).
Whole-home dehumidifier info	Unit B (installed 2009). Nominal capacity 110 pints/day, efficiency 6.4 pints/kWh (not listed as an energy factor). Nominal blower capacity 275 cfm at zero pressure drop. Dehumidifier designed for either stand-alone or ducted installation; in this case a duct connection plenum is attached to the intake (top) of the unit. Air enters this plenum from two separate ducts, one connected to the main home return air duct, the other to an outdoor air duct. The duct plenum is shallow (about 2.5 in. deep in the direction of airflow), making it unlikely that the two airstreams are fully mixed as they enter the unit.
Central humidifier model	None.

Parameter	Description
Location of mechanical equipment	All equipment is located in basement.
Zoning	Single heating and cooling zone for entire home. Dehumidifier draws air from the main home return air duct and from a direct outdoor air duct and delivers air exclusively to the basement (there is no supply air path from the dehumidifier to the main duct of the whole-house).
Ducting	Sheet-metal duct system with main trunk runs in basement. Supply registers in all finished spaces, two registers in unfinished basement. Return registers in finished first-floor spaces (not including bathrooms); no return registers in basement.
Controls	Dehumidifier has humidity control mounted in unit, which senses conditions in surrounding air through vents. Heating and cooling are controlled by thermostat on first floor.
Typical control settings	Dehumidifier control typically set to 40% RH in summer and 50% RH in winter. The only time the unit runs in the winter is when there is a need to dry laundry indoors. Air conditioning usually is set to 78 °F, heating to 68 °F.
Laundry location and venting	Basement. Dryer vented to outdoors.
Moisture problems	None reported.
Unusual moisture sources	Owners dry some of their laundry in the basement near the dehumidifier, especially during winter months.

2.2.3 Characteristics of WHD-Site03

The WHD for WHD-Site03 was set to run throughout the year. The study site was selected because an advanced control system operates the WHD, which responded to dehumidification requirements of multiple zones.

One of the inlet air ducts to the WHD took in air from the basement zone (this could cause negative pressure). 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 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). Figure 2-3 shows how the ducts are connected and Table 2-4 provides more information about WHD-Site03.

Table 2-4 Information for WHD-Site03

Parameter	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. Volume of home: first floor 13,165 cu ft (8.8-ft ceiling height); second floor 13,120 cu ft (8-ft ceiling height); basement 10,015 cu ft (7.8-ft ceiling height).
Construction type	Wood frame. Basement is cast-in-place concrete with concrete slab floor. Finished basement space has wood furring and drywall finish over concrete walls.
Number of occupants	Two full-time occupants; adult children visit occasionally.
Furnace model	American Standard AUY100R9V4W5 (natural gas forced-air furnace).
Central AC model	Heil CA3036UKA1 (split-system CAC, evaporator coil in furnace plenum, condenser unit outside home).
Whole-home dehumidifier info	Unit C (installed 2005). Nominal capacity 90 pints/day, energy factor 2.2 L/kWh. Nominal blower capacity 310 cfm at 0.4-inch water column pressure. See spec sheet and manual for more information.
Central humidifier model	Aprilaire 700.
Energy recovery ventilator	NewAire R100.
Location of mechanical equipment	Basement, unfinished mechanical space.
Zoning	The main HVAC system serves a single, whole-home zone that includes the finished basement. The WHD serves two zones. The first is the whole-home zone served by the HVAC system. The second is the finished basement area only. The dehumidifier serves the second zone though a single independent return duct and a single independent supply duct. Air delivery to the two zones is controlled by four electric dampers, two normally opened dampers on the return and supply ducts to the basement zone, and two normally closed dampers on the return and supply ducts connected to the main HVAC system ducting.
Ducting	Sheet-metal duct system with main trunk runs in basement and risers to second floor. Supply registers in all finished spaces, including finished basement space. Return registers in finished spaces (not including bathrooms) and in finished basement space.

Parameter	Description
Controls	All heating, cooling, whole-home dehumidification, and humidification of the main home zone are controlled by an Aprilaire Home Comfort Control 8910. A call for dehumidification from the main home controller turns on the dehumidifier until the control setting is met. Dehumidification control of the basement zone relies on air sampling. An internal timer turns on the dehumidifier blower at a pre-set interval (currently once per hour), drawing air from the basement area to the unit. If the absolute humidity sensed within the unit exceeds the control setting, the compressor is activated and the dehumidifier operates until the control setting is met. Operation of the main home zone always takes precedence, however: a dehumidification call from the main home zone controller prevents the basement zone sampling from occurring and interrupts a basement zone operating cycle, closes the dampers for basement operation and opens the dampers for the whole-house. The energy recovery ventilator (ERV) nominally is controlled by a humidity controller near the Aprilaire Home Comfort Control on the first floor; however, the controller appears to be disconnected or otherwise non-operational. The operation of ERV appears to be connected to the main air handler. It is possible that some portion of air from the air handling system return duct and ERV outlet pass through the WHD during its standby or off mode.
Typical control settings	The RH setting on the main zone Home Comfort Control generally is 58% RH, apparently year round. The dehumidifier's internal control for the basement zone is a dew point (absolute humidity) setting, typically set to "4," which corresponds to a dew point of 52 °F. Air conditioning is set according to comfort needs, with a typical setting of 74 °F. Heating typically is set to 71 °F. The humidifier control is set to off. The ERV control is set to off, and the unit did not operate when the set point was changed during installation of monitoring equipment.
Laundry location and venting	First floor. Dryer vented to outdoors.
Moisture problems	None reported.
Unusual moisture sources	None identified

2.3 Dehumidifier Configurations and Metering Plans

Each of the three study sites was heated by a gas furnace, cooled by a central air conditioner, and dehumidified by a WHD. However, the systems configuration, ducts layout, and equipment location required customized monitoring plans for each study site. Figure 2-1 through Figure 2-3 show each WHD in relation to the air-handling equipment, the direction of airflows, the position of dampers, and the placement of the meters and sensors.

At WHD-Site01 (Figure 2-1), the main locations of measurements were (1) the basement zone, (2) the duct connecting WHD and the supply air path to the whole house, and (3) the main supply air duct to the whole house.

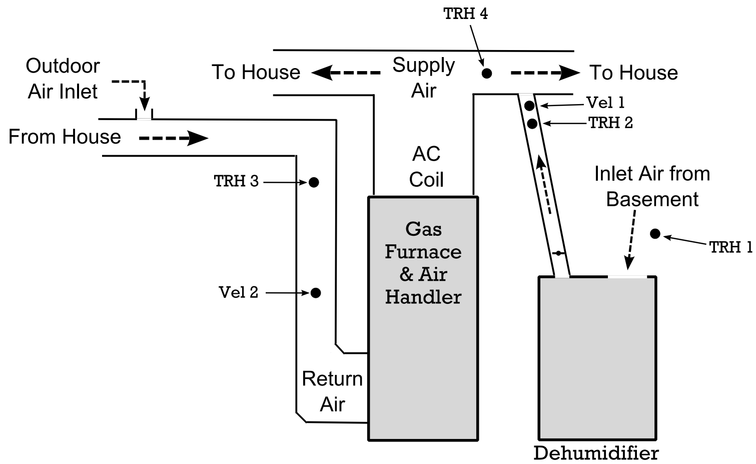

Figure 2-1 WHD-Site01 Ducting and Sensor Configuration

Notes for Figures 2-1 to 2-3:

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

At WHD-Site02 (Figure 2-2), the primary sensor locations were (1) the incoming air to the WHD, which was drawn from the whole-home return air and the outdoor air inlet, (2) exit air to the basement, and (3) supply air to the home.

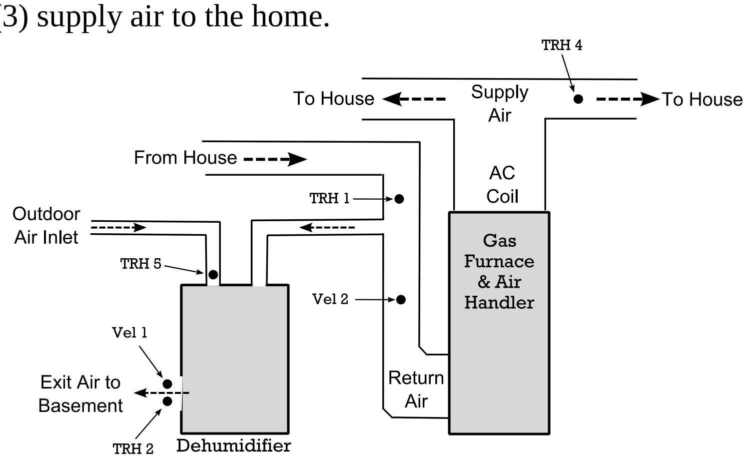

Figure 2-2 WHD-Site02 Ducting and Sensor Configuration

At WHD-Site03 (Figure 2-3), the main 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.

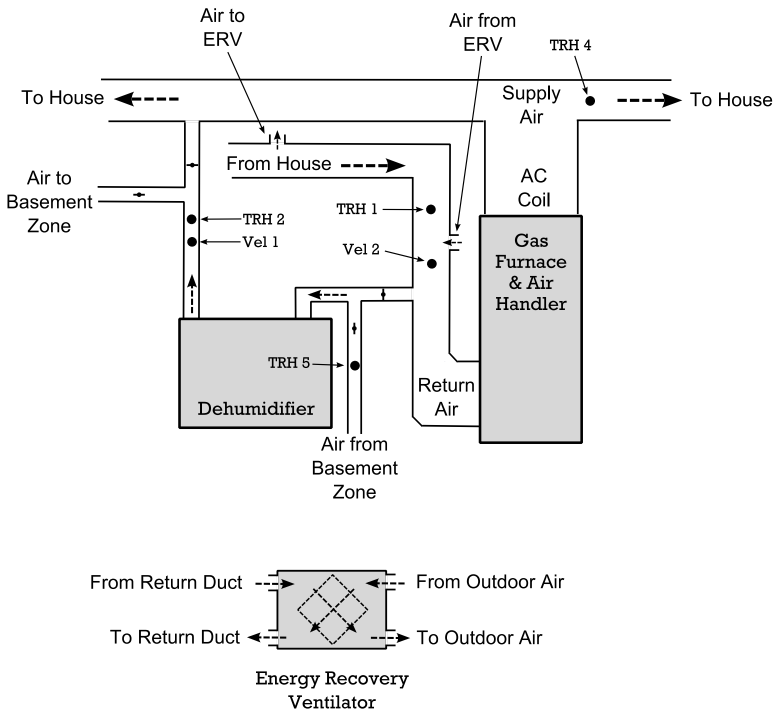

Figure 2-3 WHD-Site03 Ducting, Sensor Configuration, and Energy Recovery Ventilator

3 MEASUREMENT METHODS AND DATA ANALYSIS

Information gathered during site visits included the configuration of the WHDs in connection with the home's air handling system, the operation characteristics and controls, and potential locations for placement of sensors and metering equipment. In the pilot phase, the monitoring efforts included the following parameters:

- Temperature and relative humidity of air entering and leaving the WHD
- Air flow rate of the air leaving the WHD
- Temperature and relative humidity of air entering and leaving the main air handler
- Air flow rate of the air entering the main air handler
- Power consumption
- Operating status of the WHD and main air handler
- Condensate generation

- Indoor temperature and relative humidity

All measurements were carried out continuously under normal operating conditions throughout a period of at least five months. At the time of this report, the data collection is still ongoing and will continue through December 2013. The data reported here includes a shorter period, i.e. between June and September 2013.

3.1 Instrumentation

Temperature and relative humidity (RH) were measured using analog output devices manufactured by Vaisala.[c] The airflow velocity devices (pitot tube and averaging airflow station) were connected to analog output pressure transducers manufactured by Setra.[d] Those analog signals were connected as inputs to a Campbell Scientific CR1000 data acquisition system.[e] 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 monitors digital inputs from current switches, records counted pulses from condensate measurement devices, and queries power measurement devices. All inputs were recorded at one second interval. Onset temperature and RH sensors and loggers[f] were used to meter indoor and outdoor temperature and RH. Table 3-1 shows the parameters and devices used in the monitoring for the pilot phase.

Table 3-1 Data Parameters and Measuring Devices for Phase 1 Study

Data	Parameter	Measuring Device
Energy Use	Total unit power	WattNode power meter, CR1000
	AC compressor, air handler power	WattNode power meter, CR1000
	Status of compressor and fan	Veris H308, CR1000
System performance	Inlet and outlet temperatures and RH	Omega H94 series or similar sensor
	Volumetric flow rate of blower	Pitot tube
	Pressure change (inlet, outlet)	Pitot tube
	Mass flow rate through condensate drain	Analog-output weight scale
Environmental parameters	Indoor air temperature and RH	Onset data logger U12-011
	Outdoor air temperature and RH	Onset data logger U23-002 and RS3 shield

3.2 Power Measurement

[c] http://www.vaisala.com/en/energy/Pages/default.aspx
[d] http://www.setra.com/products/current/
[e] http://www.campbellsci.com/cr1000
[f] Onset Computer Corporation: http://www.onsetcomp.com/products/data-loggers/u12-011

Power measurements were collected using WattNode power meters[g] and Accu-CT current transformers.[h] A WattNode was installed in the main power distribution panel at each home, with the three channels connected to monitor power consumption of the furnace circuit (that is, the main air handler plus controls and other components of the furnace) and of the air conditioner condenser unit. In each case, both legs of the 240 V condenser circuit were monitored. At WHD-Site01, a second WattNode was placed in the main distribution panel to monitor energy consumption of the dehumidifier, which was located on a separate circuit. At WHD-Site02 and WHD-Site03, the second WattNode was placed in an enclosure near the dehumidifier, and the three inputs were used to separately monitor the entire unit, the compressor, and the blower.

3.3 Condensate Measurement

Systems at WHD-Site01 and WHD-Site02 were provided with tipping bucket gauges (rain gauges) for measuring condensate. WHD-Site03 did not have enough height above the floor for a tipping bucket, and rigid ductwork connections made it impractical to lift a bucket higher. To measure condensate at WHD-Site03, we installed a condensate pump having a pulse flow meter on the outflow line.

A condensate pump must fill to the point of triggering a float switch before the pump cycles. The pump then 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. Volume per pulse is presented, as calculated from mass per pulse using an assumed density of water of 8.331 lbs/gal. Tipping buckets offered higher resolution, recording a pulse in response to just a few milliliters of condensate flow (see Table 3-2). 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 the unit, and condensate pulses were often delayed until after the start of dehumidifier operation and condensate production. Thus, the correlation of measured condensate with compressor operation was expected to be poor when performed over short intervals. Aggregate daily condensate volume was expected to be more representative of condensate generation rate.

Table 3-2 Condensate Metering Pulse Factors

	WHD-Site01	**WHD-Site02**	**WHD-Site03**
Condensate volume per pulse	8.23 ml (0.002174 gal)	4.73 ml (0.001250 gal)	2.620 ml (0.0006922 gal)
Condensate mass per pulse	0.01811 lb	0.01041 lb	0.005767 lb

[g] http://www.ccontrolsys.com/w/WattNode_Pulse
[h] http://www.ccontrolsys.com/w/News:Accu-CT_Released

3.4 Equipment Calibration

The following sections describe the equipment used to collect data and how that equipment was set up, tested, and calibrated.

3.4.1 Calibration of air handler flow measurements

The monitoring system for each site included a Dwyer PAFS averaging airflow station[i] connected to a Setra differential pressure transducer, which measured the velocity pressure of the airflow (similar to a pitot tube measurement averaged over several points across the duct section). We developed calibration curves for the airflow measurements by recording velocity pressures through the monitoring system while simultaneously measuring flow rate using an Energy Conservatory True Flow air handler flow meter and a DG-700 pressure gauge. For each calibration, we ran tests with the air handler fan operating at three different speeds, accomplished either by operating the system in heating, cooling, and fan-only modes, or by adjusting fan speed via controls in the furnace. We allowed a brief period for operation to stabilize before collecting data at each site. Data were collected during an approximate 30-second period in each test case at each site.

3.4.2 Measurement of WHD air flow

The monitoring systems included a pitot tube placed in the outflow duct from the whole-home dehumidifier. In the case of WHD-Site02, the outflow is an open port to the room, so we mounted the pitot tube on the exterior of the dehumidifier so as to face into this air stream. The pitot tube and associated pressure transducer provided a signal related to the velocity pressure of the dehumidifier airflow, which could be converted to a mass flow rate after calibration, similar to the procedure used with air handlers.

We used an Energy Conservatory Duct Blaster for measuring dehumidifier flow. For WHD-Site01, we connected the duct blaster to the open inlet of the dehumidifier. For the other systems, we disconnected the inlet ducting to the dehumidifier and connected the duct blaster to provide incoming air. In each case, we operated the dehumidifier and Duct Blaster across the range of flow rates that covered the manufacturer's nominal rated flows.

3.4.3 Measurement of static pressure across WHD

We measured the external static pressure across the dehumidifier (the pressure differential between the inlet and outlet) while it was operating. The measurements were made with static pressure probes placed in the entry and exit ducts, if available, that were connected to the dehumidifier, with no more than one duct elbow between a probe and the dehumidifier. For non-ducted units, we measured the pressure differential with reference to the room air, or with the

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[i] http://www.dwyer-inst.com/Product/AirVelocity/PitotTubes/SeriesPAFS-1000

probe place inside the systems. Difficulties in obtaining consistent readings for non-ducted systems suggest that the pressure differential data could be erroneous. Therefore, only the result from WHD-Site03 is useful for comparing with the rated condition. For future measurement, an external duct should be used to obtain data for non-ducted systems. The measurement results are shown in Table 3-3.

Table 3-3 Static Pressure of Dehumidifier Systems

Operating Status	**WHD-Site01**	**WHD-Site01**	**WHD-Site02**	**WHD-Site03**
	With outlet probe placed in the system	With outlet probe placed in room air near opening	With inlet probe located in room air near opening	With probes place in the ducts (whole-home configuration only)
		Pa (IWC)		
Dehumidifier blower ON; air handler blower OFF	11 (0.04)	1.8 (0.01)	56 (0.23)	57 (0.23)
Dehumidifier blower ON; air handler blower ON	36 (0.14)	28 (0.11)	69 (0.27)	72 (0.29)

* Pa = pascals.

At WHD-Site01, the dehumidifier has open inlets with no attached ducting. We measured static pressure two ways: first with the intake pressure probe placed inside the dehumidifier body, then with the intake probe in room air. For site WHD-Site02, the static pressure was measured with the outflow pressure probe connected to the outlet of the unit via the pitot tube that was part of the monitoring system. The static pressure measurement for WHD-Site03 was made in the ducts with the main home zone dampers open.

3.4.4 Blower door testing

We tested air leakage from the blower door at each site using an Energy Conservatory blower door, DG-700 digital pressure gauge, and laptop with Tectite software installed. This setup allows for a multi-point air leakage test. The Tectite software presents the results as a standard leakage rate corrected to 50 Pa, and has the parameters for a power function curve fit using the equation:

$$\text{Airflow} = C\,(P)^n$$

Airflow is predicted air leakage in cubic feet per minute (cfm) across the housing structure envelope at any uniformly applied pressure. P is the uniformly applied pressure in Pascals, C is the flow coefficient, and n is the flow exponent. C and n are empirical values obtained by the testing (see Table 3-4).

Table 3-4 Results of Blower Door Tests

Parameter	WHD-Site01	WHD-Site02	WHD-Site03
Air leakage, cfm at 50 Pa	1,018 (+/- 0.8%)	863 (+/- 0.2%)	2,178 (+/- 1.8%)
C	67.6 (+/- 6.2%)	43.5 (+/- 2.0%)	215.9 (+/- 13.2%)
N	0.693 (+/- 0.017)	0.763 (+/- 0.006)	0.591 (+/- 0.037)
Correlation coefficient	0.998	0.999	0.989

3.4.5 Air handler power draw threshold

To sum humidity ratio and enthalpy during air handler operation, we needed to determine whether the main air handler blower was operating. We used the power draw of the furnace circuit, with a threshold of 50 W, as an indicator of blower operation. Based on the data, the typical power draw of the furnace circuit for each site when the blower was not operating was 7W for WHD-Site01, 6W for WHD-Site02, and between 12-15W for WHD-Site03. The current switch mounted on the blower power wire in each WHD provided explicit information on dehumidifier fan operation.

3.5 Quality Assurance

We obtained data at one-second intervals. Each data record—primarily power consumption, temperature and relative humidity data—was screened for error. Outliers such as power spikes with values more than 1500 W or RH values greater than 100% were excluded. Furthermore, 24-hour data analysis revealed several days with substantial missing data. These days were excluded from subsequent analysis. At site WHD-Site02, we learned that a portion of data was not correctly uploaded by the monitoring system during the first month of the study. Pending further investigation, we excluded this portion of data from the analysis. Table 3-5 summarizes the number of data records processed and removed from the analysis.

Table 3-5 Site Records

Site	Initial Number of Records in Seconds (Days)	Errant Records (Days)
WHD-Site01	11,906,663 (139)	-
WHD-Site02	7,515,265 (87)	44
WHD-Site03	7,734,783 (90)	7

3.6 Data Analysis

This section describes our methods for analyzing the data obtained from the three study sites. We developed profiles of daily energy use, air temperature, and RH. We calculated how many minutes and hours each WHD operated in each mode and calculated absolute humidity (vapor density). We determined the relationships between energy usage and inlet/ outlet air conditions. We estimated the field efficiency and the water removal by the WHD.

3.6.1 Identification of dehumidifier modes

The data for each site were categorized into modes after examining a scatter plot of the dehumidifier demand throughout the metering period. Each interval was categorized as: compressor with fan, fan-only, or standby mode. Standby mode was defined as consuming more than 0 but less than 25 W. Fan-only mode was determined to be between 26 and 300 W. Any values greater than 300 W were categorized as representing compressor with fan mode.

3.6.2 Profiles for energy use, temperature, and RH

After the data records were screened and binned by mode, the 1-second data were aggregated (summed) by minutes, hours, and days. The various intervals enabled better assessment of the WHDs' operating patterns and their effects on dehumidification in the home.

Hourly energy use for each site was plotted for the entire monitoring period to reveal any energy use patterns and the corresponding hourly changes in temperature and RH. Summaries of daily power consumption and energy use prepared as are tables below (Section 4.1, Section 4.2, and Section 4.3). Minute-by-minute data were averaged for each time stamp across all monitored days to obtain a daily load profile for each WHD. The 24-hour energy use profile was plotted along with the temperature and RH profiles.

3.6.3 Daily operating time and water removal in each mode

The 1-second data on power consumption were used to determine the amount of time each WHD spent in each mode. The results were summarized in minutes per day (for a daily summary) and later presented as the percentage of time spent in each mode during a 24-hour period.

To quantify the amount of water removed from the air when the dehumidifier (compressor) was operating, we determined the start and stop time of each compressor cycle in order to calculate the compressor run time and the corresponding change in absolute humidity (vapor density). Compressor run time per cycle was used to determine the volume of air passing through the system; the change in absolute humidity was used to calculate the amount of water removed from the passing air.

3.6.4 Calculation of absolute humidity (vapor density)

Assuming a standard atmospheric pressure at 101.3 kPa and using the measured data for temperature and RH values corresponding to the time of day, vapor density (g/m^3) was estimated using the equations below.

$$d_v = v/W$$

where: d_v is vapor density, v is specific volume in m^3/g_a, and W is humidity ratio in g_w/g_a.

Specific volume is calculated using the following equation:

$$v = \frac{R_a T(1 + (1.607\,858)W)}{p}$$

where: R_a is a gas constant for air, T is the measured dry-bulb temperature in °C, and p is total pressure in kPa.

Humidity ratio is calculated as follows:

$$\mathrm{W} = 0.621\,945 \frac{\mathrm{p_w}}{\mathrm{p} - \mathrm{p_w}}$$

where: p_w = partial pressure of water vapor

4 METERING RESULTS

This section presents results of our preliminary analysis of field data collected from the three WHD systems in this pilot study. Because of the distinct differences among the WHD systems and their configurations, we discuss results separately for each study site. For each site, we first present profiles of climate conditions and how they relate to system operation. Second, the power consumption and energy use of each system are summarized. Then we present some plausible correlations between climate conditions and each system's operating time and energy use. Finally, we compare each system's field efficiency to its rated efficiency based on the amount of water removed during each compressor cycle.

4.1 Results for WHD-Site01

The WHD configuration was installed to allow dehumidification using a single-pass air flow from the basement to the main supply air duct of the house. The WHD was operated based on a controller located in the basement. Thus, the lowest RH measured at the inlet of the system when the compressor shut off could represent the actual set point.

This configuration could cause negative pressure to the basement zone of the house, which would negate the purpose of dehumidification by increasing air infiltration and moisture from outdoor, or cause inter-zonal mixing with other zones in the house. For these reasons, this was not an ideal configuration for a WHD. However, because of the system placement in the basement, pulling the air from the same room seemed to be a logical choice. A better method to avoid this leakage issue would be to install a duct system that supplies outdoor air directly to the inlet air plenum of the WHD.

4.1.1 Energy use and environmental conditions at WHD-Site01

Figure 4-1 shows the profiles of temperature, RH, and absolute humidity by operational mode at the system inlet for WHD-Site01. Each data point represents 1 hour (summarized from the data collected at 1-second intervals). The top row shows the energy use profile, which illustrates the various system modes. Temperature, RH, and absolute humidity are presented in the second, third, and fourth rows, respectively.

Figure 4-1 Hourly Profiles of Energy Use, Temperature, RH, and Absolute Humidity at the Air Inlet of WHD-Site01

The profile for relative humidity appears to indicate that RH was lower when the compressor was running than during the fan-only mode. One would expect fan-only mode to operate when RH had reached the set point, so that RH would be lowest during that mode; however it is possible for fan-only mode to occur periodically before the set point has been reached to prevent or eliminate frost on the condenser coils. Potential explanations for this finding include (1) system leakage, whereby not all the dehumidified air is supplied to the whole-home zone, (2) possible backflow from the upper floor to the basement, or (3) a steadily rising RH after the compressor was off leading to a higher average. There was no clear difference in RH between system standby mode and fan- or compressor-on modes, indicating that air infiltration issues—caused by a negatively pressured basement—was not a major determinant of dehumidification during the monitoring period. RH was maintained at between 40 percent and 50 percent at the inlet location when the compressor was operating. RH during fan-only mode was kept in the range of 44-50%.

Figure 4-2 shows that the WHD provided dehumidification. When the compressor was operating, the RH decreased at the system outlet duct; when only the fan was running, the RH level did not vary substantially. According to our initial site survey, the set point on the humidity controller was 40 percent RH. There may be some tolerance on the controller, so that it will not turn on when the RH is slightly over the set point, for instance at 41%.

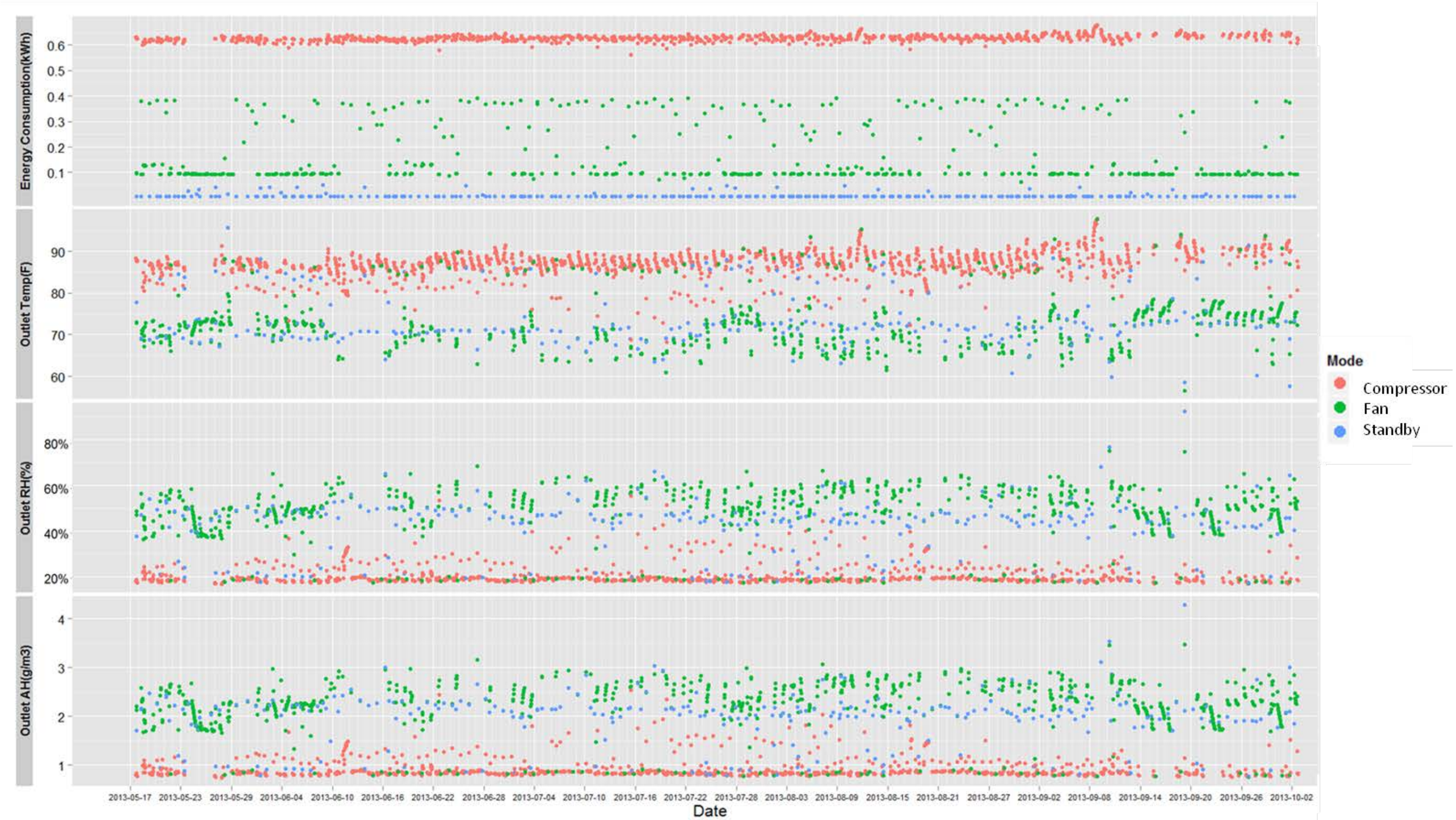

Figure 4-2 Hourly Profiles of Energy Use, Temperature, RH, and Absolute Humidity at the Air Outlet for WHD-Site01

Summary statistics of temperature, RH, and absolute humidity (AH) are given in Table 4-1. The mean inlet air temperature, RH, and absolute humidity did not differ substantially for the three modes. When the compressor was on, the temperature at the outlet was raised by 15°F, to 87°F, and the RH declined by 21 percentage units to a low average of 20 percent RH. The change in humidity achieved at WHD-Site01 indicated the system worked well as a dehumidifier. The higher outlet RH at fan-only mode could indicate the airstream is evaporating some of the water condensed on the evaporator while the compressor is not running. Although the RH of the outlet may be low during the compressor mode, by the time it mixes with ambient air, the humidity level may not be a problem; inlet RH ranged from 40-50%, which is appropriate for comfort and health.

Table 4-1 Inlet and Outlet Temperature, RH, and Absolute Humidity for Different Modes of Operation at WHD-Site01

Mode	**Mean Inlet T***	**SD† Inlet T**	**Mean Outlet T**	**SD Outlet T**
Compressor	72.2	2.04	**87.1**	3.09
Fan-only	70.9	2.06	72.8	5.55
Standby	71.6	1.73	73.6	6.59
Mode	**Mean Inlet RH**	**SD Inlet RH**	**Mean Outlet RH**	**SD Outlet RH**
Compressor	42.8	2.85	**20.03**	3.81
Fan-only	46.5	2.76	48.12	10.59
Standby	44.2	3.58	42.28	12.08
Mode	**Mean Inlet AH‡**	**SD Inlet AH**	**Mean Outlet AH**	**SD Outlet AH**
Compressor	1.95	0.13	**0.89**	0.18
Fan-only	2.12	0.13	2.19	0.49
Standby	2.02	0.17	1.93	0.56

* T = temperature in °F.
† SD = standard deviation.
‡ AH = absolute humidity (vapor density).

The 24-hour profiles of temperature, RH, and absolute humidity during weekdays and on weekends are plotted in Figure 4-3 and Figure 4-4 for inlet and outlet air, respectively. For most days in the monitoring period, the system operated only between 7 AM and 9 PM, so the plots were generated for that period. Each data point represents a 1-minute total for energy use and an average for environmental parameters. As shown in the legend, the weekday line is purple and the weekend is light brown.

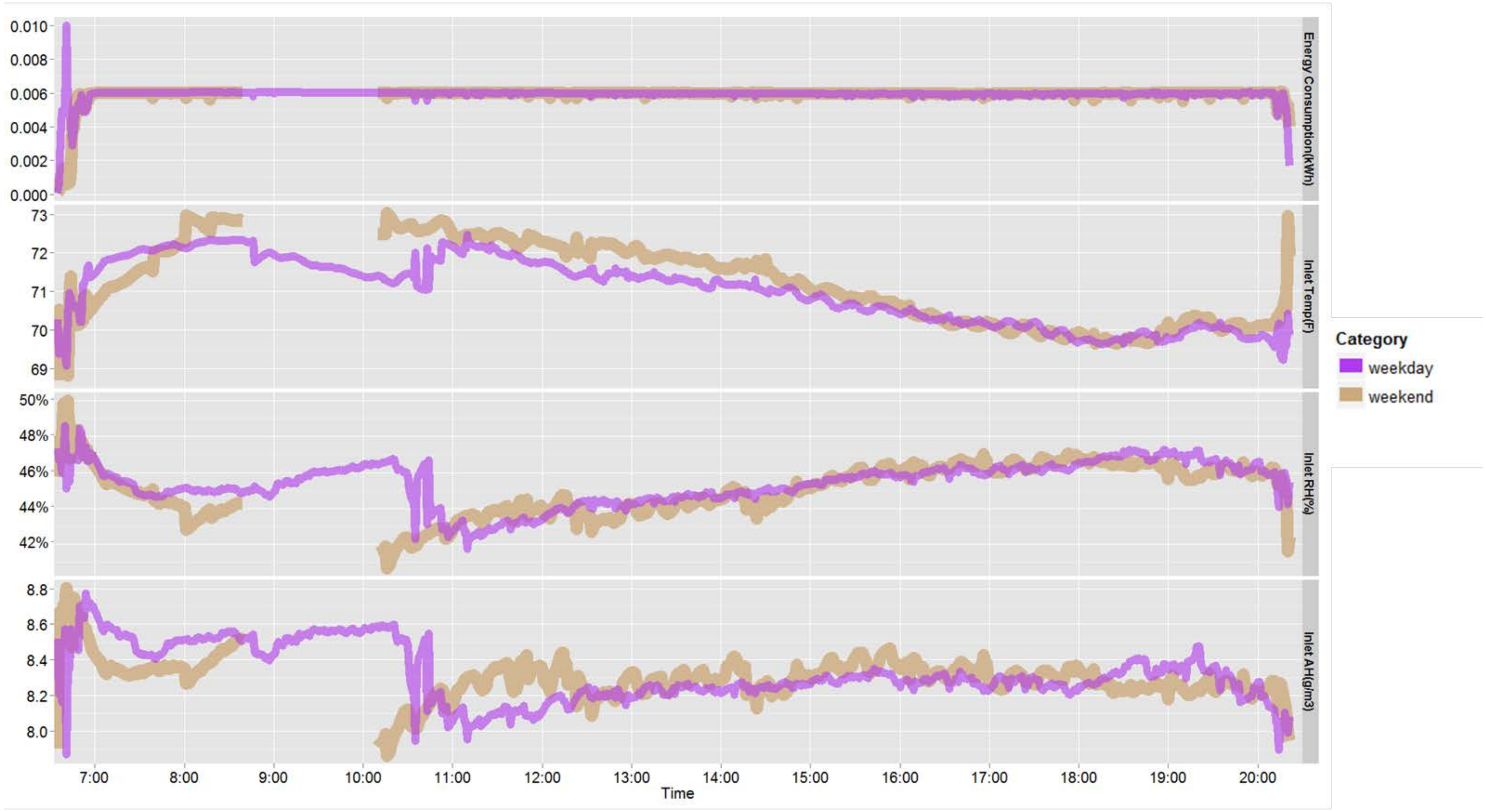

Figure 4-3 Daily Profiles for Average Energy Demand and Inlet Temperature, RH, and Absolute Humidity During Weekdays and Weekends for WHD-Site01

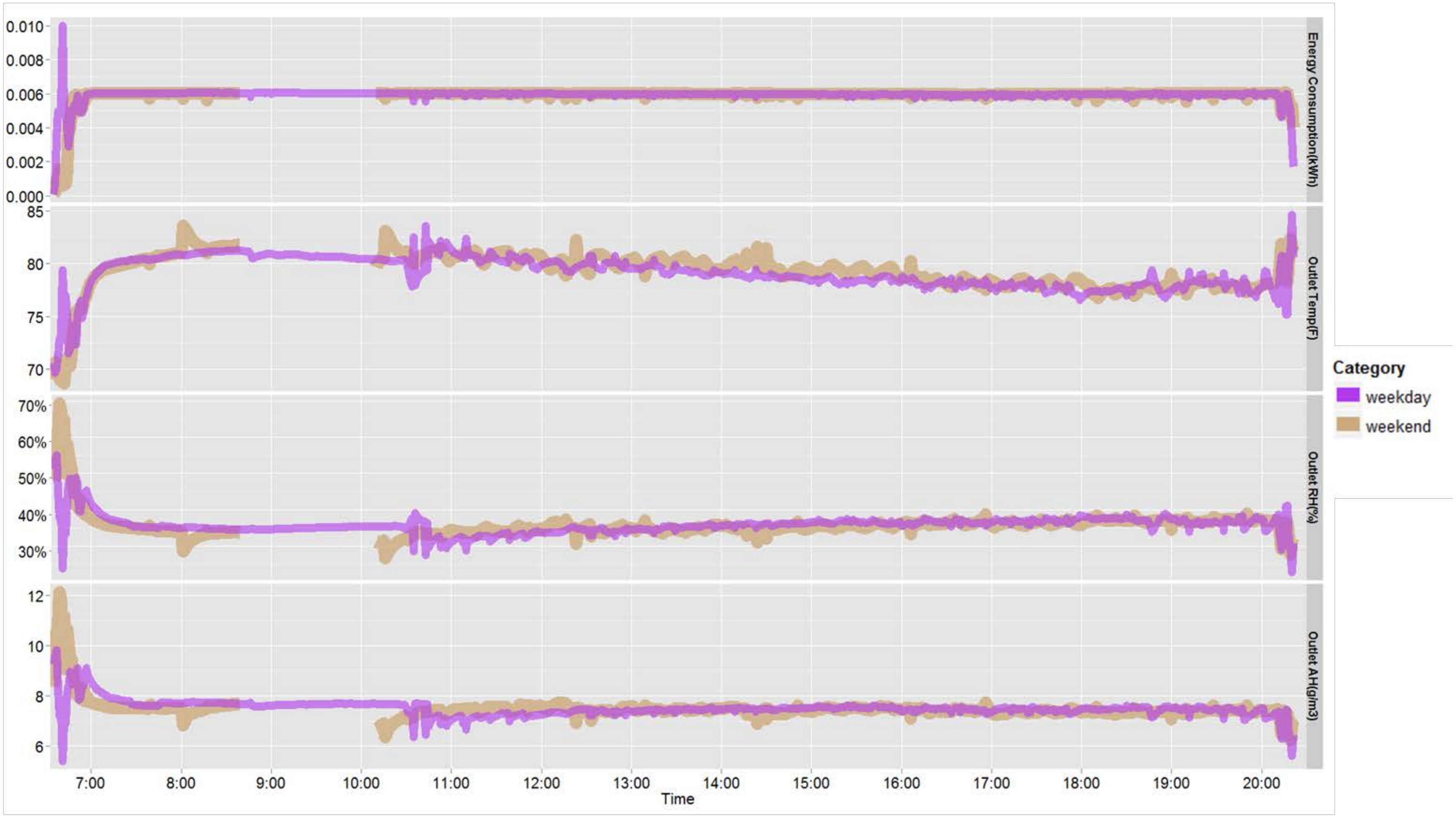

Figure 4-4 Average 24-Hour Profiles for Energy Use and Outlet Temperature, RH, and Absolute Humidity During Weekdays and Weekends for WHD-Site01

The profiles show that inlet air conditions did not differ significantly between weekdays and weekends. Inlet RH, which essentially represents basement air, reached its peak at the start of the system , followed by a decrease of about 4 percent at 10:30 AM, then a gradual increase throughout the rest of the day. This level in morning could be explained by the RH buildup during the night when the unit was turned off. Because the RH levels were generally above 40 percent (set point), the system was operating almost continuous at an almost constant energy usage, as seen in the minute-by-minute energy consumption profile. The unit demonstrated no observable pattern of compressor operation.

The conditions of the exiting air were relatively consistent throughout each 24-hour period, which suggests the WHD achieved almost constant temperature and RH, although there was a noticeable offset between the controller set point and our data. Combining both the compressor and fan-only modes, the average minute-by-minute RH levels of the exiting air were kept within 30 percent and 40 percent.

4.1.2 Power consumption, energy use, and mode of operation

Table 4-2 lists the average power consumption, daily energy use, and percentage time in each operational mode. The WHD was "on" 58 percent of the time. The WHD Compressor (and fan) mode consumed on average 630 W, amounting to about 7,260 watt-hours of energy use per day.[j] The fan used about 145 W and consumed 820 watt-hours per day.

Table 4-2 Summary Statistics of Power Consumption, Energy Use, and Percent of Time in Different Modes of Operation for WHD-Site01

Mode	Power Consumption (W)		Daily Energy Use (kWh/day)		Percentage Time in 24 hours (%)
	Mean	Min–Max	Mean	Min–Max	Mean
Compressor and fan	629.2	608.4–660.7	7.26	1.28–9.91	37.9
Fan-only	145.3	92.4–390.3	0.82	0.19–1.74	16.1
Standby	5.8	5.1–20.9	0.016	0.005–0.074	0.96

Figure 4-5 shows the total energy use for every hour of the day averaged over the 4.5-month monitoring period. The distribution shows that the compressor's peak energy use occurred around 9 AM, indicating that the compressor was operating fully during each morning startup period. Energy use decreased gradually, reaching its lowest point in the late afternoon, then picked up again between 7 and 8 PM before the system shut off at 9 PM. The compressor began running shortly after the system's fan turned on in the morning. Similarly, after the compressor

[j] Daily energy use was calculated by summing all the energy use data points from each 1-second measurement interval.

stopped, the fan continued to run briefly. Those events led to the fan-only peaks at 6 AM and 8 PM.

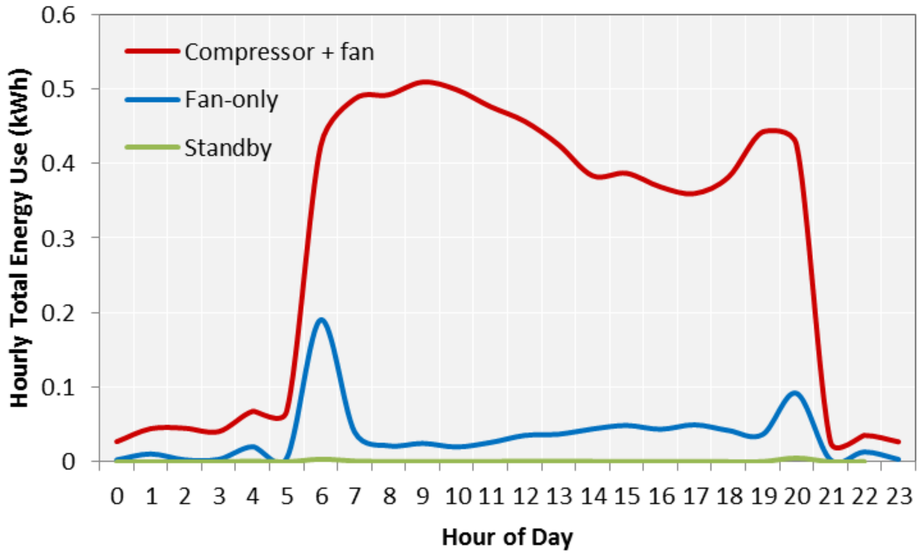

Figure 4-5 Total Energy Use for Every Hour of the Day at WHD-Site01

4.1.3 Effects of dehumidification on environmental conditions; associated energy use

Figure 4-6 and Figure 4-7 depict the relationships between daily energy use and differences in RH and temperature in the incoming and exiting air streams.

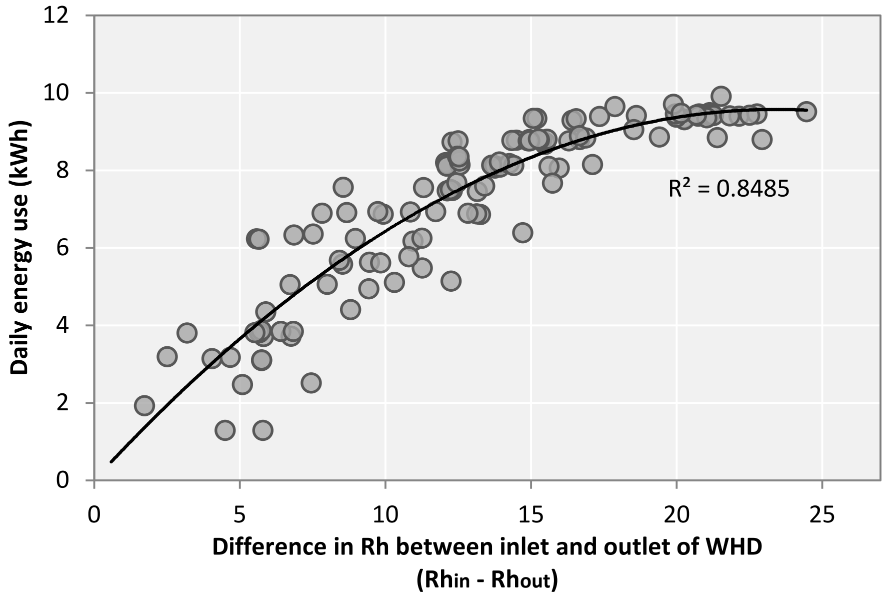

Figure 4-6 Daily Energy Use as a Function of the Difference Between RH in Inlet and in Outlet Air for WHD-Site01

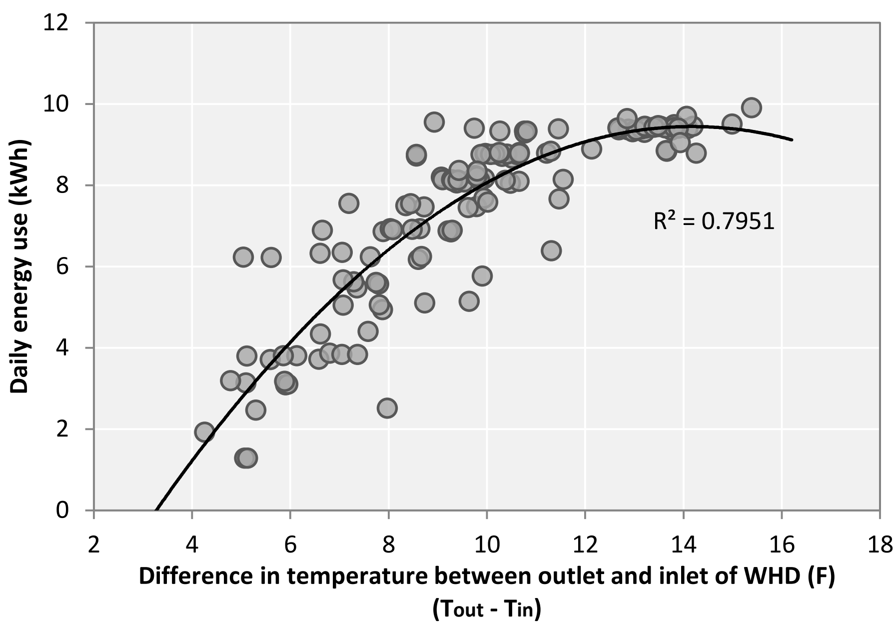

Figure 4-7 Daily Energy Use as a Function of the Difference Between Temperature in Inlet and in Outlet Air for WHD-Site01

Daily energy use increased as dehumidification and temperature increased. The maximum achievable reduction in RH was about 25 percent. Greater reductions in RH appear to have had a diminishing effect on energy use, as the system reached its maximum dehumidification capacity. The dehumidification process at maximum capacity could increase the temperature of the supply air by 15 °F. The following equations were derived from Figure 4-6 and Figure 4-7.

$$\text{Daily EU} = -0.0174(\Delta RH)^2 + 0.817(\Delta RH) \qquad [1]$$

$$\text{Daily EU} = -0.0795(\Delta T)^2 + 2.253(\Delta T) - 6.518 \qquad [2]$$

Where:

Daily EU = estimated energy use per day for each unit of decrease in relative humidity [1] or each degree of increase in temperature [2],

ΔRH = difference between the RH of the incoming and exiting air, and

ΔT = difference between the temperature of the incoming and exiting air.

4.1.4 Daily system efficiency and water removal

Our measurements of condensate generation yielded no meaningful results: the inconsistency of condensate flow resulted in a paucity of data. Therefore, to determine the field efficiency of the WHD (the ratio of water removed from the treated air to energy consumed) we used the absolute humidity to determine the variation in moisture content in the air during each compressor cycle. The air flow rate of the blower was used to determine the amount of air passing through the system during each cycle.

Table 4-3 shows the parameters derived from our calculation of the field efficiency and daily water removal rate of WHD-Site-01. The calculated efficiency of the system was 24 percent lower than the rated efficiency (2.24 versus 2.90). The amount of water removed per day was substantially less than the capacity of the system. Because the RH of the inlet air was already low, about 45 percent, each compressor cycle extracted only about 1.2 gram of water per cubic meter of air (g/m^3) that passed through. Note also that the rated ambient conditions are higher in temperature (80 °F). Additionally, the rated capacity assumes continuous operation over 24 hours at the constant 80F 60% RH conditions, not cycling as needed by the ambient conditions. Dehumidifier performance drops off with decreasing temperature even at constant RH.

Table 4-3 Parameters Used in Calculating Efficiency and Water Removal for WHD-Site01

Parameter	Mean (min–max)
Daily compressor run time per cycle (minutes)	329 (34–844)
Daily energy use per cycle (kWh)	3.45 (0.35–9.30)
Daily change in absolute humidity per cycle (g/m^3)	1.24 (0.10–2.36)
System air flow (cfm)	240
Daily field efficiency (L/kWh)	2.24 (rated: 2.90)
Daily water removal (pints/day)	12.2 (0.35–27.2)

4.2 Results for WHD-Site02

The inlet air for WHD-Site02 comprised of two air streams, the return air of the central air handler, and outdoor air. Both air streams were ducted directly to the WHD. The outlet air of this WHD was not returned to the whole home, but only to the basement. The make-up air therefore created negative pressure to the main part of the home, drawing in air (and possibly moisture) from outdoors. The makeup air could come from the basement as well, where there would be a net positive pressure. In this case, the configuration of the WHD increased the dehumidification load for the whole-home air-handling system every time the WHD operated.

4.2.1 Energy use and environmental conditions at WHD-Site02

Figure 4-8 shows the hourly profile for inlet air conditions and energy use throughout the monitoring period. At this site, the WHD's operation characteristic caused the unit be either in compressor mode or on standby. The energy use profile shows a consistent energy use of slightly more than 0.6 kWh per hour. There were a few hours when the system operated in fan-only mode. Airflow measurements indicated that the inlet air primarily comprised returned air from the whole home (the outdoor air flow was measured at 9 cfm, or about 3 percent of total air flow).

Figure 4-8 Hourly Profiles of Energy Use, Temperature, RH, and Absolute Humidity at the Air Inlet for WHD-Site02

Air temperature at the inlet air duct ranged from 69 °F to 75 °F. There was no significant difference in temperature between compressor and standby modes. The inlet RH ranged from 45 percent to 70 percent when the unit was in standby mode. The large swing in RH that occurred from day to day showed the need for a WHD at this site. When the compressor was running, the inlet RH was maintained at the lower end of the range (45 percent to 50 percent), indicating that the WHD was able to maintain the whole-home RH at a set point of 50 percent.

Figure 4-9 shows the hourly profile for outlet air conditions and energy use throughout the monitoring period. The figure shows that the compressor reduced the RH of the incoming air to as low as 18 percent. After that air was mixed with the whole-home air, the RH might reach 50 percent before the air was supplied back to the system's main air duct. The RH level during standby hours was also substantially lower in the outlet air (30 percent to 50 percent) than in the inlet air (45 percent to 70 percent), indicating that some portion of the return air was probably passed through WHD system because of pressure or leakage in the ducts when the main air handler blower is operating. The effect of dehumidification on air temperature is shown in the temperature plot. When the compressor was operating, the air temperature reached as much as 85°F to 90°F. Figure 4-9 shows that the WHD was able to control RH and temperature consistently. The day-to-day variations observed in Figure 4-8 were not observed in the outlet air plots.

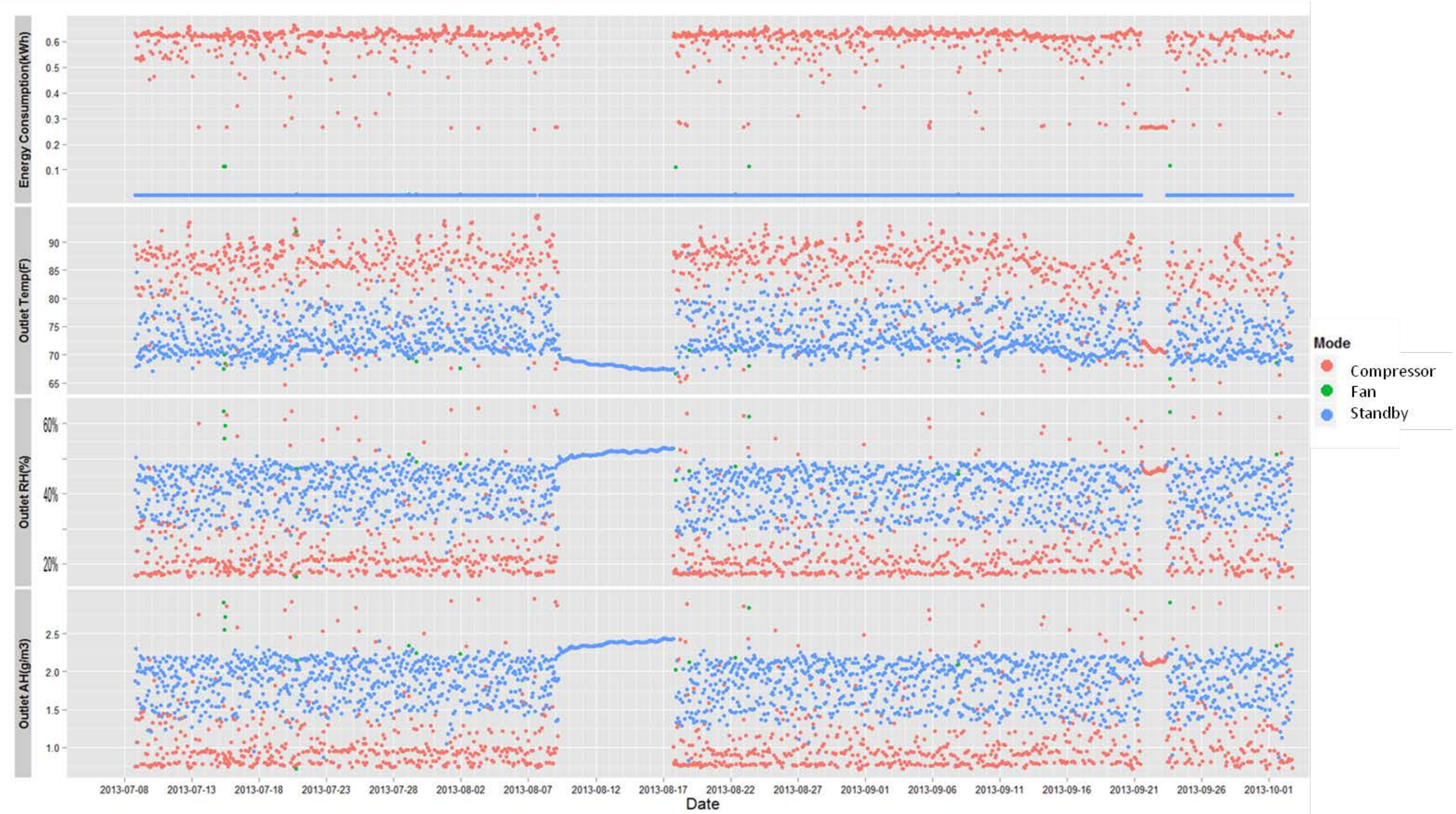

Figure 4-9 Hourly Profiles of Energy Use, Temperature, RH, and Absolute Humidity at the Air Outlet for WHD-Site02

Summary statistics for temperature, RH, and absolute humidity (AH) for WHD-Site02 are presented in 4-4.

Table 4-4 Inlet and Outlet Temperature, RH, and Absolute Humidity for Different Modes of Operation at WHD-Site02

Mode	Mean Inlet T*	SD† Inlet T	Mean Outlet T	SD Outlet T
Compressor	71.4	1.45	**84.7**	5.77
Fan-only	71.0	1.27	70.3	6.18
Standby	70.6	1.20	73.0	3.63
Mode	**Mean Inlet RH**	**SD Inlet RH**	**Mean Outlet RH**	**SD Outlet RH**
Compressor	48.6	2.43	**24.7**	10.2
Fan-only	51.8	6.19	50.1	11.5
Standby	54.3	6.84	42.0	6.51
Mode	**Mean Inlet AH‡**	**SD Inlet AH**	**Mean Outlet AH**	**SD Outlet AH**
Compressor	2.22	0.11	**1.11**	0.47
Fan-only	2.36	0.28	2.29	0.53
Standby	2.48	0.31	1.91	0.30

* T = temperature in °F.

† SD = standard deviation.

‡ AH = absolute humidity (vapor density).

The mean inlet air temperature, RH, and absolute humidity did not differ substantially among the three modes, although the mean RH during standby was about 5 percent higher than during compressor mode. When the compressor was on, the temperature at the outlet increased by 13 °F, to 85 °F, and the RH decreased by 24 percent to as low as 25 percent RH. These results indicate that the WHD system was functioning as intended.

The 24-hour profiles of energy use, temperature, RH, and absolute humidity for both weekdays and weekends are plotted in Figure 4-10 and Figure 4-11 for inlet and outlet air conditions, respectively. Each data point represents a 1-minute total for energy use and the average for environmental parameters. As shown in the legend, the weekday line is purple and the weekend light brown.

Figure 4-10 Average 24-Hour Profiles for Energy Use-and Inlet Temperature, RH, and Absolute Humidity During Weekdays and Weekends for WHD-Site02

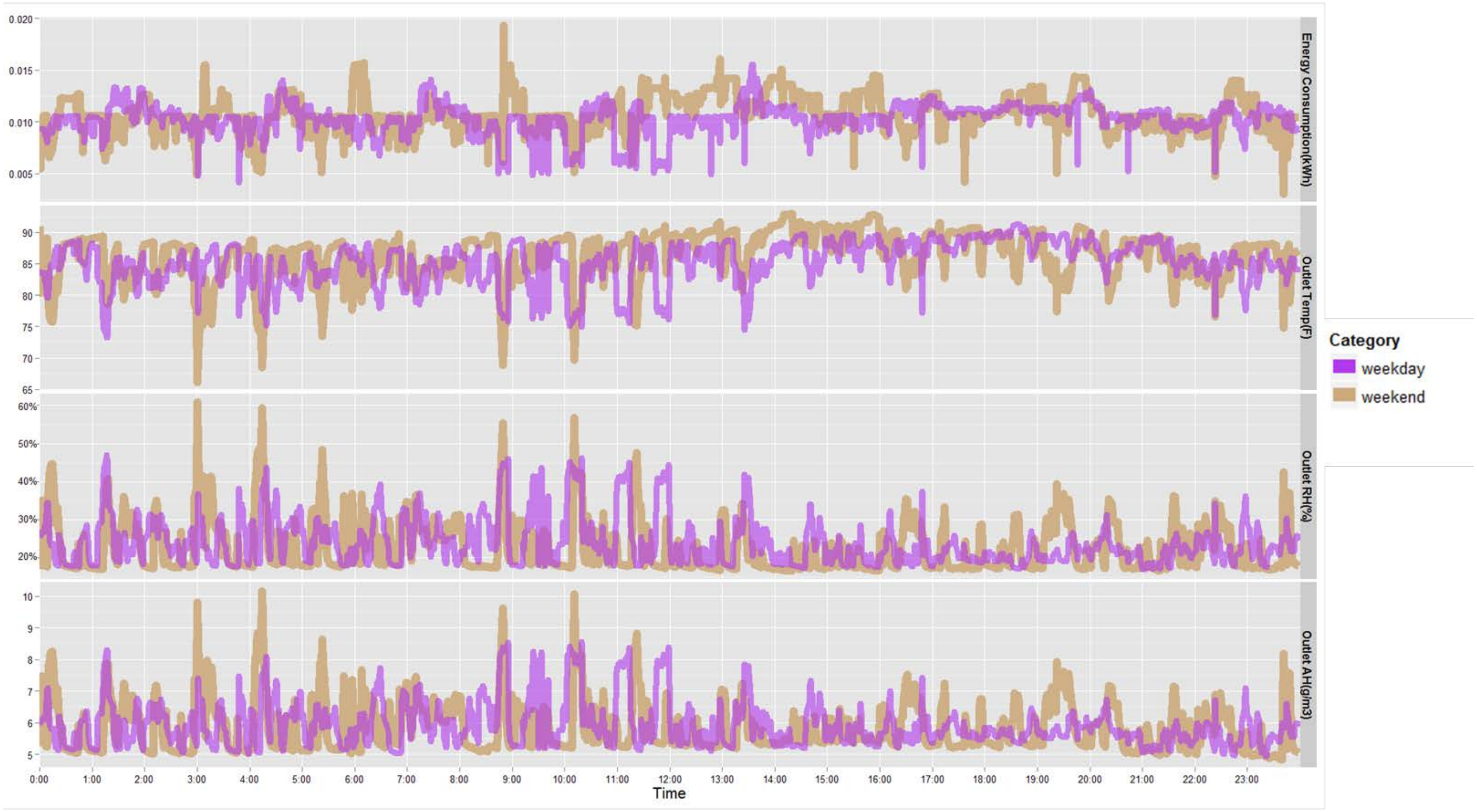

Figure 4-11 Average 24-Hour Profiles for Energy Use and Outlet Temperature, RH, and Absolute Humidity During Weekdays and Weekends for WHD-Site02

The results show little difference between inlet air conditions on weekdays and weekends. Both profiles show air temperature generally higher in the afternoon. In the afternoon, the weekend temperature profile was about 1 degree lower than the weekdays. Inlet RH, mostly from the whole home, was the same on weekdays and weekends.

The trend in the energy profile plot shows that there was one compressor cycle every 3-hour on weekdays. Each cycle started with a spike in energy use, followed by a slow decline that reached steady state after about an hour. This cycle was approximately halved during the weekends. The daily cycles affected the condition of the outlet air. When energy use increased, the temperature at the outlet increased and RH decreased.

4.2.2 Power consumption, energy use, and mode of operation

Table 4-5 lists the average power consumption, daily energy use, and percentage time in each operational mode for WHD-Site02.

Table 4-5 Summary Statistics of Power Consumption, Energy Use, and Percent of Time in Different Modes of Operation for WHD-Site02

Mode	Power Consumption (W)		Daily Energy Use (kWh/day)		Percentage Time in 24 hours (%)
	Mean	Min–Max	Mean	Min–Max	Mean
Compressor and fan	592.9	265.9–641.1	8.52	1.72–11.8	27.7
Fan-only	47.4	2.1–115.5	0.069	0.002–0.34	0.69
Standby	1.83	1.78–1.84	0.041	0.009–0.044	30.1

The WHD was "on" 58 percent of the time. The compressor was active only about 28 percent of the time. The compressor (and fan) consumed on average 593 W, for about 8,520 watt-hours of energy use per day. The fan used about 47 W and consumed 69 watt-hours per day. Standby mode used about 41 watt-hours per day, representing a higher percentage of daily dehumidifier use, much more than the mean of 16 watt-hours consumed in standby mode at WHD-Site 01.

Figure 4-12 depicts the total energy use for every hour of the day throughout the monitoring period.

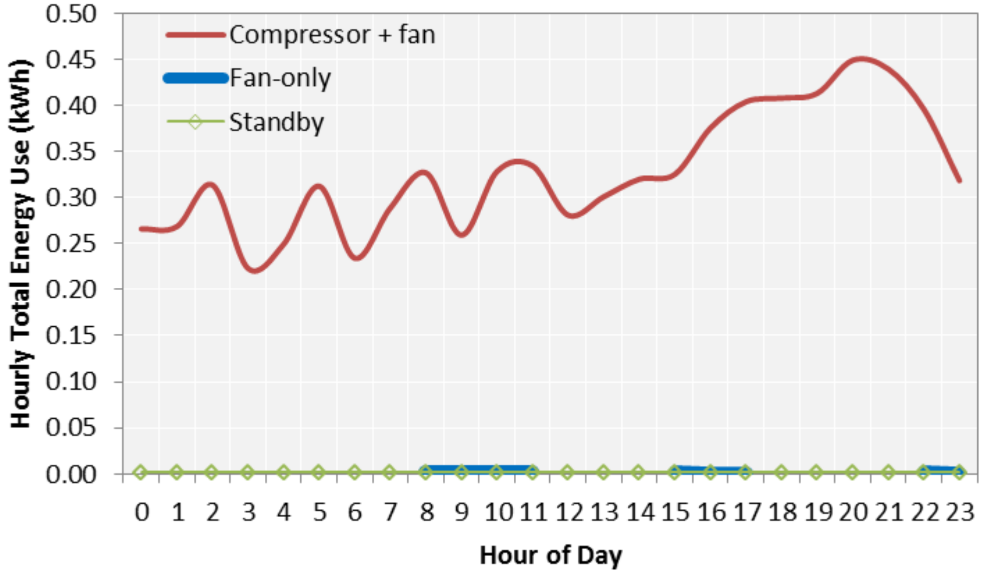

Figure 4-12 Total Energy Use for Every Hour of the Day at WHD-Site02

Figure 4-12 indicates that fan-only mode used almost no energy. A compressor cycling pattern occurred every 3 hours in the morning, gradually increasing energy use. Between 12 noon, and 8 PM, the energy use gradually increased from 0.30 to 0.45 kWh before dropping sharply between 9 PM and 12 midnight.

4.2.3 Effects of dehumidification on environmental conditions; associated energy use

Figure 4-13 and Figure 4-14 depict the relationship between daily energy use and changes in RH and temperature in the incoming and exiting air streams at WHD-Site02.

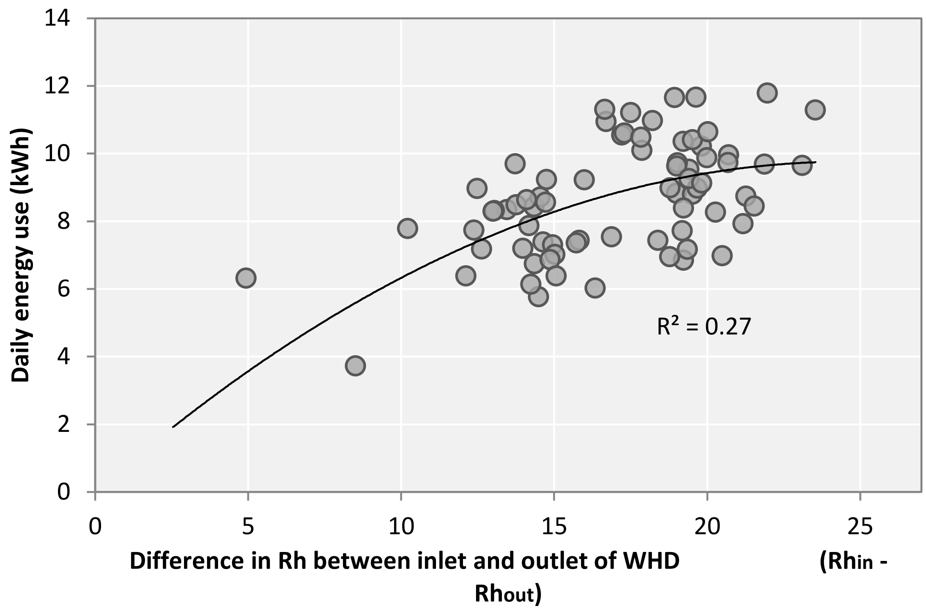

Figure 4-13 Daily Energy Use as a Function of the Difference Between RH in Inlet and in Outlet Air for WHD-Site02

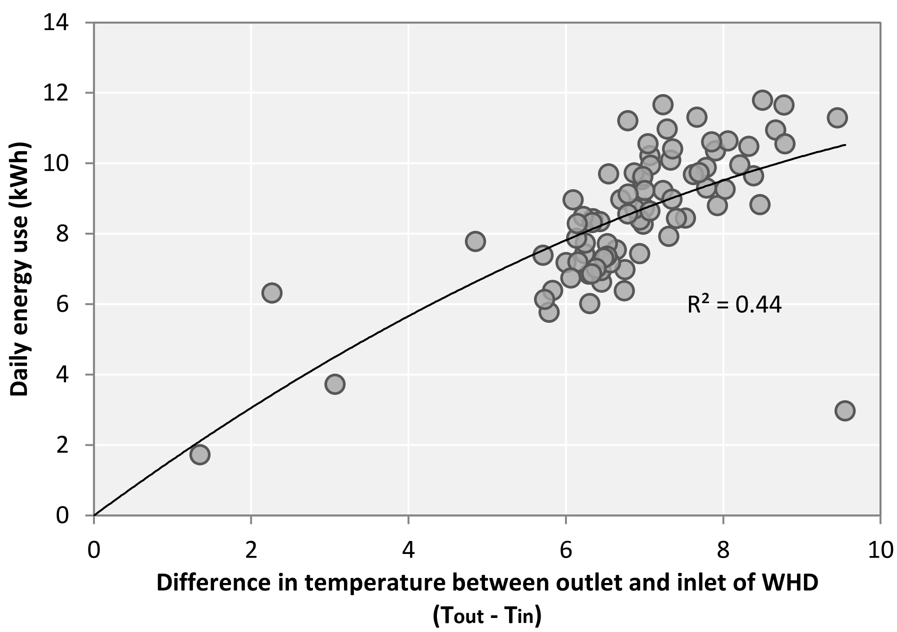

Figure 4-14 Daily Energy Use as a Function of the Difference Between Temperature in Inlet and in Outlet Air for WHD-Site02

Daily energy use increased along with dehumidification and increased temperature. The maximum achievable reduction in RH was about 24 percent. As with WHD-Site01, greater reductions in RH appear to have a diminishing effect on energy use as the system reaches its maximum dehumidification capacity. At maximum capacity, dehumidification could increase air temperature by 12 °F. We derived the following equations from the relationships.

$$\text{Daily EU} = -0.0162(\Delta RH)^2 + 0.7945(\Delta RH) \quad [3]$$

$$\text{Daily EU} = -0.0565(\Delta T)^2 + 1.6417(\Delta T) \quad [4]$$

Where:

Daily EU = estimated energy use per day for each unit of relative humidity decrease [3] or each degree of increase in temperature [4],
ΔRH = difference between incoming and exiting air RH, and
ΔT = difference between incoming and exiting air temperature.

4.2.4 Daily system efficiency and water removal

We determined the field efficiency of the WHD (the ratio of water removed from the treated air to the energy consumed). As with WHD-Site01, we used absolute humidity to determine the variation in moisture content in the air during each compressor cycle. The air flow rate of the fan was used to determine the amount of air passing through the system during each cycle.

Table 4-6 summarizes the parameters used in our calculation of the field efficiency and daily water removal rate of WHD-Site02. The calculated efficiency was 10 percent lower than the rated efficiency (2.73 versus 3.02). The amount of water removed per day was substantially less than the capacity of the system, because the RH of the inlet air coming from the main air handler was already low (about 50 percent). As observed previously, the temperature was lower than the rating condition. Note that the average inlet temperature was higher and the inlet RH was lower than for WHD-Site01. While it did not in this situation, a lower inlet RH could have the effect of lowering the efficiency. The inlet air would not be as humid, so the system would have to cool the air to a lower dew point to get condensation. Capacity will be dramatically affected if there is a large amount of time in standby mode, which is not accounted for in the capacity test. The amount of water extracted was about 35 pints per day.

Table 4-6 Parameters Used in Calculating Efficiency and Water Removal for WHD-Site02

Parameter	Mean (min–max)
Daily compressor run time per cycle (minutes)	42 (21–87)
Daily energy use per cycle (kWh)	2.83 (0.27–6.26)
Daily change in absolute humidity per cycle (g/m^3)	0.322 (0.001–0.769)
System air flow (cfm)	275
Daily field efficiency (L/kWh)	2.73 (rated: 3.02)
Daily water removal (pints/day)	35.1 (1.57–109)

4.3 Results for WHD-Site03

The dehumidifier at WHD-Site03 was intended to achieve two functions: to dehumidify the whole home (primary function) and to dehumidify the basement (secondary). All heating, cooling, and whole-home dehumidification and humidification were managed by one set of controls. Although the default configuration controlled basement dehumidification, the needs of the main home zone took precedence. In other words, a dehumidification call from the main zone controller would interrupt the basement zone operating cycle.

The WHD was set to cycle hourly using an internal timer that turn on the fan, drawing air from the basement area to the unit. If the RH sensed within the unit exceeded the control set point, the compressor was activated and the dehumidifier operated until the setting was met.

4.3.1 Profiles of energy use and environmental conditions at WHD-Site03

The profiles of energy use and inlet and outlet air conditions are presented in Figure 4-15 and Figure 4-16. The plots do not distinguish between the basement and the whole-home configuration. The inlet location (Figure 4-15) showed almost no difference in temperature or RH among the three operational modes. Because the controller is conditioning both the basement and home, interior climate conditions never got too far out of the desired range. Data gaps in the figures reflect sensor failures.

Figure 4-15 Hourly Profiles of Energy Use, Temperature, RH, and Absolute Humidity at the Air Inlet for WHD-Site03

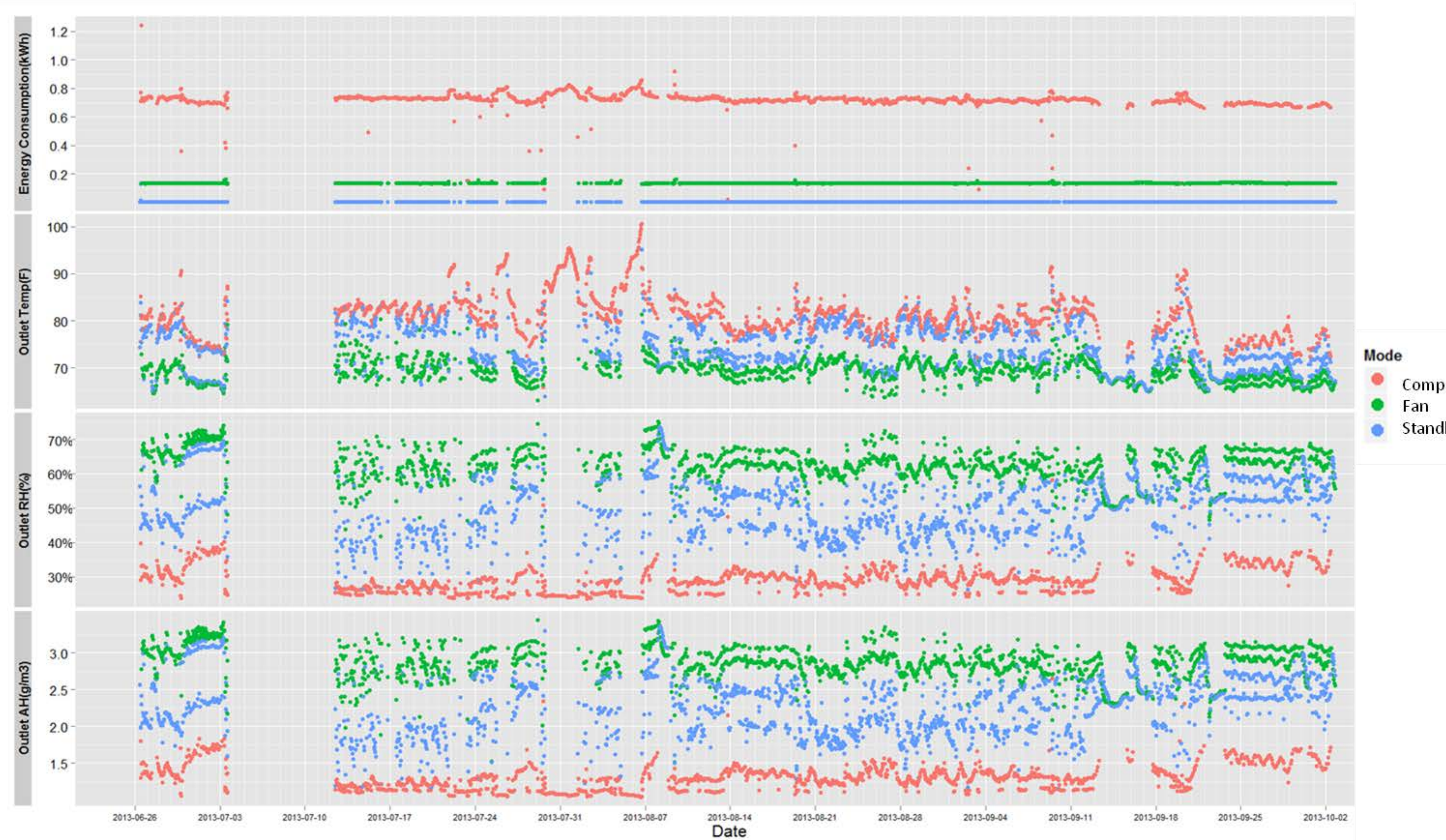

Figure 4-16 Hourly Profiles of Energy Use, Temperature, RH, and Absolute Humidity at the Air Outlet for WHD-Site03

The effect of dehumidification is illustrated clearly in Figure 4-16 because the RH levels of the outlet air differed among the three modes. When the compressor was on, the lowest RH recorded was in the range of 25 percent to 35 percent (combined whole-home and basement configurations). When only the fan was running, the RH increased to a range of 60 percent to 70 percent. The outlet air profiles generally show two lines for each operating mode, the higher RH representing the whole home, and the lower RH representing the basement configuration.

The basement zone generally required less dehumidification than did the whole home. Table 4-7 shows that the inlet RH level was in the range of 47 percent to 51 percent in the basement.

Table 4-7 Inlet and Outlet Temperature, RH, and Absolute Humidity for Different Modes of Operation at WHD-Site03 (Basement Configuration)

Mode	Mean Inlet T*	SD† Inlet T	Mean Outlet T	SD Outlet T
Compressor	69.8	2.07	80.5	3.06
Fan	68.2	1.85	69.2	2.33
Standby	68.7	1.95	74.1	4.64
Mode	**Mean Inlet RH**	**SD Inlet RH**	**Mean Outlet RH**	**SD Outlet RH**
Compressor	47.2	5.34	**29.0**	3.33
Fan	50.9	4.83	62.6	4.73
Standby	49.8	5.12	49.7	8.00
Mode	**Mean Inlet AH‡**	**SD Inlet AH**	**Mean Outlet AH**	**SD Outlet AH**
Compressor	2.16	0.25	1.31	0.16
Fan	2.33	0.23	2.87	0.22
Standby	2.28	0.24	2.26	0.38

* T = temperature in °F.
† SD = standard deviation.
‡ AH = absolute humidity (vapor density).

Table 4-8 reports a range in inlet RH of 56 percent to 59 percent for the whole home. Dehumidification for the whole-home configuration reduced RH by as much as 35 percent, whereas the reduction for the basement was less than 20 percent.

Table 4-8 Inlet and Outlet Temperature, RH, and Absolute Humidity for Different Modes of Operation at WHD-Site03 (Whole-Home Configuration)

Mode	Mean Inlet T*	SD‡ Inlet T	Mean Outlet T	SD Outlet T
Compressor	71.9	2.68	**89.1**	4.48
Fan	70.4	2.34	74.2	6.52
Standby	70.4	2.50	75.7	7.03
Mode	**Mean Inlet RH**	**SD Inlet RH**	**Mean Outlet RH**	**SD Outlet RH**
Compressor	58.4	3.83	**24.9**	2.05
Fan	57.2	4.76	52.5	12.9
Standby	56.3	3.49	48.9	12.8
Mode	**Mean Inlet AH†**	**SD Inlet AH**	**Mean Outlet AH**	**SD Outlet AH**
Compressor	2.66	0.17	1.11	0.10
Fan	2.61	0.21	2.39	0.60
Standby	2.57	0.16	2.22	0.60

* T = temperature in °F.
† SD = standard deviation.
‡ AH = absolute humidity (vapor density).

The 24-hour profiles of energy use, temperature, relative humidity, and absolute humidity for weekdays and weekends are plotted in Figure 4-17 and Figure 4-18 for inlet and outlet air conditions, respectively. The plots combine whole-home and basement configurations. Each data point represents a 1-minute total for energy use and an average for environmental parameters. As shown in the legend, the weekday line is purple, and the weekend brown.

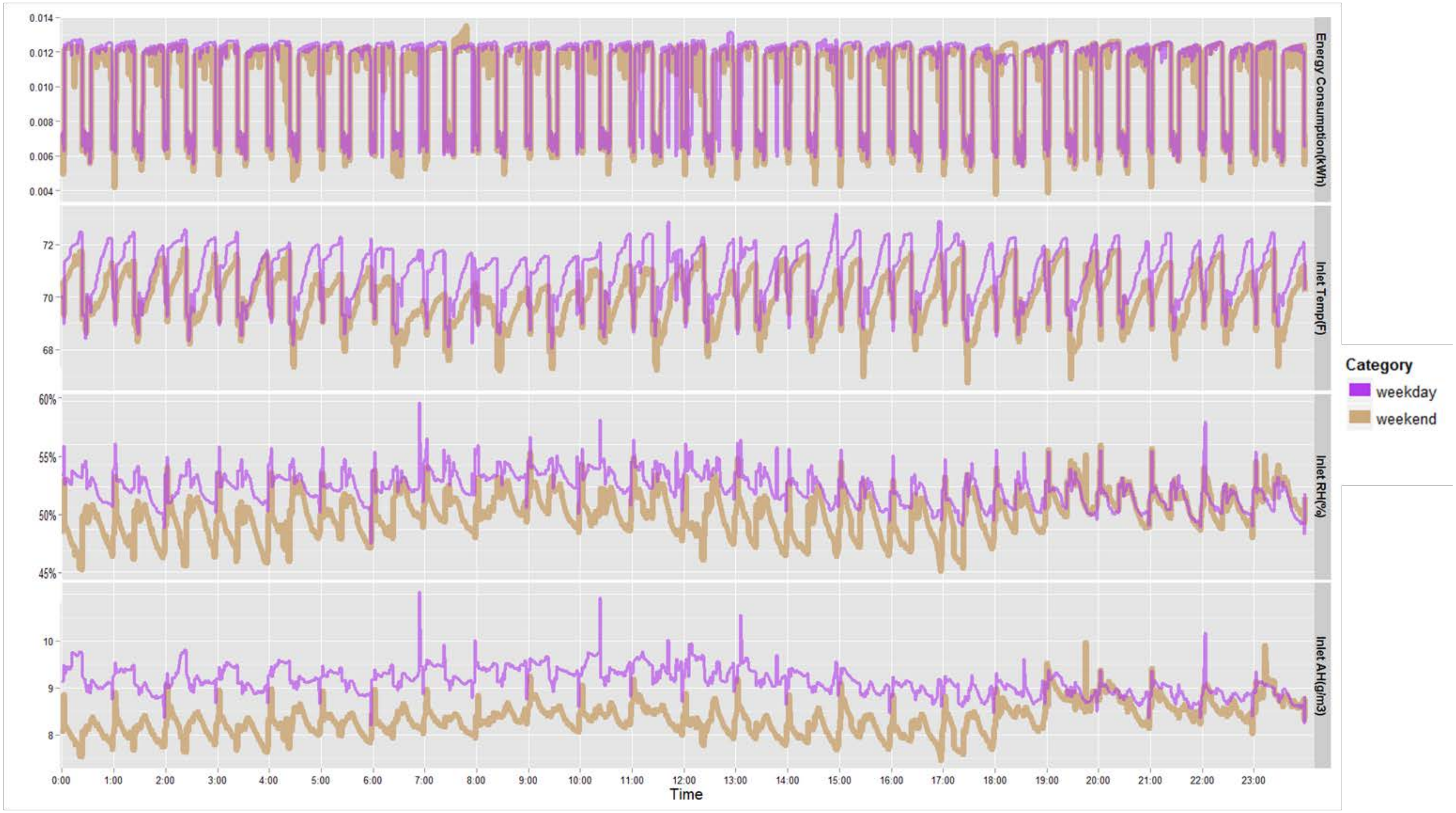

Figure 4-17 24-Hour Profiles for Average Energy Use and Inlet Temperature, RH, and Absolute Humidity During Weekdays and Weekends for WHD-Site03

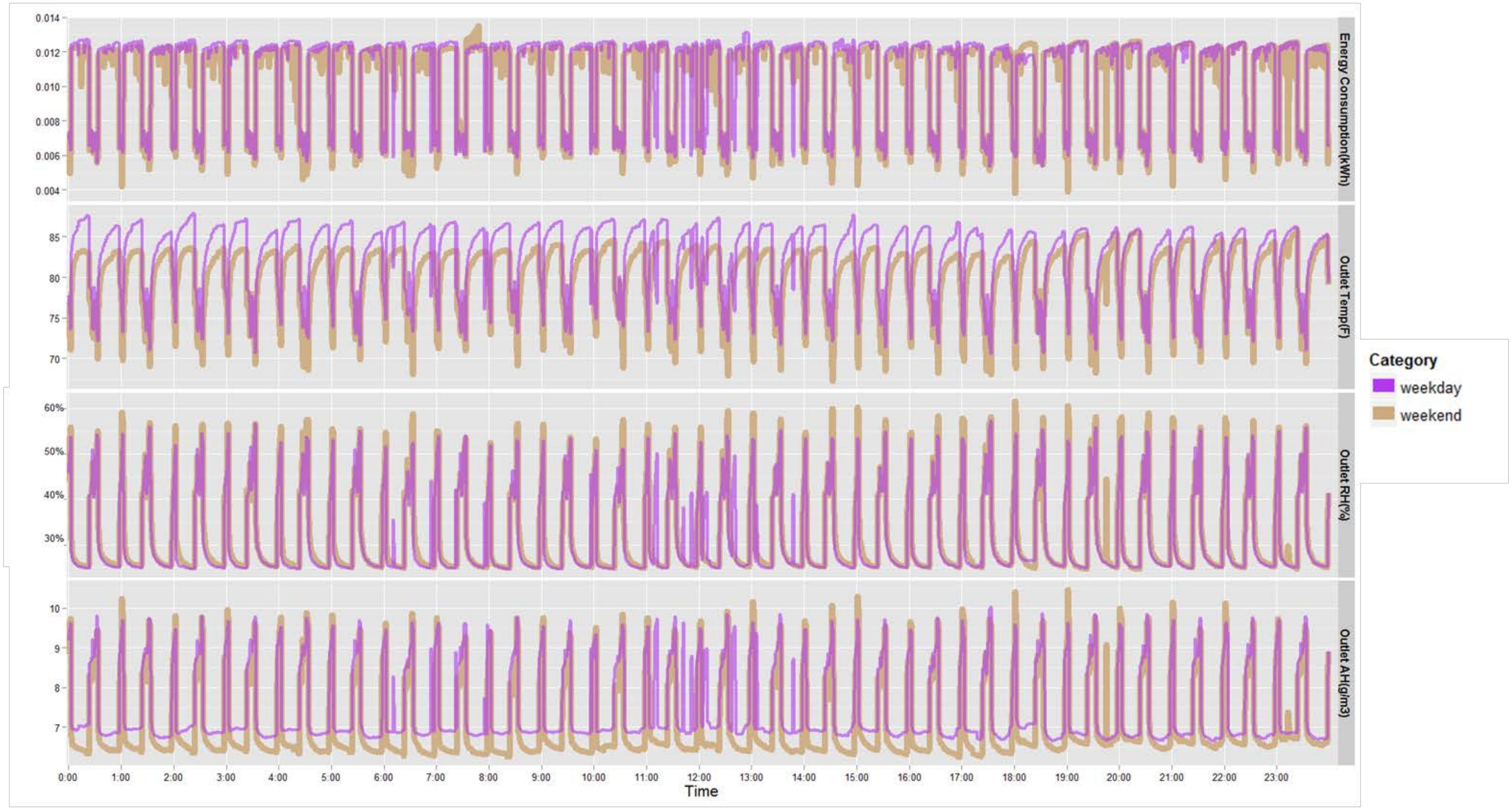

Figure 4-18 Average 24-Hour Profiles for Energy Use and Outlet Temperature, RH, and Absolute Humidity During Weekdays and Weekends for WHD-Site03

The results show no difference in inlet air conditions between weekdays and weekends. Temperature ranged from 68°F to 74°F; RH from 40 percent to 60 percent. Based on the energy use profile, there apparently were two compressor cycles per hour, although the site survey indicated one cycle per hour. Inlet air conditions varied with the cycles because the blower operated to measure indoor RH, triggering the compressor if the level exceeded the set point.

The 30-minute cycles clearly affected conditions of the exiting air (Figure 4-18). When energy use increased, the temperature at the outlet increased and RH decreased. The operational mechanism of this WHD produced a RH profile that differs greatly from those of the other sites. When the system was on standby (compressor off) every 30 minutes, the RH increased to a range of 50 percent to 60 percent; as soon as the system came on, the RH decreased markedly to the 25 percent to 30 percent range. The pattern repeated consistently throughout 24 hours.

4.3.2 Power consumption, energy use, and mode of operation

Table 4-9 lists the average power consumption, daily energy use, and percentage time in each operational mode for WHD-Site03's basement configuration.

Table 4-9 Summary Statistics of Power Consumption, Energy Use, and Percent of Time in Different Modes of Operation for WHD-Site03 (Basement Configuration)

Mode	Power Consumption (W)		Daily Energy Use (kWh/day)		Percent Time in 24 Hours (%)
	Mean	Min–Max	Mean	Min–Max	Mean
Compressor and fan	716.4	671.6–775.3	12.1	1.38–17.8	26.2
Fan-only	134.5	89.7–138.3	2.83	0.14–3.43	4.28
Standby	3.03	2.93–3.17	0.062	0.006–0.076	61.3

Because default operation was dedicated to the basement configuration, the WHD was "on" for most (92 percent) of the time in that configuration, although the compressor was active for less than a third of the time (26 percent). Compressor (and fan) consumed on average 716 W, which accounted for about 12,100 watt-hours of energy use per day. The fan consumed 135 W and used 2,830 watt-hours per day. The standby mode used about 62 watt-hours per day, and, as a percentage of total daily watt-hours, is more than any other site or configuration.

Table 4-10 presents the average power consumption, daily energy use, and percentage time in each operational mode for WHD-Site03's whole-home configuration.

Table 4-10 Summary Statistics of Power Consumption, Energy Use, and Percent of Time in Different Modes of Operation for WHD-Site03 (Whole-Home Configuration)

Mode	Power Consumption (W)		Daily Energy Use (kWh/day)		Percent Time in 24 Hours (%)
	Mean	Min–Max	Mean	Min–Max	Mean
Compressor and fan	772.9	714.4–920.9	7.56	0.78–19.5	19.7
Fan only	146.1	131.3–157.7	0.27	0.14–0.60	0.013
Standby	3.08	2.64–4.24	0.016	0.003–0.136	0.002

In the whole-home configuration, the WHD operated for only about 20 percent of the time. Power consumption was about 10 percent higher than in the basement configuration. Despite a shorter period of operation, energy use per day was substantial (7,600 watt-hours), about the same as for the other study sites.

Figure 4-19 depicts the total energy use for every hour of the day averaged over the monitoring period. The regular cycling of the compressor spread the total energy use almost evenly throughout a 24-hour period. The compressor used on average 0.55 kWh every hour; the fan used about 0.1 kWh every hour.

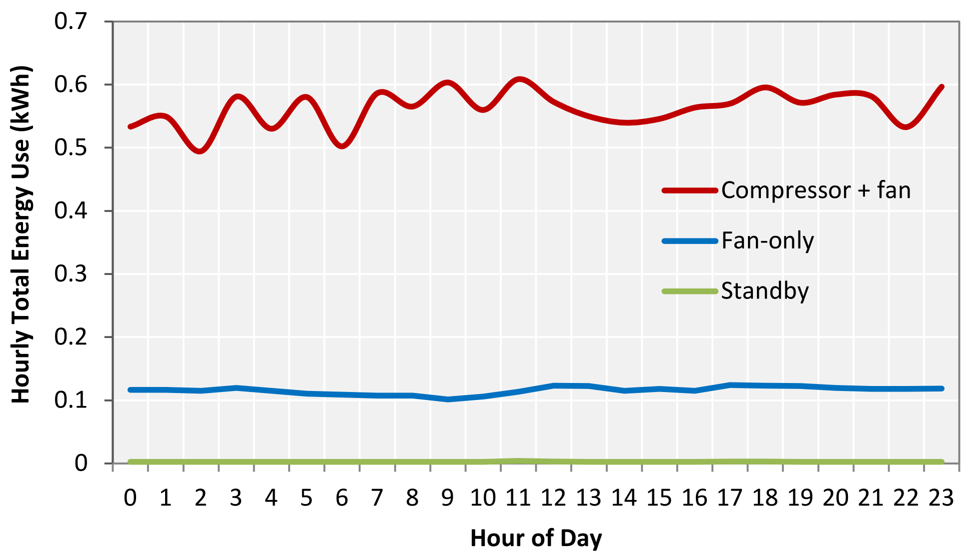

Figure 4-19 Total Energy Use for Every Hour During 4.5 Months at WHD-Site03

4.3.3 Effects of dehumidification on environmental conditions; associated energy use

Figure 4-20 and Figure 4-21 depict the relationships between daily energy use and the changes in RH and temperature in the incoming and exiting air streams for WHD-Site03 operating in the basement configuration.

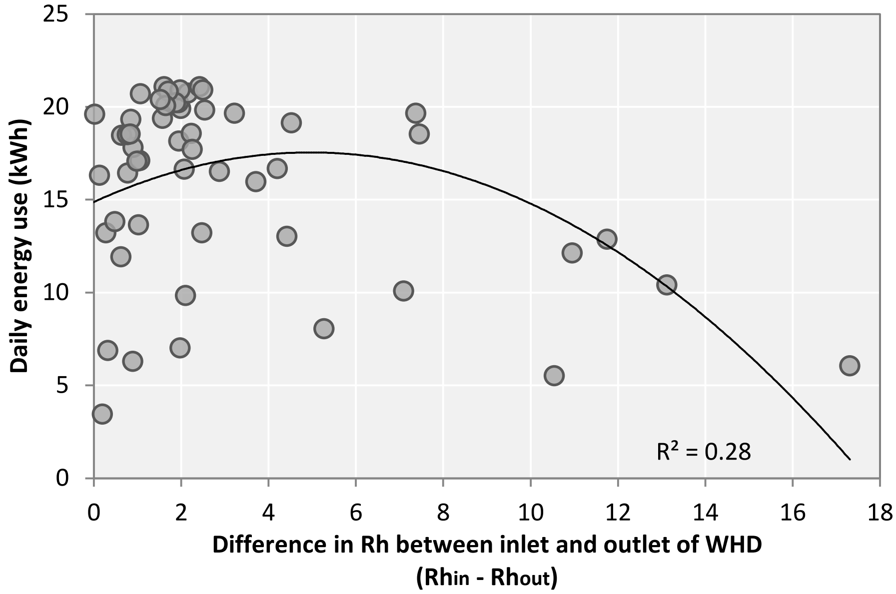

Figure 4-20 Daily Energy Use as a Function of the Difference Between RH in Inlet and in Outlet Air for WHD-Site03 (Basement Configuration)

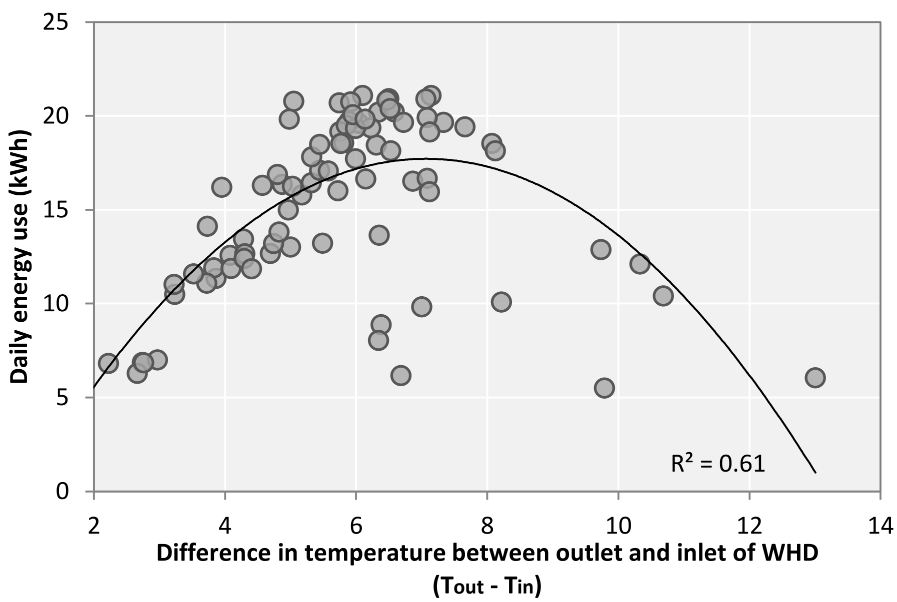

Figure 4-21 Daily Energy Use as a Function of the Difference Between Temperature in Inlet and in Outlet Air for WHD–Site03 (Basement Configuration)

In the basement configuration, the daily energy use peaked when the difference in RH was about 6 percent. There was a trend of decreasing energy use with greater reductions in RH, perhaps because the short compressor cycle created a period of “free” dehumidification after the compressor turned off. The maximum achievable reduction in RH was 18 percent. The equations derived from the relationships are as follows.

$$\text{Daily EU} = -0.1085(\Delta RH)^2 + 1.0763(\Delta RH) + 14.875 \quad [5]$$

$$\text{Daily EU} = -0.4735(\Delta T)^2 + 6.6892\,(\Delta T) - 5.911 \quad [6]$$

Where:

Daily EU = estimated energy use per day for each unit of RH decrease [5] or each degree of temperature increase [6],
ΔRH = difference between the RH of incoming and exiting air, and
ΔT = difference between the temperatures of incoming air and exiting air.

Figure 4-22 and Figure 4-23 depict the relationships between daily energy use and the changes in RH and temperature in the incoming and exiting air streams for WHD-Site03 operating in the whole-home configuration.

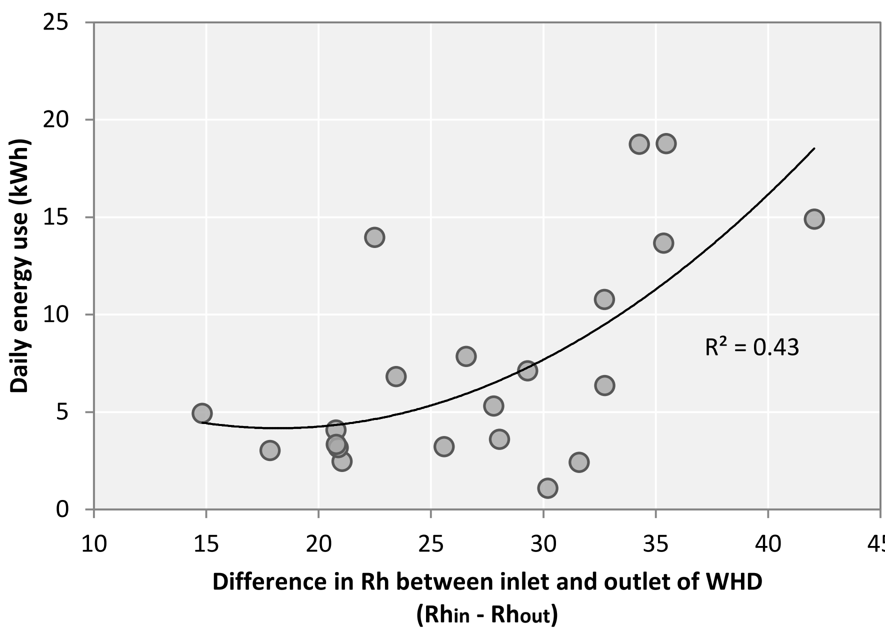

Figure 4-22 Daily Energy Use as a Function of the RH Difference Between RH in Inlet and in Outlet Air for WHD–Site03 (Whole-Home Configuration)

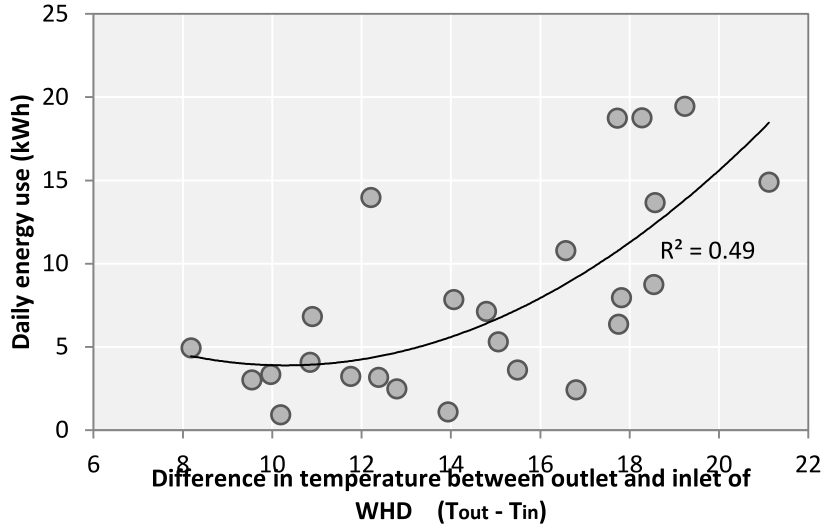

Figure 4-23 Daily Energy Use as a Function of the Temperature Difference Between Temperature in Inlet and in Outlet Air for WHD--Site03 (Whole-Home Configuration)

Data points were insufficient to establish reasonable correlations for the whole-home configuration. The trends are, however, consistent with results for WHD-Site01 and WHD-Site02, although the change in RH was most profound at this site. The maximum achievable reduction in RH was 42 percent. The equations derived from the relationships are as follows.

Daily EU = $0.0252(\Delta RH)^2 - 0.9177(\Delta RH) + 12.517$ [8]

Daily EU = $0.1245(\Delta T)^2 - 2.564(\Delta T) - 17.091$ [9]

Where:

Daily EU = estimated energy use per day for each unit of relative humidity decrease [8] or each degree of temperature increase [9],
ΔRH = difference between the RH of the incoming and exiting air, and
ΔT = difference between the temperatures of the incoming and exiting air.

4.3.4 Daily field efficiency and water removal

As with the other study sites, we determined the field efficiency of WHD-Site03 (the ratio of water removed from the treated air to the energy consumed) by using the absolute humidity to determine the variation in moisture content in the air during each compressor cycle. The air flow rate of the fan was used to determine the amount of air passing through the system during each cycle.

Table 4-11 and Table 4-12 summarize the parameters derived from the calculation of field efficiency, the calculated result, and daily water removal rate of the WHD for basement and whole-home configurations, respectively.

Table 4-11 Parameters Used in Calculating Efficiency and Water Removal for WHD-Site03, Basement Configuration

Parameter	Mean (min–max)
Daily compressor run time per cycle (minutes)	41 (8–87)
Daily energy use per cycle (kWh)	0.53 (0.38–0.76)
Daily change in absolute humidity per cycle (g/m^3)	2.02 (0.56–2.43)
Air flow (cfm)	310
Daily field efficiency (L/kWh)	1.20 (rated: 2.20)
Water removal rate (pints/day)	26.4 (0.83–79.4)

Table 4-12 Parameters Used in Calculating Efficiency and Water Removal for WHD-Site03, Whole-Home Configuration

Parameter	Mean (min–max)
Daily compressor run time per cycle (minutes)	266 (34–707)
Daily energy use per cycle (kWh)	5.06 (0.24–19.3)
Daily change in absolute humidity per cycle (g/m^3)	1.41 (0.51–1.71)
Air flow (cfm)	310
Daily in-field efficiency (L/kWh)	2.20 (rated: 2.20)
Water removal rate (pints/day)	25.8 (4.98–71.7)

The efficiency of the system was much lower when operating in the basement configuration than in the whole-home configuration because of the frequent system cycling. In whole-home mode, the field efficiency matched the manufacturer's rating. The amount of water removed per day, about 26 pints for both configurations, was substantially lower than the capacity of the system.

4.4 Estimated versus Metered Energy Use

To evaluate the rated energy factor (EF) of the three whole-home dehumidifiers, we used the rated EF and the recorded daily average operating hours to calculate a daily average energy use. We then compared the metered daily average power consumption with the calculated daily average energy use. Table 4-13 summarizes the results for calculated and metered daily energy use. We found energy consumption of all units was slightly lower than the estimated energy use, except for WHD-Site03 in the basement configuration.

Table 4-13 Estimated Energy Use Compared to Metered Daily Energy Use

	Rated EF (liters/kWh)	Rated Capacity (pints/day)	Estimated Daily Energy Use (kWh/day)	Actual Average Daily Energy Use (kWh/ day)
WHD-Site01	2.9	105	9.64	8.10
WHD-Site02	3.0	110	9.93	8.63
WHD-Site03 (B)	2.2	90	10.9	14.99
WHD-Site03 (WH)				7.85

* Site WHD-Site03 in basement configuration.

Table 4-14 Metered Results: Mean Temperature, Mean RH, and Compressor Power

Site (application)	Rated Capacity (pints/day)	Mean Temperature Inlet / Outlet (compressor mode, °F)	Mean RH Inlet / Outlet (compressor mode, %)	Average Compressor Power Consumption (W)
WHD-Site01 (whole-home)	105	72.2 / 87.1	42.8 / 20.3	629
WHD-Site02 (basement)	110	71.0 / 84.7	48.6 / 24.7	593
WHD-Site03 (whole-home)	90	71.9 / 89.1	58.4 / 24.9	716
WHD-Site03 (basement)	90	69.8 / 80.5	47.2 / 29.0	773

4.5 Laboratory Test Results

The National Renewable Energy Laboratory (NREL)[k] tested six residential mechanical/refrigerative dehumidifiers. Two of the six dehumidifiers were WHDs. NREL's objective was to measure the performance of each dehumidifier to develop performance curves for rate of water removal and for energy factor. Dehumidifiers having multiple fan speeds were tested at high fan speeds only. Testing began when steady state conditions were met. The project's goals did not include estimating the power demand of fan-only or standby mode. Nor did the project estimate the percentage of time during a 24-hour period when the dehumidifier operated in various modes. Table 4-15 summarizes results for the two WHDs NREL tested.

[k] Winkler, R. et al. 2010. Laboratory Test Report for Six ENERGY STAR Dehumidifiers. National Renewable Energy Laboratory. Golden, CO. NREL/TP-5500-52791

Table 4-15 Results for WHDs Tested by NREL

Parameter	Source	Ultra-Aire XT150H	Ultra-Aire 70H
Capacity (pints /day)	Manufacturer reported	150	70
	Measured value	146.8	77.1
Airflow rate (cfm)	Manufacturer reported	415	160
	Measured value	330	165
Energy factor[3] (L/kWh)	Manufacturer reported	3.7	2.32
	Measured value	3.65	2.56
Power (W)	Measured value	792.98	593.65

Note: all manufacturer-reported and measured values based on the inlet condition of 80 °F, 60% RH.

NREL tested the units at different temperatures and relative humidity levels (see Table 4-16). However, no comparison between the compressor powers from our metering studies and NREL tests can be made because dehumidifier compressor power is likely a function of specific manufacturer/brand designs rather than inherent to the capacity of the unit. Compressor power is also a function of the operating conditions. When operated in the same ambient conditions, higher capacity dehumidifiers will have higher power compressors. However, once temperature and humidity change, the compressor power will change based on the different refrigerant conditions. In general, a lower ambient temperature will lead to lower compressor power because the system will be at a lower pressure. Similarly, a lower RH leads to lower compressor power because the heat exchangers operate at lower temperatures, also creating a lower system pressure. Table 4-16 shows this trend. The trend in power versus capacity is opposite for the metered units than for the NREL units. NREL had higher power with higher capacity, while metered units showed highest power with the lowest capacity units.

Table 4-16 RH and Compressor Power Variations from NREL Testing

Test Model	**Capacity (pints/day)**	**Median Temperature (compressor mode, °F)**	**Maximum RH (compressor mode, %)**	**Average Compressor Power Consumption (W)**
NREL WHD #1	150	70	44.8	672.68
			70.6	723.88
			79.7	743.37
NREL WHD #2	70	70	52.9	504.82
			73.9	556.73
			88.6	599.04

5 CONCLUSIONS

Lawrence Berkeley National Laboratory conducted a pilot study investigation WHD energy use using a field-monitoring approach. The main objectives of this pilot study are (1) to obtain information on the applications and configurations of WHDs in use in homes, (2) to understand the operational characteristics and times of use, (3) to collect data on energy use and environmental conditions, and (4) to estimate the field performance (efficiency) of the systems. We selected three study sites. Each site represented a different application and configuration of WHDs. Monitoring started in June 2013 and will end in December 2013 (for this report, only June-September 2013 period was reported).

This pilot study revealed that the field applications and configurations of WHDs varied substantially depending on the householder's needs. Three types of WHD applications were reported in this study: (1) basement, (2) whole-house, and (3) combination of basement and whole-house. Furthermore, because the systems were used in conjunction with the house CAC, the air flow distribution and control mechanism were unique to each study sites. The table below summarizes the configuration of each system.

Table 5-1 Summary Table for System Configuration

Characteristics	WHD-Site01	WHD-Site02	WHD-Site03
Ducting layout	Inlet: basement (not ducted) Outlet: whole-house (ducted)	Inlet: whole-house (ducted) Outlet: basement (not ducted)	Inlet: whole-house and ERV (ducted) Outlet: whole house (ducted) OR Inlet: basement (ducted) Outlet: basement (ducted)
Direct outdoor air	No	Yes	Partially through ERV
Connection to CAC	Partially connected (supply only)	Partially connected (inlet only)	Fully connected for whole-house application, not connected for basement application

All WHDs monitored in this study were able to achieve and maintain a relatively low relative humidity at the exit air location. The dehumidifier air was then supplied to the basement or mixed with supply air stream of the CAC and supplied to other sections of the house. A decrease of RH in the range of 18-34% (mean, daily) was recorded among the study sites. However, the effect was associated with elevated air temperature in the range of 11°F to18°F (mean, daily).

Despite differences in dehumidification loads, the average power consumptions of the WHDs among the three sites were within a comparable range of 590-770 W. The systems consumed between 7.85 and 14.99 kWh per day with estimated efficiency ranging between 1.2 and 2.7 L/kWh. Based on the result from one of the sites, it is evident that WHD applications and control mechanism could substantially impact the energy use and efficiency, for example, the lowest efficiency level was attributable to a basement application of WHD that was not connected to the CAC system and programmed with frequent compressor cycle, as opposed to its second application for whole-home use where it was fully connected to CAC and operated the compressor on longer and continuous cycle.

The operation time during compressor mode was in the range of 20-38% of each 24-hour period. The time of compressor operation was close in the two basement configurations. The standby and fan-only modes differed more widely among the three sites. The table below summarizes the operation time in percentage. The systems were off (without power) for the remainder of the time.

Table 5-2 Summary Table for Time of Operation

	Capacity (pints/day)	Percentage time of operation* (%)		
		Compressor	Fan-only	Standby
WHD-Site01 (whole-home)	105	38	16	0.96
WHD-Site03 (whole-home)	90	20	0.01	0.02
WHD-Site02 (basement)	110	28	0.69	30
WHD-Site03 (basement)	90	26	4.3	61

Our results indicate that the dehumidification effects—as shown in RH and temperature changes—were associated with energy use. Greater reduction in RH and increase in temperature were correlated with higher energy use. The impacts were clearer for one of the WHD-Site01 locale (R^2:0.80) compared to other sites (R^2:0.3-0.6).

Additional Dehumidifier Field Testing

Our limited data set reflects the operation of three distinct whole-home dehumidifier configurations. A greater number of sites will enable us to identify categories of WHD configurations and examine WHD performance within those categories. We also plan to undertake performance mapping and further develop the relationship between environmental conditions and energy use with more study sites and data.

Further investigation will provide insight into the effects that differences in geographic location, dehumidifier configuration with respect to the air-handling system, and householder behaviors have on percentage of time WHDs spend in each operational mode, particularly in compressor run time, the primary driver for dehumidifier energy consumption.

6 ACKNOWLEDGMENTS

The authors wish to thank the following individuals for their contributions to this study: D. Ahl, D. Ash, B. Auchter, D. Cautley, L.B. Derouches, R.H. Galore, M. Iyer, A.B. Lekov, J.D. Lutz, D.H. Powers, G.J. Rosenquist, and A.A. Williams.