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Publication Date

2013-02-08

LBNL-xxxxE

Field-Metered Data from Portable Unit Dehumidifiers in the U.S. Residential Sector: Initial Results of a Pilot Study

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January 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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1 INTRODUCTION

The work described herein is intended to enrich the body of literature regarding dehumidifiers in residential settings—in particular the hours of use and energy consumption of various types of dehumidifiers. In the United States, portable unit dehumidifiers most commonly are used in basements during humid summer days in northern climates. Dehumidifier energy consumption differs among households depending on settings selected by the user, frequency of use, and conditions of operation. Although some estimates of dehumidifier use have been developed, and a few metering studies performed, there remains a paucity of metered data collected from individual households that use dehumidifiers.

For this study we obtained field data on the energy consumption of dehumidifiers to supplement currently available analyses. Our goal was to obtain data from a pilot study that we could use to develop initial distributions describing the capacities and applications of dehumidifiers used in individual homes. More precisely characterizing the use of dehumidifiers in real-world applications will enable a more accurate estimate of the range of energy use in various operational modes. Our pilot field-metering exercise was aimed at compiling real-time data on the energy consumption of portable dehumidifiers in residential households in the New England and Mid-Atlantic areas. Our analysis furthers the process of developing a more precise estimate of dehumidifier energy use, which will support the evaluation of the potential energy savings and attendant costs associated with more energy efficient dehumidifiers.

2 PRODUCT DESCRIPTION

Although higher air temperatures can make people uncomfortable, that discomfort is increased greatly when the air is moist, because moisture affects what the temperature feels like (the heat index). Warm, moist air also supports the growth of mold, mildew, bacteria, and dust mites, which reduce indoor air quality and often cause allergies. Humidity, which concerns the amount of moisture or water vapor in the air, most often is described in terms of relative humidity (RH). RH is the amount of water vapor in the air at a given temperature compared to the greatest amount of water vapor the air can hold at that temperature.

The optimum RH level for a building generally is considered to be between 30 percent and 50 to 60 percent.[1] In colder climates, during the heating season, it is recommended that RH levels be in the range of 30 percent to 40 percent to prevent window condensation.

Figure 2-1 shows that the range in RH for avoiding poor air quality is 30 percent to 60 percent. In terms of comfort, the ideal relative humidity set point is between 45 percent and 50 percent.

That level of humidity enables a human body to feel the same as the temperature at which the thermostat is set, while maintaining enough humidity to avoid dry or irritated skin and lungs.

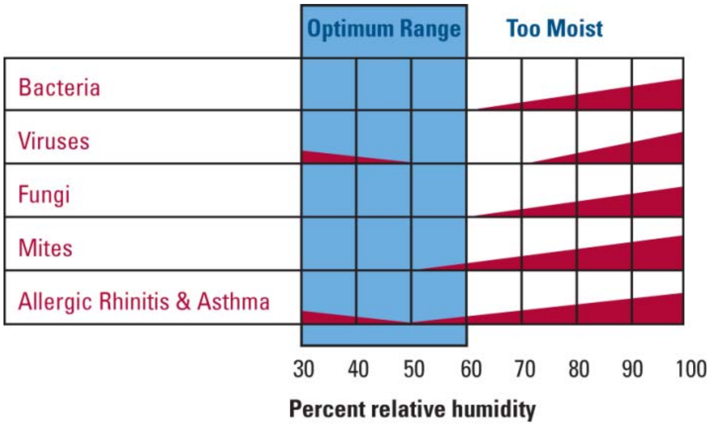

Figure 2-1 Effects of Relative Humidity

Many dehumidifiers include a built-in humidistat, a device that enables the user to set the desired RH level for a room. After the room reaches the set RH level, the dehumidifier automatically cycles on and off to maintain that level. In other systems dehumidifier operation relies on a timer, which may or may not initiate operation in response to sensed RH.

The following sections describe how various dehumidifiers work and the types of dehumidifiers intended for residential applications. We also describe some issues related to unit dehumidifiers, in particular the most prevalent type, the mechanical/refrigerative.

2.1 Product and Technology Types

Dehumidifiers can be categorized by either product or technology type. Dehumidifier products can be classified as whole-house or portable units. We also describe three technologies used for dehumidification.

Whole-house dehumidifiers (WHDs) are designed to be either ducted directly into a home's HVAC system or installed with their own ducting system. Technologically, WHDs are almost identical to mechanical/refrigerative or desiccant dehumidifiers; however, the WHD may have separate fresh-air intake vents. WHDs operate at a larger capacity than portable unit dehumidifiers, resulting in increased air movement, water removal (capacity), and efficiency. Because of their larger size, WHDs always rely on a dedicated drainage line rather than a drainage bucket to dispose of condensate. Although most drainage lines use gravity to dispose of the condensate, supplemental pumps can be installed when necessary.

2.1.1 Mechanical/refrigerative dehumidifier

The most common type of residential dehumidifier removes moisture through air cooling. The device comprises a compressor, cooling coils (an evaporator), reheater, fan, and humidistat.

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 interior space. The air is returned to the interior space drier and at a slightly higher temperature. The moisture that condenses out of the air drops either into a drainage bucket that is emptied manually or into a drain line.

A mechanical/refrigerative dehumidifier was defined by the U.S. Department of Energy as "a self-contained, electrically operated, and mechanically encased assembly consisting of—

1. a refrigerated surface (evaporator) that condenses moisture from the atmosphere;
2. a refrigerating system, including an electric motor;
3. an air-circulating fan; and
4. a means for collecting or disposing of the condensate."

Some dehumidifiers incorporate a condensate pump. In addition to mechanical/refrigerative dehumidifiers, we describe two other technology types.

2.1.2 Desiccant dehumidifier

A desiccant dehumidifier draws moist air over a desiccant material, such as silica gel. Desiccant materials naturally attract moisture from the air by creating an area of low vapor pressure at the surface of the desiccant. The higher vapor pressure of the moist air causes water molecules in the air to move to the desiccant material. Desiccant dehumidifiers eliminate the need to cool the air prior to dehumidification, making the technology especially suited for cooler climates. Desiccant dehumidifiers comprise four components:

1. a desiccant holder to contain the silica gel,
2. a fan that draws in air and passes it over the desiccant,
3. a heater to warm the air inside the unit, and
4. a fan to remove the water vapor from the gel so that it can again absorb moisture.

Desiccant dehumidifiers may have many configurations, including liquid spray-tower, solid packed tower, rotating horizontal bed, multiple vertical bed, and rotating honeycomb. Some incorporate a refrigerant component for added moisture removal. The most widely used configuration for a home-sized appliance is the solid packed tower.

2.1.3 Electronic dehumidifier

Electronic dehumidifiers utilize a peltier heat pump (named after the French physicist Jean-Charles Peltier) to create a cool surface for condensing water vapor from air. The operation of an electronic dehumidifier is similar to that of an air conditioner. Moisture is removed from the air as a fan draws indoor air over a heat exchange coil having a temperature that has been reduced to near freezing. Water in the air condenses on the coil and is drained into a tank below. The air is reheated and returned to the room. Because they have no mechanical converters and thus are extremely quiet, heat pump dehumidifiers are well suited to an environment where noise is a concern.

2.2 Issues Associated with Residential Dehumidifiers

The two primary issues concerning use of residential dehumidifiers are disposal of the collected water and the potential for ice buildup in some units.

2.2.1 Disposal of collected water

When determining dehumidifier energy use, one must account for product off-times when the bucket of collected water requires emptying. Most portable dehumidifiers include a receptacle for collecting the condensate produced through dehumidification. The receptacle typically is equipped with a float sensor that detects when the vessel is full. A signal is then sent to shut off the dehumidifier to prevent an overflow of collected water. The receptacle may need to be emptied manually several times a day to provide for continued operation. Units designed around a desiccant gel or heat pump also have collection tanks.

Most portable dehumidifiers have a fitting that enables the user to attach an ordinary garden hose directly to the collection tank. The user can avoid having to empty the receptacle by directing the hose into a floor drain or sump pump. When gravity drainage is not possible, a dedicated condensate pump can be used to move collected water to a disposal location. Some models can be drained into the plumbing system of the house or utilize a built-in water pump to self-empty as they collect moisture.

The large amount of water removed by a whole-house dehumidifier requires the use of a connected drainage line.

2.2.2 Ice buildup

Frost and ice can form on the condensing coils of a mechanical/refrigerative dehumidifier if the ambient air temperature drops below 65 degrees, causing the compressor to cycle on and off repeatedly without removing moisture from the air. Under certain conditions of temperature and humidity, ice can form on the cooling coils of a mechanical dehumidifier.1 Ice buildup can impede airflow and eventually form a solid block that encases the cooling coils. Not only does ice buildup prevent the dehumidifier from operating effectively, but it can also cause water damage if water that drips off the accumulated ice does not fall into the collection tank.

Many higher-end dehumidifiers have a so-called frost or ice sensor that turns off the machine when needed, allowing the icy coils to warm and defrost before automatically restarting. Most ice sensors are simple thermal switches that do not directly sense the presence or absence of ice buildup. An alternative design senses the impeded airflow and shuts off the cooling coils in a similar manner.

3 ENERGY USE AND OPERATING HOURS ESTIMATES, AND DATA SOURCES

Limited literature and data exist on dehumidifier energy use, hours in operation, and efficiency, but little of it has involved field-measured data. The following sections describe current estimates for energy use and hours of operation, one major field metering effort performed to date, and the data currently available regarding the energy consumption of dehumidifiers.

3.1 Current Practice for Estimating Energy Use

Estimates for energy use under rated conditions have relied on three quantities: dehumidifier capacity, hours of use, and dehumidifier energy efficiency. Using the following equation[i], studies have derived the annual energy consumption values based on estimation of power draw and assumption regarding usage. This model requires further verification using actual field-measured data.

$$DEH_{ENERGY} = \frac{CAP \times \left({}^{0.473}/_{24}\right) \times Hours}{Efficiency}$$

Where:

DEH_{ENERGY} = dehumidifier annual energy consumption (kWh/year),
CAP = capacity (pints/day),
0.473 = conversion factor for liters in a pint,
24 = number of hours in a day,
$Hours$ = annual operating hours, and
Eff = efficiency (liters/kWh).

The following sections describe the characteristics of dehumidifiers that affect the effectiveness and efficiency of their performance. In addition to the factors of capacity, rated efficiency, and hours of operation, operational mode also must be considered in evaluating efficiency.

3.1.1 Capacity

Dehumidifiers are sold by capacity, as represented by the number of pints of moisture the unit can remove from the air in a 24-hour period. Manufacturers note a dehumidifier's capacity on the unit's label assuming specified ambient air conditions of RH and temperature. Two factors determine the required capacity for a given application: the size of the space to be dehumidified and the conditions in the space before dehumidification. To estimate the capacity needed, a user can consult a table similar to Table 3-1.

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[i] Federal standard, Code of Federal Regulations, Title 10, Part 430, Subpart C

Table 3-1 Dehumidifier Capacity Required for Various Conditions and Areas

Condition without Dehumidification	Capacity (pints) Needed for Given Area (ft^2) 500	1,000	1,500	2,000	2,500
Moderately Damp (space feels damp and has musty odor only in humid weather.)	10	14	18	22	26
Very Damp (space always feels damp and has musty odor. Damp spots show on walls and floor.)	12	17	22	27	32
Wet (space feels and smells wet. Walls or floor sweat, or seepage is present.)	14	20	26	32	38
Extremely Wet (laundry drying, wet floor, high load conditions.)	16	23	30	37	44

Source: Association of Home Appliance Manufacturers (AHAM)

3.1.2 Hours of operation

Table 3-2 lists studies that report average monthly dehumidifier use. The studies assume that dehumidifiers are not used in fall, winter, or early spring. All the studies indicate peak usage occurs in July and August. Studies differ regarding the number of hours of use in the months preceding July and following August.

Table 3-2 Monthly Hours of Dehumidifier Use

Source	Hours/month Jan-Mar	Apr	May	June	July	Aug	Sept	Oct	Nov-Dec	Hours/year
AHAM low	0	0	70	210	245	245	70	35	0	875
AHAM mid	0	14	86	231	288	288	130	58	0	1,095
AHAM high	0	37	110	256	329	329	183	73	0	1,315
Arthur D. Little (ADL)*[2]	0	0	180	360	360	360	180	180	0	1,620
ENERGY STAR†[6,7]	0	0	475	475	475	475	475	475	0	2,851

* Based on peak dehumidification period of 3 months (at 360 hours/month) with half that usage (180 hours/month) during the remaining 3 months.

† Based on 6 months of operation with a 0.66-duty cycle.

3.1.3 Efficiency

The efficiency of a dehumidifier is represented by the quantity of moisture removed per unit of energy consumed. Each manufacturer notes a dehumidifier's efficiency along with the capacity of the unit on the unit's label. The annual energy use (AEU) of a dehumidifier is calculated by multiplying the machine's capacity by the number of hours it is operated, then dividing that result by the energy efficiency of the unit.

The AEU value is imprecise, however, because of two unknowns.

- The humidity setting applied by the user.
  Most manufacturers recommend setting the dehumidifier control to attain 50-percent humidity. Users can set the humidity higher or lower depending on the type of dehumidifier.
- The number of hours the device functions in each mode of operation.

3.1.4 Annual energy use

Table 3-3 summarizes the annual usage of dehumidifiers derived from several studies and sources. None of the studies, unfortunately, is based on metered data; rather they rely on power measurements and assumptions regarding usage to estimate values for annual energy consumption.

Table 3-3 Annual Usage Data for Dehumidifiers

Study/Source	**Annual Energy Use** *kWh/year*	**Power Use** *Watts*	**Operating Hours per Year**
LBNL (1992)[2]	Average: 400 Range: 200–1,000	NA	NA
ADL (1998)[3]	Average: 972	Average: 600	1,620
LBNL (2005)[4]	Range: 500–4,650	Range: 520–710	1,620, 4,320
Energy Center of Wisconsin (2005)[5]	Average: 600 Range: +/- 300 (WI only)	Average: 350 Range: +/- 250	NA
Central Maine Power Co. (2006)[6]	Average: 540 (Maine only)	NA	NA
ENERGY STAR® (ES) Fact Sheet (from website, 2006)[7]	ES: 2,161 non-ES: 2,378	ES: 1,334 Non-ES: 1,368	1,620
ENERGY STAR Calculator (from website, 2006)[8]	Range, ES: 937–2,061 Range, non-ES: 1,022–2,616	Range, ES: 329–723 Range, non-ES: 358–918	2,851

3.1.5 Operational modes

Dehumidifiers do not always operate at full capacity when they are drawing power. The modes of operation of a dehumidifier include:

- standby mode and/or bucket-full mode, during which only the control panel lights consume energy;
- fan-only mode, during which the cooling coils are defrosted; and
- operating mode, during which both the fan and compressor consume energy.

The percentage of time a device operates in each mode affects its AEU. Unverified assumptions regarding energy use, the hours of operating time, and efficiency levels are required to establish energy use using the current practice.

3.2 Energy Center of Wisconsin—Field Metering

The Energy Center of Wisconsin (ECW), with assistance from Focus on Energy, performed one of the few field studies of portable unit dehumidifiers. As reported in its study titled *Dehumidification and Subslab Ventilation in Wisconsin Homes*[9] ECW monitored dehumidifier use in 40 Wisconsin homes during a 4-month period in the summer and fall of 2009. The sample consisted of 20 newer (built since 2000) Wisconsin Energy Star Homes (WESH) and 20 randomly selected homes. One goal was to assess the net electricity savings from subslab ventilation systems installed in WESH homes that use basement dehumidifiers. A second goal was to obtain general field data on dehumidifier operation (hours and energy use) in Wisconsin homes to support the first goal, and to support potential additional energy saving strategies related to dehumidifier use.

Although their primary focus was dehumidifier use related to subslab ventilation systems, the researchers gathered some data on residential dehumidifier use in general. They estimated that the stand-alone dehumidifiers in the Wisconsin homes that report using dehumidifiers had an annual energy consumption of 477 kilowatt-hours (kWh). Although they found that dehumidifier use varies dramatically throughout a year; some units remain idle most of the year, while others run almost nonstop. Households in the upper quartile of use often consumed more than 1,000 kWh per year to dehumidify their homes.

The ECW also found significant variation in the amount of time units spent in different modes of operation (off, fan only, or compressor). Cycling rates also varied widely depending on dehumidifier design. As the authors noted, frequent cycling lowers efficiency, because cycling involves losses related to the cool-down of coils and evaporation of condensate from the coils at the end of a cycle. The authors did not attempt to quantify the effect.

3.3 Publicly Available and Industry Data

We obtained data regarding dehumidifiers available on the market, as sold and installed, and their modes and hours of usage. Primary sources of data include the Residential Energy Consumption Survey of 2009 (RECS 2009),[10] the California Energy Commission (CEC) Appliance Database, the ENERGY STAR database, and shipments information found in Association of Home Appliance Manufacturers (AHAM) publications and *Appliance Magazine*.[11]

3.3.1 RECS data

We obtained data from RECS 2009 regarding consumers' use of dehumidifiers, including the geographic locations where they are used most frequently and the hours of usage reported by survey respondents.[10] The five U.S. census divisions that show the highest percentage of dehumidifier use are the New England, Middle Atlantic, East North Central, West North Central, and South Atlantic divisions (see Figure 3-1).

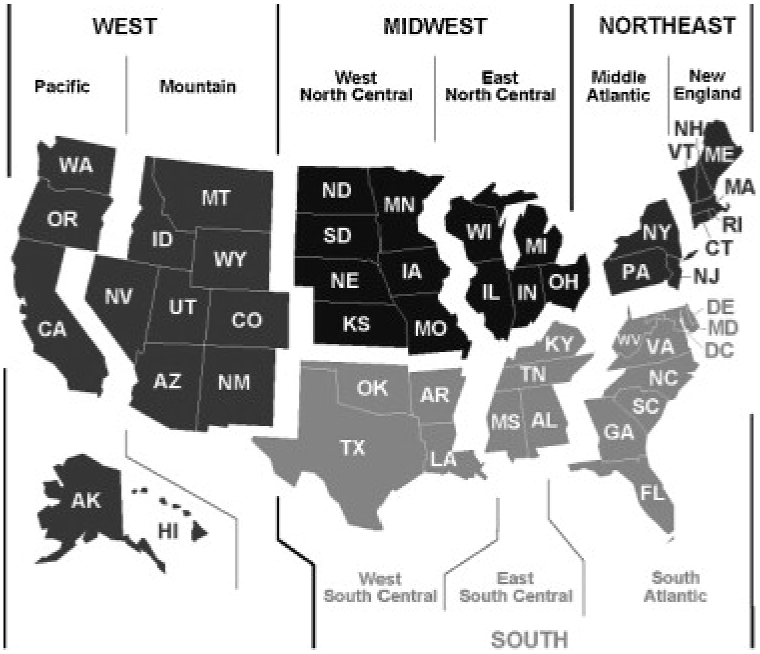


Figure 3-1 Census Regions and Divisions

Nationally, RECS 2009 found the saturation of dehumidifiers in the United States to be about 12 percent.[10] For census divisions west of the South Atlantic and West North Central, dehumidifier use drops to less than 4 percent. Dehumidifier use and frequency for the five other census divisions are reported in Table 3-4.

Table 3-4 Dehumidifier Variables in RECS 2009

Variable	All	New England	Mid-Atlantic	South Atlantic	East North Central	West North Central
Dehumidifier Use (%)	13.2	10.1	23.8	13.5	29.9	13.2
Frequency of Dehumidifier Use (months)						(%)
1-3	43.6	47.9	42.8	43.6	39.6	42.8
4-6	30.4	27.4	30.9	26.1	33.8	36.6
7-9	7.2	7.2	7.9	7.2	7.5	6.0
10-11	2.6	2.7	3.1	2.2	2.2	1.0
On all year	16.3	14.9	15.4	20.9	17.0	13.6

3.3.2 CEC appliance database

The State of California's Energy Commission (CEC) collects data on many household appliances, including dehumidifiers.[ii] The CEC database provides parameters for 213 models from 9 manufacturers. These parameters include manufacturer name, brand name, model number, capacity (pints), energy factor, and the date the record was added to the database. Table 3-5 shows the number of models by manufacturer. The CEC database lists GD Midea, General Electric, and Gree multiple times under slightly different names**.** Table 3-6 shows the number of models by energy factor and capacity.

Table 3-5 CEC Database: Manufacturers and Numbers of Models

Manufacturer	No. of Models
Dalian Haier Air Conditioner Corp., Ltd.	1
DeLonghi America Inc.	27
GD Midea Air Conditioning Equipment Co., Ltd.	15
GD Midea Commercial Air-Conditioning Equipment Co.	47
GE Consumer & Industrial	3
General Electric	8
Gree	2
Gree Air Conditioning	4
Gree Electric Appliances, Inc., of Zhuhai	53
Haier America Trading, LLC	36
Kaiping New Widetech Electric Co., Ltd.	3
LG Electronics, Inc.	13
Oreck Manufacturing Co.	1
Total	**213**

[ii] California Energy Commission, http://www.appliances.energy.ca.gov/, last accessed January 22, 2013.

Table 3-6 CEC Database: Energy Factors of Models by Capacity

Capacity (pints/day)	**Energy Factor (liters/kWh)**									**Total No. Models**
	1.2	**1.3**	**1.4**	**1.5**	**1.6**	**1.7**	**1.8**	**1.9**	**2.1**	
16	1									1
20		1								1
23	2									2
25	9									9
30	3		32	2				9		46
32			6							6
34			1							1
35			2							2
40				7	1			2		10
41						2				2
45				16	2			3		21
48					2					2
50					28		1	9	3	41
51					1	3				4
63						1				1
64							1			1
65							19	1		20
70							26	16		42
74							1			1
Grand Total	**15**	**1**	**41**	**25**	**34**	**6**	**48**	**40**	**3**	**213**

3.3.3 ENERGY STAR database

The ENERGY STAR database lists energy efficient appliances that qualify for the ENERGY STAR label. The database for dehumidifiers lists qualifying models by manufacturer, capacity, and energy factor. The data from ENERGY STAR cover 2010–2013. Table 3-7 shows, by capacity, the energy factor required to qualify for the ENERGY STAR label. Table 3-8 shows the number of ENERGY STAR models by manufacturer, and Table 3-9 shows the number of models by capacity and energy factor. ENERGY STAR recently updated its qualifications and will be updating its database.

Table 3-7 Qualifications for ENERGY STAR Dehumidifiers

Product Capacity (pints/day)	**Energy Factor (liters/kWh)**
< 75	> 1.85
≥ 75 to ≤ 185	> 2.80

Table 3-8 ENERGY STAR Partners and Numbers of Models

ENERGY STAR Partner, Manufacturer Name	Total No. of Models
Danby Products Inc.	20
De'Longhi America, Inc.	11
Friedrich Air Conditioning Company	3
GE Appliances	2
Gree Electric Appliances, Inc., of Zhuhai	6
Guangdong Kelon Air Conditioner Co., Ltd.	20
Haier America	14
Midea USA, Inc.	25
Therma-Stor Products	4
Grand Total	105

Table 3-9 ENERGY STAR Models by Capacity and Energy Factor

Product Capacity (pints/day)	Energy Factor (liters/kWh)			Total No. of Models
	1.85	2.88	2.89	
25.0	3			3
28.0	3			3
30.0	18			18
35.0	3			3
40.0	2			2
45.0	9			9
50.0	26			26
60.0	5			5
65.0	3			3
70.0	28			28
70.0	1			1
90.0		2		2
120.0			2	2
Grand Total	101	2	2	105

3.3.4 Additional information

Shipments numbers serve to corroborate the RECS data in ascertaining how many dehumidifiers currently are operating within the United States. We obtained data regarding dehumidifiers shipped within the United States from AHAM publications and *Appliance Magazine*.

Historical shipments data are available from AHAM for 1949–2011. *Appliance Magazine* information covers 1991–2007. As seen in Figure 3-2, the two datasets align closely.

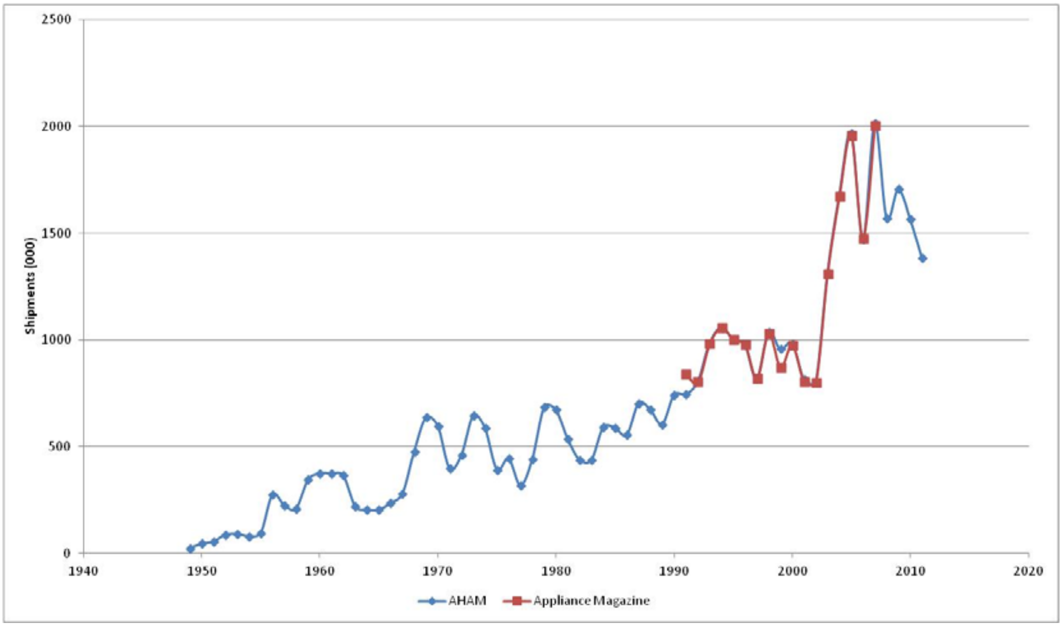
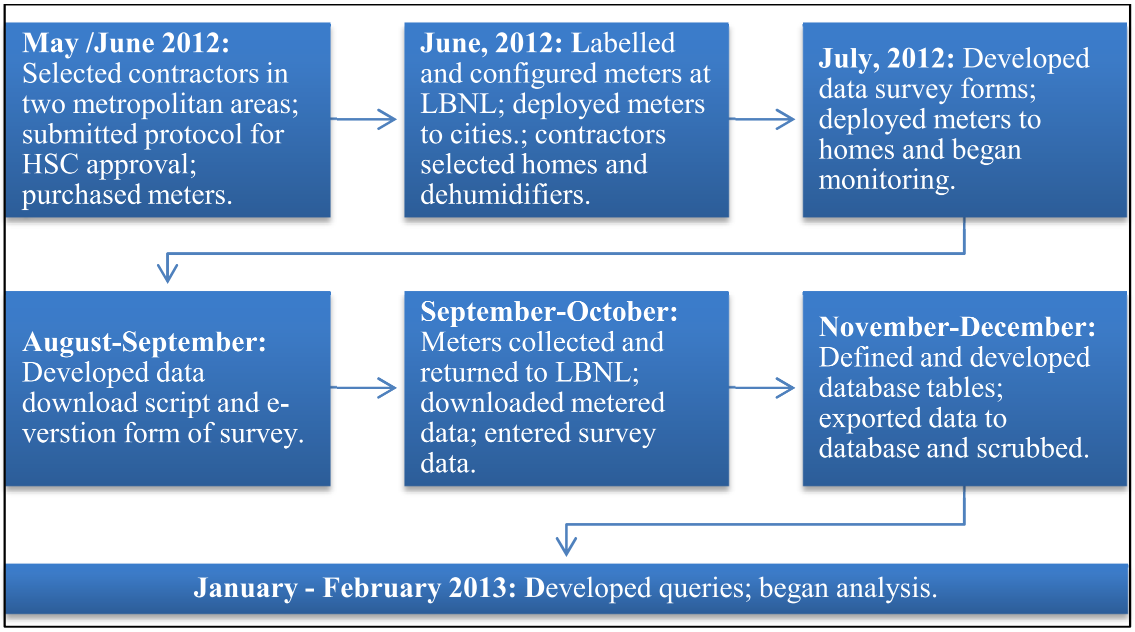


Figure 3-2 Dehumidifier Shipments, 1949–2011

4 DATA-GATHERING METHODOLOGY

To expand the understanding of energy use and operational modes primarily for mechanical/refrigerative dehumidifiers, and the relationship of those factors to household demographic characteristics, we supplemented publicly available data by performing our own field-metering study. Figure 4-1 shows the dates of the pilot study, from the selection of subcontractors to the analysis of the data.



May /June 2012: Selected contractors in two metropolitan areas; submitted protocol for HSC approval; purchased meters.

June, 2012: Labelled and configured meters at LBNL; deployed meters to cities.; contractors selected homes and dehumidifiers.

July, 2012: Developed data survey forms; deployed meters to homes and began monitoring.

August-September: Developed data download script and e-verstion form of survey.

September-October: Meters collected and returned to LBNL; downloaded metered data; entered survey data.

November-December: Defined and developed database tables; exported data to database and scrubbed.

January - February 2013: Developed queries; began analysis.

Figure 4-1 Timeline of Metering Events

We obtained data on the energy consumption of residential dehumidifiers by placing metering devices in the field. We also surveyed users in the field regarding household demographics and the particulars of each housing unit. (See Appendix A.) We placed meters in 29 houses in Portland, Maine, and 61 houses in Philadelphia, Pennsylvania. Based on the humidity and season, we aimed to collect data for the summer months of June through September, but for a minimum of 6 weeks. Table 4-1summarizes the metering installations for this project. The start and stop dates of metering period are reported in Appendix B.

Table 4-1 Summary of Metering Installations in Portland and Philadelphia

	Portland, ME	**Philadelphia, PA**
Total number of meters delivered	60	71
Number of housing units	29	61
Total number of meters and sensors installed	31	70
Total number of meters and sensors with data	26	60
Date of first installation	July 3, 2012	June 24, 2012
Date of last installation	September 10, 2012	July 27, 2012
Date to begin retrieving meters	September 27, 2012	October 1, 2012
Number of inoperative meters found at interim check	1	0

4.1 Equipment

We used portable WattsUp meters[iii] to measure the power consumption of the dehumidifiers and HOBO sensors[iv] to meter temperature and relative humidity (T/RH). We preset the meters' time-recording interval before deploying them in the field. Recording power for approximately 3 months required all the data storage capacity of the WattsUp meters, so those meters collected data on no other variables. See Appendix C for a selection of meter installations.

Dehumidifiers were plugged into the WattsUp meters, and the Onset HOBO sensors were located beside the WattsUp meters. The energy data were recorded at 2-minute intervals. The T/RH data were recorded at 6-minute intervals. All data were stored on board each device for later collection. This report reflects the data from 86 pairs of meters and sensors that were successfully deployed, installed, and retrieved containing data. Survey data and demographic forms were developed and deployed along with consent forms for home occupants to sign. Participants were given instructions to record all power outages and were informed of points of contact for assistance.

Data from 86 pairs of equipment, along with associated demographic information, were downloaded into the database. Data were not collected from 45 of the 131 WattsUp meters deployed for the following reasons.

[iii] Think Tank Energy Products Inc: https://www.wattsupmeters.com/secure/products.php?pn=0

[iv] Onset Computer Corporation: http://www.onsetcomp.com/products/data-loggers/u12-011

- Meters have not yet been returned (3).
- Meters were not deployed (27).
- Data were pulled before the download (5).
- Data were mismatched with the survey sheets (10).

4.2 Philadelphia Installations

Approximately 1,000 emails were sent to community groups in Philadelphia describing the dehumidifier metering project. Seventy WattsUp meters and 69 HOBO T/RH sensors were placed in 61 households where occupants had expressed interest in participating in the project. Households that had multiple dehumidifiers received multiple meters. All but three meters were installed between June 24 and July 5, 2012. Because a few participants did not have working dehumidifiers, additional participants were found and/or new dehumidifiers were purchased. The final three installations were completed on July 27, 2012.

Meter recordings frequently were interrupted by electrical storms, at which point the digital display on the meters would "zero out" and start recording again. Although the data on current watt usage were not lost, the digital readout would start over again. Although the meters generally performed adequately, in a couple of installations they did not perform accurately. In those cases the dehumidifier was working but the wattage readings showed only 3W (normal fan cycle consumes about 60W and operation about 650W). After those meters were unplugged and reset, they worked appropriately.

Almost all meters were in place for the full duration of the project, or approximately 90 days. They were installed sometime between June 24 and July 27 and removed between October 1 and 12. It took additional time for the three participants who had nonworking dehumidifiers to replace them or for us to find new participants. A couple of households that were away on vacation also started late. Four participants ran their dehumidifiers intermittently, such as only if the space smelled bad, if it rained, or if there was water on the basement floor.

4.3 Portland Installations

Sixty solicitations were sent to households that had received prior energy audits. Of those 60 households, 29 agreed to have their dehumidifiers metered. Twenty-nine meters and sensors, which were installed on June 18, functioned for periods ranging from 30 to 87 days. No power outages were reported, and participants kept their dehumidifiers running throughout the study. Meters were removed between September 27 and October 12, 2012.

4.4 Data Download and Database Development

After all field data were collected, we performed two actions to develop our database. First, we developed a data download script and downloaded the data from returned meters and sensors. Second, we developed an electronic version of the hard-copy survey forms and entered the survey data collected from each participating household. The following steps were part of developing the database:

1. Refined the time stamps of the power consumption data.
2. Screened the data files to produce a reliable database.
3. Linked the tables created from the WattsUp meters data, the T/RH sensor data, and the survey form information.
4. In order to link the data, replicated each row in the T/RH data thrice to convert the 6-minute interval of the T/RH meter into the 2-minute interval of the WattsUp meters.

The database consists of the four large data tables described below.

- *Survey Form*: This table contains all the data entered from the survey forms (datasheets), which contain product and household information provided by participants. The data were incorporated into the database using a python script.
- *WattsUp Meter*: This table compiles all the power consumption data from downloaded WattsUp meters, including the WattsUp IDs, wattage data, time stamp, and power cycle information. We treated this table as the parent table of the database. In other words, the WattsUp IDs present in the *Survey Form* table must be present in the *WattsUp Meter* table. Because WattsUp meters have no time clock, we retained only data having no more than one power outage. By using the starting and stopping times from the survey forms, the time stamps of the WattsUp data files were calculated using a python script.
- *Relative Humidity/Temperature sensor (RH/T)*: This table contains all the data from the Onset HOBO sensors and loggers. We are still evaluating the time offset between this sensor and the WattsUp meters. There are two tables of RH/T sensors data.
    - *RH/T_Sensor6*: This table contains temperatures and humidity data collected from the RH sensors at an interval of 6 minutes and added to the database using the python script. The table has five columns.
        - idRH_Sensor1 (the sensor id);
        - SequenceNbr (every row is numbered in automated sequential order);
        - DateTime (time stamps recorded by the sensor);
        - Temp_F (temperature recorded by the sensor); and
        - RH (relative humidity recorded by the sensor).
    - *RH/T_Sensor2:* This table is the same as *RH/T_Sensor6* except that the data are populated at 2-minute intervals by using the python script to replicate each row twice.

Finally, using the Mysql script, the time stamp, WattsUp ID, and wattage were selected from the *WattsUp Meter* table; RH and temperature were selected from the *RH/T_sensor2* table; and the WattsUp ID from the survey form served as a foreign key to join the two tables. The summary (result) table was exported to Microsoft Excel in CSV format.

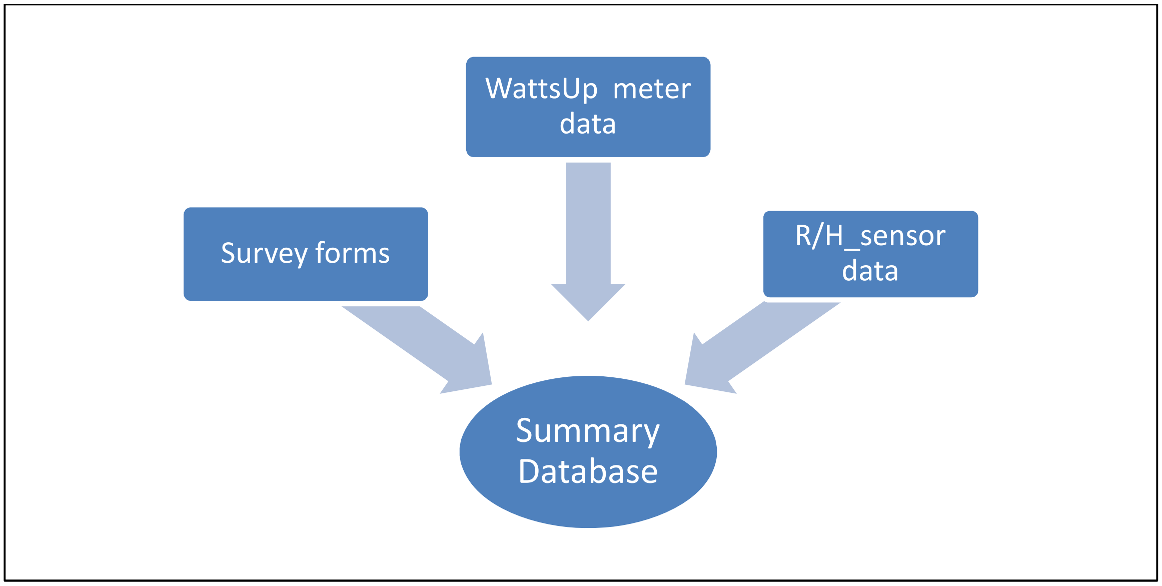


Figure 4-2 Development of Database

5 PILOT METERING RESULTS

This section describes initial results of our summer field-metering effort. In section 5.1 we summarize characteristics of the housing units that affect the performance of dehumidifier units and indoor humidity. We then list brands and models monitored in the study, along with information on their capacity and ENERGY STAR rating. Section 5.2 describes the modes of operation, the percent time associated with each mode, and the summary of operational hours by month. In section 5.3 we discuss some results of the power consumption analysis. Section 5.44 reports the average daily energy use, and the positive association between energy use and humidity level.

5.1 Characteristics of Housing Units

The area and room conditions were recorded for most of the monitored dehumidifiers. Although most of the metering was performed in Maine and Pennsylvania, dehumidifiers in New Hampshire and New Jersey also were metered. Information included whether the room was climate controlled, and whether the home had a central air conditioner (CAC). For basements, the presence of a sump pump was recorded. Table 5-1 shows that most dehumidifiers operated in basement or storage areas were not climate controlled. Half the dehumidifiers incorporated direct drainage rather than a manually emptied bucket.

Table 5-1 Characteristics of Housing Units

States	Dehumidifier Location (%)			Sump Pump (%)	CAC (%)	Direct Drainage (%)	Most Prevalent Brand (%)
	Climate Controlled		Not Climate Controlled				
	Household Room (%)	Garage, Basement, or Storage (%)	Garage, Basement, or Storage (%)				
PA (N=67) and NJ (N=1)	10.3	26.5	61.8	36.8	60.3	54.4	Frigidare 26.5
ME (N=17) and NH (N=1)	-	27.8	66.7	22.2	-	50	Frigidare 22.2

The types of dehumidifiers included in the field study, along with their capacities and efficiencies, are described in the following section.

Table 5-2 presents the major brands of dehumidifiers metered. Although a total 26 brand names were found, 5 brands dominate the survey data. Frigidaire, Soleus Air, Kenmore, Whirlpool, and LG accounted for almost 62 percent of metered dehumidifiers. Other brands accounted for about 38 percent of surveyed units.

Table 5-2 Major Brand Names of Metered Dehumidifiers

Brand Name	Number of Units	Percent of Total
Frigidaire	22	25.6
Soleus Air	9	10.5
Kenmore	9	10.5
Whirlpool	8	9.3
LG	5	5.8
Subtotal	**53**	**61.6**
Others	33	38.4

Of the total 86 metered units, 71 demonstrated identifiable moisture removal capacity (see Figure 5-1). Some older model numbers had no corresponding capacity listed in either the CEC or the ENERGY STAR database. The percentage of each product class in the metered dehumidifiers is given below.[v]

1. Up to 35.00 pints/day: 16 units, 22.5%;
2. 35.01–45.00 pints/day: 19 units, 26.8%;
3. 45.01–54.00 pints/day: 12 units, 16.9%;
4. 54.01–75.00 pints/day: 22 units, 31.0%; and
5. More than 75.00 pints/day: 2 units, 2.8%.

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[v] The product classes are based on the current U.S. Department of Energy standard for dehumidifiers.

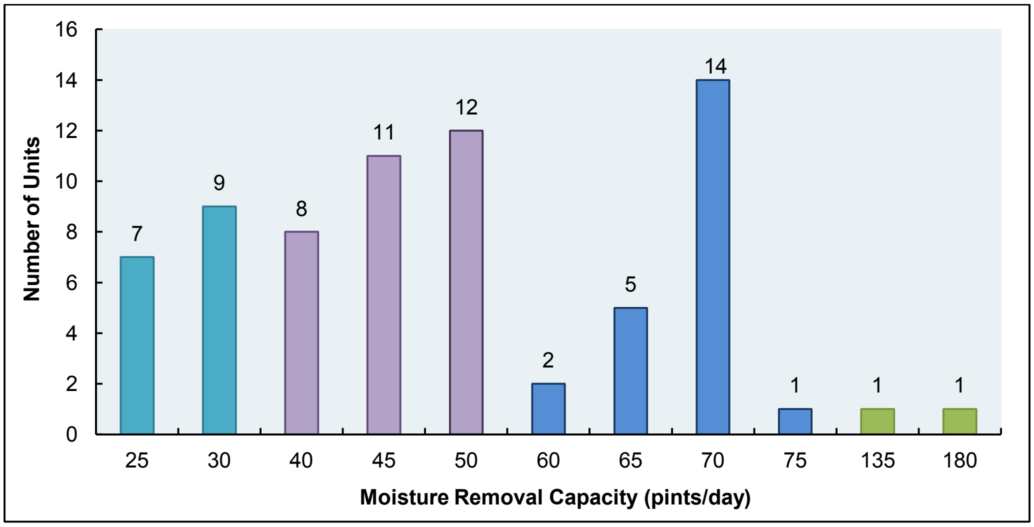


Figure 5-1 Moisture Removal Capacity of Measured Dehumidifiers

Of the 71 units having an identified capacity, ENERGY STAR (ES) qualified units accounted for 62 percent, and non ENERGY STAR qualified units for 22 percent. Twelve units had no model numbers, making it impossible to check their energy efficiency status. Figure 5-2 presents the energy efficiency status of identifiable dehumidifiers in the field study.

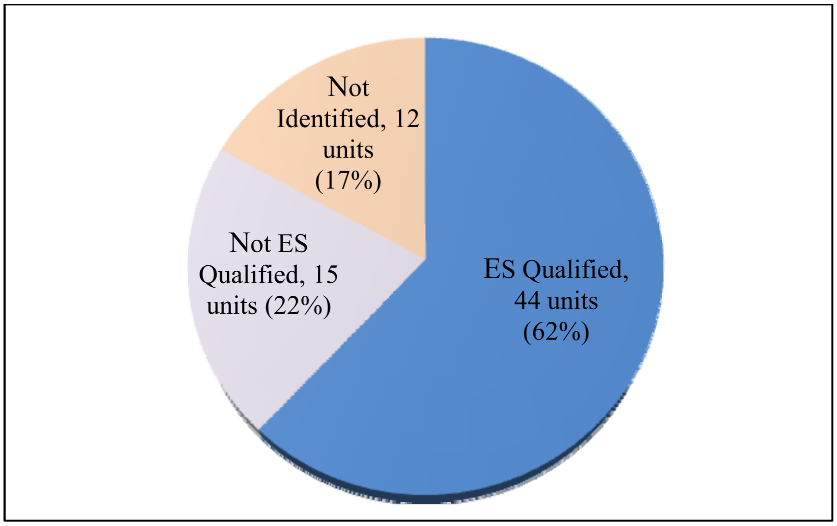


Figure 5-2 Energy Efficiency of Metered Dehumidifiers

5.2 Modes of operation and hours of use

Our summary analysis of the power consumption data confirms three operational modes of the portable dehumidifiers: (1) when both the compressor and fan were running, (2) when only the fan was running, and (3) when the unit was on standby. Figure 5-3 shows the percentages of time the units were operated in each mode throughout the monitoring period.[vi] The time spent in each mode differed for every unit. Eighteen percent of dehumidifier units were operated fully—with compressor and fan running—more than 75 percent of the time; 12 percent were operated fully between 50 percent and 75 percent of the time. On the other hand, about a quarter of the homes used the compressor less than 20 percent of the time. On average, the dehumidifier units were operated in full mode 51.5 percent of the time in Portland, but only 37.1 percent of the time in Philadelphia.

Fan-only mode is used to defrost a dehumidifier's cooling coils. Thus this mode is expected to be used for a small fraction of the unit's operating time. Our analysis shows that fan-only mode was not even used by about half the metered units. Those units were either running on compressor-and-fan mode or were off or in standby mode. Perhaps the 2-minute measurement interval was insufficient to capture short periods of fan operation for units having a high cycling rate. On the other hand, 8 units ran in fan-only mode more than 25 percent of the time. We later discovered that the occupants turned some of those units on manually to serve as air recirculation devices. On average, fan-only mode was used 8.6 percent and 5.3 percent of the time by the Portland and Philadelphia units, respectively.

Although our study was conducted in the summer (mid-June to mid-September 2012), when higher ambient humidity was expected, about 30 percent of the units were in standby mode more than 50 percent of the time.[vii] Furthermore, six units were almost entirely off (more than 90 percent of the time), which suggests that some occupants used dehumidifiers only as needed. We also note that units in Philadelphia were turned off 28.7 percent of the time, almost twice the amount of time as the units in Portland (14.8 percent). Detailed analysis of each site is required to understand the pattern of operation and estimate the cycle rate. Specifically, we plan to further evaluate metered data and site characteristics of Philadelphia units 134 through 162, because they seemed to represent a cluster in which dehumidifier units were off most of the time.

We calculated the average number of hours a dehumidifier was ‘on’ per month for the data set collected from each of 76 meters. A dehumidifier was considered ‘on’ if its power draw was greater than 0W, which included compressor-and-fan, fan-only and standby modes. The number of meters used in the calculation of monthly average hours varied because of the different monitoring periods of the dehumidifiers. Table 5-3 highlights the month of July for which the largest number of units was monitored.

[vi] Because of the screening we applied to data collected by the WattsUp meters, the actual monitoring time included in the analysis varies substantially among units, from about 2 to 10 weeks.

[vii] Contrary to expectation, measurements of RH did not suggest a consistently high humidity season for the study locations. Only about a third of the data records indicated greater than 60 percent RH. If that is the normal unit set point, some of the units probably did not fully utilize the dehumidification capacity.

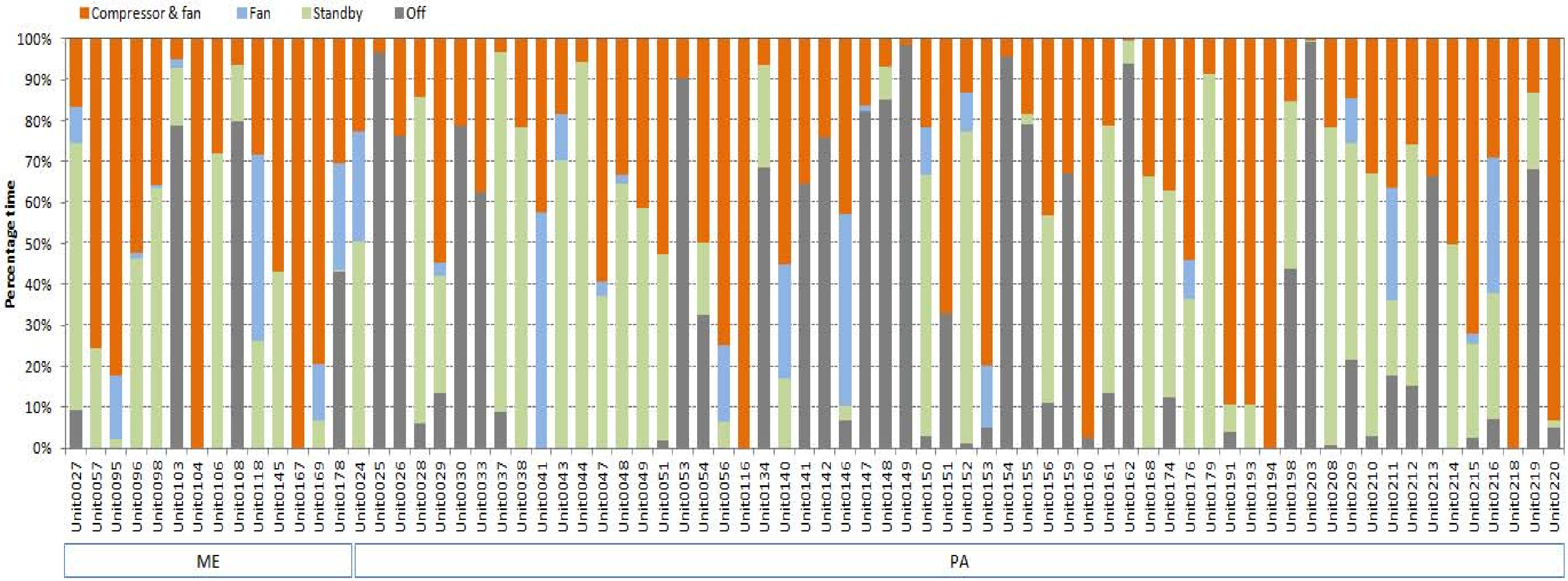


Figure 5-3 Percentage of Dehumidifier Use by Mode of Operation

Figure 5-4 presents the Table 5-3 data in graphical form. The plot shows that the metered hours per month are significantly greater than the hours per month from the AHAM, Arthur D. Little, or ENERGY STAR data. Several reasons might account for the difference, such as problems in determining when a dehumidifier is on. It may be that the earlier data are consistent with averages for the entire United States; whereas our field data represent two regions where substantial dehumidifier use occurs during summer. Of note, for our field study, the data sets are mostly not complete for June and September and in a few cases for August the values for hours per month for those months are extrapolated based on the available data. The extrapolation was done by calculating average daily ratio of time each unit spent during each operational mode and applying the same ratio over the number of missing days from each month of monitoring. This was only done for units with at least one-week continuous data.

Table 5-3 Average Hours per Month Dehumidifiers are On

Source	**Hours/Month**			
	June	**July**	**August**	**Sept.**
LBNL Field Metering	510	547	584	571
No. of meters:	45	75	47	38
Past studies or reports:				
AHAM low	210	245	245	70
AHAM mid	231	288	288	130
AHAM high	256	329	329	183
Arthur D. Little*	360	360	360	180
ENERGY STAR†	475	475	475	475

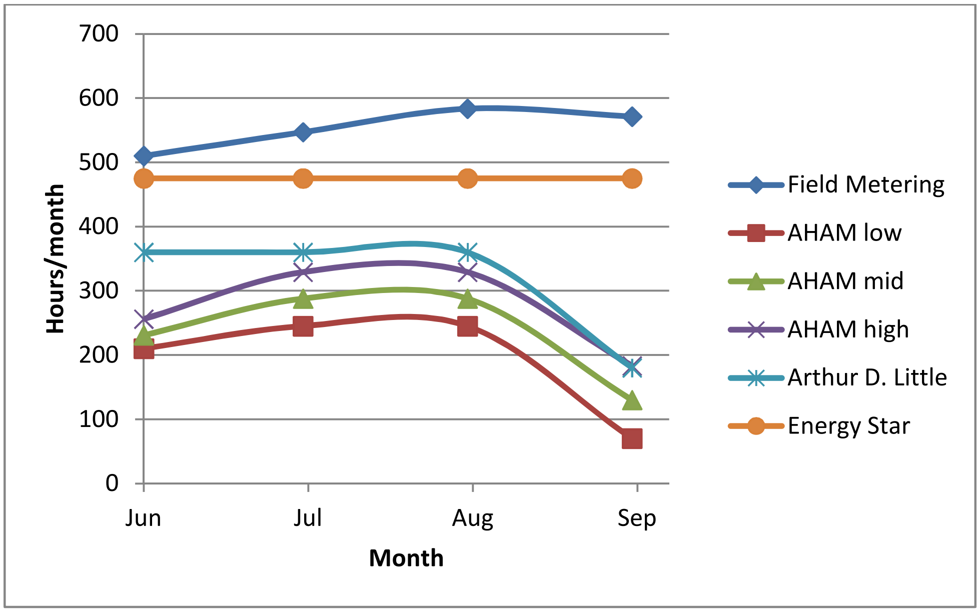
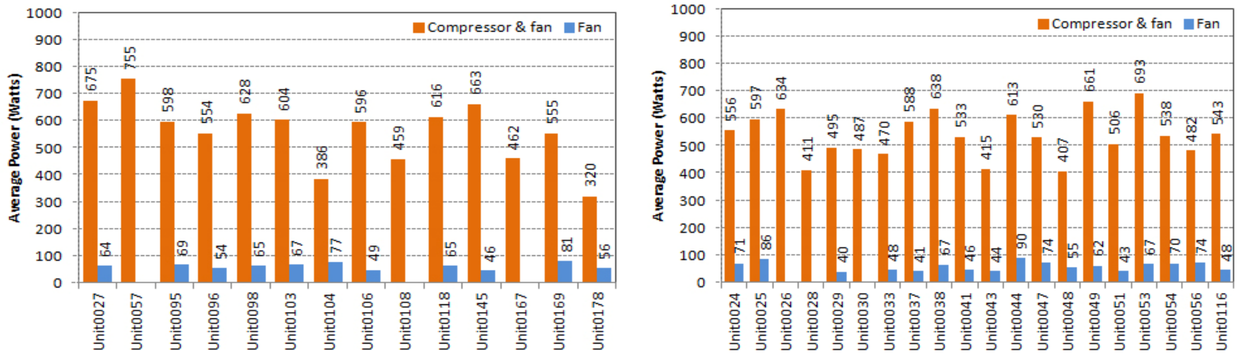


Figure 5-4 Hours of Energy Use per Month

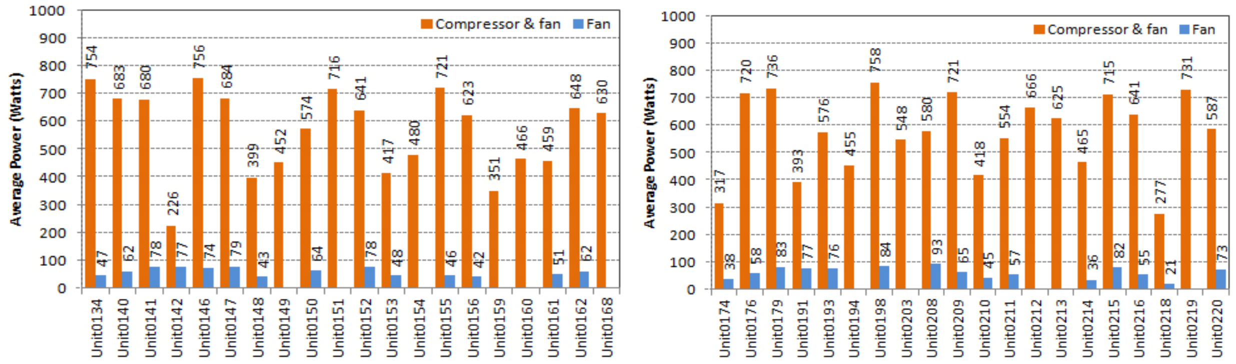
5.3 Power consumption

Power consumption data were collected at 2-minute intervals. After the database was populated, we screened all data sets for outliers[viii] and high meter power cycles.[ix] We calculated the frequency distribution of the data to create bins for the ranges of each operation mode. Figure 5-5 shows the average power consumption in watts for metered units in Portland (Figure 5-5A) and one-third of units in Philadelphia (Figure 5-5B). Figure 5-6A and 5-6B shows the other two-thirds of the Philadelphia data. The average power consumption for all dehumidifiers in full operation mode was 560.9±126.2 W (N=75); range: 226.1 to 757.6 W. The fan-only mode consumed 61.6±16.0 W (N=75); range: 21.4 to 80.9 W. There was no significant difference in power consumption between units in the two regions.



A B

Figure 5-5 Average Wattage of Units in (A) Portland, ME, and (B) Philadelphia, PA (1/3)



A **B**

Figure 5-6 Average Wattage of Units in Philadelphia, PA: (A), 2/3, and (B), 3/3

[viii] Peaks of high power (as much as ~3,200 W) have been identified in previous studies. Our data records revealed a unique and repeated number associated with each metering device.

[ix] Data sets with greater than three power outages were excluded from the analysis because the lack of a real timer created high uncertainties in the data.

Figure 5-7 compares measured power consumption among brand names (N=75). Our analysis revealed no significant difference among the brands (F=1.28, P>0.10).[x] The lowest power draw was recorded for Zenith units at 438.1 W (average), followed by General Electric (473.3 W), LG (523.8 W), and Frigidaire (545.1 W). This finding is limited, of course, by the low number of units monitored for each brand in this study. A more representative and balanced sample is needed to obtain a conclusive result.

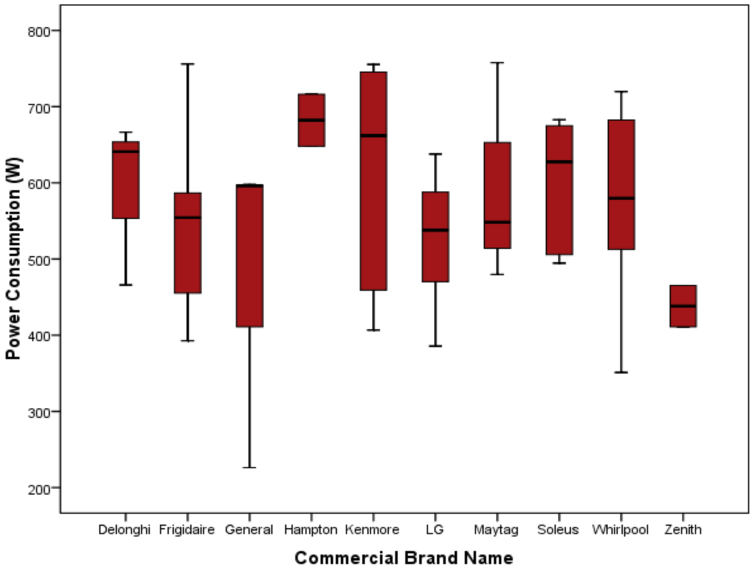


Figure 5-7 Average Wattage by Brand Name

Note: Each boxplot represents the minimum (lower end of whisker), the lower quartile (lower end of box), the median (line within the box), the upper quartile (upper end of box), and the maximum (upper end of whisker)

Figure 5.8 shows that moisture removal capacity is positively associated with power consumption (F=8.1, P<0.001). Assuming that the relationship is linear, a capacity increment of 10 pints per day would be equivalent to an increased power consumption of approximately 60 W.

Figure 5-9 shows that about 20 percent of the field-metered units could be considered new (less than one year old), and more than 55 percent were more than 3 years. The efficiency of the refrigeration components could have deteriorated in at least some of the units.

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[x] The statistics are based on between-group analysis (one-way analysis of variance), where F-ratio is a measure of how different the group means are relative to variability within each group. P is a measure of significance of the difference among group means (the smaller the P-value, the lower the probability that the observed difference is due to chance). The critical value of P is usually set as 0.05 or 5%. In other words, group comparison with P-value<0.05 is considered significantly different.

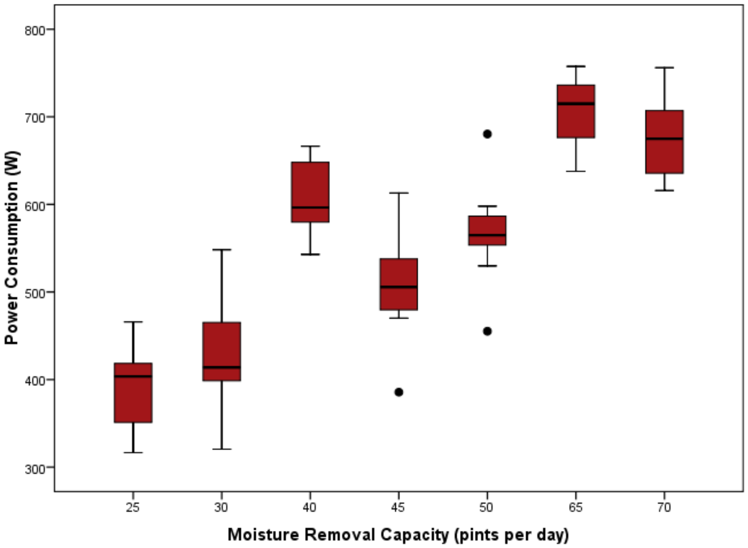

Figure 5-8 Average Wattage by Moisture Removal Capacity

Note: Each boxplot represents the minimum (lower end of whisker), the lower quartile (lower end of box), the median (line within the box), the upper quartile (upper end of box), and the maximum (upper end of whisker). Points outside the whiskers represent values that are removed from the bulk of the data (more than one and a half box lengths).

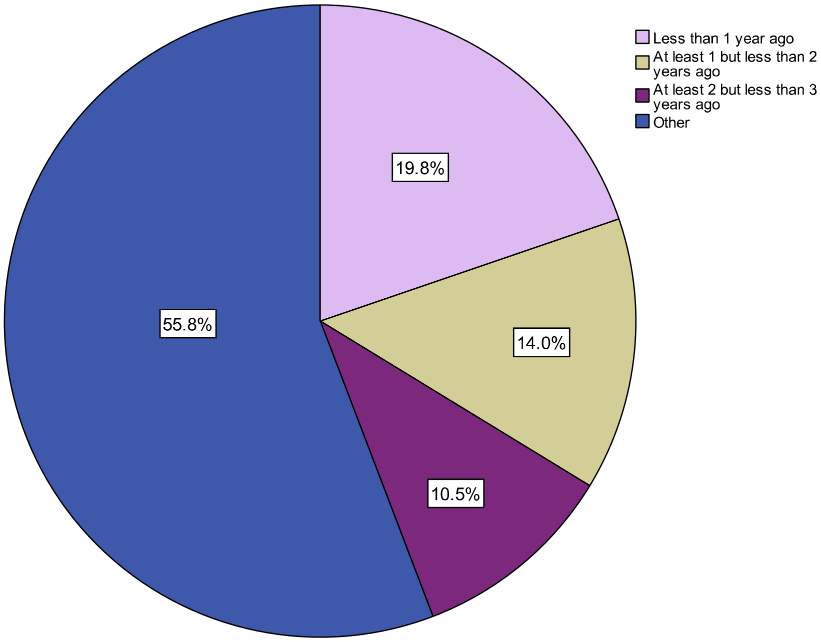

Figure 5-9 Distributions of Metered Dehumidifiers by Age

5.4 Energy Use and Relative Humidity

The following three figures display results related to RH and average energy use of metered dehumidifiers. Figure 5-10 illustrates daily RH measured near the inlet of each dehumidifier unit.

The average daily RH for all installations ranged from 39.9 percent to 76.9 percent (average: 56.5±9.5 percent). Some houses exhibited large swings in relative humidity, indicating that the dehumidifier units were not placed in a climate-controlled area or were located in a leaky space. Note that the RH measurements refer to the relative humidity in the room or space where the dehumidifier was located.

Figure 5-11 shows the measured daily average energy use of dehumidifier units sorted by relative humidity (same order as Figure 5-10). Average daily energy use ranged from 0.1 to 13.1 kWh (average: 5.9±3.7 kWh). The range and some outlier points in this plot indicate that dehumidifiers were operated continuously on some days.

In Figure 5-12, we paired the daily average RH and daily average energy use for all the units metered in this study.[xi] The plot and fitted curve indicate that lower RH might be associated with increased daily energy consumption. The result also shows that some units were operated continuously without producing any significant dehumidification. A plausible explanation is that the unit locations were either iced up, very leaky or too large, so that the dehumidification capacity was insufficient. In addition, indoor-generated moisture could dampen the dehumidification effect. We will address such cases after we have the opportunity to perform additional analysis.

We calculated energy use for every two minutes as the product of two-minute power consumption data and standardized 2 minutes interval. We then summed up the two-minute energy use data to derive daily energy use. We added daily energy use for each month to determine monthly energy use. These steps were carried out for each dehumidifier unit. For units with incomplete data on daily energy use, we used the average daily energy use for the month of interest and applied this to the rest of the days without data. To determine the monthly energy use of each unit, we excluded daily energy use data that was less than one kWh per day. Finally, when calculating the monthly average energy use, we excluded two units, which represented the outlier points in our analysis.[xii] The results are shown in Table 5-4. Our analysis accounted for the time each unit spent in each operational mode and the corresponding power consumption but included an assumption that missing days had the same energy use as the daily average. Hence, the results are close to the actual monthly energy use for dehumidifiers in Portland and Philadelphia.

[xi] Because data points were not screened for non-operational days, the R-squared value was low (less than 0.3). As will be discussed in subsequent report, further analysis is needed to determine and exclude days when the units were mostly not in operation.

[xii] These units recorded energy use of more than 1000 kWh per month. This is more than twice the maximum data points for most units. We found that the power consumption were out of the typical range for similar product capacity, i.e. 25 and 40 pints/ day.

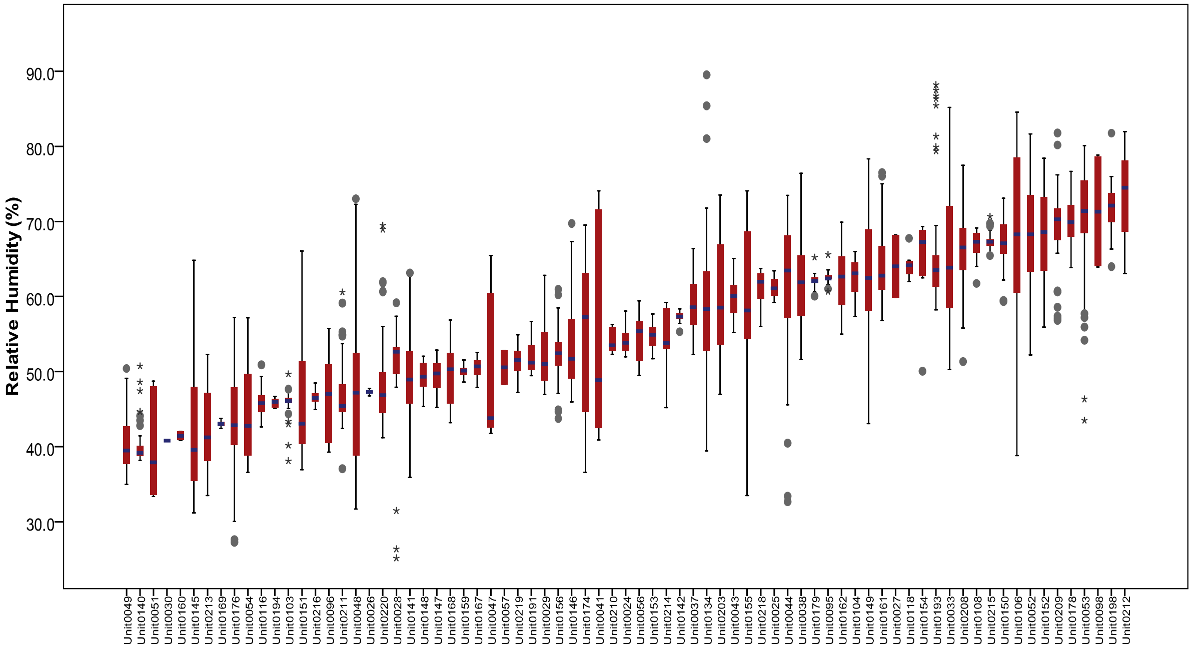

Figure 5-10 Daily Room RH for all Dehumidifier Units

Note: Boxplot represents the minimum (lower end of whisker), the lower quartile (lower end of box), the median (line within the box), the upper quartile (upper end of box), and the maximum (upper end of whisker). Points outside the whiskers represent values that are more than one and a half box lengths.

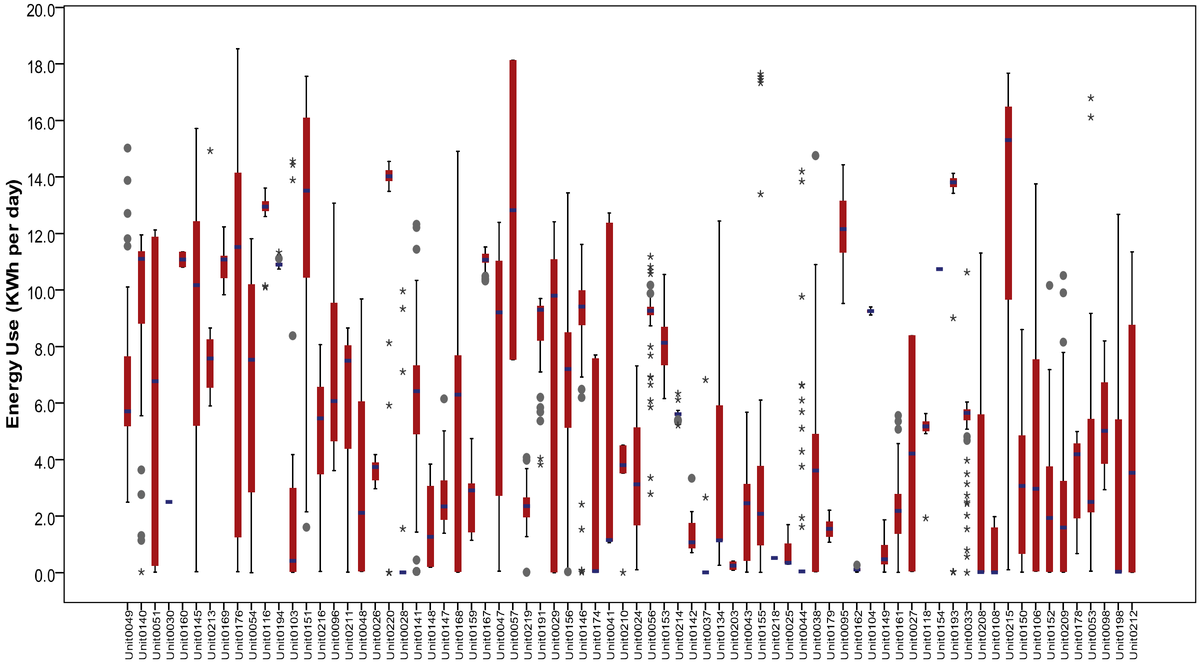

Figure 5-11 Daily Average Energy Use for all Dehumidifier Units

Note: Boxplot represents the minimum (lower end of whisker), the lower quartile (lower end of box), the median (line within the box), the upper quartile (upper end of box), and the maximum (upper end of whisker). Points outside the whiskers represent values that are more than one and a half box lengths.

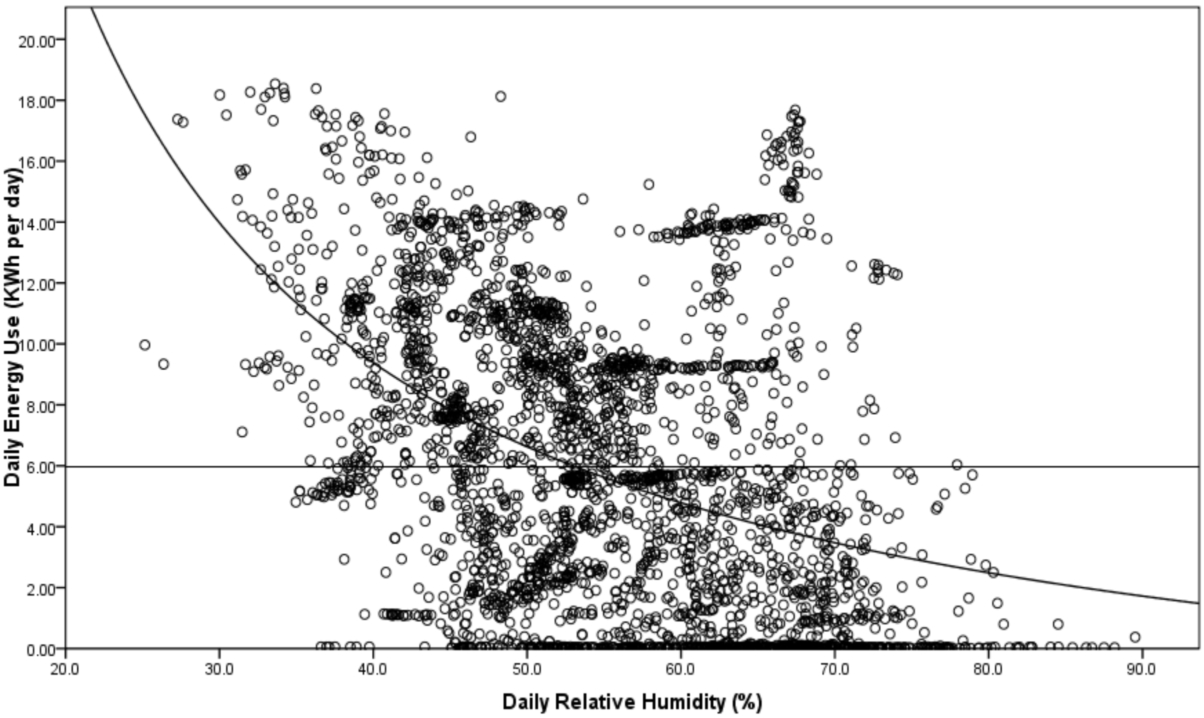

Figure 5-12 Correlations Between Daily Room RH and Average Energy Use

Figure 5-133 summarizes total monthly energy consumption during the metering period. Our results show that average energy use did not differ substantially during the months of monitoring. August was the most energy-intensive month, while energy use decreased toward the end of summer. In order to compare the results with AHAM estimation (see Table 3.2), we made the assumption that the same hours of dehumidification is needed between April and June as between September and October. We estimated the AEU for dehumidification as 1,191.0 kWh..[xiii] This estimate is similar to some middle- to upper-bound estimates from the studies by AD Little and LBNL, 1992 and 2005. A recent study[5] showed lower estimates for the energy requirements for dehumidifiers operation, whereas another source[6] found significantly higher estimates of energy use.

Figure 5-4 shows the percent of time the metered dehumidifiers operated in each mode during four months based on the number of meters listed in Table 5-3. Dehumidifier use did not vary substantially between June and July 2012. The charts also show that energy use reflected the amount of time units were operated in full (compressor) mode.

[xiii] Based on estimated total operational time of 3658 hours per year.

Table 5-4 Monthly Average Energy Use by Meter

	Monthly energy use			
Unit ID	June	July	August	Sept.
Unit0024	.	95.11	.	.
Unit0025	13.98	.	.	.
Unit0026	92.27	107.53	.	.
Unit0027	.	45.21	.	.
Unit0028	231.68	.	.	.
Unit0029	304.25	163.50	228.68	.
Unit0030	11.68	.	.	.
Unit0033	83.84	119.56	176.59	166.72
Unit0037	.	19.92	.	.
Unit0038	183.54	97.16	83.97	103.57
Unit0041	.	32.86	181.55	367.54
Unit0043	.	53.95	.	.
Unit0044	165.60	41.99	.	12.65
Unit0047	196.52	321.32	185.45	84.82
Unit0048	164.55	78.67	114.45	89.26
Unit0049	217.50	211.96	215.66	148.14
Unit0051	186.34	.	.	.
Unit0052	.	.	.	.
Unit0053	.	59.10	179.27	.
Unit0054	.	177.96	.	.
Unit0056	184.28	281.85	287.92	269.12
Unit0057	.	178.11	.	.
Unit0095	.	351.40	384.03	.
Unit0096	.	164.20	.	.
Unit0098	.	120.43	.	.
Unit0103	.	75.40	.	.
Unit0104	.	.	281.73	272.16
Unit0106	.	.	104.35	143.29
Unit0108	.	20.61	.	.
Unit0116	.	386.66	.	.
Unit0118	.	135.69	.	.
Unit0134	181.03	28.74	26.52	.
Unit0140	293.48	283.17	289.90	.
Unit0141	79.51	201.28	170.90	184.44
Unit0142	41.94	31.89	.	.
Unit0143	100.43	101.37	127.39	.
Unit0145	.	262.13	276.04	305.83
Unit0146	119.71	226.15	301.46	294.60
Unit0147	57.13	89.20	83.08	64.63
Unit0148	.	50.11	.	.
Unit0149	27.39	19.03	19.76	22.54

	Monthly energy use			
Unit ID	June	July	August	Sept.
Unit0150	67.51	85.92	127.80	63.97
Unit0151	356.34	434.58	359.03	348.79
Unit0152	125.57	55.56	63.16	67.07
Unit0153	216.13	237.71	257.28	259.16
Unit0154	192.31	.	.	.
Unit0155	.	108.11	122.83	71.83
Unit0156	.	206.76	223.03	170.54
Unit0159	85.93	23.24	.	.
Unit0160	136.01	.	.	.
Unit0161	56.94	67.84	74.18	.
Unit0162	.	.	.	.
Unit0167	.	337.00	347.12	318.50
Unit0168	.	147.14	.	.
Unit0169	.	308.07	.	.
Unit0173	.	.	.	.
Unit0174	.	.	170.58	119.63
Unit0176	.	304.91	331.95	191.27
Unit0178	.	90.25	120.32	.
Unit0179	47.21	44.55	.	.
Unit0187	.	47.85	121.62	57.01
Unit0191	232.20	268.73	241.11	.
Unit0193	323.43	429.70	428.70	30.74
Unit0194	.	307.13	.	.
Unit0198	132.13	79.78	.	.
Unit0203	.	7.03	.	.
Unit0205	.	.	.	.
Unit0208	.	36.36	90.16	111.44
Unit0209	57.28	158.02	.	.
Unit0210	.	195.24	.	.
Unit0211	.	157.81	230.46	101.47
Unit0212	259.23	106.81	.	.
Unit0213	.	230.94	.	.
Unit0214	124.51	173.42	174.86	156.58
Unit0215	239.68	486.84	255.61	240.00
Unit0216	91.29	136.20	195.20	25.89
Unit0218	9.68	15.32	.	.
Unit0219	59.86	73.33	67.98	70.45
Unit0220	274.07	435.87	366.28	395.20

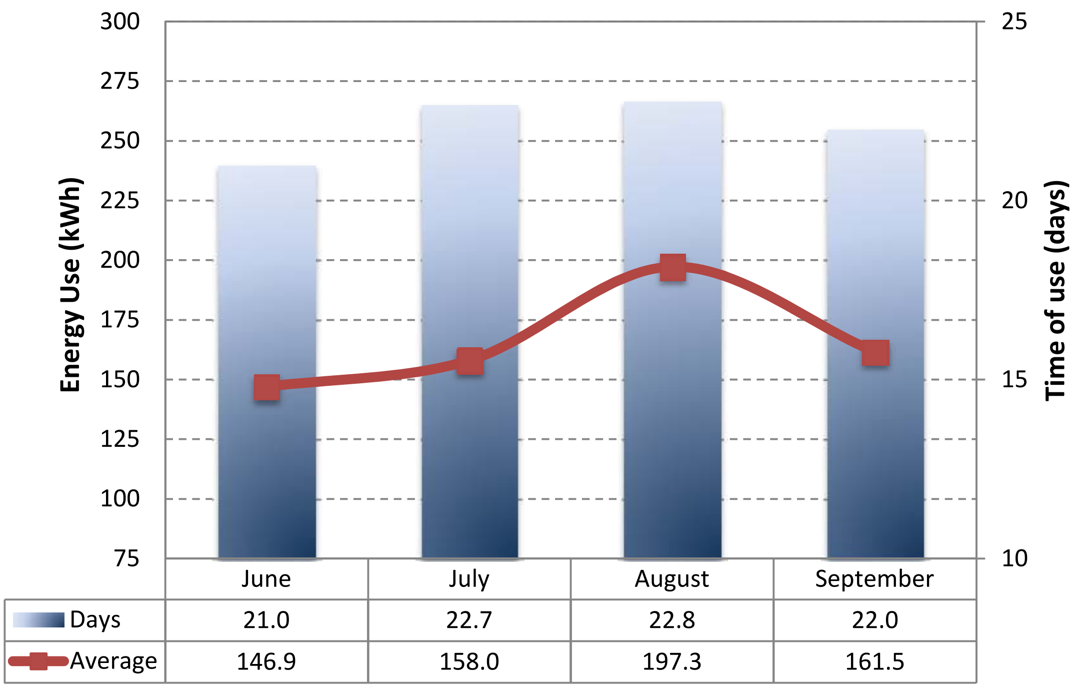

Figure 5-133 Four month energy and time use summary

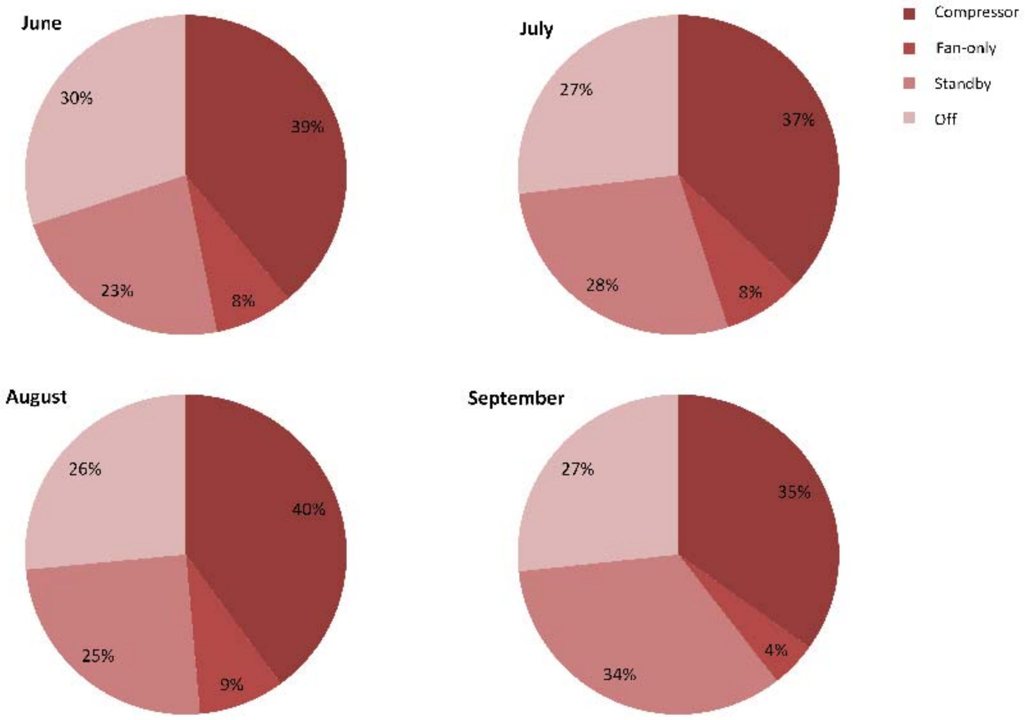

Figure 5-14 Percentage Time in Various Operational Modes

6 INITIAL ANALYSIS OF A SET OF METERED DATA

This section describes our initial analysis of the data collected from our field-metering study of dehumidifier use. In Section 6.2 we examine selected data regarding compressor cycling and temperature increases caused by dehumidifier operation.

6.1 Cases Based on Complete Data

In this section we present our initial analysis of the field-metered data for a complete set of data from one dehumidifier. From those data we quantify the effects of outdoor temperature and humidity on indoor air conditions. Developing a relationship between outdoor and indoor air conditions will enable us to generalize the limited data we collected from Philadelphia and Portland to a geographically wider set of households.

The case that provides consistent and complete dehumidifier data consists of one portable mechanical/refrigerative dehumidifier running in an enclosed space that is not climate controlled (a basement) and does not require a container to be emptied. The dehumidifier is set to an 8-hour on/off cycle (4 hours on and 4 off). Most of the cases we examined in this study had much shorter and more erratic cycles than this case. In this case, the dehumidifier operates independently of humidity.

Figure 6-1 shows the entire range of raw data collected from the complete data case. The monitored record contains significant inconsistent data (erratic dehumidifier operation). For our initial analysis, the inconsistent data were excluded.

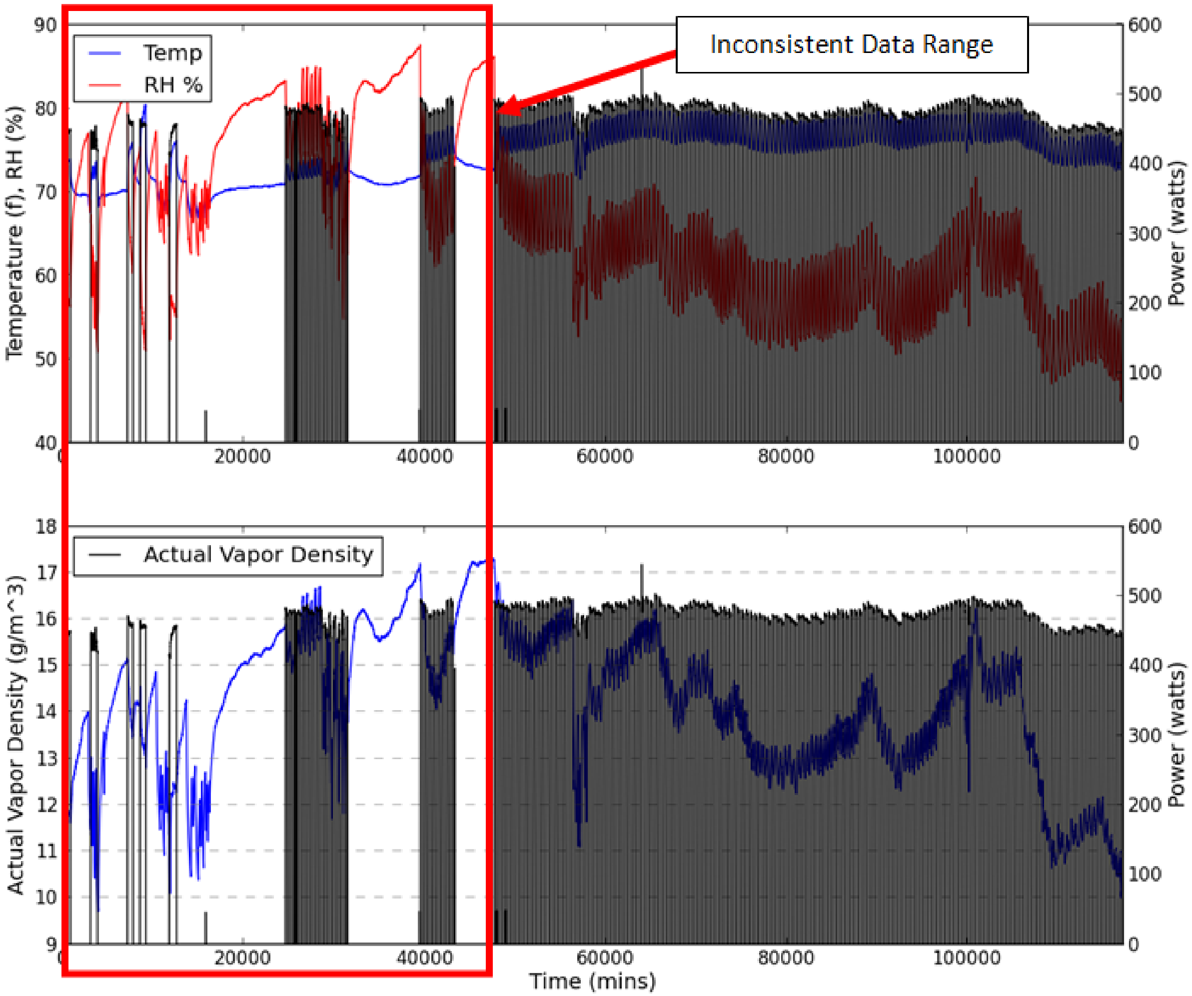

Figure 6-1 Entire Range of Data Collected for Complete Data Case

Figure 6-2 shows the raw data without the inconsistent data. The graph shows that the temperature and RH change in response to the on/off cycles of the dehumidifier. A zoomed-in section of the Figure 6.2 graph is presented in Figure 6-3.

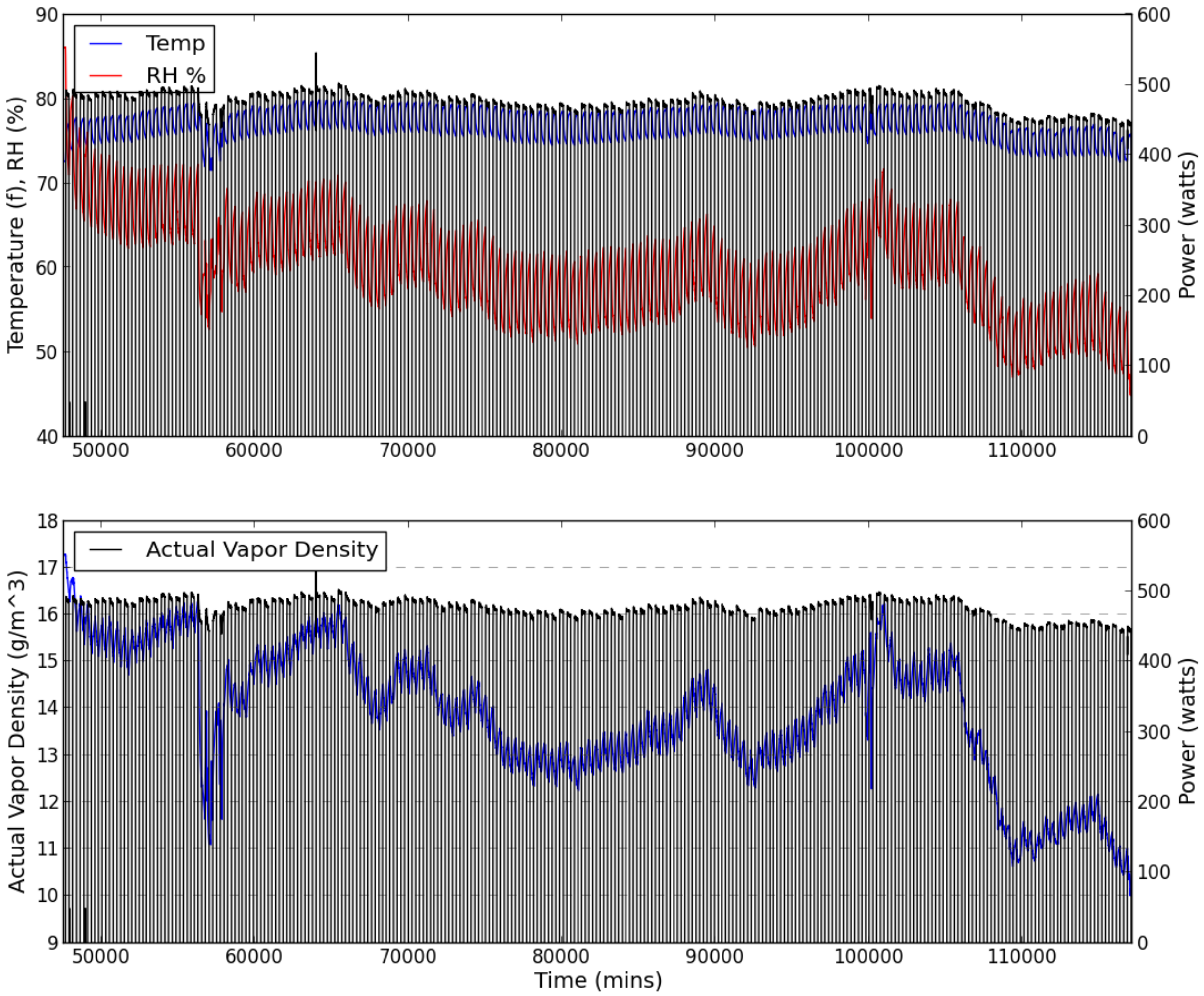

Figure 6-2 Raw Data Cleaned of Inconsistent Data

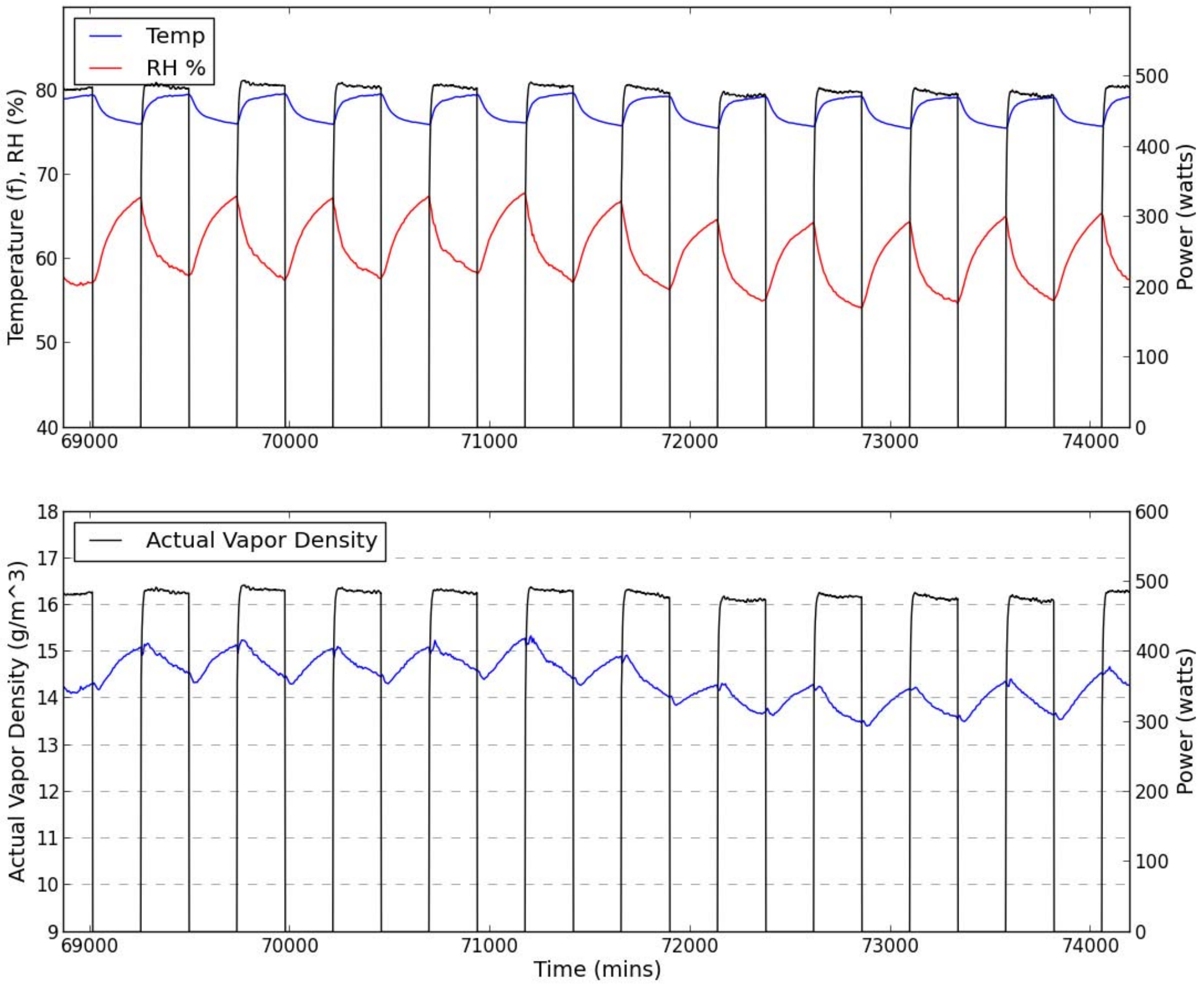

Figure 6-3 Raw Data Cleaned of Inconsistent Data (Zoomed)

The equation used to determine the moisture content of the ambient air is as follows.

$$RH = \frac{Actual\ Vapor\ Density\ ({}^{g}/_{m^3})}{Saturation\ Vapor\ Density\ ({}^{g}/_{m^3})} * 100\%$$

Where:

$$Saturation\ Vapor\ Density\ ({}^{g}/_{m^3}) \\ = 5.018 + 0.32321 * (t) + 8.1847 * 10^{-3} * (t^2) + 3.1243 * 10^{-4} * (t^3)$$

Where *t* is temperature in degrees Celsius.

Because one goal of this analysis is to determine whether outdoor weather affects the operation of a dehumidifier (by affecting indoor RH), we obtained weather station data based on zip code for the days the data collection took place. The data were disaggregated, usually into 5- or10-

minute intervals throughout a day. Each weather station report included data on time, temperature, dew point, pressure, wind direction, wind direction degrees, wind speed, gust wind speed, humidity, hourly precipitation, and daily rain. The detail within those data enabled us to match the actual vapor density (AVD) of outdoor conditions to indoor conditions and dehumidifier operation, as seen in Figure 6-4.

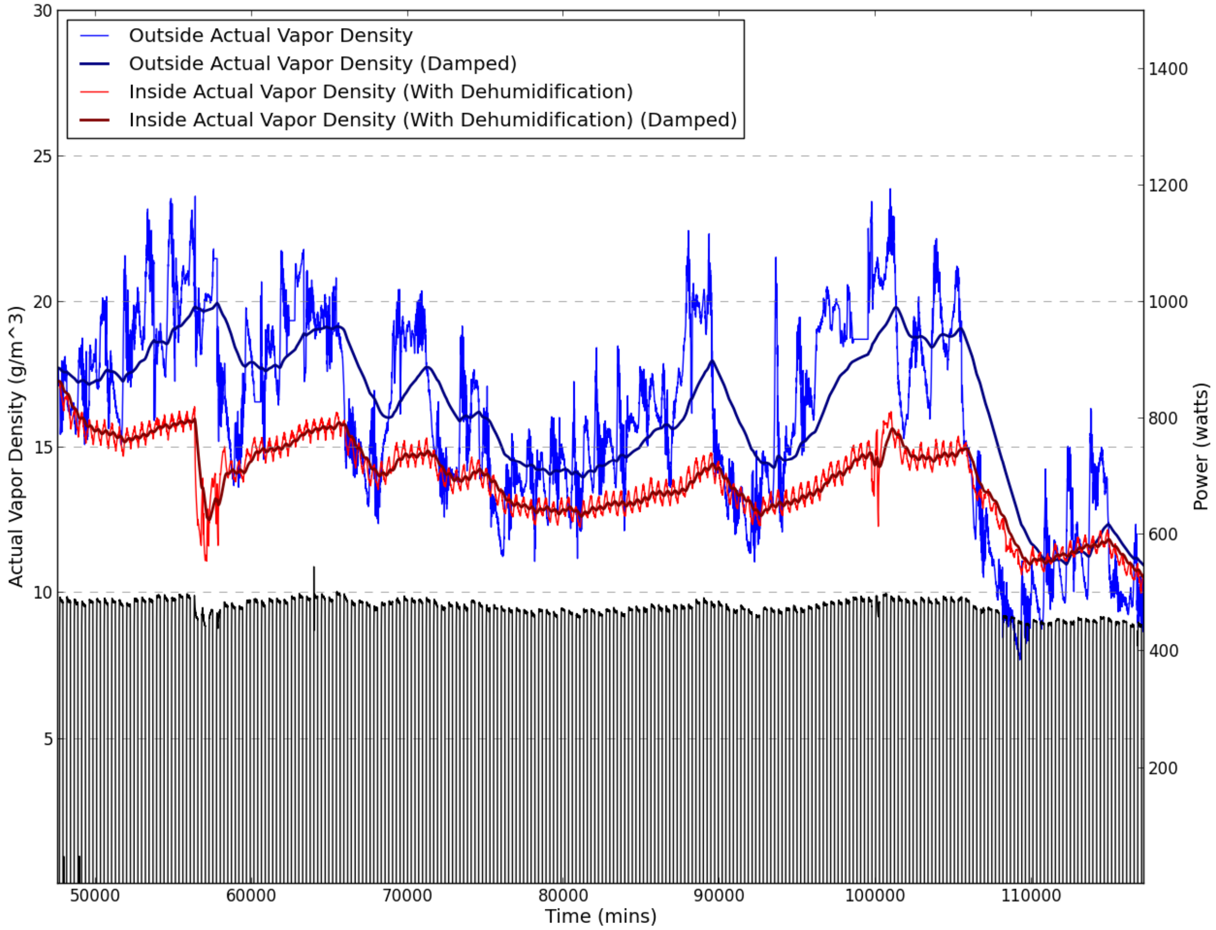

Figure 6-4 Indoor and Outdoor Actual Vapor Density

The quickly changing nature of outdoor weather conditions produced significant noise in the data, but the fluctuations in outdoor conditions would not affect indoor conditions immediately. We developed and examined a damped outdoor weather signal to try to mimic the influence of outdoor conditions on indoor conditions. We dampen the signal using the following equation. A damped signal for indoor AVD also was generated to reduce noise and enable an easier comparison with outdoor conditions. The damped signals are shown in Figure 6-5

$$Damped\ AVD\ Out_{(i)} = Damped\ AVD\ Out_{(i-1)} + C * (AVD\ Out_{(i)} - Damped\ AVD\ Out_{(i-1)})$$

The constant *C* represents the ability of outdoor conditions to affect indoor conditions. The smaller the value of *C*, the less the effect of outdoor conditions. The value for *C* used in Figure 6-4 was 0.0008.

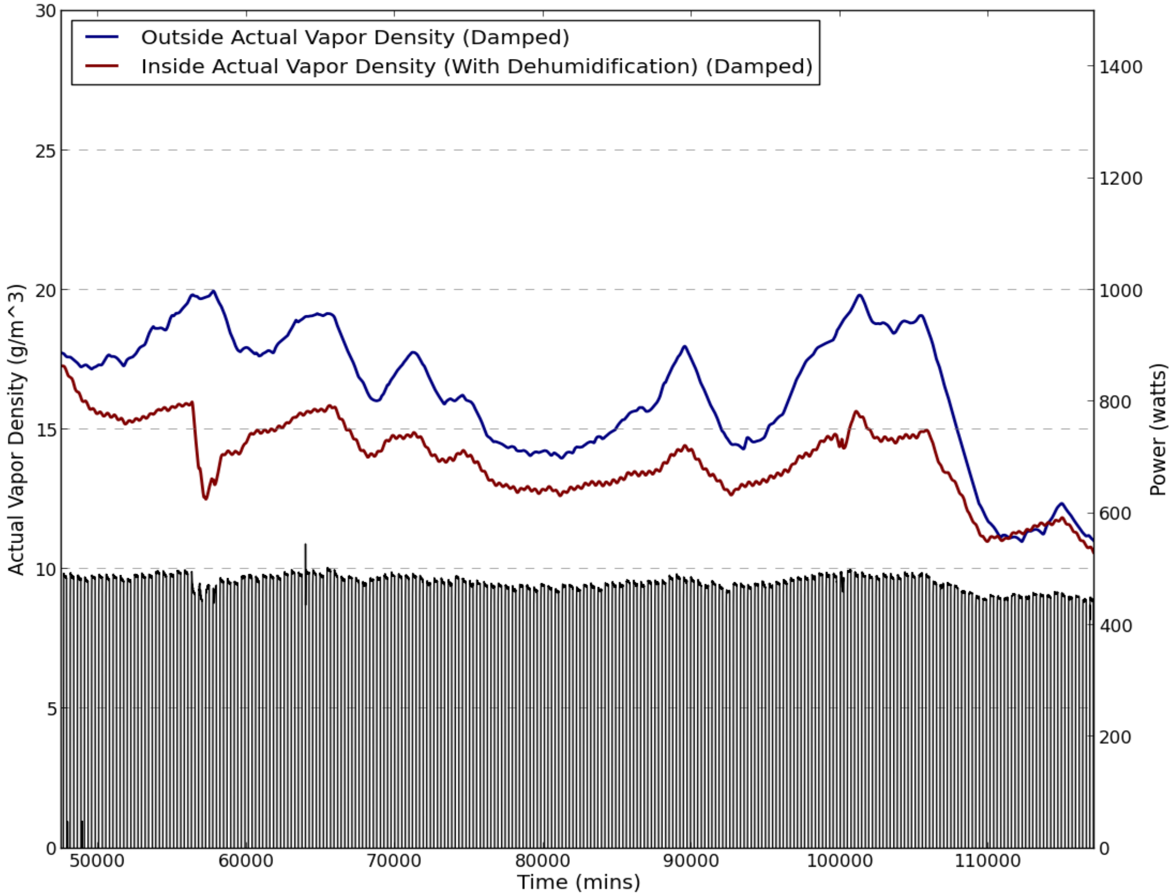

Figure 6-5 Damped Outdoor AVD Data Compared to Damped Indoor AVD

As expected, there is a clear a correlation between the outdoor and indoor data. The indoor AVD consistently stays below the outdoor AVD, which is to be expected because the dehumidifier cycles continually, no matter what changes occur outdoors.

The average change in indoor AVD while the unit was on is -0.6485 grams per cubic meter (g/m^3) +/- 0.41 g/m^3. The average change in indoor AVD while the unit was off is 0.6039 g/m^3+/- 0.23 g/m^3. While operating, the dehumidifier consumes an average of 472.6 watts, which equates to an effectiveness of 0.3436 g/m^3 per kWh while the unit is running.

6.2 Detailed Analysis of Selected Metered Data

Of the 86 dehumidifier units, 37 were selected for further detailed analysis. The selection was based on the completeness of the data, which had to include a listed start time, sufficient data within the first power cycle, a zip code for outdoor weather data collection, and no visible signs of hardware malfunction (determined by examining data).

6.2.1 Compressor cycle

For each selected dehumidifier unit the compressor cycles were calculated based on the number of on-off cycles that occurred throughout the metering. For some units cycles occurred rarely during the metering duration. Figure 6-6 presents a graph of the distribution of the number of compressor cycles per day. The average was 28.3 compressor cycles per day, with a deviation of 41.1 cycles per day. The compressor cycle time correlates with the ability of a dehumidifier to maintain the ambient humidity of the space. The rate of cycling also depends on the control strategy the manufacturer incorporated into the unit.

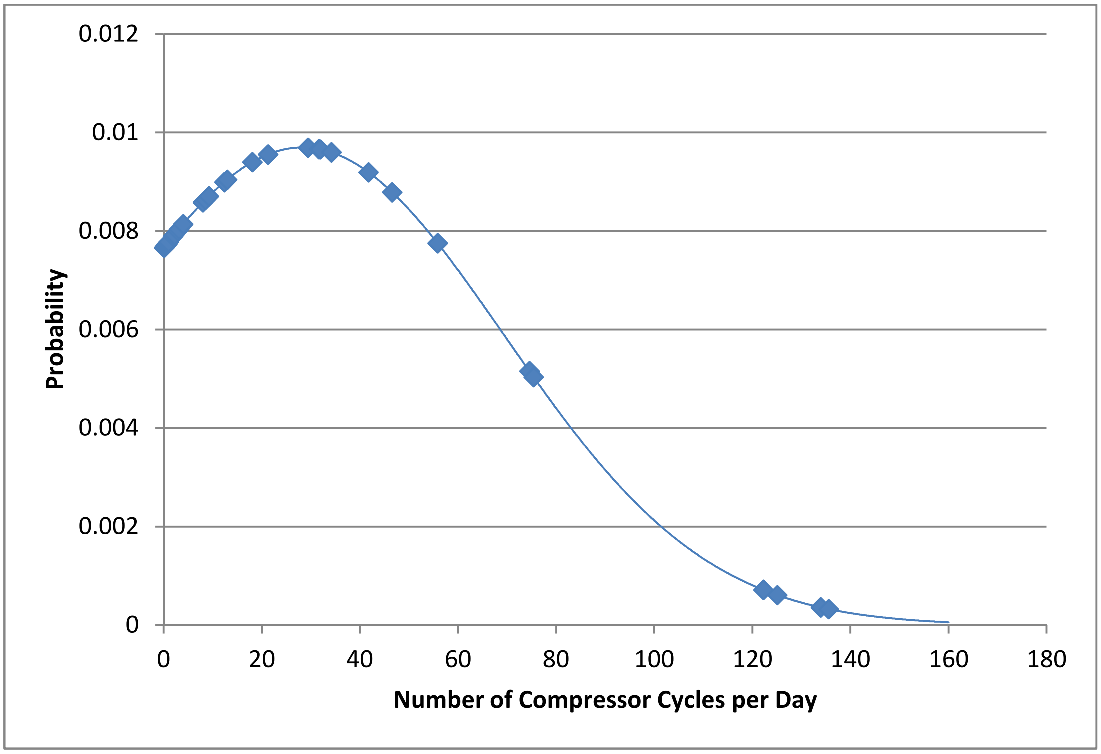

Figure 6-6 Distribution of Compressor Cycles per Day for Selected Dehumidifier Units

Figure 6-7 illustrates the ability of a dehumidifier to hold a constant humidity as a function of the number of cycles per day. In general, the more cycles a dehumidifier compressor goes through per day, the more consistent the ambient humidity. Figure 6-8 demonstrates the same correlation when the standard deviation of overall indoor humidity is compared to the average cycle time of the humidifier's compressor. Modes included in the figure include compressor and fan mode and fan-only mode.

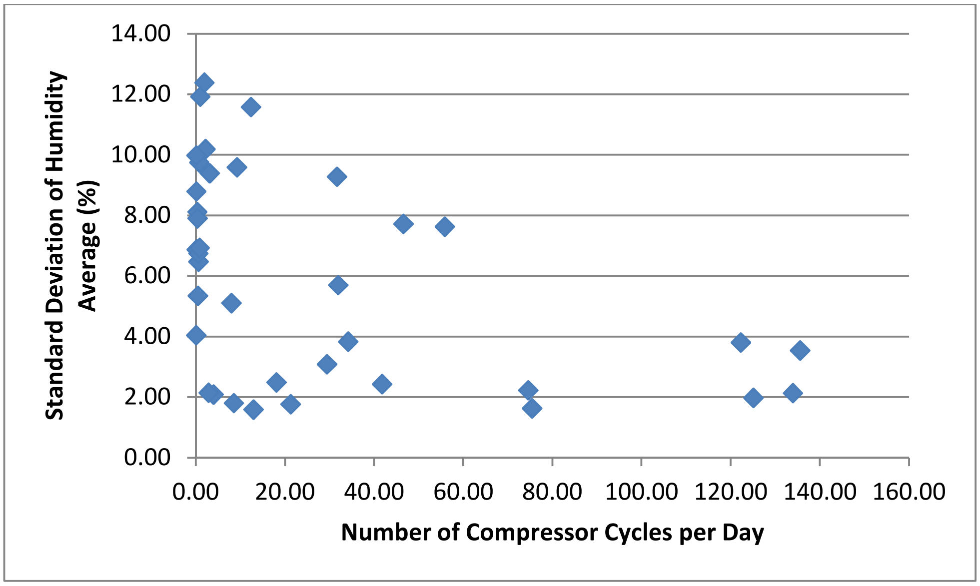

Figure 6-7 Standard Deviation of Overall Indoor Humidity as a Function of Number of Compressor Cycles per Day

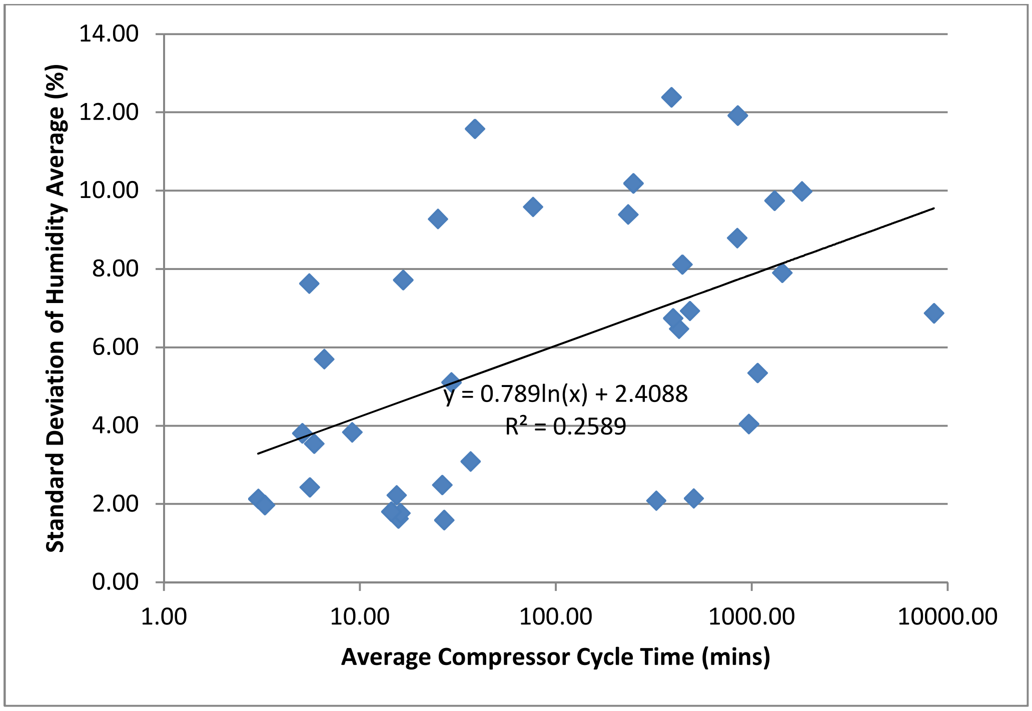

Figure 6-8 Standard Deviation of Overall Humidity as a Function of Average Compressor Cycle Time

We would expect that a longer dehumidifier compressor cycle is associated with a larger change in relative humidity and actual vapor density (AVD). Figure 6-9 does indeed indicate that as compressor cycle time increases, so does the average change in humidity and vapor density.

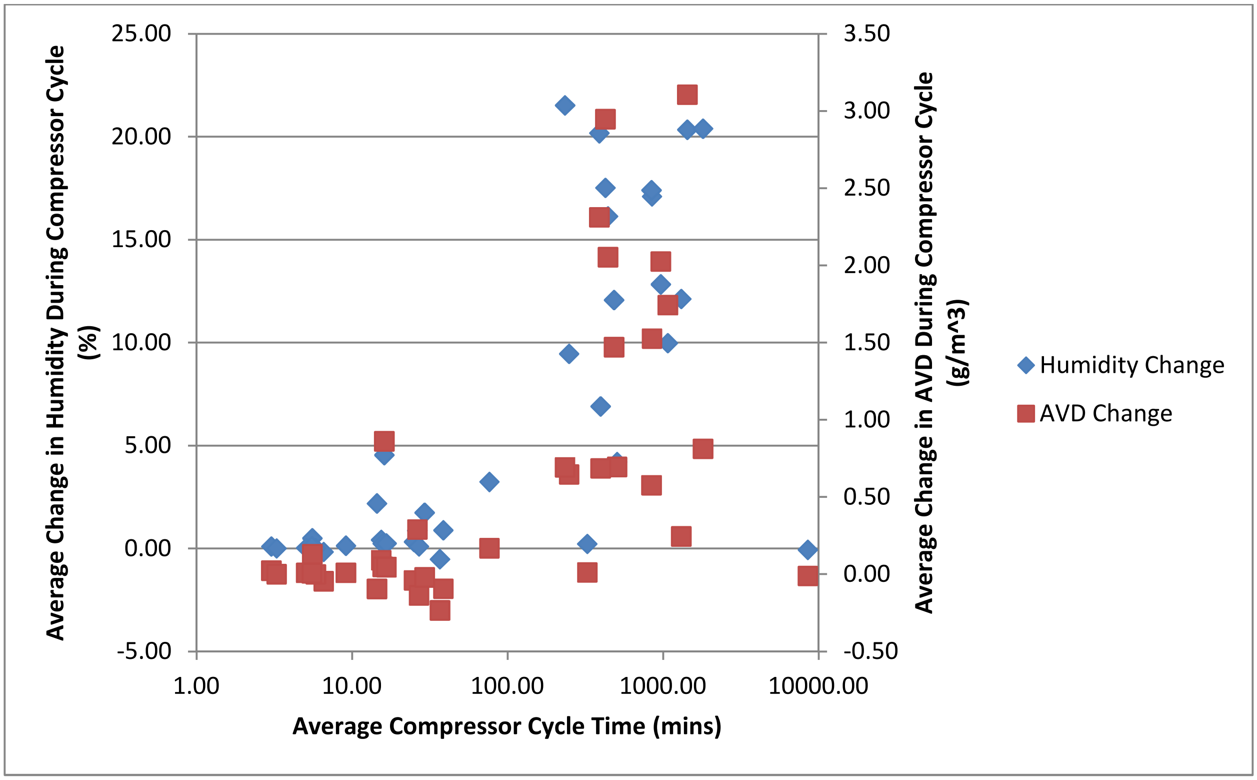

Figure 6-9 Change in Humidity and Vapor Density as a Function of Compressor Cycle Time

Eight of the 37 units (21 percent) assessed for the detailed analysis had cycle times of less than 10 minutes and in some cases less than 5 minutes (2 units). Units having such short cycle times may have a malfunctioning humidistat or a humidistat that is placed, by design, within the dehumidifier in such a way that it does not read the ambient humidity accurately. Based on some anecdotal evidence, owners of portable dehumidifiers regularly report that their units cycle very frequently. When the owners attempt to have the unit replaced they discover that the behavior is considered normal for that dehumidifier model. Some owners reported that they were able to move their dehumidifier's humidistat outside the dehumidifier's housing; afterwards the dehumidifier cycle decreased to an expected period. Further investigation is required to examine whether short cycle times indicate a malfunctioning or poorly placed humidistat.

6.2.2 Increase in temperature from dehumidifier use

When a dehumidifier's compressor operates, it generates waste heat that increases the temperature of the ambient air. Because relative humidity is a function of temperature, changes in temperature produce changes in RH. When the temperature of the ambient air increases, RH decreases. Figure 6-10 illustrates the effect of a dehumidifier's compressor cycle on moisture removed from the air (actual vapor density in g/m^3 air), the change in relative humidity, and the increase in temperature.

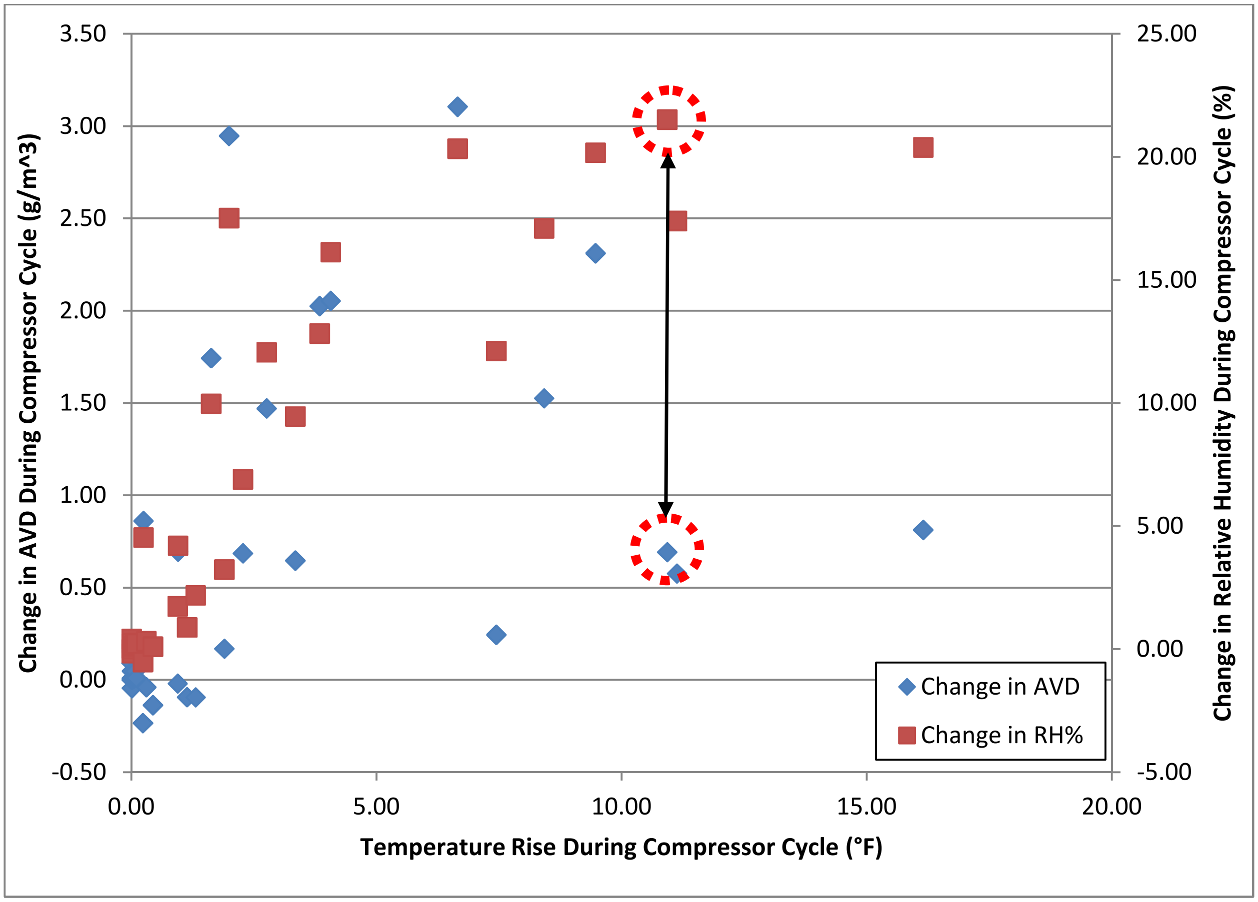

Figure 6-10 Change in Relative Humidity and Vapor Density Compared to Temperature Rise during Compressor Cycle

Figure 6-10 shows that although RH may decrease, the decrease often occurs because the dehumidifier increases the temperature of the ambient air. As indicated by the two red circles on the plot, the average change in RH for this unit was 21.5 percent, with an average temperature increase of 10.9 °F. Although the 21.5-percent change in RH makes it seem that this unit was removing large amounts of moisture, the change in actual vapor density was only 0.7 g/m^3. The average change in vapor density was 0.6 g/m^3 with a deviation of 0.9 (which includes negative average changes in AVD). Ignoring negative average changes, the average change in vapor density is 0.8 g/m^3 with a deviation of 0.9 g/m^3. The changes are illustrated in Figure 6-11.

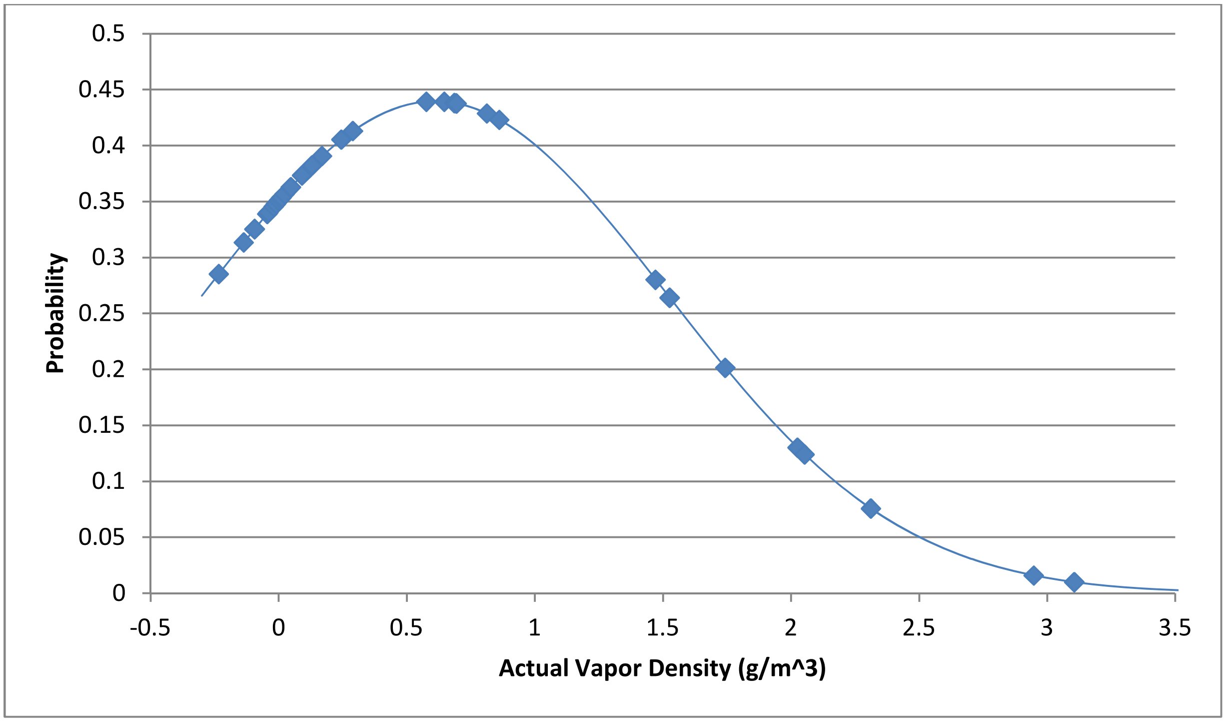

Figure 6-11 Distribution of Changes in Actual Vapor Density During Compressor Cycle

7 CONCLUSIONS

Our field study enables us to draw some tentative conclusions about market saturation, hours of use, and energy consumption of portable dehumidifiers in climates such as those of Portland, Maine and Philadelphia, Pennsylvania. The primary goal of this study was to increase information regarding the hours of operation and energy consumption associated with the three modes of operation of residential dehumidifiers. Secondarily, the study acquired information on the market saturation of dehumidifiers in residences. Although our pilot study did not attempt to quantify the saturation of dehumidifiers in residences, we found that, of households with a dehumidifier, more than 10 percent of households had more than one dehumidifier unit. Consideration should be given to conducting surveys to confirm the RECS 2009 results for quantities of dehumidifiers nationwide.

We calculated the average number of hours per month a dehumidifier was drawing electricity (or "on"). A dehumidifier was considered to be on if its power draw exceeded 0 watts. Hours per month for the metered data ranged from 510 in June to a high of 584 in August. The hours per month derived from our metered data are substantially higher than the estimates provided by AHAM, Arthur D. Little, or ENERGY STAR, for which the monthly range is a low of 210 hours in June to a high of 475 hours in August. The differences might be attributable to different definition of a unit's on cycle or to the fact that our metered data were collected from two regions known to have a high use of dehumidifiers, whereas other studies estimate hours of operation for the entire country. Further metering is warranted to reconcile the different time usage ranges.

We calculated the energy consumption of each dehumidifier in terms of accumulated kilowatt hours for each month. Additional results are discussed in sections 5.3 and 5.4. Assuming the compressor and fan run, on average, between 35 percent and 40 percent of the time, monthly energy use during summer is estimated to range from 145 to 200 kWh. Total annual energy use was determined to be approximately 1,200 kWh. Previous reports have suggested that dehumidifier energy use covers a wide spectrum, from 300 to 2,000 kWh per year. Our field-metered data fall within the median of this range, which suggests that ways to reducing energy dehumidifier consumption may exist. For example, it would be valuable to investigate the extent to which environmental and housing characteristics affect the performance of portable dehumidifiers and how the units' control mechanisms can be improved to address those issues.

8 ACKNOWLEDGEMENTS

The authors wish to thank the following individuals for their contributions to this study: Deborah Ash, Erin Claybaugh, Sophia Dauria, R.H. Galore, Jeff Greenblatt, Karlyn Harrod, Colin Lawrence-Toombs, Alex Lekov, Bill Mettler, David Mettler, David Milliken, Sarah Price, Gregory Rosenquist, Marley Walker, and Alison Williams.

9 APPENDIX A: DEHUMIDIFIER RESEARCH SURVEY

The following text reproduces the field survey given to participants in our field-metering study.

Qualifications: U.S. residents at least 18 years old.

This survey is about the dehumidifiers in your home. If you have more than one home, please answer based on the home where you spend the most time.

Please pay careful attention to the description of each appliance. That will help us get useful data. Thanks!

1. A ***dehumidifier*** removes moisture from the air. It is a device that is self-contained and is electrically operated. The most common type of dehumidifier condenses moisture from the atmosphere has an electric motor, an air-circulating fan; and a means for collecting or disposing of the condensate the water it has removed from the air.

How many dehumidifiers are plugged in at your home right now?

DO NOT INCLUDE:

- Room air conditioners
- Central air conditioners
- Air purifiers

INCLUDE:

Portable dehumidifier.

Whole home dehumidifier.

Check the number of *<u>dehumidifiers</u>*

☐ 0

☐ 1

☐ 2

☐ 3

☐ 4

☐ 5

☐ Don't know

If you answered "0 or "Don't Know"" to the above question, YOU CANNOT PROCEED WITH THE SURVEY! PLEASE STOP.

If you have more than one dehumidifier unit, please restrict your responses below to your largest-capacity unit.

2. What type of dehumidifier do you have in your house?

☐ Whole-home (This type is hooked into the duct work of the home and often operates at the same time as the central air conditioning unit)

☐ Portable (This type is self-contained and is often wheels to move to the best location for operation)

3. What type of portable dehumidifier do you have in your house?

☐ Mechanical/Refrigerative

☐ Adsorption/Desicant

☐ Don't know

3. In which room is your dehumidifier located?

- ☐ Climate-controlled garage, basement or storage space
- ☐ Another climate-controlled space in your home
- ☐ Enclosed space that is not climate-controlled (such as an unheated basement or storage shed)
- ☐ Don’t know

4. Does your dehumidifier have a container that requires emptying?

- ☐ Yes
- ☐ No
- ☐ Don’t know

5. Is your dehumidifier hooked directly into a drain by hose and therefore doesn’t require having its container emptied?

- ☐ Yes
- ☐ No
- ☐ Don’t know

6. **House components, please check all that apply?**

☐ Concrete basement floor
☐ Presence of Central Air Conditioning
☐ Sump presence

7. **Did you purchase your dehumidifier new?**

☐ Yes
☐ No, bought used.
☐ Don’t know

8. **If you purchased your dehumidifier as a new unit, how much did you pay for your dehumidifier? (If your dehumidifier was purchased as a used unit or you don’t know, please skip this question.)**

- Up to $25
- Between $26 and $50
- Between $51 and $75
- Between $76 and $100
- Between $101 and $125
- Between $126 and $150
- Between $151 and $200
- Between $201 and $250
- Between $251 and $300
- Between $301 and $350
- Between $351 and $400
- Between $401 and $500
- Between $501 and $600
- Between $601 and $700
- Between $701 and $800
- Between $801 and $1000
- Between $1001 and $1200
- Between $1201 and $1400
- Between $1401 and $1600
- Between $1601 and $1800
- Between $1801 and $2000
- Between $2001 and $2500
- Between $2501 and $3000
- $3001 or more
- Don’t know

9. If you received any kind of rebate, how much was it?

- No rebate
- Up to $10
- Between $11 and $20
- Between $21 and $30
- Between $31 and $40
- Between $41 and $50
- Between $51 and $60
- Between $61 and $80
- Between $81 and $100
- Between $101 and $125
- Between $126 and $150
- Between $151 and $200
- Between $201 and $250
- Between $251 and $300
- Between $301 and $400
- Between $401 and $500
- $501 or more
- Don’t know

10. How long ago did you purchase your new dehumidifier?

- Less than 1 year ago
- At least 1 but less than 2 years ago
- At least 2 but less than 3 years ago
- At least 3 but less than 4 years ago
- At least 4 but less than 5 years ago
- At least 5 but less than 6 years ago
- At least 6 but less than 8 years ago
- At least 8 but less than 10 years ago
- At least 10 years ago
- Don’t know

11. Was this dehumidifier . . .

☐ The first one you have owned?
☐ A replacement of the same type of dehumidifier that you owned before?
☐ An upgrade to the dehumidifier you owned before?
☐ An additional dehumidifier to the one you still own?
☐ Don’t know

12. Have you had your dehumidifier repaired?

☐ Yes
☐ No
☐ Don’t know

13. What was the cost of the repair?

14. Please enter the brand name of your dehumidifier: ☐

15. What is the full model number of your dehumidifier? If you don't know, please skip this question.

Please enter model number: ☐

Demographics:

Please answer honestly; we need to collect accurate demographic information!

16. We are interested in the part of the country where you live. What is the name of your State?

☐

17. What is your five digit zip code?

18. What is your gender?

☐ Female
☐ Male

19. Are you Hispanic or Latino?

☐ Yes
☐ No

20. What is your race? Please check all that apply:

- ☐ American Indian or Alaska Native
- ☐ Asian
- ☐ Black or African American
- ☐ Native Hawaiian or Other Pacific Islander
- ☐ White or Caucasian
- ☐ other

21. What is your highest education level?

- ○ No schooling completed
- ○ Kindergarten to grade 12 (No Diploma)
- ○ High school diploma or GED
- ○ Some college, no degree
- ○ Associate's degree (for example: AA, AS)
- ○ Bachelor's degree (for example: BA, BS)
- ○ Master's degree (for example: MA, MS, MBA)
- ○ Professional degree (for example: MD, JD)
- ○ Doctorate degree (for example: PhD, EdD)

22. Please indicate the number of people in your household by age:

Age 9 or less	
Age 10 to 19	
Age 20 to 29	
Age 30 to 39	
Age 40 to 49	
Age 50 to 59	
Age 60 to 69	
Age 70 or above	

23. What is your combined annual household income?

☐ $0-$19,999 per year

☐ $20,000-$39,999 per year

☐ $40,000-$59,999 per year

☐ $60,000-$79,999 per year

☐ $80,000-$99,999 per year

☐ $100,000-$119,999 per year

☐ $120,000 or more per year

24. Comments?

10 APPENDIX B: LIST OF METERS AND DURATION OF METERING

Unit ID	Metering date*		
	Start date	Stop date	Number of days
Unit0024	02-Jul-2012	11-Jul-2012	9
Unit0025	26-Jun-2012	29-Jun-2012	3
Unit0026	24-Jun-2012	03-Jul-2012	9
Unit0027	10-Jul-2012	11-Jul-2012	1
Unit0028	28-Jun-2012	15-Jul-2012	17
Unit0029	27-Jun-2012	22-Aug-2012	56
Unit0030	26-Jun-2012	26-Jun-2012	0
Unit0033	27-Jun-2012	16-Sep-2012	81
Unit0037	25-Jun-2012	15-Jul-2012	20
Unit0038	25-Jun-2012	16-Sep-2012	83
Unit0041	23-Jul-2012	08-Sep-2012	47
Unit0043	02-Jul-2012	11-Jul-2012	9
Unit0044	27-Jun-2012	16-Sep-2012	81
Unit0047	29-Jun-2012	16-Sep-2012	79
Unit0048	25-Jun-2012	16-Sep-2012	83
Unit0049	28-Jun-2012	16-Sep-2012	80
Unit0051	27-Jun-2012	01-Jul-2012	4
Unit0052	26-Jun-2012	16-Sep-2012	82
Unit0053	05-Jul-2012	16-Sep-2012	73
Unit0054	02-Jul-2012	11-Jul-2012	9
Unit0056	24-Jun-2012	16-Sep-2012	84
Unit0057	11-Jul-2012	12-Jul-2012	1
Unit0095	11-Jul-2012	10-Aug-2012	30
Unit0096	15-Jul-2012	20-Jul-2012	5
Unit0098	12-Jul-2012	15-Jul-2012	3
Unit0103	11-Jul-2012	16-Sep-2012	67
Unit0104	07-Aug-2012	16-Sep-2012	40
Unit0106	10-Aug-2012	16-Sep-2012	37
Unit0108	12-Jul-2012	24-Jul-2012	12
Unit0116	02-Jul-2012	26-Jul-2012	24
Unit0118	10-Jul-2012	17-Jul-2012	7
Unit0134	18-Jun-2012	11-Aug-2012	54
Unit0140	26-Jun-2012	10-Aug-2012	45
Unit0141	29-Jun-2012	14-Sep-2012	77
Unit0142	27-Jun-2012	06-Jul-2012	9
Unit0143	29-Jun-2012	16-Sep-2012	79

Unit ID	Metering date*		
	Start date		Start date
Unit0145	03-Jul-2012	16-Sep-2012	75
Unit0146	30-Jun-2012	16-Sep-2012	78
Unit0147	30-Jun-2012	16-Sep-2012	78
Unit0148	02-Jul-2012	11-Jul-2012	9
Unit0149	25-Jun-2012	16-Sep-2012	83
Unit0150	28-Jun-2012	16-Sep-2012	80
Unit0151	25-Jun-2012	15-Sep-2012	82
Unit0152	22-Jun-2012	16-Sep-2012	86
Unit0153	28-Jun-2012	16-Sep-2012	80
Unit0154	29-Jun-2012	11-Jul-2012	12
Unit0155	24-Jun-2012	16-Sep-2012	84
Unit0156	02-Jul-2012	16-Sep-2012	76
Unit0159	28-Jun-2012	02-Jul-2012	4
Unit0160	25-Jun-2012	26-Jun-2012	1
Unit0161	25-Jun-2012	05-Aug-2012	41
Unit0162	27-Jul-2012	02-Sep-2012	37
Unit0167	10-Jul-2012	16-Sep-2012	68
Unit0168	02-Jul-2012	20-Jul-2012	18
Unit0169	13-Jul-2012	25-Jul-2012	12
Unit0173	10-Jul-2012	13-Jul-2012	3
Unit0174	06-Jul-2012	16-Sep-2012	72
Unit0176	30-Jun-2012	16-Sep-2012	78
Unit0178	10-Jul-2012	11-Aug-2012	32
Unit0179	28-Jun-2012	14-Jul-2012	16
Unit0187	29-Jul-2012	16-Sep-2012	49
Unit0191	28-Jun-2012	10-Aug-2012	43
Unit0193	28-Jun-2012	09-Sep-2012	73
Unit0194	03-Jul-2012	14-Jul-2012	11
Unit0198	28-Jun-2012	26-Jul-2012	28
Unit0203	01-Jul-2012	26-Jul-2012	25
Unit0205	22-Jul-2012	23-Jul-2012	1
Unit0208	02-Jul-2012	13-Sep-2012	73
Unit0209	27-Jun-2012	04-Aug-2012	38
Unit0210	02-Jul-2012	06-Jul-2012	4
Unit0211	05-Jul-2012	13-Sep-2012	70
Unit0212	29-Jun-2012	20-Jul-2012	21
Unit0213	02-Jul-2012	20-Jul-2012	18
Unit0214	28-Jun-2012	09-Sep-2012	73
Unit0215	28-Jun-2012	02-Sep-2012	66

Unit ID	Metering date*		
	Start date		Start date
Unit0216	27-Jun-2012	08-Sep-2012	73
Unit0218	29-Jun-2012	05-Jul-2012	6
Unit0219	28-Jun-2012	09-Sep-2012	73
Unit0220	29-Jun-2012	10-Sep-2012	73

*Listed start and stop dates are after data screening process. Data (sampling days) from some meters need to be removed because of the high number of power outages.

11 APPENDIX C: METER WITH DEHUMIDIFIER PHOTOGRAPHS

Figure 11-1 Fifties-Style Ranch House

Figure 11-2 1890s Farm House

Figure 11-3 Climate Controlled Space

Figure 11-4 Unducted whole-home unit

Figure 11-5 Dehumidifier with clothes dryer

12 REFERENCES

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