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Publication Date

2013-11-25

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LBNL-6469E

Using Field-Metered Data to Quantify Annual Energy Use of Residential Portable Unit Dehumidifiers

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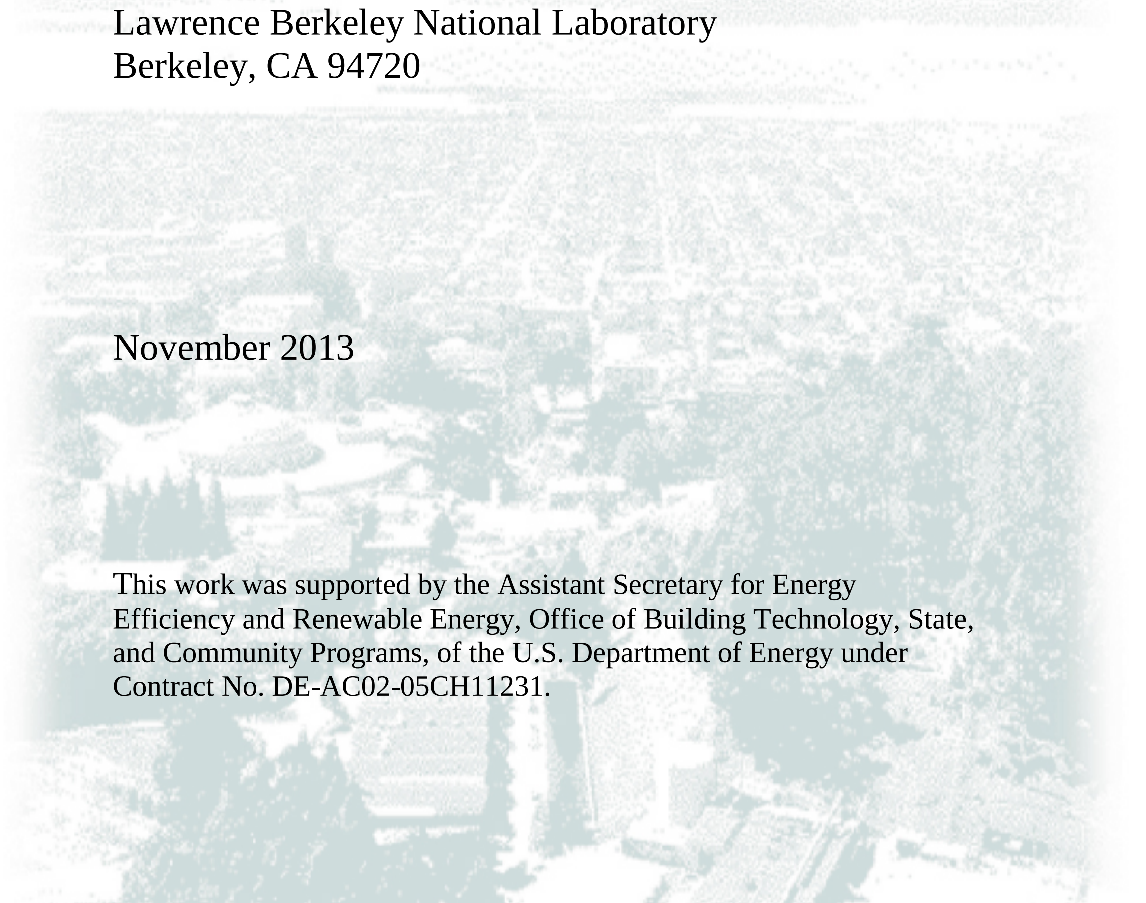

November 2013

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 of Acronyms and Terms

ACF	autocorrelation function
AEU	annual energy use
ARIMA	autoregressive integrated moving average (analysis)
CEC	California Energy Commission
DOE	U.S. Department of Energy
ECW	Energy Center of Wisconsin
EIA	U.S. Energy Information Administration
g/m3	grams per cubic meter
kWh/year	kilowatt-hours per year
L/kWh	liters per kilowatt-hour
LBNL	Lawrence Berkeley National Laboratory
NCDC	National Climatic Data Center
NOAA	National Oceanic and Atmospheric Administration
QCLCD	quality controlled local climatological data
RECS	Residential Energy Consumption Survey
RH	relative humidity
T/RH	ambient temperature and relative humidity

absolute humidity (also known as vapor density)	combination of temperature and relative humidity
0.66 duty cycle	compressor plus fan mode
Heating degree-day	a measurement that reflects the demand for energy needed to heat a building.
Cooling degree-day	a measurement that reflects the demand for energy needed to cool a building.

Using Field-Metered Data to Quantify Annual Energy Use of Residential Portable Unit Dehumidifiers

1 INTRODUCTION

The U.S. Energy Information Administration (EIA) reports that space heating and cooling no longer account for the majority of all residential energy consumption (they represented 47.7 percent in 2009). According to EIA, energy consumption for appliances, lighting, and electronics not only represents the majority of residential consumption, but continues to rise.[1] Some of the decline in energy use for space heating and cooling may be attributable to better-insulated structures and population shifts to warmer climates. Those same factors may be contributing to an increased reliance on space-conditioning appliances, specifically dehumidifiers. Additionally, as the world's climate changes, it is expected that absolute humidity will rise along with temperature. A recent study reports that continued climate warming will place significant limitations on human activity in typically hotter, more humid environments.[2] Increased human discomfort may drive an even greater use of dehumidifiers and a resulting increase in residential energy use.

In the United States, portable unit dehumidifiers most commonly are used in basements during humid summer days in northern climates.[1] Dehumidifier operation and energy consumption differ among households, depending on frequency and duration of use, user-selected settings, and outside environmental conditions. Few metering studies, however, have been performed to measure the energy use of dehumidifiers in American homes. To expand the understanding of dehumidifier energy use as related to outdoor temperature and humidity, Lawrence Berkeley National Laboratory (LBNL) undertook a field study that collected energy consumption data on portable unit dehumidifiers, along with information regarding climate conditions, housing characteristics, and consumer behavior.

The field-metering study, which focused on households that use mechanical/refrigerative dehumidifiers[a] in the New England and Middle Atlantic areas, acquired real-time data on the energy consumption of portable unit dehumidifiers during two successive humidity seasons (2012 and 2013). An initial summary report was published in December 2012.[3] The current report further analyzes the data, collected in support of achieving three goals: (1) to develop a model that mathematically describes a relationship between dehumidifier operation and climate conditions as defined by temperature and relative humidity; (2) to develop distributions of hours of dehumidifier operation for three operating modes: standby and off, fan-only, and compressor plus fan[b]; and (3) to describe how individual consumers' selection of dehumidifier capacity for a given space, consumers' selection of humidity level, and the method of condensate removal affect energy use. More importantly, understanding the operation and energy use of portable unit

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[a] The report describes other types of dehumidifiers in addition to mechanical/refrigerative.

[b] For this report, off-cycle mode was indistinguishable from standby mode

dehumidifiers in real-world applications will help characterize the increasing residential energy consumption associated with those appliances. For this report we did not analyze the effects of consumers' selection of dehumidifier capacity or consumers' selection of humidity settings. The effects of those factors on energy use will be reported after further analysis of the survey data.

2 DEHUMIDIFIER OPERATION AND COMPONENTS

In energy efficient homes, air leakage is controlled through more and better insulation, enhanced windows, and other building improvements. Effectively preventing air leakage, however, can create issues associated with tight buildings, such as moisture buildup. On the other hand, non-energy efficient homes in areas that have warm and damp seasons also can experience high levels of indoor humidity. Moist air contributes to the growth of mold, mildew, bacteria, and dust mites, which can reduce indoor air quality, cause adverse health effects, and, in the longer term, damage structures.

Vapor density, also termed absolute humidity, is a measure of water vapor per unit of air volume (g/m^3). Relative humidity (RH), a function of both the water content and temperature of air, is the amount of vapor density in the air at a given temperature and pressure compared to the maximum amount of water vapor the air can hold at that temperature and pressure. The optimum RH level for a building generally is considered to be between 30 percent and 60 percent.[4] 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 the RH ranges for avoiding poor indoor air quality. The ideal RH range for human comfort normally lies between 45 percent and 55 percent, which is the range that enables a human body to maintain enough humidity to avoid dry or irritated skin and lungs.

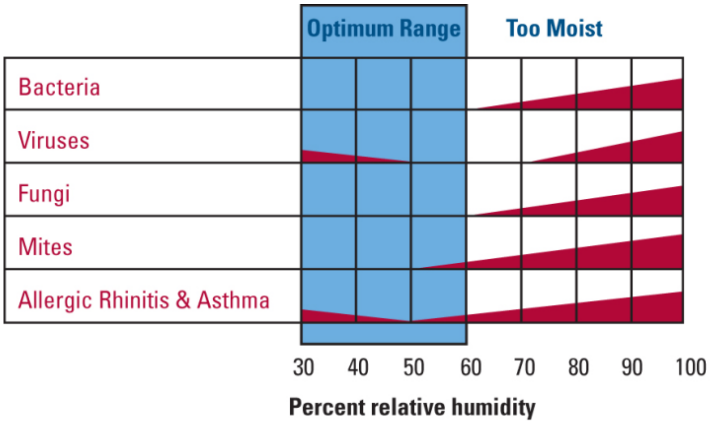

Figure 2-1 Effects of Relative Humidity

Dehumidifiers can achieve and maintain a desired humidity range in interior spaces. Dehumidifiers can be categorized by either product or technology type. As products, dehumidifiers can be classified as portable or whole-house units. For this study, we metered only portable unit dehumidifiers of the mechanical/refrigerative type. Descriptions of other technology types can be found in Dunham Whitehead et al., 2012.3

The majority of dehumidifiers, which are the mechanical/refrigerative type, have five major components: compressor, cooling coils, fan, re-heater, and water receptacle (bucket) or condensate drain. Humidity control usually is provided by a built-in humidistat 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. Some systems use a timer to operate the dehumidifier. The RH condition triggers operation of the dehumidifier, which then continues operating according to the timer setting.

A mechanical/refrigerative dehumidifier removes moisture by passing humid air through wet cooling coils. Moisture condenses on the coils, and the drier air that results is reheated before being returned to the space. The moisture that condenses out of the air eventually drops either into a receptacle that is emptied manually (a bucket) or into a drain line. Some dehumidifiers also incorporate a condensate pump to remove excess water from the drainage section.

The U.S. Department of Energy (DOE) defines a dehumidifier 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.” (42 U.S.C. 6291-6309)

3 AVAILABLE INFORMATION ON DEHUMIDIFIER PARAMETERS

Limited information is available on dehumidifier energy use, common durations of operation, consumer usage habits such as selection of set point, and efficiency. The following sections describe (1) current methods used to estimate dehumidifier energy use and hours of operation; (2) relevant information from two previous field-metering efforts; and (3) additional data related to capacity, rated efficiency, hours of operation, and operational mode, all of which affect efficiency and energy consumption. Also presented is information on the market saturation of dehumidifiers and on climate parameters.

3.1 Current Practice for Estimating Energy Use

Estimates of dehumidifier energy use using rated (testing) conditions[a] rely on three variables: capacity, hours of use, and energy efficiency. The following equation[b] generally is used to derive

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[a] Test procedure conditions are 80 °F and 65% RH.

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

annual energy consumption based on estimates of power consumption and assumptions regarding hours of use. These are engineering and manufacturer estimates, not values based on information obtained from metered dehumidifiers operating in residences.

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

Where:

DEH_{AEU} = annual dehumidifier energy use (kilowatt-hours per year [kWh/year]),
CAP = capacity (pints/day),
0.473 = conversion from pints to liters (L),
24 = number of hours in a day,
$Hours$ = annual operating hours, and
$Efficiency$ = efficiency (L/kWh).

3.1.1 Capacity

Dehumidifiers are sold by capacity, which is defined as the number of pints of moisture a unit can remove from a given area in a 24-hour period under the specified ambient conditions of 80°F and 60 percent RH. Manufacturer labeling includes information on the dehumidifier's capacity measured at the stipulated ambient RH and temperature. Selecting a capacity for an application depends on two factors: the size of the space to be dehumidified, and the dampness conditions of the space. Recommended capacities based on those factors are shown in Table 3.1. The table, however, does not include capacities of 45 pints per day or higher.

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

Condition without Dehumidification	Area Requiring Dehumidification (ft^2)				
	500	1,000	1,500	2,000	2,500
	Capacity Needed (pints per day)				
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).

Other sources suggest using higher-capacity dehumidifiers, placing less focus on room size (see Table 3.2).

Table 3-2 Dehumidifier Capacity Sizes by Application Type

Category	Capacity Range (pints/day)	Suggested Application
Small	25–35	Damp conditions in small rooms
Medium	40–50	Damp conditions in medium and large rooms
Large	65–75	Wet or damp conditions in large rooms
Whole-home	90–140	Wet or damp conditions in a small-to-medium size house

Source:http://www.homedepot.com/c/humidifiers_and_dehumidifiers_find_the_right_humidifier_or_dehumidifier_for_you_HT_BG_AP.

3.1.2 Hours of operation

Table 3.3 lists estimates of average monthly dehumidifier use obtained from various sources. All but one of the estimates assume that peak dehumidifier usage occurs in July and August and that dehumidifiers are not used in fall, winter, or early spring. The estimates differ regarding the hours of use estimated for the months preceding July and following August.

Table 3-3 Monthly Hours of Dehumidifier Use

Source	Hours/Month										Hours/ Year
	Jan–Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov–Dec	
AHAM low	0	0	0	70	210	245	245	70	35	0	875
AHAM[5] mid	0	0	14	86	231	288	288	130	58	0	1,095
AHAM high	0	0	37	110	256	329	329	183	73	0	1,315
Arthur D. Little (ADL)* [6]	0	0	0	180	360	360	360	180	180	0	1,620
Cadmus Group[7]	0	270	270	270	270	270	270	270	270	0	2,160
ENERGY STAR®,†,8,9	0	0	0	475	475	475	475	475	475	0	2,851

* Based on 3-month peak dehumidification period of June, July, and August (at 360 hours/month), with May, September, and October seeing half that usage (180 hours/month).

† Based on 6 months of operation 66% of the time (0.66 duty cycle, also known as the compressor plus fan mode).

3.1.3 Efficiency

The efficiency of a dehumidifier is derived under specified conditions as the quantity of moisture removed from the ambient air per unit of energy consumed. Along with capacity, each manufacturer notes a dehumidifier's efficiency 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 a representative dehumidifier operates, then dividing that result by the unit's energy efficiency. The AEU is imprecise, however, because of three unknowns.

1. The RH setting stipulated by the user. Although most manufacturers recommend setting the dehumidifier control to 50 percent RH, users can set the RH higher or lower depending on the type of dehumidifier.
2. The number of hours the device functions in each mode of operation (compressor and fan, fan-only, and standby/off).
3. The ambient air conditions in which the dehumidifier operates.

3.1.4 Annual energy use

Table 3-4 summarizes the AEUs of dehumidifiers reported by several studies and sources. Two of the studies are based on metered data (Energy Center of Wisconsin and The Cadmus Group). The others rely on power measurements and assumptions regarding usage to estimate annual energy consumption.

Table 3-4 Annual Usage Data for Dehumidifiers

Study/Source	Annual Energy Use (kWh/year)	Power Use (watts)	Operating Hours/Year
LBNL (1992)[10]	Average: 400; range: 200–1,000	NA	NA
ADL (1998)[6]	Average: 972	Average: 600	1,620
LBNL (2005)[11]	Range: 500–4,650	Range: 520–710	1,620; 4,320
Energy Center of Wisconsin (2005)[12]	Average: 600; range: +/- 300 (WI only)	Average: 350; range: +/- 250	NA
Central Maine Power Co. (2006)[13]	Average: 540 (Maine only)	NA	NA
ENERGY STAR (ES) Fact Sheet (from website, 2006) [8]	ES: 2,161; non-ES: 2,378	ES: 1,334 Non-ES: 1,368	1,620
ENERGY STAR Calculator (from website, 2006) [9]	Range, ES: 937–2,061; non-ES: 1,022–2,616	Range, ES: 329–723; non-ES: 358–918	2,851
Energy Center of Wisconsin (2009)			
The Cadmus Group (2012) [7]	Average: 1,000	Average: 459	2,160

3.1.5 Operational modes

Dehumidifiers do not operate continuously at full power. The modes of operation of a dehumidifier are:

- active mode, during which both the compressor and fan consume energy;
- fan-only mode, during which the cooling coils are being defrosted or air is being circulated over the humidistat after the set point has been reached;
- standby mode, off-mode, and/or bucket-full mode, during which only the control panel lights consume energy; and
- off-cycle mode, during which certain controls or sensors may use energy that would not be consumed in off or bucket-full mode.

The percentage of time a device operates in each mode affects its AEU because each mode consumes a different amount of power.

3.2 Field Studies

Below we describe the two studies from Table 3-4 that are based on field metering, one by the Energy Center of Wisconsin and the other by The Cadmus Group.

3.2.1 Study by the Energy Center of Wisconsin

The Energy Center of Wisconsin (ECW) monitored dehumidifier use in 40 Wisconsin homes during a 4-month period in the summer and fall of 2009.[14] One goal was to assess the net electricity savings from subslab ventilation systems that utilize basement dehumidifiers. A second goal was to obtain general field data (hours and energy use) regarding dehumidifier operation in Wisconsin homes to support both the first goal and potential additional energy-saving strategies for dehumidifiers.

ECW researchers estimated that the stand-alone dehumidifiers in the Wisconsin homes that reported using dehumidifiers had an average AEU of 477 kWh. They found that dehumidifier use varied dramatically; some units remained idle most of the year, while others ran almost continuously. Households in the upper quartile of use often used 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 each mode 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 results in 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 of cycling on energy use.

3.2.2 Study by The Cadmus Group, Inc.

The Cadmus Group metered 21 residential dehumidifiers in the Northeast and Middle Atlantic regions for as long as 12 weeks beginning in mid-fall 2011. In addition, participants provided information about their patterns of dehumidifier use. Because the metering effort did not capture a peak humidity period, results likely are conservative. The study found that:

- dehumidifier run time was as long as 9 hours per day;
- units were used for as long as 8 months of the year (per participant reporting);
- compressor power averaged 459 watts;
- standby power for half the units was between 0.4 and 1.9 watts; the other units drew no standby power;
- average metered electricity consumption was 4.2 kWh/day; and
- more than 70 percent of dehumidifiers had buckets for collecting condensate.

3.3 Publically Available Databases

We obtained limited data regarding dehumidifiers sold on the market and their modes and hours of operation. Primary sources of data were the EIA’s Residential Energy Consumption Survey of 2009 (RECS 2009),[15] the California Energy Commission’s (CEC’s) appliance database, and the ENERGY STAR database. Climatological data were obtained from the National Oceanic and Atmospheric Administration (NOAA).

3.3.1 RECS data

The RECS 2009 collected data on consumers' use of various appliances, including dehumidifiers, recording the geographic locations where dehumidifiers were found and the hours of use reported by survey respondents.[10] The five U.S. census divisions that showed the highest percentage of dehumidifier ownership were the New England, Middle Atlantic, East North Central, West North Central, and South Atlantic divisions (Figure 3-1).

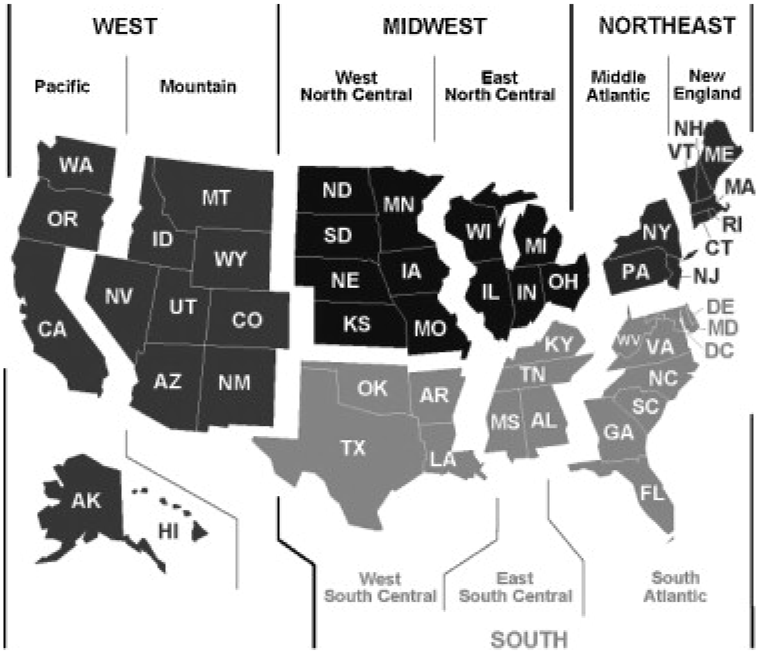

Figure 3-1 Census Regions and Divisions

Overall, RECS 2009 found the market saturation of dehumidifiers to be about 13.2 percent of all U.S. households.**Error! Bookmark not defined.**[5] For census divisions west of the South Atlantic and West North Central divisions, dehumidifier use dropped to less than 4 percent of the population. Dehumidifier use and frequency of use for the other five census divisions are reported in Table 3-5. Dehumidifiers are used more in the East North Central (30 percent of homes) and Middle Atlantic (24 percent) than in other regions. Among the population who use dehumidifiers, between 40 percent and 48 percent indicated that they run their dehumidifiers for between 1 and 3 months. Between 26 percent and 34 percent of respondents reported running dehumidifiers for between 4 and 6 months. Between 14 percent and 21 percent of the population in the East North Central and Middle Atlantic divisions indicated 12-month continuous operation of their dehumidifiers, a finding that suggests those homes have high levels of indoor-generated moisture related to basement moisture, activities of residents, or occupants leaving units running (plugged in using standby power) year round.

Table 3-5 Dehumidifier Variables in RECS 2009

Variable	All	New England	Middle Atlantic	South Atlantic	East North Central	West North Central
Dehumidifier use (%)	13.2	10.1	23.8	13.5	29.9	13.2
Households having dehumidifiers (000)		1,522	3,576	2,023	4,487	1,977
Frequency of dehumidifier use (%)						
1–3 months	43.6	47.9	42.8	43.6	39.6	42.8
4–6 months	30.4	27.4	30.9	26.1	33.8	36.6
7–9 months	7.2	7.2	7.9	7.2	7.5	6.0
10–11 months	2.6	2.7	3.1	2.2	2.2	1.0
All year long	16.3	14.9	15.4	20.9	17.0	13.6

Portable unit dehumidifiers generally are purchased additions to existing homes rather than installed appliances in new homes. Table 3.6 shows the percentage of households that have a dehumidifier for each RECS dataset from 1987 to 2009. Incomplete decades or house vintage ranges are not shown.

Table 3-6 Percentage of Homes Having Dehumidifiers by House Vintage

House Vintage	Year Data Collected*						
	1987 (%)	1990 (%)	1993 (%)	1997**	2001 (%)	2005 (%)	2009 (%)
Before 1950	22.7	24.1	20.6		27.3	30.0	16.4
1950–1959	10.6	16.2	10.9		15.9	17.1	16.7
1960–1969	10.3	12.2	12.2		10.7	14.3	14.5
1970–1979	20.2	10.7	7.8		8.5	8.8	12.1
1980–1989		56.8	37.7		21.2	20.2	12.2
1990–1999					35.4	19.7	11.0
2000–2004						33.2	11.2
2005–2009							8.4

*All data reported are from RECS data sets.

**No dehumidifier data were collected for RECS 1997.

3.3.2 CEC appliance database

The CEC collects data on many household appliances, including dehumidifiers.[a] The parameters included in the CEC database for dehumidifiers are manufacturer name, brand name, model

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[a] California Energy Commission, http://www.appliances.energy.ca.gov/. Last accessed September 27, 2013.

number, capacity (pints/day), energy factor, and the date the record was added to the database. The database provides parameters for 285 dehumidifier models from 10 manufacturers. Table 3-7 shows the number of models by manufacturer. The CEC database lists GD Midea, General Electric, and Gree multiple times under slightly different names**.**

Table 3-7 CEC Database: Manufacturers and Numbers of Models*

Manufacturer	No. of Models
Dalian Haier Air Conditioner Corp., Ltd.	1
Danby	29
DeLonghi America Inc.	27
GD Midea Air Conditioning Equipment Co., Ltd. †	34
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	55
Haier America Trading, LLC	58
Kaiping New Widetech Electric Co., Ltd.	3
LG Electronics, Inc.	13
Oreck Manufacturing Co.	1
Total	**285**

* Database last viewed September 27, 2013.

† Manufacturers the Frigidaire brand.

Table 3-8 shows the number of dehumidifier models in the CEC database by energy factor for various capacities. Listed models listed that have an energy factor of less than 1.4 do not meet the current DOE energy efficiency standard.

Table 3-8 CEC Database by Energy Factor for Various Capacities*

Capacity (pints/day)	Energy Factor (L/kWh)									No. of 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									10
30	3		36	2				18		58
32			9							9
34			1							1
35			2							2
40				7	1			4		12
41						2				2
45				21	2			9		32
48					2					2
50					31		1	20	3	55
51					1	3				4
60							2	5		7
63						1				1
64							1			1
65							19	3		22
70							28	34		62
74							1			1
Totals	**15**	**1**	**48**	**30**	**37**	**6**	**52**	**93**	**3**	**285**

* Database last viewed September 27, 2013.

3.3.3 ENERGY STAR database

The ENERGY STAR database[a] lists appliances that qualify for ENERGY STAR's energy efficiency label. The database for dehumidifiers, which includes both portable and whole-home dehumidifiers, lists qualifying models by manufacturer, capacity, and energy factor. Table 3.9 shows, by capacity, the energy factor required to qualify for the ENERGY STAR label.

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[a] http://www.energystar.gov/index.cfm?c=dehumid.pr_basics_dehumidifiers

Table 3-9 Qualifications for ENERGY STAR Dehumidifiers

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

Table 3-10 shows the number of ENERGY STAR models by brand name, and Table 3-11 shows the number of models by capacity and energy factor as of November 13, 2013. ENERGY STAR updated its qualifications in October of 2012, updates that are reflected in the table.[4]

Table 3-10 ENERGY STAR Partners and Numbers of Models

Brand Name	No. of Models	Brand Name	No. of Models
Amana	5	Honeywell	3
ARCTICAIRE	7	IMPECCA	2
Basement Systems	1	Kenmore	2
CLASSIC	3	Keystone	1
Comfort-Aire	3	KUL	2
Crawlspace Concepts	1	Norpole	1
Crosley	3	Ocean Breeze	2
Danby	2	Perfect aire	2
Danby Premiere	10	PerfectAire	4
Dayton	3	PrimeAire	2
Dehumidifer	1	Professional Series	1
Delonghi	1	Quest	6
De’Longhi	11	Santa Fe	5
Edgestar	3	Sante Fe	1
Friedrich	3	Soleusair Powered By Gree	6
Frigidaire	6	SPT	6
Garrison	6	Sylvania	3
GE	2	Ultra-Aire	5
Generations	1	Westpointe	4
GREE	8	Whirlpool	5
Haier	10	Whynter	4
Hisense	9		

Table 3-11 ENERGY STAR Models by Capacity and Energy Factor

Capacity (pints/day)	Energy Factor (L/kWh)								No. of Models
	1.85	2.4	2.88	2.89	3.0	3.1	3.4	4.2	
25.0	3								3
28.0	3								3
30.0	27								27
35.0	3								3
40.0	5								5
45.0	13								13
50.0	33								33
60.0	6								6
65.0	4								4
70.0	47	6							53
90.0			2						2
105.0								4	4
110.0					3				3
120.0				2					2
155.0							4		4
184.0						1			1
Total	**144**	**6**	**2**	**2**	**3**	**1**	**4**	**4**	**166**

3.3.4 NOAA climate data

NOAA, which is part of the U.S. Department of Commerce, is a scientific agency focused on the conditions of the oceans and the atmosphere. Among other activities, NOAA collects and stores climate data from hundreds of weather stations around the country. Data collected include heating and cooling degree-days,[a] temperature, and absolute humidity. For this analysis we used the Quality Controlled Local Climatological Data (QCLCD) available at NOAA's National Climatic Data Center (NCDC).[b]

4 DATA COLLECTION FOR THIS STUDY

During the humidity seasons of 2012 and 2013, we conducted a field study in two regions of

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[a] Heating degree-day is a measurement designed to reflect the demand for energy needed to heat a building. Cooling degree-day is a measurement designed to reflect the demand for energy needed to cool a building.

[b] http://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/quality-controlled-local-climatological-data-qclcd.

high humidity, where dehumidifiers commonly are found. Our goals were to expand the understanding of (1) energy use and operational modes of portable unit mechanical/refrigerative dehumidifiers; (2) the effect of humidity on the operation of dehumidifiers; and (3) the influence of various factors such as climate-controlled space, house size, and humidistat setting on energy use of units having different capacities. A climate-controlled space has a finished ceiling, floor, and walls and is either heated or cooled.

We collected data on the energy consumption of residential dehumidifiers by placing energy-metering devices and relative humidity/temperature sensors in homes and by surveying participants regarding household demographics and the particulars of their housing unit. For 2012's humidity season, we placed energy meters in 29 houses in Portland, ME, and 61 houses in Philadelphia, PA. For 2013's humidity season, we used a different meter to collect energy data at 11 Philadelphia homes. Depending on the humidity and season, we aimed to collect a minimum of 6 weeks and as many as 12 weeks of data for June through September. Table 4-1 summarizes the metering installations for this project.

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

Factor	Portland, ME	Philadelphia, PA (1)	Philadelphia, PA (2)
Number of housing units	29	61	11
Sets of meters and sensors installed	31	70	11
Sets of meters and sensors that provided data	26	60	11
Date of first installation	July 3, 2012	June 24, 2012	May 20, 2013
Date of last installation	Sept. 10, 2012	July 27, 2012	June 14, 2013
Date to begin retrieving meters	Sept. 27, 2012	Oct. 1, 2012	Sept. 30, 2013

4.1 Field Equipment

Below we describe the kinds of metering and sensor devices installed for the 2012 and 2013 humidity seasons in Portland, ME, and Philadelphia, PA.

4.1.1 Metering in 2012

In 2012, we used portable WattsUp meters[a] to measure the power consumption of dehumidifiers and used Onset HOBO sensors[b] to meter ambient temperature and relative humidity (T/RH). Household dehumidifiers were plugged into the WattsUp meters, and the HOBO sensors were placed beside the meters. The WattsUp data were recorded at 2-minute intervals and the T/RH data at 6-minute intervals. All data were stored on board each device for later collection. Data

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[a] Think Tank Energy Products Inc: https://www.wattsupmeters.com/secure/products.php?pn=0. (Last accessed October 5, 2013.)

[b] Onset Computer Corporation: http://www.onsetcomp.com/products/data-loggers/u12-011. (Last accessed October 5, 2013.)

were downloaded from 86 pairs of meters and sensors. Power outages were the primary cause of incomplete days' worth of data.

After identifying potential participants through e-mail, online lists, personal contacts, or other means, we sent an informational flyer and informed consent form for participants' consideration. Survey and demographic questionnaires were developed and distributed along with the consent forms. Participants were asked to record all power outages and were given points of contact for assistance. For more information regarding the 2012 metering effort, please refer to Dunham Whitehead et al., 2012.3

4.1.2 Metering in 2013

In 2013, we changed the method used to collect energy use data. We replaced the WattsUp meters with wireless Enerati[a] meters that enabled real-time monitoring and provided a time stamp associated with energy use. After connecting the energy meter, one HOBO sensor was installed at the air inlet of the dehumidifier and another in the outlet air stream close to the ceiling, about 20 to 30 feet away depending on the size of the room. Both sensors were located away from any external heat sources (such as lights); out of the pathways of external air flows such as doorways, fans, or open windows; and away from standing water. As in 2012, the energy data were recorded at 2-minute intervals and the T/RH data at 6-minute intervals. Data from the energy use meters were streamed to a secure cloud server. Each HOBO sensor stored its data for later collection. Other than adding a second HOBO sensor, the installation method for 2013 followed that used in 2012.

We metered dehumidifiers in 11 homes in Philadelphia and southeastern Pennsylvania from June through September 2013. As in 2012, after identifying potential participants through e-mail, online lists, personal contacts, or other means, we sent an informational flyer and informed consent form for participants' consideration. Home owners recorded quantities of bucket condensate emptied if applicable to their unit.

4.2 Data Download and Database Development

After collecting the metering instruments, we developed a data download script and downloaded the data from meters and sensors. We also developed an electronic version of the hard-copy survey forms and entered the survey data from each participating household. We took the following steps to develop the database.

1. Refined the time stamps of the power consumption data from the WattsUp meters. The Enerati meters did not require this step.
2. Screened the data files to produce a reliable database.

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[a] https://www.enerati.com/Default.aspx.

3. Created and linked tables created from the 2012 WattsUp meter data, the T/RH sensor data, and the survey form information. The 2013 Enerati meter data were linked with the T/RH sensor data and the survey information.
4. To link the data, replicated each row in the T/RH data thrice to convert the 6-minute interval of the T/RH meter to the 2-minute interval of the WattsUp and Enerati meters.

Using the Mysql script, we created tables for energy use and indoor climate conditions. The time stamp, WattsUp ID or Enerati ID, and wattage were selected from the *WattsUp Meter* or *Enerati Meter* table; RH and temperature were selected from the *T/RH_sensor2* table; and the WattsUp ID from the survey form served as a foreign key to join the two tables. The summary table was exported to Microsoft Excel in the common comma-separated values format. Figure 4-1 outlines the steps taken to develop the database.

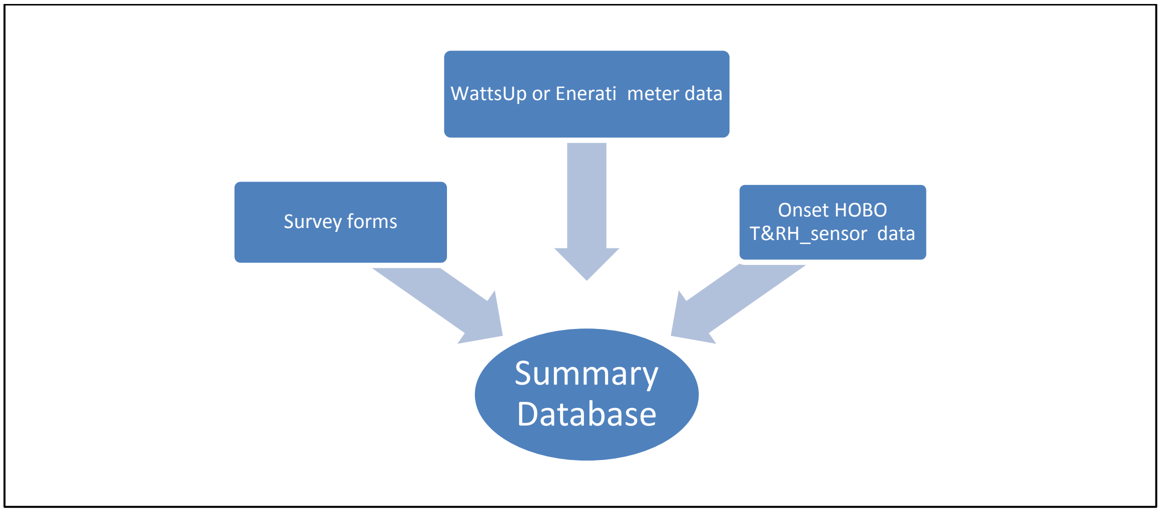

Figure 4-1 Development of Database

4.3 Linking RECS Households to Climate Parameters

Although our metered data represent only a small geographic area, dehumidifiers are used in similar climates throughout the United States, as illustrated by the RECS database. To apply dehumidifier energy use data from our limited field study to U.S. households in general, we matched the locations of RECS households with those of the NCDC QCLCD weather stations. This match enabled us to include, for each RECS household, hourly temperature and relative humidity parameters that could be used to estimate the dehumidifier operation and energy use for the nation’s entire population.

4.3.1 Derivation of outdoor air temperatures

RECS 2009 provides yearly heating and cooling degree-days but no monthly data or humidity data. To obtain more precise temperature information for the households in the RECS sample, LBNL developed a method for assigning a physical location to each RECS household. The following steps were taken.

1. We obtained from NCDC QCLCD from 202 weather stations that provide hourly outdoor air temperatures and humidity. From those weather stations we also obtained the 2009 heating and cooling degree-days at a base temperature of 65 °F. RECS also reports both heating and cooling degree-days at a base temperature of 65 °F for each housing record. The period covered by the 2009 heating and cooling degree-days from the weather stations matches the period used to determine degree-days in RECS 2009.
2. We assigned each RECS household to one of the 202 weather stations by calculating which weather station (within the appropriate census region or large state) best matched the 2009 heating and cooling degree-days in the RECS data set.

The following equation calculates the degree-day distance between the 2009 weather station data and RECS 2009 data.

$$DDD = \sqrt{(HDD_2 - HDD_1)^2 + (CDD_2 - CDD_1)^2}$$

Where:

DDD = degree-day distance,
HDD_1 = heating degree-days from 2009 weather station data,
HDD_2 = heating degree-days from RECS 2009 data,
CDD_1 = cooling degree-days from 2009 weather station data, and
CDD_2 = cooling degree-days from RECS 2009 data.

We then took the following steps to develop energy use profiles for portable unit dehumidifiers in U.S. households.

1. Used field-metering data from 2012 and 2013 paired with NCDC weather station data to determine the relationship between outdoor and indoor conditions and the time lag between them.
2. Developed models to predict dehumidifier operation based on hourly (lagged) outdoor conditions.
3. Used the models developed in step 2 and the NCDC weather data to estimate dehumidifiers’ hours of operation for RECS households. The RH setpoint was not recorded for each field metered dehumidifier.
4. Calculated annual dehumidifier energy use for RECS households.

Figure 4-2 gives an overview of the study protocol and analysis plan, which consisted of household data extracted from RECS 2009, outdoor environmental variables obtained from NCDC, and relational models developed for this field study.

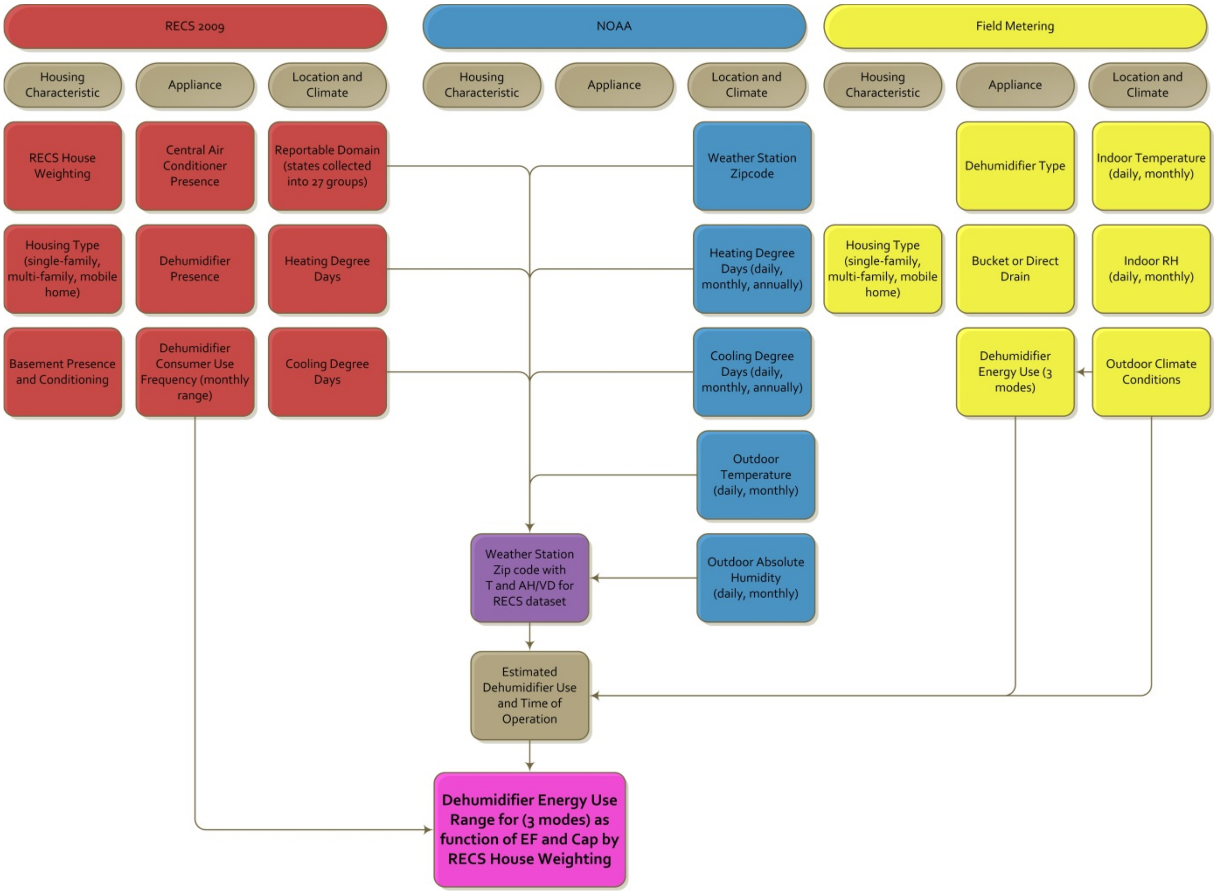

Figure 4-2 Outline of Study Protocol and Analysis Plan

5 ANALYTICAL RESULTS

This section presents analytical results developed to achieve the project’s several goals. We summarize information about the metered dehumidifiers, then characterize their energy use and operational modes. We also demonstrate the relationship between dehumidifier operation and climate conditions as expressed by absolute humidity (also known as vapor density), which combines temperature and relative humidity. We use RECS data to then estimate the national energy use of portable unit dehumidifiers.

5.1 Information about Metered Dehumidifiers

Figure 5.1 shows the age distribution of the portable unit dehumidifiers we metered. About half the units were 3 years old or younger. The rest were almost evenly distributed within a range of 4 to 10 years old. Because further analysis showed no correlation between age of unit and energy use, we did not use this variable in estimating energy use.

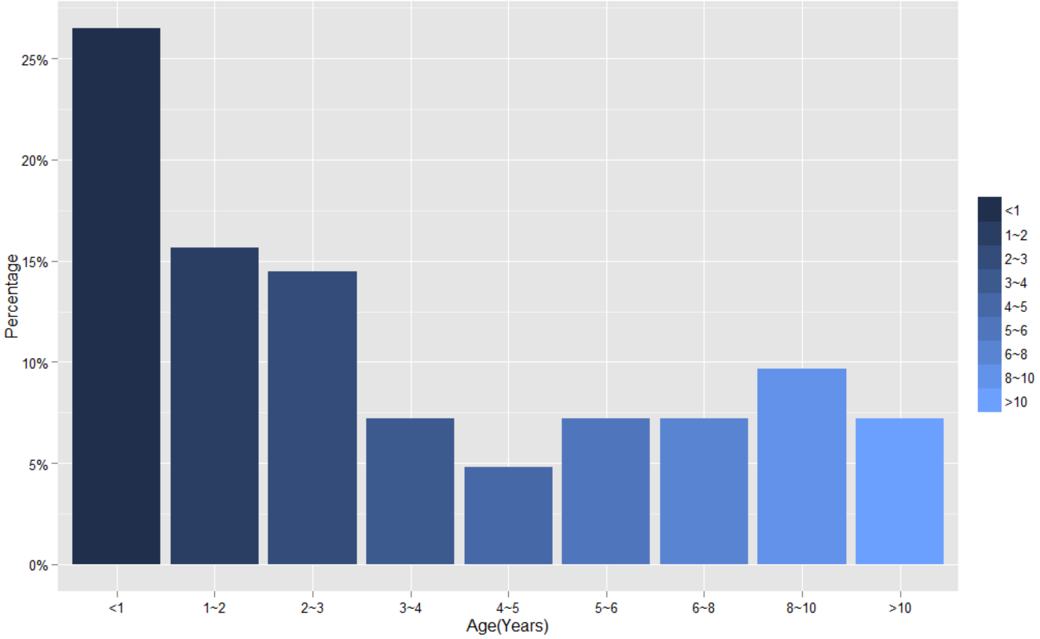

Figure 5-1 Range of Dehumidifier Vintages

Figure 5-2 and Figure 5-3 show the number of metered units in our field study by brand and capacity. The most common brand of portable unit dehumidifiers was Frigidaire (25 percent). The top four brands accounted for 60 percent of the units monitored in the study. The moisture removal capacity varied by brand. The most common capacities were 50 and 70 pints per day, for brands manufactured by Frigidaire, Kenmore, and SoleusAir.

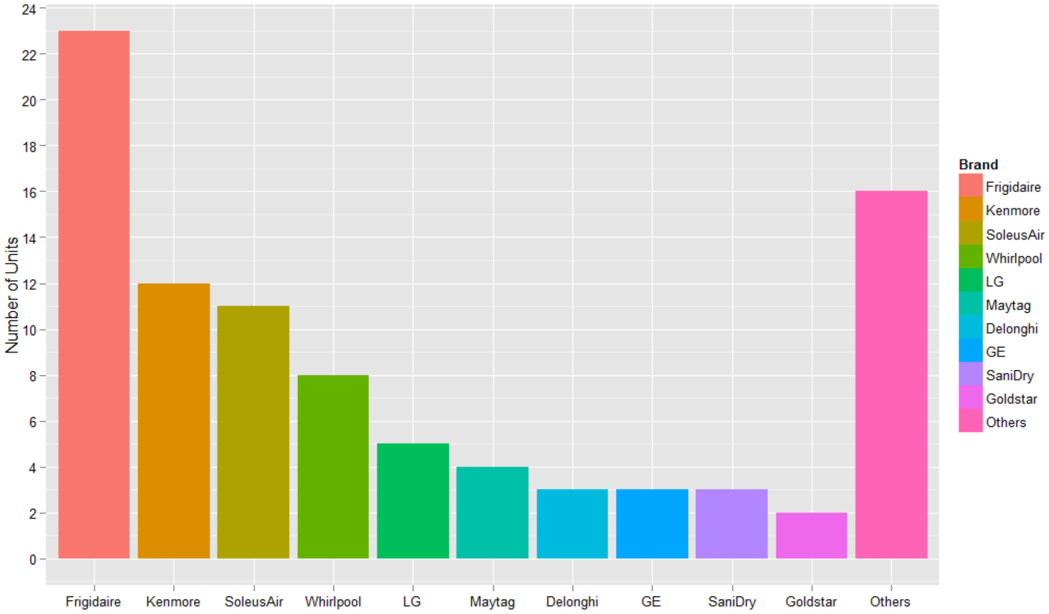

Figure 5-2 Number of Metered Dehumidifiers by Brand

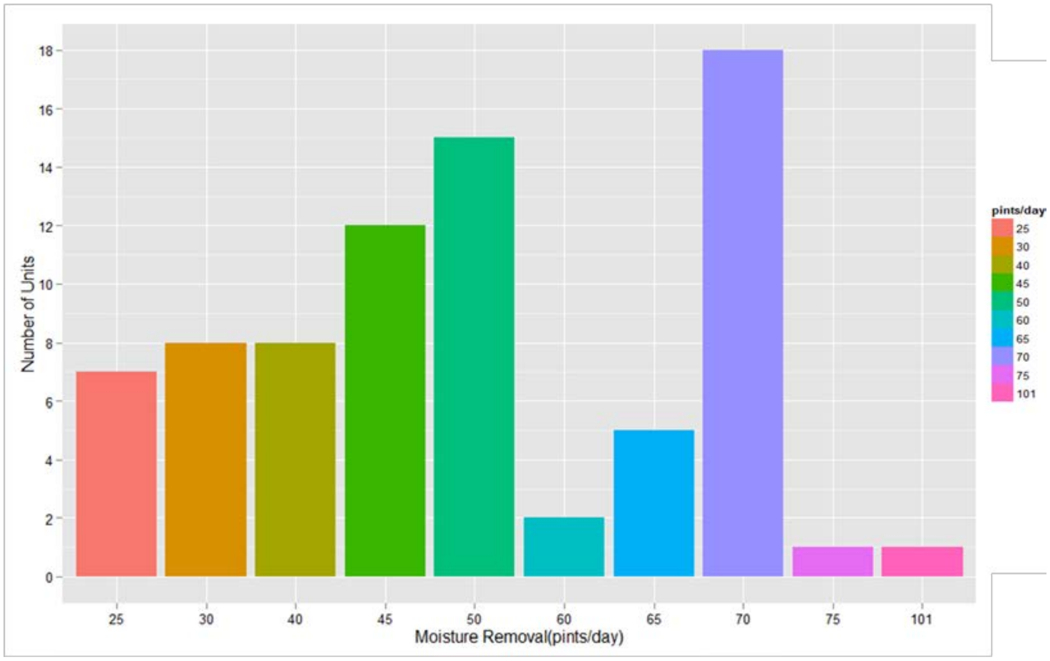

Figure 5-3 Number of Metered Dehumidifiers by Capacity

Almost the same number of units had a condensate collection bucket (54 percent) as had direct drainage (46 percent). Sixty-four percent of units were located in rooms that were not climate controlled; 36 percent were in climate-controlled spaces (see Figure 5-4). Because the operation of dehumidifiers that have buckets will turn off when a threshold of water in the bucket is reached, the presence of a bucket was included in the analysis as a categorical variable. We also included climate control as a categorical variable, because it directly affects dehumidification needs in the space where the portable unit dehumidifier is located.

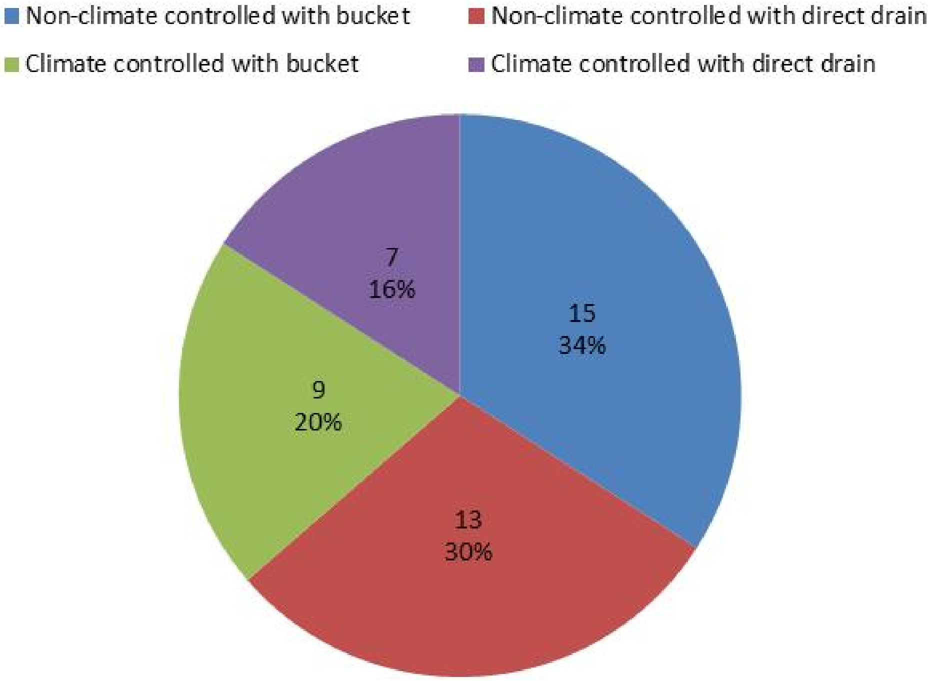

Figure 5-4 Percentages and Numbers of Dehumidifiers by Type of Space Conditioning and Condensate Removal

5.2 Dehumidifier Modes, Duration of Operation, and Energy Use

Figure 5-5 depicts both a typical daily average temperature in a space being dehumidified and the daily energy use of the portable unit dehumidifier. As the chart shows, energy use ranged from 3 to 8 kWh per day. The profiles of the two RH and temperature sensors were consistent with each other and varied systematically by about 4 percent RH (higher for air inlet sensor) and about 0.5 °F (lower for air inlet sensor). Daily outdoor temperature and RH, however, did not match indoor conditions perfectly, probably because of the thermal lag related to factors such as the home’s thermal mass, air infiltration rate, and occupant activities. In the next section we describe the methods used to determine the lag time between the outdoor and indoor data sets.

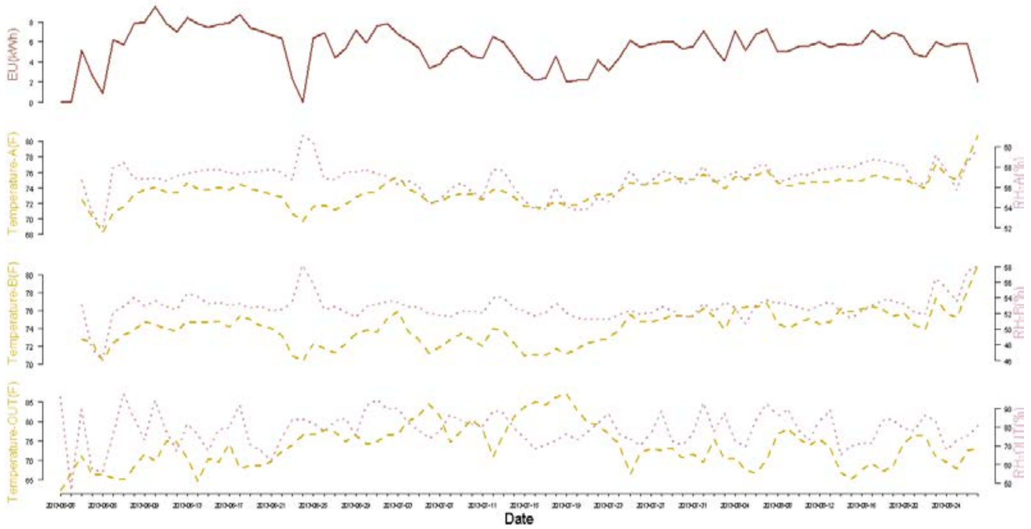

Figure 5-5 Temperature, Relative Humidity, and Energy Use for a Representative Dehumidifier

Figure 5-6 shows the relationship between hourly indoor conditions and energy use for a representative dehumidifier unit. The result is shown here to demonstrate general trends commonly observed in the data sets. A positive but relatively weak association was observed between temperature and energy use; a reasonably good but negative relationship was found between RH and energy use. This general trend of decline in RH with increasing energy use is consistent with previously reported results (Whitehead et al, 2012). The curves shown in this figure were taken from a two-dimensional area fitted to the data set. The model for this data set is as follows:

$$EU = -0.65 \times T + 0.19 \times RH + 60.4 \times \log(T) - 41.1 \times \log(RH) - \frac{745.1}{RH} - 40.1$$

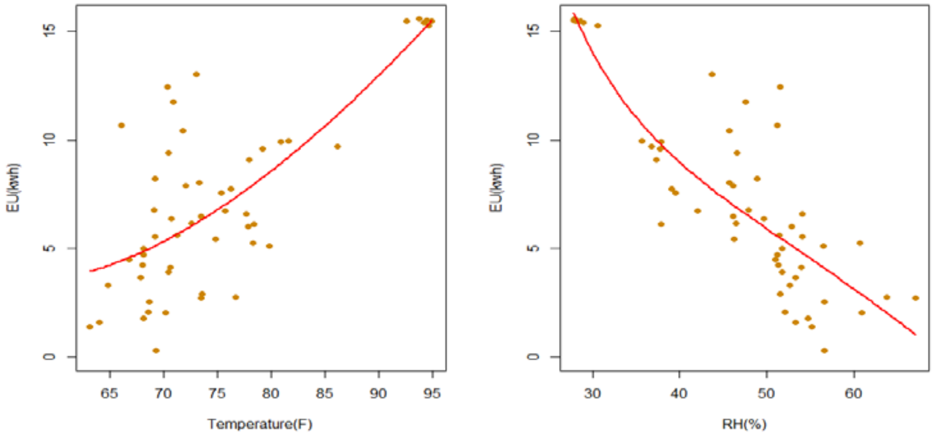

Figure 5-6 Correlations Between Energy Use and Temperature and Between Energy Use and Relative Humidity –

5.3 Outdoor and Indoor Environmental Conditions

We explored various environmental parameters to correlate indoor and outdoor conditions. Absolute humidity was identified as the best parameter, because its variations track with variations in relative humidity and it was also determined using dry-bulb temperature. Furthermore, the difference in absolute humidity could be used to predict moisture removal. We calculated the change in absolute humidity every time compressors were running (between start and stop of each cycle) and then correlated this variable with the compressors' run time. The result, shown in Figure 5-7, suggests a relatively good association between outdoor conditions and compressor run time.

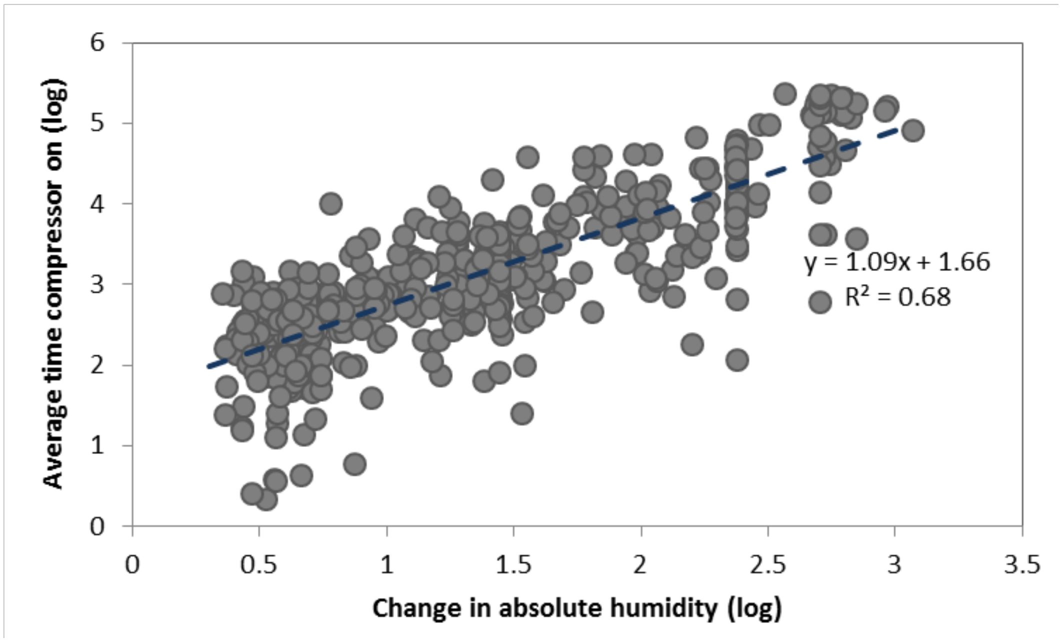

Figure 5-7 Compressor Time as a Function of Outdoor Absolute Humidity

To determine the time lag between outdoor and indoor conditions, we applied an autoregressive integrated moving average (ARIMA) analysis[a] to calculate the residuals when the data sets were shifted. The predictor in this model was outdoor absolute humidity; the dependent variable was indoor absolute humidity. The autocorrelation function series residual (ACF) shows a sinusoid shape (Figure 5-8), which indicates that there was a time lag effect in the compared data set. The partial ACF plot shows that calculated residuals decreased below the criteria after the 5th hour lag, therefore, we applied a time lag of 6 hours in our analysis. . Our analysis also shows that the Akaike's information criterion[b] of the model was the smallest for absolute humidity and

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[a] A time-series forecasting method. Degiannakis (2010) Autoregressive Conditional Heteroscedasticity (ARCH) models: A Review.

[b] The Akaike information criterion (AIC) is a measure of the relative quality of a statistical model, for a given set of data.

temperature, among all possible combinations of predictors, i.e.temperature, RH, and absolute humidity.

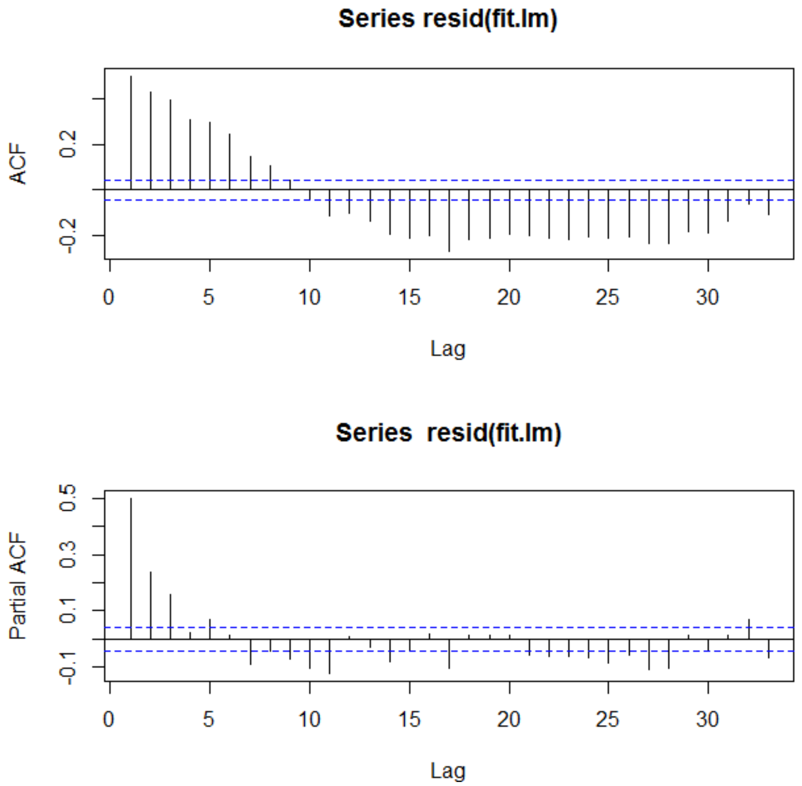

Figure 5-8 Sinusoidal Shape of ACF by Lag Time Between Outdoor and Indoor Absolute Humidity

5.4 Effect of Environmental Conditions on Dehumidifier Operation

This analysis examined 49 data sets from households having installed meters. We specified the type of space in which the dehumidifier was located (climate controlled or non-climate controlled) and the method for removing dehumidifier water (bucket or direct drain). Of the 49 data sets, 5 were excluded because they contained less than 2 weeks of data. Figure 5-9 shows the numbers of meters that provided data for various ranges of metered days.

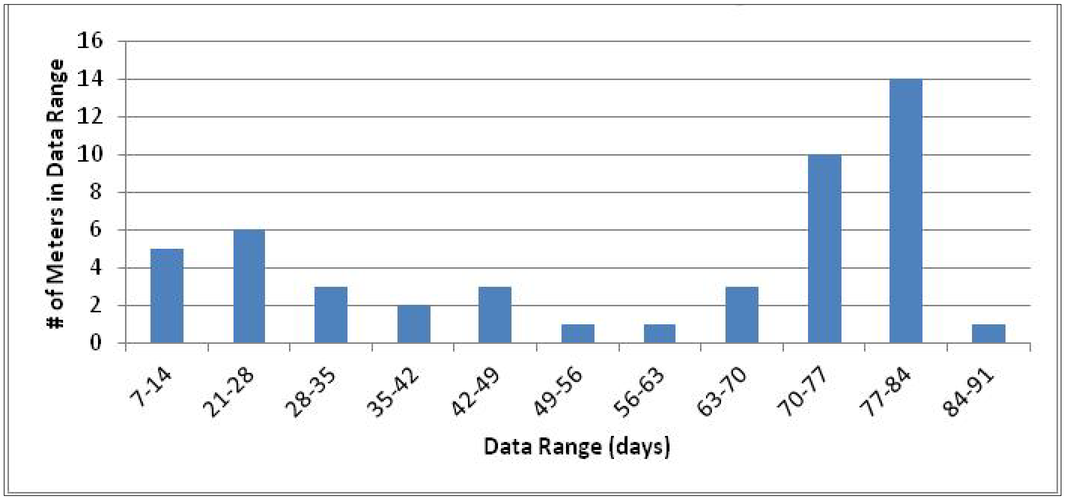

Figure 5-9 Number of Meters in each Range of Days

The 44 data files were run through a programming script to aggregate the data by hour. The minutes per hour by dehumidifier mode and the average indoor and outdoor conditions were calculated for each hour. We then applied the 6-hour time lag. The resulting data set consisted of 64,877 hours of dehumidifier use from the 44 data files.

The processed data sets were assigned to four categories: climate-controlled space with bucket, climate-controlled space with direct drain (without using a bucket that required emptying), non-climate controlled space with bucket, and non-climate controlled space with direct drain. We used those categories because the presence of climate control or a bucket affects the relationship between outdoor vapor density and compressor run time. As shown in Figure 5-10, most days reflect a non-climate controlled space and a bucket, followed by those representing non-climate controlled spaces without a bucket.

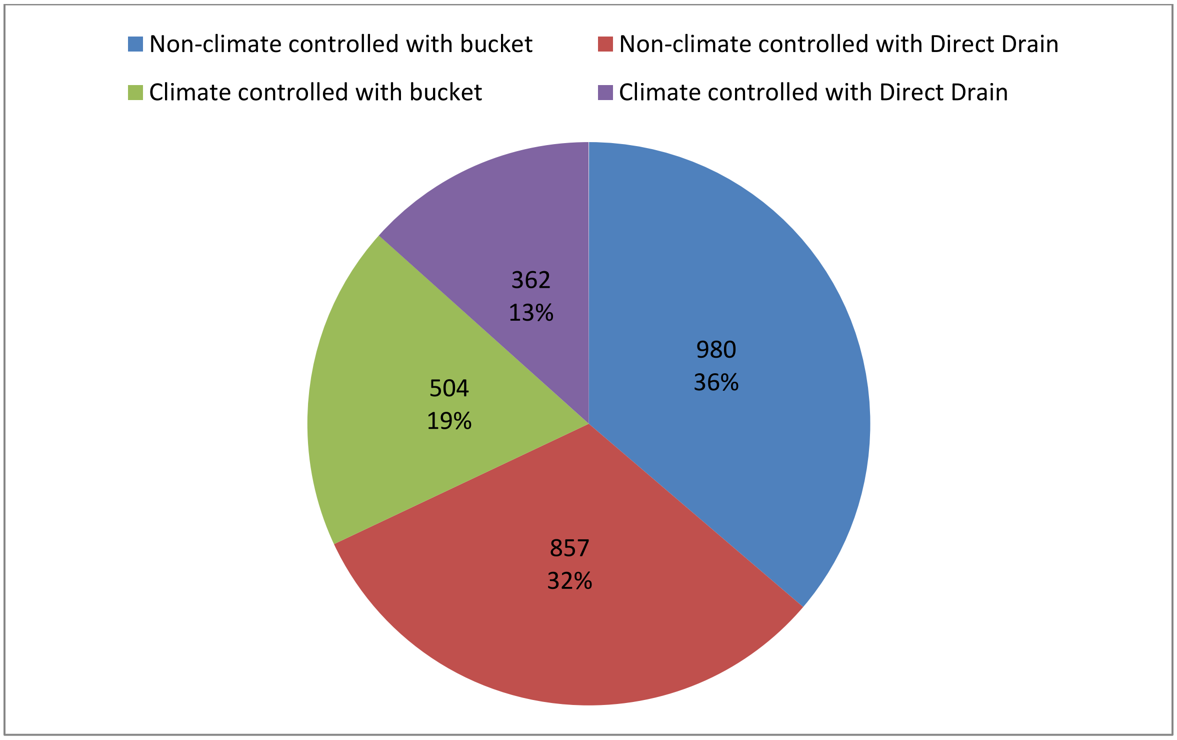

Figure 5-10 Days Represented in Data Categories

Before examining the frequency and duration of compressor operation, we excluded any hours in any data set in which the compressor run time was equal to 0 minutes. Several factors could cause 0 minutes of compressor mode, for instance if the humidity set point was met, the condensate bucket was full, or the dehumidifier malfunctioned. At first we examined scatter plots of the resulting data; however, it was difficult to determine interdependent relationships among parameters using scatter plots. Because the objective of this analysis was to determine an average relationship between dehumidifier run time and outdoor vapor density, the hourly data for compressor run time for each category (using the 6-hour lag from outdoor vapor density) were binned, in increments of 0.5 g/m^3, from 4.0 to 22.0 g/m^3. The values in each vapor density bin were averaged and fit with a linear regression. Figure 5-11 and Figure 5-12 show the average amounts of time portable unit dehumidifiers spent in compressor mode in climate-controlled and non-climate controlled spaces, respectively.

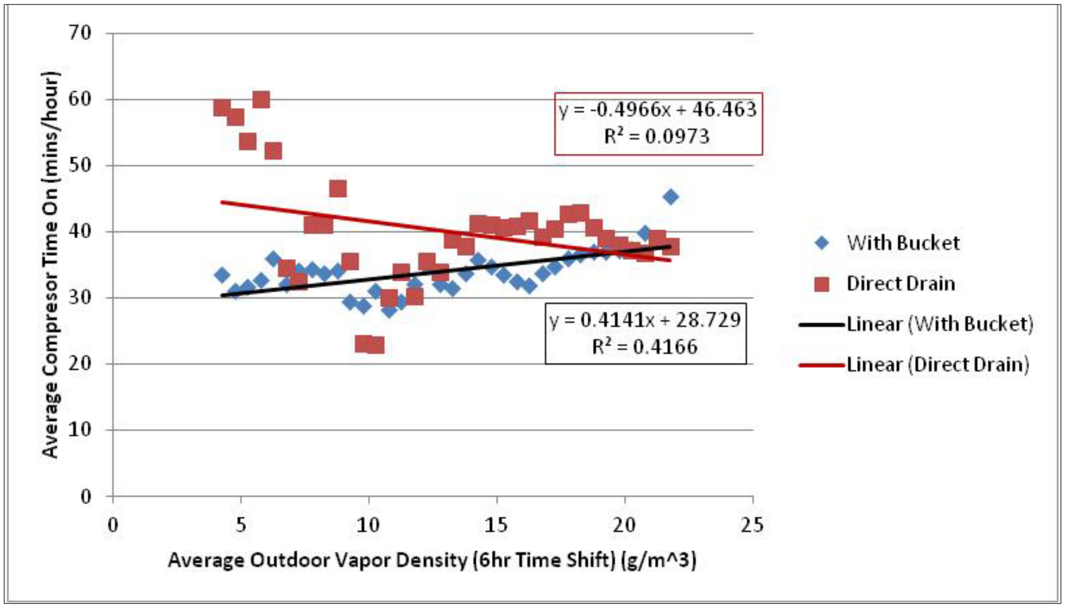

Figure 5-11 Average Time in Compressor Mode for Climate-Controlled Spaces (Excluding Hours Having 0 Minutes of Compressor Mode)

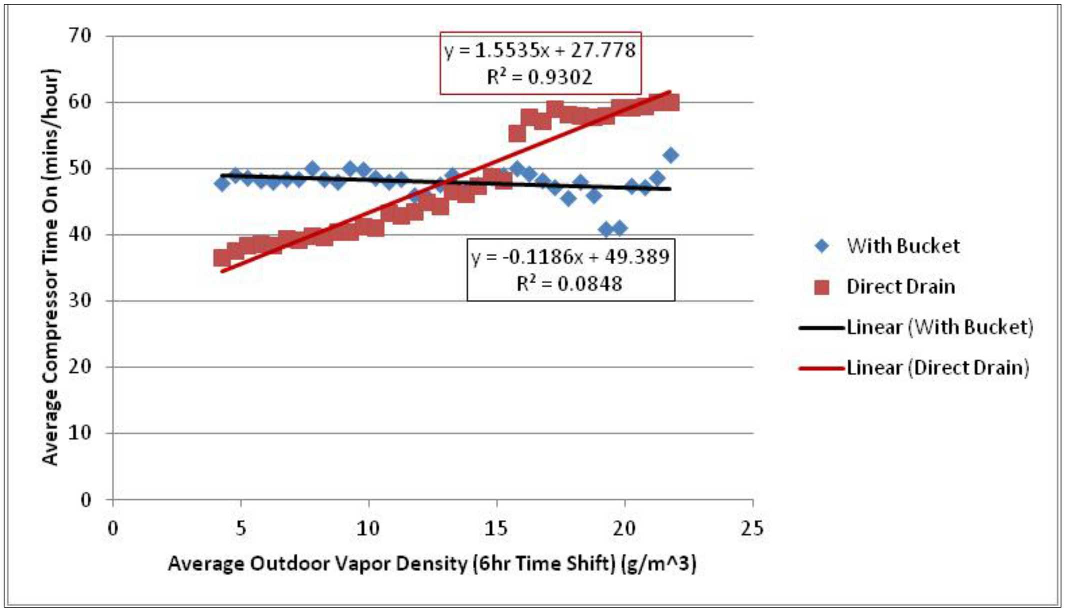

Figure 5-12 Average Time in Compressor Mode for Non-Climate Controlled Spaces (Excluding Hours Having 0 Minutes of Compressor Mode)

After we determined the uninterrupted compressor run time related to outdoor vapor density, we determined the percentage chance that an hour would have more than 0 minutes of compressor mode. We calculated the hours that the compressor had more than 0 minutes of operation as a percentage of the total number of hours in each bin for outdoor vapor density. This relationship established how each combination of type of space conditioning and water removal method performs in the field. The relationships are illustrated for climate-controlled and non-climate controlled spaces in Figure 5-13 and Figure 5-14, respectively.

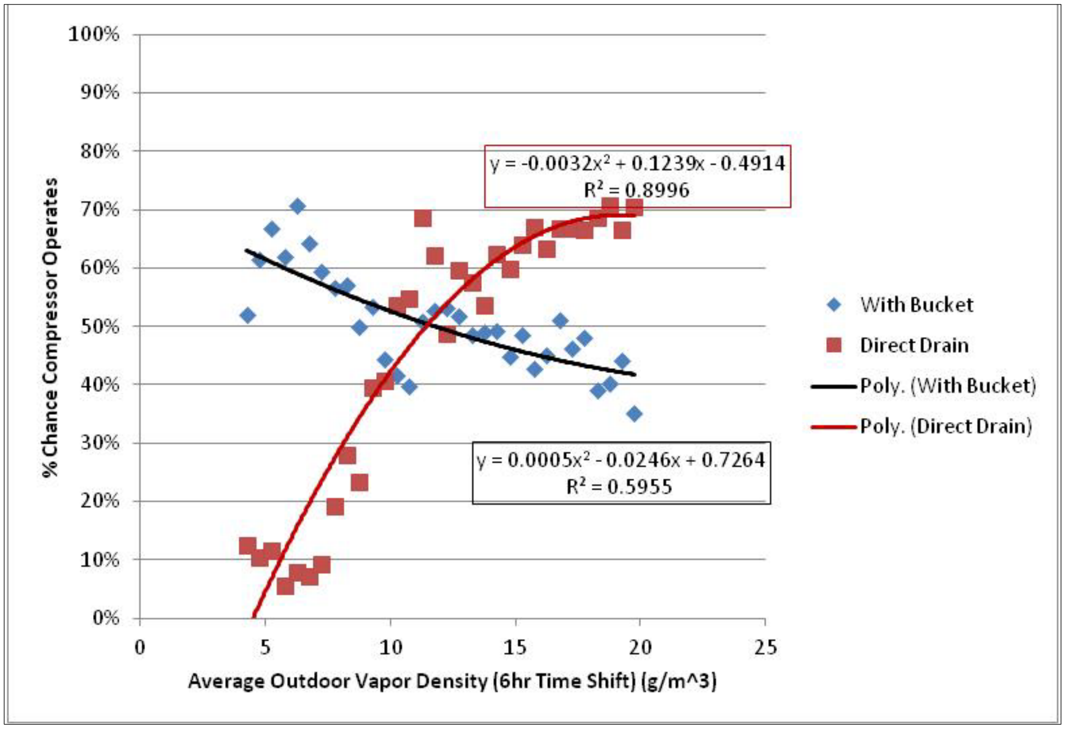

Figure 5-13 Percent Chance an Hour will have More than 0 Minutes in Compressor Mode as a Function of Outdoor Vapor Density for Climate-Controlled Spaces

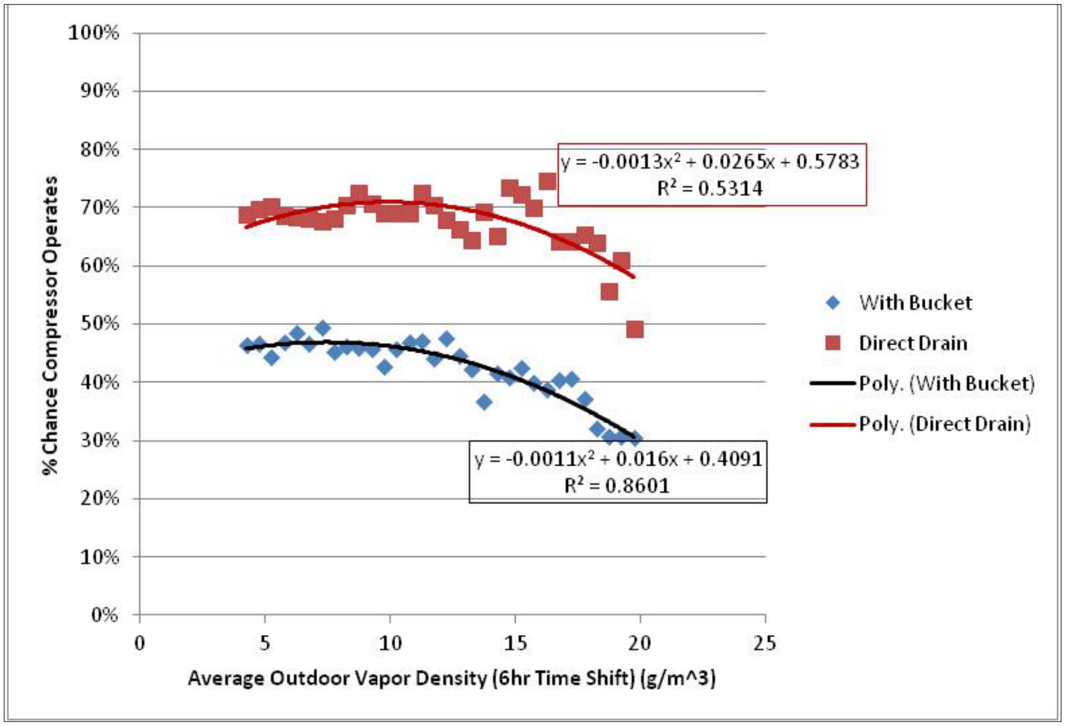

Figure 5-14 Percent Chance an Hour will have More Than 0 Minutes in Compressor Mode as a Function of Outdoor Vapor Density for Non-Climate Controlled Spaces

We next combined the equations developed for average compressor run time and percent chance an hour will have more than 0 minutes in compressor mode (Figure 5-11 through Figure 5-14) to predict compressor run time in response to outdoor vapor density. The result is an equation that describes the compressor run time (in minutes/hour) as a function of average outdoor vapor density for each category of dehumidifier. The equations describe only an average relationship between compressor run time and outdoor vapor density. Although individual dehumidifiers may differ greatly from the models, the equations describe, on average, the manner in which large populations of dehumidifier units would operate.

The results from the predicted versus actual average compressor run times for the four categories of dehumidifiers are presented in Figure 5-15 through Figure 5-18, along with the derived model equations. Predicted versus actual compressor run times for all categories are shown in Figure 5-19. The models reveal some counter-intuitive relationships, such as the decrease in average compressor run time at higher vapor densities. Direct-drain units can operate for extended periods at high outdoor vapor densities (see Figures 5-15 and Figure 5-17), because there is no full bucket threshold reached to stop dehumidifier operation. Figure 5-18 shows the full bucket condition, in which the dehumidifier operates less at higher than at lower outdoor vapor densities because the full bucket is not emptied, thereby halting dehumidifier operation. The figure includes the zero minutes during the compressor hours.

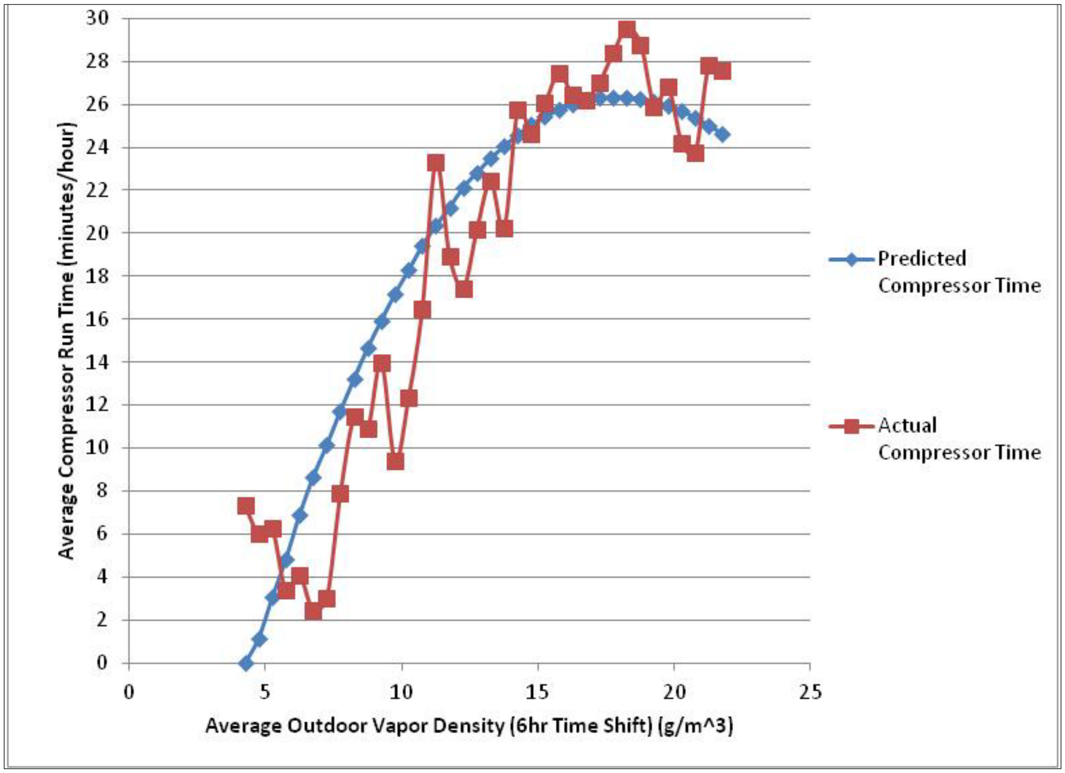

Figure 5-15 Predicted versus Actual Average Compressor Run Time as a Function of Outdoor Vapor Density for Climate-Controlled, Direct-Drain Dehumidifiers

Equation for climate-controlled, direct-drain dehumidifiers:

$$CC(DD) Compressor\ Run\ Time\ \left(\frac{mins}{hour}\right) = (-0.4966 * VD_{out} + 46.463) * (-0.0032 * {VD_{out}}^2 + 0.1239 * VD_{out} + 0.4914)$$

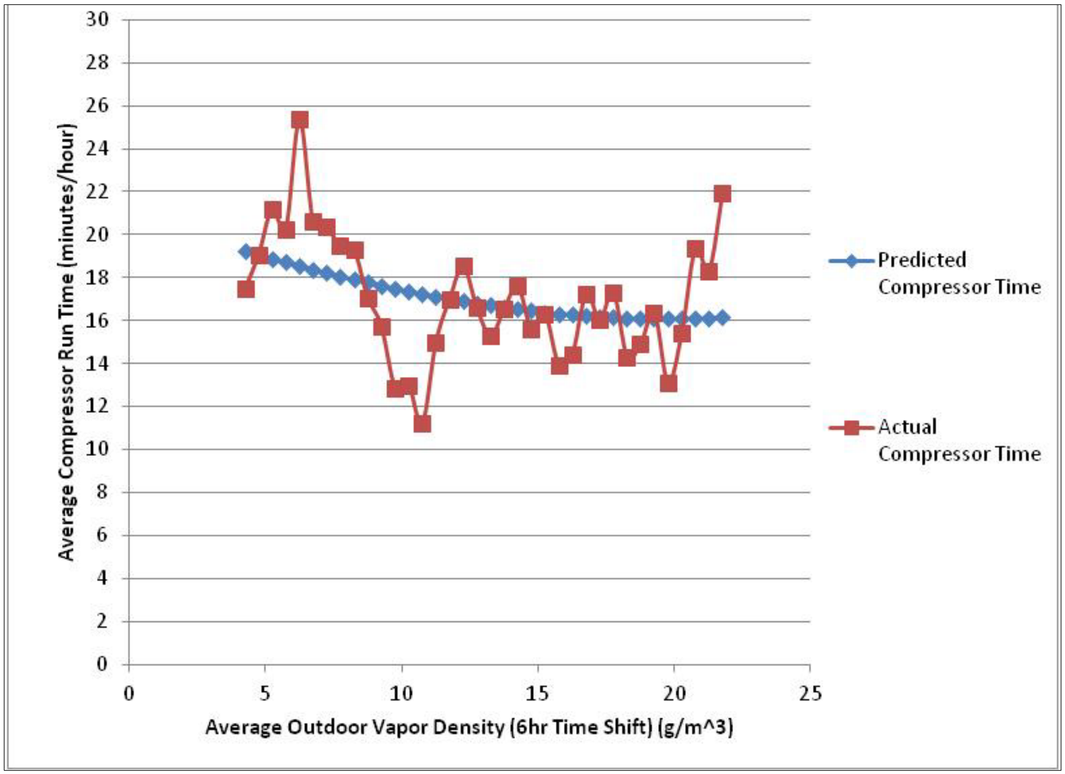

Figure 5-16 Predicted versus Actual Average Compressor Run Time as a Function of Outdoor Vapor Density for Climate-Controlled Dehumidifiers with Bucket

Equation for climate-controlled dehumidifiers with bucket:

$$CC(B)Compressor\ Run\ Time\ \left(\frac{mins}{hour}\right) = (0.4141 * VD_{out} + 28.729) * (-0.0005 * {VD_{out}}^2 - 0.0246 * VD_{out} + 0.7264)$$

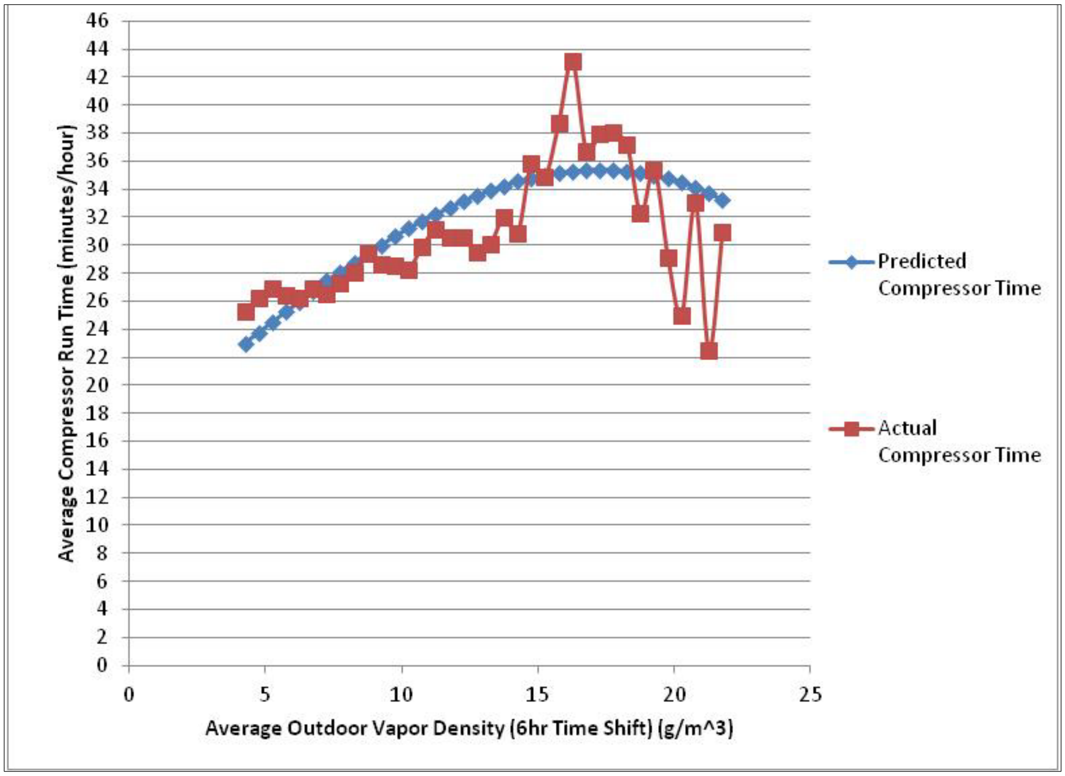

Figure 5-17 Predicted versus Actual Average Compressor Run Time as a Function of Outdoor Vapor Density for Non-Climate Controlled, Direct-Drain Dehumidifiers

Equation for non-climate controlled, direct-drain dehumidifiers:

$$NCC(DD) Compressor\ Run\ Time\ \left(\frac{mins}{hour}\right)$$
$$= (1.5535 * VD_{out} + 27.778) * (-0.0013 * {VD_{out}}^2 + 0.0265 * VD_{out} + 0.5783)$$

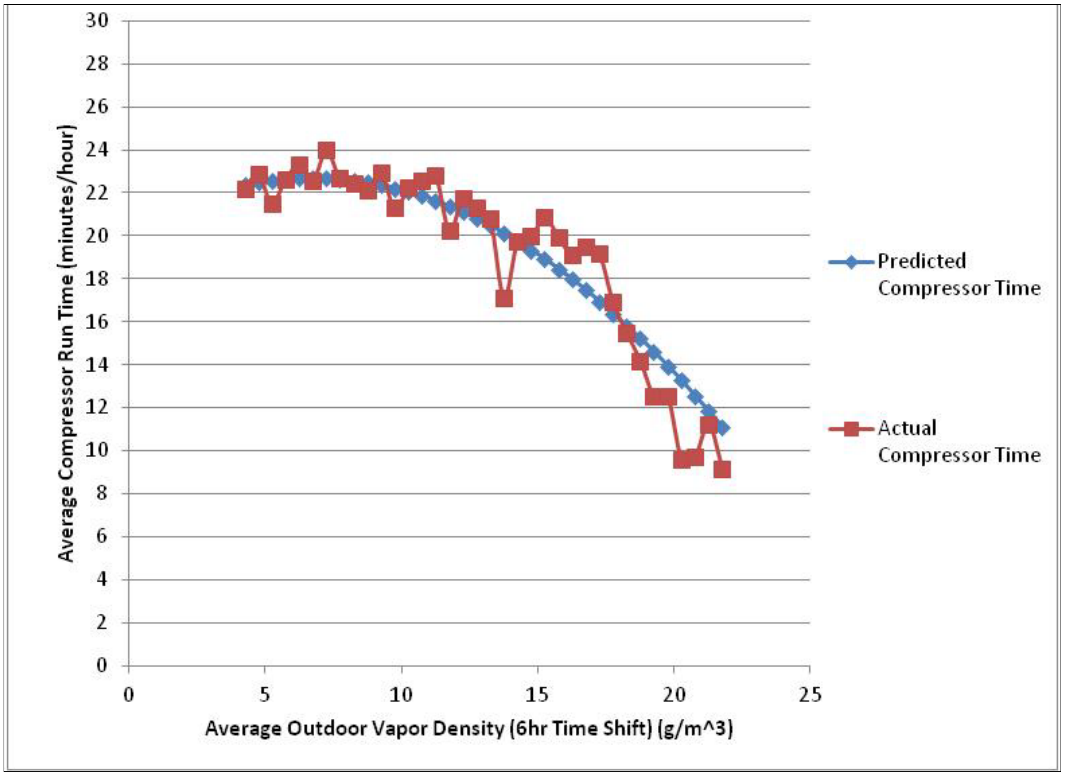

Figure 5-18 Predicted versus Actual Average Compressor Run Time as a Function of Outdoor Vapor Density for Non-Climate Controlled Dehumidifiers with Bucket

Equation for non-climate controlled dehumidifiers with bucket:

$$NCC(B)Compressor\ Run\ Time\ \left(\frac{mins}{hour}\right) = (-0.1186 * VD_{out} + 49.389) * (-0.0011 * VD_{out}{}^{2} + 0.016 * VD_{out} + 0.4091)$$

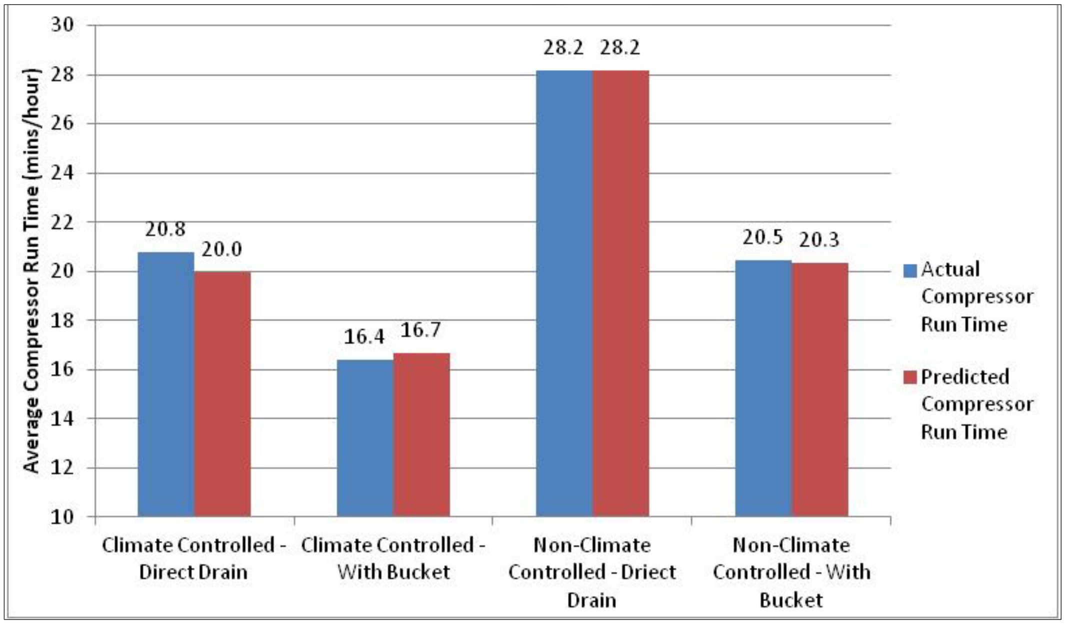

Figure 5-19 Predicted versus Actual Average Compressor Run Time by Dehumidifier Category

We developed another model to predict fan run time as a function of compressor operation.[a] We plotted the average fan-only run time against the average compressor run time for the entire data set. We found that the amount of time that the fan operates is related to the amount of time that the dehumidifier operates in compressor mode. This relationship is illustrated in Figure 5-20.

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[a] The objective was only to find an average usage of fan as a function of compressor time for a large data set. This is not meant to be representative of individual dehumidifier units since the variation of each dehumidifier is large.

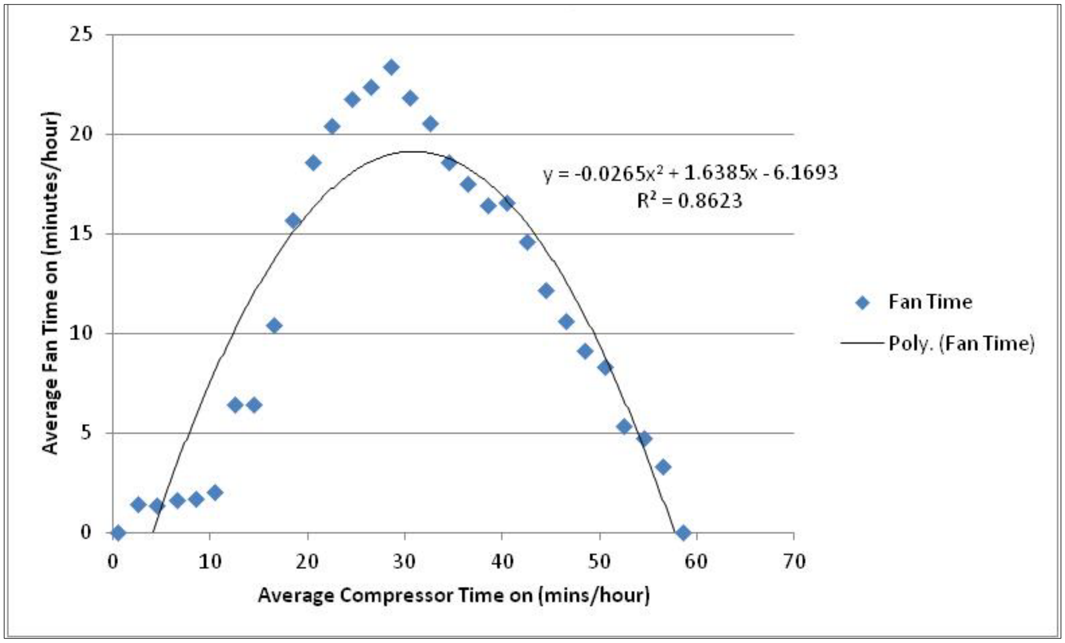

Figure 5-20 Fan Run Time as a Function of Average Compressor Time

After correlating fan-only run time with compressor run time, we determined the percent chance the fan would operate by calculating the number of hours in which the fan-only run time was greater than 0 as a percent of total hours. The result is plotted in Figure 5-21.

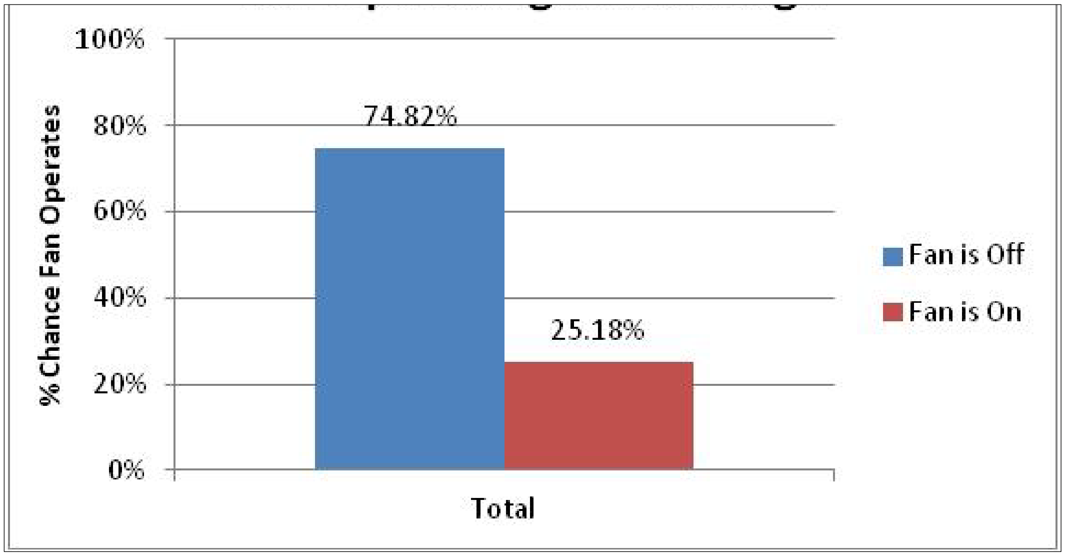

Figure 5-21 Percent Chance an Hour will have More Than 0 Minutes of Fan Mode

The two relationships can be combined in a similar method as the equations for predicting compressor run time. The resulting equation for fan run time is:

$$Fan\ Run\ Time\ \left(\frac{mins}{hour}\right) = \ (.2518) * (-0.0265 * \mathrm{t_{comp}}^2\ +\ 1.6385 * (\mathrm{t_{comp}})\ -\ 6.1693)$$

Where:

$$T_{comp} = Time\ in\ Compressor\ Mode\ (\frac{mins}{hour})$$

The predicted compressor run time (in minutes per hour for each category of climate and method of condensate removal), as calculated above, was used to predict the average fan run time. Predicted versus actual fan run time is shown in Figure 5-22. This result likely would not accurately describe the fan use of an individual dehumidifier, because there can be a large variation in usage among individual installations. Our method describes average fan use as a function of average compressor use for a large population of dehumidifier units.

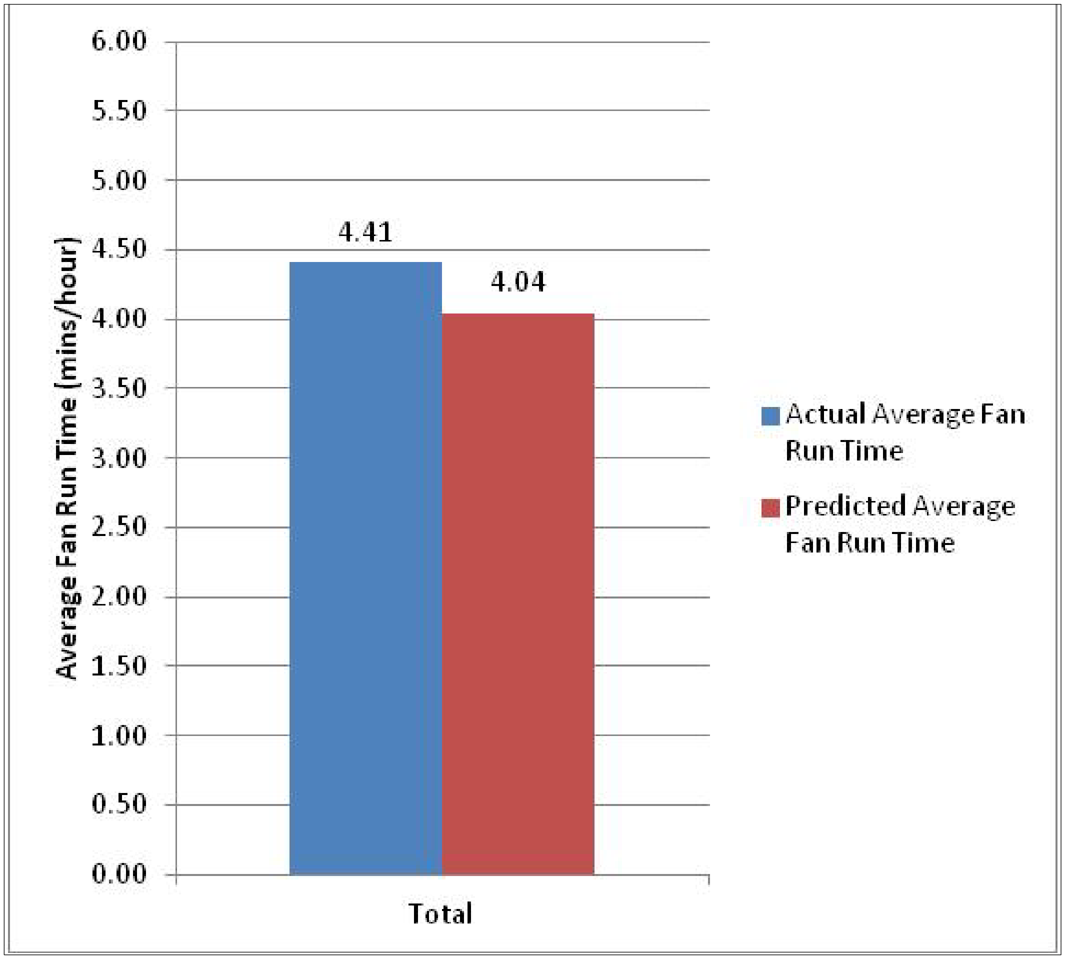

Figure 5-22 Predicted versus Actual Average Fan Run Time

5.5 Estimating Energy Use for RECS Households

Because the objective of the models developed in section 5.4 was to determine the average compressor and fan run times for a population of dehumidifiers, we applied the models to a subset of RECS households that reported dehumidifier use. The outdoor conditions for those households were determined based the NCDC weather data associated with each RECS household.

Having no data to indicate differently, we used the distribution observed in our data to divide dehumidifier-owning RECS households evenly between those having dehumidifiers with a direct drain and those owning dehumidifiers with a bucket. Because RECS data indicate the type of climate control in each household, we could divide the homes into climate controlled and non-climate controlled. We assumed that homes having central air-handling were climate controlled and that the dehumidifiers in those homes were in climate-controlled spaces. RECS provides five categories for the number of months a dehumidifier is in use (plugged in): 1 to 3, 4 to 6, 7 to 9, 10 to 11, and 12 months. Each household was assigned a uniform distribution in the range of months that was indicated for that household.

After assigning each RECS household NCDC weather data, we calculated the average vapor density for each month of the year. The number of months that the dehumidifier was used (as indicated by RECS data) was mapped onto the months having the highest vapor density. The vapor density for each month was used to calculate the average compressor run time as a fraction of an hour (X_{Comp}). From this result we calculated the average fan run time as a fraction of an hour (X_{Fan}). Any period in the RECS data set that was not indicated as involving compressor or fan mode was considered to be standby mode ($X_{Standby}$).

Because we found no relationship between unit capacity and fan or standby power, we assigned the most common values found in our field study: 65 watts (kW_{Fan}) for fan power and 1.0 watt for standby power ($kW_{Standby}$). The distributions for fan and standby power are shown in Figure 5-23 and Figure 5-24, respectively. The power of the compressor mode (kW_{Comp}) was calculated using the rated capacity and rated efficiency. Calculating the compressor power in this manner assumes that the compressor power is the same at all temperatures and relative humidities, which may not be the case. The efficiency and capacity values were measured using a temperature of 80 °F and humidity set point of 60 percent. A single combination of capacity and efficiency (used to calculate kW_{Comp}) was applied to the RECS data set to obtain the average energy use for each capacity and efficiency.

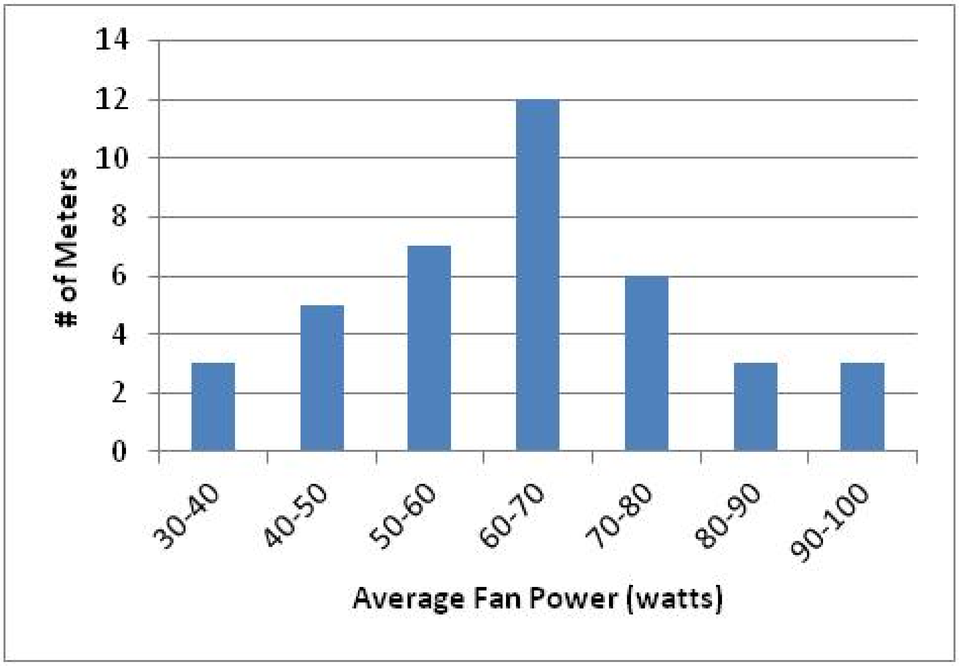

Figure 5-23 Distribution of Fan Power

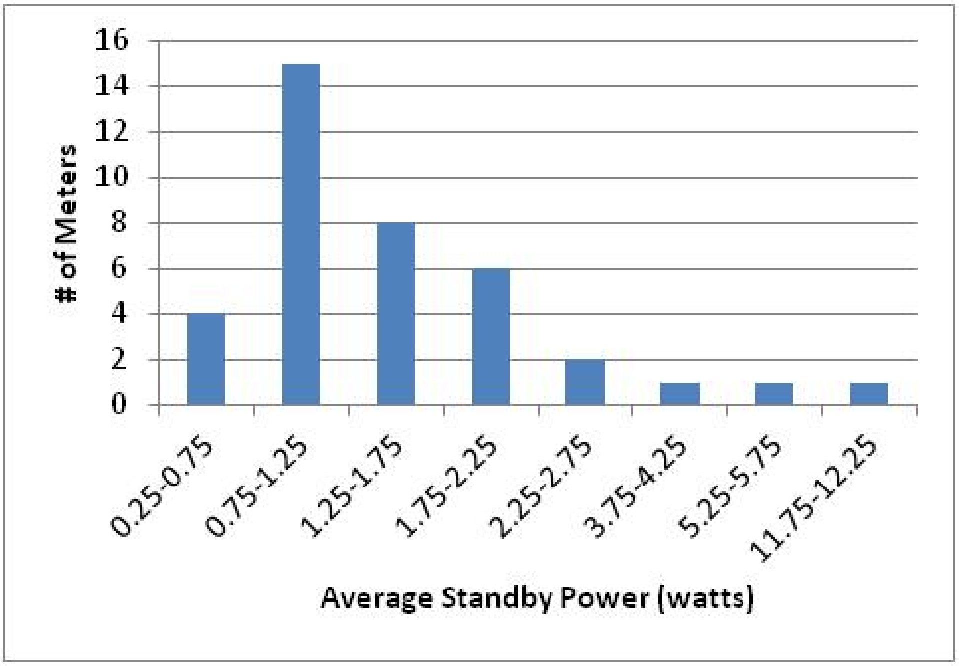

Figure 5-24 Distribution of Standby Power

Using the RECS data set and the methods described above, we derived the data presented in Table 5-1 and Table 5-2. Table 5-1 gives the average time a portable unit dehumidifier in the subset of dehumidifier-using RECS households spent in each operational mode. The results given in Table 5-1 are average hours by dehumidifier category for the subset of RECS households. The predicted average time a dehumidifier compressor is on ranges from 1,078 to 1,785 hours per year depending on the dehumidifier category.

The dehumidifier's operation will vary based on the ambient conditions. So, applying the capacity or EF as determined at 80F and 60% RH may not apply to the range of operating conditions throughout the year.

Table 5-1 Average Time Spent in Each Mode by Dehumidifier Category

Dehumidifier Category	Average Time in Compressor Mode (hours/year)	Average Time in Fan Mode (hours/year)	Average Time in Standby Mode (hours/year)
Climate controlled, with bucket	1,136.0	234.7	2,525.9
Climate controlled, direct drain	1,077.9	203.3	2,615.5
Non-climate controlled, with bucket	1,266.6	249.3	2,040.7
Non-climate controlled, direct drain	1,784.7	277.8	1,494.1

We amended the annual energy use equation described in section 3.1 to account for fan-only and standby modes. The hours of compressor use is replaced by the fraction of time spent in compressor mode and added two additional quantities: fraction of time and power use for fan-only mode and standby mode. After obtaining estimates of average time spent in each mode of dehumidifier operation, we used the following equation to calculate annual energy use for each capacity and efficiency of dehumidifier.

$$\boldsymbol{AEU} = \sum_{i=1}^{12\ months} (Total\ Hours\ of\ Use)_i * \begin{bmatrix} \left(\dfrac{Cap * 0.473 * \left(X_{Comp}\right)_i}{Efficiency * 24} \right) \\ +((X_{Fan})_i * kW_{Fan}) \\ + \left(\left(X_{Standby}\right)_i * kW_{Standby} \right) \end{bmatrix}$$

Where:

$$Efficiency = \frac{Liters\ Removed}{kWhr_{Comp}} = \frac{Cap * 0.473}{kW_{Comp} * 24}$$

$$\frac{Total\ Hours\ of\ Use}{Year} = \#\ of\ hours\ the\ dehumidifier\ is\ used\ per\ year\ (i.e., > 0\ watts)$$

$$Cap = \frac{Pints\ Removed}{Day}$$

$$\begin{cases} X_{Comp}: fraction\ of\ time\ in\ compressor\ mode \\ X_{Fan}: fraction\ of\ time\ in\ fan\text{–}\ only\ mode \\ X_{Standby}: fraction\ of\ time\ in\ standby\ mode \end{cases}$$

$$\begin{cases} kW_{Comp}: kW\ power\ of\ compressor\ mode\ (compressor + fan + standby\ power) \\ kW_{Fan}: kW\ power\ of\ fan\ only\ mode\ (fan + standby\ power) \\ kW_{Standby}: kW\ power\ of\ standby\ mode \end{cases}$$

Note:

$$\frac{Cap * 0.473 * X_{Comp}}{Efficiency * 24} = X_{Comp} * kW_{Comp}$$

Table 5-2 presents the AEU of dehumidifier units by capacity and efficiency. The annual energy use for a medium-capacity unit (45.01 to 54 pints per day) at an efficiency level of 1.60, for example, is estimated to be 773 kWh.

Table 5-2 Annual Energy Use by Capacity and Efficiency

Capacity (pints/day)	Efficiency (L/kWh)	Annual Energy Use (kWh/year)
0–35	1.35	560.10
35.01–45	1.50	668.62
45.01–54	1.60	772.91
54.01–75	1.70	943.93
More than 75.01	2.50	798.85

6 CONCLUSIONS

Data from our field monitoring enabled us to develop relationships between compressor run time and outdoor vapor density (incorporating a 6-hour lag). Further investigation provided insight into the effect differences in location and condensate drainage type have on compressor run time, the primary driver for energy consumption by portable unit dehumidifiers. Disaggregating the data into four categories (based on type of climate control and type of condensate removal) yielded some surprising relationships between outdoor vapor density and dehumidifier compressor run time. Units having buckets operated for less time under conditions of higher vapor density than of lower vapor densities. Assuming that the bucket is emptied at the same frequency regardless of vapor density, the faster the bucket fills up, the less amount of time the compressor will run. Further investigation into consumer habits regarding emptying dehumidifier buckets is warranted.

6.1 Average Energy Use Determined from RECS Data

Average energy use for each dehumidifier capacity and efficiency range can be estimated using data on power consumption and outdoor climate, the RECS data set, and outdoor vapor density matched to the RECS data set. Using the predicted values for compressor use, average compressor run time ranged from 1,000 and 1,800 hours per year. Dehumidifier compressors in non-climate controlled areas typically demonstrated longer run times than those in climate-controlled areas.

6.2 Additional Dehumidifier Field Testing

Our data set ultimately represented 44 meters divided unevenly among four installation categories. Although the data sets were analyzed using a single method, the analysis yielded different results for different types of installations. Additionally, the data (and the usage equations based on those data) reflect approximately three summer months in two regions. A larger-scale metering project could confirm the representativeness of the results presented herein.

Additional field-metering efforts should enrich the data in two ways: by providing a larger sample size of the four installation categories and by metering for a longer duration (ideally, 12 consecutive months). Additionally, metered dehumidifiers should be inspected for level of proper functioning. The metered homes should be representative of the regions of reported dehumidifier use in the RECS data set. Measurements should consist of dehumidifier power consumption, water removal (by liters drained or records of bucket emptying), indoor temperature and humidity, outdoor temperature and humidity, and general dehumidifier installation information. Such a data set would enable comparing the field performance of portable unit dehumidifiers to the capacity and efficiency determined by the published test procedure.

7 ACKNOWLEDGEMENTS

The authors wish to thank the following individuals for their contributions to this study: Deborah Ash, L.B. Desroches, R.H. Galore, Bill Mettler, David Mettler, David Milliken, D.H. Powers, Sarah Price, G.J. Rosenquist, and Alison Williams.

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