Title

Development of Smart Ventilation Control Algorithms for Humidity Control in High-Performance Homes in Humid U.S. Climates:

Authors

Less, Brennan
Ticci, Sara

Publication Date

2016-12-01

ERNEST ORLANDO LAWRENCE
BERKELEY NATIONAL LABORATORY

Development of Smart Ventilation Control Algorithms for Humidity Control in High-Performance Homes in Humid U.S. Climates

Brennan Less, Iain Walker & Sara Ticci
2016

Energy Technologies Area

Disclaimer

Acknowledgements

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

Executive Summary

Past field research and simulation studies have shown that high performance homes experience elevated indoor humidity levels for substantial portions of the year in humid climates. This is largely the result of lower sensible cooling loads, which reduces the moisture removed by the cooling system. These elevated humidity levels lead to concerns about occupant comfort, health and building durability. Use of mechanical ventilation at rates specified in ASHRAE Standard 62.2-2013 are often cited as an additional contributor to humidity problems in these homes. Past research has explored solutions, including supplemental dehumidification, cooling system operational enhancements and ventilation system design (e.g., ERV, supply, exhaust, etc.). This project's goal is to develop and demonstrate (through simulations) smart ventilation strategies that can contribute to humidity control in high performance homes. These strategies must maintain IAQ via equivalence with ASHRAE Standard 62.2-2013. To be acceptable they must not result in excessive energy use. Smart controls will be compared with dehumidifier energy and moisture performance.

This work explores the development and performance of smart algorithms for control of mechanical ventilation systems, with the objective of reducing high humidity in modern high performance residences. Simulations of DOE Zero-Energy Ready homes were performed using the REGCAP simulation tool. Control strategies were developed and tested using the Residential Integrated Ventilation (RIVEC) controller, which tracks pollutant exposure in real-time and controls ventilation to provide an equivalent exposure on an annual basis to homes meeting ASHRAE 62.2-2013. RIVEC is used to increase or decrease the real-time ventilation rate to reduce moisture transport into the home or increase moisture removal. This approach was implemented for no-, one- and two-sensor strategies, paired with a variety of control approaches in six humid climates (Miami, Orlando, Houston, Charleston, Memphis and Baltimore). The control options were compared to a baseline system that supplies outdoor air to a central forced air cooling (and heating) system (CFIS) that is often used in hot humid climates. Simulations were performed with CFIS ventilation systems operating on a 33% duty-cycle, consistent with 62.2-2013. The CFIS outside airflow rates were set to 0%, 50% and 100% of 62.2-2013 requirements to explore effects of ventilation rate on indoor high humidity. These simulations were performed with and without a dehumidifier in the model. Ten control algorithms were developed and tested.

Analysis of outdoor humidity patterns facilitated smart control development. It was found that outdoor humidity varies most strongly seasonally—by month of the year—and that all locations follow the similar pattern of much higher humidity during summer. Daily and hourly variations in outdoor humidity were found to be progressively smaller than the monthly seasonal variation. Patterns in hourly humidity are driven by diurnal daily patterns, so they were predictable but small, and were unlikely to provide much control benefit. Variation in outdoor humidity between days was larger, but unpredictable, except by much more complex climate models. We determined that no-sensor strategies might be able to take advantage of seasonal patterns in humidity, but that real-time smart controls were required to capture variation between days. Sensor-based approaches are also required to respond dynamically to indoor conditions and variations not considered in our analysis. All smart controls face trade-offs between sensor accuracy, cost, complexity and robustness.

Summary and conclusions:

- Baseline simulations with CFIS ventilation systems suggest that supplemental moisture control is required in only a subset of high performance humid climate homes, namely those that are smaller, with higher moisture gains, located in the most humid locations. In these high humidity cases, the fractions of annual hours >60% RH were in the 10-40% range. Periods above 70% RH were limited to between 0 and 5% of annual hours. Extended continuous periods of high humidity were in the 30-60 hour range. Some locations had high indoor humidity all year, whereas others experienced it only during summer months. As found in past research, shoulder seasons had the highest humidity, due to low sensible cooling loads and similar indoor and outdoor absolute humidity. During summer, humidity was sometimes above 60% despite moisture removal by the cooling system (but often by only a few % RH), whereas shoulder seasons experienced excursions into the 70 to 80% range.

- Varying the mechanical ventilation rate between 0, 50 and 100% of ASHRAE 62.2-2013 requirements led to varied changes in high indoor humidity hours. Increasing ventilation either consistently increased high humidity hours, reduced high humidity hours, or reduced hours (from 0 to 50% of 62.2) and then increased hours (from 50 to 100% of 62.2). These effects were strongly dependent on the combination of location, house size and internal moisture gains. While effects on indoor moisture were variable, reductions in the ventilation rate led to predictable IAQ penalties. At the 50% of 62.2-2013 levels, relative exposure and dose were roughly doubled and were increased by a factor of five at the 0% level. As such, we do not consider reducing the ventilation rate as an acceptable (or effective) method for moisture control.

- When correctly sized dehumidifiers with a 55% RH set point were simulated in these same homes indoor moisture was always adequately controlled (maximum fraction >60% RH was roughly 3% of annual hours). Use of dehumidifiers always increased energy use, anywhere from 0 to 1,200 kWh per year. Dehumidifier energy use scaled positively with fractions of annual hours >60% RH in the baseline cases. In addition to the energy used by the dehumidifier, substantial energy use was also attributed to secondary effects on the heating and cooling loads. Use of a dehumidifier worsened the moisture impact of ventilation in general, and it enhanced the negative impacts of increasing the ventilation rate.

- Ten smart ventilation control strategies were evaluated that did not use dehumidifiers. Humidity control was not complete, in that sometimes substantial periods of time remained >60% RH. Yet, smart controls decreased hours of high humidity and shifted the indoor humidity distribution downward, eliminating most of the highest humidity hours, and increasing hours in the range between 55 and 63% RH. All controls maintained equivalence with a continuous 62.2-2013 ventilation fan. While effective, the smart ventilation strategies did not lead to complete moisture control (i.e., no hours >60% RH) as might be expected from a dehumidifier. Estimated energy use for smart controls was roughly equivalent to that used by mechanical supplemental dehumidification strategies. On average, the best performing strategy was able to shift 7.4% of annual hours (648 hours) from above to below the 60% RH threshold with an average energy use increase of 1,983 kWh. These reductions were greater and the energy use smaller in the most humid locations. In the most humid case (small Miami home with high moisture gains), this best strategy reduced 16% of annual hours (1,393 hours) from above to below 60% RH, while using 558 kWh annually.

- Examples of the consistently most effective strategies included the following:

    - **Control 7 – *Fixed sensor + Cooling system tie-in + Variable dose***, the decision to operate the mechanical ventilation was determined by whether the absolute humidity was greater inside or outside, using two sensors. If more humid outside, the ventilation operated whenever cooling was demanded, and the controller otherwise under-vented, targeting a relative dose greater than 1 (in the range of 1.1 to 1.3). If it was more humid inside than outside, then the fan was controlled to over-ventilate, targeting a relative dose less than 1 (in the range of 0.36 to 0.66).
        - This was most effective in the hottest and most humid locations. Substantial heating energy penalties occurred in climates with significant heating demand. In these somewhat colder climates, approaches that limited over-ventilation during winter should be considered.

    - **Control 12 – *Monthly Seasonal + Cooling system tie-in***, the decision to operate the mechanical ventilation and the target ventilation rate were determined by the month of the year. Baseline simulations were used to identify months where on average it was more humid inside than outside, and the controller over-ventilated during those months (and vice versa during periods with more humid outside air). In addition to this seasonal over- and under-ventilation, the control always operated the ventilation system during cooling cycles.
        - This control was substantially more effective than either of the two approaches by themselves (Monthly Seasonal and Cooling tie-in). It used no sensors, but did rely on pre-calculation of months to over- and under-ventilate. As significant over-ventilation occurred during the drier winter, strong energy penalties were incurred in locations with greater heating demand.

- Smart control strategies varied in their complexity, use of sensors, robustness against actual occupant behaviors, etc. Sensor-based approaches appeared to be superior, but their additional cost, complexity, service needs and long-term accuracy/reliability must be considered. The most successful strategies operated the ventilation and cooling systems coincidentally, used indoor and outdoor moisture sensors, and targeted relative dose values that varied (either above or below 1) by direction of the real-time moisture gradient (inside - outside). Schedule-based and one sensor approaches were not effective in this work.

- Energy and moisture performances varied strongly by climate zone and house factors. Climates with substantial heating demand were particularly sensitive to control strategies that over-vented during the drier heating season.

- In many cases, smart ventilation controls offer a lower-energy alternative to mechanical dehumidification, with the understanding that complete control of indoor humidity below 60% RH is not achieved. The highest indoor humidity levels in the 70-80% range can be reduced or eliminated, and indoor humidity distributions are shifted downwards. High humidity hours become more concentrated in the 55 to 63% RH range. But if complete humidity control is required, then the typically higher energy consumption mechanical dehumidification is the appropriate path.

- In cases where complete moisture control is required/preferred, we hypothesized that smart ventilation controls could reduce the dehumidifier load and required energy. Yet, when the ten non-dehumidifier-based control strategies were combined with a dehumidifier, annual energy use always increased and moisture control often improved very marginally (i.e., from 2 to 1% of annual hours >60% RH). Use of smart controls did not reduce energy used for dehumidification, as had been expected. Notably, this work did not assess operation of smart controls with under-sized dehumidifiers that cannot maintain strict RH thresholds, as is commonly found in field-installed units.

- New control strategies were developed that targeted humidity control along with energy savings (via temperature-based controls) when used alongside a dehumidifier, and these were reasonably successful at offsetting some of the energy use of moisture control. The median fraction of dehumidification energy use that was saved by the new smart ventilation controls was 22% (mean values skewed high at 49% due to outliers in Baltimore). The average energy saved by smart controls was 150 kWh annually (from 6 to 360 kWh).

:

Table of Contents

List of Tables

List of Figures

List of Acronyms

ACH_{50}	Air changes per hour at 50 Pascal depressurization, result of a blower door airflow test
AER	Air exchange rate (hr^{-1})
ASHRAE	American society of heating, refrigeration
CFIS	Central Fan Integrated Supply ventilation system
DOE	Department of Energy
FSEC	Florida Solar Energy Center
HRdiff	Indoor minus outdoor humidity ratios
HVAC	Heating, ventilation and air conditioning
IAQ	Indoor air quality
IECC	International Energy Conservation Code
kWh	Kilowatt-hour
REGCAP	Register Capacity, simulation program developed at LBNL for combined heat, mass and airflow modeling
RH	Relative humidity
RIVEC	Residential integrated ventilation controller
SEER	Seasonal energy efficiency ratio
TMY3	Typical meteorological year weather data files

1 Introduction

Elevated indoor humidity levels in homes represent a risk to occupant thermal comfort and health, as well as building durability. The human health effects of elevated indoor humidity and acceptable humidity ranges in buildings have been discussed in detail in comprehensive literature reviews (Arundel, Sterling, Biggin, & Sterling, 1986; Baughman & Arens, 1996). Increases in indoor temperature and humidity have also been associated with poorer perceived indoor air quality (L. Fang, Clausen, & Fanger, 1998). Several recent reviews of the epidemiological literature have reaffirmed consistent positive associations between evident dampness or mold in buildings with allergic and respiratory health effects (Fisk, Lei-Gomez, & Mendell, 2007; Mendell, Mirer, Cheung, Tong, & Douwes, 2011).

1.1 Past Research

High relative humidity levels have been documented in mechanically vented, high performance homes in monitoring studies (Rudd & Henderson, Jr., 2007; Rudd, Listiburek, & Ueno, 2005), as well as predicted in building simulations (Henderson & Rudd, 2010; Lstiburek, Pettit, Rudd, Sherman, & Walker, 2007; Martin, 2014; Walker & Sherman, 2007). In standard (non-high performance) homes, indoor humidity is kept at least partially in-check by operation of the central cooling system and its associated moisture removal. The improved thermal properties of high performance homes leads to less cooling load and less associated moisture removal. While ventilation is often cited as a contributor to higher indoor relative humidity in high performance homes, it is a secondary factor along with home moisture capacitance. Primary factors include varying internal moisture generation rates, sensible gains (as they impact cooling system runtime), thermostat set points and duct location (Henderson & Rudd, 2010; Rudd, 2013a). The impact of ventilation on humidity levels in high performance homes is unclear, because the effects depend on many other factors.

A tabular summary of past field and simulation research in this realm is provided in Table 1. We see that estimates and measurements of humidity in high performance homes are quite variable. Simulations using the REGCAP model, including this research and Lstiburek, Pettit, Rudd, Sherman, & Walker (2007), estimate high annual fractions of hours >60% RH. Other simulations, such as those from the ASHRAE RP-1449 (Rudd, 2013), estimated very low annual fractions of high humidity hours. Field measurements in occupied homes, such as those reported by Rudd & Henderson (2007) and Kerrigan & Norton (2014) are between these extremes, and have consistently found that high performance homes without supplemental dehumidification have approximately 30% of annual hours >60%, and those with dehumidification could be reduced to 15-20% of annual hours, on average. Many factors influence the estimation and measurement of humidity levels in high perfromance homes, and without fixed input parameters, it is very difficult to identify why the predictions/findings are not more consistent. It may be the case that variability in modeled/measured sensible cooling loads and/or internal moisture generation is driving this variability.

Reference	***Description***	***High Humidity (>60% RH) – No Dehumidification***	***High Humidity (>60% RH)– With Dehumidification***	***Energy/Other Notes***
(CDH Energy Group & Building Science Corporation, 2005) & (Rudd & Henderson, 2007)	Long-term field measurements in standard and high performance homes, with different ventilation and dehumidification features. Ducts in conditioned space. Homes built pre-2000.	30% (24-78%)	15% (5-42%)	Hard to interpret cooling runtimes, but when indoor RH >60%, cooling runtimes averaged 53% (17-100%) of hours. High.
(Rudd, Henderson, Bergey, & Shirey, 2013)	TRNSYS Simulations for ASHRAE RP-1449. HERS 50 home, ducts in conditioned space.	Houston: 380 hours (4%) Orlando: 1,011 hours (12%) Miami: 822 hours (9%)	Assumed all hours eliminated	3,250 to 4,400 hours cooling runtime (rough estimate)
(Martin, 2014)	Simulations using Energy Gauge USA and Energy Plus. DOE Challenge homes in humid locations.	9-23%, varied by climate zone		Data not in tabular form, so estimates made based in figures
(Kerrigan & Norton, 2014)	Field measurements. 10 HP new homes in New Orleans built 2008-2011. With and without dehumidification (6 & 4 homes, respectively). Unvented attics, ducts in conditioned space.	BEoptE+ predictions: 1,353 hours (15%); Field measurements: 31% (13-46%)	BEoptE+ predictions: 232-292 hours (3%); Field measurements: 15% (0-29%).	No clear difference in energy use between homes with and without supplemental dehumidification
(Lstiburek et al., 2007)	REGCAP simulations of home performance with varying ventilation system	54-70% of hours	NA	
(Moyer, Chasar, Hoak, & Chandra, 2004)	2-week measurements in high performance, unoccupied test home in Cocoa, FL (simulated occupancy), serial installation of different ventilation/dehumidification systems	Very small, <5% of hours	Dehumidifier provides very small reduction in average indoor RH (49 vs. 47.9% RH) and reduces variability (StdDev 1.2 vs 0.8%)	
(X. Fang, Winkler, & Christensen, 2010)	Simulations. Houston, TX (CZ 2A); 50% source energy savings over Building America benchmark; ducts in conditioned space; 6.7 kg/day moisture gains	3,141 (36%); >70%: 968 (11%)		Dehumidification increased energy use by 731 to 1,342 kWh/yr., depending on system type (7-12% source energy increases).

Table 1 Comparison of measured and simulated humidity in high performance and humid climate homes.

Simulation efforts and field studies have described and assessed the costs and effectiveness of strategies to reduce indoor humidity levels in high performance, humid climate homes (Kerrigan & Norton, 2014; Moyer et al., 2004; Rudd, 2013b; Rudd & Henderson, Jr., 2007; Rudd et al., 2005; Withers & Sonne, 2014). The main goal of these efforts was to reduce the number of hours above 60% RH to an unspecified, "acceptable" level. Strategies have included:

- Dehumidifiers, including stand-alone and integrated with ventilation and central HVAC systems;
- Energy recovery ventilators;
- Enhanced cooling strategies (e.g., reduced airflow per ton, sub-cooling of space and sub-cooling plus reheat).

These strategies have had mixed effectiveness in terms of humidity control and highly variable installation costs, ranging between $400 and $2,000 (Rudd, 2013b). Supplemental humidity control increases energy use approximately 170 kWh per year[1] (Rudd, 2013b), with estimated increases in annual utility bills ranging from $10-$58[2] (Martin, 2014). This stands in contrast to past field research in conventional homes, which suggests that dehumidifiers in homes use between 300 and 2,000 kWh annually, averaging 1,000 to 1,200 kWh per year (Mattison & Korn, 2012; Whitehead et al., 2013). This field research was not done on dehumidifiers used to maintain conditions in high performance homes and humidity set points varied between 35 and 65% RH (average of 50%). The effectiveness of ERVs has been only modestly better than normally ventilated high performance homes (Martin, 2014; Rudd & Henderson, Jr., 2007; Rudd et al., 2005), and their capital and installation costs on average are approximately $1,300 (National Efficiency Measures Database). Enhanced cooling strategies have been effective in simulations, but the sub-cooling of the indoor space by 2-3°F may present unacceptable comfort issues for many occupants (Rudd & Henderson, Jr., 2007). The sub-cooling plus reheat solution eliminates this comfort problem and has estimated costs of $1,600 to $1,750 (Rudd, 2013b). Enhanced cooling strategies also had the highest first costs (~$1,700) of any humidity control strategy assessed by Rudd et al. (2005), but this may have been relative to a reference case that lacked a high performance HVAC unit, and may not be relevant when such a unit was going to be installed anyways. Estimates of the installed costs of dehumidifiers vary from $150 for stand-alone units located in closets with louvered doors, to $1,500 for whole-house ducted units (Kerrigan & Norton, 2014). Other proposed solutions, such as two-speed or variable speed cooling systems, have not proven effective in simulation assessments (Rudd, 2013b).

As supplemental dehumidification is the most common strategy, we address this realm further. The energy required for supplemental dehumidification varies widely, both in simulations and field research, and it depends strongly on the level of humidity in the home and the humidity set point used. X. Fang et al (2010) estimated the energy use of supplemental dehumidification in a high performance home (50% source energy savings), and they found that dehumidifiers with 60% RH set points used between 731 and 1,635 kWh per year, depending on the technology used. This is consistent with measurements of dehumidifier energy use in conventional U.S. homes, which average 1,000 to 1,200 kWh (and range from 300 to 2,000 kWh) (Mattison & Korn, 2012; Whitehead et al., 2013). Kerrigan & Norton (2014) detail energy and indoor environment measurements made in high performance homes in New Orleans, with and without dehumidifiers. They found that dehumidifiers used between 160 and 1,180 kWh annually ($15 to $129). Simulations by Martin (2014) suggested that between $10 and $58 are required annually

---

[1] This assumes a 60% RH set point. A 50% set point increases this energy use approximately 5-fold.

[2] This assumes a stand-alone dehumidifier with an Energy Factor of 1.47 L/kWh. Recent field data suggest that dehumidifiers operate at approximately half this efficiency (0.8 L/kWh) (Mattison & Korn, 2012).

for supplemental dehumidification in DOE Challenge Homes, which at $0.11 per kWh means between 100 and 530 kWh annually with a 60% RH set point. Rudd (2013b) used simulations to estimate that dehumidifiers in a HERS 50 home will use 170 kWh annually with a 60% RH set point, and five times as much for a 50% RH set point.

It is also worth discussing the installed effectiveness of residential dehumidifiers at controlling high humidity hours in high performance homes. When dehumidifiers have been analyzed in simulation efforts they are assumed (or controlled) to eliminate all hours of high indoor humidity. Some have dealt with dehumidification in a post-processing fashion (Martin, 2014), and others have integrated dehumidifier models into their simulations directly (X. Fang et al., 2010; Rudd et al., 2013). Yet, when measured in field studies, installed dehumidifiers have been shown to *reduce but not eliminate* hours of high humidity (CDH Energy Group & Building Science Corporation, 2005; Kerrigan & Norton, 2014).

To illustrate this, independent analysis by LBNL of tabular data provided in CDH Energy Group & Building Science Corporation (2005) is presented in Figure 1 showing fractions of the year >60% in occupied high performance homes with and without supplemental dehumidification. This figure illustrates how use of supplemental dehumidification cuts median high humidity hours in half, from 30% to 15% of annual hours. Data from Kerrigan & Norton (2014) show the same result in a sample of 10 high performance homes, with supplemental dehumidification reducing high humidity hours from 31% to 15% of annual hours.

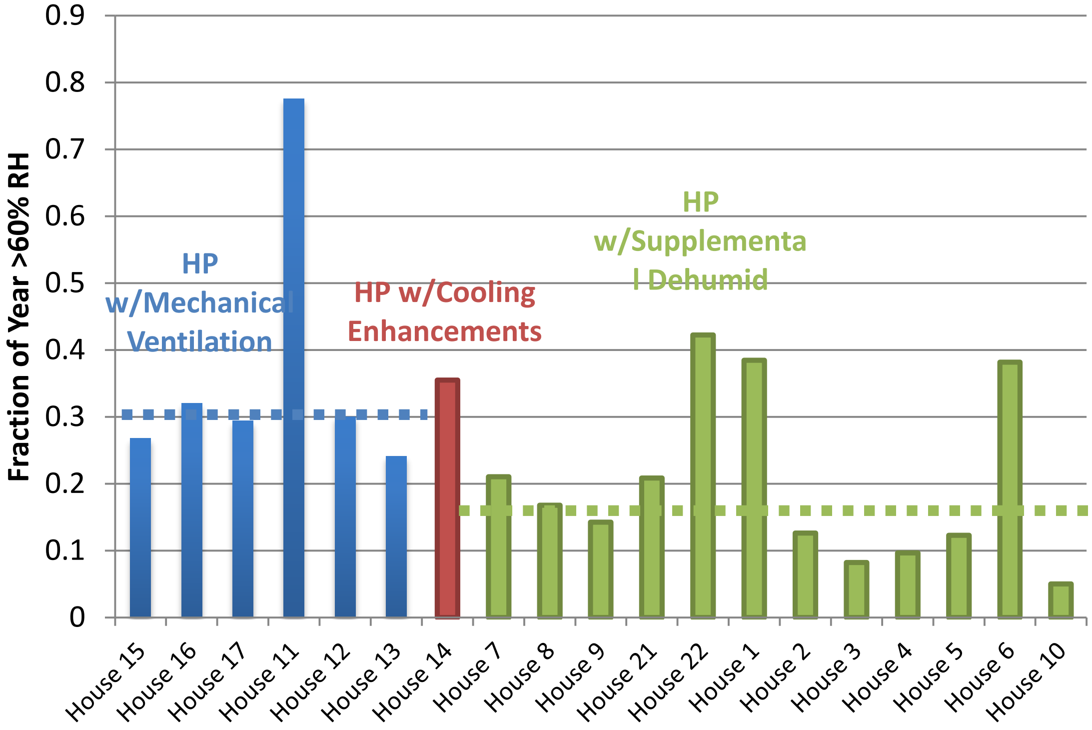

Figure 1 Summary of field measurements in high performance (HP) homes in hot-humid climates, with mechanical ventilation, and with/without supplemental dehumidification. Independent LBNL analysis of data provided in CDH Energy Group & Building Science Corporation (2005). Annual high humidity periods presented by group.

1.2 Smart Ventilation Control

A strategy that has not been assessed to-date is the smart control of ventilation systems to time-shift ventilation to reduce the humidity loads when the outside air is humid and to enhance humidity removal when outdoor air is dryer than indoors. Such systems would be designed to reduce the number of hours of high indoor humidity, while maintaining acceptable IAQ. Acceptable IAQ is defined as providing annual pollutant exposure equivalent to a continuously operated ventilation fan sized to ASHRAE Standard 62.2-2013. Smart ventilation strategies have been previously applied to energy conservation and peak demand reduction using time-based controls as well as sensors for other ventilation fans (Max H. Sherman & Walker, 2011), and based on indoor/outdoor temperatures (Less, Walker, & Tang, 2014). The same principles will be applied in this study for humidity control.

Smart controls can contribute to lower indoor humidity levels in three primary ways:

(1) Direct removal of moisture at its source through local exhaust fans (i.e., kitchen, bathroom and laundry exhaust);
(2) Strategic changes in air exchange rate that will increase net-moisture transfer from inside to outside, based on the indoor-outdoor humidity differential;
(3) Use of the ventilation system to advantageously increase the sensible cooling load and the associated moisture removal of cooling system operation.

Some existing technologies exist as parts of standard practice in high performance homes to address the operation of local exhaust. Automated fan controls are common in bathrooms, and when associated with a sufficiently high airflow, moisture removal at the source can be effective. Moisture sources in the kitchen are not dealt with as effectively. Both cooking activities and dishwashing generate water vapor, which if not removed from the home, contribute to the internal moisture load. Robust automatic controls do not exist for the control of kitchen ventilation systems, and kitchen exhaust installation and usage is relatively low across the population (Klug, Lobscheid, & Singer, 2011; Mullen et al., 2014; Price, Sherman, Lee, & Piazza, 2007), and is no better in high performance homes (Less, 2012). While not part of the scope of this research, the installation, commissioning and usage of kitchen exhaust fans in high performance homes is a key opportunity for reductions in moisture loading.

The other three ways represent opportunities to control whole house mechanical ventilation systems for reduction of indoor humidity. Controls can be based on *ventilation scheduling*, as informed by patterns in outdoor humidity (based on weather data files) and patterns in high-humidity events simulated or measured in homes. Careful scheduling of ventilation could both increase net-moisture transport from inside to outside, as well as to increase sensible cooling load and system run time. These schedule-based controls would represent both the lowest-cost and least-robust option, but they might provide substantial and adequate benefit. The more costly and robust option would be to control ventilation based on *measured humidity levels*, either outdoor only or preferably indoor and outdoor. While more costly, this approach would ensure that variations in weather from year-to-year were accounted for, as well as variations in individual homes, including variable thermostat set points, internal gains, occupant density and activities, etc. Notably, robust and accurate humidity sensors are not currently in-use in homes, and their reliability over a time period of 15-20 years (lifetime of ventilation system) is questionable.

This project’s goal is to develop and demonstrate (through simulations) smart ventilation strategies that can contribute to humidity control in high performance homes. These strategies must maintain IAQ via equivalence with ASHRAE Standard 62.2-2013. To be acceptable they must not result in excessive energy use.

2 Control algorithm development

2.1 Patterns in Typical Weather Data

In order to understand the potential for smart ventilation strategies to mitigate moisture issues in high performance homes, it is first essential to understand patterns in outdoor humidity. Useful patterns occur by month over the course of the year, and by hour over the course of a day. These are discussed below in the context of smart ventilation controls that maintain equivalence with a continuous fan sized to ASHRAE 62.2-2013.

We selected six representative climate locations for detailed analysis in this work, with the intention of including sites throughout humid climates in the U.S., including hot- and mixed-humid locations. Locations and their relevant climatic design conditions are summarized in Table 2. We began by selecting the representative cities for moist climate zones 1A, 2A, 3A and 4A—Miami, FL, Houston, TX, Memphis, TN and Baltimore, MD, respectively. Two additional locations were added, because they were subjects of analyses in the reviewed moisture control literature—Orlando, FL and Charleston, SC.

City, State	***IECC Zone***	***TMY3 ID***	***Heating Degree Days / Cooling Degree Days (base 18.3°C)***[a]	***1% Dehumidification Design Conditions (Dew Point Temperature (°C) / Humidity Ratio (kg/kg) / Mean Coincident Dry-Bulb Temp (°C))***[a]
Miami, FL	1A	722020	70 / 2521	25.3 / 0.0205 / 28.5
Orlando, FL	2A	722050	359 / 1841	24.0 / 0.0189 / 27.6
Houston, TX	2A	722430	762 / 1699	25.2 / 0.0204 / 28.0
Charleston, SC	3A	722080	1044 / 1309	25.4 / 0.0206 / 28.6
Memphis, TN	3A	723340	1610 / 1252	24.3 / 0.0195 / 29.4
Baltimore, MD	4A	724060	2529 / 701	23.4 / 0.0183 / 27.1

[a] Climatic data were retrieved from the ASHRAE Handbook of Fundamentals 2013 SI Edition, Chapter 14 (ASHRAE, 2013).

Table 2 Simulation city and state locations, associated TMY3 IDs and relevant climatic design data.

Analysis is presented below for humidity ratio or absolute humidity (*w,* kg/kg), which is the ratio of the mass of water vapor to the mass of dry air. This value does not change with temperature, as is the case for relative humidity. For a fixed absolute humidity value, increasing temperature lowers the relative humidity, and decreasing temperature increases the relative humidity, until reaching saturation (i.e., 100% RH).

2.1.1 TMY3 Weather Data Seasonal Decomposition

We assessed patterns in outdoor absolute humidity by performing seasonal decomposition on TMY3 data, breaking the variability down into three components: the monthly, the daily and the hourly trend cycles. An example decomposition is pictured in Figure 2 for the Houston, TX outdoor humidity ratio data. The top plot shows the hourly outdoor humidity ratio time-series. Below that are monthly averages of the outdoor humidity ratio, which are then subtracted from the hourly time series to produce the monthly detrended data in the third plot. Daily averages are pictured in the fourth plot, which are then subtracted from the monthly detrended data to produce daily detrended values in the fifth plot. This final plot effectively shows hourly outdoor data, detrended by the monthly and daily averages. Seasonal decomposition plots are provided for all climate zones considered in the Appendix in Figure 39 through Figure 44.

It is during periods with the highest variability in outdoor humidity that smart controls will most be able to reduce indoor humidity levels. When variability is low, then the timing of when ventilation occurs is expected to have little effect on moisture transport. Accordingly, we assessed the variability in monthly, daily and hourly values using interquartile ranges. These reflect the extent of the variation around the median value for each assessed time period. As pictured in Figure 3, the variability in outdoor humidity decreases going from monthly, to daily and hourly periods.

As pictured in Figure 4, the monthly variation in outdoor humidity is fairly predictable and consistent across locations, with higher values of outdoor humidity during summer months and lower values during the rest of the year. Variation in outdoor absolute humidity is relatively high between days, but daily patterns are not predictable and therefore cannot be used for schedule-based controls. This is because they are not driven by diurnal or annual seasonal patterns. Rather they are controlled by variable weather patterns, which can be predicted by much more advanced weather models, but are not suitable for scheduled control. For example, we cannot easily create timer-based controller that over-vents on certain days or under-vents on others, because we cannot predict which days fall into which categories. Control strategies that take advantage of daily humidity variability would have to be sensor-based. It is notable that the variation in outdoor humidity from day-to-day is much lower during the summer months (see Figure 2), than it is during other periods of the year. This means that even real-time sensor-based controls are unlikely to be effective at reducing indoor moisture levels during these times of year. Or framed differently, timer-based controls may be nearly as effective during these periods as sensor-based controls. The hourly patterns are diurnally driven and therefore more predictable, but variation within hours of a day is small, so the value of hourly control is limited. From these considerations, control based on the month of the year is simple, practical and will have the most benefit in controlling indoor humidity.

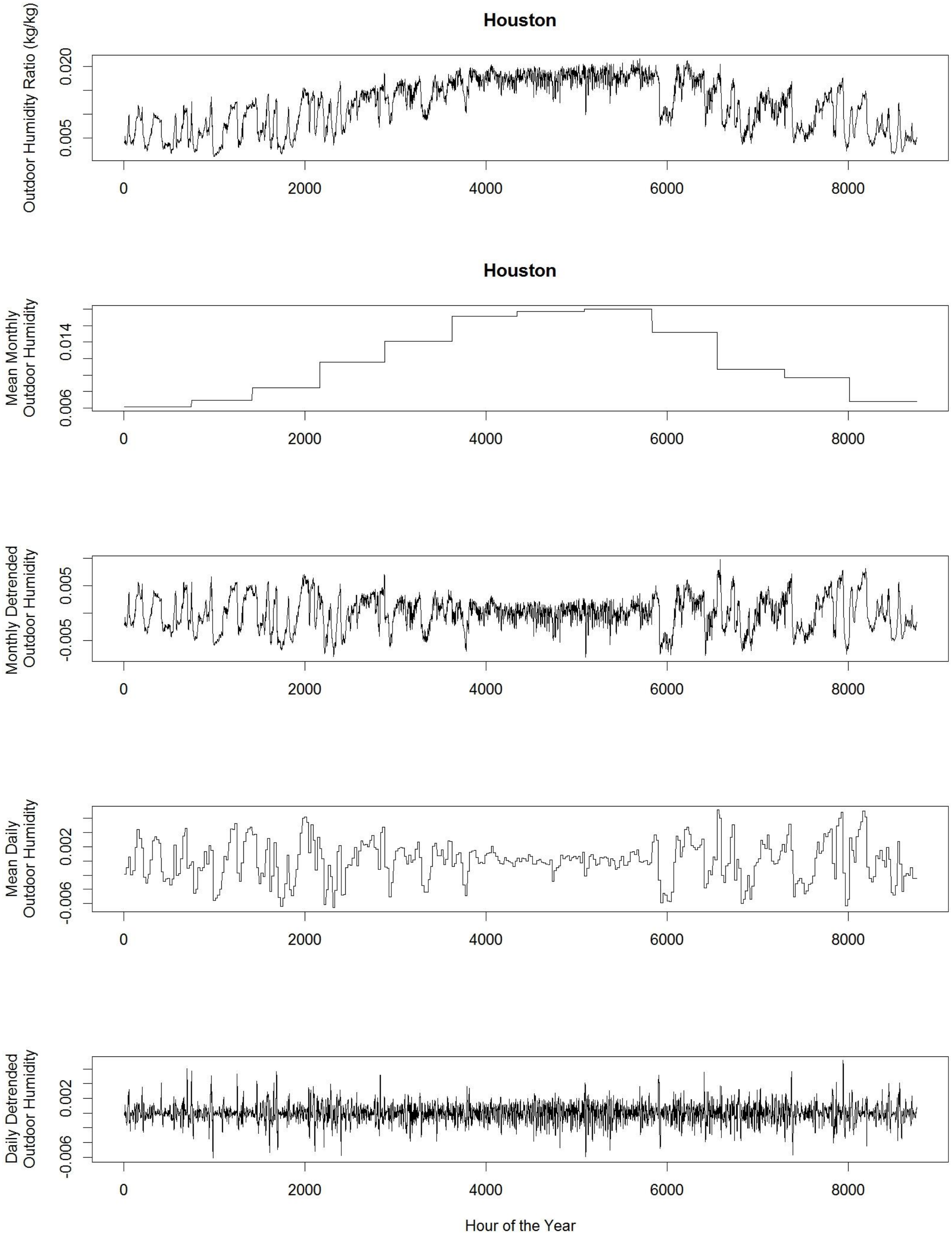

Figure 2 Time series decomposition of hourly outdoor humidity ratio in Houston, TX.

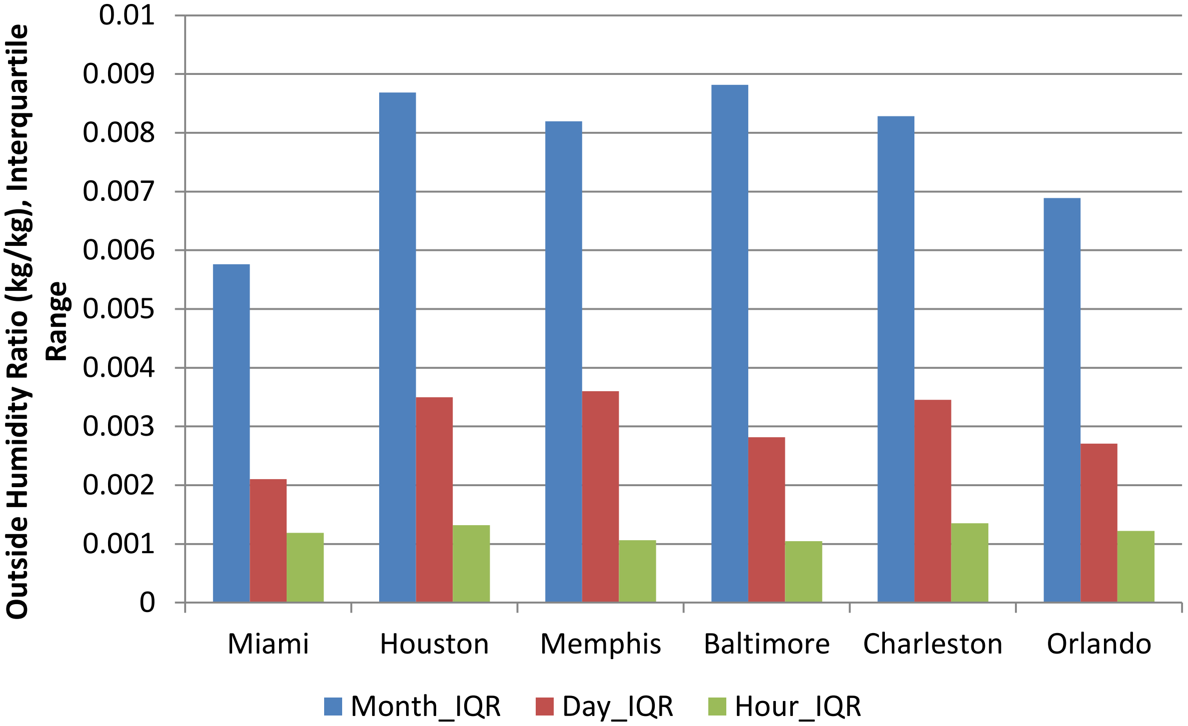

Figure 3: Interquartile ranges of outdoor humidity in select hot-humid cities based on monthly, daily and hourly decomposed trends.

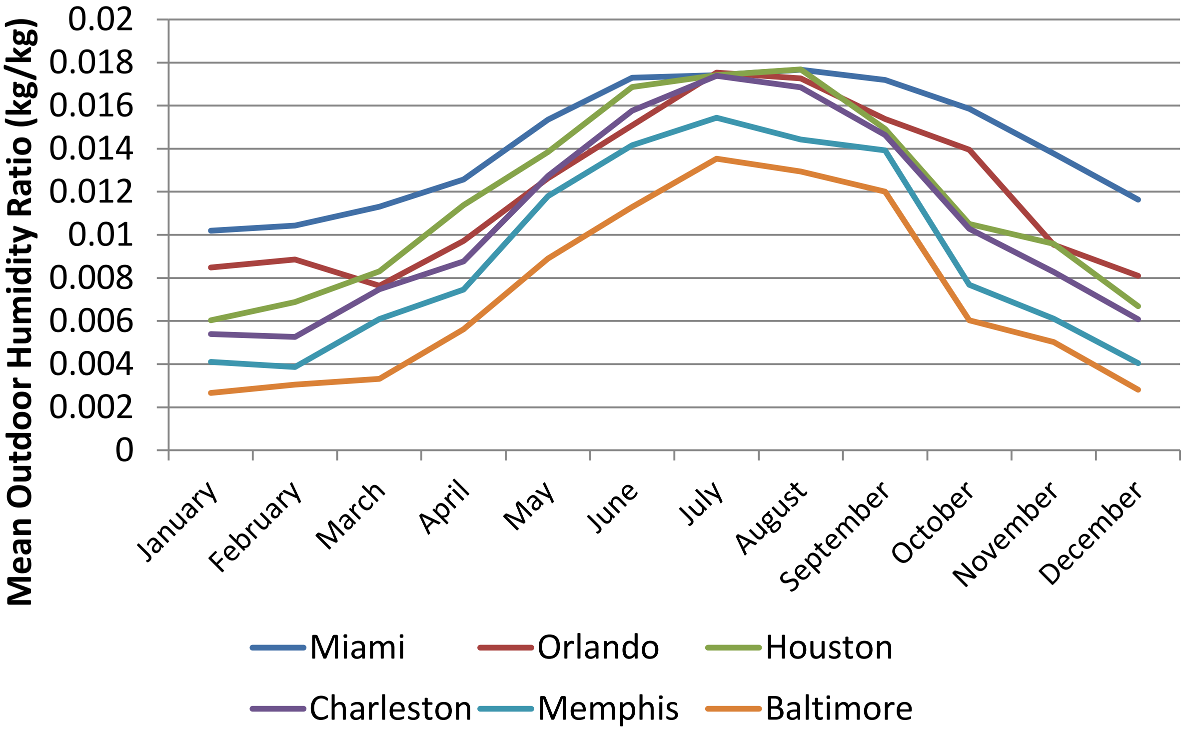

Figure 4 Monthly mean outdoor absolute humidity in select hot-humid cities, summer months are consistently higher in absolute outdoor humidity.

The hourly signal in Figure 2 (lower most plot) appears similar to white noise (i.e., random), which would make it a poor signal to use for ventilation control. Nevertheless, we calculated daily hourly profiles for periods before, during and after the summer, as determined by the monthly seasonal control. An example is provided in Figure 5 for the summer season, where we do in fact see hourly patterns within the average summer day. We observe a consistent pattern across climate zones, with a dip in outdoor humidity as sunrise approaches, with increasing humidity during the morning and a subsequent dip in the afternoon. This pattern is roughly consistent in the other seasons, as well, when averaged across climate zones (pictured in Figure 6). While these patterns pattern could be used for schedule-based controls, it is important to note that the variation relative to the daily average humidity (represented by the zero on the y-axis) is small. For example, in Orlando the maximum and minimum in the summer profile are 0.00074 and -0.00050 kg/kg, respectively. This means that for a fictional day with average outdoor humidity of 0.015 kg/kg, the variation within the day is from 0.01574 to 0.01450 kg/kg. This represents a very weak signal for humidity control. In essence, the humidity within any given day can be treated as constant. So, if time-of-day schedule controls are to be used, it will be based on factors other than the outdoor humidity, such as targeting increased sensible cooling load.

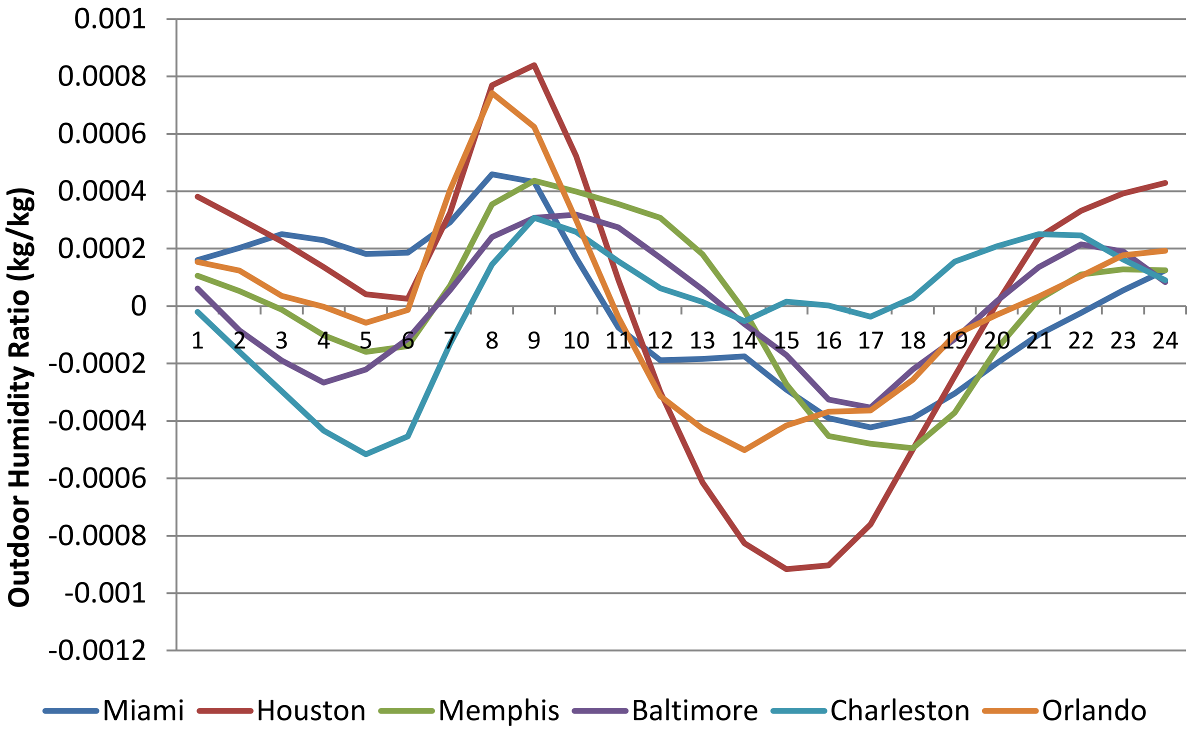

Figure 5 Detrended hourly profiles of outdoor humidity ratio, for summer months.

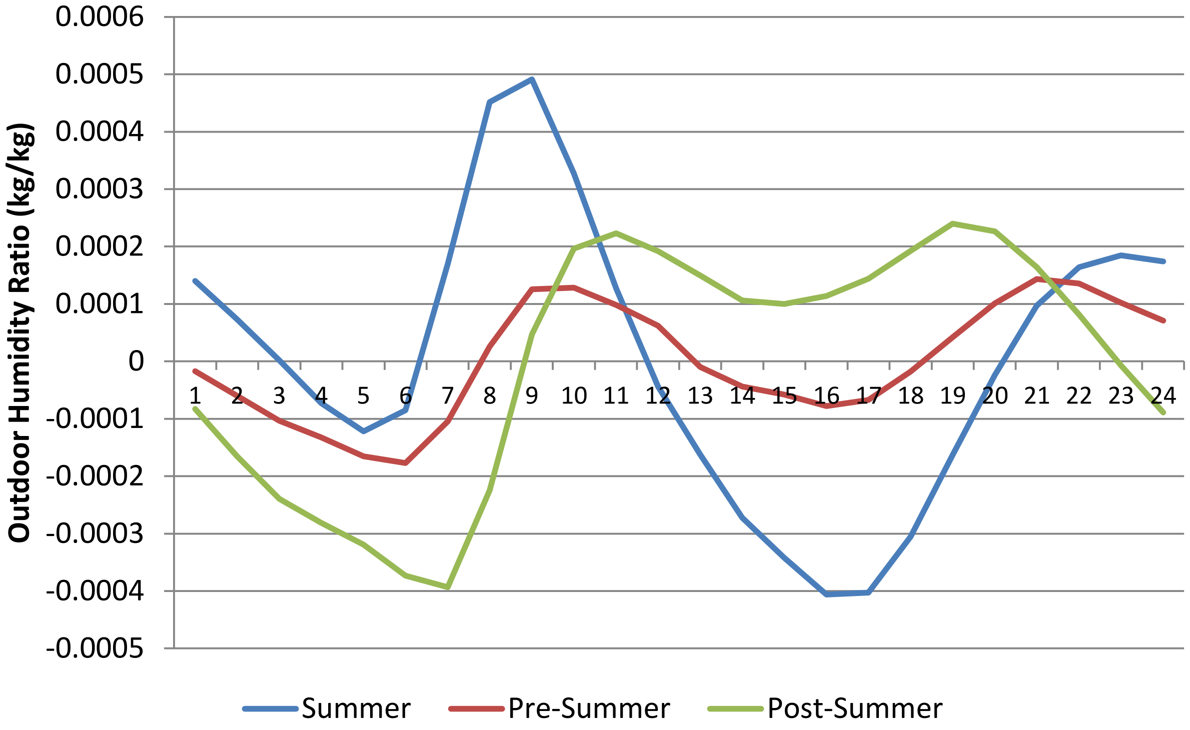

Figure 6 Detrended hourly profiles of outdoor humidity ratio, average of al climate zones. Pre-summer, summer and post-summer trends.

2.1.2 Dew point depression

In addition to considering the outdoor absolute humidity, the dew point depression is a useful indicator of the dehumidification potential of outside air in a mechanically cooled space. The dew point depression is the outdoor dry bulb temperature minus the outdoor dew point temperature, and larger values are reflective of a greater ratio of sensible-to-latent load. When air is brought into a home with a large dew point depression, operation of the air conditioning for the sensible load can result in more moisture being removed than there is moisture being brought into the home by ventilation. Therefore a design parameter that may be used in the future to replace humidity difference between indoor and outdoor air is the difference between the Sensible Heat Ratio (SHR)[3] of the air being brought in and the equipment being used to condition the air. Smart ventilation based on dew point depression assumes that ventilation is used to compel dehumidification by a central cooling system. This strategy will increase energy use relative to a continuous fan, as it is explicitly designed to force greater HVAC runtime.

The median dew point depression for each hour of the day is pictured in Figure 7 below for a variety of locations. While dew point depression is on average larger in dryer climates and smaller in humid climates, the peak time of day is roughly consistent across all locations (approximately noon to 6pm). Additional patterns useful for smart ventilation controls do not appear in comparisons by month. This gives clear and consistent direction for smart ventilation control based on dew point depression.

---

[3] Or Latent Heat Ratio (LHR).

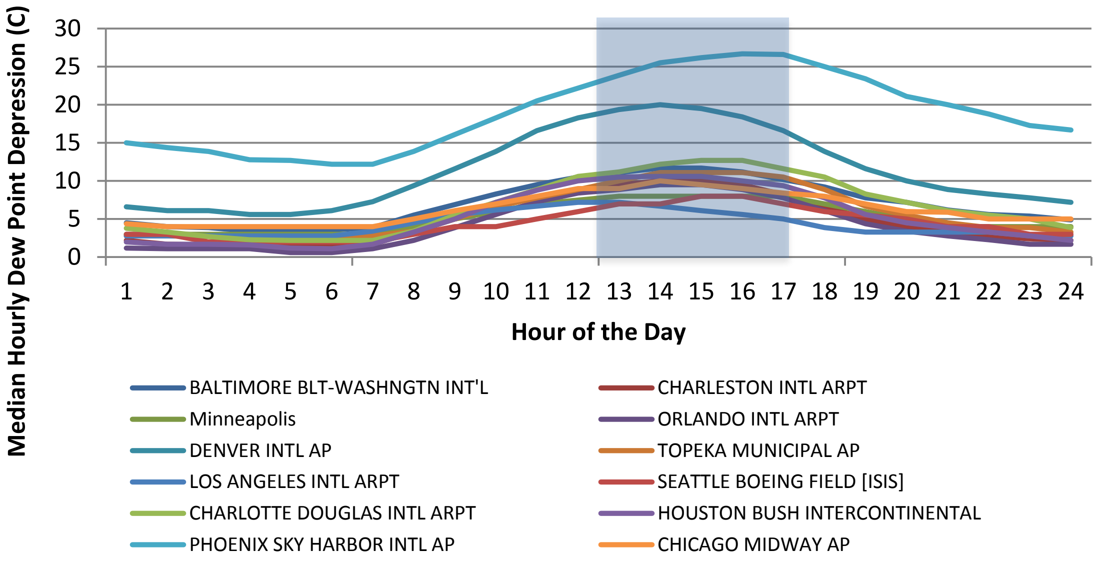

Figure 7 Hourly profiles of the median dew point depression in varying climate zones. The peak is quite consistent across climates, with the hours of 12pm to 6pm having the largest values, indicative of greater dehumidification potential in mechanically cooled spaces.

2.2 Assessments of humidity in high performance homes

In the context of these patterns in outdoor humidity, it is now useful to examine efforts that have assessed the humidity risks in high performance homes. Elevated indoor humidity in high performance homes was first demonstrated through measurements in Texas and Florida homes between 2001 and 2007 (Rudd & Henderson, Jr., 2007). These were further explored in detailed simulation efforts performed as part of the ASHRAE research project 1449 (Rudd et al., 2013) and by the Florida Solar Energy Center and IBACOS (Martin, 2014). Excellent summaries of these past efforts are provided in the publication resulting from the Building America expert meeting on humidity control in high performance homes (Rudd, 2013a), as well as in an assessment for the state of Florida Building Commission (Withers & Sonne, 2014). Key findings relevant to smart ventilation control are summarized below, as are novel analyses based upon simulation outputs from the FSEC/IBACOS effort.

The Florida Solar Energy Center (FSEC) and IBACOS performed simulations using Energy Gauge USA in order to assess the impacts of mechanical ventilation on humidity levels in high performance homes (Martin, 2014). The results below are a novel analysis performed by LBNL of the hourly output files from a subset of the prototypes assessed by FSEC. These results reflect only 1-story cases, oriented north, with simple exhaust ventilation systems.

2.2.1 Impact of mechanical ventilation rates

As outdoor humidity varies substantially throughout the year, there are likely periods when ventilation provides a net-humidity benefit, and times when it is a net-liability. This is consistent with monitoring in occupied homes in IECC climate zone 2 showing a substantial vapor pressure drive from outside to inside from April through October (Arena, Karagiozis, & Mantha, 2010), and the reverse in other months.

Our analysis of simulations performed by FSEC using full sized (62.2-2013 Q_{fan}) and undersized fans (50% of 62.2-2013) is illuminating in terms of the months of the year when ventilation increases or decreases indoor humidity. The indoor humidity ratios were compared for each hour of the year between the 100% airflow rate and the 50% airflow rate simulations. The ratio of the indoor humidity ratios for the two flow rates was calculated and averaged for each month and location (see Table 3). In months with average ratios greater than 1 (red), the 100% flow rate led to increased indoor humidity levels relative to the lower 50% flow, and in months with ratios less than 1 (green and yellow), the 100% flow rate decreased indoor humidity levels relative to the lower 50% flow.

Many have concluded that increased ventilation rates in humid climate homes lead to moisture problems, namely unacceptably high indoor relative humidity. Yet Table 3 suggests that a higher ventilation rate often provides a net-humidity benefit. Many occurrences of hours above 60% are attributed to increased ventilation rates, because annual analysis periods suggest that more occurrences occur at higher airflows. But what the results in Table 3 suggest is that for hours >60% RH occurring in "green" months, too little ventilation may be to blame, not too much. We next look at hours predicted to exceed 60% RH in the FSEC simulations. This is illustrated in Figure 8 for a 1.5 ACH_{50} Houston, TX home, where the blue bars indicate the monthly count of hours with indoor humidity >60%, and the red line plots the ratio values from Table 3. Several things are notable in this plot. First, 65% of hours with indoor humidity >60% were during months where the higher ventilation rate provided a net-benefit. Second, peak months (April and November) occurred when the ventilation rate had no net-effect (i.e., values from Table 3 are very close to 1). This aligns with the typical shoulder season effect, where the highest humidity is during months with elevated outdoor humidity but negligible sensible cooling load. Others have similarly found that the highest indoor humidity occurs during shoulder seasons in humid climate homes (Arena et al., 2010; Trowbridge, Ball, Peterson, Hunn, & Grasso, 1994). The 65% number is deceivingly high, because the two shoulder season peak months had ratio values of ~0.99. If these two months are removed from the category of providing net-humidity benefit, then the 65% number becomes 29%. So, in this Houston home, 35% of hours >60% occurred when ventilation was a net-penalty, 35% when ventilation made no net-impact, and 29% occurred when ventilation provided net-benefit. It is important to remember that increasing or decreasing the ventilation based on values in Table 3 may or may not reduce the indoor humidity to below 60%, but we do expect indoor humidity to be reduced by some amount.

Annual summaries of this type of analysis are provided in Figure 9 for each of the climate zones considered in the FSEC simulation analysis. These values only represent the 1.5 ACH_{50} homes. On average, across all climate zones, 60% of annual hours >60% RH occurred in months when ventilation provided a net-penalty, and 40% occurred during months where ventilation provided a net-benefit. This information suggests that smart control of the ventilation rate may be able to provide some humidity benefit indoors, by changing the ventilation rate for each month of the year.

Month	Houston	Orlando	Phoenix	Charlotte	Charleston	Los Angeles	Kansas City	Baltimore	Seattle	Chicago	Denver	Minneapolis
January	0.88	0.89	0.78	0.83	0.83	0.87	0.85	0.82	0.83	0.77	0.81	0.80
February	0.86	0.92	0.87	0.83	0.82	0.86	0.79	0.81	0.80	0.74	0.79	0.80
March	0.90	0.97	0.86	0.84	0.89	0.84	0.84	0.80	0.79	0.80	0.76	0.81
April	0.99	1.04	0.78	0.89	0.95	0.89	0.86	0.84	0.84	0.86	0.83	0.86
May	1.11	1.11	0.89	1.04	1.06	0.95	0.99	0.96	0.90	0.91	0.91	0.94
June	1.15	1.15	0.95	1.12	1.14	1.03	1.13	1.09	0.96	1.04	1.00	1.02
July	1.15	1.16	1.04	1.15	1.15	1.05	1.15	1.13	1.02	1.12	1.04	1.13
August	1.15	1.16	1.04	1.16	1.15	1.07	1.15	1.13	1.05	1.11	1.03	1.11
September	1.13	1.15	1.01	1.12	1.14	1.07	1.06	1.10	0.99	1.05	0.93	1.00
October	1.05	1.11	0.98	0.99	1.05	1.00	0.91	0.88	0.85	0.85	0.87	0.85
November	1.00	1.07	0.89	0.85	0.94	0.90	0.79	0.84	0.81	0.78	0.77	0.79
December	0.85	0.97	0.81	0.81	0.81	0.85	0.80	0.78	0.80	0.73	0.77	0.78
Average	***1.02***	***1.06***	***0.91***	***0.97***	***1.00***	***0.95***	***0.94***	***0.93***	***0.89***	***0.90***	***0.88***	***0.91***

Table 3 Monthly average ratios of indoor absolute humidity in DOE Challenge Home prototypes with ventilation fans sized at 100% and 50% of ASHRAE 62.2-2013. Values greater than 1 indicate that the 100% flow rate led to higher indoor humidity, and values less than 1 indicate that the 100% flow rate led to reduced indoor humidity.

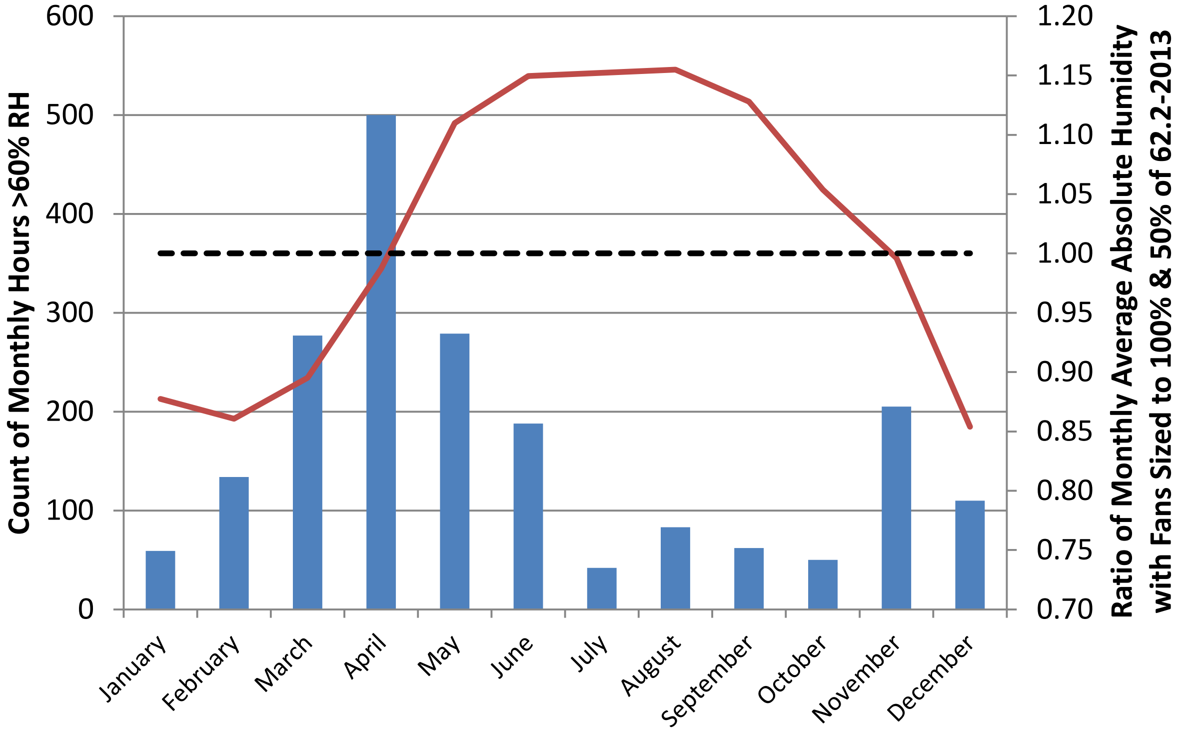

Figure 8 Monthly plot of hours exceeding 60% RH (blue bars) and ratios of indoor absolute humidity with ventilation fans sized to 100% and 50% of 62.2-2013 (solid red line). Houston, TX 1.5 ACH_{50} home.

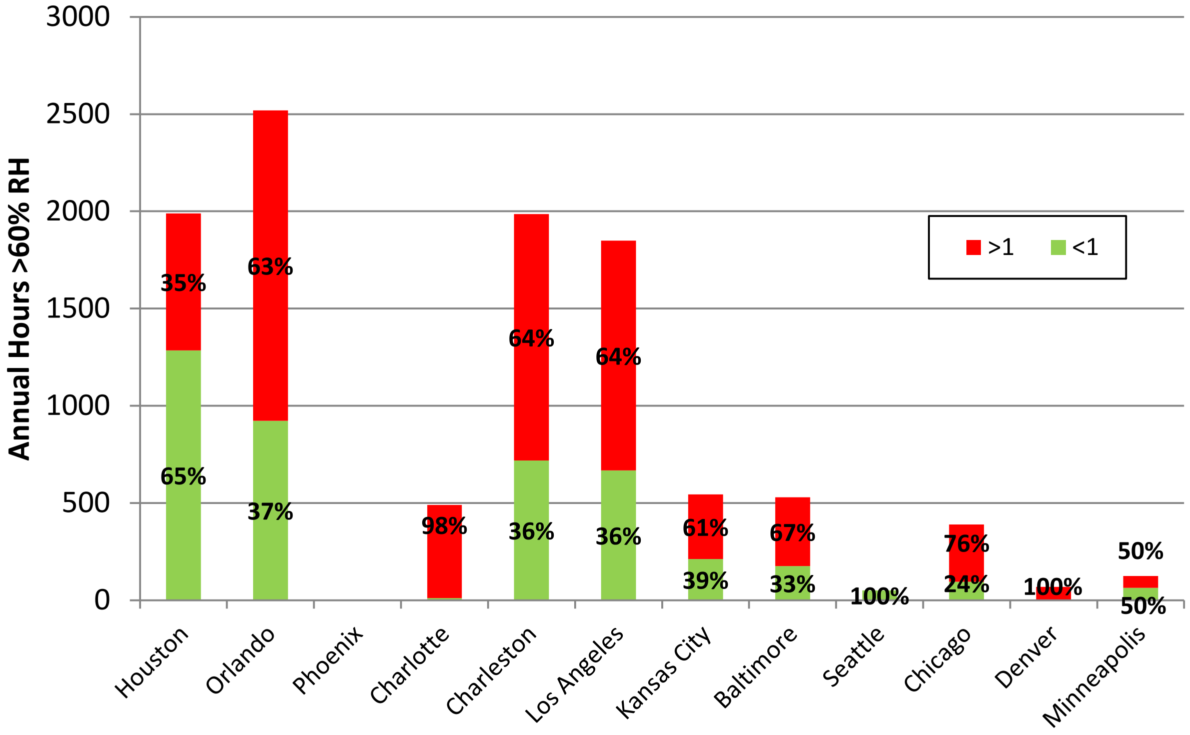

Figure 9 Proportion of annual hours with indoor humidity exceeding 60% RH, attributed to time periods where ventilation was providing a net-benefit (ratios <1, green) or a net-penalty (ratios >1, red). Data from FSEC simulations of 1.5 ACH_{50} home (Martin, 2014).

2.2.2 High humidity and cooling system operation

Simulation and field measurements have demonstrated that the majority of hours of high indoor relative humidity occur when the central cooling system is not operating due to negligible sensible cooling loads, whether this is at nighttime or during shoulder seasons. For example, FSEC simulations demonstrated that in the climate zones with the most hours of high humidity (Charleston, Houston, Orlando and Los Angeles), hours with high indoor humidity were most frequent during “floating” periods with no HVAC operation (heating or cooling) (Martin, 2014). Others have reported similar associations between HVAC operation and indoor humidity levels (Arena et al., 2010; Lstiburek et al., 2007; Rudd et al., 2013). Yet, it is notable that in all climate zones with hours of elevated humidity, hours above 60% RH still occurred during cooling system operation. For example, in Orlando, hours above 60% RH were equally likely to occur during floating and cooling hours. This suggests that the humidity removal associated with cooling operation was not always sufficient to control indoor humidity, even in hours when the system was running. Arena et al (2010) separated homes with and without moisture problems and showed that for hot humid climates, homes with problems were more humid in winter/shoulder seasons and less humid in the summer.

2.2.3 Seasonal and monthly variation in simulated humidity problems

There are three types of humidity problems based on the time of year they occur—yearlong, summer-only and no problem locations. Table 4 indicates the climate zones in which the Challenge Home prototypes simulated by Martin (2014) exhibited these seasonal indoor humidity problems, and it also briefly summarizes the patterns observed in these cases. These different humidity problem patterns may be best addressed using different smart ventilation strategies.

Time of year	Locations	Notes
Yearlong	Charleston Houston Los Angeles Orlando	Peak problem time is generally April-June, but highly variable
Summer-only	Baltimore Charlotte Kansas City Chicago Minneapolis	Issues begin in May (June for Chicago) and extend through September/October
None	Phoenix Denver Seattle	NA

Table 4 Summary of humidity problem types and their locations.

2.2.4 Hourly, time-of-day variation in simulated humidity problems

In the FSEC Challenge Home simulations, the highest number of hours exceeding 60% relative humidity occurred in the early morning hours, between approximately 4am and 12pm (see Figure 10). This is consistent with reports from the ASHRAE RP-1449. This pattern remains consistent when assessed as an hourly profile for each month, as well. This is most likely due to a lack of sensible load during these hours, both with little activity indoors, no solar gain and cooler nighttime temperatures. Accordingly, the number of hours above 60% RH in each climate zone peaks during approximately the same period (except Los Angeles). It is not clear whether the ventilation rate has anything to do with these high humidity instances in early morning hours, rather no cooling demand exists. It may be beneficial to either increase or decrease the ventilation rate during these periods, depending on the balance between indoor and outdoor humidity.

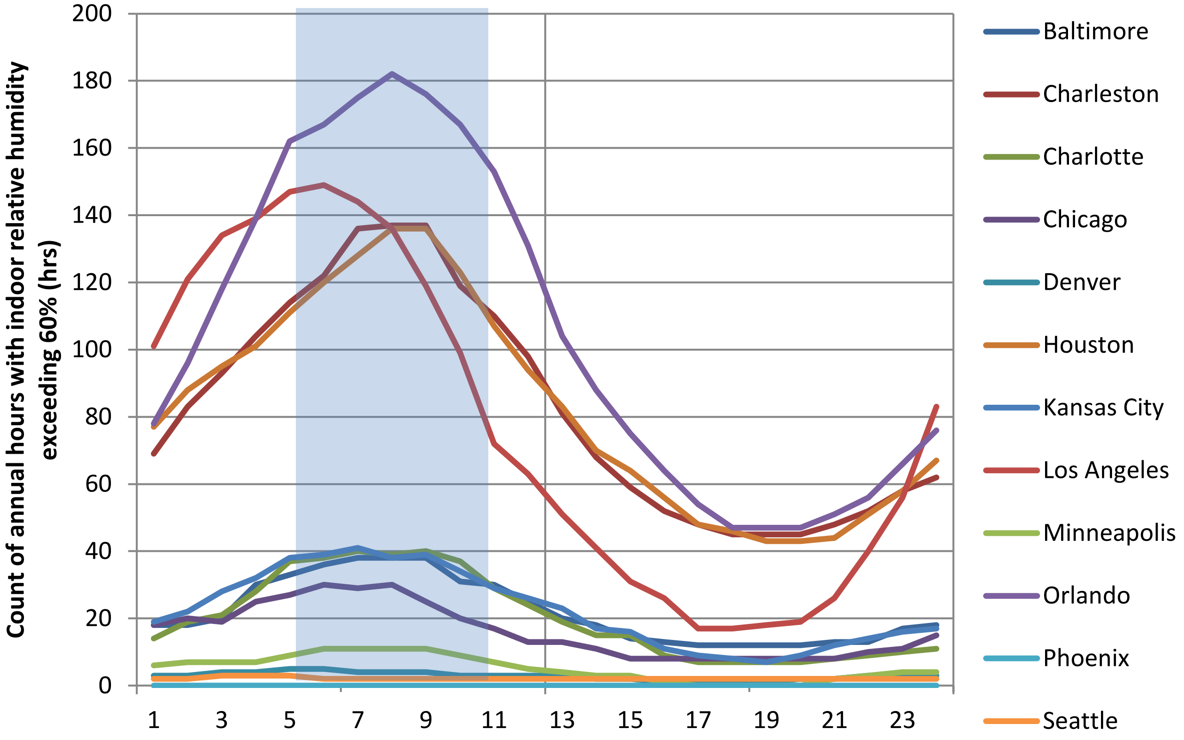

Figure 10 Hourly count of annual hours with indoor relative humidity exceeding 60% in a prototype 1.5 ACH_{50} DOE Challenge Home with simple exhaust ventilation.

2.3 Humidity Control Metrics

We start from the position that humidity thresholds or durations that objectively provide an "acceptable" indoor environment are highly unclear, as they relate to human health, occupant comfort and building durability. This makes performance metrics based on simple indoor humidity thresholds potentially unstable and of questionable value. As a result, it is difficult to assess the performance of humidity control strategies.

As noted in this document's introduction, the most common metric used in the research literature on moisture control in residences is hours with indoor relative humidity exceeding 60%. This is based on the common framing of indoor humidity as acceptable between 30 and 60% RH, due to combined effects on human comfort, indoor biological growth and occupant health (Arundel et al., 1986; Baughman & Arens, 1996). At best, the 60% value is a rough trade-off between various factors. Baughman & Arens (1996) noted that with one exception (dust mites), all known biological health agents of concern in the indoor environment grow on the surfaces of the building, its systems and furnishings/finishes. As a result, their growth is only indirectly related to measured temperature and moisture conditions in the air volume. Control of indoor micro-environmental conditions may actually be the crucial part, for example temperature/moisture conditions at windows, near thermal bridges or in carpeting. Furthermore, much of the work documenting the linkages between condensation and biological growth at ambient room RH >60% were from cold climates, where the microenvironments would be much, much colder than expected in the humid locations in the Southeastern U.S. As such, there might in fact be very little risk whatsoever associated with room conditions at or above 60% RH in high performance homes in the humid Southeast. Nevertheless, designers need to have a simple metric to target, which can actually be measured and assessed; thus the recommended range of 30% to 60% RH in the ASHRAE Standard 62-1989.

The U.S. DOE Building America *Expert Meeting: Recommended Approaches to Humidity Control in High Performance Homes* (Rudd, 2013a) brought together experts and stakeholders across the industry to address questions about humidity control performance metrics in light of recent research efforts. Specifically, the expert meeting addressed:

1. If targeting indoor humidity below 60% in high performance homes was generally agreed upon and why?
2. If the count of hours exceeding 60% RH was the best metric for assessing supplemental moisture control strategies, and if hourly counts provided similar results to counting events of 4- or 8-hour duration?

Rudd (2013a) reported that the experts meeting decided that hours exceeding 60% RH was the best metric. They suggested that while failure was not imminent at 60%, the threshold provided reasonable certainty in ensuring comfort and durability across a variety of other factors, including internal moisture gains and occupant preferences. A humidity control set point of 55% was recommended to avoid excursions above 60%. They also agreed that a simple count of high humidity hours gave essentially the same results as counts of 4- and 8-hour high humidity events, because high humidity hours tended to be clumped together, rather than occurring sporadically. These findings were specifically supported by analyses from field data (Rudd & Henderson, 2007) and simulations (Rudd et al., 2013).

We have several concerns and criticisms of this approach:

1. Humidity control strategies often do not eliminate all hours above 60% RH, so comparison of different approaches is not straightforward, unless they are all forced to achieve zero hours. This is not possible in real-world residences.
2. The risks associated with elevated indoor humidity likely vary with the magnitude and duration of high humidity events, as well as with factors specific to the home and its occupants. For example, indoor RH between 60 and 70% for extended periods is likely less damaging than a shorter duration event >80%. Unfortunately, no clear-cut methods are available for determining the time- and magnitude-dependent effects of indoor humidity levels. In building envelope assembly assessments, ASHRAE Standard 160-2009 is used (ASHRAE, 2009), and its primary metric is that 30-day running average surface relative humidity should be below 80% when surface temperatures are between 5 and 40°C. Clearly, the likelihood of exceeding this ASHRAE 160 metric increases as the house air volume humidity increases. Yet, it is possible to design building envelopes that will not have moisture problems under indoor conditions at or above 60% RH. In fact, high performance homes may in some cases specifically be designed in ways that limit the potential damage caused by elevated humidity (e.g., through use of continuous exterior insulation, which warms the susceptible wood sheathing).
3. Shifts in the indoor humidity distribution are not reflected in a single threshold metric. In cases where indoor humidity is substantially elevated, control strategies may remove substantial moisture mass, but may not achieve indoor RH below 60%. For example, a home in Miami FL during the springtime could have indoor RH above 70 or 80%. Surely there is substantial value in lowering this level to 65%, but the currently proposed metrics would not credit this shift.

As it currently stands, a strategy may be effective and get no credit (e.g., reducing high indoor humidity, but to a level above the 60% threshold), or a strategy might fully address a “problem” that does not truly exist (e.g., indoor humidity elevated slightly above 60%, but not reaching levels of real concern).

Given the uncertainty of using any single metric for controlling indoor humidity to an acceptable level in homes, we assess a variety of metrics in this work, including *counts of hours* and *duration of the longest continuous high humidity events*. We assess these metrics for RH thresholds of *60%* and *70%*. We also provide histogram plots of the annual indoor humidity distribution, which reflects changes in indoor humidity across all moisture levels, not just changes above or below a threshold value. Our metrics are not necessarily superior in terms of assessing indoor humidity control, but they provide a broader picture of changes in indoor humidity distribution.

2.3.1 Annual Humidity Index

In this work, we have developed and explored another metric called the *Annual Humidity Index.* This index can be thought of as *effective saturation hours*, as it is expressed in units of hours and is a summation of weighted average values calculated at each time-step with linear weights from 0 to 1 between 60% and saturation at 100% RH (see weighting factors in Figure 11). This is done in addition to reporting of the threshold values of 60 and 70% RH. This index provides a single quantitative measure to incorporate the distribution of all hours exceeding some RH threshold. Changes in this metric reflect shifts in the humidity distribution, rather than simply movement above and below an RH threshold. This approach gives more weight to hours with higher humidity. It also limits the credit given to shifting hours that were just barely above 60% to below 60%, an effect that we expect to have little to no real impact. The low weighting applied at the lower end of the 60-100% spectrum would limit the effect of the specific threshold chosen (55 vs. 60 vs. 65%), and it would credit downward shifts in the distribution that do not actually bring indoor RH below the threshold, such as shifting hours from 80 to 65% RH.

The index value was calculated for each minute of the year using Equation 1, and the Annual Humidity Index was calculated using Equation 2. We do not present this metric as the primary humidity control metric in this paper, but it is included as an alternative, which we think avoids many of the notable limitations of the currently popular threshold metrics. Future work might develop this metric (or others) for broader use.

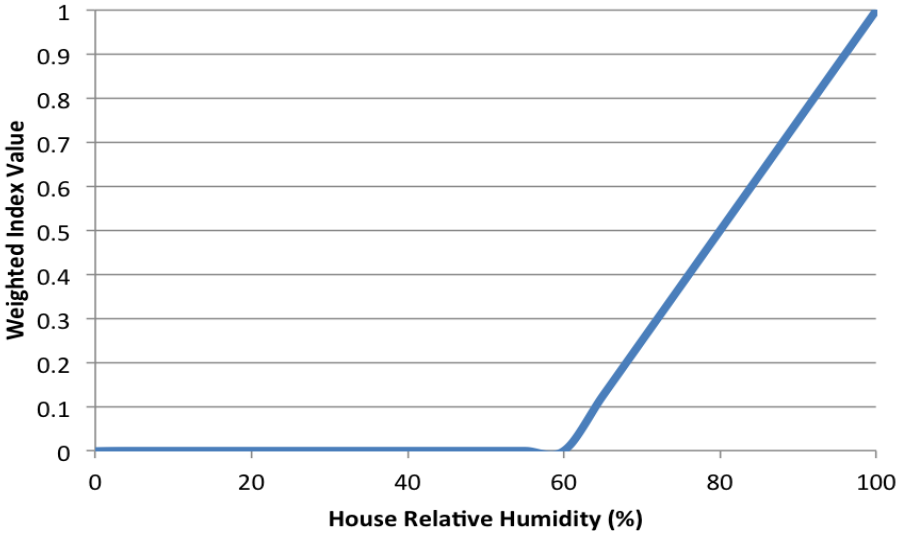

Figure 11 Linear weighting for an improved humidity control metric that gives credit for shifts in the indoor humidity distribution, rather than just the change in hours exceeding a fixed RH threshold.

$$Index_{weighted}[i] = \frac{(RH_{house}[i]-60)}{(100-60)}$$

$Index_{weighted}[i]$= Weighted index value for timestep *i*, scaled from 0 to 1 between 60 and 100% RH
$RH_{house}[i]$ = House relative humidity at timestep *i*, %

Equation 1 Weighted index calculation for new indoor humidity metric.

$$AnnualHumidityIndex = 8760 \times \frac{\sum_{i=1}^{525600} Index_{weighted}[i]}{525600}$$

AnnualHumidityIndex = Index value representing effective hours at saturation, hours

Equation 2 Calculation of Annual Humidity Index.

This may not be the most desirable or final metric to be used in all humidity assessments. Possibly the threshold for calculating the index should be 55% or 65%, though the low weights in this spectrum limit the impact of threshold selection. Furthermore, it is not obvious that the weighting factors should be linear in the 60 to 100% RH range. Possibly an exponential curve would better approximate the increased risk at higher humidity. Nevertheless, we believe the approach outlined above provides substantial value beyond the current metrics.

2.4 Use of Dose and Exposure in Real-Time Ventilation Controls

The derivation and use of the calculation methods for ventilation equivalence are presented in detail in (Max H. Sherman & Walker, 2011). In that paper, the authors describe how dynamic changes in the ventilation rate can be expressed relative to a target steady-state ventilation rate, such that exposure to pollutants can be controlled to be equivalent between the dynamic and the steady-state case. The calculations used in the REGCAP simulations are presented briefly below for turnover (see Equation 3), relative exposure (see Equation 4) and relative dose (see Equation 5). The target steady-state ventilation rate (A_{eq}) is the total ventilation rate (Q_{tot}) required by ASHRAE 62.2-2013. In the turnover calculation, the air exchange rate assumed by the controller is the sum of the mechanical ventilation airflows (62.2-

2013 fan, bathroom exhausts, dryer and kitchen) and the annual estimated infiltration rate from ASHRAE 62.2-2013 (Q_{inf}). This simplification reflects the fact that any real world controller is not going to know the real-time infiltration rate of the home, and the simple addition assumption of mechanical and natural ventilation airflows reflects current calculations in 62.2-2013, but simple addition does not reflect the fact that combined, unbalanced air flows are always sub-additive.

$$\tau_i = \frac{1 - e^{-A_i \Delta t}}{A_i} + \tau_{i-1} e^{-A_i \Delta t}$$

τ_i = Turnover at time-step *i*
τ_{i-1} = Turnover at the previous time-step, *i-1*
A_i = Air exchange rate at time-step *I,* hr^{-1}
Δt = RIVEC time-step, 1/60 hours

Equation 3 Turnover equation used in equivalence calculations.

$$e_i = A_{eq} * \tau_i$$

e_i = Relative exposure at time-step i
Aeq = Target steady-state ventilation rate, hr^{-1}
τ_i = Turnover at time-step *i*

Equation 4 Relative exposure equation used in equivalence calculations.

$$d_i = A_{eq} \tau_i \left(1 - e^{-\Delta t/24\text{hours}}\right) + d_{i-1} e^{-\Delta t/24\text{hours}}$$

d_i = Relative dose at time-step i
A_{eq} = Target steady-state ventilation rate, hr^{-1}
τ_i = Turnover at time-step *i*
Δt = RIVEC time-step, 1/60 hours

Equation 5 Relative dose equation used in equivalence calculations.

Both relative exposure and relative dose are calculated for each minute of the year in the REGCAP simulations. The exposure represents the instantaneous comparison between the continuous fan and the control case. The relative dose is roughly equivalent to the average relative exposure over a running 24-hour period. Accordingly, relative exposure changes rapidly with real-time changes in the ventilation rate, and the relative dose value changes much more slowly.

We use the relative exposure and relative dose values calculated by the RIVEC controller in real-time to control the ventilation system. Effectively, these values indicate either over- or under-ventilation (<1 or >1), relative to the continuous fan case (dose or exposure equal to 1). Changes in the exposure and dose values are roughly inversely proportional to changes in the air exchange rate. Some example calculations are presented across a range of dose and exposure values in Table 5 with a target air exchange rate (A_{eq}) of 0.35 hr^{-1} at dose equal to 1. For example, a dose value of 0.5 effectively doubles the air exchange rate

(1/0.5), which in the example case changes the AER from 0.35 to 0.7 hr^{-1}. Similarly, a dose value of 1.5 effectively reduces the air exchange rate by 33% (1/1.5), shifting the AER from 0.35 down to 0.23 hr^{-1}.

It is notable that equal changes in exposure or dose above and below one do not have equal effects on the air exchange rate. This is illustrated in the examples above. Shifting the dose by 0.5 either doubles the ventilation rate or reduces it by only 33%. This is relevant in the annual balancing of the relative dose in order to achieve equivalence (annual dose < 1). For any period of time with reduced ventilation (dose >1), an offset period with over-ventilation is required (dose <1), and in terms of the annual air exchange, the over-ventilation periods will be strongly dominant. This is particularly relevant in climates with substantial heating demand, where over-venting during typically drier outside periods, leads to increased heating energy consumption.

In smart controls, limits are set for both exposure and dose, such that short- and long-term effects are accounted for. For example, the exposure limit when under-ventilating never exceeds 2.5, which is a protective value for 24-hour calculation periods, based on the ratio of acute-to-chronic exposure limits (M. H. Sherman, Logue, & Singer, 2011). In this under-ventilation case, the dose limit of 1 may not be reached, but the real-time ventilation rates are considered too low if the exposure exceeds the 2.5 threshold, and the ventilation system is turned on. When using both exposure and dose values in smart controls, the lower value is ultimately the one that controls the ventilation rate. So, if over-ventilation were the goal, and the exposure limit was 0.5 and the dose limit was 1, the dose would be driven down to the lower exposure limit of 0.5, because that lower value dominates the controller function.

Dose/Exposure	**AER Multiplier (1/Dose)**	**AER**
0.5	2.00	0.70
0.6	1.67	0.58
0.7	1.43	0.50
0.8	1.25	0.44
0.9	1.11	0.39
1	***1.00***	***0.35***
1.1	0.91	0.32
1.2	0.83	0.29
1.3	0.77	0.27
1.4	0.71	0.25
1.5	0.67	0.23
1.6	0.63	0.22
1.7	0.59	0.21
1.8	0.56	0.19
1.9	0.53	0.18
2	0.50	0.18
2.1	0.48	0.17
2.2	0.45	0.16
2.3	0.43	0.15
2.4	0.42	0.15
2.5	0.40	0.14

Table 5 Approximate relationship between changes in dose and exposure and changes in the air exchange rate.

2.5 Sensor and control options

In this study, we developed smart ventilation control strategies using patterns in outdoor weather data, paired with indoor humidity data from baseline simulations. Baseline simulations were run using CFIS continuous ventilation systems sized to 0%, 50% and 100% of ASHRAE 62.2-2013.

The following issues were considered when developing, implementing and assessing the smart humidity control strategies:

1) Humidity control approach
    a) As noted below, smart ventilation can attempt to exploit differences in indoor vs. outdoor humidity, or to exploit HVAC cooling system dehumidification.
2) Input types
    a) Inputs could include time-of-day schedule-type inputs, or sensor inputs. The inputs types are directly related to the complexity of the strategy, its costs, effectiveness, etc.
3) Algorithm complexity
    a) All things being equal, simpler algorithms are better. We give preference to approaches that do not introduce unnecessary complexity, or only do so for limited incremental benefit.
4) Robust performance
    a) Strategies should perform well outside of the fixed set of assumptions used in our modeling. For example, the controls should still provide some humidity control in homes with different sensible and latent loads or HVAC equipment.
5) Maintaining equivalence with 62.2-2013
    a) In order to be considered, all strategies must maintain annual equivalence with a continuously operated fan sized according to ASHRAE Standard 62.2-2013.
6) Climate zone variance
    a) Preferably, a strategy would work robustly across varying climate zones. But we expect that some strategies will work well in some climates and poorly in others. The heating and cooling loads and the control strategy will likely be the driving factor.
7) Moisture performance
    a) We do not expect perfect moisture control from any strategy. So, the question then becomes how much reduction in high humidity hours is considered “good” or “acceptable”? And how much is a reduction in high humidity hours worth in terms of its energy cost?
8) Energy performance
    a) Control strategies are likely to increase energy use. The acceptable energy cost associated with any given reduction in indoor moisture levels is a design and engineering decision that must be made on a case-by-case basis. We anticipate comparing energy use associated with smart controls against other supplemental humidity control strategies, such as stand-alone dehumidification.
9) Sensor reliability, maintenance needs and cost
    a) Use of sensors may have obvious benefits, but also substantial costs, maintenance and uncertainty. Approaches such as the use of web-based weather data may alleviate some of these problems.

2.5.1 Humidity Control Approaches Using Ventilation

In general, the smart control of household ventilation can reduce interior moisture levels in a number of ways:

1. Direct removal of moisture at its source through local exhaust fans (i.e., kitchen, bathroom and laundry exhaust).
2. Strategic changes in air exchange rate that will increase net-moisture transfer from inside to outside, based on the indoor-outdoor humidity differential.
3. Use of the ventilation system to advantageously increase the sensible cooling load and the associated moisture removal of cooling system operation.

The removal of any indoor contaminant, including moisture, is best achieved by local exhaust before the contaminant disperses throughout the space. This is possible when moisture sources are known and local, as in bathrooms or kitchens. This first strategy listed above is commonly implemented through use of an automatic bathroom exhaust fan, tied to a humidity sensor. Less common, is the automatic control of kitchen exhaust fans to remove moisture generated from cooking activities. While important, these automatically controlled local exhaust approaches are not relevant in control of whole house ventilation systems for humidity control. Accordingly, local emissions of moisture are not considered in our building simulations or controls development, and internal moisture gains are at a constant rate (e.g., do not vary with time of day, day of week, etc.). To the extent that internal moisture gains do vary with time of day and are known, then a smart controller could certainly use a timer-based approach to increase whole house ventilation during those periods. We did not evaluate this approach in the current study.

The second strategy listed above uses smart ventilation controls to directly increase net-moisture transport out of the home, or limit net-moisture transport into the home. This is done based on the humidity difference between the house and outside. Ventilation airflow will either transport moisture into or out of the home, depending on the sign and magnitude of the humidity ratio difference ($w_{house} - w_{outside}$) (HRdiff). Positive values lead to moisture removal from the house, and negative values lead to moisture transport into the house. Larger values of HRdiff lead to more moisture transport and smaller values lead to little net-transport. Various smart control strategies can be used to take advantage of this, including controls that function by month of the year, time-of-day or in real-time.

For each simulated test case, we calculated the humidity ratio difference (HRdiff) between the house and outside for every hour of the year. This HRdiff is shown for an example case in Figure 12 for a medium sized home in Charleston, SC. We then averaged these values over different time periods of interest, namely annually and monthly. We refer to this annual average as the net-humidity balance. For each combination of house size, occupancy rate and climate zone, there is an annual net-humidity balance (average of all HRdiff values for the year), which is either positive or negative. Positive means that on average for the year, it is more humid inside than outside, and more ventilation will provide net-moisture removal. Negative means that on average, it is more humid outside than inside, and more ventilation will provide net-humidification. These same principles function on a monthly basis as well, which we explore below in Section 2.6.4 in development of our seasonal control algorithm.

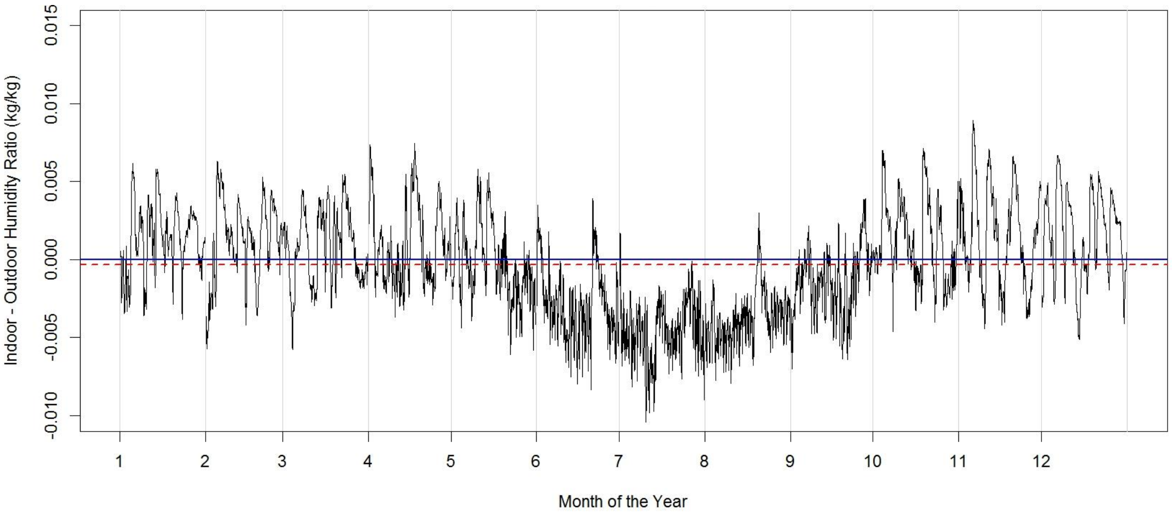

Figure 12: Time series plot of hourly humidity ratio differences (HRdiff) for a medium size Charleston home with medium moisture generation rate, and ventilation sized at 100% of 62.2-2013. Solid blue line represents value of zero, and the dashed red line is the annual average for this case.

The third smart ventilation strategy listed above uses ventilation to act secondarily on indoor humidity levels, through changes in the operating time of the cooling system. For a number of reasons, synchronizing ventilation with cooling system operation enhances moisture removal by the system. First, air passing over the coil should have a higher ratio of latent-to-sensible heat, which enhances moisture removal. This happens because ventilation air introduced on the return side mixes only with the return air volume, and not the whole house volume. So, the ratio of latent-to-sensible heat in the air entering the coil increases and moisture removal increases. Second, the sensible cooling load is increased through introduction of hot outside air, and this increases cooling system runtime. So long as these processes remove more moisture than is brought in by ventilation (and, generally, this is true) then this lowers indoor humidity levels. Numerous approaches are possible for using smart ventilation controls to increase sensible cooling loads, including time-of-day controls and run-time control.

2.5.2 Control Input Options and Considerations

Smart control strategies are designed to use one or more of the approaches described above. These strategies are implemented using a variety of inputs. Some strategies employ multiple input types. Primary inputs considered in this work included the following:

(1) Schedule-based—hourly or monthly controls
(2) Sensor-based—real-time controls with one or two sensors, indoors and/or outdoors
(3) Relative dose targets
(4) Cooling system tie-in

A summary of the primary advantages and disadvantages of schedule- and sensor-based controls is provided in Table 6.

	Advantages	***Disadvantages***
Schedules	Simple; Robust; Low first cost; Take advantage of consistent, predictable variations in humidity on the monthly (and maybe diurnal) time-scale.	Unable to respond to dynamic changes, such as variations in weather, internal moisture generation and other household activities; Unable to control ventilation based on daily variations in humidity (only knowable by advanced climate models).
Sensors	Respond to real-time variations in moisture dynamics; May be able to effectively control ventilation during periods where scheduled controls fall short, such as during shoulder season transitions.	More complex; Sensor reliability problems; High first cost.

Table 6 Summary of the primary advantages and disadvantages of schedule- and sensor-based control strategies.

This variety of inputs was selected, because the inputs used for a controller can affect the controller's effectiveness in humidity control, as well as its cost, accuracy and performance over-time. For example, strategies that rely on humidity sensors appear desirable, but they are both more complex than scheduled controls, and they may be plagued by sensor accuracy issues, in particular sensor drift over-time. Furthermore, it is possible that some or all of the benefit available from smart control can be captured by scheduled approaches, which would eliminate the need for sensors.

2.5.2.1 Schedule-Based

Control strategies are considered scheduled if the controls function based solely on the month of the year, or on the hour of the day, without sensor inputs. Scheduled approaches were developed for monthly and hourly controls, and these are considered to be the lowest cost, easiest to implement and most simple approaches. These approaches generally relied on the consistent and predictable changes in outdoor humidity that occur over the course of the year. In all locations, outdoor absolute humidity peaks during summer periods, and is substantially lower during other months. These months generally correspond to periods when the humidity gradients between inside and outside are consistently positive or consistently negative. But scheduled approaches are only able to respond to predictable variations in humidity, which will make their performance suboptimal in certain situations. They are not robust to circumstances that deviate from the average, such as moisture generation events inside the home or outdoor weather patterns that vary strongly from year-to-year or day-to-day.

2.5.2.2 Sensor-Based

Sensor-based strategies used one or two sensors (combined temperature and humidity), which were located either solely outside, or both inside and outside the home. Sensor based approaches are better suited to responding to unpredictable events, with one- and two-sensor approaches having increasingly more reliable and flexible responses. For example, a one sensor control can respond to variations in outdoor humidity that occur from day-to-day and year-to-year. While two sensor controls are the only option that can respond to variation in internal moisture generation rates—both the total generation rate and the way the generation varies with time-of-day or by season. Two types of two-sensor approaches were tried, one with a simple on/off indoor-outdoor humidity balance (called “Fixed sensor” in the Control Name column of Table 7), and the other with a proportional control approach (“Proportional sensor” in Table 7). In “Proportional sensor” control cases, the amount of over- or under-ventilation was proportional to the real-time difference between indoor and outdoor humidity ratios. This was done so that when humidity differences were large, large changes in ventilation rate were allowed, and when humidity differences were small, ventilation rates were adjusted only minimally. This was an attempt to avoid excessive over- or under-ventilation when there was little anticipated value. “Fixed sensor” controls over- or under-ventilated to their maximum allowed levels whenever the humidity balance shifted between indoor and outdoor.

Yet, sensor based approaches are plagued by increased costs, system complexity and substantial sensor reliability/accuracy issues over-time. Moisture sensors are typically less accurate and more expensive then temperature sensors. Typical sensors for use in HVAC control have specified accuracy of ±3%RH but are often outside this range depending on temperature and RH, with considerable variability from manufacturer to manufacturer (NBCIP, 2004). Of particular concern would be sensor drift over-time, with indoor and outdoor sensors drifting at different rates and potentially in different directions. Typically humidity transducers have recommendations for recalibration every 6-12 months (NBCIP, 2004). As a result, their long-term use in a smart control strategy may be questionable. The one outdoor sensor strategies were conceived to circumvent this problem. The idea was that web-connected smart control systems could use outdoor humidity data from cloud-based sources, such as Weather Underground APIs, in lieu of an on-site sensor. This would introduce errors in terms of the local humidity microclimate, but it would place the responsibility for sensor accuracy, cost and maintenance on more reliable third parties.

2.5.2.3 Relative Dose Targets

While all controllers calculated relative exposure and relative dose in real-time, the targets used varied substantially, and were either “fixed” or “variable”. When using fixed relative dose targets, a threshold value of one was always used. This approach ensured that no extended periods of under- or over-ventilation occurred. Relative exposure was allowed to vary as high as the 2.5, as long as the dose constraint was met. Variations in the ventilation rate were controlled more or less within a 24-hour timeframe, and any variation in indoor-outdoor humidity over longer periods could not be leveraged in these approaches. Variable dose target controls set the dose target to either above or below one, depending on the control conditions (e.g., absolute humidity higher indoors than outdoors, or vice versa). This leads to sometimes extended, continuous periods of either over- or under-ventilation (still with the exposure limit of 2.5). This approach allowed for overall lower ventilation rates during the humid summer season, with compensating overall increased ventilation rates during the drier winter season. In order to maintain annual equivalence (i.e., annual relative dose <= 1), controllers using variable dose targets must know ahead of time how long they will be in the high dose target vs. low dose target modes, which is not always straightforward to predict. In some cases, this was done statistically (see 2.6.9), and in other cases iteratively, using outputs of one simulation to inform incremental changes to the next simulation (see 2.6.5).

2.5.2.4 Cooling System Tie-In

This approach was used as an isolated control strategy, as well as in combination with most of the other controls described. In essence, the ventilation system operated at full capacity during any minute of space cooling operation. This approach was useful for two reasons. First, air passing over the coil should have a higher ratio of latent-to-sensible heat, which enhances moisture removal. This happens because ventilation air introduced on the return side mixes only with the return air volume[4], and not the whole house volume. So, the ratio of latent-to-sensible heat in the air entering the coil increases (relative to house air) and moisture removal increases. Second, the sensible cooling load is increased through introduction of hot outside air, and this increases cooling system runtime. So long as these processes remove more moisture than is brought in by ventilation (and, generally, this is true) then this lowers indoor humidity levels. Furthermore, the relative dose and exposure are reduced during this period of over-ventilation (at ~300% of 62.2 rate), such that the system does not ventilate for substantial remaining portions of the day.

2.5.3 Fan Sizing Considerations

For time-shifting ventilation strategies to work, multiple fan speeds are required. Initial investigations suggest that completely turning the fan off in airtight homes, during periods of low infiltration, leads to unacceptably large fan over-sizing requirements when trying to maintain annual equivalence. In this study, we assessed central fan integrated supply ventilation systems, with airflow rates sized at 300% of 62.2-2013 and set to run on a 33% duty cycle (300 x 0.33 = 100). This is one of the most common ventilation system types installed in hot-humid climate, high performance homes. In real-time, the mechanical ventilation was either ON (300% of 62.2-2013) or OFF (0% of 62.2-2013). But the smart controller decision was made once every 10 minutes. So, the system was effectively able to control to seven discrete hourly average mechanical ventilation rates, from 0 to 300% of 62.2-2013, by 50% increments (each representing 10-minutes of runtime in the hour). As was found by Less et al (2014), larger ventilation fans increase the ability to engage in smart control strategies, while maintaining annual equivalence. For this reason, the CFIS system provides an excellent opportunity for smart ventilation control, though its energy use is typically greater due to use of the central air handler fan for distribution.

2.6 Smart Control Strategies

The following section provides brief descriptions of the logic and details behind the 10 control strategies that were tested in this research. All 10 strategies were simulated in each combination of house size (100, 200 and 300 m^2) and internal moisture gains (3, 6.5 and 11.8 kg/day). All strategies used the RIVEC controller to track relative exposure and relative dose in real-time, and the ventilation system was controlled to provide the specific dose or exposure level. All other exhaust fans were ignored in the ventilation rate calculations used in dose and exposure calculations. The main features of the 10 controls strategies are summarized in Table 7, and they are described in detail in Sections 2.6.1 through 2.6.10.

---

[4] This would only be true for CFIS ventilation systems, where mixing occurs in the return plenum prior to passing over the chilled coil.

ID	*Control Name*	*Schedule*	*Sensors*	*Relative Dose Target*	*Cooling Tie-In*
1	Cooling system tie-in	N	0	Fixed	Y
6	**Monthly seasonal**	**Y**	**0**	**Variable**	**N**
8	Monthly seasonal + Hourly	Y	0	Variable	N
12	Monthly seasonal + Cooling system tie-in	Y	0	Variable	Y
13	**Annual medians**	**N**	**1**	**Variable**	**N**
14	**Monthly quartiles**	**N**	**1**	**Variable**	**N**
2	**Fixed sensor**	**N**	**2**	**Fixed**	**N**
3	**Fixed sensor + Cooling system tie-in**	**N**	**2**	**Fixed**	**Y**
9	**Fixed sensor + Variable dose target**	**N**	**2**	**Variable**	**N**
7	**Fixed sensor + Cooling system tie-in + Variable dose target**	**N**	**2**	**Variable**	**Y**

Table 7 Comparison of key elements of the 10 smart ventilation control strategies. Bold entries were identified as best performers and were tested in other home configurations.

2.6.1 Control 1: Cooling system tie-in

Scheduled approach: Yes
Sensors: None

This control strategy operates the ventilation system so that the relative dose is controlled to 1 in all months of the year, but the relative exposure is limited to either 2.5 or 0.95, in the cooling and non-cooling seasons, respectively. The cooling season is defined as times when the seven-day running average of the outdoor temperature is above 15.6°C (60°F) as used by the California State Energy Code (California Energy Commission, 2012). In addition, during the cooling season, the ventilation fan always operates whenever the cooling system operates. This forms a feedback loop, where the ventilation system operation drives longer cooling system run-times.

Condition	**Ventilation ON**
Cooling Season	Cooling system ON OR Exp >= 2.5 OR Dose > 1
Non-Cooling Season	Exp >= 0.95 OR Dose > 1

Table 8 Control logic for the Cooling system tie-in control

2.6.2 Control 2: Fixed sensor

Scheduled approach: No
Sensors: Two sensors, indoor and outdoor

This control strategy uses the measured indoor and outdoor humidity levels to control operation of the ventilation system (see Table 9). Relative dose is controlled to 1 at all times of the year. Two main regimes are tested with indoor relative humidity either above or below 55%. This assumes that when indoor RH is below 55%, there is no problem and therefore no need for ventilation controls. Accordingly, when the indoor RH is below 55%, we simply control the relative dose to 1 and the relative exposure limit is 0.95. When the indoor RH exceeds 55%, then the HRdiff value determines the controls. When

HRdiff is negative (more humid outside than inside), the relative exposure limit is 2.5, and when HRdiff is positive (more humid inside than outside), the relative exposure limit is 0.5.

In summary, the primary effect of this control strategy is that when indoor RH is >55%, the controller halves the ventilation rate when HRdiff is negative (more humid outside than inside) and doubles the ventilation rate when HRdiff is positive (more humid inside than outside). It also allows time shifting of ventilation within a 24-hour period when it is more humid outside than inside. So, if during a 24-hour period, the HRdiff was sometimes negative and sometimes positive, the controller would advantageously shift ventilation between these periods. But when HRdiff is consistently negative during a 24-hour period, the controller has little effect relative to a non-controlled fan. When HRdiff is positive, the exposure is limited to 0.5, and while the dose limit is technically 1, the lower exposure threshold drives the dose down to approximately 0.5, as well (see Section 2.4).

Condition	Ventilation ON
Indoor RH >= 55% AND $W_{out} >= W_{in}$	Exp >= 2.5 OR Dose > 1
Indoor RH >= 55% AND $W_{out} < W_{in}$	Exp >= 0.5 OR Dose > 1
Indoor RH < 55%	Exp >= 0.95 OR Dose > 1

Table 9 Control logic for the Fixed sensor controller.

2.6.3 Control 3: Fixed sensor + Cooling system tie-in

Scheduled approach: Yes
Sensors: Two sensors, indoor and outdoor

This strategy is identical to the Fixed sensor approach (Control 2), but it adds a rule that the ventilation system operates when the cooling system operates, if the indoor RH is above 55% and HRdiff is negative. Otherwise, the dose and exposure controls are exactly the same as the Fixed sensor control. During periods with positive HRdiff and indoor RH above 55%, the ventilation rate is effectively doubled. Relative to the Fixed sensor control, the cooling system tie-in means the relative dose is often below 1 during the summer cooling season. On average this means the ventilation rate is increased during the cooling season, but it is advantageously timed to remove humidity prior to entering the home, and to increase cooling run-time.

Condition	Ventilation ON
Indoor RH >= 55% AND $W_{out} >= W_{in}$	Cooling system ON OR Exp >= 2.5 OR Dose > 1
Indoor RH >= 55% AND $W_{out} < W_{in}$	Exp >= 0.5 OR Dose > 1
Indoor RH < 55%	Exp >= 0.95 OR Dose > 1

Table 10 Control logic for Fixed sensor + Cooling system tie-in control.

2.6.4 Control 6: Monthly seasonal

Scheduled approach: Yes
Sensors: None

The monthly seasonal controller is designed to take advantage of the largest and most consistent variation in outdoor absolute humidity—seasonal variation by month of the year (see Figure 3 in Section 2.1.1). We demonstrated in Section 2.2.1 using FSEC simulation data, that different ventilation rates (100% and 50% of 62.2-2013) led to different indoor humidity levels.

Supported by these results we developed a schedule-based control using the month of the year to either increase or decrease the ventilation rate. We used the results of our baseline simulations (see Section 4.1) with fans sized to 100% of 62.2-2013 to determine which months to control on. The humidity ratio difference was calculated between inside and outside for each hour of the year (HRdiff), and then monthly averages were calculated. These monthly averages were averaged across home sizes and internal moisture generation rates, to create an average monthly pattern that was reasonably robust across house configurations (e.g., home size, occupant density, etc.). These average HRdiff values are presented by month and climate zone in Table 11. Positive values (green cells) indicate the ventilation will provide a net-humidity benefit, and negative values (red cells) indicate a net-penalty. Light-green and pink cells indicate months with marginal smaller net-humidity differences. As noted in the seasonal decompositions, monthly seasonal patterns are strong and consistent, with outdoor humidity consistently exceeding indoor humidity during the “summer”, which we define here as months when average outdoor humidity is greater than indoor. This consistent state is maintained by dehumidification provided by the cooling system in these months. An alternate approach would be to select months for control based on cooling system operation, which would be even less dependent on the home size and internal generation rates.

Climate Zone	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
Miami	0.0001	-0.0012	-0.0021	-0.0034	-0.0057	-0.0076	-0.0079	-0.0079	-0.0074	-0.0060	-0.0039	-0.0018
Orlando	0.0002	0.0005	0.0005	-0.0011	-0.0036	-0.0057	-0.0081	-0.0075	-0.0058	-0.0042	-0.0005	0.0007
Houston	0.0011	0.0008	0.0004	-0.0019	-0.0042	-0.0072	-0.0080	-0.0081	-0.0055	-0.0014	-0.0001	0.0011
Charleston	0.0015	0.0014	0.0006	-0.0005	-0.0031	-0.0060	-0.0076	-0.0071	-0.0047	-0.0009	0.0007	0.0016
Memphis	0.0017	0.0012	0.0014	0.0002	-0.0025	-0.0049	-0.0062	-0.0053	-0.0043	0.0005	0.0015	0.0016
Baltimore	0.0014	0.0015	0.0012	0.0014	-0.0005	-0.0026	-0.0045	-0.0039	-0.0025	0.0017	0.0015	0.0016

Table 11 Monthly average humidity ratio differences (HRdiff) in each climate zone, averaged across house sizes and moisture gains. Includes on cases with ventilation sized to 100% of 62.2-2013. All values >0 are green, <0 are red.

When comparing between the house size and occupancy rate parameters, the seasonal monthly patterns do not change in most cases, but the magnitude of the humidity differences shift up or down. In cases where the seasonal pattern does shift, the mean values of the humidity differences during those months tend to be small (i.e., an order of magnitude smaller than the differences found in non-shifting months). This limits the overall impact of any given month going from a positive to negative humidity difference (i.e., from green to red or vice versa).

Based on the analysis of baseline simulations presented in Table 11, we describe our proposed seasonal ventilation control strategy in Table 12. The red months are the periods when ventilation is a liability, and the green months when ventilation is a benefit. Therefore a seasonal controller should increase the ventilation rate during green months and decrease it during red months. The magnitude of these increases and decreases must be designed so that annual exposure to pollutants is equivalent with a continuous 62.2-2013 fan. For our control strategy, this means targeting different relative dose values in different months (see Table 12). In red months, we target higher relative dose values and lower dose values in green months. There are differing numbers of red and green months depending on the climate zone, and the dose targets were allowed to take on different values. So, for each climate, we used Equation 7 along with *LowDoseTarget*s between 0.4 and 1 to calculate the required *HighDoseTarget*s for the red months, such that the annual average would be less than one (actual value used was 0.98 to ensure equivalence)[5]. We then selected the most appropriate combination of *HighDoseTarget* and *LowDoseTarget* that maintained equivalence. These varying dose targets ensure that when averaged over a full year, the occupants' exposure to pollutants is equivalent between the controlled and continuous fan scenarios. A real-time ventilation (RTV) controller was then used to achieve these exposure targets. The RTV controller used the equivalence approach (Sherman, M. H., Walker, I. S., & Logue, J. M. (2012) to operate the CFIS system to achieve the target exposure rates.

$$LowDoseTarget = \frac{AnnualDoseTarget - \left(HighDoseTarget \times \left(\frac{HighDoseMonths}{12}\right)\right)}{\left(\frac{LowDoseMonths}{12}\right)}$$

LowDoseTarget = Value < 1, represent level of over-ventilation during green months
HighDoseTarget = Value > 1, represent level of under-ventilation during red months
AnnualDoseTarget = Annual target value for relative dose, defaults to 1
HighDoseMonths = Number of months controlled to *HighDoseTarget*
LowDoseMonths = Number of months controlled to *LowDoseTarget*

Equation 6 Simple weighted average formula used to calculate dose targets In smart controls.

	Green Months	Dose Target	Red Months	Dose Target	Green Months	Dose Target
Miami	Jan	0.76	Feb-Dec	1.0	NA	NA
Orlando	Jan-March	0.54	Apr-Nov	1.2	Dec	0.54
Houston	Jan-March	0.53	Apr-Oct	1.3	Nov-Dec	0.53
Charleston	Jan-March	0.53	Apr-Oct	1.3	Nov-Dec	0.53
Memphis	Jan-Apr	0.466	May-Sep	1.7	Oct-Dec	0.466
Baltimore	Jan-Apr	0.466	May-Sep	1.7	Oct-Dec	0.466

Table 12 Monthly seasonal control strategy, based on monthly average humidity ratio differences (see Table 11).

Condition	**Ventilation ON**
Red month	Exp >= 2.5 OR Dose > 1.5
Green month	Dose > DoseTarget (see Table 12)

Table 13 Control logic for Monthly seasonal + Cooling system tie-in.

---

[5] This equation assumes equal weighting for all months, despite different numbers of day. Future efforts should weight the average according to the number of days in each month, to be more precise.

2.6.5 Control 7: Fixed sensor + Cooling system tie-in + Variable dose target

Scheduled approach: Yes
Sensors: Two sensors, indoor and outdoor

This control strategy builds upon the Fixed sensor + Cooling system tie-in (Control 3), but allows for variable dose targets (i.e., not equal to 1). Critically, there is no 55% RH threshold used in this control, so unlike Control 3, the variable dose targets apply to all hours of the year. The variable dose target allows the controller much more flexibility in increasing and decreasing the ventilation rate, relative to what was allowed in the Fixed sensor + Cooling system tie-in (Control 3), which always targeted a dose of 1. To set the variable dose targets, we first used baseline simulation results (see Section 4.1 and Equation 7 to calculate the required LowDoseTarget assuming a HighDoseTarget of 1.5, based on the hours of the year in the base case that it was more humid outside than inside and vice versa (HRdiff positive and negative). This type of approach worked well for maintaining equivalence in the Monthly controller (Control 6). Unfortunately, when coupling this with real-time controls, results were not equivalent to the continuous fan baseline (i.e., the annual relative dose was >1 in all cases). Instead, we needed to generate custom dose targets for each climate zone for periods of over- and under-ventilation, which was done through manual adjustment and iteration.

$$LowDoseTarget = \frac{AnnualDoseTarget - (HighDoseTarget \times HighDoseFraction)}{LowDoseFraction}$$

LowDoseTarget = Value < 1, represent level of over-ventilation during green months
HighDoseTarget = Value > 1, represent level of under-ventilation during red months
AnnualDoseTarget = Annual target value for relative dose, defaults to 1
HighDoseFraction = Proportion of annual hours controlled to *HighDoseTarget*
LowDoseFraction = Proportion of annual hours controlled to *LowDoseTarget*

Equation 7 Simple weighted average formula used to calculate dose targets In smart controls.

Why was the weighted average approach not equivalent? The reason was that this controller sets the DoseTarget and controls to it based on the real-time HRdiff. The Monthly controller did the same, but based on monthly HRdiff averages, not real-time inputs. In the monthly case, if the average monthly HRdiff was >0, then you targeted a low dose all month. In contrast, the real-time controller cycles back and forth between targeting high and low DoseTargets, because the HRdiff shifts from positive to negative in real-time (e.g., within a day or week). This is the benefit of the real-time sensor control; you are never over-ventilating when it's more humid outside than inside, and vice versa. But it also means that if the controller cycles between high and low dose targets quickly enough, then substantial periods of time are spent not at the target dose values, but either above or below them. If this were the case during all months, then these issues would likely balance themselves out over the course of the year. But this is not the case. During high dose periods (generally summer), HRdiff is almost always negative, because these are the periods when the cooling system is providing dehumidification. For example, see the Charleston example HRdiff time series plotted in Figure 12 (see Section 2.5.1). The high dose months are roughly June through September, and during this period, the HRdiff is consistently negative, with some excursions in early June and late September. As a result, the controller consistently controls to the high dose target for months on end. This is not the case during the low dose periods, which are characterized by frequent shifts between high and low dose modes (again, see Figure 12 as the plot cycles above and below 0). Cycling is non-existent in the Monthly approach, with essentially only one full cycle during the entire year (from low to high and back to low). All of this combines to contradict the assumption of our simple weighted average approach, which assumes that low dose hours are controlled to the LowDoseTarget, which was not the case when using real-time controls.

To further complicate the issue, different house sizes and moisture generation rates lead to different proportions of the year with positive and negative HRdiff's, and therefore different time periods controlled to the differing dose targets. Again, this means the simple weighted average approach is insufficient. It is consistently the case that larger homes with lower generation rates have higher proportions of the year where it is more humid outside than inside (HRdiff < 0). Conversely, smaller homes with high generation rates have higher proportions of the year where it is more humid inside than outside (HRdiff > 0).

To address these issues, we first determined that we needed to select one set of dose targets that would maintain equivalence in all simulated home sizes and tested moisture generation rates. This meant controlling to the worst-case, which in this context would be the large home with low moisture generation, because this case would be controlled to the high dose target (1.5) for the most number of hours (increasing the annual average dose above 1). As discussed above, when using real-time sensor controls, there is no way to identify dose targets that will provide equivalence without iteratively doing full annual simulations. This is due to the cycling between high and low dose targets. This is exactly what we did. We iteratively reduced the high and low dose targets, using full annual simulations, until all cases maintained equivalence with a continuous fan. The resulting dose targets are provided in Table 14. Some level of engineering judgment was used in setting these targets, with a general preference to not over-ventilate too much in climates with substantial heating loads (i.e., Charleston, Memphis and Baltimore). Reduced HighDoseTargets were not of too much concern, since these periods typically also coincide with cooling system operation.

As these targets were designed based on the worst-case, large home with low moisture generation rate, they are suboptimal for other home configurations. For example, in the medium sized home, fewer hours of the year were in the HighDoseTarget regime, so higher target values would have still maintained equivalence. In other words, ventilation rates could have been further reduced during negative HRdiff periods, and over-ventilation could have been lessened (reducing energy use).

	HighDoseTarget	LowDoseTarget
Miami	1.1	0.38
Orlando	1.2	0.36
Houston	1.2	0.36
Charleston	1.2	0.47
Memphis	1.2	0.64
Baltimore	1.3	0.66

Table 14 High and low dose targets used in Fixed sensor + Cooling system tie-in + Variable dose target.

Condition	**Ventilation ON**
$W_{out} >= W_{in}$	Cooling system ON OR Exp >= 2.5 OR Dose > *HighDoseTarget* (see Table 14)
$W_{out} < W_{in}$	Dose > *LowDoseTarget* (see Table 14)

Table 15 Control logic for Fixed sensor + Cooling system tie-in + Variable dose target

2.6.6 Control 8: Monthly seasonal + Hourly

Scheduled approach: Yes
Sensors: None

This control strategy builds upon the Monthly seasonal control (Control 6) by adding to it additional strategies based on the hour of the day (see Table 16). Monthly DoseTargets were identical to those in Table 12. We then overlaid hourly controls using the detrended hourly profiles generated by seasonal decomposition for each climate zone (see examples in Figure 5 and Figure 6). We have already noted that these variations in outdoor humidity were very small on an hourly basis, relative to the daily average. Nevertheless, we identified some consistent patterns across all climates and implemented these in the Monthly seasonal + Hourly control strategy. These patterns were determined as blocks of time during which all (or nearly all) climate zones had positive or negative values, relative to the daily average HRdiff. The ventilation fan was always OFF during blocks with consistently positive values (more humid than daily average, 7-11AM in red months), and the ventilation fan was always ON for negative blocks (less humid than the daily average, 3-7AM in green months and 2-6PM in red months).

Condition	**Ventilation ON**
Red Month	2PM to 6PM AND NOT 7AM to 11AM OR Exp >= 2.5 OR Dose > DoseTarget (see Table 12)
Green Month	3AM to 7AM OR Dose > DoseTarget (see Table 12)

Table 16 Control logic for the Monthly seasonal + Hourly control.

2.6.7 Control 9: Fixed sensor + Variable dose target

Scheduled approach: Yes
Sensors: Two sensors, indoor and outdoor

This control strategy combines the Fixed sensor (Control 2) with variable dose targets, and it is very similar to the Fixed sensor + Cooling system tie-in + Variable dose target control (Control 7). As discussed for Control 7, custom variable dose targets were established based on the worst-case (large home, low moisture generation rate) through iterative adjustments and full annual simulations. In Control 7, the cooling system tie-in effectively reduced the average relative dose during the HighDoseTarget periods, and the annual relative dose was lower as a result. This benefit did not exist in this case, so the dose targets had to be adjusted further, with lower HighDoseTargets in most cases (relative to those in Table 14). LowDoseTargets were fixed by either the minimum imposed by the size of the ventilation system (~0.36) or by the heating season penalty incurred in harsher climates.

Due to the aggressive reductions in the HighDoseTargets (close to 1) required to maintain equivalence, this strategy is fairly similar to the basic Fixed sensor control (Control 2). Slight under-ventilation is allowed during the High Dose periods, and over-ventilation is either lesser or greater, depending on the climate zone (Control 2 targeted ~0.5 exposure vs. 0.36-0.66 in this control). The critical difference is that there is no indoor 55% RH threshold; so much more of the year is controlled to the LowDoseTarget, particularly in locations with generally lower indoor humidity levels, such as Baltimore. This increase in ventilation incurs a heating energy penalty in colder climates, but has little effect in hotter locations.

Climate Zone	HighDoseTarget	LowDoseTarget
Miami	1.05	0.38
Orlando	1.15	0.38
Houston	1.15	0.36
Charleston	1.15	0.47
Memphis	1.2	0.64
Baltimore	1.25	0.66

Table 17 DoseTargets for the Fixed sensor + Variable dose target control.

Condition	Ventilation ON
$W_{out} >= W_{in}$	Exp >= 2.5 OR Dose > *HighDoseTarget* (see Table 17)
$W_{out} < W_{in}$	Dose > *LowDoseTarget* (see Table 17)

Table 18 Control logic for the Fixed sensor + Variable dose target control.

2.6.8 Control 12: Monthly seasonal + Cooling system tie-in

Scheduled approach: Yes
Sensors: None

This control strategy combines the Monthly controller (Control 6) with a cooling system run-time feature (as in Control 1). The target relative dose changes depending on the month of the year, as specified in Table 12. In addition to this monthly control, the ventilation system is always operated whenever the cooling system operates. This combined strategy is summarized in Table 19 below.

Condition	Ventilation ON
Cooling system ON	Always
Red month	Exp >= 2.5 OR Dose > DoseTarget (see Table 12)
Green month	Dose > DoseTarget (see Table 12)

Table 19 Control logic for Monthly seasonal + Cooling system tie-in.

2.6.9 Control 13: Annual medians

Scheduled approach: No
Sensors: One sensor, outdoor

This control strategy uses the annual median outdoor humidity ratio value (see Table 20) to control increases and decreases in the ventilation rate as outlined in Table 21. Using the 50th percentile value for outdoor humidity means the strategy will over and under ventilate for equal hours of the year. In order to maintain equivalence, the dose targets are adjusted equally above and below one. In this case, by 0.5. As noted in Section 2.4, these equal changes in the target dose do not lead to equal changes in over- and under-ventilation. Rather the dose of 1.5 is approximately a 33% reduction in AER and the dose of 0.5 is an approximate doubling of the ventilation rate. Unfortunately, from an energy perspective, the doubling of the ventilation rate occurs during winter, with obvious impacts on heating energy use in harsher climates.

CZ/Location	**1A**	**2A**	**2A**	**3A**	**3A**	**4A**
	Miami	**Houston**	**Orlando**	**Charleston**	**Memphis**	**Baltimore**
Annual Median Humidity Ratio (kg/kg)	0.016	0.012	0.012	0.011	0.009	0.006

Table 20 Annual median values of outdoor humidity ratio.

Condition	**Ventilation ON**
W_{out} >= *Annual median*	Exp >= 2.5 OR Dose > 1.5
W_{out} < *Annual median*	Dose > 0.5

Table 21 Control logic for Variable outdoor HR cutoff

2.6.10 Control 14: Monthly quartiles

Scheduled approach: Yes
Sensors: One sensor, outdoor

Visual inspection of the baseline indoor and outdoor humidity plots suggested that in general, indoor and outdoor absolute humidity were highly correlated, but that larger differences were most common when the outdoor humidity was changing rapidly and was at a peak or valley. These are likely to be periods with substantial positive or negative values of HRdiff, depending on the outdoor trend. This makes sense, as you think about the indoor space as being a lagged value of the running average of the outdoor humidity, with storage capacity to buffer out the peaks and valleys (and some added humidity from indoor sources). The large differences in indoor and outdoor humidity during daily outdoor peaks and valleys is illustrated in Figure 13, particularly in the winter months November through April.

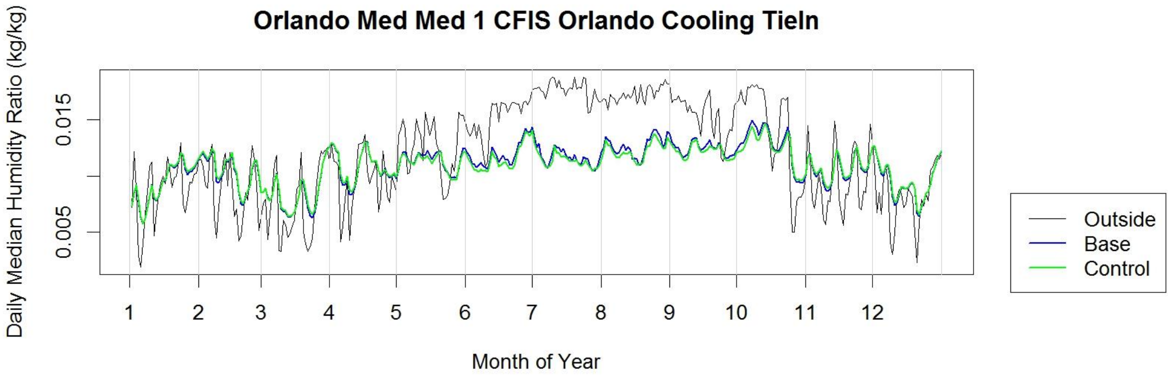

Figure 13 Time-series plot of daily median humidity ratios for outside and inside the home (baseline and control cases) for an example medium sized home with medium moisture generation in Orlando, FL.

Consistent with this phenomenon, this control strategy attempts to limit ventilation control to only those periods in any given month when the outdoor humidity is high or low, relative to the monthly average. This was done using the 25th and 75th percentile values of outdoor humidity ratio for each month of the year (see Table 22 and Table 23). The controller under-ventilates when the outdoor humidity exceeds the 75th percentile, and it over-ventilates when outdoor humidity is below the 25th percentile (see Table 24). This approach means that equal portions of each month are controlled to over- and under-ventilate, as was also the case with the simple control based on the outdoor median humidity ratio. In the simulations, we pre-calculated these values, but a real-world controller could implement this strategy using running average data distributions and percentiles from the prior 30-days.

Frequent shifting between dose targets may affect this strategy similarly to the issues encountered in the Fixed sensor + Variable dose target control (Control 9). Again, the issue is that when shifting between dose targets, the target values are not consistently achieved. This approach should lead to equal shifting between high and low targets, which will hopefully balance each other out, as was not the case with the Fixed sensor + Variable dose target approach.

CZ	**1A**	**2A**	**2A**	**3A**	**3A**	**4A**
Month	**Miami**	**Houston**	**Orlando**	**Charleston**	**Memphis**	**Baltimore**
Jan	0.007617	0.003767	0.006825	0.003443	0.002157	0.001544
Feb	0.00788	0.003633	0.006621	0.002928	0.001965	0.001656
Mar	0.008541	0.004794	0.004624	0.004944	0.003942	0.002088
Apr	0.01135	0.009156	0.008061	0.006458	0.004622	0.00405
May	0.0142	0.01258	0.0107	0.01091	0.008859	0.005879
Jun	0.01629	0.01622	0.01371	0.01402	0.01275	0.009515
Jul	0.01667	0.01674	0.01668	0.01629	0.01426	0.01163
Aug	0.01686	0.01683	0.01676	0.01626	0.01239	0.01059
Sep	0.01632	0.01145	0.01404	0.01356	0.01097	0.008891
Oct	0.01459	0.007891	0.0105	0.007493	0.005427	0.003945
Nov	0.01225	0.006043	0.00714	0.005258	0.004299	0.00322
Dec	0.008715	0.004294	0.006652	0.002604	0.002277	0.001505

Table 22 Monthly 25th percentile outdoor humidity ratios.

CZ	**1A**	**2A**	**2A**	**3A**	**3A**	**4A**
Month	**Miami**	**Houston**	**Orlando**	**Charleston**	**Memphis**	**Baltimore**
Jan	0.01309	0.008834	0.01045	0.006975	0.005521	0.003239
Feb	0.01312	0.01022	0.01132	0.007043	0.005011	0.003664
Mar	0.01418	0.01196	0.01102	0.01	0.008272	0.004254
Apr	0.01405	0.0141	0.01208	0.0113	0.009934	0.007268
May	0.0163	0.01579	0.0147	0.01461	0.0143	0.01107
Jun	0.01805	0.01801	0.01655	0.01797	0.0163	0.01329
Jul	0.01846	0.01863	0.01869	0.01848	0.01691	0.01545
Aug	0.01852	0.01874	0.01799	0.01763	0.01642	0.01573
Sep	0.01801	0.01767	0.01673	0.01579	0.01683	0.01473
Oct	0.01748	0.01274	0.01775	0.01318	0.009623	0.007804
Nov	0.01662	0.01309	0.01188	0.01143	0.007715	0.005929
Dec	0.01452	0.009124	0.01007	0.008957	0.00509	0.003709

Table 23 Monthly 75th percentile outdoor humidity ratios.

Condition	**Ventilation ON**
W_{out} *>= Monthly 75th percentile (see* Table 23*)*	Exp >= 2.5 OR Dose > 1.5
W_{out} *< Monthly 25th percentile (see* Table 22*)*	Dose > 0.5
All other values of W_{out}	Exp >= 0.95 OR Dose > 1

Table 24 Control logic for the Monthly quartiles control.

2.6.11 New Smart Controls Paired with Dehumidification

As described later in Section 4.2, the previously described smart ventilation control strategies were effective (to varying degrees) at reducing some periods of high indoor humidity, but when paired with a dehumidifier, they served to increase rather than save energy. As dehumidifiers adequately controlled indoor moisture during nearly all hours of the year in all cases, the goal of the smart ventilation control became to save energy. In order to further explore if smart controls could be advantageously combined with dehumidification, we made some adjustments to two of the smart control strategies, with the goal of reducing the energy use required for the strategy. This included reducing the amount of ventilation during cooling operation, and also scaling the ventilation rate depending on the temperature difference between house and outside. These approaches combined humidity and temperature controls together to get similar moisture results with less energy consumption, all while maintaining annual equivalence with a continuous fan.

2.6.11.1 New Control 7: Reduced Cooling Tie-In

For the Miami location homes, we were able to adjust the approach of Control 7 to reduce the combined energy consumption of the smart controls and the dehumidifier. We made two adjustments:

1. Rather than always ventilating during cooling operation, we controlled the relative dose to less than or equal to 1 during cooling operation.
2. We then took the original Control 7 high dose targets (see Table 14) and reduced them by 0.075 (i.e., a slight reduction in the amount of under-ventilation), in order to maintain equivalence. This left winter over-ventilation targets unchanged.

Condition	**Ventilation ON**
$W_{out} >= W_{in}$	Cooling system ON AND Dose >=1 OR Cooling system OFF AND Dose > (*HighDoseTarget – 0.075, see* Table 14*) OR* Exp >= 2.5
$W_{out} < W_{in}$	Dose > *LowDoseTarget* (See Table 14)

Table 25 Control logic for New Control 7, Fixed sensor + Cooling system tie-in + Variable dose target

This new control strategy is shown in operation in Figure 14, along with the house RH, relative dose and exposure, and equipment operation (cooling, ventilation and dehumidifier). Notice that during cooling operation (grey regions), the ventilation is controlled to a relative dose of 1 (aqua).

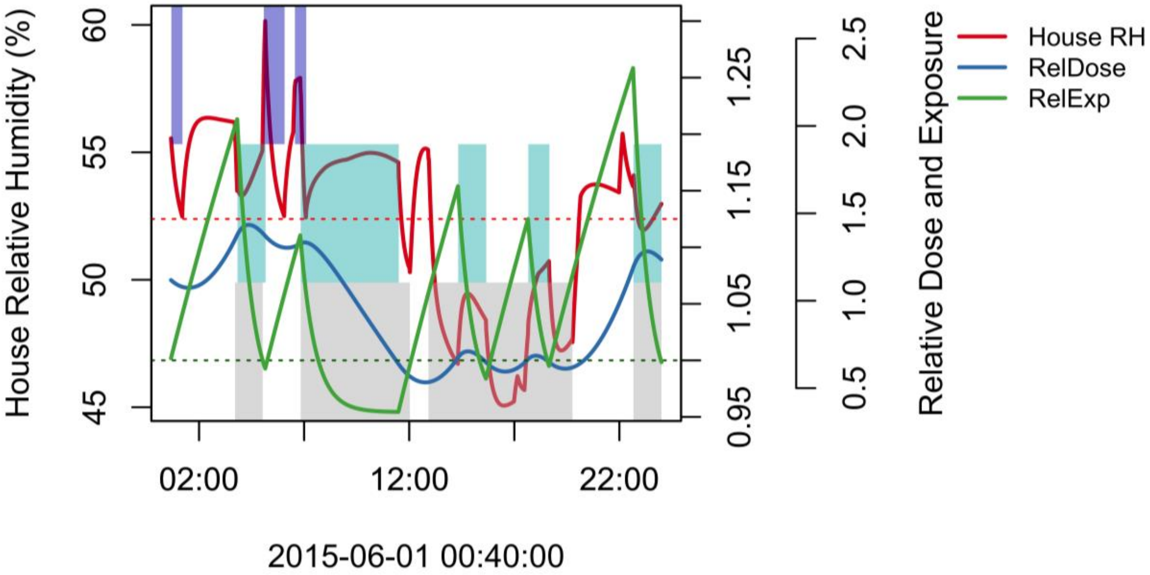

Figure 14 Plot of house relative humidity, relative dose and exposure in an example of the New Control 7. Small home with high gains in Miami, FL. Equipment operation periods are highlighted for cooling (grey), CFSI ventilation (aqua) and dehumidifier (purple). The dashed horizontal green line highlights the dose target of 1, and the high dose target is the dashed red horizontal line. Relative exposure never reaches the 2.5 limit. Dose is the first y-axis on the right, exposure is the second y-axis on the right.

2.6.11.2 New Control 5: Temperature Based Control

To target enhanced performance in climate locations other than Miami, we made an additional smart control strategy. In this New Control 5, we implemented an approach that over-ventilated during mild periods and under-vented when substantial heating penalties would be incurred. This was achieved by calculating a variable relative exposure target that depended on the temperature difference between inside and outside, relative to typical temperature differences experienced in that climate zone. This was done only for time periods when it was more humid inside than outside, which typically was during the heating season. We found that a median temperature difference of roughly 15°C was broadly applicable in the relevant climate zones during the heating season months. Smaller winter temperature differences were more common in Miami, and larger differences more common in Memphis and Baltimore, but we used this central simplification with good results. So, when more humid inside than outside, a variable relative exposure target was calculated that was scaled by the ratio of the current temperature difference against the typical 15°C difference. An initial relative exposure target (*relExpTarget*) was calculated using Equation 8. If this value was less than 0.5, then *relExpTarget* was set to 0.5. If the initial value was greater than 1, then Equation 9 was used to adjust the *relExpTarget* downwards by 10%. This effectively limited the under-ventilation that occurred during periods with the greatest temperature difference, and it was a required add-on in order to maintain equivalence with 62.2-2013. The calculated relative exposure targets are shown across a spectrum of temperature differences in Figure 15, again these were only used during periods where $W_{out} < W_{in}$.

$$relExpTarget = 0.5 - (0.5 - 1) \times \left(\frac{abs(T_{house} - T_{outside})}{15}\right)$$

relExpTarget = relative exposure target value

T_{house} = house temperature, °C

$T_{outside}$ = outside temperature, °C

Equation 8 Calculation of relative exposure target in New Control 5, varying with indoor-outdoor temperature difference

$$relExpTarget_{new} = 1 + 0.9 \times (relExpTarget_{old} - 1)$$

$relExpTarget_{new}$ = New relative exposure target value
$relExpTarget_{old}$ = Old relative exposure target value

Equation 9 Adjustment to relative exposure target when old value is >1.

Condition	Ventilation ON
$W_{out} >= W_{in}$	Cooling system ON AND Dose >=0.95 OR Exp >= 2.5 OR Dose >=1
$W_{out} < W_{in}$	Exp >= relExpTarget (see Equation 8 and Equation 9)

Table 26 Control logic for New Control 5.

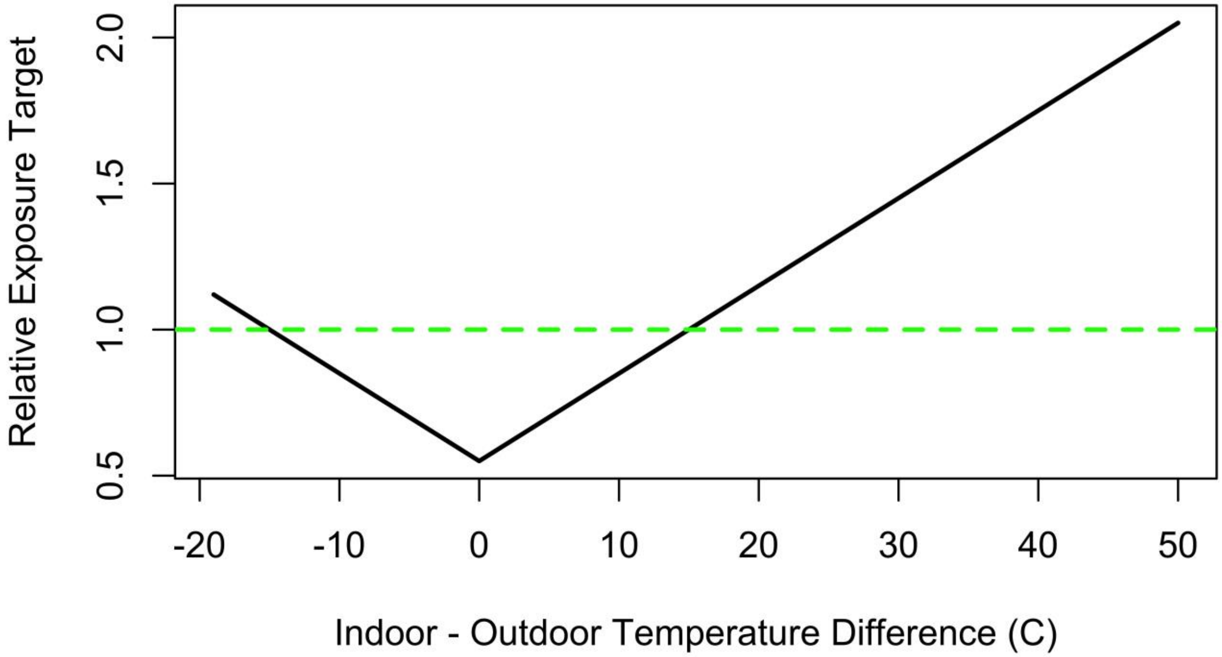

Figure 15 Relative exposure targets (black line) varying with indoor - outdoor temperature differences in New Control 5: Temperature Based Control.

The varying hourly average fan airflow rate is pictured for an example case in Figure 16, along with the varying hourly average temperature differences. As the temperature differences get smaller, the ventilation rate is increased and vice versa. When temperature difference data in Figure 16 are binned into four equal size groups the median hourly airflow rates in these bins varies from 0.54 hr^{-1} at the smaller temperature differences, down to 0.18 hr^{-1} at the highest differences. This gives a rough sense for how much variability in the airflow rates was allowed.

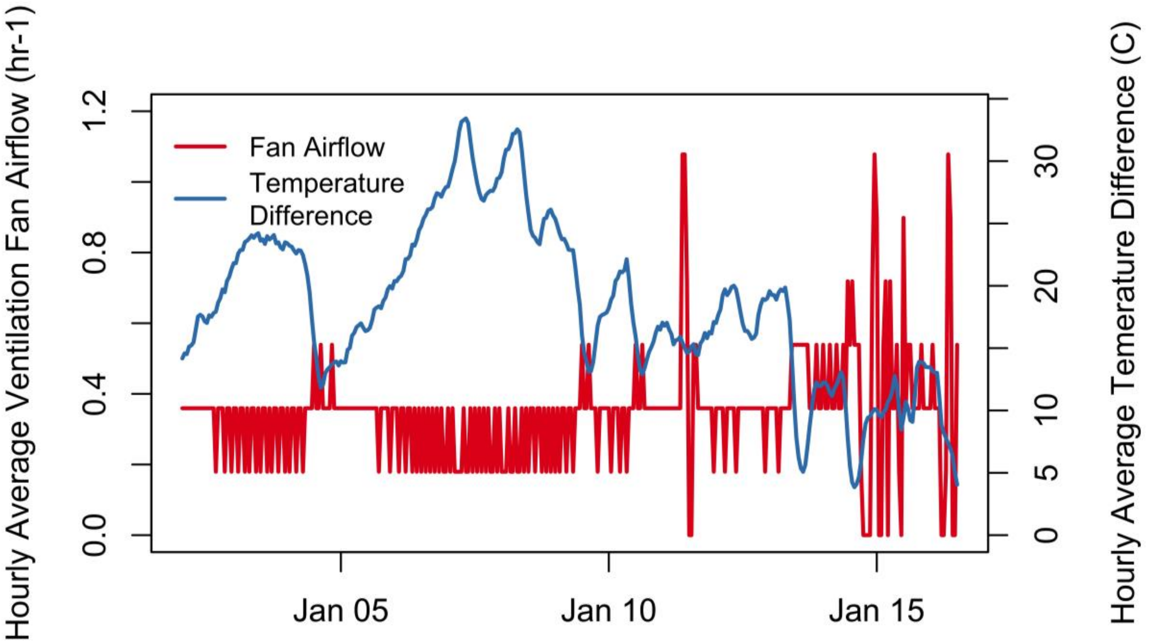

Figure 16 Example of the hourly average relationship between ventilation fan airflow (red) and indoor-outdoor temperature difference (blue) with New Control 5. Small home with medium moisture gains and a dehumidifier in Memphis, TN. The line at roughly 0.38 represents an exposure target of 1.

3 Simulation Outline

The REGCAP simulation tool[6] was used to provide estimates of indoor humidity, energy use, air exchange rates, and relative dose and exposure amongst ventilation control strategies. The REGCAP simulation combines detailed models for mass-balance ventilation (including envelope, duct and mechanical flows), heat transfer, HVAC equipment and moisture. Two zones are simulated: the main house and the attic (the separate attic is important if the HVAC system is located in the attic). REGCAP was implemented using a one-minute time-step to capture sub-hourly fan operation and the dynamics of cycling HVAC system performance. TMY3 weather data were linearly interpolated from one-hour to one-minute time steps for use in the REGCAP. The decision to turn the whole house fan on or off based on current exposure and dose values was made once every ten minutes (per the control strategies described in Section 2.6).

All simulations were of a high performance, single-family home that meets the U.S. DOE Zero Net-Energy Ready home requirements. The project followed this process:

1. Simulations were first performed for baseline cases, using central fan integrated supply (CFIS) ventilation systems with 33% duty cycles. Systems were sized to provide 0%, 50% or 100% of the required airflow from ASHRAE 62.2-2013. These baseline simulations provide the comparison cases for all of the smart control cases, and were used in development of the control strategies described in Section 2.6 above. All combinations of home size and internal moisture gains were included in the baseline parametric runs. Each baseline combination of location, house size and

---

[6] The REGCAP model is described in detail in Appendix 1 of (Walker & Sherman, 2006).

moisture gains was simulated with and without a mechanical dehumidifier. The parameters that were varied are summarized in Table 27.

2. All 10 control strategies were simulated in the subset of baseline cases where indoor humidity was unacceptably high, which included all small homes with high and medium moisture gains, as well as all medium homes with high moisture gains. These cases were run with and without supplemental mechanical dehumidification.
3. We iteratively developed and tested the New Control 5 and New Control 7 strategies to pair advantageously with the supplemental dehumidifiers. These new smart control strategies were simulated only in the combined SVC+dehumidifier cases.

The description of the test house is presented below, followed by the baseline simulation results, the results of the 10 control cases and the results of the SVC+dehumidifier cases.

<table>
<tr><td rowspan="6">CLIMATE ZONES</td><td colspan="6">Miami, FL (1A)</td></tr>
<tr><td colspan="6">Orlando, FL (2A)</td></tr>
<tr><td colspan="6">Houston, TX (2A)</td></tr>
<tr><td colspan="6">Charleston, SC (3A)</td></tr>
<tr><td colspan="6">Memphis, TN (3A)</td></tr>
<tr><td colspan="6">Baltimore, MD (4A)</td></tr>
<tr><td>HOME SIZE</td><td colspan="2">LARGE (300 m^2)</td><td colspan="2">MEDIUM (200 m^2)</td><td colspan="2">SMALL (100 m^2)</td></tr>
<tr><td>FAN SIZE – 62.2-2013 FRACTION</td><td colspan="2">0%</td><td colspan="2">50%</td><td colspan="2">100%</td></tr>
<tr><td>INTERNAL MOISTURE GAINS</td><td colspan="2">HIGH (11.8 kg/day)</td><td colspan="2">MEDIUM (6.5 kg/day)</td><td colspan="2">LOW (3.0 kg/day)</td></tr>
<tr><td>Dehumidification</td><td colspan="3">YES</td><td colspan="3">NO</td></tr>
</table>

Table 27 Summary of the parameters varied in simulations, including climate zone, home size, fraction of 62.2-2013, internal moisture gains and presence of a dehumidifier.

3.1 Test house and parameters of interest

A variety of locations were chosen in hot- and mixed-humid climate zones to assess the effectiveness of humidity control by smart ventilation control (see Table 2 in Section 2.1). These locations were prioritized because past simulations have shown them to have high indoor humidity (Martin, 2014), or they were the representative cities in climate zones 1A-4A. Three one-story house geometries were assessed with varying conditioned floor areas (see details in Table 28). The building envelopes and equipment performance specifications in Table 29 and Table 30 are based on the requirements of the U.S. DOE Zero Energy Ready home (U.S. Department of Energy, 2013). Where not specified by the DOE program, envelope elements complied with the IECC 2012 (see Table 32). All test cases are representative of very high performance, efficient homes, with IECC 2012 envelopes, Energy Star windows, HVAC ducts located in conditioned space with no leakage, etc. Henderson & Rudd (2010) noted primary factors affecting moisture in high performance homes, and these were varied in our simulations, including internal moisture generation rates and sensible gains. Fixed cooling and heating set points of 76°F (24.4°C) and 71°F (21.7°C) were used, which match assumptions of the Building America reference home (Engebrecht & Hendron, 2010).

Geometry	***Home Size***		
	Small	***Medium***	***Large***
Conditioned Floor Area (m^2)	100	200	300
Conditioned Volume (m^3)	250	500	750
Stories (#)	1	1	1
Wall Length (m)	14.14	20.00	24.49
Wall Width (m)	7.07	10	12.25
Perimeter Length (m)	42.43	60	73.48
Window Area (m^2)	20	40	60
Above Grade Wall Area (m^2)	92.4	119.0	134.7
Height Above Ground (m)	0.3	0.3	0.3
Wall Height (m)	2.5	2.5	2.5
Floor Height (m)	0.15	0.15	0.15
Height at Soffit (m)	2.95	2.95	2.95
Roof Overhang (m)	0.5	0.5	0.5

Table 28 Simulation home geometry.

	Hot Climates (zones 1-2)	***Mixed Climates (zones 3-4 except marine)***
Furnace AFUE	80	90
Air Conditioner SEER	18	15
Ventilation System	1.4 cfm/watt	1.4 cfm/watt
Window SHGC	0.25	0.27
Window U-value	0.4	0.3

Table 29 U.S. DOE Zero Energy Ready Home HVAC program requirements.

IECC Climate Zones	***1-2***	***3-4***
Infiltration (ACH_{50})	3	2.5

Table 30 U.S. DOE Zero Energy Ready Home airtightness requirements.

For moisture storage in the home, a mass transport coefficient and total mass storage capacity were used that were determined empirically by comparing predicted humidity variation to measured field data in houses (from (CDH Energy Group & Building Science Corporation, 2005; Rudd & Henderson, 2007)). Both coefficients scale with house size (floor area): the total mass capacity for storage was 12.3 lbs./ft^2 (60 kg/m^2) of floor area, and the mass transport coefficient was 0.0006 lbs./(s-ft^2) (0.003 kg/(s-m^2)). The resulting damping in indoor air moisture variability is close to the empirical formulation in the Environmental Protection Agency's (2001) Indoor Humidity Assessment Tool, which uses a capacitance term to allow only 5 to 10% of moisture flow into a space to go into the air and assumes the other 90 to 95% is absorbed by building contents (U.S. EPA, 2001).

Three moisture generation rates were used to represent typical, high and low occupancy homes—6.5, 11.8 and 3 kg/day, respectively. From our previous work (Walker & Sherman, 2007), the typical value of 6.5 kg/day is based on design values from ASHRAE 160 (2009) for a three bedroom four occupant homes (13.8 kg/day). We assume that bathing, cooking and dishwashing moisture is exhausted through local fans, so we subtract 4 kg/day (estimate from NIST (Emmerich, Howard-Reed, & Gupte, 2005)) from this design value. The resulting rate of 9.8 kg/day is then corrected to 6.5, with an assumption that the home is only occupied 2/3 of the time. The high occupancy level assumes continuous occupancy and an additional two occupants (who each add 1 kg/day per ASHRAE 160) for a total of 11.8 kg/day (9.8 + 2).

The low occupancy case would only have two people in the home 2/3 of the time for a generation rate of 3 kg/day.

Sensible internal heat gains (see Table 31) also varied with occupancy and were calculated using the formula for the reference home in the Home Energy Rating System (HERS) Standards (RESNET, 2006) Table 303.4.1(3). We assumed that the moisture and sensible loads are generated evenly throughout the day.

Conditioned Floor Area (m^2)	Number of Occupants	Sensible Heat Gains (w)
100	6	773
200	4	836
300	2	899

Table 31 Sensible heat gains (w) calculated across floor areas and occupancies.

Local exhausts simulated in REGCAP include bathroom and kitchen fans, as well as a vented clothes dryer. The dryer is assumed to have airflow of 71 l/s, kitchen exhaust is 47 l/s and all bathroom fans are 24 l/s. Bathroom exhaust fans are operated in a way that scales with the level of occupancy. Regardless of home size, 14,600 minutes of annual bathroom exhaust fan usage is assumed per occupant (i.e., 40-minutes per day per person). This leads to 29,200 (80 minutes per day), 58,400 (160 minutes per day) and 87,600 minutes (240 minutes per day) of annual bathroom exhaust usage in the 2, 4 and 6 occupant test cases, respectively.

Envelope Insulation Requirements	***1A***	***2A***	***3A***	***4A***
Window U-value	0.4	0.4	0.3	0.3
Window SHGC	0.25	0.25	0.27	0.27
Ceiling	30	38	38	49
Wood frame wall	13	13	20	20
Floor	13	13	19	19
Slab	0	0	0	10/2ft
Crawlspace wall	0	0	5 or 13	10 or 13

Table 32 Building envelope requirements from the 2012 International Energy Conservation Code (IECC 2012).

Baseline cases were run with whole house ventilation fans sized to meet 100%, 50% and 0% of the 62.2-2013 Q_{fan} requirement. The whole house ventilation system was modeled as a CFIS system sized to meet ASHRAE 62.2-2013 requirements. The total ventilation rate (Q_{tot}) was calculated using Equation 10, and the annual average infiltration (Q_{inf}) was estimated using Equation 11. The CFIS system (Q_{fan}), which ran on a 33% duty cycle, was then sized according to Equation 12, as the total ventilation rate minus the estimated infiltration rate multiplied by three. In the baseline case, the CFIS system always operated for 20 minutes of every hour, independent of heating or cooling cycles. For the 50% and 0% cases, the Q_{fan} value was either halved or eliminated. The power use of the central air handler was assigned to mechanical ventilation when no heating or cooling demand existed. Fan energy was otherwise assigned to the central air handler.

$$Q_{tot} = 0.15A_{floor} + 3.5(N_{br} + 1)$$

Q_{tot} = total required ventilation rate, L/s
A_{floor} = conditioned floor area, m^2
N_{br} = number of bedrooms

Equation 10 ASHRAE 62.2-2013 Total Required Ventilation Rate, Equation 4.1b

$$Q_{inf} = \frac{NL \times wsf \times A_{floor}}{1.44}$$

Q_{inf} = effective annual average infiltration rate, L/s
NL = normalized leakage
wsf = weather and shielding factor (normative appendix B)
A_{floor} = floor area, m^2

Equation 11 ASHRAE 62.2-2013 Effective annual average infiltration rate, Equation 4.5b.

$$Q_{fan} = 3 \times (Q_{tot} - Q_{inf})$$

Q_{fan} = required mechanical ventilation rate, L/s
Q_{tot} = total required ventilation rate, L/s
Q_{inf} = effective annual average infiltration rate, L/s

Equation 12 ASHRAE 62.2-2013 Required Mechanical Ventilation Rate, Equation 4.6, operated on a 33% duty-cycle.

3.1.1 REGCAP Dehumidifier Model and Sizing

For the purposes of this work, a dehumidifier model was developed and added to the existing REGCAP program. The dehumidifier implementation in the model accounts for house- and system-level interactions. For example, moisture removal by the dehumidifier affects cooling coil performance and system runtime, and sensible heat gains from the dehumidifier serve to increase the cooling and reduce the heating loads. When dehumidifiers are implemented in post-processing (as in Martin (2014)), these interactions are lost, and they can account for substantial portions of the energy use attributed to dehumidification.

Dehumidifier performance can be characterized by two values—Capacity and Energy Factor. The AHAM DH-1-2008 test method specifies the standard conditions and methods under which these values should be measured (ANSI, 2008). Capacity is defined as "…a measure of the ability of a dehumidifier to remove moisture from its surrounding atmosphere" and is measured in pints per day. Energy Factor is defined as:

$$EF = \frac{m}{e\rho}$$

EF = energy factor (L/kWh);
m = mass of condensate collected during the capacity test period (kg);
e = energy consumption measured during the capacity test period (kWh);
ρ = density of water at the test temperature (1.0 kg/L).

Equation 13 Energy factor calculation from AHAM DH-1-2008 test method.

Why the test method uses a mix of unit systems is not clear, but it can lead to incorrect values if the user is not careful. Maybe the Capacity is in IP for historical reasons or consumer acceptance, while the Energy Factor is new and was calculated in SI. We have kept the units of the model inputs as defined for consistency. Until recently both Energy Star and DOE have used the standard test condition for measurement of Capacity and Energy Factor (see table below). However, due to concerns that this condition was at a higher temperature than typically experienced by either portable or central residential dehumidifiers, the DOE standards have recently been revised to use lower temperatures.

Test	Dry-bulb Temperature	Wet-bulb Temperature	Corresponding RH
Standard	80° F (26.7° C)	69.6° F (20.9° C)	59.3%
Maximum operating conditions	90° F (32.2° C)	74.8° F (23.8° C)	49.1%
Low Temperature	65° F (18.3° C)	56.6° F (13.7° C)	59.2%

Table 33 Dehumidifier standard test conditions for determination of capacity and Energy Factor.

The new revisions to the DOE test standards will: (1) Incorporate provisions for representative test setup and test conduct for whole-home dehumidifiers; (2) reduce the test room ambient dry-bulb temperature for portable dehumidifiers to 65 degrees Fahrenheit (°F), and for whole-home dehumidifiers, to 73 °F; (3) modify the definition for 'off-cycle mode' to incorporate fan operation when the compressor has cycled off; (4) introduce a test procedure for off-cycle mode; (5) incorporate instructions for determining whole-home dehumidifier case volume; and (6) introduce various adjustments to further improve repeatability and reproducibility while minimizing test burden (Department of Energy, 2014).

Testing performed at NREL found that a single set of performance curves can accurately predict the performance of all the dehumidifiers they assessed (J. Winkler, Christensen, & Tomerlin, 2011; Jon Winkler, Christensen, & Tomerlin, 2014). The form of the Capacity and Energy Factor adjustment curves used in the REGCAP model are provided in Equation 14 and the coefficients are listed in Table 34.

$$AdjustmentFactor = a + b * T + c * T^2 + d * RH + e * RH^2 + f * T * RH$$

Equation 14 Performance parameter adjustments developed in dehumidifier testing by NREL.

Coefficient	**Capacity**	**Energy Factor**
a	-1.1625	-1.9022
b	0.022715	0.063467
c	-0.00011321	-0.00062284
d	0.021111	0.039540
e	E-6.9303E-05	-0.00012564
f	0.00037884	-0.00017672

Table 34 Normalized Capacity and Energy Factor coefficients.

User inputs in the REGCAP model include dehumidification capacity (pints/day), energy factor (L/kWh), relative humidity set point (%) and the dead band (+/-%). Outputs of the model include energy use (kWh), humidity removed (kg), and hours of operation.

First the moisture removal capacity is converted from pints/day to kg/s using Equation 15. Then the real-time moisture removal capacity is calculated using Equation 16. This condensate flow (kg/s) is scaled down linearly during the first four minutes of each dehumidifier cycle, such that the full condensate flow is not achieved until minute four (minute one = 25% of flow, minute two = 50% of flow, etc.). The resulting moisture removal mass flow rate is used in the house moisture balance. Power demand of the dehumidifier is calculated with Equation 17, and sensible heat gains to the space are calculated with Equation 18. Energy factors were assigned based on dehumidifier capacity, with Energy Factors of 1.85 and 2.8 assumed for units <75 and >75 pints/day of capacity, respectively.

$$capacityRated = cap * 0.4732 / (24 * 60 * 60)$$

capacityRated = Removal capacity in SI units (kg/s)
cap = Rated mass flow rate of moisture removal by dehumidifier (pints/day)

Equation 15 Conversion from rated capacity from pints/day to kg/second.

$$condensate = capacityRated * capacity_{adj}$$

condensate = real-time mass flow rate of moisture removal by dehumidifier (kg/s)
capacityRated = rated moisture removal capacity (kg/s, see Equation 15)
$capacity_{adj}$ = capacity adjustment factor, calculated with Equation 14 and house air dry-bulb temperature and relative humidity conditions.

Equation 16 Real-time condensate removal rate.

$$power = \frac{condensate * 3{,}600 * EF}{EF_{adj}}$$

power = dehumidifier energy demand (watts)
condensate = real-time mass flow rate of moisture removal by dehumidifier (kg/s)
EF = rated Energy Factor
EF_{adj} = adjustment factor from Equation 14, using real-time dry-bulb temperature and relative humidity conditions.

Equation 17 Dehumidifier power consumption calculation.

$$sensible = condensate \times h_{da} + power$$

sensible = sensible heat gains (watts)
condensate = real-time mass flow rate of moisture removal by dehumidifier (kg/s)
h_{da} = heat of vaporization for moist air mixture (J/kg)
power = dehumidifier energy demand (watts)

Equation 18 Sensible heat gains generated by dehumidifier operation.

The dehumidifiers included in each simulation were sized consistent with Table 2 in Rudd (2013b), and the specific capacities used in REGCAP simulations are listed for all combinations of house size and moisture gains in Table 35.

House Size	***Dehumidifier Rated Capacity (pints per day)***		
	Internal Moisture Gains		
	Low	***Medium***	***High***
Small	46	52	62
Medium	46	52	62
Large	66	72	82

Table 35 Rated dehumidifier capacities used in REGCAP simulations.

4 Results

4.1 Baseline Simulations

High performance, zero-energy ready homes were simulated in six humid climates. The simulations used CFIS systems that operated for 20 minutes out of every hour. The CFIS ventilation flows were set to achieve 50% and 100% of ASHRAE 62.2-2013 when averaged over an hour (i.e., the airflow rate when operating was three times the 50% or 100% targets). These were done for prototype homes with and without mechanical dehumidification. Homes varied in size (small, medium and large) and in internal moisture gains (low, medium and high). The results are summarized and discussed below. All baseline simulation data are provided in tabular form in Appendix Table 44, including energy end-uses, cooling and dehumidifier runtimes, average air exchange, relative dose and exposure, and hours of indoor RH >60 and >70%.

4.1.1 Performance at 100% of 62.2-2013

4.1.1.1 Annual Humidity Performance

The humidity performances for simulations with mechanical ventilation sized to 100% of ASHRAE 62.2-2013 are summarized by climate zone and presence of a dehumidifier in Table 36. Values presented include indoor humidity distribution statistics, fraction of annual hours above 60% and 70% RH, maximum continuous periods of high indoor humidity, and Annual Humidity Index. These values are averaged across house sizes and moisture gains. The variability within climate zones, internal moisture gains and house sizes are highlighted in Figure 17, Figure 18 and Figure 19, respectively. Not surprisingly, hours of high indoor humidity increased as climates became hotter and more humid, internal gains increased, and houses became smaller. As a reference, these same plots are provided for the Annual Humidity Index (see calculation in Section 2.3.1) in the Appendix in Figure 45, Figure 46 and Figure 47. The trends are all similar, as expected.

In roughly 1/3 of baseline simulations without dehumidification (100% of 62.2-2013) more than 5% of annual hours exceeded the 60% RH threshold, and we consider these cases to require supplemental humidity control of some sort. These cases tended to be smaller homes, with higher moisture gains in more hot and humid locations. In these higher moisture cases, annual fractions of hours >60% RH were in the range of 10 to 40% of the year, which is in good alignment with field measurements in high performance homes (Kerrigan & Norton, 2014; Rudd & Henderson, Jr., 2007). Periods of indoor humidity >70% were much more rare, occurring on average less than 1% of annual hours (0 to 5%).

Continuous periods of high indoor humidity persisted in these cases, with average durations in the 30- to 60-hour range. The maximum duration for any simulated home was 95-hours continuously >60% RH, and this was the small home with high moisture gains located in Charleston. The maximum durations of high indoor humidity were not the longest in the hottest and most humid location (i.e., Miami), rather locations like Orlando, Houston and Charleston had much longer continuous periods. This was likely the result of their relatively lower cooling demands.

When these same homes were simulated with appropriately sized mechanical dehumidification equipment, indoor humidity conditions were maintained in the acceptable range (see Table 36), with generally less than 1% of annual hours remaining >60% RH. Shifts in annual average moisture levels were very small (1-2%), but the maximum indoor humidity was typically reduced substantially. This actually contrasts with field measurements of high performance homes in humid climates with whole-house dehumidifiers, where annual hours >60% RH typically remain in the 10-15% range (Kerrigan & Norton, 2014; Rudd & Henderson, Jr., 2007). This may be the result of installation of insufficient dehumidification capacity. It could also be the result of the indoor moisture gain assumptions used in our modeling—namely the moisture gain is constant throughout the day. This assumption likely reduces the peaks (positive and negative) in daily indoor RH, which could reduce periods during each day that would exceed 60% temporarily in an actual occupied home.

In general, the dehumidifiers eliminated all continuous periods of high indoor humidity, though some remained in the cases with the highest indoor humidity. The maximum fraction of annual hours above 60% RH with a dehumidifier operating was 2.9% (and the maximum hours >70% RH was 0.1% of the year).

For a detailed view of dehumidifier and ventilation system interaction, Figure 20 shows one-minute data from the 1st of June for a small Houston home with high moisture gains. The outdoor humidity ratio (red line) is substantially higher than the indoor HR (purple line) during the entire day. As a result, every time the CFIS system operates (shaded teal regions), the indoor RH (green line) is driven rapidly upwards. The dehumidifier set point (55%) and dead band (+/- 2.5%) are shown by horizontal dotted lines. Whenever indoor RH exceeds the upper dead band (dotted red), the dehumidifier operates (shaded grey regions). Once the house RH drops below the lower dead band (dotted blue), the dehumidifier turns off. During some periods, the ventilation airflow and indoor-outdoor humidity difference is sufficient to overwhelm operation of the dehumidifier, leading to continued net-increases in indoor moisture and RH (for example, see the cycles between 03:00 and 05:00AM).

Dehumidifier?	*Climate Zone*	*Indoor Relative Humidity (%)*						*Annual Hours (%)*		*Max Period (hours)*		*Annual Humidity Index (hours)*
		Min	*25th*	*Median*	*Mean*	*75th*	*Max*	*>60 % RH*	*>70 % RH*	*>60 % RH*	*>70 % RH*	
Yes	Miami	35	47	50	50	53	72	0.6	0.1	11.3	6.0	4.1
No	Miami	35	48	51	52	56	82	11.4	0.7	31.9	12.7	100.7
Yes	Orlando	30	44	48	48	52	61	0.2	0.0	0.2	0.0	0.6
No	Orlando	30	45	49	49	54	79	8.7	0.8	62.0	14.4	85.3
Yes	Houston	25	43	48	47	52	62	0.3	0.0	0.3	0.0	0.8
No	Houston	25	44	49	49	54	79	9.7	0.8	47.8	7.6	89.4
Yes	Charleston	24	43	48	47	52	62	0.3	0.0	0.3	0.0	0.7
No	Charleston	24	44	49	48	54	73	8.7	0.6	49.3	7.7	76.7
Yes	Memphis	19	36	44	42	48	61	0.1	0.0	0.2	0.0	0.15
No	Memphis	19	36	44	43	49	67	2.5	0.1	6.6	0.8	16.7
Yes	Baltimore	17	28	40	38	46	60	0.0	0.0	0.1	0.0	0.0
No	Baltimore	17	28	40	38	47	64	1.4	0.0	6.6	0.2	8.4

Table 36 Annual humidity summary by climate zone of homes with and without dehumidifiers, averaged across house size and moisture gains. Includes only homes with 100% of 62.2-2013 mechanical ventilation rates.

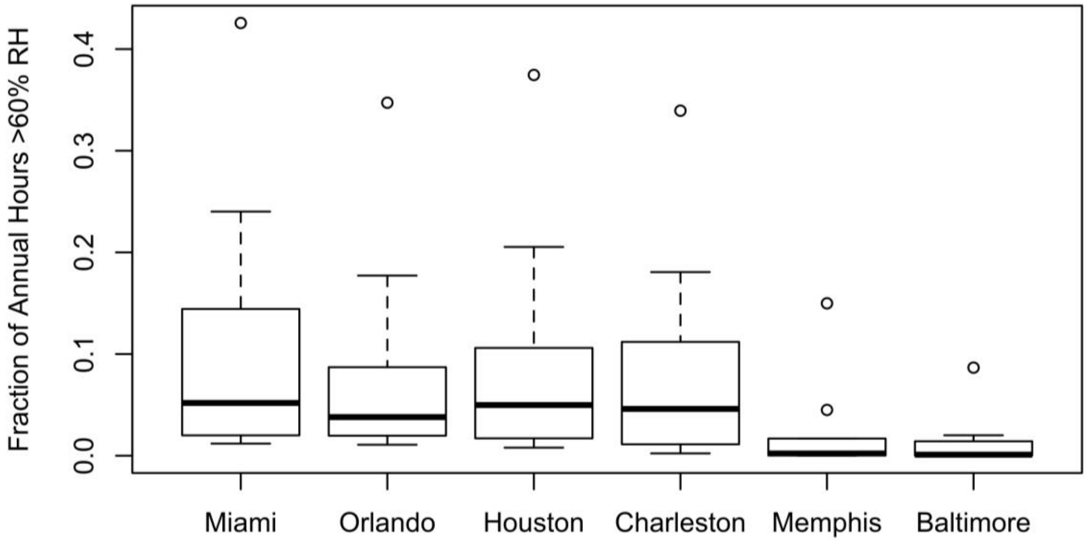

Figure 17 Variability in the fraction of annual hours exceeding 60% RH by climate zone, averaged across house size and moisture gains (n = 9 for each climate location). Includes only homes with 100% of 62.2-2013 ventilation rates and no dehumidification.

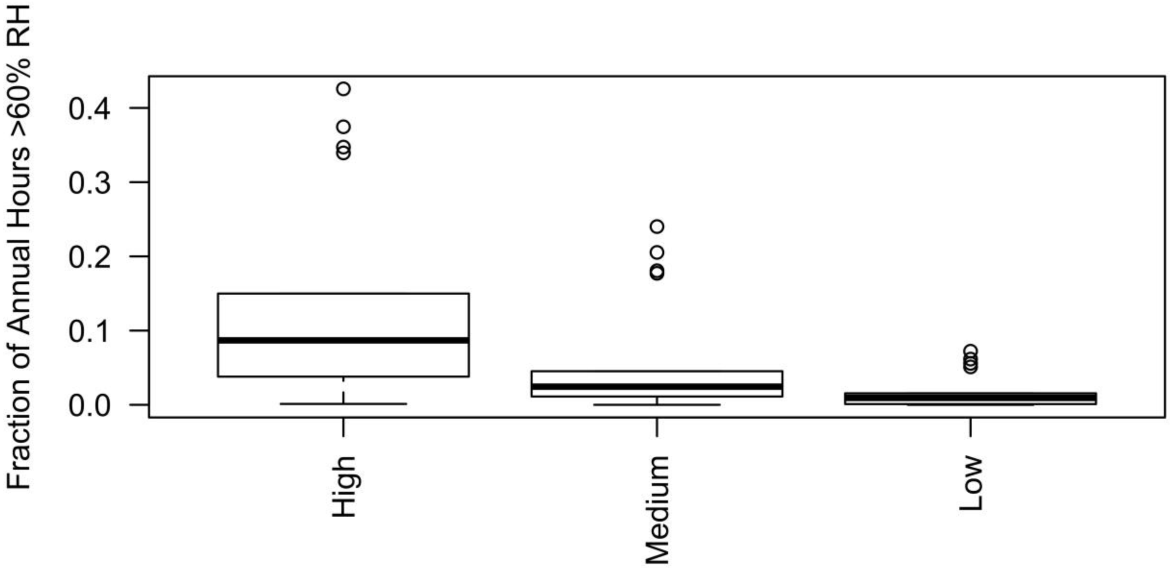

Figure 18 Variability in the fraction of annual hours exceeding 60% RH by internal moisture gains, averaged across house size and climate zones (n = 18 for each moisture gain rate). Includes only homes with 100% of 62.2-2013 ventilation rates and no dehumidification.

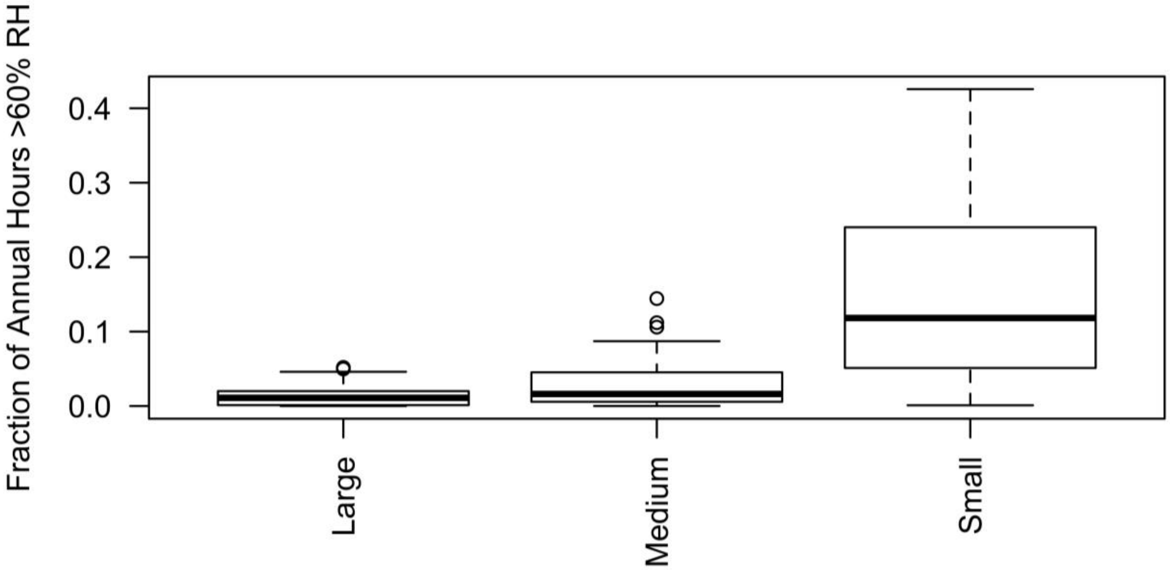

Figure 19 Variability in the fraction of annual hours exceeding 60% RH by house size, averaged across internal moisture gains and climate zones (n = 18 for each house size). Includes only homes with 100% of 62.2-2013 ventilation rates and no dehumidification.

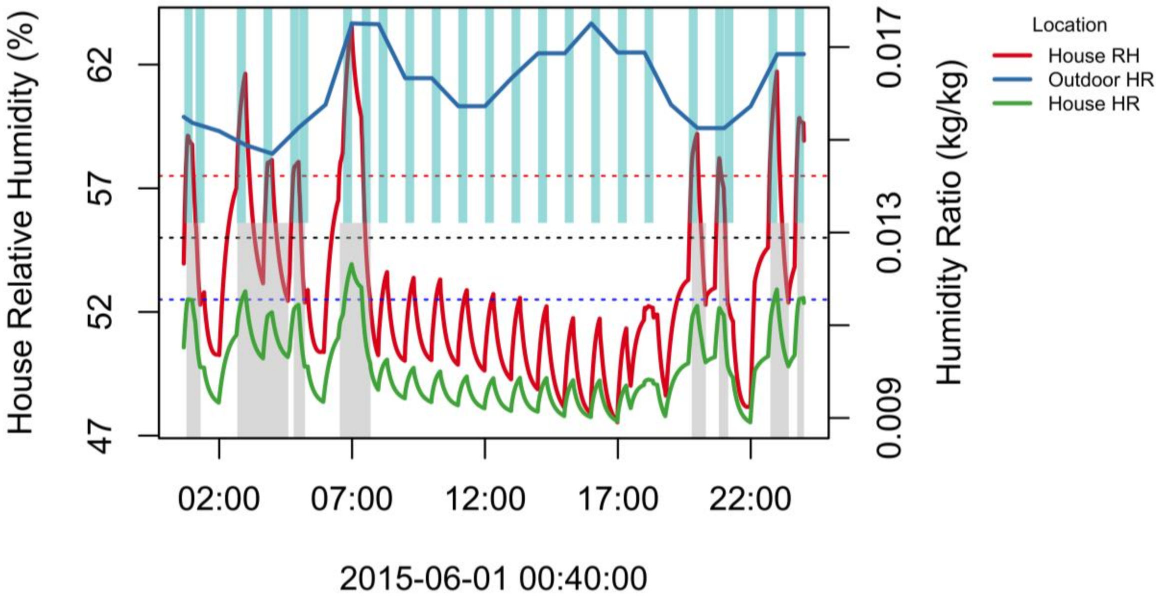

Figure 20 Example plot of house relative humidity, as well as indoor and outdoor humidity ratios during dehumidifier (shaded grey regions) and CFIS ventilation fan operation (shaded teal regions) in a small home with high moisture gains in Houston, TX. A single, continuous cooling cycle occurs roughly between 07:00 and 19:00, hence moisture removal during periods with CFIS off.

4.1.1.2 Seasonal and Daily Patterns in High Indoor Humidity

In order to understand the patterns in elevated humidity in the simulated homes, we created monthly and hourly profiles of high humidity. These are essentially the count of hours during a given period where indoor RH was >60%. These were calculated for each simulation run, and then they were averaged for each climate zone. We included only those runs where more than 5% of annual hours were >60% RH (as mentioned above, this was 19 of 54, or 35% of baseline cases). This removed most of the zero values from the climate zone-averaged trends. The monthly and hourly profiles are pictured in Figure 21 and Figure 22, respectively.

In the monthly profiles (Figure 21), we see the clear pattern for indoor humidity to peak during shoulder seasons, when outside moisture levels are increasing, but the sensible cooling load is low. These shoulder season months are different in each climate zone, but they generally include February-April and September-November. Increasing outdoor moisture, coupled with little cooling operation, leads to elevated indoor RH. Nearly all locations have the best humidity control during the summer, when cooling operation is strong, even in these low-load homes.

In the hourly profiles (Figure 22), we see the clear pattern for indoor humidity to be lowest during the day, increase over the nighttime period and peak during the early morning hours. Again, we believe this is the result of cooling system operation being aligned with sensible heat loads, which are driven by daytime solar radiation.

These results are consistent with reports from past research on moisture in high performance homes that found the highest indoor humidity during early morning hours and during shoulder seasons (Rudd et al., 2013; Rudd & Henderson, Jr., 2007).

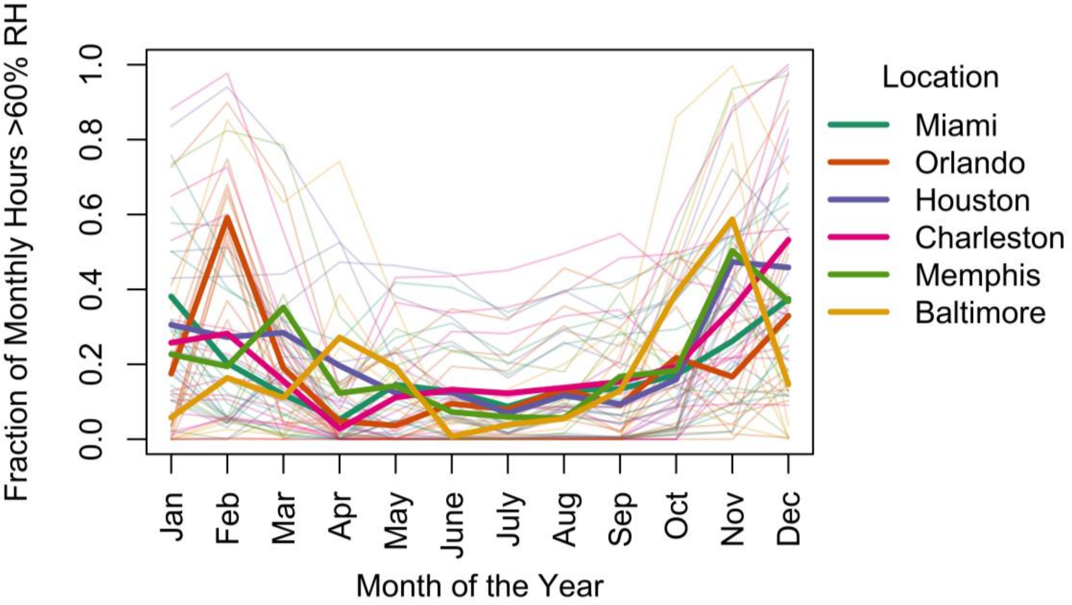

Figure 21 Average fraction of monthly hours above 60% RH, grouped by climate zone. Includes only homes with no dehumidification, where more than 5% of annual hours were >60% RH. The lighter, opaque lines represent individual simulations (colored by climate zone), while the bold lines represent the climate zone averages.

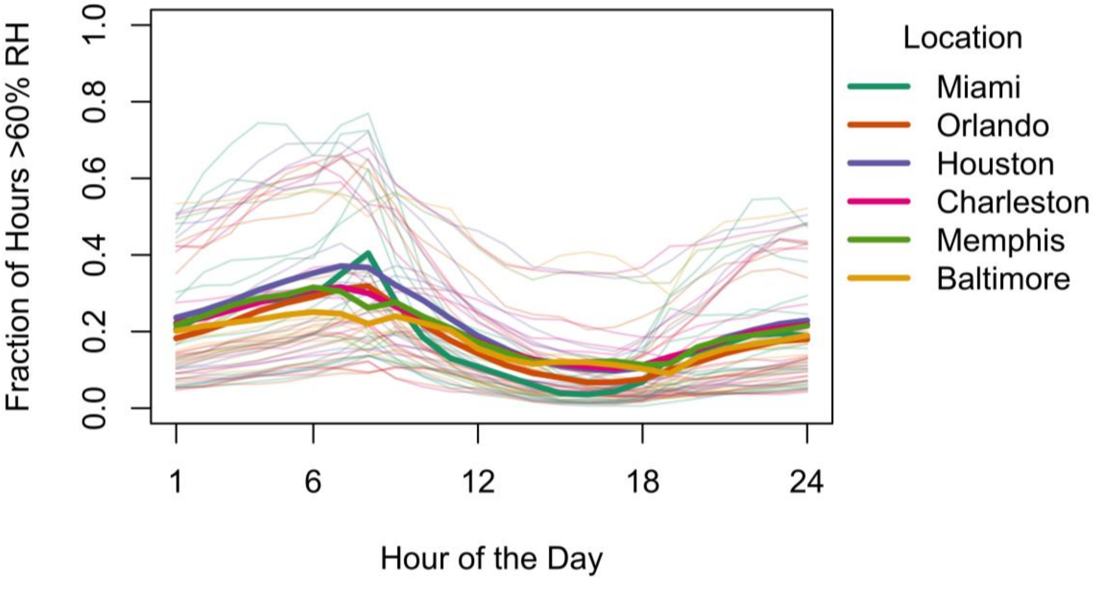

Figure 22 Average fraction of hours above 60% RH, grouped by climate zone. Includes only homes with no dehumidification, where more than 5% of annual hours were >60% RH. The lighter, opaque lines represent individual simulations (colored by climate zone), while the bold lines represent the climate zone averages.

4.1.2 Annual Energy Performance

For the baseline cases with mechanical ventilation systems sized to 100% of ASHRAE 62.2-2013, the energy performances (Table 37) are summarized by climate zone for each end-use below, including total HVAC, air handler, heating, cooling, mechanical ventilation and dehumidifier energy consumptions. These values are averaged across house sizes and moisture gains. The variability of dehumidifier energy consumption with climate zone, internal moisture gains and house sizes are highlighted in Figure 23, Figure 24 and Figure 25, respectively. Unsurprisingly, dehumidifier energy consumption follows the same trends as the indoor humidity results presented in Section 4.1.1.1.

Addition of a dehumidifier always increased annual total HVAC energy consumption (see Table 37), ranging roughly from 0 to 1,200 kWh. These values are right in line with data from dehumidifier energy consumption in occupied homes (Whitehead et al., 2013), albeit not high performance homes. Not surprisingly, dehumidifier energy use scaled roughly with the fraction of annual hours >60% RH (see Figure 26, colored by climate zone). The energy consumption required for this mechanical humidity control varied most strongly by location and internal moisture gains. Dehumidifier energy use increased as homes became smaller, and as outdoor humidity and moisture gains increased. This was the case even though the installed capacities were lower in these smaller homes.

Secondary dehumidifier impacts on HVAC energy end-uses (e.g., heating and cooling) are marginal, but worth noting. Heating energy typically went down, due to sensible heat released by operation of the dehumidifier (see Section 3.1.1). Cooling energy and runtime increased with a dehumidifier. We expected cooling system runtimes to be reduced when a dehumidifier operated due to the higher sensible heat ratios (SHR) experienced in a dehumidified home. The higher SHR should require less runtime to meet a given sensible load, since more of the cooling capacity is going to temperature change, rather than moisture removal. But the increased sensible heat gains from dehumidifier operation clearly overwhelmed this runtime effect. In our model, CFIS fan energy is only counted against ‘Mechanical Ventilation’ when there is no heating or cooling call, so not surprisingly, Mechanical Ventilation energy was reduced slightly with dehumidifier operation, since more hours of operation occurred during the increase cooling runtime.

		Annual Energy Consumption (kWh)					
Dehumidifier?	***Climate Zone***	***Dehumidifier***	***Air Handler***	***Heating***	***Cooling***	***Mechanical Ventilation***	***Total***
Yes	Miami	437	458	17	5869	202	6984
No	Miami	0	444	21	5713	208	6386
Yes	Orlando	298	343	1209	4250	188	6289
No	Orlando	0	335	1254	4155	192	5936
Yes	Houston	332	348	4680	3930	182	9473
No	Houston	0	340	4739	3829	186	9094
Yes	Charleston	321	335	4052	4066	266	9040
No	Charleston	0	326	4112	3955	270	8663
Yes	Memphis	105	343	7613	3674	255	11990
No	Memphis	0	339	7618	3630	257	11844
Yes	Baltimore	57	290	12269	2329	187	15131
No	Baltimore	0	288	12279	2304	187	15059

Table 37 Annual end-use energy consumption by climate zone of simulated homes with and without mechanical dehumidification, averaged across house size and moisture gains. Includes only homes with 100% of 62.2-2013 mechanical ventilation rates.

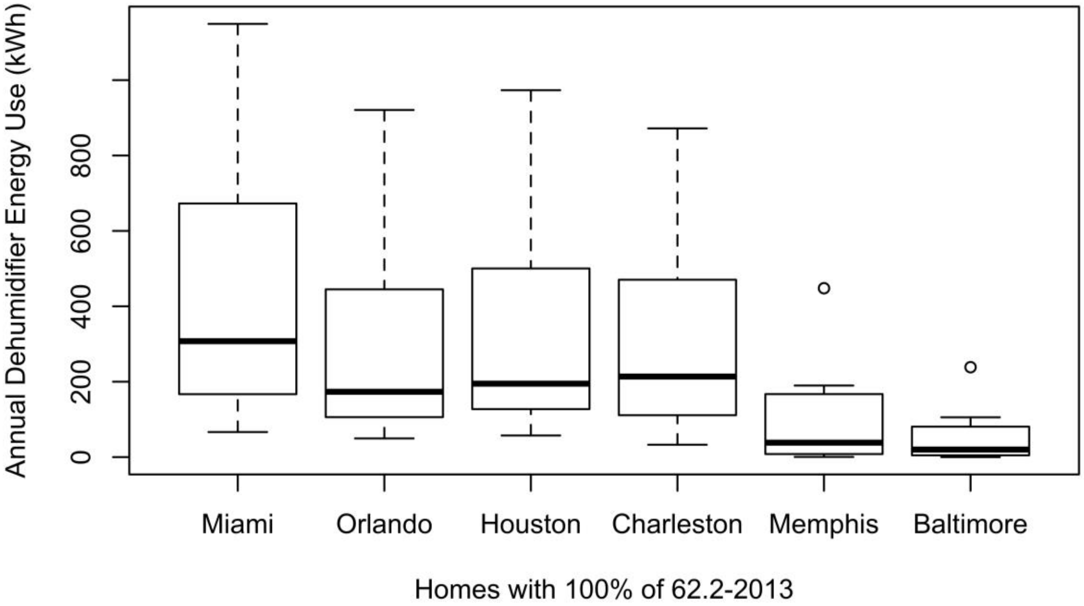

Figure 23 Variability in annual dehumidifier energy consumption by climate zone. Includes only homes with 100% of 62.2-2013 ventilation rates with dehumidification.

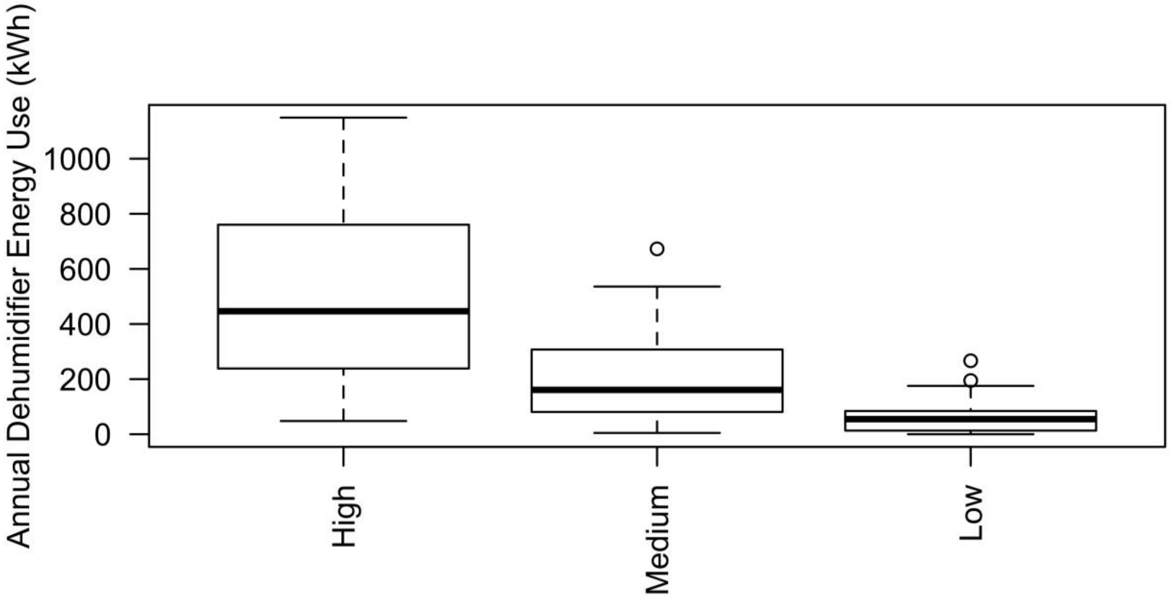

Figure 24 Variability in annual dehumidifier energy consumption by internal moisture gains, averaged across climate zones and house size. Includes only homes with 100% of 62.2-2013 ventilation rates with dehumidification.

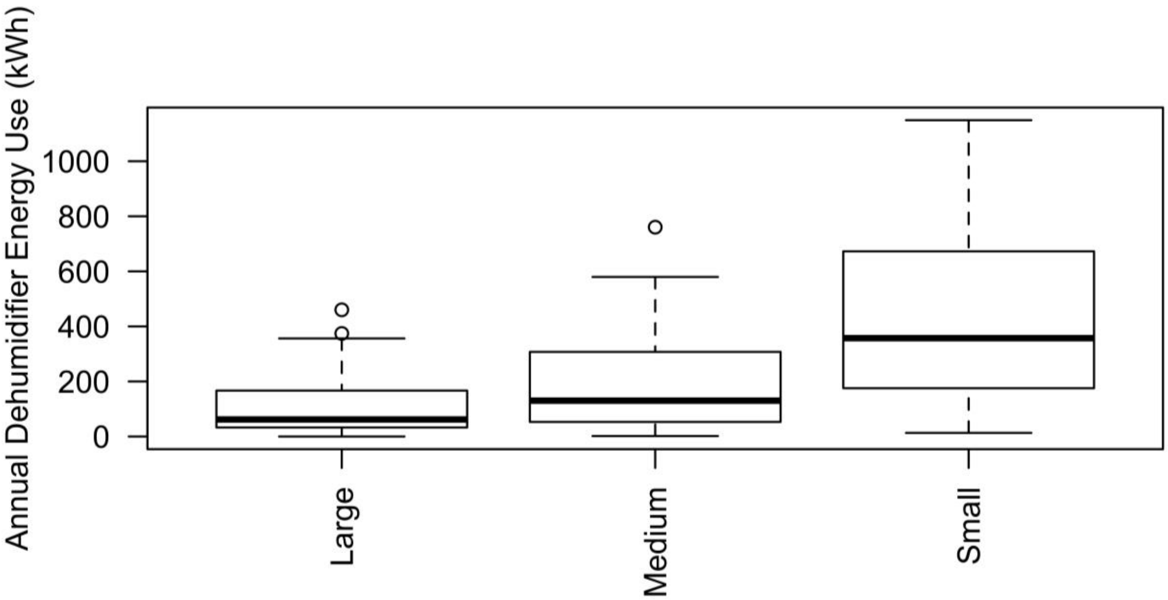

Figure 25 Variability in annual dehumidifier energy consumption by house size, averaged across climate zones and internal moisture gains. Includes only homes with 100% of 62.2-2013 ventilation rates with dehumidification.

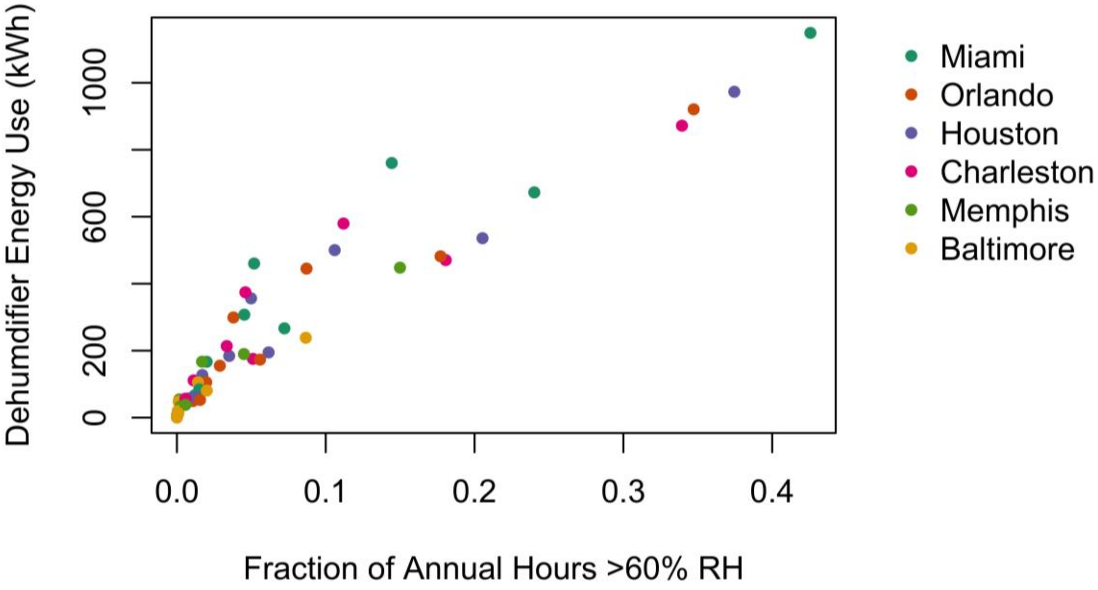

Figure 26 Correlation between the fraction of the year >60% RH and the dehumidifier energy consumption (colored by climate zone), includes only homes with mechanical ventilation sized to 100% of 62.2-2013.

4.1.3 Impacts of Varying the Ventilation Rate

The data presented in the prior sections were based on mechanical ventilation systems sized to 100% of ASHRAE 62.2-2013. Simulations were also performed with ventilation sized to 0 and 50% of 62.2-2013 requirements. Reducing ventilation rates had severe IAQ penalties. At the 50% level, exposures were approximately doubled and were increased by a factor of five at the 0% level. These are clearly not acceptable, and this analysis is given here solely for the purpose of examining the impact of mechanical ventilation on indoor humidity.

The effect on the fraction of annual hours above 60% RH of increasing the ventilation from 0 to 50 to 100% of 62.2-2013 is pictured for each combination of climate zone, house size and moisture gain in Figure 27. This figure includes only those cases where the 0% ventilation rate had more than 5% of annual hours >60% RH and there was no dehumidification, because the two-thirds of cases without any high humidity periods obscured the trends highlighted in Figure 27. Not surprisingly, in most cases, the change from 0 to 50% had a much larger impact on indoor humidity levels than the change from 50 to 100% of 62.2. The effect of changing the ventilation rate depended strongly on the combination of location, house size and moisture gains. The annual hours >60% RH were almost always greatest in the 0% ventilation case, with a few exceptions for small homes with higher gains in Miami and Orlando.

Overall, there were three categories that homes fell into in terms of how changes to the ventilation rate affected their moisture levels (see Figure 27). First, those where increasing the ventilation rate consistently reduced indoor humidity (generally smaller homes with high moisture gains in the less humid locations). Second, those where increasing the ventilation rate consistently increased indoor humidity (small homes in Miami). The third (and most common) category were those in which going from 0 to 50% of 62.2 reduced indoor humidity, but increasing from 50 to 100% increased indoor moisture once again. These subsequent increases were typically small (but not always).

Consistent with these changes in high humidity periods, there were also changes in the energy consumed by dehumidifiers in homes with different ventilation rates. Dehumidifier energy use is pictured in Figure 28 as it varied by location and ventilation rate. On average, higher ventilation rates led to greater dehumidifier energy use in the more humid locations, an effect that was strongest in the most humid locations (e.g., Miami).

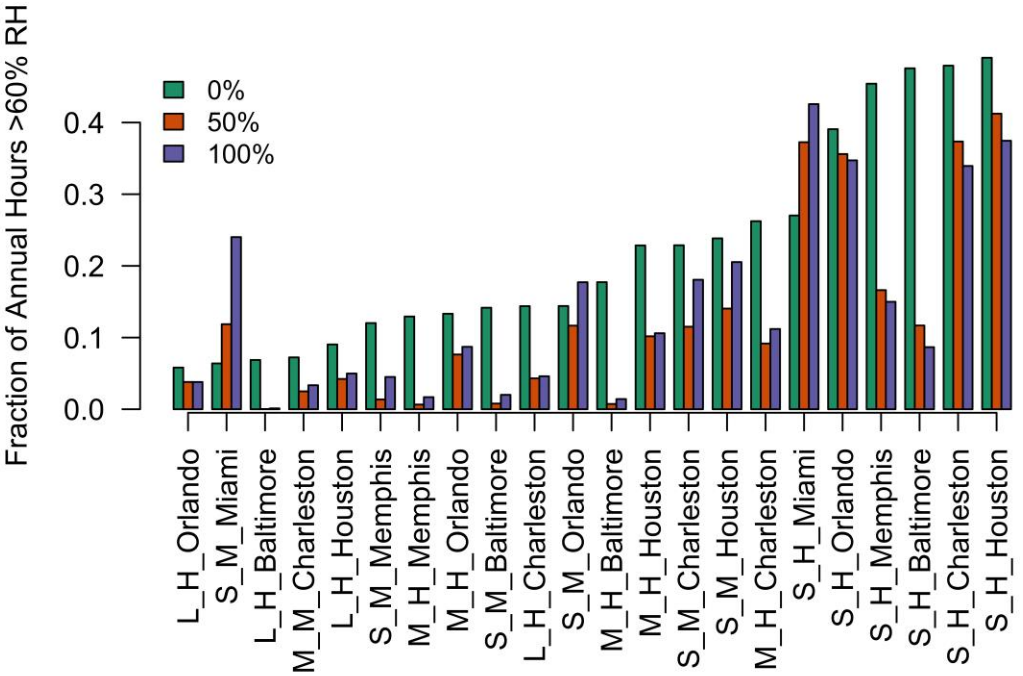

Figure 27 Changes in annual fractions of hours >60%RH due to changing the ventilation rate from 0 to 50 to 100% of ASHRAE 62.2-2013 requirements. Includes only those cases where the 0% ventilation rate led to annual fractions of at least 0.05. Labels are House Size (Small, Medium or Large)_MoistureGains (Low, Medium or High)_Location.

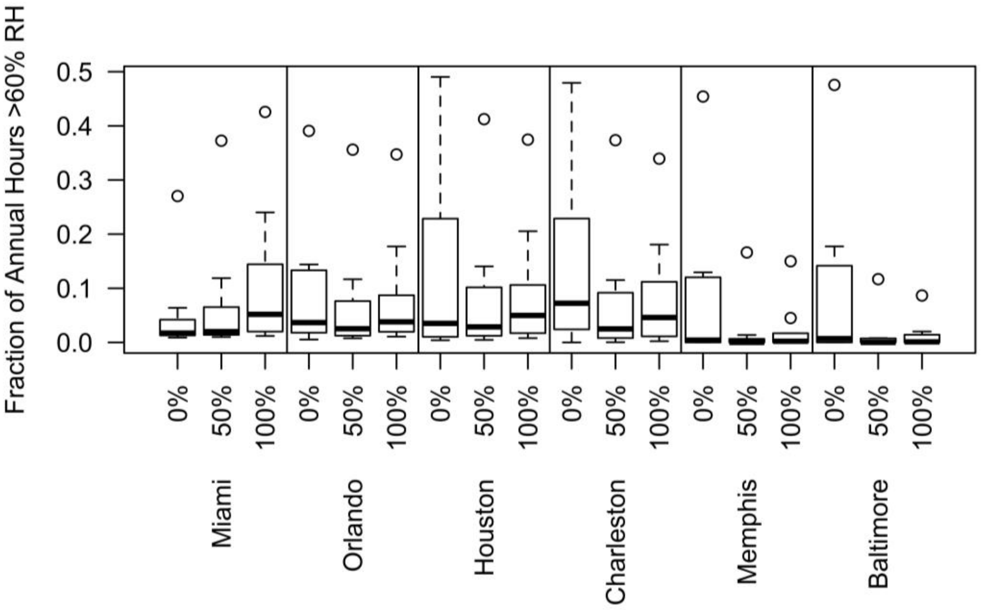

Figure 28 Variability in annual dehumidifier energy consumption by ventilation rate and climate zone, averaged across house sizes and internal moisture gains.

The expected change in indoor humidity when varying the ventilation rate is that for periods when indoor humidity is greater than outdoor, ventilation will reduce indoor moisture and lower RH. The opposite is true for periods where it is more humid outside than inside; ventilation will bring additional moisture into the home and increase RH. This effect can be assessed by looking at the difference in absolute humidity between inside and outside. We calculated this for each minute of the year, and we refer to these differences in absolute humidity as *HRdiff*. Positive values indicate it is more humid inside than outside, and negative values mean outside is more humid.

We thought that this effect would hold over the course of the year, such that if on average it was more humid inside than outside, increased ventilation would reduce indoor RH. Yet, there was not a very strong relationship, as pictured in Figure 29. This plot shows the annual average humidity ratio difference, and it shows what happened to the fraction of hours >60% RH when increasing the ventilation rate (filled circles represent changes from 0 to 50% 62.2, and filled triangles represented changes from 50 to 100%). While some trend is apparent in the expected direction (i.e., sloping down and to the right), there are many cases where it was more humid outside than inside (left quadrants), and in roughly half these cases high humidity hours increased with more ventilation (upper left), and in others high humidity hours were reduced with more ventilation (lower left). This suggests that the annual average values are not strongly predictive, likely due to complicating factors such as cooling system operation or the distribution of humidity differences (annual means could be strongly affected by shorter periods of large differences).

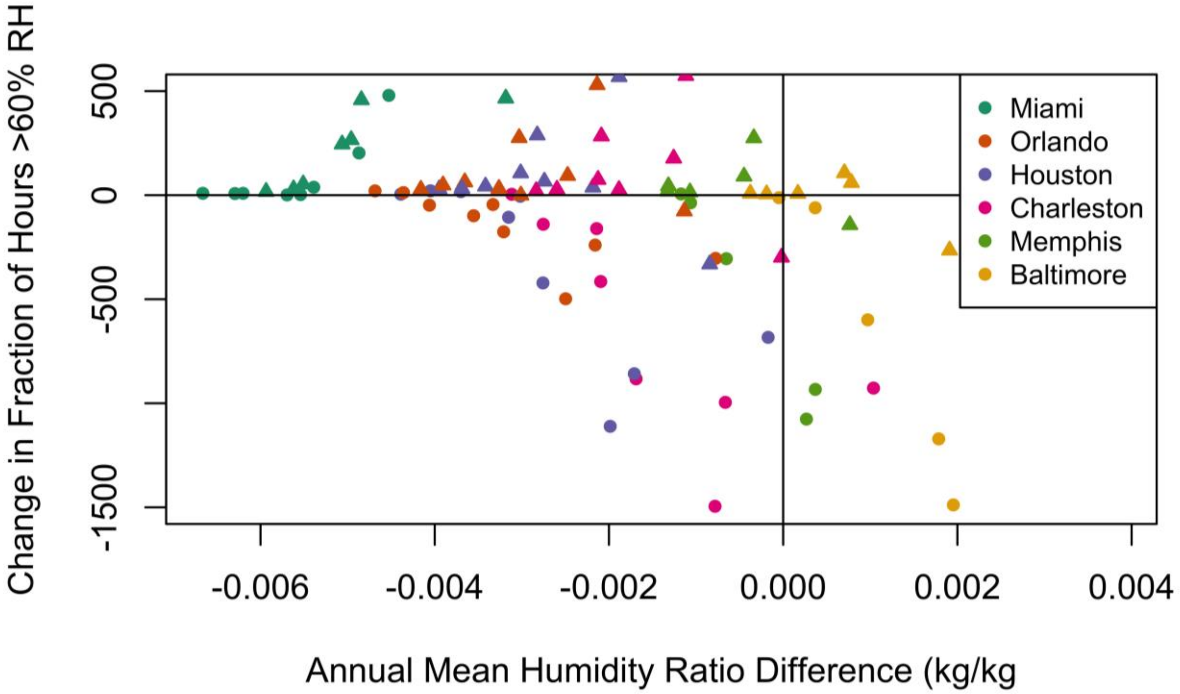

Figure 29 Changes in annual fraction of hours >60% RH, relative to the annual average humidity ratio difference inside - outside. From 0 to 50% of 62.2-2013 are filled circles, and from 50 to 100% of 62.2-2013 are filled triangles. Includes only cases without dehumidification, and where the 0% 62.2 ventilation rate led to more than 5% of annual hours >60% RH.

Unlike annual results, the monthly indoor humidity results responded as expected to changes in the ventilation rate. When more humid inside, ventilation reduced high humidity hours, and vice versa when more humid outside. These monthly data are plotted in Figure 30. Here the relationship is much more clear, and there are many fewer cases showing unexpected behavior. This highlights the fact that the effect of ventilation on indoor humidity is highly dependent on time of year and other factors, and that no overall statement is valid (e.g., we should increase/decrease ventilation to reduce/increase indoor humidity).

When mechanically dehumidifying a home, the average difference in absolute humidity gets increasingly negative (more humid outside than inside, more hours of the year). This is expected, as moisture mass is removed from the house air by the dehumidifier, while the outdoor conditions remain fixed. This shift results in larger negative humidity differences when it is more humid outside than inside, and smaller positive humidity differences when less humid outside than inside. Furthermore, some hours are shifted from a positive to a negative humidity ratio difference. These shifts are not large, but they are visible in comparing the median humidity ratio differences for all cases with and without dehumidification (at 100% of 62.2), -0.0025 vs. -0.0021 kg/kg. This larger negative humidity ratio difference means that a fixed ventilation rate will bring more moisture into a dehumidified home. The moisture introduced with outside air remains unchanged, but the moisture removed from the house with ventilation air is reduced. As a result, the time periods when ventilation provide a humidity benefit are reduced, and the periods where ventilation introduces additional moisture loading increase. This is effectively like shifting all of the points in Figure 30 up on the y-axis and left and x-axis. Not only are the time periods shifted, additional net-moisture mass is also introduced for each unit of additional air volume. These effects make the moisture penalty of ventilation worse in homes with mechanical humidity control.

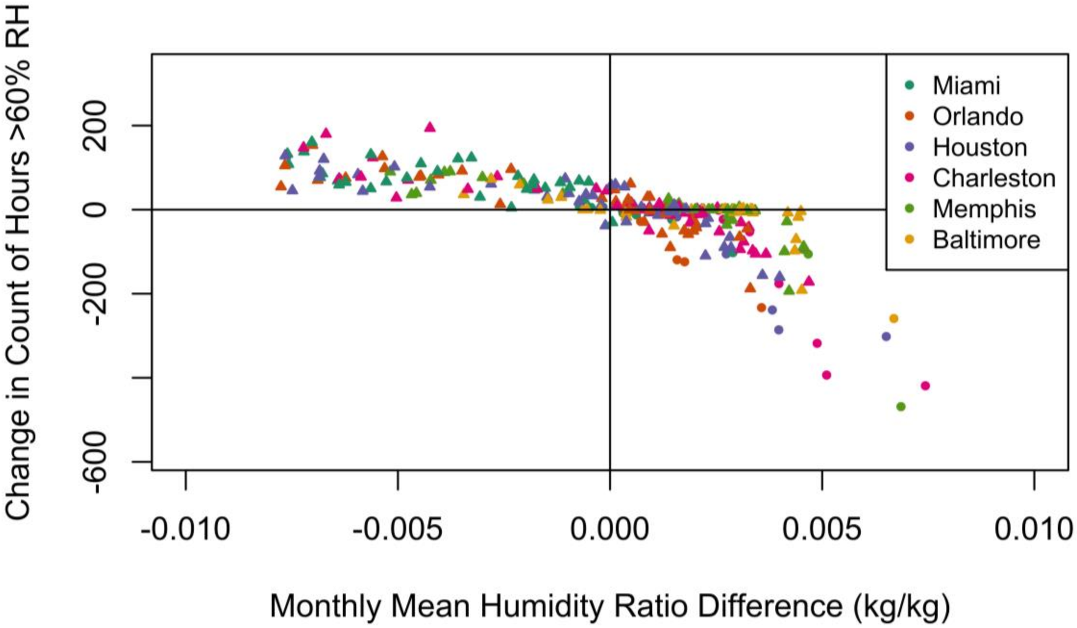

Figure 30 Correlation between monthly mean humidity ratio differences and changes in the monthly hours >60%RH. From 0 to 50% of 62.2-2013 are filled circles, and from 50 to 100% of 62.2-2013 are filled triangles. Includes only homes without dehumidification and months with hours >60% RH.

4.2 Smart Control Simulations

Smart ventilation control simulations were carried out only for those cases with ventilation systems sized to 100% of 62.2-2013, where the baseline simulations showed substantial periods of the year with indoor humidity above 60% RH (see Table 38). The ten control strategies were simulated in each climate zone with and without dehumidification for the combinations of house sizes and internal moisture gains indicated in Table 38. All smart control simulation data are provided in tabular form in Appendix Table 45, including energy end-uses, cooling and dehumidifier runtimes, average air exchange, relative dose and exposure, and hours of indoor RH >60 and >70%.

House Size \ Moisture Gains	***High***	***Medium***	***Low***
Small	X	X	
Medium	X		
Large			

Table 38 Summary of the test cases included in the smart ventilation control simulations.

4.2.1 Annual Humidity and Energy Performance

4.2.1.1 Smart Controls vs. Dehumidification

Smart ventilation controls targeting lower indoor relative humidity were reasonably successful in the simulated homes. The controls achieved substantial reductions in the annual fraction of hours >60% RH, and they shifted the indoor humidity distribution downwards. They increased annual HVAC energy consumption by amounts comparable to mechanical dehumidifiers in many cases. In some cases, the energy used to achieve reduction in high humidity was substantially less than used by a properly sized dehumidifier. The best strategies included the cooling system tie-in, variable dose targets and use of sensors. But humidity control was not equivalent between the smart control and dehumidifier cases. Smart controls provided a substantial improvement in indoor humidity conditions, without providing complete control to an RH threshold, as dehumidifiers provided.

The fraction of annual hours >60% RH and the Annual Humidity Index values are tabulated for the baseline cases (with and without dehumidification) and for smart controls (with and without dehumidification) in Table 39. These are averaged across climate zones, house sizes and internal moisture gains. The annual HVAC energy use for these four case types are in Table 40. Annual HVAC energy use increases (relative to the baseline without dehumidification) are presented in Table 41 for dehumidification alone, smart controls alone, and smart controls+dehumidification.

The only strategies that successfully reduced indoor high humidity hours controlled ventilation dynamically using two sensors, and/or used the cooling tie-in approach. Within this subset of control strategies, the most successful used high and low dose targets depending on the season, and they combined the cooling tie-in with two-sensor control. Most energy use associated with smart controls resulted from over-ventilation during the drier heating season. Strategies that limited dynamic ventilation control to periods with indoor RH >55% reduced heating energy penalties, but had poorer humidity control overall. Neither use of a single outdoor sensor nor schedules were effective. These features are discussed in greater detail below.

Control Strategy	Fraction of Annual Hours >60% RH				Annual Humidity Index (hours)			
	Base No Dehumid	Control No Dehumid	Base Dehumid	Control Dehumid	Base No Dehumid	Control No Dehumid	Base Dehumid	Control Dehumid
1	17.1%	14.1%	0.7%	0.3%	162	125	2	1
12	17.1%	12.8%	0.7%	0.2%	162	109	2	1
13	17.1%	14.3%	0.7%	1.2%	162	135	2	5
14	17.1%	16.6%	0.7%	1.3%	162	170	2	5
2	17.1%	15.5%	0.7%	0.3%	162	158	2	1
3	17.1%	14.1%	0.7%	0.3%	162	120	2	1
6	17.1%	16.5%	0.7%	1.7%	162	166	2	8
7	***17.1%***	***9.7%***	***0.7%***	***0.1%***	***162***	***74***	***2***	***1***
8	11.0%	9.9%	0.2%	0.5%	125	117	1	2
9	13.1%	10.9%	0.5%	1.2%	134	113	2	6

Table 39 Comparison of humidity performance for each control strategy, including fraction of annual hours >60% RH and the Annual Humidity Index values. Results are averaged across climate zone, house size and moisture gains. Smart control cases that were not equivalent to the base case were removed (this is why the baseline values are different for Controls 8 and 9).

Control Strategy	Total Annual HVAC Energy Consumption (kWh)			
	Base_NoDehumid	Control_NoDehumid	Base_Dehumid	Control_Dehumid
1	7225	7666	7902	8230
12	7225	9097	7902	9651
13	7225	8867	7902	9517
14	7225	8212	7902	9002
2	7225	7322	7902	8103
3	7225	7400	7902	8103
6	7225	8611	7902	9297
7	7225	9208	7902	9664
8	8218	10114	8650	10498
9	8883	11701	9364	12158

Table 40 Comparison of annual HVAC energy use for each control strategy, averaged across climate zone, house size and moisture gains. Smart control cases that were not equivalent to the base case were removed (this is why the baseline values are different for Controls 8 and 9).

Control Strategy	***Annual HVAC Energy Use Increase (kWh)***		
	Base_Dehumid	***Control_NoDehumid***	***Control_Dehumid***
1	677	441	1005
12	677	1872	2426
13	677	1642	2292
14	677	987	1777
2	677	97	878
3	677	175	878
6	677	1386	2072
7	677	1983	2439
8	432	1896	2280
9	481	2818	3275

Table 41 Annual HVAC energy use increases resulting from use of dehumidifiers, smart ventilation controls and smart controls+dehumidification, relative to 100% 62.2-2013 baseline. Averaged across climate zones, house sizes and moisture gains.

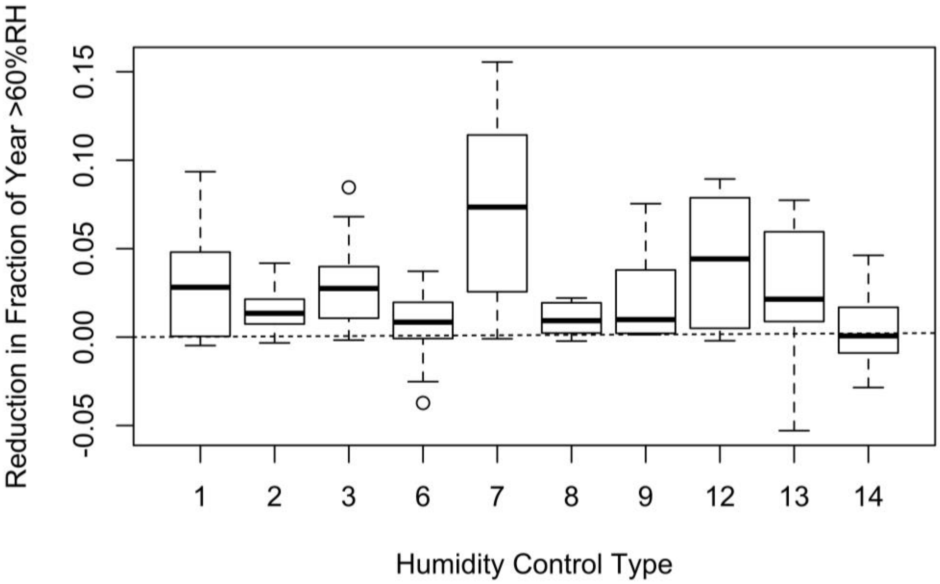

Figure 31 Distributions of the reduction in the fraction of the year >60% RH by each smart control strategy. Includes only cases without dehumidification. Reductions are absolute, not relative, in that 0.10 means that 10% of hours were shifted from above to below the 60% RH threshold.

The most effective control strategy was Control 7, which combined variable dose targets and a cooling system tie-in (see Section 2.6.5). It achieved the highest humidity reductions, with energy requirements that varied strongly by climate zone. On average, the controller eliminated 43% of high humidity hours (from 17 to 10% of annual hours). In the hottest locations with the lowest heating load, HVAC energy increases were modest, but in the climates with higher heating demand, energy use was substantial, due to the seasonal shifting of over- and under-ventilation roughly between winter and summer periods. Notably, the highest indoor humidity was found in the locations with the lowest heating loads, so the energy penalty for smart control was less in the most humid locations. The colder locations would benefit from control strategies that limited the use of over-ventilation during the winter, such as Controls 2 and 3.

The shift in the distribution of indoor relative humidity for Control 7 is pictured in Figure 32 for an example case of a small Miami home with high moisture gains. This includes the baseline cases with and without dehumidification (pink and orange lines), as well as the Control 7 cases with and without dehumidification (green and purple lines). The Control 7 was able to substantially shift the indoor humidity distribution downwards, in addition to simply reducing hours >60% RH. In fact, it looks as if hours were added to the RH bins right around 60%, such that some hours remained above 60%, but only very marginally (e.g., 61 or 62% RH). This illustrates the limitations of the hours >60% metric, which fails to give credit for this overall shift. The Control 7 achieved a 57% reduction in time in the 65-79% range (1,210 hours removed from this range). The impact of these reductions on the RH>60 metric was lessened by the increase in hours spent in the 60-64% range (as well as in the 56-59% range). The Annual Humidity Index (described in Section 2.3), applied a linear weighting to all hours with indoor RH >60%, which gives more weight to higher humidity periods. This approach values reductions in indoor RH, even if they do not fall below the 60% threshold, and it gives greater value to reductions of the highest humidity hours. For example, in the small Miami home with high gains, the reduction in the RH>60% metric was 35% (from 43 to 28% of hours), while the Annual Humidity Index indicates a 54% reduction.

As expected, the presence of a dehumidifier strongly and almost perfectly controlled moisture, as can be seen by the green and pink lines in Figure 32. A handful of hours remained >60% RH with the dehumidifier (pink), and adding Control 7 to the dehumidifier marginally reduced the distribution even further (green). If complete control of indoor humidity to a threshold value is desired, then dehumidification is the only available option in most cases.

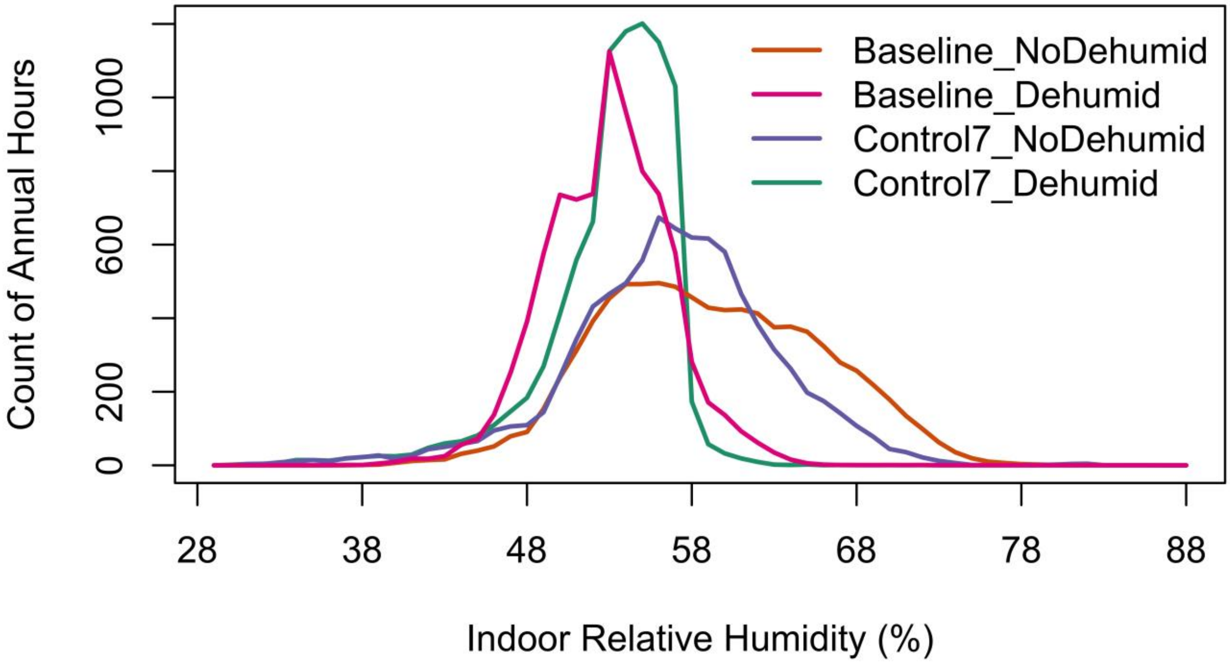

Figure 32 Annual histogram plot of indoor relative humidity distributions in baseline and smart control (Control 7 - Fixed sensor + Cooling system tie-in + Variable dose target) ventilation scenarios, with and without dehumidification. Small Miami home with high moisture gains.

Control 1 (*Cooling system tie-in)*, which effectively synced ventilation to cooling system operation (see Section 2.6.1), and otherwise controlled to typical conditions, was quite effective given its simplicity. This approach required no sensors or pre-set schedules, yet on average it out-performed many of the other smart control strategies. This approach was also used in many of the other most effective strategies, such as Controls 3, 7 and 12. The average energy consumption of this approach was only 441 kWh, and in most cases it did not diverge strongly from this amount, unlike some other strategies whose energy requirements could double or triple in certain climate locations. Of course, the cooling tie-in feature has less energy impact, because of the high efficiency cooling equipment used in the simulations. Lower efficiency equipment would come with greater energy penalties, as would systems with duct leakage to outside. An example two-day period of Control 1 operation is pictured in Figure 33 for a small Houston home with high moisture gains. Notice how the vast majority of CFIS ventilation operation occurs during cooling cycles, as opposed to occurring continuously throughout the day. This increases cooling runtime, and increases moisture removal at the coil due to lower sensible heat ratios. Control 7 would look very similar to Figure 33, the only difference is that rather than maintaining a dose of 1 during summer, Control 7 targets a higher dose. In the case of the two days plotted, this would have largely avoided the two substantial CFIS cycles that occur before the start of the two cooling cycles.

The shift in indoor relative humidity distribution achieved by Control 1 is pictured for a small Miami home with high moisture gains in Figure 34. While the shift is not as drastic as with Control 7 (see Figure 32), the changes are still substantial. Again, this approach shifted a lot of hours to the band surrounding 60% RH. Control 1 reduced by 30% the hours spent between 63 and 79% RH (863 hours), and it increased by 30% the hours spent in the 60 to 62% RH range (375 hours). It also increased the hours spent in the 56-59% RH range by 32% (596 hours). Due to this shifting to the +/- 60% RH range, the RH>60% metric shows less improvement than the Annual Humidity Index. The RH>60% metric was reduced in this example by 18% (from 43 to 35% of hours), while the Annual Humidity Index showed a 34% reduction, due to its crediting the shift in the distribution.

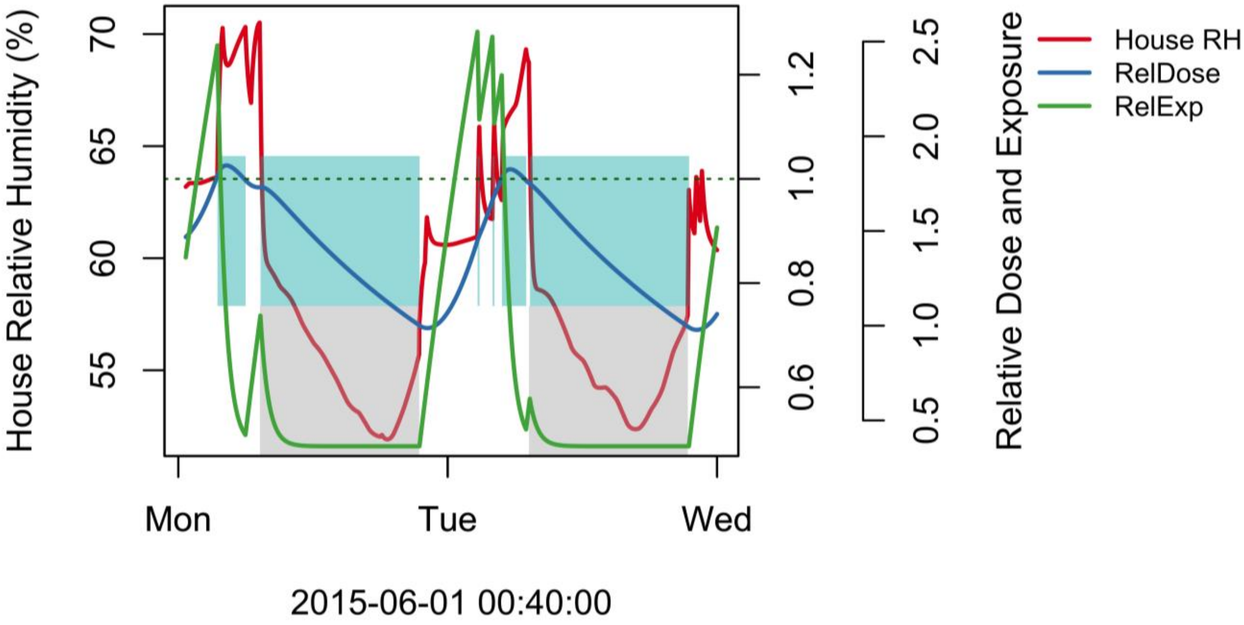

Figure 33 Time series plot of house RH, relative dose and exposure in Control 1 Cooling system tie-in, with cooling system (grey) and CFIS (teal) operations highlighted. Relative dose is on the inner right-hand y-axis and exposure is on the outer right-hand y-axis. CFIS is coincident with cooling, and otherwise controlled to a dose of 1 and exposure of 2.5. Nearly all ventilation operation occurs during cooling operation.

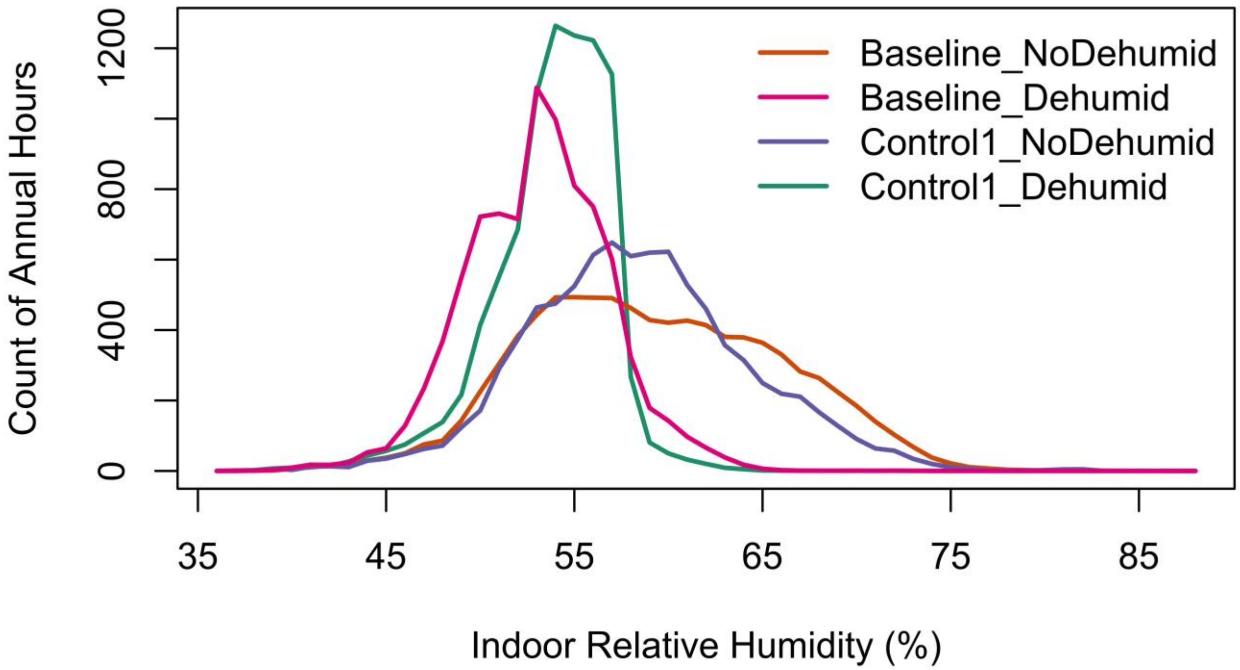

Figure 34 Annual histogram plot of indoor relative humidity distributions in baseline and smart control (Control 1 – Cooling system tie-in) ventilation scenarios, with and without dehumidification. Small Miami home with high moisture gains.

Control 12 was the second most effective strategy overall, and it used no sensors. This approach combined Controls 1 and 6, and the combined performance was improved beyond either individual approach. Control 6 (Seasonal) varied the ventilation rate between high and low depending on the monthly average differences in absolute humidity (see Section 2.6.4), but this strategy was not very effective, and sometimes it led to increased high humidity periods. Yet, when combined with a cooling tie-in, performance improved substantially. Again, this strategy required no sensors, but it did require pre-calculation of months targeting high and low ventilation rates. The average energy use for Control 12 was 1,872 kWh, which is very similar to use for Control 7—1,983 kWh. In the most humid location (small Miami home with high gains), Control 12 used 575 kWh, very similar to the 558 kWh used in the most effective Control 7. But the annual fraction of high humidity was 35% for Control 12 vs. 28% in Control 7. Clearly, use of indoor and outdoor sensors facilitated greater humidity reductions.

The annual shift in indoor relative humidity achieved by the Control 12 approach in a small Miami home with high moisture gains is pictured in Figure 35. Again, the results look familiar, with the right-side of the distribution shifted downwards, concentrating points in the band around 60% RH. The RH>60% metric showed an 18% reduction (from 43 to 35% of hours), while the Annual Humidity Index showed a 34% reduction.

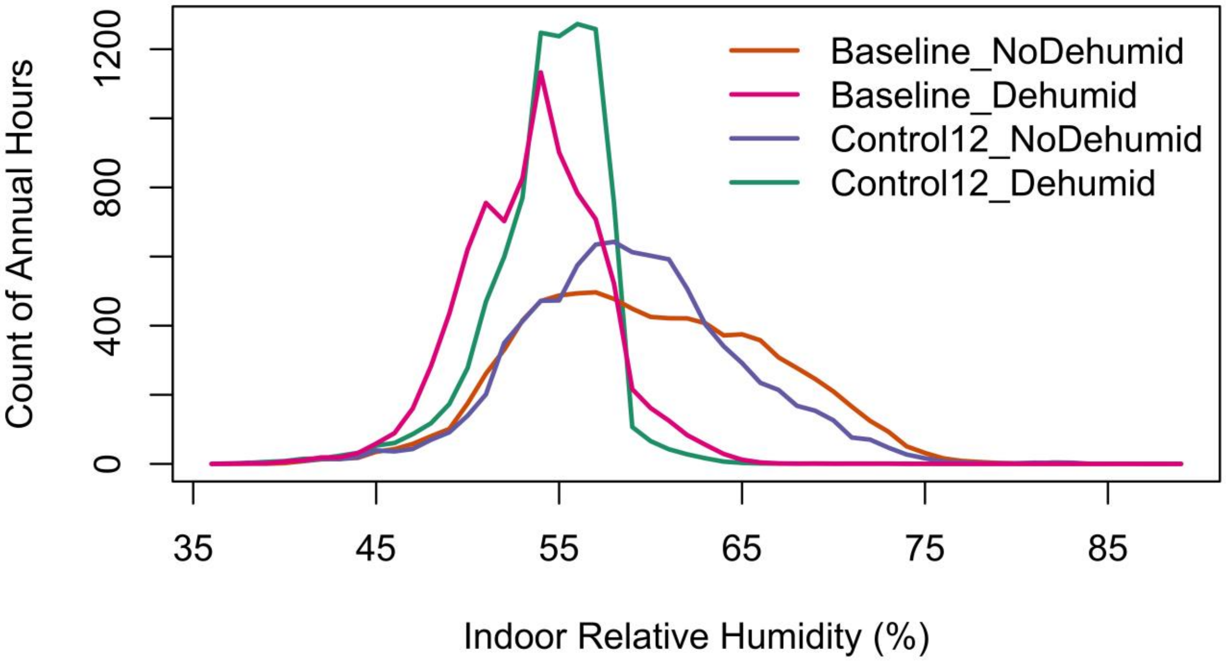

Figure 35 Annual histogram plot of indoor relative humidity distributions in baseline and smart control (Control 12 – Monthly seasonal + Cooling system tie-in) ventilation scenarios, with and without dehumidification. Small Miami home with high moisture gains.

Control 3 used two sensor locations and included a cooling tie-in, but it did not target a higher relative dose during humid times of year, and all of its control features were disabled if the house RH was <55%. This strongly reduced its energy impacts in colder locations. Control 3 still targeted much higher ventilation rates during times when it was more humid inside than outside (typically during the heating season), but this feature was disabled when indoor RH was <55%. As such, its energy use was much lower than strategies that did not limit heating season over-ventilation (e.g., Control 7 or Control 9)—average of 175 kWh annually vs. >1,000 for almost all other approaches. Indoor humidity reductions were not equivalent with Control 7, but they were still good.

Strategies that relied solely upon schedules (monthly or hourly) were not effective. Controls 6 and 8 had the least impact on reducing high indoor humidity of any of the strategies. Similarly, the controls using only a single outdoor humidity sensor did not perform well (Controls 13 and 14). Without an indoor humidity sensor there was no way to detect dynamic changes in the moisture gradient between inside and outside. Yet, performance was better than the scheduled Control 6 and 8 approaches, which simply scheduled over- or under-ventilation for fixed months of the year or hours of the day.

4.2.1.2 Smart Controls As Dehumidifier Alternatives

By themselves, smart ventilation controls contributed significantly to reductions in the indoor humidity distribution, but in most cases they did not provide complete indoor humidity control. In situations where complete control is desired or necessary, then dehumidifiers are required. But in situations where substantial improvement is desired at a lower energy cost, smart controls can be an appropriate strategy. For example, the base case 100% 62.2-2013 home with the highest indoor humidity was the small home with high moisture gains located in Miami, FL. In this case, Control 7 reduced 15% of annual hours from above to below the 60% RH threshold, while only consuming 558 kWh. This case had the highest reduction in indoor humidity for the lowest energy cost of all cases assessed. For comparison, the dehumidifier in this home increased whole house HVAC consumption by 1,621 kWh. But annual hours >60% RH were not equivalent. The baseline case had 42.6% of hours >60%, while Control 7 and the dehumidifier cases had 27.7% and 2.9%, respectively.

Cases where smart ventilation controls both reduced indoor humidity and saved energy relative to a dehumidifier are summarized by smart control strategy in Table 42 (Fraction of annual hours remaining >60% RH, reduction in hours >60% and energy savings relative to a dehumidifier), and each case is plotted in Figure 36 (colored by control strategy).

Control Strategy	*Fraction of Year >60% RH*	*Reduction in Fraction of Year >60% RH*	*Energy Savings vs. Dehumidifier (kWh)*	*Count of Cases (#)*
1	18%	4%	432.8	12
12	19%	7%	453.0	5
13	22%	4%	708.3	4
14	29%	3%	561.1	5
2	17%	2%	650.1	16
3	16%	3%	564.4	16
6	23%	1%	433.2	4
7	15%	12%	443.2	5
8	17%	1%	204.6	1
9	29%	5%	183.2	1

Table 42 Summary of annual humidity and energy performance for simulation cases where use of smart ventilation controls achieved some indoor humidity reduction and saved energy relative to a dehumidifier.

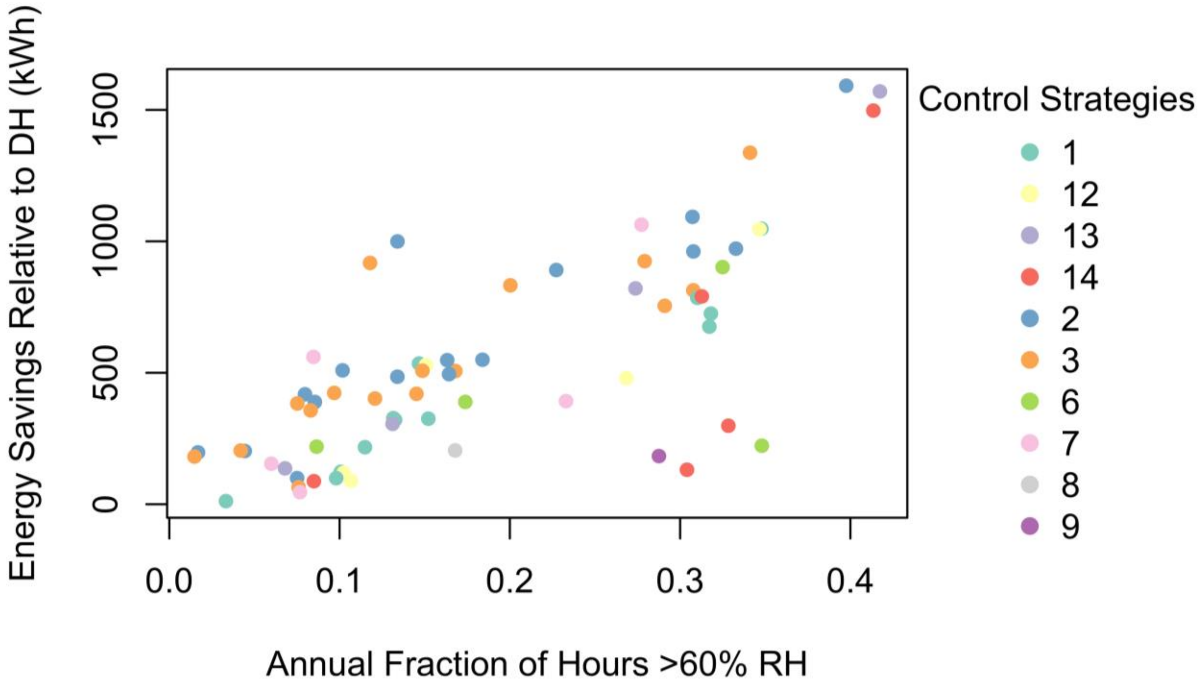

Figure 36 Smart ventilation control energy savings relative to a dehumidifier and annual fractions of hours >60% RH, by smart control strategy. X-axis values represent fraction of annual hours >60% RH in the smart control cases, not reductions.

4.2.1.3 Smart Controls + Dehumidification

We anticipated that the energy required for dehumidification would be lessened by the reduction in moisture gains achieved by smart controls. We hoped that this would lead to overall HVAC energy savings. This was not the case in our initial set of simulations (see Table 40 and Table 41). Instead, combining smart controls and mechanical dehumidification led to increases in total annual HVAC energy use, plus slight improvements in moisture control (e.g., from 0.7 to 0.1% of annual hours >60% RH using Control 7, averaged across all cases). This is illustrated for the Houston location in Figure 37. In all cases the controls+dehumidification (triangles) used more HVAC energy than the dehumidification alone (diamonds). In some controls, these increases were small, but in others the increase in consumption was dramatic. Notably, this work did not assess the operation of smart controls with under-sized dehumidifiers that are not able to maintain complete relative humidity thresholds, as may be the case for many field-installed systems.

All the simulation results indicate that there is no “free lunch” in humidity control. While the smart controls did improve indoor moisture conditions, they required energy to do this. They might have increased ventilation rates during the winter, to compensate for reduced rates during the hot humid summer. This led to net-increases in energy consumption. Similarly, some controls prompted increases in mechanical cooling system runtimes, which also increased energy consumption. These effects were combined with the shifts in indoor humidity resulting from dehumidification that worsened the moisture penalty of ventilation (see Section 4.1.3), and this lessened the efficacy of smart controls and exacerbated their energy consumption. When a dehumidifier is operated, the absolute moisture content of indoor air goes down, while the outside moisture content remains the same. This means that more hours of the year fall into the category where ventilation introduces rather than removes moisture from the home. This means that there are more hours of the year where a reduced ventilation rate would be beneficial, and in order to compensate for these reduced rates, the winter ventilation rates must be further increased, which again increases energy consumption.

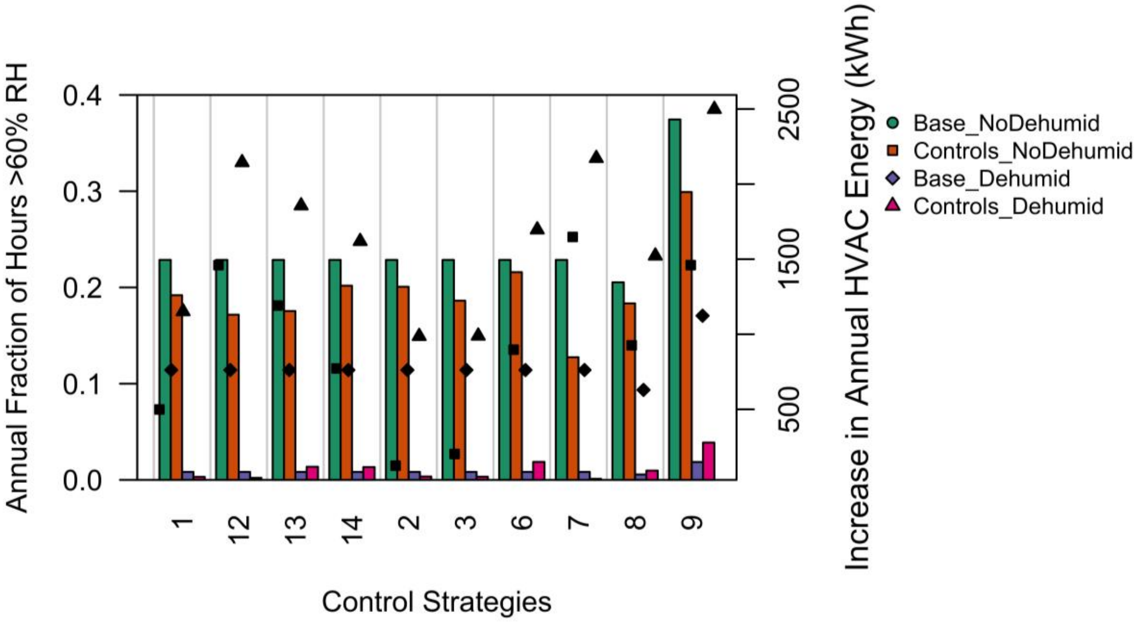

Figure 37 Comparison of smart control strategy performance averaged across house sizes and moisture gains in Houston, TX. Includes baseline and control cases, with and without dehumidification.

4.2.2 New Control Results

As discussed in Section 2.6.11, in an attempt to optimize smart ventilation strategies to work together with dehumidification, we developed and tested two new smart control strategies. These illustrate what the energy savings can be using smart controls when complete humidity control with a dehumidifier is required. Simulations were run for the New Control 7 and New Control 5 (see Section 2.6.11) with dehumidification installed. Energy reductions relative to a dehumidifier alone were achieved in many of the cases (see Table 43 and Figure 38), and humidity control was similar or slightly better, while maintaining annual equivalence (i.e., relative dose less than or equal to 1). The median fraction of dehumidification energy use that was saved by the new smart ventilation controls was 22% (the mean value was 49% but was skewed high due to two outliers in Baltimore). The average energy saved by the smart controls was 150 kWh annually (ranging from 6 to 360 kWh).

The New Control 7 reduced energy consumption only in the Miami climate, where it achieved substantial reductions in energy use relative to the dehumidifier alone, but this approach increased total energy consumption in all other climate zones. The New Control 5 had more widespread efficacy, though it was not as effective in the Miami homes.

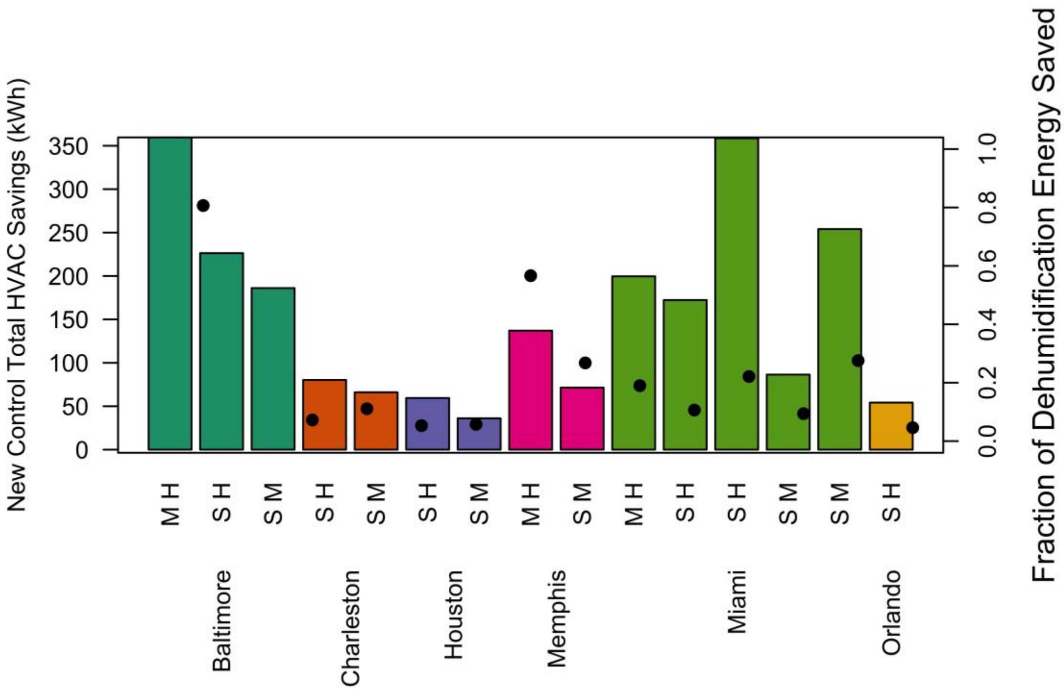

Figure 38 Annual HVAC energy savings when combining the new smart ventilation control strategies with mechanical dehumidification. Absolute total HVAC savings (bars, colored by climate zone) and the fraction of dehumidifier energy saved (black circles). The fraction saved includes all energy uses associated with dehumidifier use (e.g., increased cooling runtime, reduced heating runtime, etc.). Case IDs are: <HouseSizeL/M/S> <MoistureGainsH/M/L>.

		Total HVAC Energy (kWh)					
Control	***Case***	***Base_NoDehumid***	***Base_Dehumid***	***Control_Dehumid***	***Dehumidifier Energy (kWh)***	***Control Savings (kWh)***	***Control Savings (%)***
New5	M_H_1_Y_4	12302	12544	12407	242	137	57%
New5	M_H_1_Y_7	15522	15659	15300	137	360	262%
New5	M_H_1_Y_C	9085	9753	9748	668	6	1%
New5	S_H_1_Y_1	4633	6255	6083	1622	172	11%
New5	S_H_1_Y_2	5864	6987	6928	1123	59	5%
New5	S_H_1_Y_4	7308	7891	7737	583	154	26%
New5	S_H_1_Y_7	9048	9328	9102	281	226	81%
New5	S_H_1_Y_C	5534	6644	6564	1110	80	7%
New5	S_H_1_Y_O	4152	5331	5277	1179	54	5%
New5	S_M_1_Y_1	4103	5024	4938	922	86	9%
New5	S_M_1_Y_2	5500	6129	6093	629	36	6%
New5	S_M_1_Y_4	6861	7128	7056	267	71	27%
New5	S_M_1_Y_7	8625	8730	8544	105	186	177%
New5	S_M_1_Y_C	5124	5720	5654	597	66	11%
New7	M_H_1_Y_1	6928	7980	7780	1052	200	19%
New7	S_H_1_Y_1	4633	6255	5896	1622	359	22%

New7	S_M_1_Y_1	4103	5024	4770	922	254	28%

Table 43 The annual HVAC energy use of baseline cases with and without dehumidification, compared with new control strategies+dehumidification. Increased energy used by dehumidifier (includes secondary effects on heating, cooling, etc.), Annual HVAC savings by smart controls, and fraction of dehumidifier energy reduced by smart controls.

5 Summary & Conclusions

- Baseline simulations with CFIS ventilation systems suggest that supplemental moisture control is required in only a subset of high performance humid climate homes, namely those that are smaller, with higher moisture gains, located in the most humid locations. In these high humidity cases, the fractions of annual hours >60% RH were in the 10-40% range. Periods above 70% RH were limited to between 0 and 5% of annual hours. Extended continuous periods of high humidity were in the 30-60 hour range. Some locations had high indoor humidity all year, whereas others experienced it only during summer months. As found in past research, shoulder seasons had the highest humidity, due to low sensible cooling loads and similar indoor and outdoor absolute humidity. During summer, humidity was sometimes above 60% despite moisture removal by the cooling system (but often by only a few % RH), whereas shoulder seasons experienced excursions into the 70 to 80% range.

- Varying the mechanical ventilation rate between 0, 50 and 100% of ASHRAE 62.2-2013 requirements led to varied changes in high indoor humidity hours. Increasing ventilation either consistently increased high humidity hours, reduced high humidity hours, or reduced hours (from 0 to 50% of 62.2) and then increased hours (from 50 to 100% of 62.2). These effects were strongly dependent on the combination of location, house size and internal moisture gains. While effects on indoor moisture were variable, reductions in the ventilation rate led to predictable IAQ penalties. At the 50% of 62.2-2013 levels, relative exposure and dose were roughly doubled and were increased by a factor of five at the 0% level. As such, we do not consider reducing the ventilation rate as an acceptable (or effective) method for moisture control.

- When correctly sized dehumidifiers with a 55% RH set point were simulated in these same homes indoor moisture was always adequately controlled (maximum fraction >60% RH was roughly 3% of annual hours). Use of dehumidifiers always increased energy use, anywhere from 0 to 1,200 kWh per year. Dehumidifier energy use scaled positively with fractions of annual hours >60% RH in the baseline cases. In addition to the energy used by the dehumidifier, substantial energy use was also attributed to secondary effects on the heating and cooling loads. Use of a dehumidifier worsened the moisture impact of ventilation in general, and it enhanced the negative impacts of increasing the ventilation rate.

- Ten smart ventilation control strategies were evaluated that did not use dehumidifiers. Humidity control was not complete, in that sometimes substantial periods of time remained >60% RH. Yet, smart controls decreased hours of high humidity and shifted the indoor humidity distribution downward, eliminating most of the highest humidity hours, and increasing hours in the range between 55 and 63% RH. All controls maintained equivalence with a continuous 62.2-2013 ventilation fan. While effective, the smart ventilation strategies did not lead to complete moisture control (i.e., no hours >60% RH) as might be expected from a dehumidifier. Estimated energy use for smart controls was roughly equivalent to that used by mechanical supplemental dehumidification strategies. On average, the best performing strategy was able to shift 7.4% of annual hours (648 hours) from above to below the 60% RH threshold with an average energy use increase of 1,983 kWh. These reductions were greater and the energy use smaller in the most humid locations. In the most humid case (small Miami home with high moisture gains), this best strategy reduced 16% of annual hours (1,393 hours) from above to below 60% RH, while using 558 kWh annually.

- Examples of the consistently most effective strategies included the following:
    - **Control 7 – *Fixed sensor + Cooling system tie-in + Variable dose***, the decision to operate the mechanical ventilation was determined by whether the absolute humidity was greater inside or outside, using two sensors. If more humid outside, the ventilation operated whenever cooling was demanded, and the controller otherwise under-vented, targeting a relative dose greater than 1 (in the range of 1.1 to 1.3). If it was more humid inside than outside, then the fan was controlled to over-ventilate, targeting a relative dose less than 1 (in the range of 0.36 to 0.66).
        - This was most effective in the hottest and most humid locations. Substantial heating energy penalties occurred in climates with significant heating demand. In these somewhat colder climates, approaches that limited over-ventilation during winter should be considered.
    - **Control 12 – *Monthly Seasonal + Cooling system tie-in***, the decision to operate the mechanical ventilation and the target ventilation rate were determined by the month of the year. Baseline simulations were used to identify months where on average it was more humid inside than outside, and the controller over-ventilated during those months (and vice versa during periods with more humid outside air). In addition to this seasonal over- and under-ventilation, the control always operated the ventilation system during cooling cycles.
        - This control was substantially more effective than either of the two approaches by themselves (Monthly Seasonal and Cooling tie-in). It used no sensors, but did rely on pre-calculation of months to over- and under-ventilate. As significant over-ventilation occurred during the drier winter, strong energy penalties were incurred in locations with greater heating demand.
- Smart control strategies varied in their complexity, use of sensors, robustness against actual occupant behaviors, etc. Sensor-based approaches appeared to be superior, but their additional cost, complexity, service needs and long-term accuracy/reliability must be considered. The most successful strategies operated the ventilation and cooling systems coincidentally, used indoor and outdoor moisture sensors, and targeted relative dose values that varied (either above or below 1) by direction of the real-time moisture gradient (inside - outside). Schedule-based and one sensor approaches were not effective in this work.
- Energy and moisture performances varied strongly by climate zone and house factors. Climates with substantial heating demand were particularly sensitive to control strategies that over-vented during the drier heating season.

- In many cases, smart ventilation controls offer a lower-energy alternative to mechanical dehumidification, with the understanding that complete control of indoor humidity below 60% RH is not achieved. The highest indoor humidity levels in the 70-80% range can be reduced or eliminated, and indoor humidity distributions are shifted downwards. High humidity hours become more concentrated in the 55 to 63% RH range. But if complete humidity control is required, then the typically higher energy consumption mechanical dehumidification is the appropriate path.

- In cases where complete moisture control is required/preferred, we hypothesized that smart ventilation controls could reduce the dehumidifier load and required energy. Yet, when the ten non-dehumidifier-based control strategies were combined with a dehumidifier, annual energy use always increased and moisture control often improved very marginally (i.e., from 2 to 1% of annual hours >60% RH). Use of smart controls did not reduce energy used for dehumidification, as had been expected. Notably, this work did not assess operation of smart controls with under-sized dehumidifiers that cannot maintain strict RH thresholds, as is commonly found in field-installed units.

- New control strategies were developed that targeted humidity control along with energy savings (via temperature-based controls) when used alongside a dehumidifier, and these were reasonably successful at offsetting some of the energy use of moisture control. The median fraction of dehumidification energy use that was saved by the new smart ventilation controls was 22% (mean values skewed high at 49% due to outliers in Baltimore). The average energy saved by smart controls was 150 kWh annually (from 6 to 360 kWh).

6 References

ANSI. (2008). AHAM DH-1-2008 Dehumidifiers. American National Standards Institute. Retrieved from http://webstore.ansi.org/RecordDetail.aspx?sku=AHAM+DH-1-2008

Arena, L. B., Karagiozis, A., & Mantha, P. (2010). Monitoring of Internal Moisture Loads in Residential Buildings - Research Findings in Three Different Climate Zones. Presented at the Buildings XI: Thermal Performance of Exterior Envelopes of Whole Buildings International Conference, Clearwater Beach, FL: ASHRAE. Retrieved from http://web.ornl.gov/sci/buildings/2012/2010%20B11%20papers/75_Arena.pdf

Arundel, A. V., Sterling, E. M., Biggin, J. H., & Sterling, T. D. (1986). Indirect health effects of relative humidity in indoor environments. *Environmental Health Perspectives*, *65*, 351.

ASHRAE. (2009). *ASHRAE Standard 160-2009 - Design Criteria for Moisture Control in Buildings*. Atlanta, GA: ASHRAE. Retrieved from http://www.techstreet.com/products/1619025

ASHRAE. (2013). *2013 ASHRAE Handbook - Fundamentals* (SI). Atlanta, GA: ASHRAE.

Baughman, A., & Arens, E. A. (1996). Indoor Humidity and Human Health–Part I: Literature Review of Health Effects of Humidity-Influenced Indoor Pollutants. *ASHRAE Transactions*, *102*, 193.

California Energy Commission. (2012). *2013 Building Energy Efficiency Standards for Residential and Non-Residential Buildings - Title 24, Part 6 and Associated Administrative Regulations in Part 1* (No. CEC-400-2012-004-CMF-REV2). Sacramento, CA: California Energy Commission. Retrieved from http://www.energy.ca.gov/2012publications/CEC-400-2012-004/CEC-400-2012-004-CMF-REV2.pdf

CDH Energy Group, & Building Science Corporation. (2005). *Analysis of Indoor Environmental Data* (Building America Report No. 0601). Building Science Corporation. Retrieved from http://buildingscience.com/documents/bareports/ba-0601-analysis-of-indoor-environmental-data/view

Department of Energy. Energy Conservation Program: Test Procedures for Dehumidifiers, 10 Code of Federal Regulations § 429 and 430 (2014). Retrieved from http://energy.gov/sites/prod/files/2015/01/f19/dehumid_snopr.pdf

Emmerich, S. J., Howard-Reed, C., & Gupte, A. (2005). *Modeling the IAQ Impact of HHI Interventions in Inner-city Housing* (No. NISTIR 7212). Washington, D.C.: National Institute of Standards and Technology. Retrieved from http://fire.nist.gov/bfrlpubs/build05/PDF/b05054.pdf

Engebrecht, C., & Hendron, B. (2010). *Building America Simulation Protocols* (No. DOE/GO-102010-3141). U.S. Department of Energy. Retrieved from http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&ved=0CDYQFjAA&url=http%3A%2F%2Fwww.nrel.gov%2Fdocs%2Ffy11osti%2F49246.pdf&ei=Sg3_UIXBKMvliwLfzoCAAg&usg=AFQjCNFmX2z9pAOxdKzU68jvn3UV2Yn-9Q&bvm=bv.41248874,d.cGE

Fang, L., Clausen, G., & Fanger, P. O. (1998). Impact of temperature and humidity on the perception of indoor air quality. *Indoor Air*, *8*(2), 80–90.

Fang, X., Winkler, J., & Christensen, D. (2010). Advanced Dehumidification Analysis on Building America Homes Using EnergyPlus (pp. 3187–1 to 3187–8). Presented at the International High Performance Buildings Conference, Purdue University: Purdue e-Pubs. Retrieved from http://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=1006&context=ihpbc

Fisk, W. J., Lei-Gomez, Q., & Mendell, M. J. (2007). Meta-analyses of the associations of respiratory health effects with dampness and mold in homes. *Indoor Air*, *17*(4), 284–296. https://doi.org/10.1111/j.1600-0668.2007.00475.x

Henderson, H. I., & Rudd, A. (2010). Energy Efficiency and cost assessment of humidity control options for residential buildings. In *Thermal Performance of the Exterior Envelopes of Whole Buildings XI Conference*. Clearwater Beach, FL: ASHRAE.

Kerrigan, P., & Norton, P. (2014). *Evaluation of the performance of houses with and without supplemental dehumidification in a hot-humid climate*. Golden, CO: National Renewable Energy Laboratory. Retrieved from http://apps1.eere.energy.gov/buildings/publications/pdfs/building_america/houses_supplemental_dehumidification.pdf

Klug, V. L., Lobscheid, A. B., & Singer, B. C. (2011). Cooking Appliance Use in California Homes–Data Collected from a Web-Based Survey. *LBNL-5028E, Berkeley, CA, Lawrence Berkeley National Laboratory*.

Less, B. (2012). *Indoor Air Quality in 24 California Residences Designed as High Performance Green Homes*. University of California, Berkeley, Berkeley, CA. Retrieved from http://escholarship.org/uc/item/25x5j8w6

Less, B., Walker, I. S., & Tang, Y. (2014). *Development of an Outdoor Temperature-Based Control Algorithm for Residential Mechanical Ventilation Control* (No. LBNL-6936E). Berkeley, CA: Lawrence Berkeley National Laboratory. Retrieved from http://eetd.lbl.gov/publications/development-of-an-outdoor-temperature

Lstiburek, J. (2006). *Understanding Ventilation in Hot-Humid Climates* (No. BSD-107). Westford, MA: Building Science Corporation. Retrieved from http://buildingscience.com/documents/digests/bsd-107-understanding-ventilation-in-hot-humid-climates

Lstiburek, J., Pettit, B., Rudd, A., Sherman, M., & Walker, I. (2007). *Whole House Ventilation System Options - Phase 1 Simulation Study* (ARTI Report No. 30090-01). Arlington, VA: Air-Conditioning and Refrigeration Technology Institute. Retrieved from http://www.energy.ca.gov/title24/2008standards/prerulemaking/documents/2007-06-13-15_workshop/comments/AIR-CONDITIONING_REFRIGERATION_TECHNOLOGY_INST_2007-03-05.PDF

Martin, E. (2014). *Impact of Residential Mechanical Ventilation on Energy Cost and Humidity Control* (No. NREL-60675). Golden, CO: National Renewable Energy Laboratory. Retrieved from http://www.fsec.ucf.edu/en/publications/pdf/NREL-60675.pdf

Mattison, L., & Korn, D. (2012). Dehumidifiers: A Major Consumer of Residential Electricity. In *Summer Study for Energy Efficiency in Buildings* (pp. 9–204 to 9–215). Pacific Grove, CA: American Council for an Energy-Efficient Economy. Retrieved from http://www.aceee.org/files/proceedings/2012/data/papers/0193-000291.pdf

Mendell, M. J., Mirer, A. G., Cheung, K., Tong, M., & Douwes, J. (2011). Respiratory and Allergic Health Effects of Dampness, Mold, and Dampness-Related Agents: A Review of the Epidemiologic Evidence. *Environmental Health Perspectives*, *119*, 748–756. https://doi.org/http://dx.doi.org/10.1289/ehp.1002410

Moyer, N., Chasar, D., Hoak, D., & Chandra, S. (2004). Assessing Six Residential Ventilation Techniques in Hot and Humid Climates. Presented at the ACEEE 2004 Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA: American Council for an Energy-Efficient Economy. Retrieved from http://www.fsec.ucf.edu/en/publications/pdf/FSEC-PF-378-04.pdf

Mullen, N., Li, J., Russell, M. L., Hotchi, T., Singer, B. C., & In-Preparation. (2014). Results of the California Healthy Homes Indoor Air Quality Study of 2011-2013: Impact of Natural Gas Appliances on Pollutant Concentrations.

NBCIP. (2004). *Duct-Mounted Relative Humidity Transmitters* (Product Testing Report). Ames, IA: Iowa Energy Center. Retrieved from http://www.iowaenergycenter.org/wp-content/uploads/2012/05/PTR_Humidity_Rev.pdf

Price, P. P., Sherman, M., Lee, R. H., & Piazza, T. (2007). *Ventilation Practices and Household Characteristics in New California Homes* (Final Report No. CEC-500-2007-033). California Energy

Commission. Retrieved from http://www.google.com/url?sa=t&rct=j&q=%22ventilation%20practices%20and%20household%20characteristics%22&source=web&cd=1&ved=0CE4QFjAA&url=http%3A%2F%2Fwww.energy.ca.gov%2F2007publications%2FCEC-500-2007-033%2FCEC-500-2007-033.PDF&ei=anjrT72LFYbm2AXC0Yy7AQ&usg=AFQjCNH_HsNFC4J7UTstGYGW_nTZjlrOig&cad=rja

RESNET. (2006). 2006 Mortgage Industry National Home Energy Rating Systems Standards. Residential Energy Services Network. Retrieved from http://www.resnet.us/professional/standards/mortgage

Rudd, A. (2013a). *Expert Meeting: Recommended Approaches to Humidity Control in High Performance Homes* (No. NREL-57483). Golden, CO: National Renewable Energy Laboratory. Retrieved from http://www.nrel.gov/docs/fy13osti/57483.pdf

Rudd, A. (2013b). *Supplemental Dehumidification in Warm-Humid Climates* (Building America Report No. 1310). Somerville, MA: Building Science Corporation. Retrieved from http://buildingscience.com/documents/bareports/ba-1310-supplemental-dehumidification-warm-humid-climates/view

Rudd, A., & Henderson, H. I. (2007). Monitored Indoor Moisture and Temperature Conditions in Humid-Climate US Residences. *ASHRAE Transactions*, *113*(1), 435–449.

Rudd, A., Henderson, H. I., Bergey, D., & Shirey, D. B. (2013). *ASHRAE 1449- RP: Energy Efficiency and Cost Assessment of Humidity Control Options for Residential Buildings* (Research Report No. RP-1449). Atlanta, GA: ASHRAE. Retrieved from http://www.techstreet.com/products/1856921

Rudd, A., & Henderson, Jr., H. I. (2007). Monitored Indoor Moisture and Temperature Conditions in Humid-Climate US Residences. *ASHRAE Transactions*, *113*(1), 435–449.

Rudd, A., Listiburek, J. W., & Ueno, K. (2005). *Residential Dehumidification Systems Research for Hot-Humid Climates. September 1, 2001-December 30th, 2003* (No. NREL/SR-550-36643). Golden, CO: National Renewable Energy Laboratory. Retrieved from http://www.nrel.gov/docs/fy05osti/36643.pdf

Sherman, M. H., Logue, J. M., & Singer, B. C. (2011). Infiltration effects on residential pollutant concentrations for continuous and intermittent mechanical ventilation approaches. *HVAC&R Research*, *17*(2), 159–173. https://doi.org/10.1080/10789669.2011.543258

Sherman, M. H., & Walker, I. S. (2011). Meeting Residential Ventilation Standards through Dynamic Control of Ventilation Systems. *Energy and Buildings*, *43*(8), 1904–1912. https://doi.org/10.1016/j.enbuild.2011.03.037

Trowbridge, J. T., Ball, K. S., Peterson, J. L., Hunn, B. D., & Grasso, M. M. (1994). 3790 - EVALUATION OF STRATEGIES FOR CONTROLLING HUMIDITY IN RESIDENCES IN HUMID CLIMATES. *ASHRAE Transactions*, *100*(Part 2), 59–73.

U.S. Department of Energy. (2013, April 17). DOE Challenge Home National Program Requirements (Rev. 03). U.S. Department of Energy. Retrieved from http://www1.eere.energy.gov/buildings/residential/pdfs/doe_challenge_home_requirementsv3.pdf

U.S. EPA. (2001). Indoor Humidity Assessment Tool (IHAT) Reference Manual. U.S. EPA. Retrieved from http://www2.epa.gov/iaq-schools/school-advanced-ventilation-engineering-software-saves#Humidity

Walker, I. S., & Sherman, M. (2007). Humidity Implications for Meeting Residential Ventilation Requirements. In *Thermal Performance of the Exterior Envelopes of Whole Buildings*. Clearwater Beach, FL: ASHRAE. Retrieved from http://epb.lbl.gov/publications/pdf/lbnl-62182.pdf

Walker, I. S., & Sherman, M. H. (2006). *Evaluation of Existing Technologies for Meeting Residential Ventilation Requirements* (No. LBNL-59998). Berkeley, CA: Lawrence Berkeley National Lab. Retrieved from https://buildings.lbl.gov/sites/all/files/lbnl-59998.pdf

Whitehead, C. D., Willem, H., Beraki, B., Burke, T., Melody, M., Nagaraju, M., … Yang, H.-C. (Dominique). (2013). *Field-Metered Data from Portable Unit Dehumidifiers in the U.S. Residential Sector: Initial Results of a Pilot Study* (No. LBNL-6093E). Berkeley, CA: Lawrence Berkeley National Laboratory. Retrieved from https://escholarship.org/uc/item/13q224sc#page-7

Winkler, J., Christensen, D., & Tomerlin, J. (2011). *Laboratory Test Report for Six ENERGY STAR Dehumidifiers* (No. NREL/TP-5500-52791, 1032386). Retrieved from http://www.osti.gov/servlets/purl/1032386/

Winkler, J., Christensen, D., & Tomerlin, J. (2014). *Measured Performance of Residential Dehumidifiers Under Cyclic Operation*. Golden, CO: National Renewable Energy Laboratory. Retrieved from http://apps1.eere.energy.gov/buildings/publications/pdfs/building_america/dehumidifiers_cyclic_operation.pdf

Withers, C. R. J., & Sonne, J. (2014). *Assessment of Energy Efficient Methods of Indoor Humidity Control for Florida Building Commission Research* (No. FSEC-CR-1976-14). Cocoa, FL: Florida Solar Energy Center. Retrieved from http://www.floridabuilding.org/fbc/commission/FBC_0614B/Energy/Energy_Efficient_RH_control_Draft_Final_06_15_14.pdf

7 Appendix

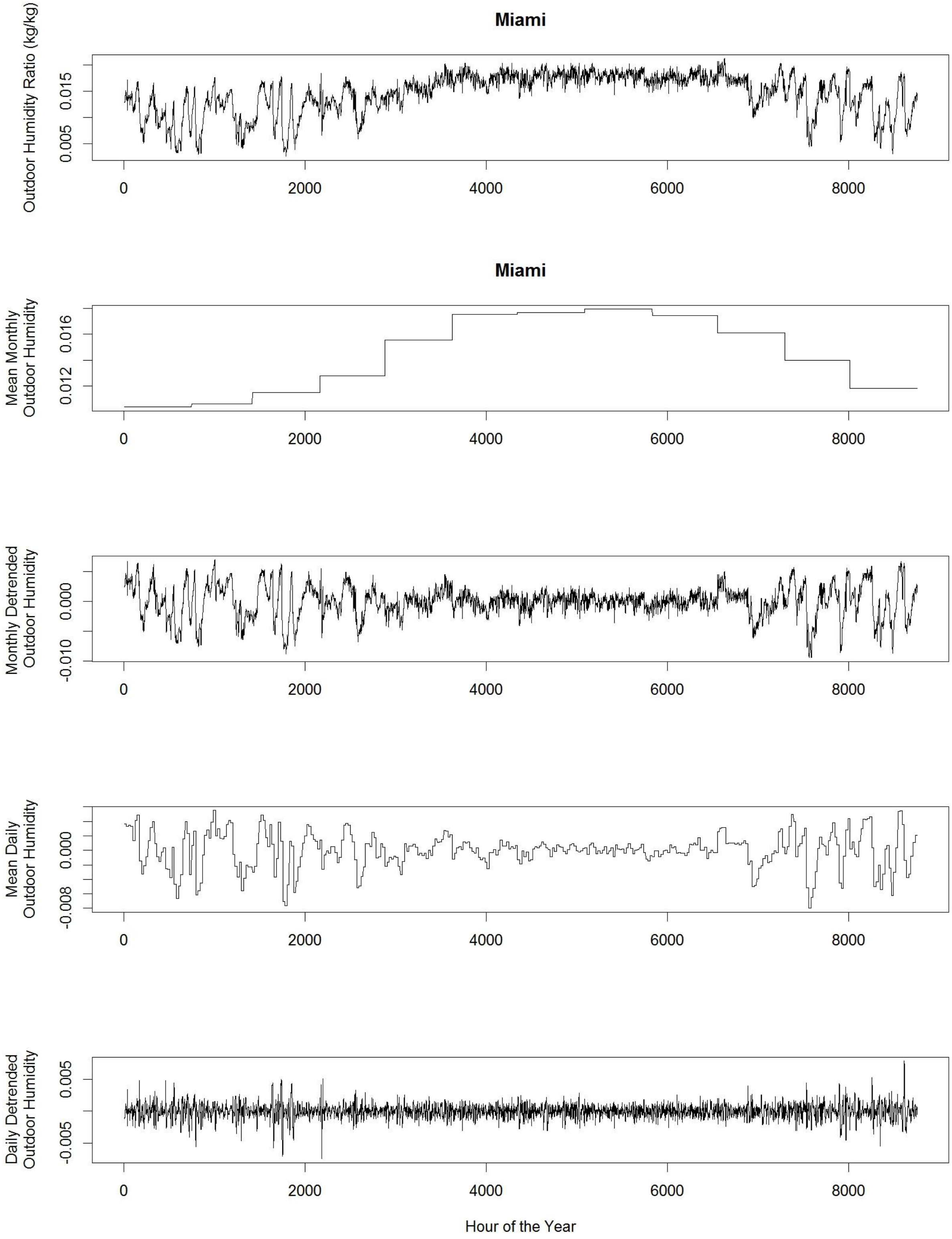

Figure 39 Time series decomposition plot for Miami.

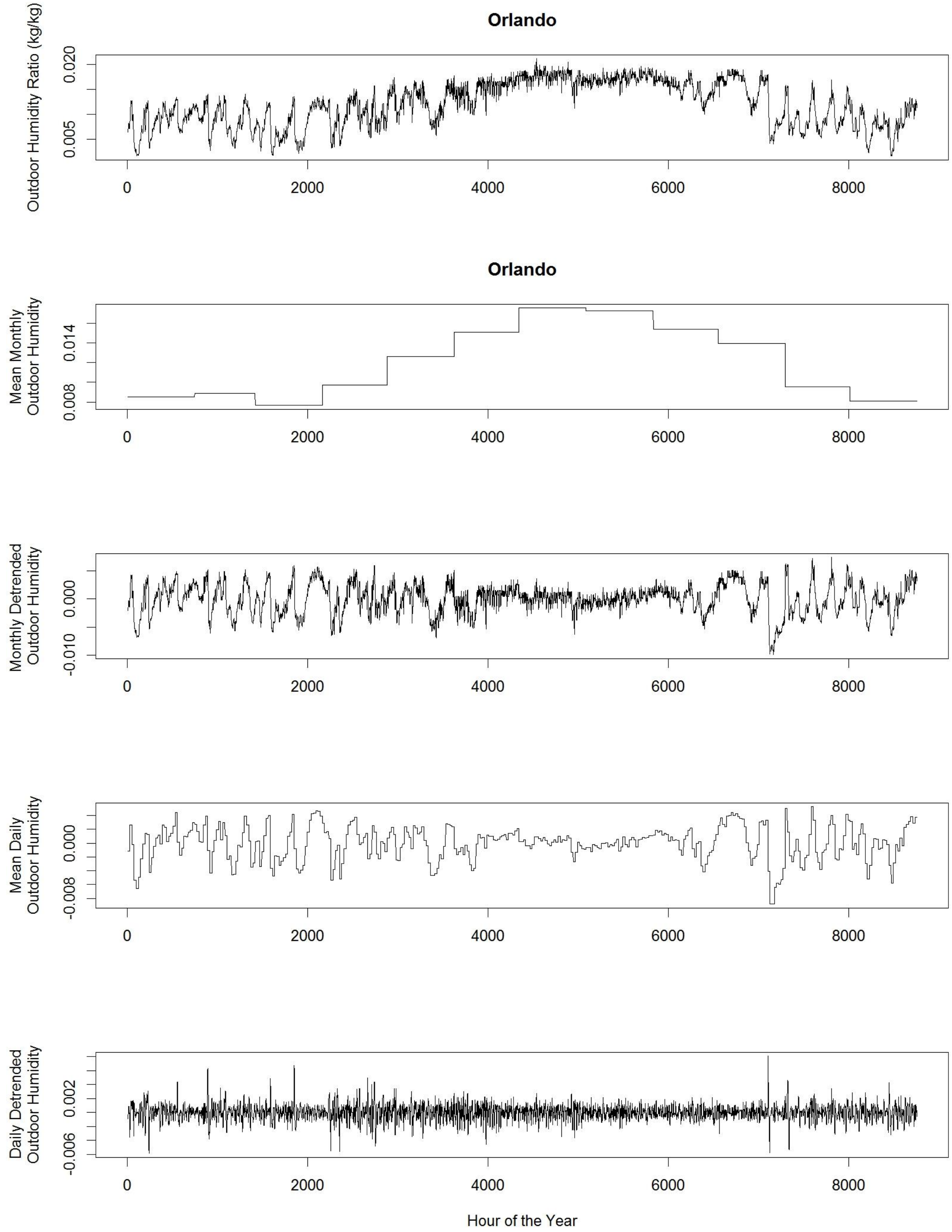

Figure 40 Time series decomposition plot for Orlando.

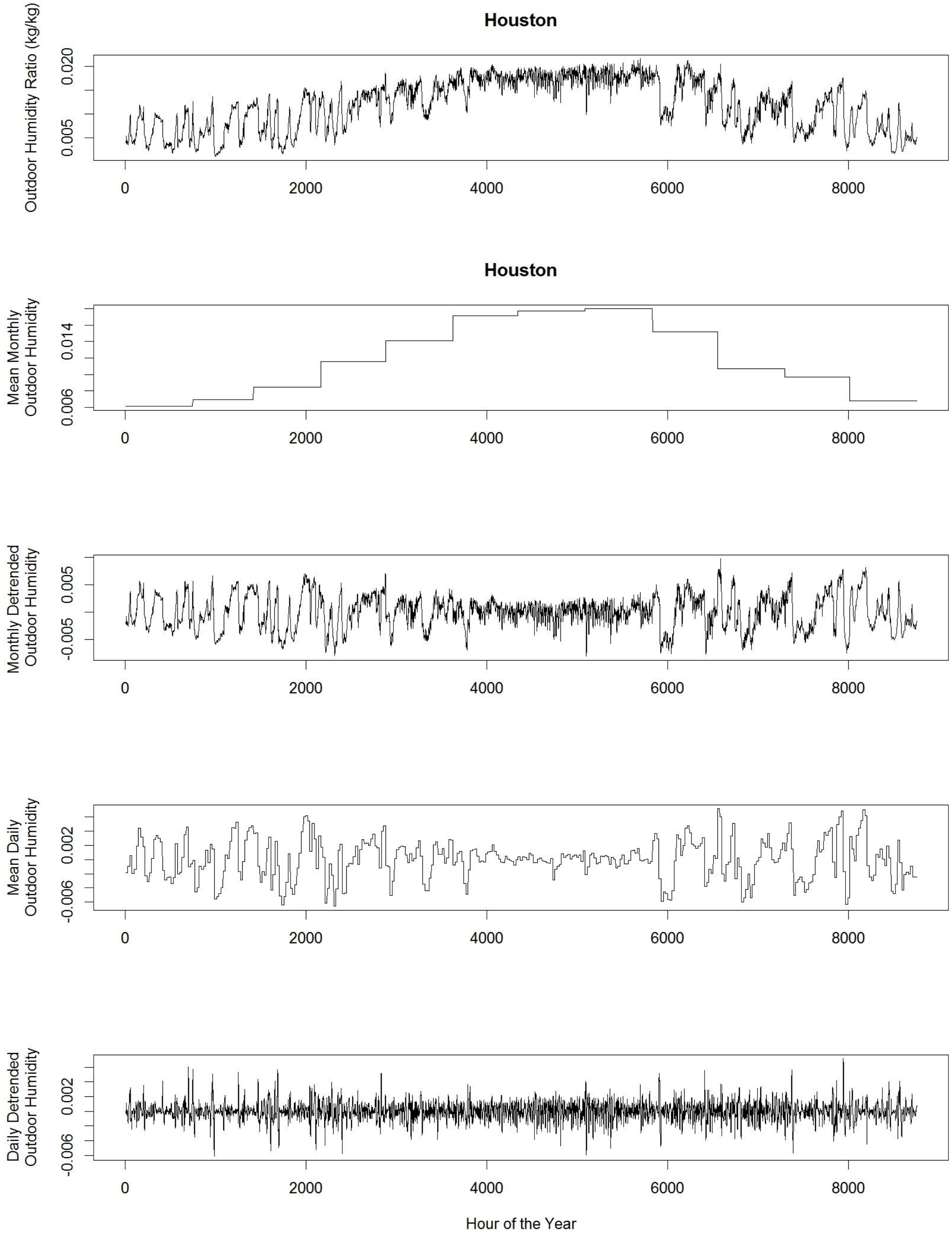

Figure 41 Time series decomposition plot for Houston.

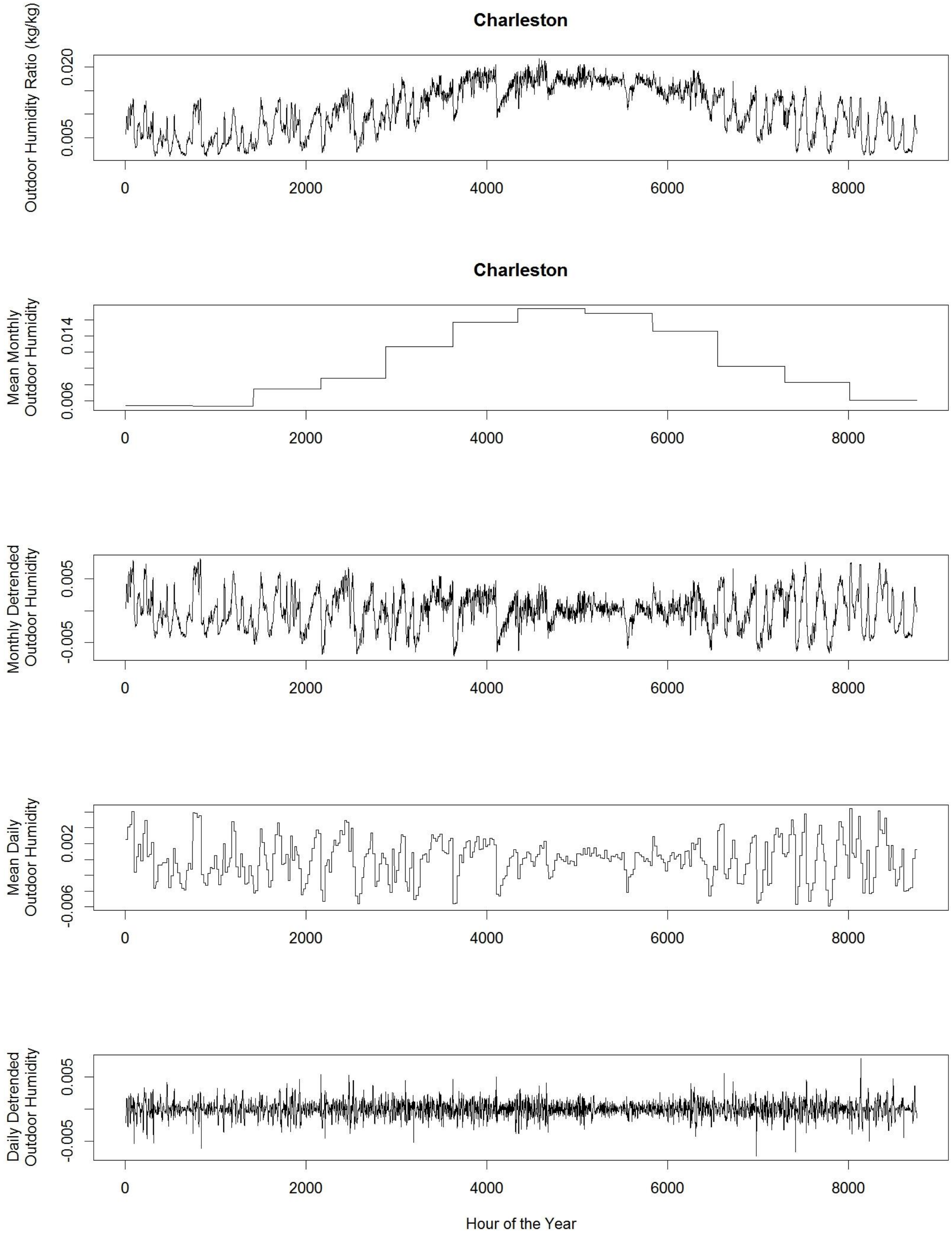

Figure 42 Time series decomposition plot for Charleston.

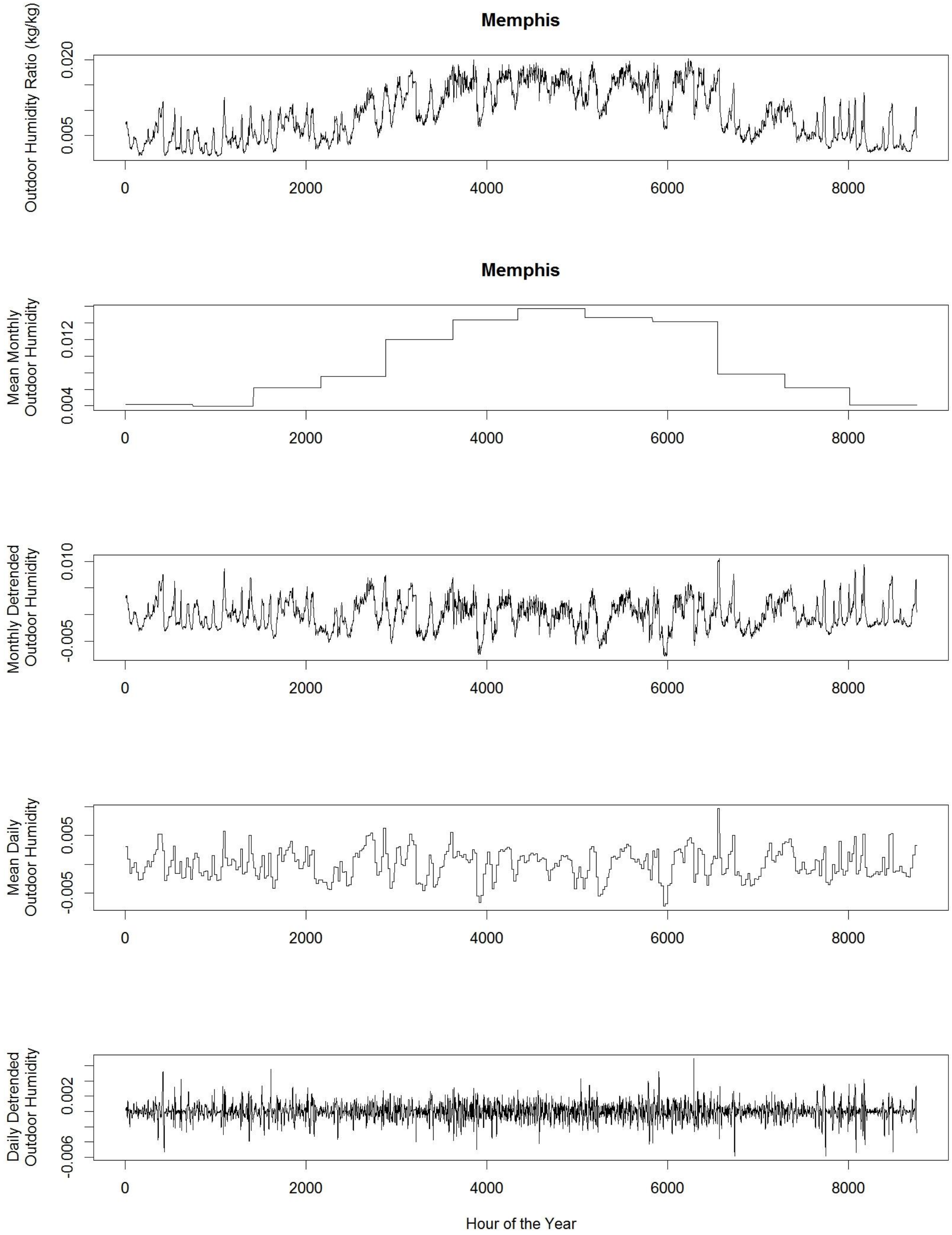

Figure 43 Time series decomposition plot for Memphis

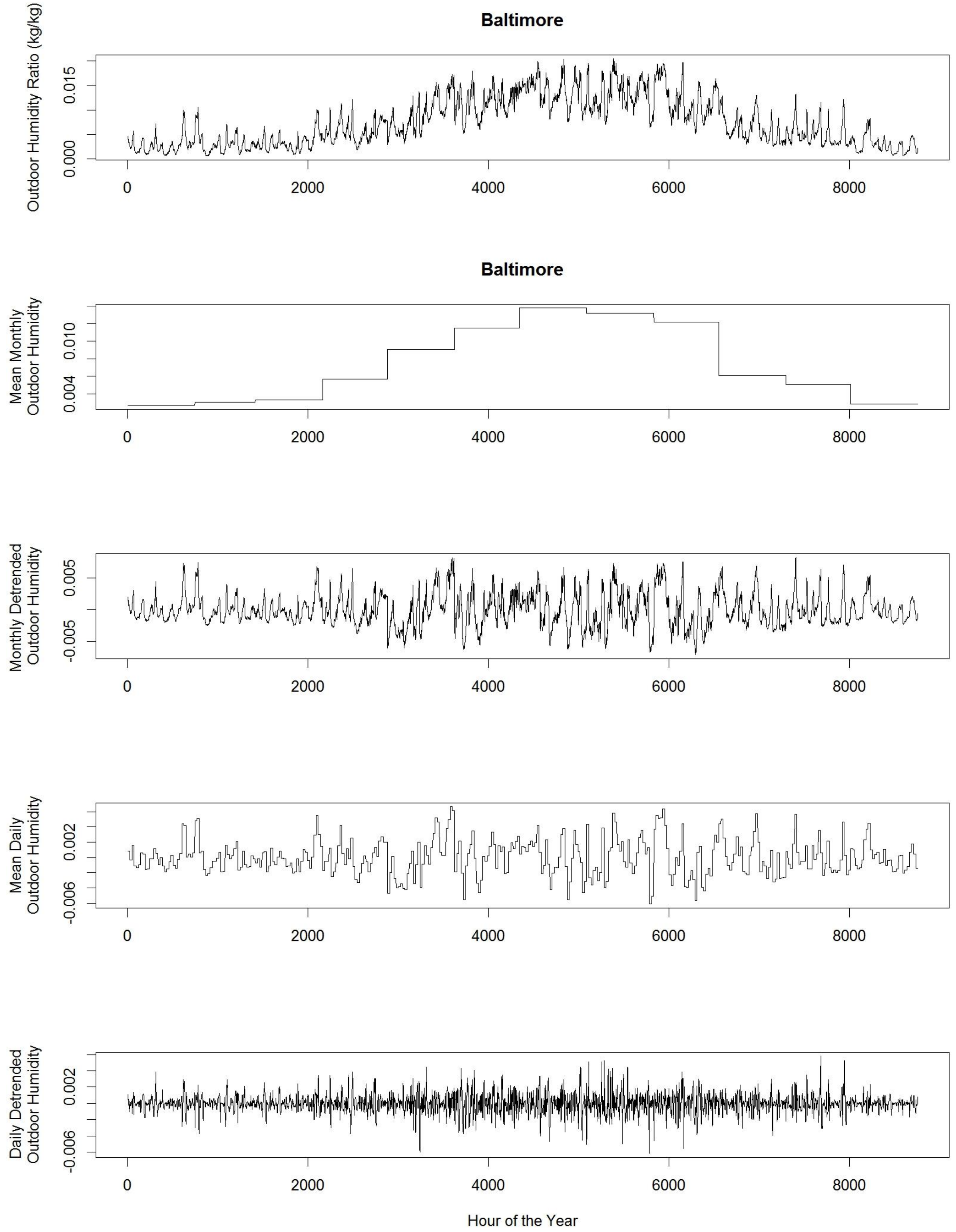

Figure 44 Time series decomposition plot for Baltimore.

House Size	Moisture Gains	Fraction of 62.2-2013	Dehumidifier (yes / no)	Climate Zone	Air Handler (kWh)	Furnace (kWh)	Compressor (kWh)	Compressor runtime	Ventilation (kWh)	Dehumidifier (kwh)	Dehumidifier Runtime	HVAC Total (kWh)	Mean Air Exchange Rate (hr^{-1})	Relative Exposure	Relative Dose	Annual Fraction >60% RH	Annual Fraction >70% RH	Annual Humidity Index (hours)
L	H	0	N	Miami	596	31	7270	46%	250	0	0%	8147	0.094	5.18	5.16	2.1%	0.3%	25
L	H	0	N	Houston	449	5550	4887	38%	214	0	0%	11100	0.104	5.05	5.04	9.0%	0.6%	80
L	H	0	N	Memphis	452	8516	4838	26%	323	0	0%	14130	0.107	5.54	5.52	3.5%	0.0%	20
L	H	0	N	Baltimore	376	13916	3175	22%	254	0	0%	17720	0.109	5.09	5.08	6.9%	0.0%	41
L	H	0	N	Charleston	442	4278	5251	28%	334	0	0%	10305	0.099	5.92	5.91	14.4%	2.5%	181
L	H	0	N	Orlando	454	1336	5403	42%	216	0	0%	7409	0.097	5.58	5.57	5.8%	1.4%	86
L	H	0	Y	Miami	597	25	7277	46%	250	65	1%	8214	0.094	5.18	5.16	0.2%	0.1%	3
L	H	0	Y	Houston	448	5217	4903	38%	214	255	4%	11037	0.104	5.05	5.04	0.0%	0.0%	0
L	H	0	Y	Memphis	451	8344	4839	26%	323	98	1%	14056	0.107	5.54	5.52	0.0%	0.0%	0
L	H	0	Y	Baltimore	374	13669	3174	22%	255	146	2%	17618	0.109	5.09	5.08	0.0%	0.0%	0
L	H	0	Y	Charleston	441	3960	5270	29%	335	264	4%	10270	0.099	5.92	5.91	0.0%	0.0%	0
L	H	0	Y	Orlando	454	1225	5416	43%	216	173	3%	7485	0.098	5.58	5.57	0.0%	0.0%	0
L	H	0.5	N	Miami	615	31	7755	47%	245	0	0%	8646	0.193	1.69	1.68	2.1%	0.2%	23
L	H	0.5	N	Houston	464	6100	5176	39%	208	0	0%	11948	0.199	1.68	1.68	4.2%	0.3%	32
L	H	0.5	N	Memphis	466	9499	5037	27%	316	0	0%	15319	0.204	1.70	1.70	0.0%	0.0%	0
L	H	0.5	N	Baltimore	392	15485	3261	22%	248	0	0%	19386	0.202	1.68	1.68	0.0%	0.0%	0
L	H	0.5	N	Charleston	454	4965	5497	29%	329	0	0%	11245	0.200	1.72	1.72	4.3%	0.2%	36
L	H	0.5	N	Orlando	464	1535	5675	43%	212	0	0%	7886	0.197	1.70	1.70	3.8%	0.7%	44
L	H	0.5	Y	Miami	618	25	7781	48%	244	128	2%	8796	0.193	1.69	1.68	0.2%	0.1%	3
L	H	0.5	Y	Houston	466	5967	5207	39%	208	200	3%	12046	0.199	1.68	1.68	0.0%	0.0%	0
L	H	0.5	Y	Memphis	467	9500	5039	27%	316	8	0%	15329	0.204	1.70	1.70	0.0%	0.0%	0
L	H	0.5	Y	Baltimore	392	15454	3263	22%	248	18	0%	19375	0.202	1.68	1.68	0.0%	0.0%	0
L	H	0.5	Y	Charleston	455	4820	5522	29%	329	173	2%	11299	0.200	1.72	1.72	0.0%	0.0%	0

L	H	0.5	Y	Orlando	465	1452	5701	43%	212	158	2%	7988	0.197	1.70	1.70	0.0%	0.0%	0
L	H	1	N	Miami	635	31	8236	49%	239	0	0%	9140	0.317	1.01	1.01	5.2%	0.2%	33
L	H	1	N	Houston	483	6840	5478	40%	202	0	0%	13003	0.322	1.01	1.01	5.0%	0.2%	33
L	H	1	N	Memphis	487	11063	5251	27%	307	0	0%	17108	0.330	1.01	1.01	0.2%	0.0%	0
L	H	1	N	Baltimore	414	17739	3342	22%	238	0	0%	21733	0.326	1.01	1.01	0.1%	0.0%	0
L	H	1	N	Charleston	470	5965	5738	29%	323	0	0%	12496	0.328	1.01	1.01	4.6%	0.1%	26
L	H	1	N	Orlando	476	1805	5955	44%	208	0	0%	8444	0.324	1.01	1.01	3.8%	0.5%	39
L	H	1	Y	Miami	650	25	8395	50%	233	460	6%	9764	0.317	1.01	1.01	0.2%	0.1%	3
L	H	1	Y	Houston	491	6762	5583	41%	199	356	5%	13392	0.322	1.01	1.01	0.0%	0.0%	0
L	H	1	Y	Memphis	490	11076	5275	27%	306	55	1%	17201	0.330	1.01	1.01	0.0%	0.0%	0
L	H	1	Y	Baltimore	416	17737	3364	22%	237	48	1%	21803	0.326	1.01	1.01	0.0%	0.0%	0
L	H	1	Y	Charleston	479	5857	5854	30%	319	374	5%	12884	0.328	1.01	1.01	0.0%	0.0%	0
L	H	1	Y	Orlando	483	1728	6041	45%	206	299	4%	8757	0.324	1.01	1.01	0.0%	0.0%	0
L	L	0	N	Miami	543	32	6429	42%	257	0	0%	7261	0.078	4.08	4.07	0.9%	0.1%	10
L	L	0	N	Houston	418	5981	4309	35%	214	0	0%	10921	0.088	3.98	3.97	0.4%	0.1%	4
L	L	0	N	Memphis	425	9058	4278	24%	320	0	0%	14081	0.091	4.36	4.35	0.0%	0.0%	0
L	L	0	N	Baltimore	361	14700	2779	20%	248	0	0%	18088	0.093	4.01	4.01	0.0%	0.0%	0
L	L	0	N	Charleston	408	4698	4608	26%	334	0	0%	10049	0.083	4.67	4.66	0.0%	0.0%	0
L	L	0	N	Orlando	415	1507	4744	39%	219	0	0%	6884	0.081	4.40	4.39	0.5%	0.0%	4
L	L	0	Y	Miami	543	27	6430	42%	257	27	0%	7285	0.078	4.08	4.07	0.2%	0.1%	3
L	L	0	Y	Houston	418	5970	4309	35%	214	18	0%	10929	0.088	3.98	3.97	0.0%	0.0%	0
L	L	0	Y	Memphis	425	9058	4278	24%	320	0	0%	14081	0.091	4.36	4.35	0.0%	0.0%	0
L	L	0	Y	Baltimore	361	14700	2779	20%	248	0	0%	18088	0.093	4.01	4.01	0.0%	0.0%	0
L	L	0	Y	Charleston	408	4697	4609	26%	334	6	0%	10054	0.083	4.67	4.66	0.0%	0.0%	0
L	L	0	Y	Orlando	414	1475	4744	39%	219	23	0%	6875	0.081	4.40	4.39	0.0%	0.0%	0
L	L	0.5	N	Miami	559	32	6850	43%	253	0	0%	7694	0.150	1.61	1.61	1.0%	0.1%	11
L	L	0.5	N	Houston	430	6346	4571	36%	209	0	0%	11556	0.156	1.61	1.61	0.5%	0.1%	5
L	L	0.5	N	Memphis	437	9793	4481	24%	316	0	0%	15027	0.162	1.63	1.63	0.0%	0.0%	0
L	L	0.5	N	Baltimore	373	15773	2886	20%	243	0	0%	19275	0.159	1.61	1.61	0.0%	0.0%	0
L	L	0.5	N	Charleston	419	5180	4858	26%	330	0	0%	10787	0.156	1.65	1.65	0.0%	0.0%	0

L	L	0.5	N	Orlando	424	1655	5009	39%	216	0	0%	7304	0.154	1.64	1.64	0.8%	0.0%	7
L	L	0.5	Y	Miami	559	27	6853	43%	253	33	1%	7725	0.150	1.61	1.61	0.2%	0.1%	3
L	L	0.5	Y	Houston	430	6336	4575	36%	209	34	1%	11584	0.156	1.61	1.61	0.0%	0.0%	0
L	L	0.5	Y	Memphis	437	9793	4481	24%	316	0	0%	15027	0.162	1.63	1.63	0.0%	0.0%	0
L	L	0.5	Y	Baltimore	373	15773	2886	20%	243	0	0%	19275	0.159	1.61	1.61	0.0%	0.0%	0
L	L	0.5	Y	Charleston	419	5176	4858	26%	330	10	0%	10793	0.156	1.65	1.65	0.0%	0.0%	0
L	L	0.5	Y	Orlando	424	1624	5009	39%	216	31	1%	7303	0.154	1.64	1.64	0.0%	0.0%	0
L	L	1	N	Miami	576	32	7270	44%	249	0	0%	8127	0.240	1.01	1.01	1.2%	0.1%	12
L	L	1	N	Houston	444	6861	4830	36%	204	0	0%	12339	0.245	1.01	1.01	0.8%	0.0%	6
L	L	1	N	Memphis	454	10935	4684	25%	308	0	0%	16381	0.253	1.01	1.01	0.0%	0.0%	0
L	L	1	N	Baltimore	390	17459	2976	20%	236	0	0%	21061	0.249	1.01	1.01	0.0%	0.0%	0
L	L	1	N	Charleston	433	5928	5089	27%	325	0	0%	11775	0.251	1.01	1.01	0.2%	0.0%	1
L	L	1	N	Orlando	434	1857	5265	40%	213	0	0%	7769	0.246	1.01	1.01	1.1%	0.0%	9
L	L	1	Y	Miami	577	27	7279	44%	248	66	1%	8198	0.240	1.01	1.01	0.2%	0.1%	3
L	L	1	Y	Houston	444	6852	4838	36%	204	57	1%	12396	0.245	1.01	1.01	0.0%	0.0%	0
L	L	1	Y	Memphis	454	10935	4684	25%	308	0	0%	16382	0.253	1.01	1.01	0.0%	0.0%	0
L	L	1	Y	Baltimore	390	17459	2976	20%	236	0	0%	21061	0.249	1.01	1.01	0.0%	0.0%	0
L	L	1	Y	Charleston	433	5893	5092	27%	325	33	1%	11776	0.251	1.01	1.01	0.0%	0.0%	0
L	L	1	Y	Orlando	434	1828	5269	40%	213	50	1%	7793	0.246	1.01	1.01	0.0%	0.0%	0
L	M	0	N	Miami	567	31	6794	44%	254	0	0%	7646	0.083	4.63	4.62	1.3%	0.1%	14
L	M	0	N	Houston	432	5732	4563	36%	214	0	0%	10940	0.093	4.52	4.51	1.0%	0.2%	12
L	M	0	N	Memphis	437	8738	4522	25%	322	0	0%	14018	0.096	4.95	4.94	0.0%	0.0%	0
L	M	0	N	Baltimore	367	14259	2954	20%	251	0	0%	17831	0.098	4.55	4.54	0.0%	0.0%	0
L	M	0	N	Charleston	423	4474	4889	27%	334	0	0%	10121	0.088	5.29	5.28	2.4%	0.0%	12
L	M	0	N	Orlando	433	1433	5033	40%	218	0	0%	7116	0.086	4.99	4.98	1.8%	0.3%	19
L	M	0	Y	Miami	567	26	6794	44%	254	35	1%	7676	0.083	4.63	4.62	0.2%	0.1%	3
L	M	0	Y	Houston	432	5715	4566	36%	214	49	1%	10977	0.093	4.52	4.51	0.0%	0.0%	0
L	M	0	Y	Memphis	437	8738	4522	25%	322	0	0%	14018	0.096	4.95	4.94	0.0%	0.0%	0
L	M	0	Y	Baltimore	367	14259	2954	20%	251	8	0%	17839	0.098	4.55	4.54	0.0%	0.0%	0
L	M	0	Y	Charleston	423	4411	4896	27%	334	58	1%	10122	0.088	5.29	5.28	0.0%	0.0%	0

L	M	0	Y	Orlando	432	1378	5033	40%	219	50	1%	7112	0.086	4.99	4.98	0.0%	0.0%	0
L	M	0.5	N	Miami	585	32	7262	45%	250	0	0%	8129	0.169	1.65	1.65	1.4%	0.2%	14
L	M	0.5	N	Houston	445	6194	4846	37%	210	0	0%	11695	0.176	1.65	1.64	1.2%	0.1%	11
L	M	0.5	N	Memphis	451	9625	4736	25%	316	0	0%	15128	0.181	1.67	1.67	0.0%	0.0%	0
L	M	0.5	N	Baltimore	381	15585	3056	21%	246	0	0%	19267	0.179	1.65	1.65	0.0%	0.0%	0
L	M	0.5	N	Charleston	435	5069	5148	27%	330	0	0%	10983	0.176	1.69	1.69	0.8%	0.0%	4
L	M	0.5	N	Orlando	442	1576	5312	41%	215	0	0%	7545	0.173	1.67	1.67	1.2%	0.2%	16
L	M	0.5	Y	Miami	586	26	7267	45%	250	47	1%	8176	0.169	1.65	1.65	0.2%	0.1%	3
L	M	0.5	Y	Houston	446	6181	4854	37%	209	63	1%	11753	0.176	1.65	1.64	0.0%	0.0%	0
L	M	0.5	Y	Memphis	451	9625	4736	25%	316	0	0%	15128	0.181	1.67	1.67	0.0%	0.0%	0
L	M	0.5	Y	Baltimore	381	15585	3056	21%	246	0	0%	19267	0.179	1.65	1.65	0.0%	0.0%	0
L	M	0.5	Y	Charleston	436	5053	5158	27%	330	42	1%	11019	0.176	1.69	1.69	0.0%	0.0%	0
L	M	0.5	Y	Orlando	442	1533	5316	41%	215	56	1%	7561	0.173	1.67	1.67	0.0%	0.0%	0
L	M	1	N	Miami	604	32	7726	46%	244	0	0%	8606	0.276	1.01	1.01	2.0%	0.2%	16
L	M	1	N	Houston	462	6844	5130	38%	203	0	0%	12639	0.281	1.01	1.01	1.7%	0.1%	11
L	M	1	N	Memphis	470	10976	4949	26%	308	0	0%	16703	0.289	1.01	1.01	0.0%	0.0%	0
L	M	1	N	Baltimore	402	17577	3148	21%	237	0	0%	21363	0.285	1.01	1.01	0.0%	0.0%	0
L	M	1	N	Charleston	451	5945	5393	28%	324	0	0%	12112	0.287	1.01	1.01	1.1%	0.0%	5
L	M	1	N	Orlando	454	1820	5592	42%	211	0	0%	8076	0.283	1.01	1.01	2.0%	0.2%	18
L	M	1	Y	Miami	609	26	7775	47%	243	167	3%	8820	0.276	1.01	1.01	0.2%	0.1%	3
L	M	1	Y	Houston	465	6835	5167	38%	202	127	2%	12796	0.282	1.01	1.01	0.0%	0.0%	0
L	M	1	Y	Memphis	470	10982	4953	26%	308	8	0%	16722	0.289	1.01	1.01	0.0%	0.0%	0
L	M	1	Y	Baltimore	402	17577	3149	21%	237	5	0%	21369	0.285	1.01	1.01	0.0%	0.0%	0
L	M	1	Y	Charleston	453	5907	5425	28%	323	111	2%	12219	0.287	1.01	1.01	0.0%	0.0%	0
L	M	1	Y	Orlando	456	1785	5615	42%	210	106	2%	8171	0.283	1.01	1.01	0.0%	0.0%	0
M	H	0	N	Miami	448	20	5538	43%	212	0	0%	6217	0.118	6.00	5.99	4.2%	0.5%	42
M	H	0	N	Houston	333	3731	3722	38%	169	0	0%	7956	0.127	5.86	5.84	22.9%	4.1%	309
M	H	0	N	Memphis	331	5696	3653	24%	271	0	0%	9952	0.131	6.42	6.40	12.9%	1.8%	143
M	H	0	N	Baltimore	272	9402	2398	21%	201	0	0%	12273	0.132	5.90	5.89	17.7%	3.5%	238
M	H	0	N	Charleston	327	2848	3978	27%	279	0	0%	7432	0.123	6.86	6.85	26.2%	9.3%	500

M	H	0	N	Orlando	339	890	4113	42%	170	0	0%	5513	0.121	6.47	6.46	13.3%	3.4%	205
M	H	0	Y	Miami	450	17	5562	43%	211	132	2%	6372	0.118	6.00	5.99	0.2%	0.1%	3
M	H	0	Y	Houston	331	3224	3751	39%	171	393	8%	7870	0.127	5.86	5.84	0.0%	0.0%	0
M	H	0	Y	Memphis	328	5289	3660	25%	274	247	5%	9798	0.131	6.42	6.40	0.0%	0.0%	0
M	H	0	Y	Baltimore	269	9039	2401	21%	203	256	5%	12167	0.132	5.90	5.89	0.0%	0.0%	0
M	H	0	Y	Charleston	324	2361	4005	27%	282	385	7%	7357	0.123	6.86	6.85	0.0%	0.0%	0
M	H	0	Y	Orlando	341	704	4148	43%	170	271	5%	5633	0.121	6.47	6.46	0.0%	0.0%	0
M	H	0.5	N	Miami	461	21	5873	44%	208	0	0%	6563	0.236	1.72	1.72	6.5%	0.4%	45
M	H	0.5	N	Houston	344	4167	3922	39%	165	0	0%	8599	0.241	1.72	1.72	10.2%	0.6%	89
M	H	0.5	N	Memphis	343	6513	3792	25%	266	0	0%	10913	0.247	1.74	1.74	0.7%	0.0%	1
M	H	0.5	N	Baltimore	284	10732	2444	21%	195	0	0%	13655	0.245	1.72	1.72	0.7%	0.0%	2
M	H	0.5	N	Charleston	336	3396	4142	27%	276	0	0%	8149	0.243	1.75	1.75	9.2%	0.8%	91
M	H	0.5	N	Orlando	346	1046	4295	43%	168	0	0%	5854	0.240	1.74	1.74	7.6%	1.1%	90
M	H	0.5	Y	Miami	470	17	5969	45%	204	314	6%	6975	0.236	1.72	1.72	0.2%	0.1%	3
M	H	0.5	Y	Houston	347	3937	3979	40%	165	326	6%	8753	0.241	1.72	1.72	0.0%	0.0%	0
M	H	0.5	Y	Memphis	344	6456	3810	25%	265	77	1%	10951	0.247	1.74	1.74	0.0%	0.0%	0
M	H	0.5	Y	Baltimore	284	10660	2454	21%	195	69	1%	13663	0.245	1.72	1.72	0.0%	0.0%	0
M	H	0.5	Y	Charleston	340	3204	4204	27%	275	309	6%	8332	0.243	1.75	1.75	0.0%	0.0%	0
M	H	0.5	Y	Orlando	349	940	4346	44%	166	257	5%	6059	0.240	1.74	1.74	0.0%	0.0%	0
M	H	1	N	Miami	476	21	6227	46%	205	0	0%	6928	0.384	1.01	1.01	14.4%	0.3%	94
M	H	1	N	Houston	358	4779	4139	40%	160	0	0%	9435	0.388	1.01	1.01	10.6%	0.4%	78
M	H	1	N	Memphis	359	7744	3941	25%	257	0	0%	12302	0.396	1.01	1.01	1.7%	0.0%	6
M	H	1	N	Baltimore	301	12543	2490	21%	188	0	0%	15522	0.392	1.01	1.01	1.4%	0.0%	5
M	H	1	N	Charleston	347	4160	4306	27%	272	0	0%	9085	0.395	1.01	1.01	11.2%	0.3%	79
M	H	1	N	Orlando	353	1249	4483	44%	165	0	0%	6251	0.390	1.01	1.01	8.7%	0.8%	76
M	H	1	Y	Miami	502	17	6507	48%	194	760	14%	7980	0.384	1.01	1.01	0.5%	0.1%	4
M	H	1	Y	Houston	370	4655	4287	42%	156	500	9%	9968	0.388	1.01	1.01	0.1%	0.0%	0
M	H	1	Y	Memphis	365	7744	4013	26%	255	167	3%	12544	0.396	1.01	1.01	0.0%	0.0%	0
M	H	1	Y	Baltimore	305	12524	2538	22%	187	106	2%	15659	0.392	1.01	1.01	0.0%	0.0%	0
M	H	1	Y	Charleston	363	4044	4503	29%	264	580	11%	9753	0.395	1.01	1.01	0.2%	0.0%	0

M	H	1	Y	Orlando	366	1175	4632	46%	161	445	8%	6779	0.390	1.01	1.01	0.0%	0.0%	0
M	L	0	N	Miami	394	21	4695	38%	220	0	0%	5329	0.092	4.35	4.34	1.1%	0.1%	12
M	L	0	N	Houston	301	4127	3150	34%	169	0	0%	7748	0.102	4.25	4.24	0.7%	0.1%	7
M	L	0	N	Memphis	303	6243	3094	22%	269	0	0%	9909	0.105	4.65	4.64	0.0%	0.0%	0
M	L	0	N	Baltimore	256	10176	2007	19%	195	0	0%	12634	0.107	4.28	4.27	0.0%	0.0%	0
M	L	0	N	Charleston	292	3231	3332	23%	280	0	0%	7136	0.097	4.98	4.97	0.3%	0.0%	1
M	L	0	N	Orlando	300	1039	3464	37%	173	0	0%	4975	0.095	4.70	4.69	0.9%	0.1%	10
M	L	0	Y	Miami	394	18	4695	38%	220	22	1%	5349	0.092	4.35	4.34	0.2%	0.1%	3
M	L	0	Y	Houston	301	4120	3151	34%	169	25	1%	7766	0.102	4.25	4.24	0.0%	0.0%	0
M	L	0	Y	Memphis	303	6243	3094	22%	269	0	0%	9909	0.105	4.65	4.64	0.0%	0.0%	0
M	L	0	Y	Baltimore	256	10176	2007	19%	195	0	0%	12634	0.107	4.28	4.27	0.0%	0.0%	0
M	L	0	Y	Charleston	292	3228	3336	23%	280	12	0%	7147	0.097	4.98	4.97	0.0%	0.0%	0
M	L	0	Y	Orlando	300	1012	3463	37%	173	24	1%	4972	0.095	4.70	4.69	0.0%	0.0%	0
M	L	0.5	N	Miami	404	21	4978	39%	217	0	0%	5621	0.170	1.63	1.63	1.2%	0.1%	12
M	L	0.5	N	Houston	309	4399	3328	34%	166	0	0%	8202	0.176	1.63	1.63	0.9%	0.1%	8
M	L	0.5	N	Memphis	313	6790	3234	22%	266	0	0%	10602	0.181	1.65	1.65	0.0%	0.0%	0
M	L	0.5	N	Baltimore	265	10983	2076	19%	191	0	0%	13516	0.179	1.63	1.63	0.0%	0.0%	0
M	L	0.5	N	Charleston	300	3582	3502	24%	278	0	0%	7662	0.176	1.67	1.67	0.3%	0.0%	1
M	L	0.5	N	Orlando	306	1145	3641	38%	171	0	0%	5263	0.174	1.66	1.66	1.0%	0.1%	12
M	L	0.5	Y	Miami	405	18	4981	39%	217	28	1%	5650	0.171	1.63	1.63	0.2%	0.1%	3
M	L	0.5	Y	Houston	310	4391	3332	34%	166	35	1%	8235	0.176	1.63	1.63	0.0%	0.0%	0
M	L	0.5	Y	Memphis	313	6790	3234	22%	266	0	0%	10602	0.181	1.65	1.65	0.0%	0.0%	0
M	L	0.5	Y	Baltimore	265	10983	2076	19%	191	0	0%	13516	0.179	1.63	1.63	0.0%	0.0%	0
M	L	0.5	Y	Charleston	300	3574	3505	24%	278	15	0%	7672	0.176	1.67	1.67	0.0%	0.0%	0
M	L	0.5	Y	Orlando	306	1130	3642	38%	171	29	1%	5278	0.174	1.66	1.66	0.0%	0.0%	0
M	L	1	N	Miami	416	21	5263	40%	214	0	0%	5915	0.267	1.01	1.01	1.5%	0.1%	14
M	L	1	N	Houston	319	4794	3506	35%	163	0	0%	8782	0.271	1.01	1.01	1.3%	0.1%	9
M	L	1	N	Memphis	324	7566	3373	22%	259	0	0%	11523	0.279	1.01	1.01	0.0%	0.0%	0
M	L	1	N	Baltimore	277	12188	2134	19%	186	0	0%	14785	0.275	1.01	1.01	0.0%	0.0%	0
M	L	1	N	Charleston	310	4121	3661	24%	272	0	0%	8363	0.277	1.01	1.01	0.6%	0.0%	2

M	L	1	N	Orlando	313	1293	3815	39%	169	0	0%	5590	0.272	1.01	1.01	1.6%	0.1%	14
M	L	1	Y	Miami	418	18	5284	40%	213	84	2%	6018	0.267	1.01	1.01	0.2%	0.1%	3
M	L	1	Y	Houston	320	4786	3517	35%	163	61	2%	8846	0.271	1.01	1.01	0.0%	0.0%	0
M	L	1	Y	Memphis	325	7569	3375	22%	259	5	0%	11533	0.279	1.01	1.01	0.0%	0.0%	0
M	L	1	Y	Baltimore	277	12187	2135	19%	186	2	0%	14787	0.275	1.01	1.01	0.0%	0.0%	0
M	L	1	Y	Charleston	311	4106	3675	24%	272	57	1%	8420	0.277	1.01	1.01	0.0%	0.0%	0
M	L	1	Y	Orlando	314	1272	3824	39%	168	53	1%	5631	0.273	1.01	1.01	0.0%	0.0%	0
M	M	0	N	Miami	418	21	5063	40%	217	0	0%	5719	0.101	5.18	5.16	1.7%	0.2%	19
M	M	0	N	Houston	315	3913	3402	36%	170	0	0%	7800	0.110	5.05	5.04	3.5%	0.3%	29
M	M	0	N	Memphis	315	5930	3337	23%	271	0	0%	9853	0.114	5.53	5.52	0.4%	0.0%	1
M	M	0	N	Baltimore	262	9759	2178	20%	199	0	0%	12398	0.115	5.09	5.08	0.7%	0.0%	3
M	M	0	N	Charleston	307	2999	3614	25%	281	0	0%	7200	0.105	5.92	5.91	7.2%	0.3%	67
M	M	0	N	Orlando	318	973	3751	40%	172	0	0%	5214	0.104	5.58	5.57	3.7%	0.6%	47
M	M	0	Y	Miami	419	17	5066	40%	217	36	1%	5754	0.101	5.18	5.16	0.2%	0.1%	3
M	M	0	Y	Houston	315	3804	3407	36%	170	99	2%	7796	0.110	5.05	5.04	0.0%	0.0%	0
M	M	0	Y	Memphis	315	5875	3336	23%	271	25	1%	9822	0.114	5.53	5.52	0.0%	0.0%	0
M	M	0	Y	Baltimore	262	9683	2178	20%	199	40	1%	12362	0.115	5.09	5.08	0.0%	0.0%	0
M	M	0	Y	Charleston	306	2887	3623	25%	281	105	2%	7202	0.105	5.92	5.91	0.0%	0.0%	0
M	M	0	Y	Orlando	318	912	3754	40%	172	72	2%	5228	0.104	5.58	5.57	0.0%	0.0%	0
M	M	0.5	N	Miami	430	21	5386	41%	213	0	0%	6050	0.200	1.69	1.68	1.7%	0.2%	18
M	M	0.5	N	Houston	325	4271	3602	37%	166	0	0%	8364	0.205	1.68	1.68	2.3%	0.2%	20
M	M	0.5	N	Memphis	327	6645	3489	23%	265	0	0%	10726	0.210	1.70	1.70	0.0%	0.0%	0
M	M	0.5	N	Baltimore	273	10813	2244	20%	194	0	0%	13525	0.208	1.68	1.68	0.0%	0.0%	0
M	M	0.5	N	Charleston	316	3472	3792	25%	277	0	0%	7857	0.206	1.72	1.72	2.5%	0.0%	14
M	M	0.5	N	Orlando	325	1093	3941	40%	170	0	0%	5528	0.203	1.70	1.70	2.5%	0.5%	28
M	M	0.5	Y	Miami	432	18	5399	42%	213	69	1%	6129	0.200	1.69	1.68	0.2%	0.1%	3
M	M	0.5	Y	Houston	326	4237	3616	37%	166	87	2%	8433	0.205	1.68	1.68	0.0%	0.0%	0
M	M	0.5	Y	Memphis	327	6645	3489	23%	265	1	0%	10727	0.210	1.70	1.70	0.0%	0.0%	0
M	M	0.5	Y	Baltimore	273	10815	2245	20%	194	3	0%	13530	0.208	1.68	1.68	0.0%	0.0%	0
M	M	0.5	Y	Charleston	317	3418	3806	25%	277	76	2%	7894	0.206	1.72	1.72	0.0%	0.0%	0

M	M	0.5	Y	Orlando	325	1059	3954	40%	170	74	2%	5582	0.203	1.70	1.70	0.0%	0.0%	0
M	M	1	N	Miami	445	21	5715	43%	210	0	0%	6391	0.322	1.01	1.01	4.5%	0.2%	27
M	M	1	N	Houston	338	4785	3806	37%	162	0	0%	9090	0.326	1.01	1.01	3.5%	0.1%	22
M	M	1	N	Memphis	341	7645	3640	24%	258	0	0%	11884	0.335	1.01	1.01	0.2%	0.0%	1
M	M	1	N	Baltimore	288	12317	2302	20%	188	0	0%	15095	0.330	1.01	1.01	0.1%	0.0%	0
M	M	1	N	Charleston	327	4130	3963	25%	272	0	0%	8692	0.333	1.01	1.01	3.3%	0.0%	16
M	M	1	N	Orlando	332	1274	4130	41%	167	0	0%	5904	0.328	1.01	1.01	2.9%	0.3%	29
M	M	1	Y	Miami	455	18	5821	44%	206	307	7%	6807	0.323	1.01	1.01	0.2%	0.1%	3
M	M	1	Y	Houston	342	4762	3859	38%	160	184	4%	9307	0.327	1.01	1.01	0.0%	0.0%	0
M	M	1	Y	Memphis	342	7645	3653	24%	258	32	1%	11931	0.335	1.01	1.01	0.0%	0.0%	0
M	M	1	Y	Baltimore	289	12319	2312	20%	187	20	0%	15127	0.330	1.01	1.01	0.0%	0.0%	0
M	M	1	Y	Charleston	333	4085	4033	26%	269	214	5%	8934	0.333	1.01	1.01	0.0%	0.0%	0
M	M	1	Y	Orlando	336	1250	4174	42%	166	155	3%	6081	0.328	1.01	1.01	0.0%	0.0%	0
S	H	0	N	Miami	294	10	3733	38%	169	0	0%	4207	0.190	8.47	8.45	27.0%	2.6%	282
S	H	0	N	Houston	223	1780	2620	26%	196	0	0%	4819	0.199	8.27	8.25	49.0%	24.1%	1241
S	H	0	N	Memphis	205	2804	2426	21%	217	0	0%	5652	0.203	9.06	9.04	45.4%	18.7%	967
S	H	0	N	Baltimore	165	4773	1607	21%	148	0	0%	6692	0.204	8.33	8.31	47.6%	20.9%	1090
S	H	0	N	Charleston	208	1338	2658	23%	222	0	0%	4426	0.195	9.69	9.66	47.9%	26.8%	1383
S	H	0	N	Orlando	231	388	2881	29%	196	0	0%	3695	0.193	9.14	9.11	39.1%	13.4%	765
S	H	0	Y	Miami	309	8	3875	40%	162	521	10%	4874	0.190	8.47	8.45	0.3%	0.0%	2
S	H	0	Y	Houston	229	1176	2736	28%	193	795	15%	5129	0.200	8.27	8.25	0.2%	0.0%	0
S	H	0	Y	Memphis	204	2029	2486	22%	221	625	12%	5565	0.203	9.06	9.04	0.0%	0.0%	0
S	H	0	Y	Baltimore	160	3970	1636	21%	152	589	11%	6507	0.204	8.33	8.31	0.0%	0.0%	0
S	H	0	Y	Charleston	213	762	2774	24%	220	766	14%	4734	0.195	9.69	9.66	0.1%	0.0%	0
S	H	0	Y	Orlando	241	192	3003	31%	190	620	12%	4247	0.194	9.14	9.11	0.1%	0.0%	0
S	H	0.5	N	Miami	303	10	3934	39%	168	0	0%	4415	0.370	1.80	1.80	37.3%	2.0%	351
S	H	0.5	N	Houston	230	2118	2731	27%	195	0	0%	5273	0.374	1.80	1.79	41.2%	6.2%	490
S	H	0.5	N	Memphis	213	3422	2487	21%	210	0	0%	6332	0.378	1.81	1.81	16.6%	0.1%	110
S	H	0.5	N	Baltimore	173	5758	1612	21%	144	0	0%	7687	0.376	1.80	1.79	11.7%	0.2%	77
S	H	0.5	N	Charleston	212	1734	2726	23%	219	0	0%	4891	0.375	1.82	1.82	37.4%	5.0%	413

S	H	0.5	N	Orlando	234	486	2968	29%	197	0	0%	3885	0.374	1.81	1.81	35.6%	4.6%	407
S	H	0.5	Y	Miami	331	8	4230	42%	154	896	16%	5619	0.369	1.80	1.80	0.4%	0.0%	2
S	H	0.5	Y	Houston	247	1809	2944	29%	187	869	16%	6056	0.373	1.80	1.79	0.2%	0.0%	0
S	H	0.5	Y	Memphis	221	3205	2600	22%	209	415	8%	6650	0.378	1.81	1.81	0.0%	0.0%	0
S	H	0.5	Y	Baltimore	177	5607	1668	22%	143	244	5%	7838	0.376	1.80	1.79	0.0%	0.0%	0
S	H	0.5	Y	Charleston	230	1511	2945	25%	211	759	14%	5656	0.375	1.82	1.82	0.1%	0.0%	0
S	H	0.5	Y	Orlando	253	367	3183	32%	187	769	14%	4760	0.373	1.82	1.81	0.2%	0.0%	0
S	H	1	N	Miami	312	10	4144	40%	166	0	0%	4633	0.587	1.02	1.02	42.6%	5.0%	490
S	H	1	N	Houston	239	2578	2855	27%	191	0	0%	5864	0.589	1.02	1.02	37.5%	4.9%	450
S	H	1	N	Memphis	223	4320	2561	21%	203	0	0%	7308	0.596	1.02	1.02	15.0%	0.4%	118
S	H	1	N	Baltimore	185	7099	1624	21%	139	0	0%	9048	0.590	1.02	1.02	8.7%	0.1%	61
S	H	1	N	Charleston	220	2296	2804	23%	214	0	0%	5534	0.595	1.02	1.02	33.9%	4.3%	400
S	H	1	N	Orlando	239	646	3072	30%	196	0	0%	4152	0.592	1.02	1.02	34.7%	4.3%	398
S	H	1	Y	Miami	353	8	4600	45%	145	1149	21%	6255	0.585	1.02	1.02	2.9%	0.0%	11
S	H	1	Y	Houston	266	2394	3175	31%	178	973	18%	6987	0.589	1.02	1.02	1.9%	0.0%	6
S	H	1	Y	Memphis	239	4260	2749	23%	196	448	8%	7891	0.596	1.02	1.02	0.5%	0.0%	1
S	H	1	Y	Baltimore	193	7041	1720	22%	136	238	4%	9328	0.590	1.02	1.02	0.1%	0.0%	0
S	H	1	Y	Charleston	247	2183	3142	27%	200	872	16%	6644	0.595	1.02	1.02	1.6%	0.0%	5
S	H	1	Y	Orlando	267	563	3399	34%	181	921	17%	5331	0.591	1.02	1.02	1.7%	0.0%	5
S	L	0	N	Miami	237	10	2880	30%	178	0	0%	3306	0.136	5.18	5.16	1.6%	0.2%	17
S	L	0	N	Houston	186	2151	2011	21%	197	0	0%	4545	0.146	5.05	5.04	2.9%	0.3%	27
S	L	0	N	Memphis	176	3313	1865	17%	214	0	0%	5568	0.149	5.54	5.52	0.0%	0.0%	0
S	L	0	N	Baltimore	148	5476	1218	17%	142	0	0%	6984	0.150	5.09	5.08	0.1%	0.0%	0
S	L	0	N	Charleston	171	1688	2011	18%	222	0	0%	4091	0.141	5.92	5.91	3.7%	0.1%	25
S	L	0	N	Orlando	186	526	2193	23%	200	0	0%	3106	0.139	5.58	5.57	2.9%	0.7%	38
S	L	0	Y	Miami	238	8	2885	31%	179	26	1%	3336	0.136	5.18	5.16	0.1%	0.0%	2
S	L	0	Y	Houston	186	2121	2014	21%	197	50	1%	4567	0.146	5.05	5.04	0.0%	0.0%	0
S	L	0	Y	Memphis	176	3298	1865	17%	215	6	0%	5559	0.149	5.54	5.52	0.0%	0.0%	0
S	L	0	Y	Baltimore	148	5471	1218	17%	142	7	0%	6986	0.150	5.09	5.08	0.0%	0.0%	0
S	L	0	Y	Charleston	171	1636	2015	18%	222	44	1%	4088	0.141	5.92	5.91	0.0%	0.0%	0

S	L	0	Y	Orlando	186	504	2195	23%	200	39	1%	3125	0.139	5.58	5.57	0.0%	0.0%	0
S	L	0.5	N	Miami	244	10	3040	31%	177	0	0%	3472	0.234	1.68	1.68	2.0%	0.2%	18
S	L	0.5	N	Houston	191	2333	2111	22%	196	0	0%	4831	0.239	1.68	1.68	2.9%	0.2%	25
S	L	0.5	N	Memphis	181	3652	1939	17%	212	0	0%	5984	0.244	1.70	1.70	0.1%	0.0%	0
S	L	0.5	N	Baltimore	154	5983	1253	17%	139	0	0%	7529	0.242	1.68	1.68	0.0%	0.0%	0
S	L	0.5	N	Charleston	175	1911	2095	18%	221	0	0%	4402	0.239	1.72	1.72	1.9%	0.0%	10
S	L	0.5	N	Orlando	190	581	2288	24%	201	0	0%	3259	0.238	1.70	1.70	2.4%	0.4%	27
S	L	0.5	Y	Miami	246	9	3057	32%	176	69	2%	3555	0.234	1.68	1.68	0.1%	0.0%	2
S	L	0.5	Y	Houston	193	2317	2126	22%	195	74	2%	4905	0.239	1.68	1.68	0.0%	0.0%	0
S	L	0.5	Y	Memphis	182	3650	1941	17%	211	6	0%	5990	0.244	1.70	1.70	0.0%	0.0%	0
S	L	0.5	Y	Baltimore	154	5983	1253	17%	139	1	0%	7530	0.242	1.68	1.68	0.0%	0.0%	0
S	L	0.5	Y	Charleston	176	1882	2108	19%	220	54	1%	4440	0.240	1.72	1.72	0.0%	0.0%	0
S	L	0.5	Y	Orlando	191	570	2303	24%	200	62	2%	3327	0.238	1.70	1.70	0.0%	0.0%	0
S	L	1	N	Miami	251	10	3195	32%	176	0	0%	3632	0.351	1.01	1.01	7.2%	0.2%	40
S	L	1	N	Houston	198	2592	2208	22%	194	0	0%	5192	0.355	1.01	1.01	6.2%	0.2%	38
S	L	1	N	Memphis	188	4124	2006	18%	206	0	0%	6523	0.362	1.01	1.01	0.6%	0.0%	3
S	L	1	N	Baltimore	161	6717	1281	17%	137	0	0%	8296	0.358	1.01	1.01	0.1%	0.0%	0
S	L	1	N	Charleston	181	2219	2172	19%	217	0	0%	4789	0.360	1.01	1.01	5.1%	0.0%	24
S	L	1	N	Orlando	194	681	2382	24%	200	0	0%	3457	0.357	1.01	1.01	5.6%	0.3%	39
S	L	1	Y	Miami	259	9	3280	33%	172	267	7%	3986	0.351	1.01	1.01	0.2%	0.0%	2
S	L	1	Y	Houston	203	2582	2266	23%	192	195	5%	5438	0.355	1.01	1.01	0.0%	0.0%	0
S	L	1	Y	Memphis	190	4125	2024	18%	205	38	1%	6582	0.362	1.01	1.01	0.0%	0.0%	0
S	L	1	Y	Baltimore	162	6717	1287	17%	136	13	0%	8315	0.358	1.01	1.01	0.0%	0.0%	0
S	L	1	Y	Charleston	186	2205	2233	19%	215	175	4%	5014	0.360	1.01	1.01	0.0%	0.0%	0
S	L	1	Y	Orlando	199	662	2432	25%	198	173	4%	3664	0.357	1.01	1.01	0.0%	0.0%	0
S	M	0	N	Miami	263	10	3254	34%	175	0	0%	3702	0.154	6.82	6.81	6.4%	0.5%	50
S	M	0	N	Houston	202	1960	2280	24%	197	0	0%	4640	0.163	6.66	6.65	23.8%	3.6%	298
S	M	0	N	Memphis	189	3024	2111	19%	216	0	0%	5540	0.167	7.30	7.28	12.0%	1.3%	117
S	M	0	N	Baltimore	155	5064	1390	19%	146	0	0%	6756	0.168	6.71	6.70	14.2%	1.5%	155
S	M	0	N	Charleston	187	1476	2293	20%	223	0	0%	4179	0.159	7.80	7.79	22.9%	7.1%	370

S	M	0	N	Orlando	206	458	2496	26%	199	0	0%	3360	0.157	7.36	7.34	14.4%	3.3%	207
S	M	0	Y	Miami	266	8	3285	34%	172	127	3%	3858	0.154	6.82	6.81	0.1%	0.0%	2
S	M	0	Y	Houston	203	1712	2309	24%	197	260	6%	4681	0.164	6.66	6.65	0.0%	0.0%	0
S	M	0	Y	Memphis	187	2803	2118	19%	218	142	3%	5469	0.167	7.30	7.28	0.0%	0.0%	0
S	M	0	Y	Baltimore	154	4890	1393	19%	147	130	3%	6714	0.168	6.71	6.70	0.0%	0.0%	0
S	M	0	Y	Charleston	187	1258	2317	21%	224	229	5%	4215	0.159	7.80	7.79	0.0%	0.0%	0
S	M	0	Y	Orlando	208	364	2525	26%	198	190	4%	3486	0.158	7.36	7.34	0.0%	0.0%	0
S	M	0.5	N	Miami	271	10	3450	35%	173	0	0%	3904	0.294	1.75	1.75	11.9%	0.3%	71
S	M	0.5	N	Houston	209	2209	2392	24%	196	0	0%	5006	0.298	1.75	1.75	14.0%	0.8%	116
S	M	0.5	N	Memphis	195	3504	2188	19%	212	0	0%	6098	0.303	1.77	1.76	1.4%	0.0%	5
S	M	0.5	N	Baltimore	163	5831	1419	19%	142	0	0%	7555	0.301	1.75	1.75	0.8%	0.0%	2
S	M	0.5	N	Charleston	192	1809	2383	21%	220	0	0%	4604	0.299	1.78	1.78	11.5%	0.4%	88
S	M	0.5	N	Orlando	210	529	2602	26%	199	0	0%	3540	0.298	1.77	1.77	11.7%	1.0%	104
S	M	0.5	Y	Miami	281	8	3547	36%	168	330	7%	4334	0.293	1.75	1.75	0.1%	0.0%	2
S	M	0.5	Y	Houston	215	2093	2467	25%	193	314	7%	5282	0.298	1.75	1.75	0.0%	0.0%	0
S	M	0.5	Y	Memphis	198	3479	2214	19%	211	83	2%	6184	0.303	1.77	1.76	0.0%	0.0%	0
S	M	0.5	Y	Baltimore	163	5800	1429	19%	142	41	1%	7576	0.301	1.75	1.75	0.0%	0.0%	0
S	M	0.5	Y	Charleston	198	1723	2457	21%	217	270	6%	4865	0.300	1.78	1.78	0.0%	0.0%	0
S	M	0.5	Y	Orlando	217	468	2671	27%	195	270	6%	3821	0.298	1.77	1.77	0.0%	0.0%	0
S	M	1	N	Miami	280	10	3641	36%	172	0	0%	4103	0.461	1.01	1.01	24.0%	0.5%	181
S	M	1	N	Houston	217	2578	2511	25%	193	0	0%	5500	0.465	1.01	1.01	20.5%	0.7%	158
S	M	1	N	Memphis	204	4188	2264	19%	204	0	0%	6861	0.472	1.01	1.01	4.5%	0.0%	22
S	M	1	N	Baltimore	173	6872	1443	19%	138	0	0%	8625	0.467	1.01	1.01	2.0%	0.0%	9
S	M	1	N	Charleston	199	2243	2466	21%	216	0	0%	5124	0.471	1.01	1.01	18.1%	0.4%	137
S	M	1	N	Orlando	215	662	2704	27%	198	0	0%	3779	0.467	1.01	1.01	17.7%	0.8%	146
S	M	1	Y	Miami	302	8	3879	39%	162	673	15%	5024	0.460	1.02	1.01	0.9%	0.0%	3
S	M	1	Y	Houston	232	2494	2680	27%	187	536	12%	6129	0.464	1.01	1.01	0.6%	0.0%	1
S	M	1	Y	Memphis	211	4181	2344	20%	201	190	4%	7128	0.472	1.01	1.01	0.1%	0.0%	0
S	M	1	Y	Baltimore	175	6858	1479	19%	137	81	2%	8730	0.466	1.01	1.01	0.0%	0.0%	0
S	M	1	Y	Charleston	213	2186	2640	23%	210	470	10%	5720	0.470	1.01	1.01	0.5%	0.0%	1

S	M	1	Y	Orlando	230	623	2864	29%	192	482	11%	4390	0.466	1.01	1.01	0.4%	0.0%	1

Table 44 Performance summary baseline data table.

House Size	Moisture Gains	Dehumidifier (Yes / No)	Climate Zone	Control Type	Air Handler (kWh)	Furnace (kWh)	Compressor (kWh)	Compressor runtime	Ventilation (kWh)	Dehumidifier (kwh)	Dehumidifier Runtime	HVAC Total (kWh)	Mean Air Exchange Rate (hr^{-1})	Relative Exposure	Relative Dose	Annual Fraction >60% RH	Annual Fraction >70% RH	Annual Humidity Index (hours)
M	H	N	Miami	1	520	21	7172	50%	144	0	0%	7857	0.59	0.841	0.841	10.1%	0.3%	70
M	H	N	Miami	12	520	21	7165	50%	155	0	0%	7860	0.60	0.823	0.823	10.2%	0.3%	72
M	H	N	Miami	13	466	21	6111	45%	401	0	0%	6999	0.58	0.907	0.909	19.7%	0.5%	155
M	H	N	Miami	14	476	21	6277	46%	303	0	0%	7077	0.50	0.960	0.960	14.9%	0.3%	100
M	H	N	Miami	2	476	21	6244	46%	239	0	0%	6981	0.42	0.953	0.953	13.4%	0.3%	98
M	H	N	Miami	3	481	21	6334	46%	227	0	0%	7062	0.43	0.942	0.942	11.8%	0.2%	75
M	H	N	Miami	6	475	21	6215	46%	240	0	0%	6951	0.41	0.978	0.978	17.0%	0.4%	122
M	H	N	Miami	7	514	21	7091	49%	200	0	0%	7826	0.63	0.848	0.847	6.0%	0.2%	38
M	H	N	Miami	8	487	21	6466	47%	225	0	0%	7198	0.48	1.011	1.011	16.2%	0.3%	117
M	H	N	Miami	9	465	21	6051	45%	295	0	0%	6833	0.43	1.028	1.028	13.2%	0.3%	89
M	H	N	Houston	1	387	4806	4844	44%	144	0	0%	10181	0.61	0.784	0.784	10.7%	0.6%	82
M	H	N	Houston	12	397	5928	4832	44%	209	0	0%	11367	0.70	0.658	0.660	10.6%	0.5%	89
M	H	N	Houston	13	356	6367	3849	38%	298	0	0%	10869	0.55	0.978	0.979	8.2%	0.1%	51
M	H	N	Houston	14	362	5541	4145	40%	225	0	0%	10274	0.51	0.958	0.959	8.9%	0.1%	60
M	H	N	Houston	2	358	4883	4147	40%	192	0	0%	9579	0.43	0.932	0.932	8.6%	0.1%	57
M	H	N	Houston	3	360	4883	4181	40%	188	0	0%	9611	0.43	0.925	0.925	8.3%	0.1%	53
M	H	N	Houston	6	361	5933	3986	39%	238	0	0%	10517	0.47	0.980	0.981	10.7%	0.5%	92
M	H	N	Houston	7	394	6092	4781	43%	210	0	0%	11477	0.70	0.722	0.723	6.0%	0.0%	34
M	H	N	Houston	8	370	6050	4159	40%	233	0	0%	10812	0.52	1.001	1.002	10.2%	0.6%	91
M	H	N	Houston	9	360	6210	3956	39%	241	0	0%	10768	0.49	1.015	1.016	6.5%	0.1%	39
M	H	N	Memphis	1	381	7717	4455	27%	253	0	0%	12806	0.52	0.885	0.885	1.6%	0.0%	5
M	H	N	Memphis	12	406	10855	4394	27%	442	0	0%	16098	0.70	0.679	0.681	1.8%	0.0%	7
M	H	N	Memphis	13	380	11285	3698	24%	469	0	0%	15831	0.57	0.945	0.946	0.7%	0.0%	3
M	H	N	Memphis	14	375	9658	3925	25%	380	0	0%	14339	0.53	0.962	0.961	2.4%	0.0%	11

M	H	N	Memphis	2	359	7723	3954	25%	310	0	0%	12346	0.43	0.932	0.932	1.7%	0.0%	8
M	H	N	Memphis	3	360	7724	3970	25%	308	0	0%	12362	0.43	0.931	0.931	1.5%	0.0%	5
M	H	N	Memphis	6	375	10863	3668	24%	476	0	0%	15381	0.56	0.980	0.981	2.0%	0.0%	8
M	H	N	Memphis	7	397	9857	4389	27%	351	0	0%	14994	0.62	0.820	0.820	0.4%	0.0%	1
M	H	N	Memphis	8	383	10461	3923	25%	418	0	0%	15184	0.57	0.988	0.989	1.7%	0.0%	6
M	H	N	Memphis	9	383	11574	3738	24%	480	0	0%	16176	0.60	0.885	0.885	1.4%	0.0%	6
M	H	N	Baltimore	1	311	12622	2724	22%	192	0	0%	15850	0.50	0.889	0.889	1.9%	0.0%	7
M	H	N	Baltimore	12	356	17085	2752	23%	272	0	0%	20465	0.68	0.718	0.720	0.9%	0.0%	3
M	H	N	Baltimore	13	344	17410	2407	21%	277	0	0%	20439	0.56	0.968	0.969	0.7%	0.0%	2
M	H	N	Baltimore	14	319	15026	2399	21%	267	0	0%	18010	0.54	0.945	0.946	1.5%	0.0%	7
M	H	N	Baltimore	2	301	12619	2486	21%	223	0	0%	15630	0.42	0.934	0.934	1.7%	0.0%	7
M	H	N	Baltimore	3	302	12620	2498	21%	222	0	0%	15642	0.42	0.932	0.932	1.6%	0.0%	5
M	H	N	Baltimore	6	342	17075	2410	21%	293	0	0%	20121	0.55	0.979	0.981	0.6%	0.0%	2
M	H	N	Baltimore	7	353	17736	2634	22%	315	0	0%	21039	0.74	0.674	0.675	1.5%	0.0%	6
M	H	N	Baltimore	8	343	16581	2532	22%	265	0	0%	19721	0.56	0.993	0.994	0.9%	0.0%	4
M	H	N	Baltimore	9	335	17067	2341	20%	321	0	0%	20065	0.61	0.840	0.841	1.2%	0.0%	5
M	H	N	Charleston	1	371	4147	4882	29%	253	0	0%	9654	0.53	0.898	0.898	9.8%	0.3%	72
M	H	N	Charleston	12	387	5729	4886	29%	344	0	0%	11346	0.61	0.819	0.820	8.6%	0.5%	66
M	H	N	Charleston	13	350	6443	3988	26%	489	0	0%	11269	0.56	0.982	0.984	5.7%	0.1%	34
M	H	N	Charleston	14	352	5374	4230	27%	418	0	0%	10373	0.53	0.957	0.957	13.0%	0.1%	95
M	H	N	Charleston	2	348	4252	4317	27%	326	0	0%	9244	0.43	0.937	0.937	10.2%	0.1%	69
M	H	N	Charleston	3	352	4247	4410	28%	320	0	0%	9330	0.45	0.926	0.926	9.7%	0.1%	61
M	H	N	Charleston	6	356	5714	4177	27%	398	0	0%	10645	0.48	0.979	0.980	10.3%	0.5%	80
M	H	N	Charleston	7	386	6350	4792	29%	383	0	0%	11911	0.65	0.853	0.852	5.0%	0.0%	28
M	H	N	Charleston	8	368	5917	4396	28%	386	0	0%	11067	0.54	1.003	1.004	10.3%	0.5%	81
M	H	N	Charleston	9	349	5482	4119	26%	388	0	0%	10338	0.48	1.010	1.010	8.1%	0.1%	54
M	H	N	Orlando	1	381	1262	5151	47%	139	0	0%	6934	0.62	0.791	0.791	8.6%	0.9%	79
M	H	N	Orlando	12	382	1640	5119	47%	202	0	0%	7343	0.69	0.693	0.695	8.6%	0.9%	79
M	H	N	Orlando	13	339	1821	4165	41%	317	0	0%	6643	0.55	0.986	0.986	6.8%	0.5%	60
M	H	N	Orlando	14	355	1597	4502	44%	238	0	0%	6692	0.52	0.961	0.959	8.5%	0.2%	63

M	H	N	Orlando	2	354	1313	4497	44%	197	0	0%	6361	0.43	0.930	0.930	8.0%	0.4%	66
M	H	N	Orlando	3	356	1315	4531	44%	195	0	0%	6396	0.44	0.924	0.924	7.5%	0.4%	61
M	H	N	Orlando	6	349	1633	4340	43%	238	0	0%	6560	0.45	0.980	0.981	8.6%	0.9%	81
M	H	N	Orlando	7	379	1726	5068	47%	218	0	0%	7391	0.70	0.732	0.733	6.1%	0.4%	47
M	H	N	Orlando	8	357	1704	4506	44%	235	0	0%	6802	0.52	0.991	0.992	8.9%	0.9%	84
M	H	N	Orlando	9	344	1552	4264	42%	224	0	0%	6384	0.43	1.131	1.130	5.8%	0.6%	51
M	H	Y	Miami	1	541	17	7426	52%	129	542	10%	8655	0.60	0.825	0.825	0.4%	0.1%	4
M	H	Y	Miami	12	541	17	7423	52%	140	555	10%	8676	0.61	0.808	0.808	0.4%	0.1%	4
M	H	Y	Miami	13	502	17	6528	48%	375	999	18%	8421	0.58	0.907	0.909	1.3%	0.1%	6
M	H	Y	Miami	14	504	17	6590	48%	291	807	15%	8208	0.50	0.960	0.960	1.2%	0.1%	6
M	H	Y	Miami	2	507	17	6593	49%	219	825	15%	8162	0.41	0.947	0.947	0.3%	0.1%	4
M	H	Y	Miami	3	507	17	6595	49%	219	826	15%	8164	0.41	0.945	0.945	0.4%	0.1%	4
M	H	Y	Miami	6	504	17	6523	48%	231	836	15%	8111	0.41	0.978	0.978	2.1%	0.1%	9
M	H	Y	Miami	7	531	17	7302	51%	180	415	8%	8445	0.63	0.839	0.839	0.2%	0.1%	3
M	H	Y	Miami	8	514	17	6764	49%	220	803	15%	8320	0.48	1.011	1.011	2.3%	0.1%	10
M	H	Y	Miami	9	490	17	6318	47%	277	706	13%	7808	0.42	1.040	1.040	1.7%	0.1%	7
M	H	Y	Houston	1	403	4687	5062	46%	138	523	10%	10813	0.62	0.765	0.765	0.0%	0.0%	0
M	H	Y	Houston	12	414	5828	5062	46%	203	573	11%	12080	0.71	0.638	0.639	0.1%	0.0%	0
M	H	Y	Houston	13	365	6265	3965	39%	295	440	8%	11331	0.55	0.978	0.979	0.2%	0.0%	0
M	H	Y	Houston	14	376	5480	4304	42%	220	460	9%	10840	0.51	0.958	0.959	0.3%	0.0%	1
M	H	Y	Houston	2	372	4721	4328	42%	177	503	9%	10101	0.42	0.940	0.940	0.1%	0.0%	0
M	H	Y	Houston	3	373	4721	4339	42%	176	505	9%	10114	0.42	0.938	0.939	0.0%	0.0%	0
M	H	Y	Houston	6	373	5825	4141	41%	234	528	10%	11101	0.47	0.980	0.981	0.4%	0.0%	1
M	H	Y	Houston	7	408	5990	4970	45%	200	400	8%	11968	0.71	0.712	0.714	0.0%	0.0%	0
M	H	Y	Houston	8	381	5937	4298	42%	228	485	9%	11329	0.52	1.001	1.002	0.3%	0.0%	1
M	H	Y	Houston	9	371	6121	4081	40%	231	373	7%	11177	0.48	1.026	1.027	0.2%	0.0%	1
M	H	Y	Memphis	1	386	7706	4521	28%	249	131	2%	12993	0.52	0.883	0.883	0.0%	0.0%	0
M	H	Y	Memphis	12	412	10856	4465	27%	439	136	3%	16308	0.70	0.672	0.674	0.0%	0.0%	0
M	H	Y	Memphis	13	384	11285	3740	24%	469	108	2%	15986	0.57	0.945	0.946	0.1%	0.0%	0
M	H	Y	Memphis	14	383	9659	4019	26%	376	206	4%	14642	0.53	0.962	0.961	0.1%	0.0%	0

M	H	Y	Memphis	2	366	7728	4043	26%	303	167	3%	12606	0.42	0.934	0.934	0.1%	0.0%	0
M	H	Y	Memphis	3	366	7731	4045	26%	302	167	3%	12612	0.42	0.935	0.935	0.0%	0.0%	0
M	H	Y	Memphis	6	379	10864	3725	24%	474	142	3%	15584	0.56	0.980	0.981	0.1%	0.0%	0
M	H	Y	Memphis	7	401	9857	4446	27%	347	97	2%	15149	0.62	0.818	0.818	0.0%	0.0%	0
M	H	Y	Memphis	8	386	10456	3967	25%	417	115	2%	15342	0.57	0.988	0.989	0.0%	0.0%	0
M	H	Y	Memphis	9	389	11574	3807	25%	473	149	3%	16392	0.59	0.892	0.892	0.1%	0.0%	0
M	H	Y	Baltimore	1	317	12611	2796	23%	189	119	2%	16031	0.51	0.885	0.885	0.0%	0.0%	0
M	H	Y	Baltimore	12	360	17068	2810	23%	272	111	2%	20621	0.68	0.708	0.710	0.0%	0.0%	0
M	H	Y	Baltimore	13	347	17412	2434	21%	277	59	1%	20529	0.56	0.968	0.969	0.0%	0.0%	0
M	H	Y	Baltimore	14	323	15028	2447	21%	265	100	2%	18163	0.54	0.945	0.946	0.0%	0.0%	0
M	H	Y	Baltimore	2	306	12620	2548	22%	218	106	2%	15798	0.42	0.935	0.935	0.0%	0.0%	0
M	H	Y	Baltimore	3	306	12621	2549	22%	218	106	2%	15801	0.42	0.935	0.935	0.0%	0.0%	0
M	H	Y	Baltimore	6	344	17071	2431	21%	293	63	1%	20202	0.55	0.979	0.981	0.0%	0.0%	0
M	H	Y	Baltimore	7	359	17735	2702	22%	310	112	2%	21219	0.74	0.672	0.673	0.0%	0.0%	0
M	H	Y	Baltimore	8	345	16566	2558	22%	265	63	1%	19797	0.56	0.993	0.994	0.0%	0.0%	0
M	H	Y	Baltimore	9	339	17073	2386	21%	318	87	2%	20204	0.60	0.843	0.844	0.0%	0.0%	0
M	H	Y	Charleston	1	388	4050	5104	31%	242	508	9%	10292	0.53	0.884	0.884	0.0%	0.0%	0
M	H	Y	Charleston	12	401	5579	5085	31%	341	515	10%	11921	0.62	0.794	0.795	0.0%	0.0%	0
M	H	Y	Charleston	13	359	6341	4097	26%	489	392	7%	11678	0.56	0.982	0.984	0.5%	0.0%	1
M	H	Y	Charleston	14	374	5321	4503	29%	403	651	12%	11252	0.53	0.957	0.957	1.0%	0.0%	2
M	H	Y	Charleston	2	366	4098	4552	29%	305	590	11%	9911	0.42	0.942	0.942	0.2%	0.0%	1
M	H	Y	Charleston	3	367	4096	4558	29%	305	606	11%	9932	0.42	0.940	0.940	0.1%	0.0%	0
M	H	Y	Charleston	6	367	5566	4316	28%	397	542	10%	11188	0.48	0.979	0.980	0.6%	0.0%	1
M	H	Y	Charleston	7	399	6258	4980	30%	371	386	7%	12395	0.65	0.838	0.838	0.0%	0.0%	0
M	H	Y	Charleston	8	378	5780	4534	29%	384	510	9%	11588	0.54	1.003	1.004	0.4%	0.0%	1
M	H	Y	Charleston	9	361	5405	4264	27%	382	460	9%	10873	0.47	1.018	1.018	0.8%	0.0%	2
M	H	Y	Orlando	1	397	1188	5363	49%	135	456	9%	7539	0.63	0.769	0.770	0.0%	0.0%	0
M	H	Y	Orlando	12	399	1600	5343	49%	197	488	9%	8028	0.70	0.670	0.671	0.0%	0.0%	0
M	H	Y	Orlando	13	350	1799	4289	43%	314	400	8%	7152	0.55	0.986	0.986	0.2%	0.0%	0
M	H	Y	Orlando	14	369	1571	4668	45%	231	431	8%	7271	0.52	0.961	0.959	0.5%	0.0%	1

M	H	Y	Orlando	2	368	1230	4673	46%	182	433	8%	6887	0.42	0.935	0.935	0.1%	0.0%	0
M	H	Y	Orlando	3	368	1232	4676	46%	182	427	8%	6885	0.42	0.935	0.935	0.1%	0.0%	0
M	H	Y	Orlando	6	362	1594	4489	45%	234	469	9%	7148	0.45	0.980	0.981	0.2%	0.0%	0
M	H	Y	Orlando	7	394	1699	5269	48%	207	370	7%	7939	0.71	0.724	0.724	0.0%	0.0%	0
M	H	Y	Orlando	8	369	1666	4652	45%	231	450	8%	7369	0.52	0.991	0.992	0.2%	0.0%	0
M	H	Y	Orlando	9	354	1538	4373	43%	218	318	6%	6801	0.42	1.142	1.141	0.2%	0.0%	0
S	H	N	Miami	1	341	10	4732	44%	124	0	0%	5207	0.82	0.891	0.891	34.8%	2.5%	324
S	H	N	Miami	12	341	10	4725	44%	132	0	0%	5208	0.83	0.873	0.873	34.7%	2.6%	323
S	H	N	Miami	13	304	10	4040	39%	330	0	0%	4685	0.87	0.913	0.915	41.7%	6.5%	537
S	H	N	Miami	14	312	10	4175	40%	260	0	0%	4758	0.76	0.962	0.963	41.3%	6.4%	522
S	H	N	Miami	2	311	10	4123	40%	219	0	0%	4663	0.65	0.950	0.950	39.8%	7.1%	506
S	H	N	Miami	3	325	10	4405	42%	178	0	0%	4918	0.73	0.908	0.908	34.1%	2.6%	333
S	H	N	Miami	6	311	10	4123	40%	207	0	0%	4651	0.62	0.978	0.978	44.1%	7.9%	572
S	H	N	Miami	7	335	10	4654	43%	192	0	0%	5192	0.91	0.869	0.868	27.7%	1.1%	225
S	H	N	Miami	8	322	10	4350	41%	220	0	0%	4902	0.76	1.032	1.032	43.0%	8.6%	578
S	H	N	Miami	9	303	10	4003	39%	274	0	0%	4590	0.70	1.000	1.000	39.1%	6.4%	485
S	H	N	Houston	1	260	2592	3283	30%	177	0	0%	6312	0.77	0.907	0.907	31.7%	3.7%	351
S	H	N	Houston	12	268	3474	3271	30%	242	0	0%	7255	0.89	0.820	0.821	28.8%	2.8%	292
S	H	N	Houston	13	239	3793	2665	26%	348	0	0%	7045	0.82	0.980	0.982	29.8%	2.8%	327
S	H	N	Houston	14	246	3280	2879	27%	284	0	0%	6689	0.78	0.960	0.961	32.8%	5.0%	412
S	H	N	Houston	2	238	2689	2828	27%	261	0	0%	6015	0.68	0.910	0.910	33.3%	4.8%	412
S	H	N	Houston	3	246	2691	2997	28%	240	0	0%	6174	0.73	0.882	0.882	30.8%	2.4%	320
S	H	N	Houston	6	243	3482	2755	27%	286	0	0%	6765	0.71	0.980	0.981	34.8%	4.9%	418
S	H	N	Houston	7	266	3821	3204	29%	289	0	0%	7581	0.97	0.806	0.808	24.2%	1.3%	219
S	H	N	Houston	8	250	3573	2904	28%	291	0	0%	7019	0.80	1.003	1.005	32.8%	4.5%	399
S	H	N	Houston	9	243	4039	2697	26%	345	0	0%	7325	0.83	0.945	0.947	29.9%	3.6%	348
S	H	N	Memphis	1	238	4340	2884	23%	212	0	0%	7674	0.75	0.911	0.911	11.5%	0.2%	86
S	H	N	Memphis	12	257	6529	2846	23%	347	0	0%	9978	0.99	0.725	0.727	9.7%	0.0%	65
S	H	N	Memphis	13	239	6877	2404	20%	382	0	0%	9902	0.86	0.947	0.948	11.3%	0.3%	90
S	H	N	Memphis	14	235	5753	2546	21%	320	0	0%	8855	0.80	0.962	0.961	14.5%	0.7%	133

S	H	N	Memphis	2	222	4371	2542	21%	270	0	0%	7406	0.66	0.922	0.922	13.4%	0.8%	122
S	H	N	Memphis	3	227	4369	2634	22%	260	0	0%	7489	0.68	0.908	0.908	12.1%	0.3%	92
S	H	N	Memphis	6	235	6530	2388	20%	378	0	0%	9530	0.83	0.979	0.981	11.3%	0.2%	90
S	H	N	Memphis	7	249	5866	2823	23%	302	0	0%	9240	0.92	0.791	0.791	8.7%	0.0%	53
S	H	N	Memphis	8	241	6291	2563	21%	346	0	0%	9440	0.85	1.007	1.008	10.1%	0.2%	79
S	H	N	Memphis	9	242	7345	2399	20%	445	0	0%	10432	0.97	0.815	0.815	12.6%	0.6%	112
S	H	N	Baltimore	1	192	7227	1773	22%	147	0	0%	9340	0.76	0.892	0.892	9.1%	0.1%	65
S	H	N	Baltimore	12	226	10466	1803	22%	199	0	0%	12695	1.00	0.737	0.738	8.9%	0.0%	56
S	H	N	Baltimore	13	219	10716	1582	20%	202	0	0%	12719	0.84	0.969	0.971	7.2%	0.1%	48
S	H	N	Baltimore	14	200	9077	1552	20%	198	0	0%	11027	0.81	0.944	0.945	7.3%	0.1%	56
S	H	N	Baltimore	2	186	7263	1607	20%	172	0	0%	9229	0.65	0.918	0.918	7.5%	0.3%	61
S	H	N	Baltimore	3	187	7262	1645	21%	169	0	0%	9264	0.67	0.907	0.907	7.6%	0.1%	55
S	H	N	Baltimore	6	217	10471	1588	20%	213	0	0%	12490	0.83	0.980	0.981	7.3%	0.1%	48
S	H	N	Baltimore	7	229	11571	1693	20%	252	0	0%	13745	1.17	0.596	0.597	7.2%	0.1%	52
S	H	N	Baltimore	8	217	10077	1661	21%	199	0	0%	12154	0.84	0.999	1.000	7.0%	0.2%	49
S	H	N	Baltimore	9	212	10661	1505	19%	254	0	0%	12632	0.96	0.761	0.763	7.0%	0.2%	55
S	H	N	Charleston	1	236	2302	3170	25%	210	0	0%	5919	0.75	0.924	0.924	31.8%	3.2%	318
S	H	N	Charleston	12	248	3405	3171	25%	270	0	0%	7094	0.87	0.863	0.864	29.3%	2.0%	269
S	H	N	Charleston	13	223	3904	2595	22%	394	0	0%	7116	0.85	0.984	0.986	26.3%	2.7%	271
S	H	N	Charleston	14	224	3197	2750	23%	343	0	0%	6513	0.80	0.959	0.959	30.4%	6.0%	411
S	H	N	Charleston	2	218	2402	2773	23%	289	0	0%	5682	0.68	0.917	0.918	30.8%	5.3%	387
S	H	N	Charleston	3	228	2407	2988	24%	266	0	0%	5889	0.74	0.891	0.891	29.1%	2.8%	292
S	H	N	Charleston	6	226	3404	2716	23%	313	0	0%	6659	0.72	0.980	0.981	31.7%	4.2%	368
S	H	N	Charleston	7	247	4145	3071	24%	363	0	0%	7826	1.01	0.814	0.814	24.5%	1.3%	204
S	H	N	Charleston	8	235	3560	2883	24%	329	0	0%	7006	0.82	1.009	1.011	30.9%	4.6%	370
S	H	N	Charleston	9	220	3250	2654	22%	338	0	0%	6461	0.76	0.961	0.962	28.8%	4.1%	340
S	H	N	Orlando	1	258	650	3463	32%	175	0	0%	4546	0.79	0.917	0.917	31.0%	3.6%	324
S	H	N	Orlando	12	258	927	3435	32%	230	0	0%	4851	0.87	0.856	0.858	26.8%	2.1%	251
S	H	N	Orlando	13	229	1060	2861	28%	360	0	0%	4510	0.83	0.989	0.989	27.4%	3.2%	295
S	H	N	Orlando	14	241	906	3098	30%	296	0	0%	4540	0.79	0.963	0.962	31.3%	5.9%	399

S	H	N	Orlando	2	237	704	3038	29%	260	0	0%	4238	0.68	0.912	0.912	30.7%	4.9%	374
S	H	N	Orlando	3	246	699	3221	31%	241	0	0%	4406	0.74	0.884	0.885	27.9%	2.7%	284
S	H	N	Orlando	6	236	925	2988	29%	280	0	0%	4429	0.70	0.979	0.980	32.5%	4.8%	389
S	H	N	Orlando	7	254	1023	3368	31%	293	0	0%	4939	0.96	0.815	0.816	23.3%	1.9%	212
S	H	N	Orlando	8	243	989	3136	30%	292	0	0%	4661	0.81	1.020	1.021	31.5%	5.1%	387
S	H	N	Orlando	9	230	883	2897	28%	300	0	0%	4309	0.71	1.048	1.047	29.5%	4.0%	337
S	H	Y	Miami	1	375	8	5149	48%	101	851	16%	6484	0.83	0.845	0.845	0.9%	0.0%	4
S	H	Y	Miami	12	375	8	5144	48%	108	857	16%	6492	0.85	0.828	0.828	1.0%	0.0%	5
S	H	Y	Miami	13	355	8	4624	45%	299	1389	25%	6674	0.87	0.913	0.915	5.9%	0.0%	25
S	H	Y	Miami	14	359	8	4712	46%	236	1301	24%	6615	0.76	0.962	0.963	4.3%	0.0%	19
S	H	Y	Miami	2	362	8	4712	46%	176	1374	25%	6632	0.62	0.954	0.954	1.4%	0.0%	6
S	H	Y	Miami	3	362	8	4721	46%	174	1354	25%	6619	0.63	0.944	0.944	1.1%	0.0%	4
S	H	Y	Miami	6	356	8	4612	46%	203	1315	24%	6495	0.62	0.978	0.978	8.3%	0.0%	48
S	H	Y	Miami	7	367	8	5038	47%	158	742	14%	6313	0.90	0.830	0.829	0.5%	0.0%	3
S	H	Y	Miami	8	365	8	4851	47%	199	1216	22%	6640	0.76	1.032	1.032	6.2%	0.0%	34
S	H	Y	Miami	9	345	8	4452	44%	253	1192	22%	6249	0.67	1.023	1.023	7.4%	0.0%	39
S	H	Y	Houston	1	283	2441	3577	33%	161	764	14%	7225	0.78	0.880	0.880	0.4%	0.0%	1
S	H	Y	Houston	12	292	3321	3577	33%	230	780	15%	8201	0.91	0.774	0.775	0.4%	0.0%	1
S	H	Y	Houston	13	262	3640	2931	29%	344	872	16%	8049	0.82	0.980	0.982	3.0%	0.0%	15
S	H	Y	Houston	14	276	3172	3239	31%	268	987	18%	7943	0.78	0.960	0.961	2.7%	0.0%	12
S	H	Y	Houston	2	273	2486	3248	32%	217	1083	20%	7306	0.64	0.937	0.937	0.9%	0.0%	3
S	H	Y	Houston	3	273	2491	3264	32%	215	1066	20%	7309	0.64	0.929	0.929	0.8%	0.0%	2
S	H	Y	Houston	6	270	3326	3066	30%	281	990	18%	7933	0.71	0.980	0.981	4.0%	0.0%	20
S	H	Y	Houston	7	289	3717	3493	32%	254	630	12%	8382	0.95	0.806	0.808	0.2%	0.0%	1
S	H	Y	Houston	8	276	3429	3211	31%	275	882	16%	8073	0.80	1.003	1.005	2.8%	0.0%	12
S	H	Y	Houston	9	270	3902	3009	30%	313	868	16%	8363	0.78	0.987	0.989	3.9%	0.0%	21
S	H	Y	Memphis	1	251	4304	3049	25%	202	318	6%	8124	0.75	0.901	0.901	0.2%	0.0%	1
S	H	Y	Memphis	12	269	6529	3000	24%	342	295	5%	10435	1.00	0.692	0.694	0.1%	0.0%	0
S	H	Y	Memphis	13	251	6874	2546	22%	381	342	6%	10394	0.86	0.947	0.948	1.0%	0.0%	3
S	H	Y	Memphis	14	253	5744	2767	23%	312	481	9%	9557	0.80	0.962	0.961	0.9%	0.0%	3

S	H	Y	Memphis	2	242	4352	2788	24%	250	492	9%	8123	0.64	0.929	0.929	0.2%	0.0%	1
S	H	Y	Memphis	3	242	4346	2794	24%	249	495	9%	8126	0.64	0.925	0.926	0.2%	0.0%	0
S	H	Y	Memphis	6	247	6518	2533	22%	372	344	6%	10015	0.83	0.979	0.981	0.8%	0.0%	2
S	H	Y	Memphis	7	260	5861	2973	24%	289	258	5%	9641	0.91	0.780	0.781	0.0%	0.0%	0
S	H	Y	Memphis	8	253	6278	2708	23%	342	337	6%	9919	0.85	1.007	1.008	0.4%	0.0%	1
S	H	Y	Memphis	9	257	7331	2577	22%	429	408	7%	11002	0.95	0.835	0.835	1.7%	0.0%	6
S	H	Y	Baltimore	1	202	7191	1911	23%	142	248	5%	9693	0.76	0.878	0.878	0.0%	0.0%	0
S	H	Y	Baltimore	12	235	10416	1932	24%	198	247	5%	13029	1.02	0.702	0.703	0.0%	0.0%	0
S	H	Y	Baltimore	13	225	10694	1654	21%	201	184	3%	12958	0.84	0.969	0.971	0.3%	0.0%	1
S	H	Y	Baltimore	14	208	9054	1657	21%	194	225	4%	11337	0.81	0.944	0.945	0.2%	0.0%	1
S	H	Y	Baltimore	2	195	7207	1727	22%	163	240	4%	9532	0.64	0.926	0.926	0.1%	0.0%	0
S	H	Y	Baltimore	3	195	7208	1737	22%	163	236	4%	9538	0.64	0.920	0.920	0.0%	0.0%	0
S	H	Y	Baltimore	6	223	10420	1654	21%	212	192	4%	12701	0.83	0.980	0.981	0.2%	0.0%	1
S	H	Y	Baltimore	7	239	11559	1832	22%	243	215	4%	14088	1.17	0.587	0.589	0.0%	0.0%	0
S	H	Y	Baltimore	8	222	10029	1734	22%	198	186	3%	12369	0.84	0.999	1.000	0.1%	0.0%	0
S	H	Y	Baltimore	9	220	10651	1603	21%	248	203	4%	12926	0.95	0.771	0.773	0.3%	0.0%	1
S	H	Y	Charleston	1	262	2208	3506	28%	191	731	13%	6898	0.76	0.899	0.899	0.4%	0.0%	1
S	H	Y	Charleston	12	271	3289	3489	28%	260	723	13%	8031	0.88	0.811	0.812	0.2%	0.0%	0
S	H	Y	Charleston	13	243	3794	2845	24%	390	707	13%	7979	0.85	0.984	0.986	2.4%	0.0%	10
S	H	Y	Charleston	14	257	3141	3172	27%	323	948	17%	7842	0.80	0.959	0.959	2.9%	0.0%	13
S	H	Y	Charleston	2	251	2259	3193	27%	248	950	17%	6902	0.64	0.940	0.940	0.9%	0.0%	3
S	H	Y	Charleston	3	252	2256	3208	27%	246	942	17%	6902	0.65	0.931	0.932	0.7%	0.0%	2
S	H	Y	Charleston	6	250	3295	3003	26%	312	849	16%	7709	0.72	0.980	0.981	3.3%	0.0%	17
S	H	Y	Charleston	7	270	4012	3380	27%	335	626	12%	8623	1.00	0.793	0.793	0.2%	0.0%	0
S	H	Y	Charleston	8	258	3438	3175	26%	318	789	14%	7978	0.82	1.009	1.011	2.2%	0.0%	10
S	H	Y	Charleston	9	245	3152	2956	25%	323	799	15%	7475	0.74	0.980	0.980	3.5%	0.0%	19
S	H	Y	Orlando	1	283	572	3772	36%	157	737	14%	5520	0.79	0.890	0.890	0.4%	0.0%	1
S	H	Y	Orlando	12	283	866	3745	35%	218	722	13%	5834	0.88	0.812	0.813	0.2%	0.0%	0
S	H	Y	Orlando	13	253	1022	3128	31%	351	807	15%	5561	0.83	0.989	0.989	2.6%	0.0%	10
S	H	Y	Orlando	14	274	878	3477	34%	279	974	18%	5882	0.79	0.963	0.962	3.3%	0.0%	15

S	H	Y	Orlando	2	272	604	3456	34%	220	1032	19%	5584	0.64	0.933	0.933	0.7%	0.0%	2
S	H	Y	Orlando	3	272	605	3459	34%	220	1017	19%	5572	0.65	0.927	0.927	0.6%	0.0%	1
S	H	Y	Orlando	6	266	866	3313	33%	275	970	18%	5690	0.70	0.979	0.980	4.1%	0.0%	19
S	H	Y	Orlando	7	278	986	3665	34%	260	605	11%	5794	0.94	0.812	0.811	0.2%	0.0%	0
S	H	Y	Orlando	8	271	932	3461	34%	277	885	16%	5827	0.81	1.020	1.021	2.9%	0.0%	13
S	H	Y	Orlando	9	256	832	3185	32%	278	805	15%	5355	0.68	1.086	1.085	3.4%	0.0%	15
S	M	N	Miami	1	300	10	4051	39%	128	0	0%	4489	0.61	0.916	0.916	14.7%	0.4%	108
S	M	N	Miami	12	300	10	4048	38%	136	0	0%	4495	0.62	0.897	0.897	15.1%	0.3%	113
S	M	N	Miami	13	275	10	3574	35%	340	0	0%	4200	0.68	0.910	0.911	29.2%	1.1%	262
S	M	N	Miami	14	280	10	3665	36%	267	0	0%	4222	0.59	0.961	0.961	26.9%	1.0%	224
S	M	N	Miami	2	279	10	3636	36%	208	0	0%	4134	0.49	0.959	0.959	22.7%	1.1%	203
S	M	N	Miami	3	283	10	3706	36%	192	0	0%	4192	0.51	0.949	0.949	20.0%	0.3%	147
S	M	N	Miami	6	279	10	3618	36%	208	0	0%	4115	0.48	0.978	0.978	27.7%	1.2%	249
S	M	N	Miami	7	296	10	3991	38%	166	0	0%	4464	0.64	0.951	0.951	8.5%	0.2%	55
S	M	N	Miami	8	287	10	3791	37%	215	0	0%	4303	0.57	1.017	1.017	26.7%	1.4%	250
S	M	N	Miami	9	273	10	3534	35%	253	0	0%	4071	0.52	1.024	1.023	22.7%	0.8%	195
S	M	N	Houston	1	232	2577	2817	27%	178	0	0%	5804	0.58	0.927	0.927	15.2%	0.7%	124
S	M	N	Houston	12	238	3280	2799	26%	242	0	0%	6559	0.67	0.851	0.852	12.1%	0.7%	107
S	M	N	Houston	13	217	3535	2356	23%	350	0	0%	6459	0.65	0.979	0.981	14.6%	0.2%	101
S	M	N	Houston	14	223	3109	2538	25%	284	0	0%	6154	0.61	0.959	0.960	18.9%	0.6%	156
S	M	N	Houston	2	217	2618	2505	25%	239	0	0%	5580	0.51	0.938	0.938	18.4%	0.6%	148
S	M	N	Houston	3	220	2618	2554	25%	231	0	0%	5623	0.52	0.930	0.931	16.8%	0.2%	121
S	M	N	Houston	6	219	3282	2422	24%	287	0	0%	6210	0.56	0.980	0.981	19.3%	1.0%	168
S	M	N	Houston	7	237	3428	2767	26%	254	0	0%	6686	0.69	0.906	0.907	8.1%	0.1%	51
S	M	N	Houston	8	227	3352	2557	25%	290	0	0%	6426	0.63	0.993	0.994	18.3%	1.1%	163
S	M	N	Houston	9	220	3538	2407	24%	308	0	0%	6473	0.60	1.007	1.009	15.6%	0.5%	119
S	M	N	Memphis	1	216	4181	2507	21%	212	0	0%	7116	0.57	0.925	0.925	3.3%	0.0%	15
S	M	N	Memphis	12	230	5909	2471	20%	353	0	0%	8963	0.76	0.757	0.758	2.4%	0.0%	11
S	M	N	Memphis	13	216	6169	2128	18%	392	0	0%	8905	0.68	0.947	0.948	3.0%	0.0%	15
S	M	N	Memphis	14	214	5274	2259	19%	327	0	0%	8074	0.63	0.963	0.962	6.1%	0.1%	36

S	M	N	Memphis	2	204	4202	2262	19%	258	0	0%	6925	0.51	0.936	0.937	4.4%	0.1%	27
S	M	N	Memphis	3	204	4193	2271	19%	255	0	0%	6924	0.51	0.935	0.935	4.2%	0.0%	21
S	M	N	Memphis	6	213	5902	2120	18%	384	0	0%	8619	0.65	0.980	0.981	3.9%	0.0%	20
S	M	N	Memphis	7	224	5413	2463	20%	287	0	0%	8387	0.68	0.882	0.882	1.2%	0.0%	4
S	M	N	Memphis	8	219	5767	2265	19%	353	0	0%	8604	0.67	1.006	1.007	3.6%	0.0%	17
S	M	N	Memphis	9	218	6369	2146	18%	412	0	0%	9145	0.71	0.878	0.878	4.3%	0.1%	25
S	M	N	Baltimore	1	179	6926	1581	20%	145	0	0%	8831	0.58	0.909	0.909	2.2%	0.0%	10
S	M	N	Baltimore	12	206	9527	1604	20%	206	0	0%	11542	0.77	0.765	0.766	1.0%	0.0%	3
S	M	N	Baltimore	13	199	9741	1399	18%	210	0	0%	11549	0.66	0.968	0.970	1.1%	0.0%	4
S	M	N	Baltimore	14	184	8426	1394	18%	201	0	0%	10206	0.64	0.946	0.947	2.1%	0.0%	11
S	M	N	Baltimore	2	173	6939	1445	19%	165	0	0%	8722	0.50	0.933	0.934	2.3%	0.0%	12
S	M	N	Baltimore	3	174	6940	1456	19%	164	0	0%	8733	0.50	0.931	0.931	2.2%	0.0%	10
S	M	N	Baltimore	6	197	9527	1400	18%	220	0	0%	11344	0.65	0.979	0.980	1.0%	0.0%	4
S	M	N	Baltimore	7	205	10049	1531	19%	238	0	0%	12023	0.85	0.701	0.702	1.7%	0.0%	7
S	M	N	Baltimore	8	197	9197	1475	19%	200	0	0%	11068	0.66	1.004	1.005	1.4%	0.0%	6
S	M	N	Baltimore	9	194	9578	1361	18%	242	0	0%	11375	0.72	0.839	0.840	1.9%	0.0%	9
S	M	N	Charleston	1	211	2237	2738	22%	213	0	0%	5399	0.58	0.933	0.933	13.3%	0.3%	101
S	M	N	Charleston	12	220	3106	2730	22%	271	0	0%	6327	0.66	0.888	0.889	10.3%	0.4%	74
S	M	N	Charleston	13	201	3494	2290	20%	396	0	0%	6380	0.66	0.984	0.986	10.3%	0.2%	74
S	M	N	Charleston	14	202	2931	2429	20%	348	0	0%	5910	0.63	0.958	0.958	19.4%	1.0%	186
S	M	N	Charleston	2	199	2294	2464	21%	268	0	0%	5225	0.51	0.938	0.938	16.4%	0.8%	140
S	M	N	Charleston	3	203	2293	2547	21%	257	0	0%	5300	0.53	0.927	0.927	14.5%	0.3%	109
S	M	N	Charleston	6	203	3100	2386	20%	316	0	0%	6005	0.56	0.980	0.981	16.1%	0.6%	131
S	M	N	Charleston	7	219	3463	2676	22%	319	0	0%	6677	0.71	0.911	0.911	7.3%	0.1%	46
S	M	N	Charleston	8	211	3246	2535	21%	331	0	0%	6324	0.64	0.995	0.996	15.9%	0.8%	136
S	M	N	Charleston	9	199	2982	2353	20%	317	0	0%	5851	0.57	1.009	1.009	14.0%	0.4%	109
S	M	N	Orlando	1	230	654	3001	29%	177	0	0%	4063	0.59	0.931	0.931	13.2%	0.9%	117
S	M	N	Orlando	12	230	868	2972	28%	232	0	0%	4301	0.66	0.881	0.882	10.7%	0.7%	86
S	M	N	Orlando	13	208	979	2536	25%	362	0	0%	4085	0.65	0.988	0.988	13.1%	0.5%	104
S	M	N	Orlando	14	217	853	2735	27%	298	0	0%	4103	0.62	0.962	0.961	18.6%	0.9%	175

S	M	N	Orlando	2	215	688	2700	27%	239	0	0%	3842	0.51	0.938	0.938	16.3%	0.7%	144
S	M	N	Orlando	3	217	687	2746	27%	233	0	0%	3882	0.52	0.930	0.930	14.9%	0.4%	114
S	M	N	Orlando	6	213	881	2627	26%	280	0	0%	4001	0.54	0.978	0.979	17.4%	0.9%	149
S	M	N	Orlando	7	228	923	2940	28%	254	0	0%	4344	0.68	0.928	0.928	7.7%	0.3%	58
S	M	N	Orlando	8	219	927	2751	27%	288	0	0%	4186	0.62	0.997	0.998	16.8%	1.0%	149
S	M	N	Orlando	9	209	826	2575	26%	266	0	0%	3876	0.52	1.126	1.125	13.4%	0.7%	111
S	M	Y	Miami	1	315	8	4224	40%	115	409	9%	5072	0.61	0.910	0.910	1.0%	0.0%	5
S	M	Y	Miami	12	314	8	4216	40%	123	414	9%	5077	0.62	0.892	0.892	1.0%	0.0%	5
S	M	Y	Miami	13	306	8	3935	39%	316	900	20%	5466	0.68	0.910	0.911	1.7%	0.0%	6
S	M	Y	Miami	14	307	8	3969	39%	251	788	17%	5323	0.59	0.961	0.961	1.6%	0.0%	5
S	M	Y	Miami	2	310	8	3972	40%	192	851	19%	5333	0.49	0.950	0.950	0.3%	0.0%	2
S	M	Y	Miami	3	309	8	3967	40%	191	841	18%	5317	0.49	0.948	0.948	0.3%	0.0%	2
S	M	Y	Miami	6	304	8	3894	39%	202	768	17%	5177	0.48	0.978	0.978	3.4%	0.0%	12
S	M	Y	Miami	7	306	8	4105	39%	150	279	6%	4848	0.63	0.953	0.953	0.3%	0.0%	2
S	M	Y	Miami	8	311	8	4063	40%	200	703	15%	5286	0.57	1.017	1.017	2.9%	0.0%	11
S	M	Y	Miami	9	297	8	3782	38%	238	690	15%	5015	0.51	1.039	1.039	3.1%	0.0%	10
S	M	Y	Houston	1	243	2499	2946	28%	169	360	8%	6216	0.58	0.923	0.923	0.5%	0.0%	2
S	M	Y	Houston	12	248	3196	2921	28%	235	351	8%	6952	0.67	0.841	0.842	0.1%	0.0%	0
S	M	Y	Houston	13	229	3475	2491	25%	346	447	10%	6989	0.65	0.979	0.981	0.9%	0.0%	2
S	M	Y	Houston	14	240	3066	2738	27%	276	555	12%	6874	0.61	0.959	0.960	1.0%	0.0%	3
S	M	Y	Houston	2	237	2523	2740	27%	221	632	14%	6353	0.50	0.942	0.942	0.1%	0.0%	0
S	M	Y	Houston	3	237	2522	2735	27%	222	628	14%	6343	0.50	0.940	0.941	0.2%	0.0%	0
S	M	Y	Houston	6	234	3209	2592	26%	281	537	12%	6854	0.56	0.980	0.981	1.3%	0.0%	4
S	M	Y	Houston	7	245	3383	2860	27%	239	240	5%	6966	0.68	0.914	0.915	0.1%	0.0%	0
S	M	Y	Houston	8	241	3296	2724	27%	280	481	11%	7022	0.63	0.993	0.994	1.0%	0.0%	3
S	M	Y	Houston	9	234	3484	2555	26%	292	449	10%	7014	0.58	1.024	1.026	1.5%	0.0%	5
S	M	Y	Memphis	1	220	4185	2565	21%	208	120	3%	7297	0.57	0.923	0.924	0.2%	0.0%	0
S	M	Y	Memphis	12	233	5905	2514	21%	351	93	2%	9096	0.76	0.748	0.750	0.0%	0.0%	0
S	M	Y	Memphis	13	221	6163	2187	19%	390	145	3%	9107	0.68	0.947	0.948	0.2%	0.0%	0
S	M	Y	Memphis	14	222	5276	2362	20%	321	228	5%	8409	0.63	0.963	0.962	0.2%	0.0%	0

S	M	Y	Memphis	2	213	4187	2374	20%	253	230	5%	7256	0.50	0.933	0.934	0.0%	0.0%	0
S	M	Y	Memphis	3	213	4191	2372	20%	252	230	5%	7258	0.50	0.933	0.934	0.0%	0.0%	0
S	M	Y	Memphis	6	219	5903	2183	19%	382	157	3%	8843	0.65	0.980	0.981	0.1%	0.0%	0
S	M	Y	Memphis	7	227	5414	2494	21%	284	67	1%	8486	0.68	0.883	0.883	0.0%	0.0%	0
S	M	Y	Memphis	8	223	5763	2323	20%	351	132	3%	8792	0.67	1.006	1.007	0.1%	0.0%	0
S	M	Y	Memphis	9	225	6369	2235	19%	403	184	4%	9416	0.71	0.886	0.886	0.2%	0.0%	0
S	M	Y	Baltimore	1	182	6931	1620	20%	143	71	2%	8947	0.58	0.907	0.907	0.0%	0.0%	0
S	M	Y	Baltimore	12	207	9518	1627	20%	205	52	1%	11610	0.77	0.756	0.758	0.0%	0.0%	0
S	M	Y	Baltimore	13	201	9741	1424	19%	210	56	1%	11632	0.66	0.968	0.970	0.0%	0.0%	0
S	M	Y	Baltimore	14	187	8423	1433	19%	199	80	2%	10323	0.64	0.946	0.947	0.0%	0.0%	0
S	M	Y	Baltimore	2	177	6940	1488	19%	162	84	2%	8850	0.50	0.934	0.934	0.0%	0.0%	0
S	M	Y	Baltimore	3	177	6943	1487	19%	162	81	2%	8850	0.50	0.934	0.934	0.0%	0.0%	0
S	M	Y	Baltimore	6	199	9518	1418	19%	220	54	1%	11408	0.65	0.979	0.980	0.0%	0.0%	0
S	M	Y	Baltimore	7	208	10049	1563	19%	234	59	1%	12113	0.85	0.701	0.702	0.0%	0.0%	0
S	M	Y	Baltimore	8	199	9187	1494	19%	199	51	1%	11128	0.66	1.004	1.005	0.0%	0.0%	0
S	M	Y	Baltimore	9	196	9583	1394	18%	239	75	2%	11488	0.71	0.842	0.843	0.1%	0.0%	0
S	M	Y	Charleston	1	222	2196	2872	24%	202	337	7%	5829	0.57	0.931	0.931	0.5%	0.0%	2
S	M	Y	Charleston	12	227	3039	2823	23%	267	286	6%	6641	0.66	0.875	0.877	0.0%	0.0%	0
S	M	Y	Charleston	13	210	3429	2405	21%	396	356	8%	6797	0.66	0.984	0.986	1.1%	0.0%	3
S	M	Y	Charleston	14	222	2900	2673	23%	334	569	12%	6698	0.63	0.958	0.958	1.2%	0.0%	3
S	M	Y	Charleston	2	218	2218	2694	23%	251	550	12%	5930	0.50	0.942	0.942	0.1%	0.0%	0
S	M	Y	Charleston	3	217	2217	2692	23%	250	548	12%	5926	0.50	0.940	0.940	0.1%	0.0%	0
S	M	Y	Charleston	6	215	3030	2531	22%	313	448	10%	6537	0.56	0.980	0.981	1.2%	0.0%	4
S	M	Y	Charleston	7	226	3408	2768	23%	308	236	5%	6946	0.71	0.911	0.911	0.1%	0.0%	0
S	M	Y	Charleston	8	223	3165	2681	23%	324	415	9%	6809	0.64	0.995	0.996	1.0%	0.0%	3
S	M	Y	Charleston	9	212	2951	2503	22%	313	416	9%	6395	0.56	1.018	1.018	1.5%	0.0%	4
S	M	Y	Orlando	1	240	628	3126	30%	167	342	8%	4503	0.59	0.928	0.928	0.5%	0.0%	2
S	M	Y	Orlando	12	239	855	3076	30%	224	294	7%	4688	0.66	0.875	0.876	0.1%	0.0%	0
S	M	Y	Orlando	13	219	960	2663	27%	357	403	9%	4603	0.65	0.988	0.988	0.8%	0.0%	2
S	M	Y	Orlando	14	236	844	2940	29%	287	553	12%	4859	0.62	0.962	0.961	1.3%	0.0%	3

S	M	Y	Orlando	2	234	642	2916	29%	225	573	13%	4590	0.50	0.939	0.939	0.1%	0.0%	0
S	M	Y	Orlando	3	234	641	2916	29%	225	573	13%	4589	0.50	0.937	0.937	0.1%	0.0%	0
S	M	Y	Orlando	6	228	858	2790	28%	275	496	11%	4648	0.54	0.978	0.979	1.2%	0.0%	3
S	M	Y	Orlando	7	236	911	3031	29%	240	222	5%	4639	0.67	0.936	0.935	0.1%	0.0%	0
S	M	Y	Orlando	8	233	903	2915	29%	277	449	10%	4777	0.62	0.997	0.998	1.1%	0.0%	3
S	M	Y	Orlando	9	221	810	2705	27%	257	384	8%	4376	0.51	1.139	1.138	1.1%	0.0%	3
M	H	Y	Miami	5_new	508	17	6675	49%	195	649	12%	8044	0.45	0.951	0.951	0.7%	0.1%	4
M	H	Y	Miami	7_new	497	17	6577	48%	220	469	9%	7780	0.49	1.002	1.002	0.4%	0.1%	4
M	H	Y	Houston	5_new	372	4668	4366	42%	176	463	9%	10045	0.44	0.949	0.949	0.3%	0.0%	1
M	H	Y	Houston	7_new	378	6021	4288	41%	221	345	7%	11253	0.53	0.920	0.922	0.2%	0.0%	0
M	H	Y	Memphis	5_new	365	7473	4083	26%	303	182	3%	12407	0.44	0.961	0.961	0.0%	0.0%	0
M	H	Y	Memphis	7_new	385	9851	4113	26%	372	97	2%	14818	0.56	0.902	0.902	0.0%	0.0%	0
M	H	Y	Baltimore	5_new	302	12101	2564	22%	223	110	2%	15300	0.42	0.989	0.989	0.0%	0.0%	0
M	H	Y	Baltimore	7_new	348	17776	2437	21%	335	110	2%	21006	0.66	0.741	0.743	0.0%	0.0%	0
M	H	Y	Charleston	5_new	365	3932	4593	29%	294	563	10%	9748	0.44	0.960	0.960	0.4%	0.0%	1
M	H	Y	Charleston	7_new	378	6276	4499	28%	410	431	8%	11994	0.58	0.911	0.910	0.2%	0.0%	0
M	H	Y	Orlando	5_new	369	1207	4706	46%	186	417	8%	6884	0.45	0.937	0.937	0.3%	0.0%	0
M	H	Y	Orlando	7_new	365	1696	4620	45%	234	314	6%	7229	0.53	0.940	0.940	0.1%	0.0%	0
S	H	Y	Miami	5_new	354	8	4692	45%	137	892	16%	6083	0.68	0.946	0.947	1.6%	0.0%	6
S	H	Y	Miami	7_new	346	8	4612	44%	173	757	14%	5896	0.75	0.986	0.986	1.0%	0.0%	4
S	H	Y	Houston	5_new	267	2410	3240	31%	195	816	15%	6928	0.67	0.944	0.944	1.3%	0.0%	4
S	H	Y	Houston	7_new	274	3709	3184	31%	269	670	12%	8107	0.84	0.902	0.904	0.8%	0.0%	3
S	H	Y	Memphis	5_new	237	4118	2783	23%	241	358	7%	7737	0.67	0.948	0.948	0.5%	0.0%	1
S	H	Y	Memphis	7_new	249	5845	2761	23%	303	240	4%	9399	0.84	0.861	0.862	0.1%	0.0%	0
S	H	Y	Baltimore	5_new	190	6784	1736	22%	163	228	4%	9102	0.65	0.974	0.973	0.1%	0.0%	0
S	H	Y	Baltimore	7_new	231	11560	1641	21%	257	216	4%	13904	1.06	0.675	0.677	0.2%	0.0%	0
S	H	Y	Charleston	5_new	247	2128	3196	27%	225	768	14%	6564	0.67	0.951	0.951	1.0%	0.0%	3
S	H	Y	Charleston	7_new	257	4018	3102	26%	350	659	12%	8386	0.91	0.860	0.861	0.7%	0.0%	2
S	H	Y	Orlando	5_new	268	584	3453	34%	203	769	14%	5277	0.69	0.923	0.923	1.2%	0.0%	3
S	H	Y	Orlando	7_new	264	988	3377	33%	278	641	12%	5548	0.84	0.905	0.904	0.6%	0.0%	2

S	M	Y	Miami	5_new	305	8	3977	39%	151	497	11%	4938	0.53	0.957	0.957	1.0%	0.0%	4
S	M	Y	Miami	7_new	298	8	3910	38%	173	382	8%	4770	0.57	1.010	1.009	0.7%	0.0%	3
S	M	Y	Houston	5_new	234	2482	2742	27%	200	435	10%	6093	0.52	0.956	0.956	0.6%	0.0%	2
S	M	Y	Houston	7_new	237	3400	2689	26%	261	321	7%	6909	0.63	0.938	0.939	0.5%	0.0%	1
S	M	Y	Memphis	5_new	211	4058	2385	20%	241	162	4%	7056	0.52	0.962	0.962	0.1%	0.0%	0
S	M	Y	Memphis	7_new	223	5392	2405	20%	297	91	2%	8408	0.65	0.909	0.909	0.1%	0.0%	0
S	M	Y	Baltimore	5_new	174	6628	1498	19%	162	83	2%	8544	0.50	0.989	0.988	0.0%	0.0%	0
S	M	Y	Baltimore	7_new	203	10077	1427	18%	250	83	2%	12039	0.78	0.740	0.742	0.0%	0.0%	0
S	M	Y	Charleston	5_new	214	2127	2687	23%	231	396	9%	5654	0.52	0.962	0.962	0.6%	0.0%	1
S	M	Y	Charleston	7_new	220	3415	2617	22%	330	308	7%	6890	0.67	0.916	0.916	0.5%	0.0%	1
S	M	Y	Orlando	5_new	232	630	2931	29%	206	396	9%	4396	0.54	0.943	0.943	0.5%	0.0%	1
S	M	Y	Orlando	7_new	229	914	2871	28%	262	307	7%	4583	0.62	0.956	0.956	0.4%	0.0%	1

Table 45 Performance summary smart ventilation control data table.

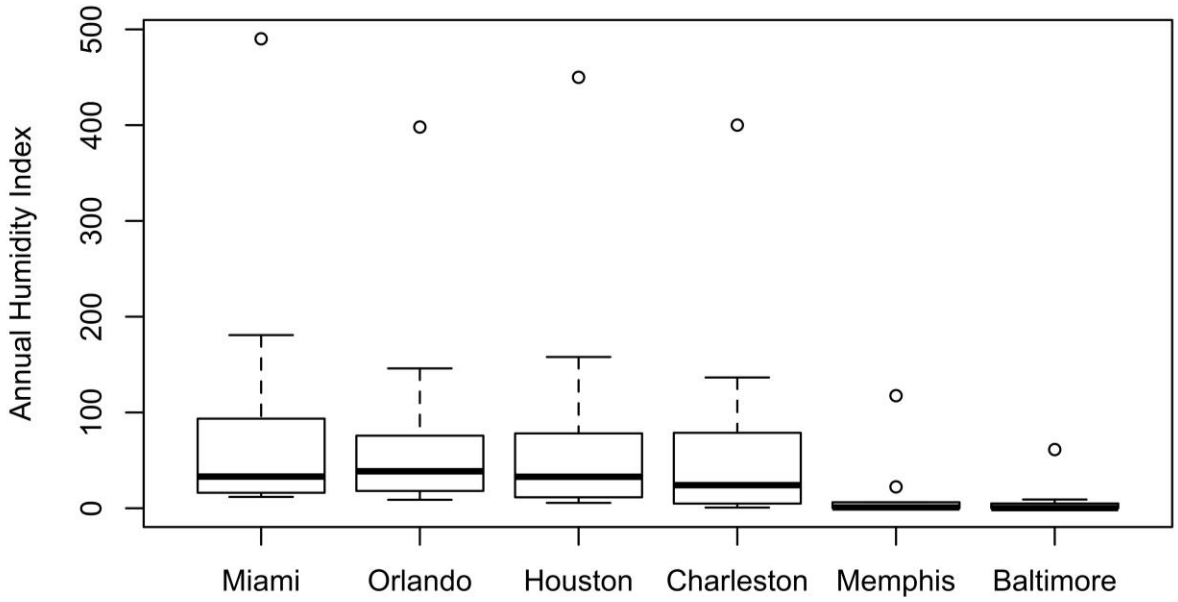

Figure 45 Variability in the Annual Humidity Index by climate zone, averaged across house size and moisture gains. Includes only homes with 100% of 62.2-2013 ventilation rates and no dehumidification.

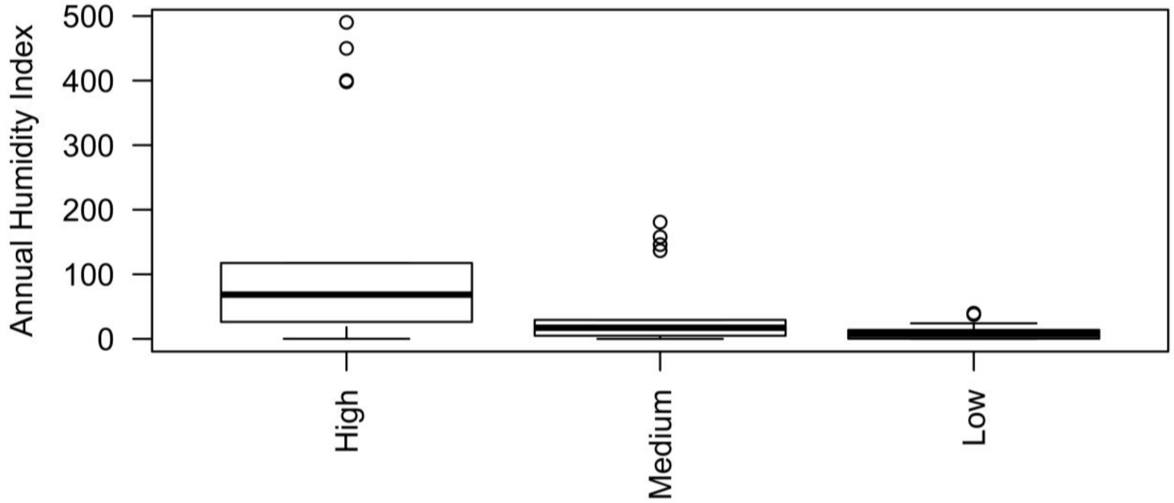

Figure 46 Variability in the Annual Humidity Index by internal moisture gains, averaged across house size and climate zone. Includes only homes with 100% of 62.2-2013 ventilation rates and no dehumidification.

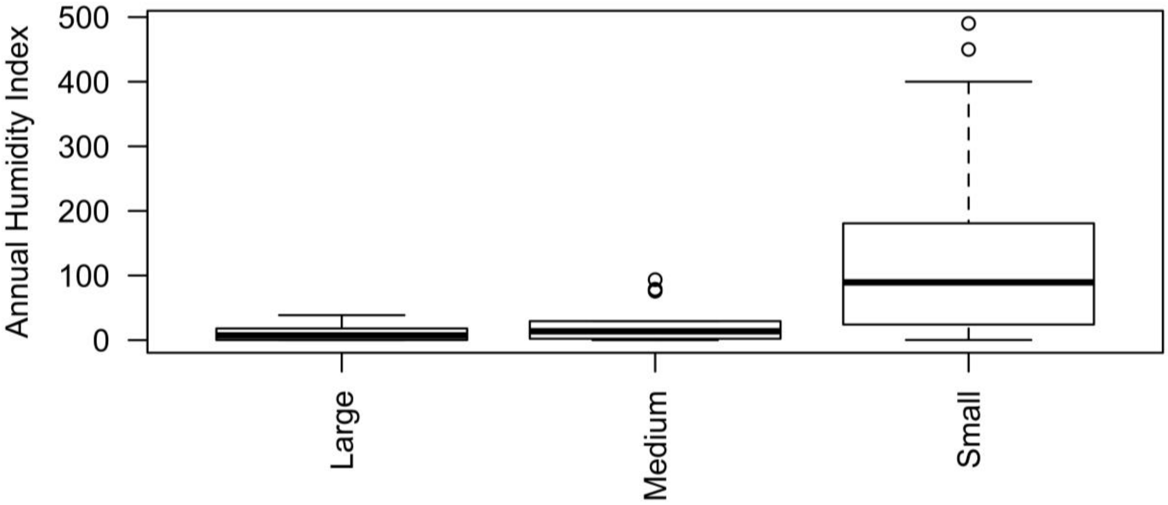

Figure 47 Variability in the Annual Humidity Index by house size, averaged across internal moisture gains and climate zone. Includes only homes with 100% of 62.2-2013 ventilation rates and no dehumidification.