13 CERV® Homes in Vermont

Keeping Occupants Healthy, Comfortable and Energy Efficient

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Foreword

Our poorly ventilated homes and buildings are making us stupid [1], sick [2], and tired [3]. The cost of being stupid, sick and tired is staggering.

A new home design paradigm is required that places human health, well-being, and productivity above all else. Too often, today's architects, builders, and home owners make "saving" energy their primary objective. The purpose of a building is the health, comfort, and security of its occupants.

Current indoor air quality standards are based on ventilation research from 80 years ago [4]. Recent research definitively shows that today's ventilation standards reduce human productivity [1] and increase disease transmission [2]. Modern materials submerge us in a variety of chemicals that didn't exist 80 years ago. Indoor air quality is severely degraded by cleansers, building materials, home furnishings, cosmetics, pesticides and countless other sources. One gas burner on a stove generates carbon dioxide at a rate equal to the respiration of 6 people while also spewing nitrogen oxides, carbon monoxide, particulates, and a variety of VOC combustion products into homes.

Improvement of today's ventilation standards can increase human productivity by a value more than 100 times the associated cost of increased ventilation. For example, research at the Harvard TH Chan School of Public Health determined the value of increased human productivity due to improvement of fresh air ventilation to be $6500 per person per year while the maximum ventilation energy cost increase would only be $40 per person per year in the harshest of US climates [5].

We spend more than 70% of our time at home, where human productivity is every bit as important as at work and school. Poor indoor air quality in our homes degrades our decision making capability, reduces our ability to complete tasks, makes us sick more often, and creates a bad study environment for our children. Sleep degradation due to poor air quality is reflected in poorer work performance the next day [3]. Ventilation standards for residences are beginning to move into the house construction market, but more often than not, fresh air ventilation in homes is considered a costly "extra" rather than a necessity.

The attached report is a detailed investigation of residential air quality, comfort, and energy usage in 13 nearly identical "Vermod" homes with an advanced CERV® fresh air ventilation system. The CERV is a "preventilator" that automatically prevents unhealthy indoor air quality conditions. These homes represent the new home design paradigm in which human health and comfort are valued above all else.

[1] Joseph G. Allen, Piers MacNaughton, Usha Satish, Suresh Santanam, Jose Vallarino, and John D. Spengler; "Associations of Cognitive Function Scores with Carbon Dioxide, Ventilation, and Volatile Organic Compound Exposures in Office Workers: A Controlled Exposure Study of Green and Conventional Office Environments";Env Health Perspectives; Oct 2015
[2] DK Milton, PM Glencross, and MD Walters; "Risk of Sick Leave with Outdoor Air Supply Rates, Humidification, and Occupants Complaints"; Indoor Air; Vol 10, pp212-221; 2000
[3] P. Strøm-Tejsen, D. Zukowska, P. Wargocki, D. P. Wyon; "The effects of bedroom air quality on sleep and next-day performance", Indoor Air; doi:10.1111/ina.12254; 2015
[4] Seichi Konzo; The Quiet Indoor Revolution; Small Homes Council-Building Research Council, University of Illinois, Urbana, IL 1992
[5] Piers MacNaughton, James Pegues, Usha Satish, Suresh Santanam, John Spengler, and Joseph Allen; "Economic, Environmental and Health Implications of Enhanced Ventilation in Office Buildings"; Int. J. Environ. Res. Public Health 2015, 12, 14709-14722; doi:10.3390/ijerph121114709

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The author appreciates the time and effort of Peter Schneider and his colleagues at Efficiency Vermont for their dedication, expertise, and tireless maintenance of several home data acquisition systems. The author, who has been involved in home and building monitoring projects since the 1970s, knows of no other home monitoring investigation that has produced data as comprehensive as that collected by Efficiency Vermont.

Ty Newell, Ph.D., P.E.

Author Biography

Ty is a co-owner and co-founder of Build Equinox, a company devoted to inventing technologies for healthy, comfortable and sustainable living. He retired from the University of Illinois in 2007 as an Assistant Dean in the College of Engineering, having advised 70 masters and doctoral graduate students, and is an emeritus professor of mechanical engineering. Ty's degrees are in mechanical engineering (BS,'74, University of Michigan and MS/PhD, '78/'80, University of Utah). He has lectured around the world on indoor air quality, comfort, solar energy, building energy efficiency, and resource conservation including keynote addresses at the Solar Energy Society of India's 25th Silver Jubilee in Hyderabad and at the TTMD Conference (Turkish ASHRAE) in Istanbul, Turkey. He has been a Fulbright Scholar at the Universidad Nacional de Salta in Argentina, an Ercotaf Scholar (European Union) at the EPFL in Lausanne Switzerland, a United Nations Workshop Leader in Beijing China, and an Academic Leader at the Tec de Monterrey Institute in Queretaro Mexico. Ty lives in a 100% solar powered home in Urbana Illinois that features automated fresh air control (CERV), two Electric Vehicles (Ford Focus EV and Ford C-Max Energi, also 100% solar energy powered), and is the first home within an Illinois municipality to be permitted for rainwater harvesting use. Build Equinox is located in a 4500sqft Morton building in Urbana IL that is also 100% solar powered.

Executive Summary

Efficiency Vermont and Build Equinox examined 21 homes over an extended period of time. Some homes were monitored for as much as two years while some had only been monitored for two months. This report covers 13 Vermod manufactured homes that incorporated the CERV fresh air conditioning system manufactured by Build Equinox.

The following list summarizes indoor air quality, comfort, overall house energy, and energy usage characteristics of the 13 Vermod-CERV homes:

Indoor Air Quality:

1) All Vermod-CERV homes are highly sealed with infiltration levels below 1ACH at 50 Pa.
2) All Vermod-CERV homes were found to have excellent IAQ with consistently low CO2 (carbon dioxide) and VOC (Volatile Organic Compound) concentration levels
3) VOCs are the dominant indoor air pollutant in half of the homes, with a quarter of the homes dominated by carbon dioxide, and the remaining quarter with similar balance of VOC (on an equivalent carbon dioxide basis) and carbon dioxide concentration levels.
4) CERV units automatically adjusted air flow required for maintaining good air quality. Average fresh air exchange ranged from 160cfm (house with high VOC generation) to 10cfm (house with low occupant activity).
5) Most homes in the study exhibited air quality that 80% or more of the population would find acceptable (average CO2 and VOCs less than 1000ppm).

Comfort:

1) The study homes were generally maintained within the boundaries of "comfort".
2) All homes have sufficient heating capacity and cooling capability sufficient for maintaining comfort throughout the year.
    a. Most homes decreased indoor temperature by choice during winter
    b. Some homes with cooling capability allowed indoor temperatures to float to uncomfortably high indoor temperatures during the summer rather than using air conditioning
    c. Some homes were maintained at a constant temperature all year long
    d. Minor temperature stratification was observed in some Vermod-CERV homes, however, these cases appear to be due to homeowner preferences, such as closing a door or decreasing the supply air to unused rooms or cooler bedroom sleeping preference.
    e. In general, homeowners displayed a wide variety of indoor preferences

Overall House Energy:

1) The 13 Vermod-CERV homes exceed European Passive Haus standards with an average energy usage of 9kWh/ft^2 (97kWh/m^2), or almost 20% less energy usage than required by the PH standard of 11kWh/ft^2 (120kWh/m^2).

2) The 13 Vermod-CERV homes have an annual occupancy energy usage of 3650kWh/person that is less than current and future PHIUS (Passive House Institute US) requirements of 6200kWh/person (current standard) and 4200kWh/person (future standard).
3) All Vermod-CERV homes exhibited energy usage during the heating season between 0.2 and 1.0kWh/F-day, in comparison to conventionally built homes that require 2.0kWh/F-day or more during the heating season. The average heating season energy usage was 0.5kWh/F-day for all homes.
4) ZEROs energy simulations of the Vermod-CERV homes predicts a heating season usage of 0.56kWh/F-day in agreement with actual Vermod home performance.
5) Occupant behavior causes significant variation in house energy usage. On average, the study homes used 11kWh per day for non-comfort energy use (lights, plug load, appliances, hot water, etc) and 12kWh per day for comfort conditioning (includes ventilation, heating and cooling). By comparison, non-comfort energy usage was shown to be 35kWh per day for five conventional homes.
6) At 0F, Vermod-CERV homes generally required less than 50kWh/day. One home (house 19), which was maintained at 75 to 80F during the winter, requires 75kWh/day. By comparison, conventionally constructed homes require 150kWh/day or more on a 0F day.
7) The average Vermod-CERV home requires heating at 55F and cooling at 62F for maintaining indoor comfort. By comparison, conventionally built homes require heat when outdoor temperatures drop below 60F and cooling when outdoor temperatures increase above 65F.

House Energy Uses:

1) Energy for maintaining house comfort (heating/cooling/ventilation) was found to be insensitive to house occupancy while energy for non-comfort energy uses (lights, plug loads, appliances, hot water, etc) were found to be highly dependent on occupancy level.
    a. Average non-comfort daily energy usage (excluding water heating) is 1.4kWh/day per Occupant plus 4.4kWh/day constant house load
    b. Average water heating energy is 0.7kWh/day per Occupant plus 1.2kWh/day baseload
2) Non-Comfort energy uses have an overall daily average of 11kWh/day with an average study home occupancy of 2.4 people
3) Average daily non-comfort energy uses are composed of the following:
    a. Miscellaneous use (lights, TVs, etc) = 3.9kWh/day
    b. Water heating = 2.9kWh/day
    c. Clothes Dryer = 1.4kWh/day
    d. Cooking (oven/stove/microwave) = 1.27kWh/day
    e. Refrigerator = 1.0kWh/day
    f. Dishwasher = 0.3kWh/day
    g. Clothes Washer = 0.1kWh/day

Introduction

The objective of home design should be healthy, comfortable shelters based on sustainable economics. Optimization of a building's life cycle cost, subject to the constraints its occupants are kept healthy, comfortable and productive will automatically result in a high performance, energy efficient, renewable energy powered home.

The Vermod manufactured home is an excellent example of a sustainable home designed by economic optimization principles that places human value at the center of the design process. A key piece to the success of the Vermod home is its CERV® fresh air ventilation system. This report examines indoor air quality, comfort, and energy characteristics of 13 Vermod homes with CERV systems.

Why place special emphases on indoor air quality and comfort over energy? Figure 1 displays daily energy consumption for the 13 Vermod study homes in relation to outdoor ambient temperature. In total, several thousand daily data points are plotted. The aggregate average energy usage of these homes is a remarkably low 23kWh per day. The average daily utility cost for this collection of homes located in one of the harshest climatic zones is $2.75 per day per home assuming 12 cents/kWh (a value based on the cost of solar PV with an installed cost of $3/W, no solar tax credits and 25 year life). With an average occupancy of 2.4 persons per residence, the average utility cost per home occupant is less than $1.15 per day, or less than half the price of a barista-made coffee.

Florence Nightingale [1] stated that a healthy home results in health savings that should be part of a building's economic analysis. She also commented that if architects and builders were held accountable for the health of their buildings' occupants, that buildings would be designed much differently. How insightful and how sad that we continue to struggle to implement her common sense ideas built on her lifetime of direct experience?

Poor indoor air quality and uncomfortable surroundings decrease human productivity and well-being. For every degree Fahrenheit outside of one's comfort band, productivity is reduced by 1% (about 5 minutes of an 8 hour workday). The cost of a 1% decrease in human productivity is $2 per person per day or nearly twice the cost for one's daily energy needs in a high performance home! Imperceptibly poor air quality decreases several areas of cognition such as decision making, creativity, and critical thinking with productivity decreases much greater than 1% [2].

The US has experienced a doubling of asthma over the past 30 years, with asthma incidence in northern latitudes afflicting nearly 10% of the population. The average annual cost of asthma is $3000 per afflicted person. Assuming an average household occupancy of 3, nearly one out of every three homes in the U.S. has someone with asthma. Averaged over all households, this is an average cost that exceeds the annual utility cost of the Vermod-CERV homes. It is time to reverse the increase in asthma by ensuring that the places we live and work have a reliable source of fresh air, with potential health cost savings and productivity gains that greatly exceed any associated energy cost to operate effective ventilation systems.

Nobel economics laureate, Robert Solow, provided insight on sustainability, stating that we cannot guess the needs of the future, but that we can provide the resources at very little cost to ensure that future generations have what they need in order to maintain a standard of living equivalent to ours [3]. Additionally, Solow discusses the incongruity of caring about the future without caring about improving the lives of those living in the present. Adding additional resources for today's less fortunate populace leads to a paradox, as described by Solow, that we may need to consume more resources now rather than reduce overall consumption in order to bring today's disadvantaged to a higher quality of living.

The Vermod home has been designed to be an affordable, high quality home for lower income earners. Vermod homes have more insulation, higher quality windows, a CERV fresh air ventilation system, a hybrid (heat pump) water heater, cold weather heat pump, and more expensive construction practices than cheaply built counterparts. Over the lifetime of a Vermod house, however, its residents experience lower, more stable monthly expenses.

The CERV fresh air ventilation system incorporated into Vermod homes automatically ensures high quality air. What is the value of high quality air? Figure 2 is a plot from a Harvard-led study [4] showing the correlation of annual salary and hourly wages to human performance on a well-vetted cognition performance test. Their study showed that doubling today's standard ventilation rate from 20cfm/person to 40cfm/person results in a cognition performance increase from 62% to 70%. The salary benefit of this increase is $6500 (or, $3.25 per hour wage increase).

At lower incomes, the impact of higher cognitive performance results in significantly higher percentage gains of disposable income in comparison to higher salary earners. Figure 3 recasts Figure 2 by differentiating the annual salary versus cognition performance correlation, and dividing the result by the annual disposable income. This operation produces a parameter showing the percentage change of disposable income per percentage change of cognition performance. Disposable income is calculated as the difference between annual salary and an assumed annual base income level of $23,809 ($11.90/hr). The base income level chosen is the salary level at 0% cognition performance of the salary model. The base income level, of course, varies across the country and on one's essential needs. The disposable income calculated for Figure 3 is meant to be purely for examination of cognitive performance trends on one's disposable income.

Figure 3 shows that any gain in cognitive performance at lower income levels results in a higher percentage gain of disposable income than realized by higher income earners. Disposable income is also plotted in Figure 3 (annual salary minus $23,809/yr). A minor improvement of 1% in cognitive performance for someone at the 10% cognitive performance level is a 10% gain of disposable income. Although the amount of disposable income gain is smaller than at higher income levels, a modest increase in disposable income for a low wage earner can be the difference between paying or not paying an unexpected repair bill (auto, home appliance, etc). That is, any gain of income is extremely important for lower income earners such that they can avoid an unending spiral of debt due to unexpected expenses.

Before we move into the details of the Vermod homes, let's definitively answer a question regarding the energy performance of the study homes: "Are Vermod homes more energy efficient than homes built with today's conventional construction practices?" Figure 4 provides this answer by comparing the daily averaged energy usage for 5 relatively new, conventional homes constructed since 2000. Also shown in Figure 4 is the daily averaged energy usage for the Equinox House, another high performance home.

The five "conventionally" built homes and Equinox House are located in Urbana Illinois. Plotting each home's daily utility usage versus the ambient outdoor temperature normalizes the effect of local climate. The conventional houses and Equinox House are 100% electric homes, with either air-source heat pumps, geothermal heat pumps or electric resistance (or some combination) of comfort conditioning systems. The conventional homes are insulated with R-19 walls and R-48 roofs, and range from 2000 to 4500sqft floor area. Windows are moderate (Energy Star) performance. No efforts beyond standard construction practices were used to seal the conventional homes (estimated 6-10 ACH at 50Pa). None of the conventional homes have fresh air ventilation systems, which means that bedrooms become polluted during nighttime occupancy if a central air circulation system is not active, resulting in poorer sleep and reduced cognition performance the next day [5]. Equinox House, built in 2010, was the first home to utilize a CERV fresh air ventilation system.

Collectively, the thirteen Vermod-CERV homes' 12,500ft^2 exceed European Passive Haus standards by nearly 20%! Vermod home primary energy usage is 9kWh/ft^2 per year (97kWh/m^2 per year) in comparison to the standard's 11kWh/ft^2 per year (120kWh/m^2 per year). The Vermod homes' occupancy energy usage is 3650kWh per person, which is less than the current PHIUS (Passive House Institute US) standard of 6200kWh per person and the future PHIUS target of 4200kWh per person. Vermod homes are in one of the harshest US climatic zones, and in small houses where the Passive Haus standards are especially challenging.

In general, one can state that Vermod homes are saving home owners at least $1000 to $2000 per year in utilities. The CERV's automatic maintenance of excellent indoor air quality provides Vermod home owners with a "hidden" value of improved health and comfort that is much greater than the energy savings of these exceptional homes.

[1] F. Nightingale, Notes on Nursing, 1859
[2] Joseph G. Allen, Piers MacNaughton, Usha Satish, Suresh Santanam, Jose Vallarino, and John D. Spengler; "Associations of Cognitive Function Scores with Carbon Dioxide, Ventilation, and Volatile Organic Compound Exposures in Office Workers: A Controlled Exposure Study of Green and Conventional Office Environments";Env Health Perspectives; Oct 2015
[3] R. M. Solow, "Sustainability: An Economists Perspective", Economics of the Environment, 4th edition, edited by R. N. Stavins, 2000.
[4] Piers MacNaughton, James Pegues, Usha Satish, Suresh Santanam, John Spengler, and Joseph Allen; "Economic, Environmental and Health Implications of Enhanced Ventilation in Office Buildings"; Int. J. Environ. Res. Public Health 2015, 12, 14709-14722; doi:10.3390/ijerph121114709
[5] P. Strøm-Tejsen, D. Zukowska, P. Wargocki, D. P. Wyon; "The effects of bedroom air quality on sleep and next-day performance", Indoor Air; doi:10.1111/ina.12254; 2015

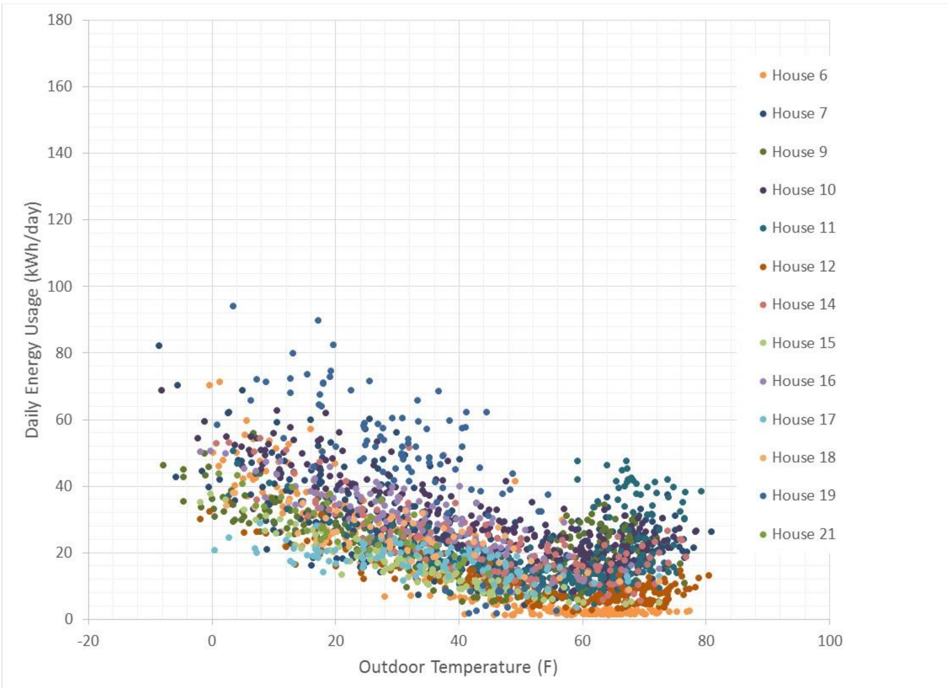


Figure 1 Daily energy usage for 13 Vermod manufactured homes.

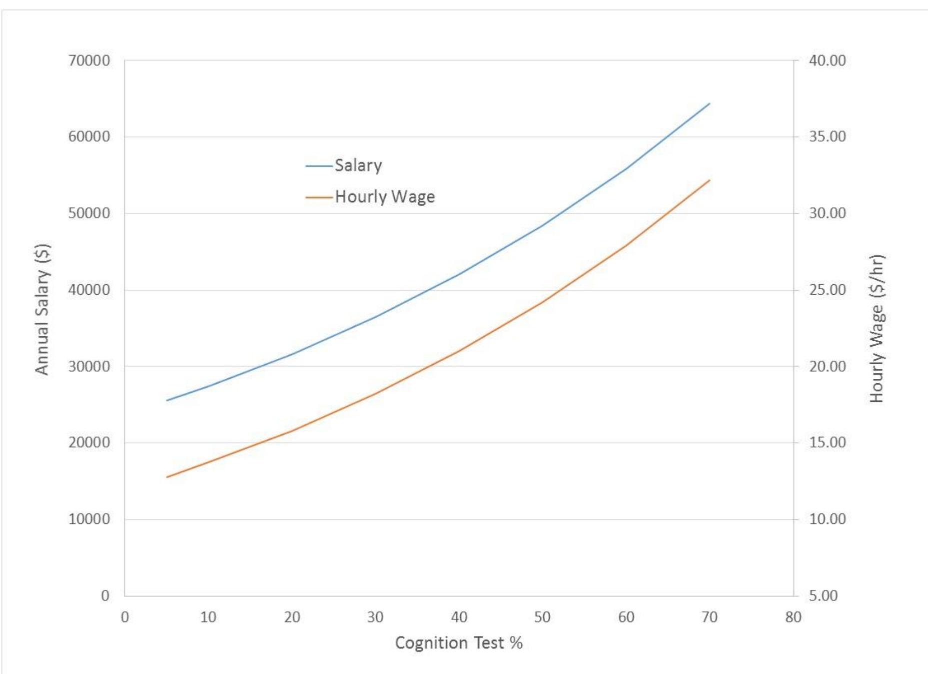


Figure 2 Annual salary and hourly wage trends as a function of cognition performance [3].

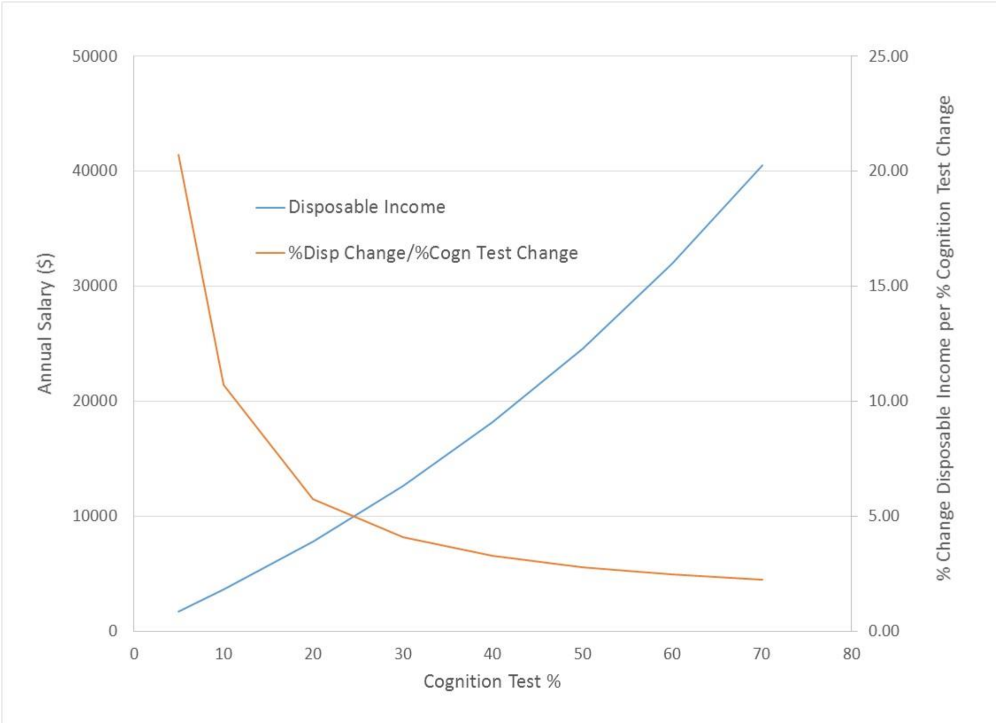


Figure 3 Annual disposable income and percentage change of salary per change of cognition performance relative to annual disposable income.

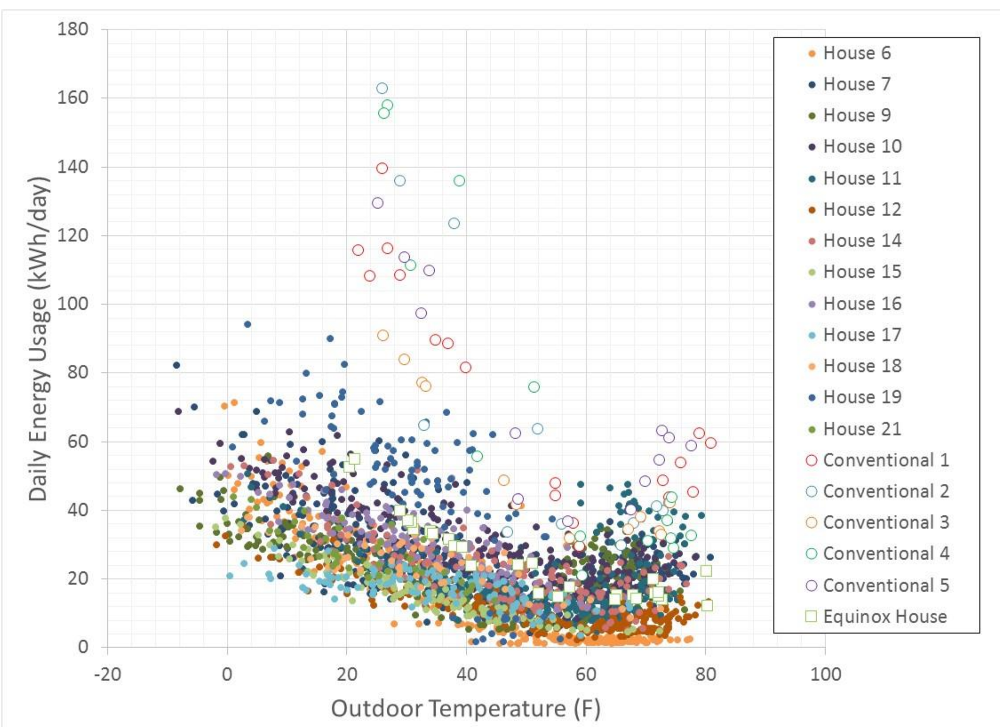


Figure 4 Daily energy usage of the 13 Vermod study homes compared to five conventional constructed homes and one high performance home (Equinox House).

Description of the Vermod-CERV Study Homes and Data Collection Systems

Vermod Study Homes

Vermod (vermodhomes.com) is a corporation located in White River Junction, Vermont. Figure 1 is a photo of the factory with a model Vermod home in the background. In association with affordable home research conducted by Efficiency Vermont (www.efficiencyvermont.com), Vermod developed a series of manufactured home designs beginning in 2013. Efficiency Vermont has provided data acquisition equipment and personnel to monitor Vermod homes. Data acquisition systems for indoor air quality, comfort and energy are discussed later in this section.

Figures 2, 3, and 4 display the ability of Vermod to produce very basic, single module homes (Figure 2) to more sophisticated, custom, multi-module homes (Figures 3 and 4). Factory installed solar photovoltaic systems are often included with the manufactured homes, resulting in affordable, net zero housing.

This study includes small (645sqft) to large (1130sqft) Vermod homes with occupancy ranging from 0 (unoccupied) to 5 occupants. Ten of the Vermod homes have 980sqft floor plan area homes. One home is 645sqft, another is 924sqft, and one home is a "double-wide" unit with 1130sqft of floor area. All thirteen of the Vermod homes are identically constructed, which provides an opportunity to study occupant effects on air quality, comfort and energy usage.

Tables 1 and 2 list Vermod study homes' physical characteristics, occupancy, and system information. All homes with blower door measurements are very well sealed with ACH values (air changes per hour) at 50Pa less than 1, indicating that fresh air ventilation is essential. All of the Vermod homes are conditioned with point-source, cold weather mini-split heat pumps (1 ton Mitsubishi "Hyper Heat") in combination with a CERV® (Conditioning Energy Recovery Ventilator) for DCV (Demand Control Ventilation) fresh air ventilation based on CO2 (carbon dioxide) and VOC (volatile organic compound) concentration sensors. The CERV utilizes a small heat pump (1/3 ton nominal capacity) for exchanging energy between fresh air and exhaust air streams when energy exchange is beneficial. The CERV's recirculation algorithms provide a means for maintaining comfort conditions and excellent air quality throughout a home in contrast to ventilation strategies with one-and-done HRV/ERV systems.

The numerical order of homes listed in Tables 1 and 2 corresponds to the date when homes were placed in service, and data collection was initiated. Monitoring data for Home 6 was initiated in Fall, 2013 while Home 21 was placed in service by November 2014. The data analyzed represents all data available for each home through mid-January 2015.

Vermod CERV System Description

A CERV fresh air ventilation system (see "BuildEquinox.com" for more detailed descriptions of components and operations) consists of a fresh air control module, a heat pump module, fresh air supply fan, stale air exhaust fan, fresh air filter box, and wireless controller. Auxiliary components that can be added to a CERV include battery-free wireless switches for triggering fresh air venting from bathrooms and kitchen, geoloop Geo-Boost heat exchanger, and remote zone dampers.

Vermod home CERVs are installed in a small mechanical closet (see Figure 5) that is shared with the hybrid water heater. The hybrid water heater can be installed in the small mechanical room because the CERV is able to circulate air from the closet throughout the home. During winter, the CERV's heated air mixes with the cooler closet air. For summertime operation, the CERV's cooled and dehumidified air and the hybrid water heater's cooled and dehumidified exhaust air are added together and help reduce the house cooling and dehumidification loads. The CERV's recirculation modes provide additional air movement throughout the house, which helps unify air quality and comfort throughout a home.

Today's high performance homes have reduced the need for large central heating and cooling systems. Instead, a smaller heating and cooling system such as the new generation of high efficiency, mini-split heat pumps can be distributed as needed for a home's bulk comfort conditioning needs. The CERV's recirculation modes provides a means for distributing the bulk conditioning throughout a house.

Figures 6 and 7 show how a Vermod home's comfort conditioning system (eg, a cold weather mini-split heat pump), hybrid water heating system ("heat pump" water heater), and CERV fresh air ventilation system operate in a synergistic manner during each season of the year.

Winter operation is shown in Figure 6. The mini-split heat pump provides heat to the main open living space (living room, dining area and kitchen). The hybrid water heater heats water by removing heat from the around it in the mechanical closet. The hybrid water heater's cool exhaust air is picked up by the CERV's house supply fan. Notice that even though the hybrid water heater removes heat from the house during the winter, which must be replaced by some combination of heat supplied by the mini-split heat pump and the CERV, that the overall house efficiency is very high. If an electric water heater had been used instead of the hybrid water heater, the winter house efficiency performance would be much lower. In effect, the mini-split heat pump and CERV combine with the hybrid water heater to form a two-stage heat pump, similar to those used in industry for high "temperature lift" processes. The mini-split and CERV are able lift energy from bitter cold outdoor temperatures to indoor air temperature, while the hybrid water heater lifts energy from room temperature to hot water temperature level.

Summer operation is shown in Figure 7. In this case, the overall house thermal performance efficiency is even greater than the winter house efficiency because the hybrid water heater has a dual benefit. The water heater heats water with a useful byproduct of cool, dehumidified air that the CERV distributes to the rest of the home. If the CERV did not circulate air from the hybrid water heater throughout the home, the mechanical closet would get cold, which significantly reduces the water heater efficiency.

Figure 8 shows some of the control screens on the CERV's wireless controller and the online CERV-ICE App. The main status screen is shown in "Assess" mode. During fresh air venting modes, the status screen is green. During heating mode, the background is red and during cooling mode the screen is blue, providing easy-to-understand visuals. Other screens shown are the pollutant threshold selection screen, comfort temperature band selection screen, auxiliary component screen, and menu navigation screen.

An important feature of the CERV is its ability to determine when outside conditions are "nicer" than inside conditions. During the spring and fall, for example, when a home often needs cooling and outside ambient temperatures are cooler than inside, the CERV will operate in "free conditioning" mode in which the house is filled with fresh outdoor air with only the ventilation fans operating. During the summer, "free cooling" often occurs at night, equivalent to automatically opening windows when it's nice outside. Filling a house with fresh air at night reduces the need to use daytime ventilation air.

Outdoor air quality during the daytime is worse than nighttime air with more pollutants (car exhaust), pollens (increased plant activity during daytime), and dust (increased atmospheric stirring of air). Note that HRV and ERV systems without smart bypass controls have no free conditioning benefit, resulting in deconditioning the air on nice days.

<u>Data Acquisition Systems</u>

All homes included in the study are monitored with Efficiency Vermont's Powerhouse Dynamics energy and sensor monitoring system. Figures 9 and 10 show pictures from the Powerhouse Dynamics energy monitoring screen and sensor monitoring screen for one of the study homes. Daily energy data values (refrigerator energy, water heater energy, CERV energy, etc) are used for most analyses. More detailed one minute interval monitoring data has been used for indoor air quality and comfort (temperature and humidity) analyses over two week winter periods. An assortment of sensors (temperature, humidity, CO_2, VOCs), which have been installed in various locations in the study homes and provide additional information on house temperature, humidity and air quality.

The CERV automatically monitors and archives temperature, humidity, CO_2 and total VOCs entering and exiting the CERV through its CERV-ICE™ ("service", CERV-Intelligently Controlled Environment) online interface. The CERV monitors "bulk" house air data rather than room specific data. For example, temperature data from the house is a mixture of all the return air streams going to the CERV unit. Figure 11 shows a screen shot of CERV-ICE data plots.

Table 1 Efficiency Vermont study homes characteristics

Home	Type	#People	Floor Area (sqft)	Stories	S Wind (sqft)	N Wind (sqft)	E Wind (sqft)	W Wind (sqft)	Blower Door CFM50	Blower Door (ACH@50Pa)
6	Vermod	1	980	1 over crawl space	53*	40*	20*	0*	125	0.98
7	Vermod	1.5	924	1 over crawl space	53*	40*	20*	0*	119	1
9	Vermod	0	980	1 over crawl space	53*	40*	20*	0*	102	0.81
10	Vermod	5	980	1 over crawl space	53*	40*	20*	0*	82	0.65
11	Vermod	1	980	1 over crawl space	53*	40*	20*	0*	106	0.84
12	Vermod	1	980	1 over crawl space	53*	40*	20*	0*	76	0.6
14	Vermod	4	980	1 over crawl space	53*	40*	20*	0*	92	0.73
15	Vermod	1	980	1 over crawl space	53*	40*	20*	0*		
16	Vermod	1	980	1 over crawl space	53*	40*	20*	0*	124	0.98
17	Vermod	1	645	1 over crawl space	53*	40*	20*	0*	78	0.89
18	Vermod	4	1130	1 double wide over crawl	54*	20*	22*	7*	59	0.38
19	Vermod	5	980	1 over crawl space	53*	40*	20*	0*	90	0.71
21	Vermod	2	980	1 over crawl space	53*	40*	20*	0*	97	0.77

*S/N/E/W window designation is desired orientation if available. Simulation predictions coupled with field results indicate that window orientation and shading is a secondary effect in Vermod homes.

Table 2 Efficiency Vermont study homes system characteristics

Home	Type	#People	Heat Sys1	AC	Water Heater type	Ventilation
6	Vermod	1	minisplit hp	yes	hpwh	CERV
7	Vermod	1.5	minisplit hp	yes	hpwh	CERV
9	Vermod	0	minisplit hp	yes	hpwh	CERV
10	Vermod	5	minisplit hp	yes	hpwh	CERV
11	Vermod	1	minisplit hp	yes	hpwh	CERV
12	Vermod	1	minisplit hp	yes	hpwh	CERV
14	Vermod	4	minisplit hp	yes	hpwh	CERV
15	Vermod	1	minisplit hp	yes	hpwh	CERV
16	Vermod	1	minisplit hp	yes	hpwh	CERV
17	Vermod	1	minisplit hp	yes	hpwh	CERV
18	Vermod	4	minisplit hp	yes	hpwh	CERV
19	Vermod	5	minisplit hp	yes	hpwh	CERV
21	Vermod	2	minisplit hp	yes	hpwh	CERV

Figure 1 Vermod manufacturing plant in White River Junction, Vermont.

Figure 2 Vermod single module, basic home.

Figure 3 Customized Vermod home.

Figure 4 Three module, net zero Vermod home with solar PV system.

Figure 5 A CERV fresh air conditioning unit, with Geo-Boost ground loop exchanger located in Vermod mechanical closet adjacent to the hybrid heat pump water heater.

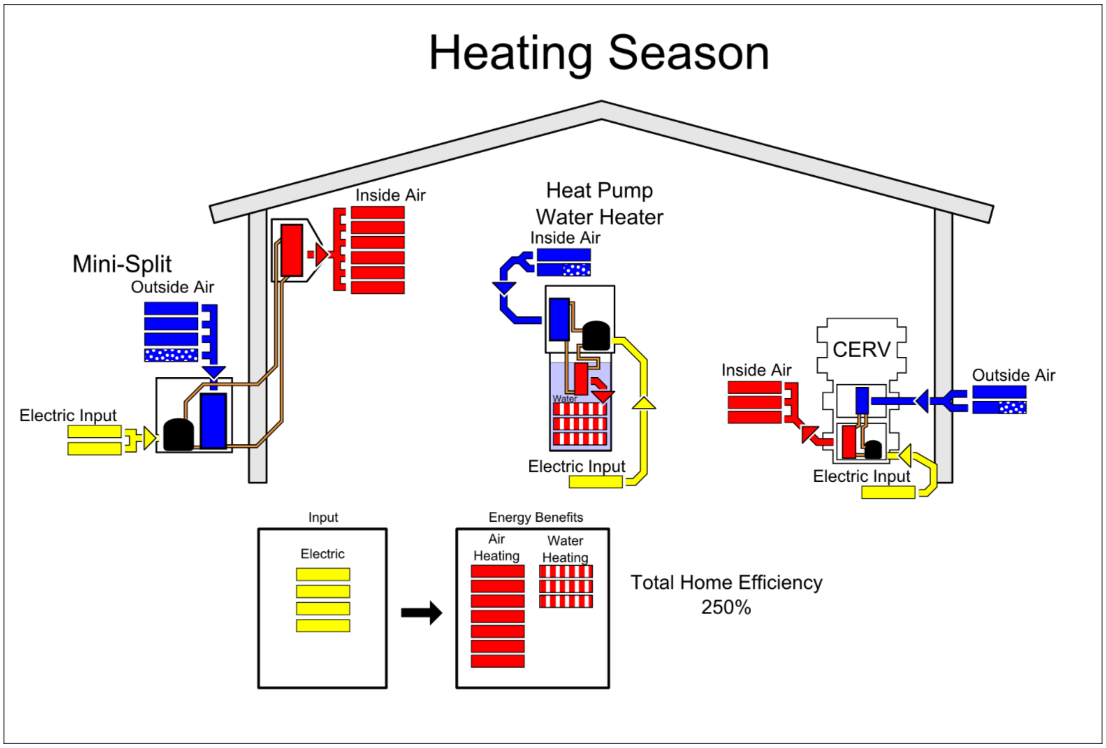


Figure 6 Winter synergy among comfort conditioning mini-split heat pump (heating), hybrid (heat pump) water heater and CERV (heating) fresh air ventilation system.

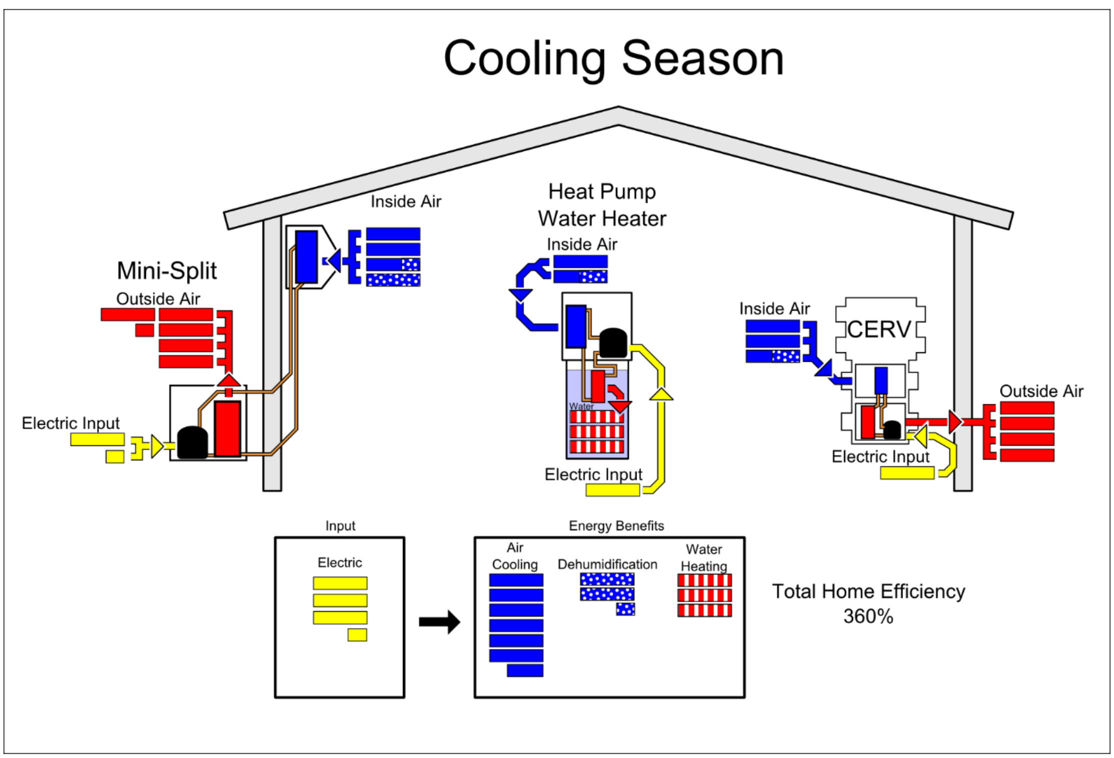


Figure 7 Summer synergy among comfort conditioning mini-split heat pump (cooling, dehumidification), hybrid (heat pump) water heater, and CERV (cooling, dehumidification) fresh air ventilation system.

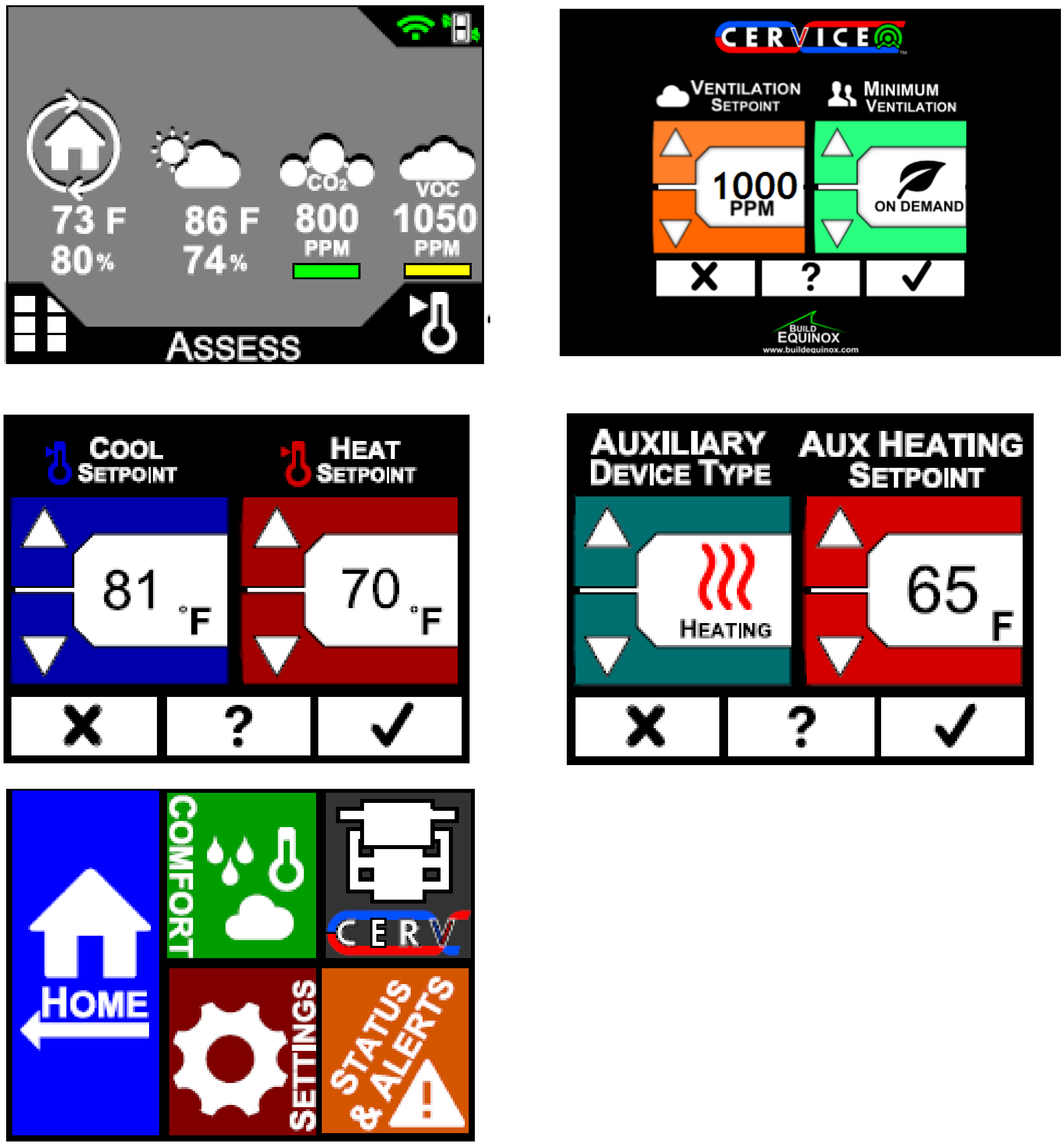


Figure 8 Example CERV control screens showing user status screen (in assessment mode), pollutant setpoint screen, comfort (temperature) setpoint mode, auxiliary device control screen (heater, air conditioner, Geo-Boost™ geoloop, zone damper, etc), and main controller screen.

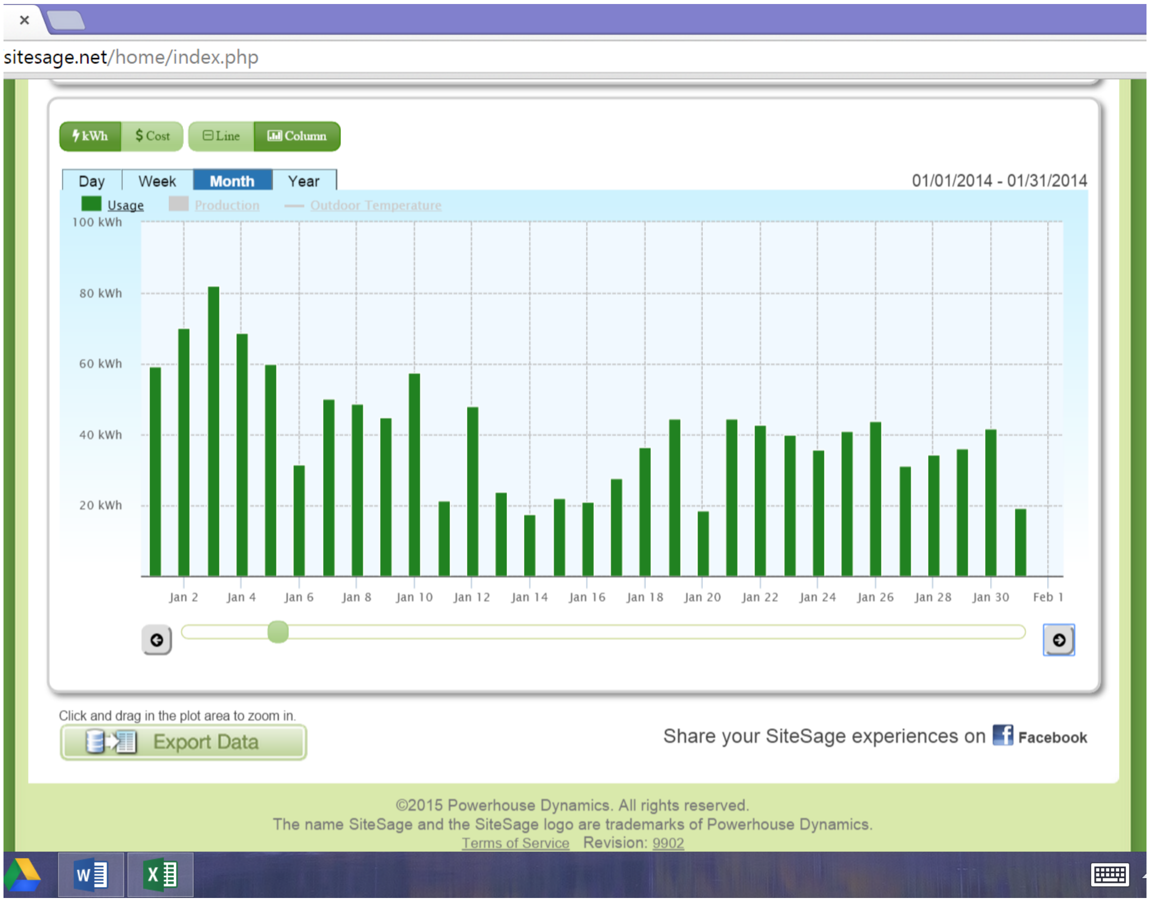


Figure 9 Screen shot from Powerhouse Dynamics energy monitoring system.

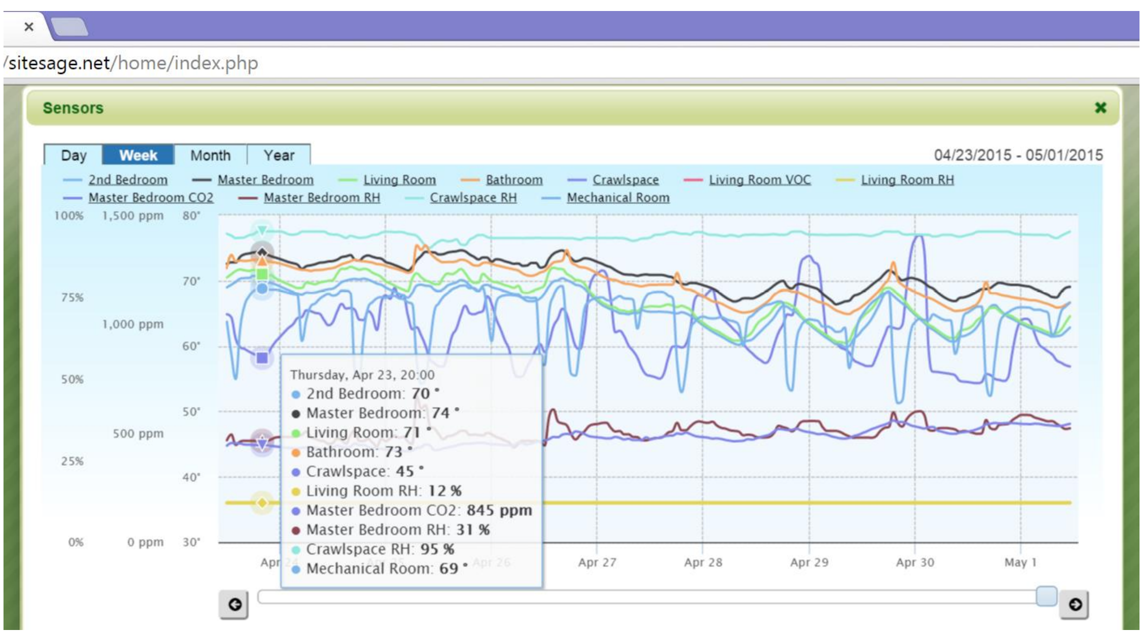


Figure 10 Screen shot from Powerhouse Dynamics sensor recording system.

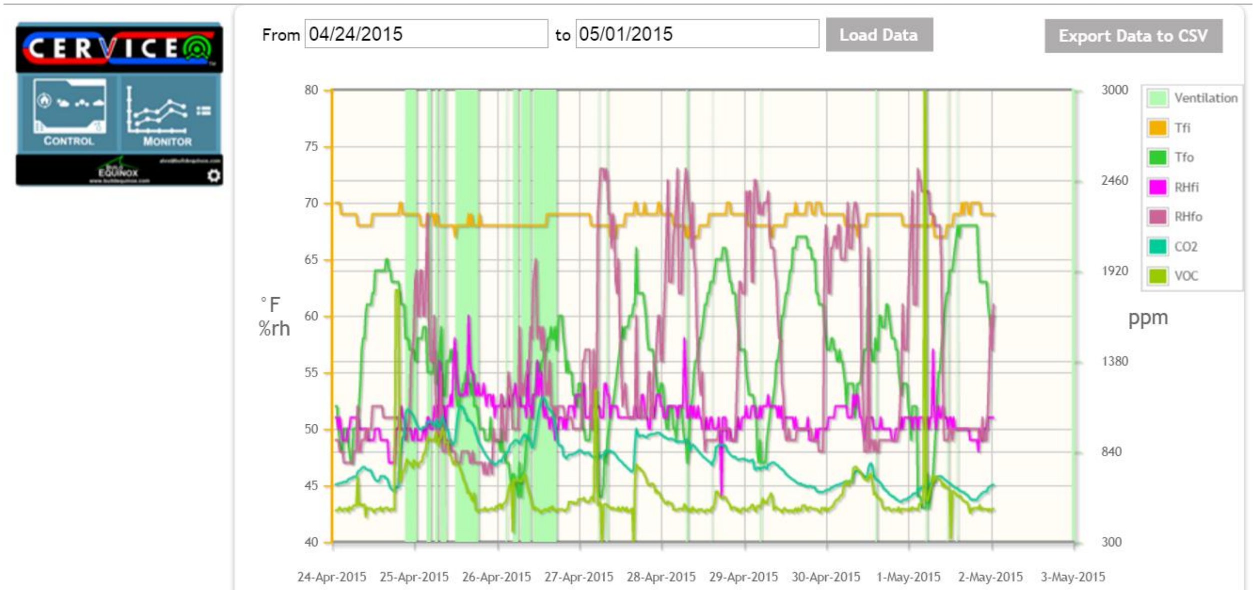


Figure 11 Screen shot from CERV-ICE online monitoring and fresh air control.

Indoor Air Quality

Introduction

Although we are generally not paid for our time at home, poor environmental quality at home decreases our cognition capabilities, and our physical and mental productivities. Our lack of well-being at home carries over to our productivity at work and school. Assuming a person's labor value to be $25 per hour for an 8 hour workday, a drop of 1% productivity is $2 per day per person and a drop of 10% productivity is $20 per day. The average total daily utility cost per person is $1.15 for the Vermod homes, which are located in one of North America's most challenging winter climates. It is amazing that 1% drop in human productivity (5 minutes of an 8 hour work day) is worth more than a person's entire home energy requirements!

In addition to reduced productivity due to poor air quality and comfort, other health factors such asthma, add additional costs to our households and our nation. Asthma has doubled over the past 30 years from 5% to nearly 10% of the population, with a higher asthma incidence in northern latitudes where people spend more time indoors in better sealed homes and buildings. Clearly, increased time spent indoors in unhealthy indoor environments in northern winters is among the most prominent factors exacerbating asthma. The overall economic impact of asthma for the United States is estimated to be $50-60 billion per year [1], or ten times the annual energy cost of refrigerator operation in US homes.

With an annual average cost of $3000 per asthma case (combined costs of medications, missed work/school, doctor visits, and emergency room visits), and assuming an average of 3 persons per household with 10% of a northern climate population afflicted, asthma costs us nearly $1000 per household, which is more than the average Vermod house annual energy cost. The Vermod homes have clearly demonstrated how to solve the energy problem in an economic manner, allowing our focus to shift our health, a much more important and costly problem.

The potential to reduce costs associated with asthma and other illnesses related to our environmental surroundings greatly outweighs any further energy cost savings. Returning to asthma levels of 30 years ago would save nearly $30 billion per year, or more than twice the annual US residential hot water energy cost needs. Why don't we do even better? Let's reduce asthma to levels much lower than 30 years ago.

HRV and ERV One-and-Done Ventilation

Super-insulated and super-sealed homes must have fresh air ventilation in order to keep its occupants healthy and productive. A ventilation system strategy in common use today in high performance homes is the "one-and-done" ventilation system depicted in Figure 1. Fresh air is distributed to primary rooms of a home (living room, dining room, bedrooms, playroom, etc), and exhaust air is removed from bathrooms, kitchen, laundry rooms and other locations with higher levels of moisture or odor concentrations.

An HRV (heat recovery ventilator) or ERV (energy or enthalpy recovery ventilator) that exchanges energy between the fresh air stream and the exhaust air stream, whether or not energy exchange is beneficial, is often used to improve energy efficiency of one-and-done ventilation systems. Energy exchange is not beneficial for much of the year in many locations, such as on a nice spring day or a cool summer evening when the outside, fresh air should only be filtered, but otherwise left as naturally nice as it is.

Figure 1 shows a schematic of a house with "one-and-done" ventilation distributed among the home's five living and sleeping areas. Fresh air from each room flows to an exhaust, typically located in a bathroom or kitchen. In large homes, there may be more areas where the fresh air is distributed, and multiple exhaust areas (eg, bathrooms, laundry, mudroom, kitchen). One-and-done ventilation has the same problems in larger homes as in smaller homes.

If the home shown in Figure 1 has two occupants with a fresh air ventilation flow of 40cfm, the home's bulk average CO2 and associated human generated VOCs will be at a concentration of 1000ppm. This CO2 concentration is typical of today's current building ventilation levels. Dividing the fresh air among the home's 5 rooms results in only 8cfm to each room. Three bad things happen with this ventilation strategy:

- Fresh air delivered to the unoccupied rooms is wasted as it passes from unoccupied rooms to the exhaust without benefiting any occupants.
- Insufficient fresh air is delivered to the occupied rooms. If the two occupants are in one room, as depicted in Figure 1, pollutant levels will exceed 3000ppm! Significant cognition degradation occurs above 900ppm, sleep is degraded, and disease is efficiently spread among occupants.
- Ventilation air flowing out of each room creates a barrier that prevents air from elsewhere in the house from flowing into the room, which keeps pollutant levels high in occupied rooms as well as dragging rooms away from comfortable conditions. Point source conditioners, such as ductless mini-split heat pumps, cannot effectively maintain comfort in other rooms.

The CERV fresh air ventilation system operates at a higher level air flow (150cfm) that quickly purges polluted air from a home. Once air pollutant levels are reduced below occupant selected levels, the CERV operates in recirculation modes. Recirculation is very important because it addresses all three of the above problems. First, fresh air stored in unoccupied rooms is utilized and never wasted. Second, air is kept fresh throughout the home. And finally, conditioned air from point source conditioning systems is delivered to unconditioned rooms, helping to keep a home more comfortable.

<u>CERV® - The World's First Smart Home Fresh Air Ventilation System</u>

The CERV, by Build Equinox, is the first of a new generation of smart ventilation systems. As described by researchers at Lawrence Berkeley National Laboratory (LBNL), without intelligent sensors capable of monitoring air quality, houses are dumb [2]. Air pollutant levels below human olfactory perception diminish our productivity, degrade our health, and disturb our sleep. Unless sensors for detecting carbon dioxide and VOCs are implemented into fresh air ventilation systems, one is simply guessing when and how much ventilation is required, resulting in either or both poor air quality and excessive energy usage.

Air quality in homes is more complex than in commercial buildings, and yet, state-of-the-art fresh air ventilation systems in homes lags commercial buildings. A home is part restaurant, part hotel, part work space, part leisure and entertainment space, part exercise center, and more. While human activity in many work places is quite routine with a fairly uniform human activity pace, human activity in homes runs from very low (sleep) to very high (exercise). Carbon dioxide output from humans varies by a factor of 30 over this range. That is, the level of pollution generation in a home is highly dependent on a person's activity in addition to the number of people in a home.

The CERV is a "preventilator". As described by LBNL [2] researchers, a smart ventilator, such as the CERV, can take advantage of filling and storing a home with fresh air during "nice" outdoor conditions, and minimizing the need for fresh air when outdoor conditions are not so favorable. For example, the CERV knows when it is nicer outside than inside, perhaps on a spring or fall day, or a cool night in the summer. Nightime fresh air ventilation is a time when dust, allergens and pollutants are low, and a time when it is frequently more energy efficient [3] to condition.

The CERV's CERV-ICE® ("service", CERV-Intelligently Controlled Environment) option provides a home's occupants with the benefit of remote monitoring and control of the CERV through any WiFi connected device. An easy-to-use app included with CERV-ICE contains historical data, trouble shooting diagnostics, and CERV "analytics". CERV analytics are an evolving set of human performance and health indices that help home occupants understand the impact of their home's air quality.

Homeowners with CERV-ICE become part of the greater CERV Community. The CERV Community is a network that benefits CERV users individually and collectively. Data from all CERV homes provides information that is important for further improvement and development of future CERV algorithms. Because all CERVs with CERV-ICE have "over-the-air" upgrading capability, new features are incorporated into existing CERVs. CERV Community data can provide important information for public health researchers, too, as they investigate the impact of the built environment on our health.

<u>Vermod Home Air Quality</u>

The CERV has maintained excellent indoor air quality in all of the Vermod study homes. The variation of fresh air needs is broad. Some homes with few people have high fresh air ventilation requirements while some homes with high occupancy have much lower fresh air ventilation needs. Regardless of each home's pollution generation characteristics, the CERV's automated air quality sensing seamlessly supplies fresh air as required.

In this section, we address a number of important air quality questions:

- What are the characteristics of occupant pollutant generation?
- How well does the CERV maintain occupant chosen pollutant threshold?
- What is the rate of pollutant generation in the homes, and how does the pollutant generation compare with the pollutant generation based on a human's metabolic processes?
- Which pollutants (CO2 or VOCs) dominate a home's indoor air quality?
- What is the variation of air exchange rate relative to the occupancy?

- What is the general population's satisfaction with air quality in the study homes?

We characterize basic indoor air quality by examining the fraction of time that a home spends in three defined bands of pollutant concentration. Air pollutant concentrations of CO2 and total VOCs less than 1000ppm are defined as "good". Note that "ppm" (parts per million) of total VOC concentration is a CO2 equivalent scale based on the VOC sensor detecting a VOC level equivalent to a human's VOC output that is calibrated to a human's CO2 output. Indoor air conditions are defined as being satisfactory when pollutant concentrations are between 1000ppm and 2000ppm, while time periods with pollutant concentrations above 2000ppm are defined as unsatisfactory.

Appendix A (Generalized Fractional Time Indoor Air Pollution Plot) provides background on "fractional time" plots used to characterize pollutants in the indoor environment relative to the average air exchange (fresh air ventilation and infiltration) per occupant pollutant generation. These fractional time plots have been developed from Build Equinox's IAQ research. Appendix A includes sample data from a several conventional homes without ventilation systems as well as homes with ventilation systems.

Figures 2 and 3 show CO2 and VOC sensor data from all homes in the study collected with CERV-ICE. The data used for Figures 2 and 3 are two week long periods in the winter. Most of the data is from mid-January, however, some data are from Nov/Dec/Feb for those homes in which January data was unavailable (WiFi disconnection). Winter was chosen for the analysis because occupants spend more time indoors, and buildup of pollutants is more likely due to closed doors and windows. CO2 and/or VOC data collected from Efficiency Vermont's "Powerwise" monitoring system is also included for homes when available. Powerwise CO2 and VOC data were in general agreement with CERV data, indicating that the CERV's recirculation feature maintained reasonably uniform air quality throughout the homes.

Figures 2 and 3 indicate that all Efficiency Vermont study homes have excellent indoor air quality with no homes exhibiting significant time periods with CO2 or VOCs above 2000ppm. In comparison to conventional "leaky" homes with no purposeful fresh air ventilation, as shown in Appendix A, the Vermod homes are significantly better. The CERV homes display a spectrum of IAQ conditions that result from home occupants' air quality preferences.

CERV-homes with DCV ventilation have a range of fresh air ventilation rates that depend on a home's pollution generation. Because the CERV's DCV operation allows occupants to choose their upper level pollutant threshold, the fractional time levels for CO2 and VOC pollutants, based on occupant perception of "fresh air", varies significantly. Some occupants prefer very fresh air with pollutants less than 1000ppm for 80-90% of the time, while others are satisfied with lower levels of "freshness" (50% of the time below 1000ppm and 50% of the time between 1000 and 2000ppm). No one in the study appears to prefer air quality with pollutant concentrations greater than 2000ppm. Only one home displayed a brief period (less than 5% of the time) when VOCs exceeded 2000ppm. This home had a time period within the two week examination session in which some VOC emission source was continuously high, such as painting, cleaning, or perhaps some type of craft activity. Note that 20% of the 40 conventional “leaky” homes and buildings in Appendix A had average pollutant concentration levels (CO_2 or VOCs) greater than 1000ppm.

Air quality changes significantly as conditions change. Without active sensing and control of fresh air ventilation, one must guess the proper ventilation air flow setting, which leads to either poor air quality or wasted energy. The transition to poor air quality happens quickly. For example, a ventilation system that is set to 40cfm quickly changes from satisfactory air quality with 2 occupants (20 cfm per person) to terrible air quality with 4 occupants (10 cfm per person) in which pollutant levels are never below 1000ppm as seen in Figures 2 and 3. The variation of required air flow also depends on occupant activities. Human generated carbon dioxide varies by a factor of 30 from sleep (0.013 cubic meters per hour of CO_2 generation) to hard work or exercise (0.38 cubic meters per hour of CO_2 generation). Fortunately, the Vermod homes are 100% electric which eliminates gas cooking from degrading air quality.

Figure 4 provides information related to the pollutant levels in CERV homes relative to the occupants’ desired setpoint levels. The ratio of average pollutant level (CO_2 and VOC data) to pollutant threshold setpoint level is plotted versus the pollutant threshold setpoint level. Unlike a thermostat that is designed to “hold” at a temperature setpoint, the CERV’s job is to minimize pollutant excursions above the pollutant threshold level. All CERV homes in the study have average pollutant levels that are below the CERV pollutant setpoint level. Most homeowners selected a pollutant threshold level of 1100ppm. One home (House 16) displays a ratio of average pollutant level to setpoint level of nearly 1 for VOCs during a couple day period, indicating that a continuous, high generation rate of VOCs kept house air at the CERV pollutant threshold. Figure 4 shows that the associated carbon dioxide level for the home with high VOCs is much lower, which indicates that high VOC levels are not human generated. Figure 4 shows that in general, the pollutant concentration to CERV threshold ratio is well below one, but that when high pollutant generation events occur, the CERV increases ventilation levels to meet pollutant generation rates.

One home in Figure 4 selected a high CERV pollutant setpoint of 2000ppm. These home owners also chose to have a fix ventilation schedule (20% of each hour), which CERV users can select in combination with the CERV’s automated sensor operation. The combination of the fixed ventilation schedule coupled with a high pollutant threshold resulted in good air quality for the home, however, we recommend that home owners set the CERV pollutant threshold to a lower value with full automated control in order to obtain maximum energy benefits without sacrificing indoor air quality.

An important question is to ask is the following: How much indoor air pollution do the occupants generate relative to the pollutants generated through a human’s metabolic processes? Figure 5 provides information related to this question, indicating that most homes have an average occupant pollutant generation rate that is below the amount of pollution generated by a sedentary human’s metabolism in a continuously occupied home. For example, if all of the pollutants (CO_2 and VOCs) were due to human metabolism, and the occupants were home for 12 hours per day, then the average pollutant generation rate would be ½ of a person per occupant.

Figure 5 shows that pollutant generation rate exceeds human pollution generation rates in a few of the homes. VOCs will exceed the level expected from a human source of VOCs due to other VOC pollutant sources such as cleansers, cosmetics, cooking odors, and anything else that contains or emits volatile, reactive substances. CO_2 can exceed occupant CO_2 generation level due to guests (additional occupants), increased occupant activity level (eg, exercising or active work), and internal combustion sources such as candles, gas cooking, and propane/kerosene heaters. The high VOC emitter home has VOC levels that are representative of VOCs generated by the metabolism of nearly 7 people. Note that candles and combustion heaters tend to produce more CO_2 than VOCs in proportion to a human's metabolic production of CO_2 and VOCs.

Appendix E is a publication that lists substances that Build Equinox has tested in order to determine the CERV's VOC sensor sensitivity to that substance. Note that reality is much more complex. For example, limonene, a common cleanser ingredient (citrus smell), reacts with ozone in a manner that creates small diameter (<2.5microns), airborne particles. How the multitude of substances in our indoor air interact, from duct tape adhesive to sunscreen to chicken noodle soup, is anyone's guess. However, it is common sense, as Florence Nightingale expressed over 150 years ago, that we need air as fresh as the outdoors to stay healthy inside.

Figure 6 examines CO_2 and VOC pollutant levels in relation to each other. The figure shows that VOCs tend to be the more dominate pollutant. Ideally, if all pollutants were human "generated", CO_2 and VOCs would be at similar levels. VOC levels that are high in proportion to CO_2 levels are indicative that other VOC pollutant generation sources are contributing to VOC concentration. Cooking odors, furnishing off-gassing, and various household chemicals are some of the VOC sources. A few homes have VOC concentration levels that are below CO_2 generation levels. As previously mentioned, there are some pollutant generators, such as candles, that exhaust CO_2 at higher rates than VOCs.

VOCs have a shorter atmospheric lifetime due to their reactive nature. CO_2 is a relatively inert chemical that is reduced in concentration by dilution with outside air. VOCs, however, will breakdown into other compounds, such as water and CO_2, or will be absorbed into various furnishings and surface finishes within a home (with some re-emitted at a later time), resulting in a faster decay rate and lower concentrations than CO_2. VOCs are even absorbed in your clothing, allowing you to carry your indoor pollution with you! Unlike the tobacco smoke in your clothes when indoor smoking was more prominent, you may not be able to smell the pollutants in your clothing, but it is there and its concentration is directly related to the pollutant concentration buildup in your home.

Figure 7 examines the variation of air exchange rate for the Vermod-CERV homes. The air exchange rate is somewhat different than the CERV's actual ventilation rate because it is a measure of the "net" fresh air flow. For example, if a home's air inlet and exhaust are physically close to each other, such that half of the inlet air is drawn from the house exhaust air stream, the net fresh air exchange rate would be half of the actual inlet air flow rate. Infiltrated air (nothing is perfectly sealed), along with outside door openings, window opening, etc are also part of the net fresh air exchange. The net air exchange rate is based on a Build Equinox analysis algorithm that examines dynamic CO_2 decay rates in a home during unoccupied periods.

House 16 is the home that displayed a time period with high VOC generation rates previously discussed. Three data points are shown for House 16 in Figure 7 from the two week, winter assessment period. During the first part of the two week data assessment period in January, the CERV pollutant setpoint was 1100ppm. The setpoint was then increased to 1550ppm during the middle portion of the two week period (CERV-ICE records setpoint settings as well as operation modes). The average air exchange rate dropped from 43cfm to 24cfm as less fresh air was required for the higher pollutant threshold. The setpoint was lowered back to 1100ppm during the last portion of the two week assessment period, resulting in an increase of the air exchange rate to 163cfm. The reason for the significant increase in air exchange rate relative to the exchange rate from the previous time with 1100ppm setpoint is unknown. Two speculations are:

1) Some high pollutant generation event, such as painting, installation of carpeting, or cleaning occurred
2) VOCs absorbed into the home's furnishings during the high CERV setpoint level period may have desorbed at a rate sufficient to require elevated fresh air venting.

Figure 8 is based on an ASHRAE "dissatisfaction" model that estimates the fraction of the populace that is generally "not dissatisfied" with the air quality in a building space. We define a "satisfaction" model that subtracts the results of the dissatisfaction model from 100%. Although the two concepts (satisfaction versus dissatisfaction) are not strictly complementary because there is a portion of the populace who are neither "satisfied" nor "dissatisfied" with air quality, we chose to reflect a more positive view.

The ASHRAE model is based on average CO2 pollutant levels, which inherently includes VOCs associated with human occupancy. We have used the model based on both CO2 and VOC levels to provide some perspective of whether CO2 or VOC levels tend to be more or less satisfactory. ASHRAE considers 700ppm above outside air CO2 concentration (nominally ~400ppm, or a total of 1100ppm) as a level where a reasonably small percentage of people (~<20%) are not dissatisfied with indoor air quality. We have chosen 1000ppm (600ppm plus outside air CO2 concentration) as a relative border between good air and air that is becoming less desirable. As previously mentioned from our building research studies, maintaining an average concentration of 1000ppm of either CO2 or VOCs indicates that pollutants are below 1000ppm for half of the time, and between 1000 and 2000ppm the other half, with insignificant time with pollutant concentrations above 2000ppm.

General populace satisfaction prediction levels for all homes in this study are very high, especially in comparison with conventional, "leaky" homes we have studied that often lack sufficient fresh air in the rooms where people live. It is important to remember that with the CERV's active control of one's indoor air quality, pollutant levels result from the occupant choice rather than chance. In addition, in leaky homes, where the leaks are (flue vents in mechanical and laundry rooms) and where people live are not the same.

[1] EPA-402-F-04-19, "Asthma Facts", EPA bulletin, US Environmental Protection Agency, Indoor Environments Div, Office of Air and Radiation, March 2013
[2] Iain Walker, Max Sherman and Brennan Less, "Houses are Dumb without Smart Ventilation", LBNL Paper LBNL-6747, March 2014
[3] Charles L. Blanchard, Shelley Tanenbaum, and Douglas R. Lawson, "Differences between Weekday and Weekend Air Pollutant Levels in Atlanta; Baltimore; Chicago; Dallas–Fort Worth; Denver; Houston; New York; Phoenix; Washington, DC; and Surrounding Areas", J. Air & Waste Manage. Assoc. 58:1598–1615, 2008, DOI:10.3155/1047-3289.58.12.1598

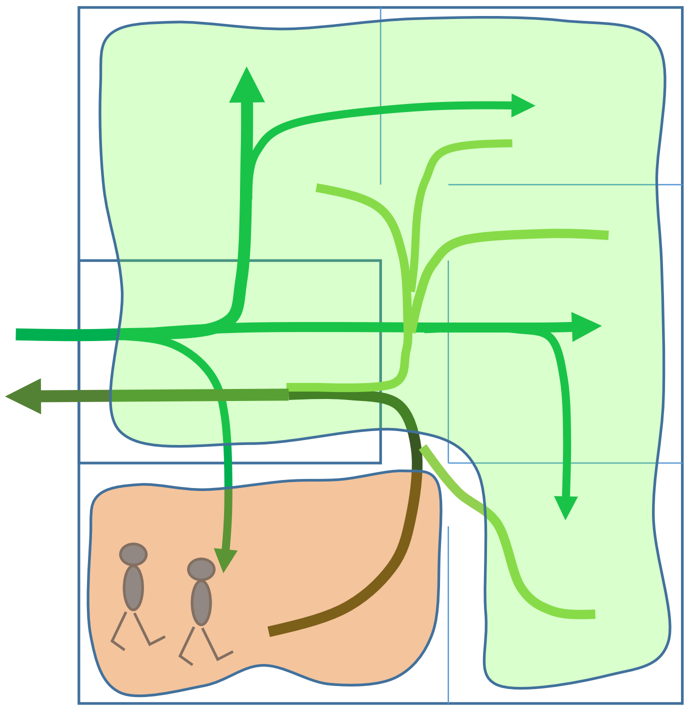


Figure 1 “One-and-done” ventilation wastes fresh air in unoccupied rooms and over-pollutes occupied rooms.

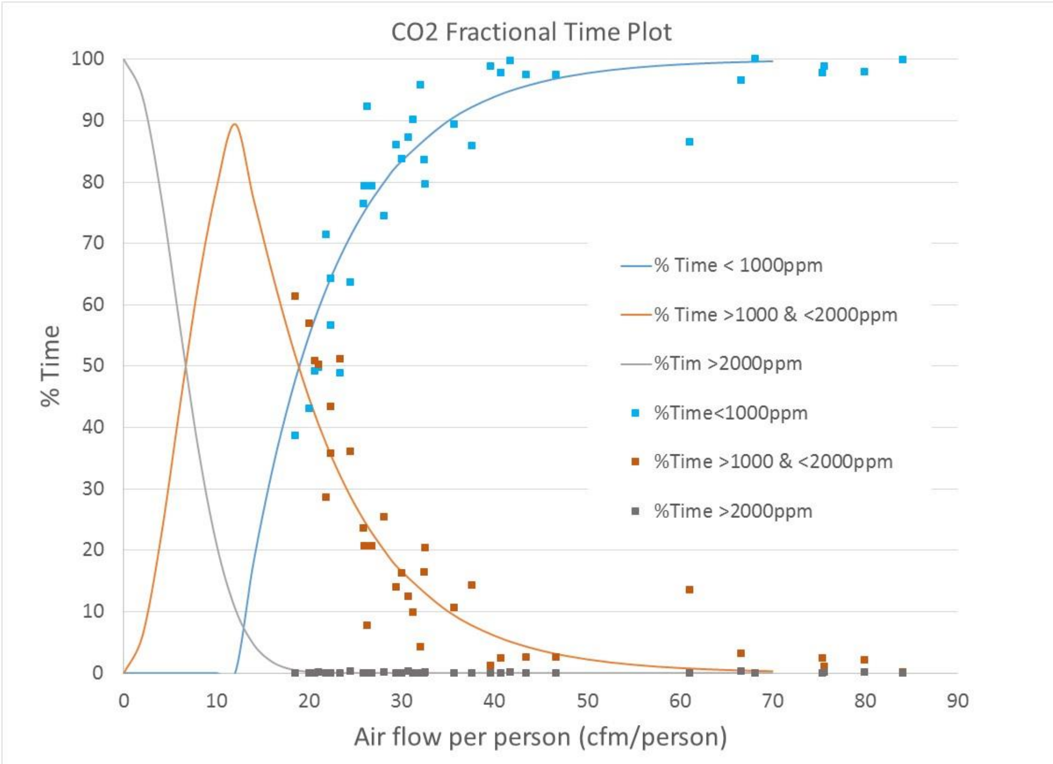


Figure 2 Carbon Dioxide fractional time plot.

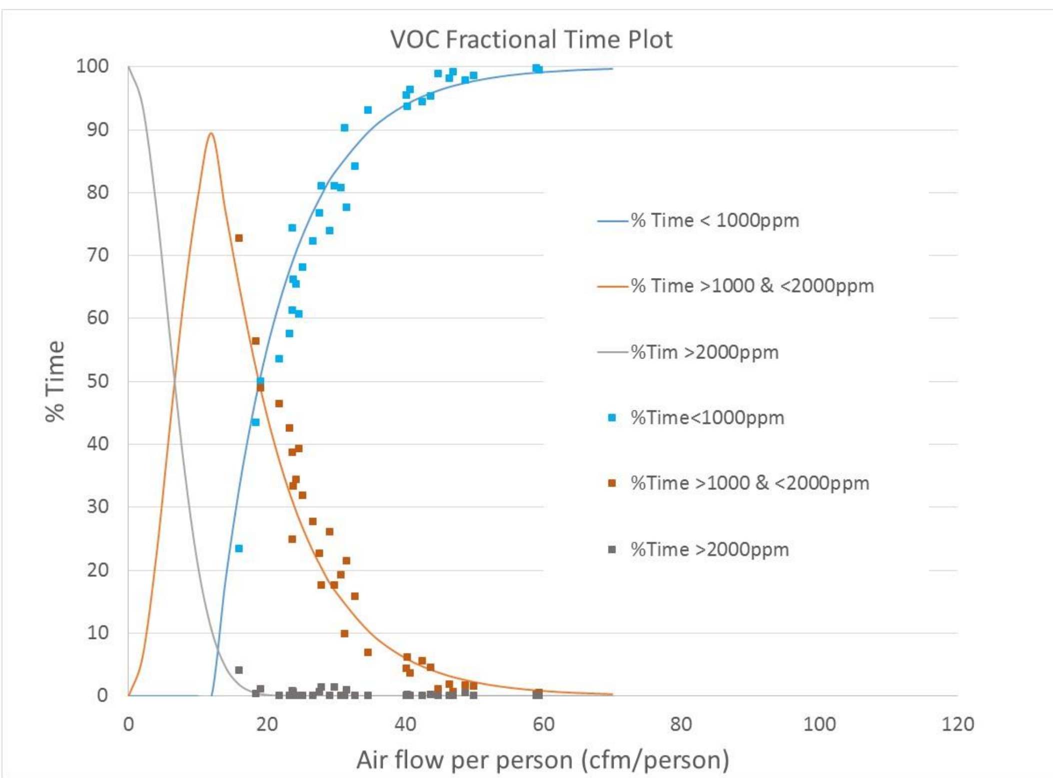


Figure 3 Volatile Organic Compound fractional time plot.

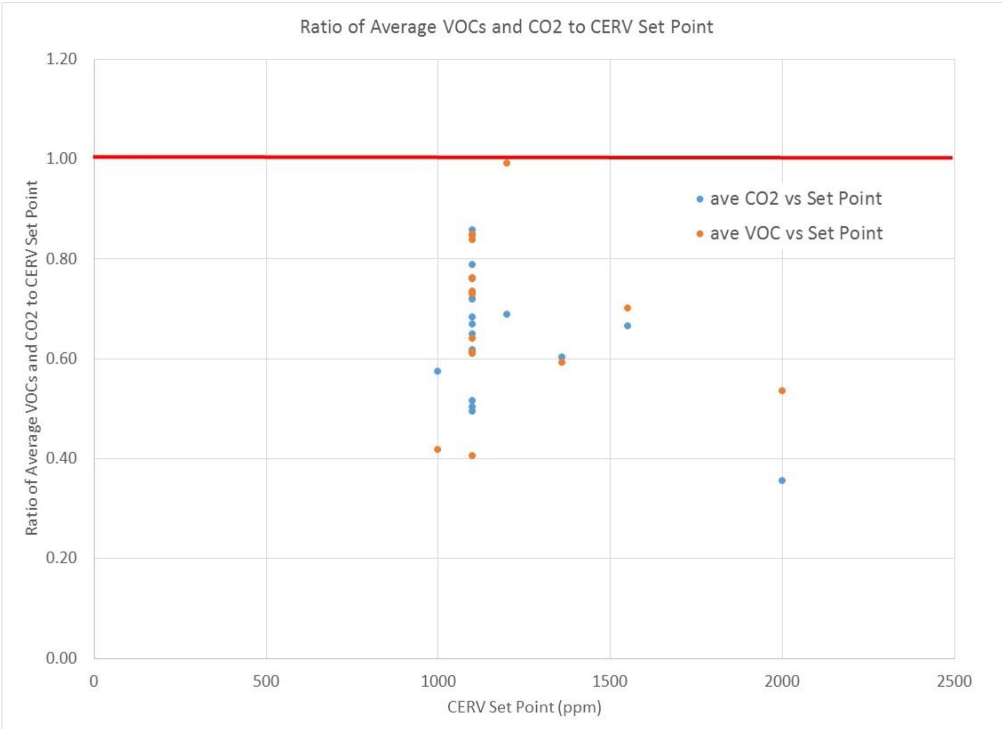


Figure 4 Comparison of average pollutant level (ppm of either CO2 or VOC) versus a resident's pollutant threshold setting on the CERV.

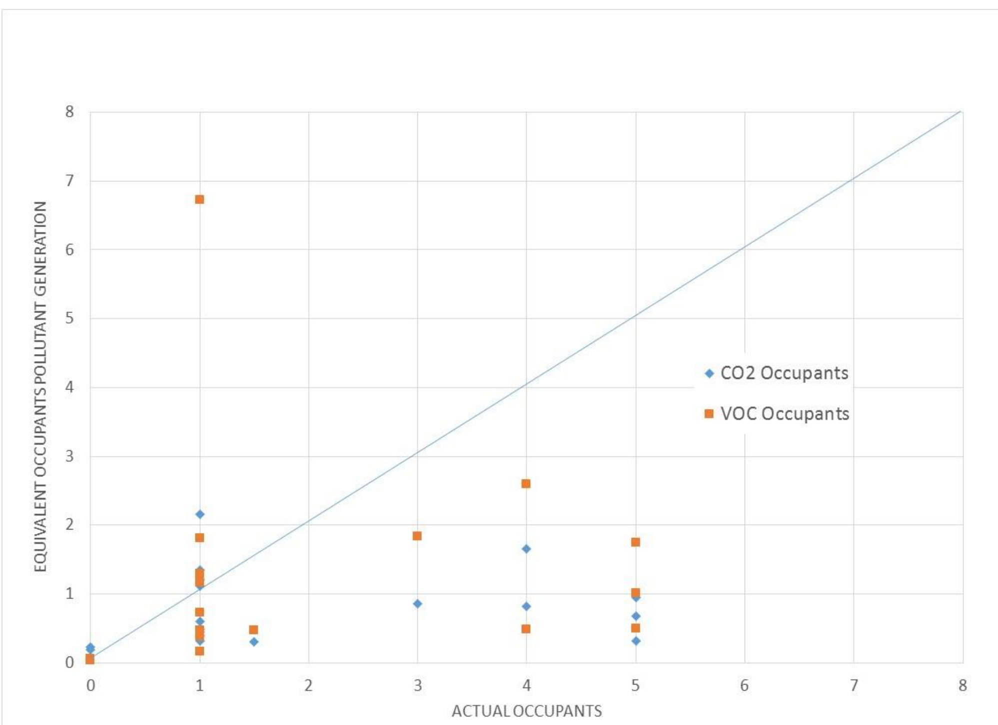


Figure 5 Comparison of "equivalent" occupant pollutant generation rates with actual number of occupants.

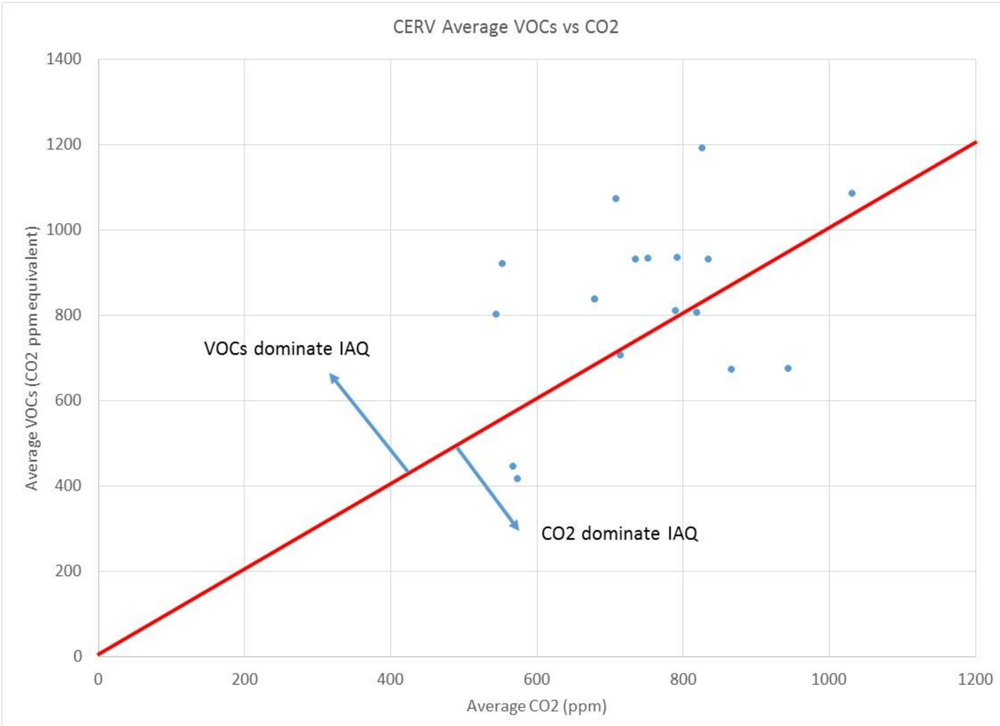


Figure 6 VOC versus CO2 average concentration levels for the two week study periods.

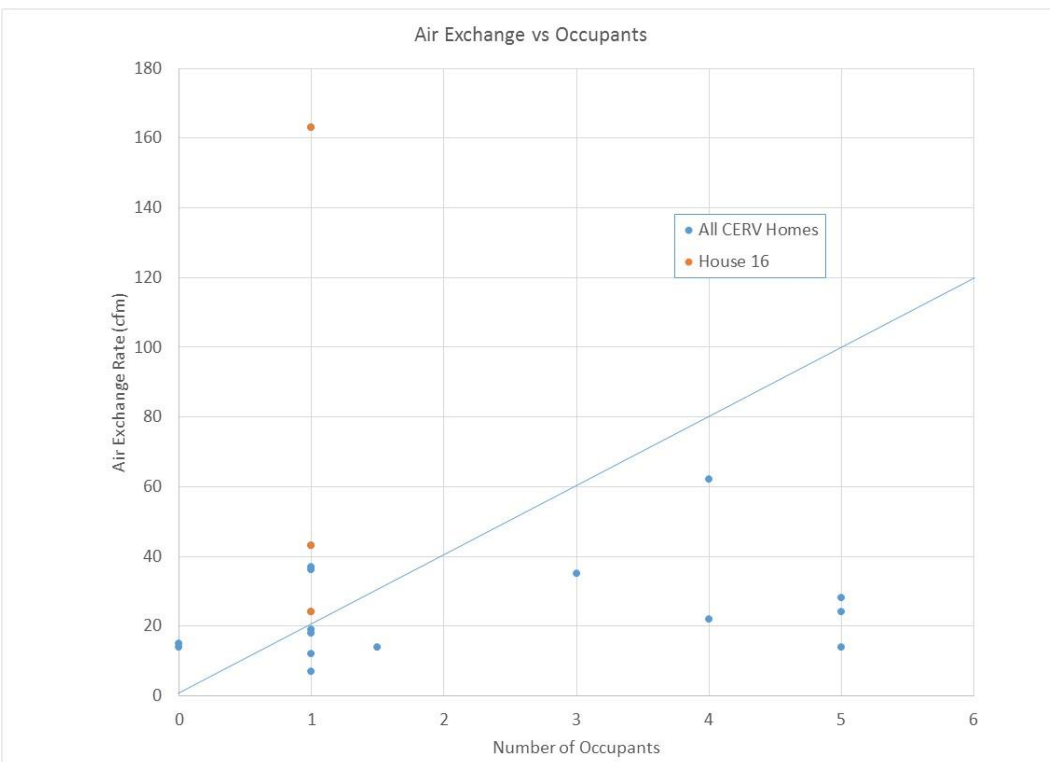


Figure 7 Average air exchange rates relative to each CERV home's occupancy.

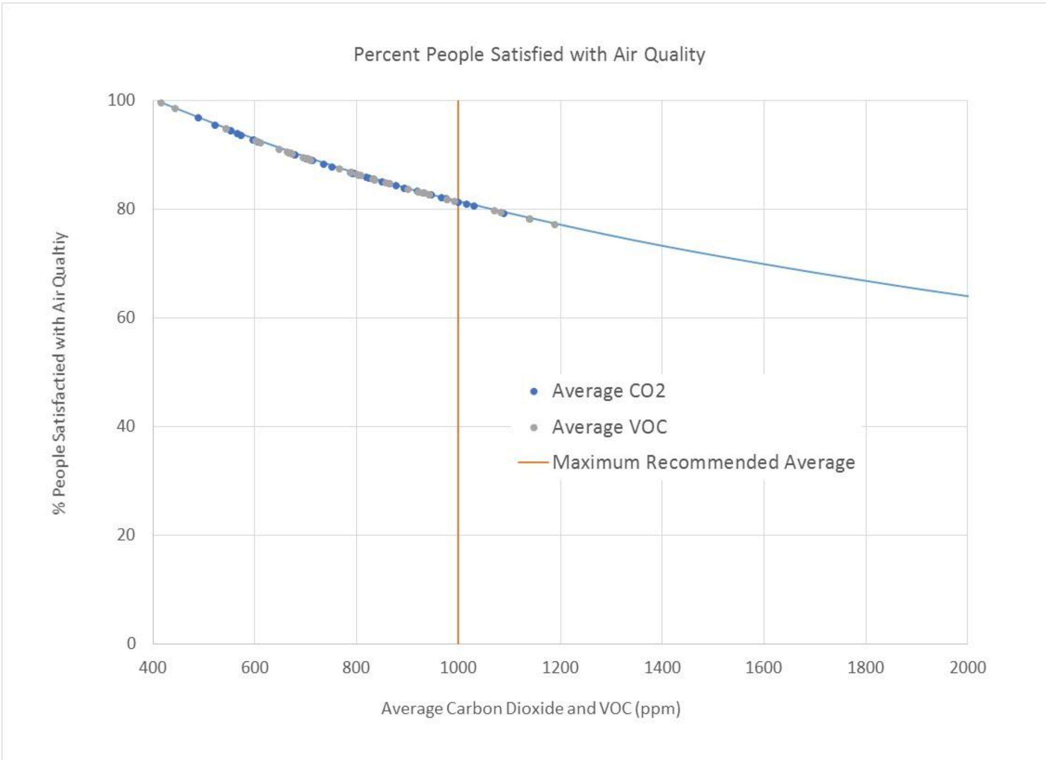


Figure 8 General population "satisfaction" with the air quality of the homes based on average CO2 and VOC concentration levels during the two week study period.

Comfort

<u>Introduction</u>

We examine characteristics of the indoor environment of the study homes in this section. Because occupants have full control of their comfort conditioning systems, the indoor conditions within the study homes are primarily due to occupant choice. For example, most of the study homes show a preference for lower indoor temperatures during the winter and higher temperatures during the summer. During the winter, most people dress in warmer clothing, resulting in comfort with lower indoor temperatures. The opposite occurs in the summer. Additionally, people acclimatize to seasonal changes.

Perhaps some of our home occupants "sacrifice" comfort to save energy. We are unable to discern this effect within the scope of our study. Our hope, however, is that home occupants never sacrifice comfort for energy, especially in homes such as the Vermod homes that are very energy efficient. As with air quality, an imperceptible 1% decrease of productivity due to discomfort (approximately 1-2F outside of one's comfort range) has a cost that is nearly double of the average daily energy cost per study home occupant.

Comfort means different things to different people. The following interacting factors impact our comfort:

- ambient air temperature
- ambient air humidity
- surrounding surface temperatures (radiant energy interactions)
- air velocity
- human activity level
- clothing
- human physiological differences (metabolism, perspiration, blood perfusion, etc)

Some people enjoy the sensation of air movement while others do not. Some people prefer long sleeves and long pants while others prefer shorts and short-sleeved shirts. Some people are active while others are sedentary. And, of course, some people who may dress the same and have similar activity levels may have totally different comfort preferences. To this end, comfort models are based on a "vote" by a collection of humans. Comfort "maps" are very fuzzy regions in which "most people" express the least discomfort. With these ideas in mind, we examine some of the variations of indoor temperatures and indoor comfort conditions for the Vermod homes without making judgements on occupant comfort preferences.

A simple comfort map, shown in Figure 1, provides some perspective on comfort. Temperature and humidity are very important factors, and in Figure 1, rough comfort (or "least discomfort") boundaries are plotted for sedentary (office work activity level) people. Long sleeves and long pants shield people from some of the effects of radiant energy transfer from surrounding surfaces and from air velocity sensitivity while people dressing in short sleeves and shorts tend to be more sensitive to these effects. Additionally, lightly clothed individuals are more directly able to cool by evaporation of perspiration than a more heavily clothed individual, providing increased comfort at elevated temperatures and humidity.

Some subtle effects are encountered in high performance homes. A heavily insulated, well-sealed home with modest windowing will feel more comfortable during winter with lower indoor ambient temperature because interior wall and ceiling temperatures are higher than in conventionally built homes and because of decreased air drafts. In contrast, a heavily windowed high performance home may require increased interior air temperatures because relatively cold window surfaces increase radiant heat losses from occupants and natural convection drafts from large window surfaces. When a significant fraction of a human's geometric view factor (fraction of surface areas that "see" a person) consist of windows, a significant cooling effect occurs. Likewise, a heavily windowed room on a sunny day will tend to radiantly overheat occupants, causing unnecessary discomfort. Vermod homes are appropriately windowed with a 10% window area to floor area ratio that is more than sufficient for good daylighting and outdoor views.

Figure 1 may seem to indicate that the moisture level increases as air temperature decreases. For example, one may feel comfortable with 85% relative humidity when the air temperature is 67F, while a humidity of only 55% relative humidity can be tolerated with an air temperature of 81F. This trend is caused by using "relative humidity" for our moisture metric rather than "specific humidity" or water vapor pressure. The upper comfort boundary of Figure 1 has a constant level of moisture with a vapor pressure level of 1.9kPa, equivalent to a specific humidity of approximately 0.012kg-water/kg-dry air. That is, the amount of water in the air at the upper range of comfort is relatively constant over the comfort temperature range. Heat rejection from a person due to evaporation from perspiration depends on the water vapor pressure difference between our skin and the surrounding air.

<u>Seasonal Indoor Temperature Variations and Comfort Condition Characteristics</u>

We discuss the variation of indoor temperature relative to the outdoor temperature in this section and the variation of indoor "comfort" conditions of the study homes. Most homes in the study display significant variations of indoor temperature with seasonal changes. That is, as is similar in most homes, occupants select warmer indoor temperatures during the summer and cooler indoor temperatures during the winter.

Indoor humidity and temperature from the Vermod homes are plotted using Figure 1 as a template. Most homes are in the comfort range most of the time. The Vermod home data provides a very interesting look at differences in personal comfort preferences as these homes are identical in construction and comfort conditioning capability. Temperature plots and comfort charts for all Vermod homes are included in Appendix B.

Two of the Vermod homes (Houses 6 and 7) daily average temperature and humidity data are plotted in Figures 2-5. These two homes are typical of the temperature variations and comfort variations displayed by most of the other homes. Figures 2 and 4 show the indoor temperature variations of each home as the outdoor ambient temperature changes. During cold weather, the average indoor temperature is held constant in each home at approximately 70F. There is variation of indoor temperature in each home in cold weather, with the bedroom areas tending to be cooler than the living room and kitchen areas. All Vermod homes have a central ductless mini-split heat pump that provides the bulk heating for the home. The CERV helps to distribute the mini-split's heating and cooling capacity, however, home occupants can reduce the distribution of comfort by closing doors to bedrooms and closing ventilation registers in bedrooms. Some people prefer sleeping in a cooler room, which may also encourage occupants to maintain cooler bedrooms in addition their interest in "conserving" energy.

Figures 2 and 4 indicate that there is no shortage of heating capability in the Vermod homes. At ambient temperatures below 0F, both homes show that they are capable of maintaining 70 to 75F interior temperatures. As previously mentioned, high performance homes with warmer wall surfaces, modest window areas, and no air drafts are more comfortable in the winter with lower indoor temperatures.

House 6 and House 7 are very different in the summer. House 6 indoor temperature increases to nearly 90F during the summer, even though the outdoor temperature never exceeds 80F. The 10F temperature rise is due to indoor heat generation caused by occupant activities (eg, cooking, computer usage, lights, etc) and solar radiation input. We will see in the next sections on house energy consumption that House 6 has very low summer energy usage, however, this may come at the expense of comfort. House 7, in contrast to House 6, is maintained at a comfortable temperature throughout the year. The main living area and the master bedroom are kept at similar temperatures throughout the year, with the second bedroom kept at a temperature somewhat lower than the main living area during the winter.

Comfort charts for House 6 (Figure 3) and House 7 (Figure 5) further show that House 7 occupants prefer comfortable conditions throughout the year while House 6 occupants tend to be more flexible regarding their comfort conditions during both winter and summer. Because both homes are similar in construction, have similar comfort conditioning systems, and are similarly occupied (1-1.5 occupants), the variations observed in comfort are primarily due to occupant preferences. In these energy efficient homes, the cost to maintain comfort is small.

All other homes in this study that have sufficient data for plotting daily indoor temperature variations and comfort charts are included in Appendix B. A few additional comments for some of the trends and characteristics observed in these homes are:

1. House 11 displays several days with cooler indoor temperatures than occur during relatively mild conditions (60'sF). Perhaps the occupants opened windows/doors during the swing season (spring and fall)? During the winter, the indoor temperature is keep at a relatively uniform temperature (~70F) with very little room temperature variation.
2. Houses 19 was a relatively new addition to the study with data collected only during the beginning of the 2014/2015 winter season. The indoor temperatures of House 19 are the highest observed of any of the study homes. House 19 is also interesting because it has a very high cooking energy usage, which is an important aspect of indoor temperature. In high efficiency homes, cooking and other electrical energy usage can significantly contribute to winter house heating (as well as overheating during the summer).

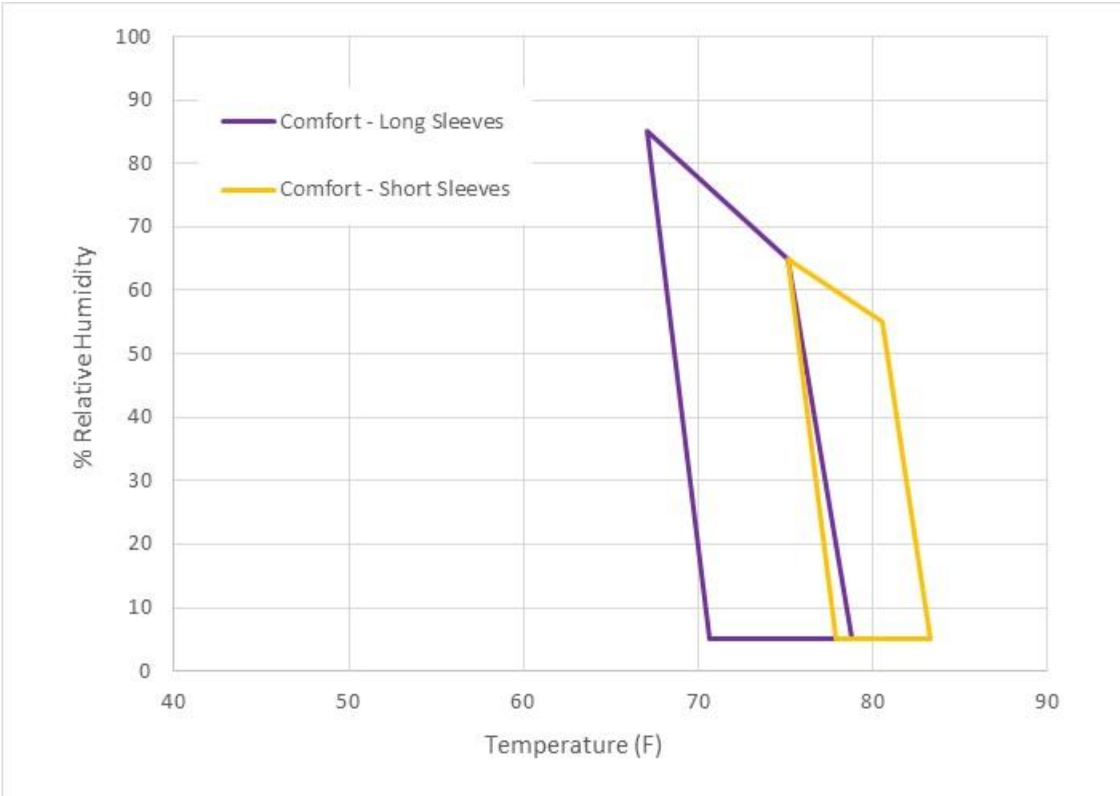


Figure 1 Simple comfort map based on temperature and relative humidity.

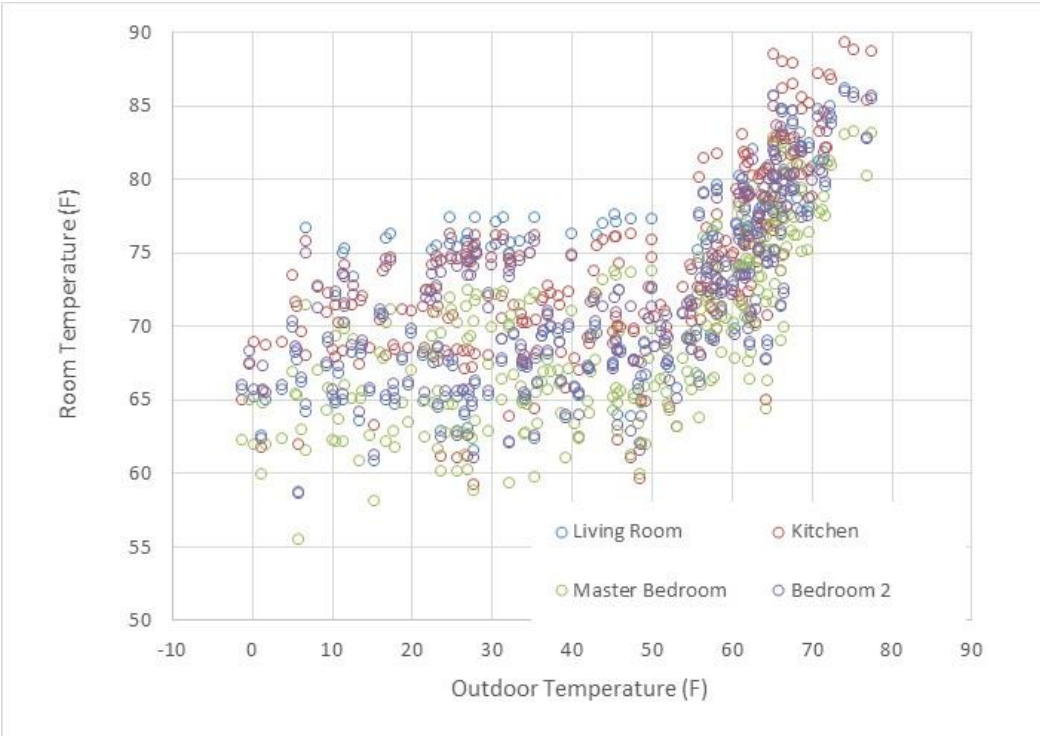


Figure 2 Variation of indoor ambient temperatures in House 6 (Vermod) versus outdoor ambient temperature.

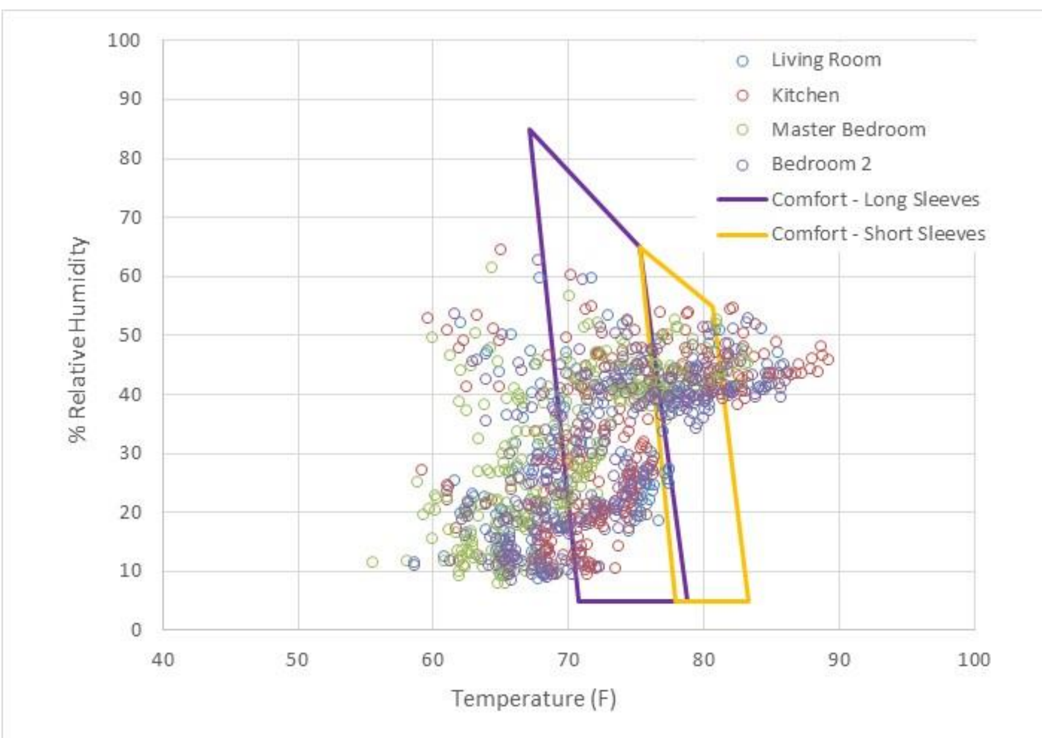


Figure 3 House 6 (Vermod) comfort map.

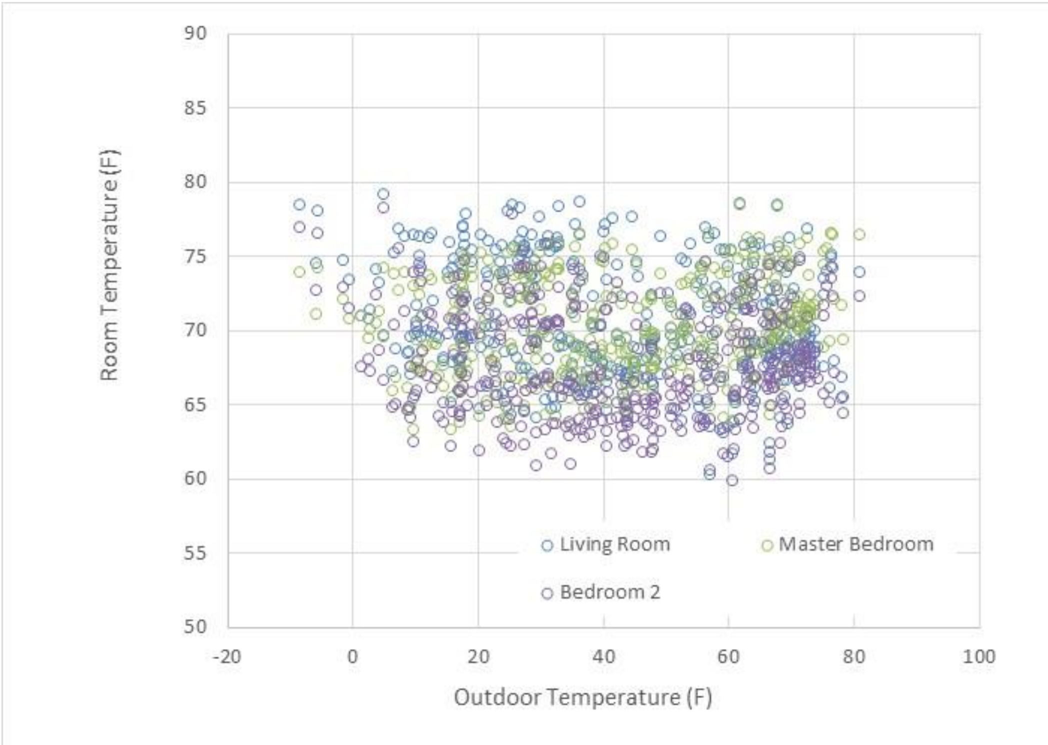


Figure 4 Variation of indoor ambient temperatures in House 7 (Vermod) versus outdoor ambient temperature.

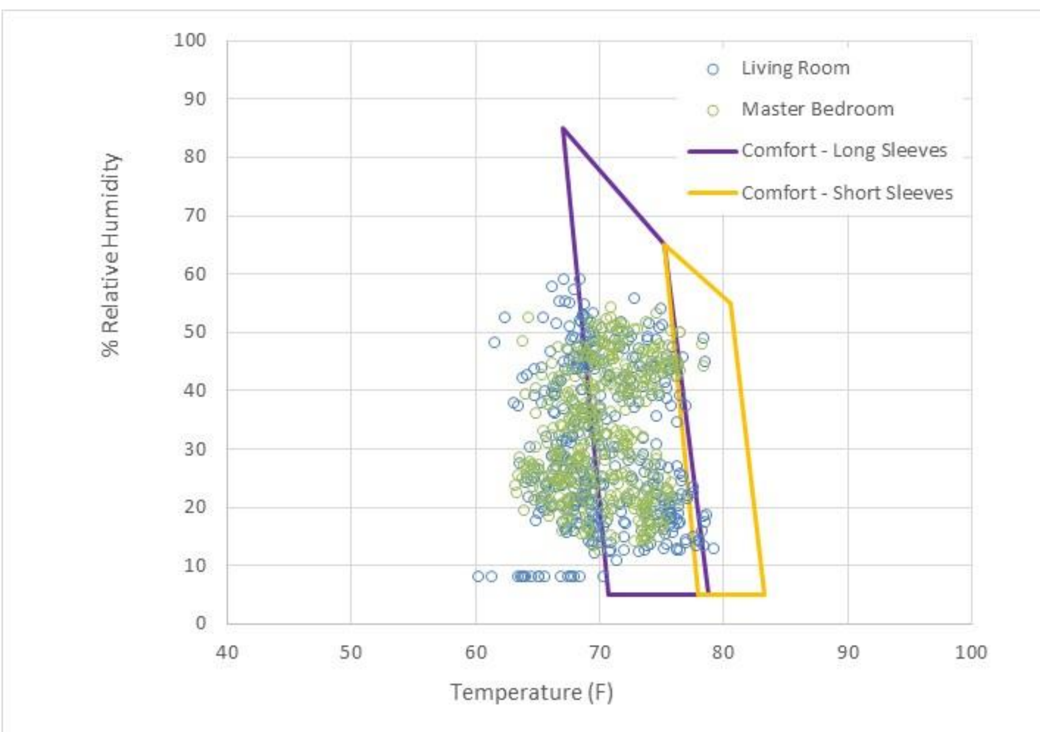


Figure 5 House 7 (Vermod) comfort map.

House Energy – Gross Usage

We explore the gross energy usage characteristics of the Vermod-CERV homes in this section. Our purpose is to gain an understanding of the trends and physical features that result in the energy usage profiles of a house. Houses are complex systems in which interrelated components impact each other's performance. For example, a television is both an entertainment device as well as an electric heater. During the winter, a television's heat is beneficial, although inefficient in comparison to a heat pump. During the summer, a television's heat is an air conditioning load. Appendix D shows how the interrelation of a home's space conditioning, water heating and CERV fresh air ventilation systems impact a house's overall "house efficiency". Vermod homes use the most efficient combination of house conditioning, water heating and ventilation conditioning by using heat pumps for these functions.

Buried within the cloud of daily home energy usage data in Figure 1 are three characteristic regions representing heating season, shoulder seasons, and cooling season. The existence and extent of the three characteristic regions vary depending on the location (climate), house design (insulation, windows, sealing), occupancy, occupant behavior, and comfort conditioning/appliance/miscellaneous electrical uses (computers, TVs, aquariums, etc). For example, region 3 (cooling season) is much greater for homes in Florida while region 1 (heating season) may be non-existent. Region 2, representing the spring and autumn shoulder seasons depend on the occupants' comfort preferences as they decide when to switch from heating to cooling, and vice-verse. Region 2 (swing season with minimal comfort conditioning needs) is very important because it provides a home's baseline energy usage.

The lines sketched on Figure 1 represent a home with a base electrical load of 16kWh per day. Conventional homes have base energy loads greater than 20kWh per day due to occupant behavior, less efficient appliances, lights, etc. The VermodCERV homes in this study have baseload energy consumption ranging from 2kWh per day (House 6) to 18kWh per day (House 10). Swing season was not available for Vermod home number 19 as it was installed after the swing season, however the trends indicate that it may have a baseload energy usage in the 20 to 30 kWh/day range. Home 19, as discussed in the comfort section, maintains a high indoor ambient temperature (75 to 80F) and the highest cooking energy load of all study homes.

A baseload of 2kWh/day is indicative of very low occupancy and very little occupant activity within the home. A home with 2kWh/day typically consists of the refrigerator load (~1kWh per day) plus standby losses from a water heater and miscellaneous parasitic power uses.

The blue (Region 1, heating season) energy usage line drawn in Figure 1 characterizes a house that requires heating when outdoor temperatures decrease below 50F. The red (Region 3, cooling season) energy usage line shows a change to air conditioning when outdoor temperature increases above 60F.

Figure 2 is a composite plot of the daily energy usage for all Vermod-CERV homes. Also plotted on Figure 2 are two ZEROs model simulation results for a Vermod-CERV home with 1 occupant and 3 occupants. ZEROs is a residential simulation model developed by Build Equinox. The ZEROs predictions of monthly average daily energy consumption falls within the actual daily energy usage for the homes and illustrates the "vee" shaped energy usage versus ambient plot that is characteristic of homes and buildings in general.

Why would a home need air conditioning (cooling) when it is only 60F outside? Every human activity heats and humidifies a home's interior. For homes with ERVs and HRVs without automatic bypass capability, cool ventilation air is deconditioned as it is heated (and humidified in the case of an ERV) by a home's warmer (more moist) exhaust air.

The "deadband" region between heating and cooling seasons is partially due to occupants shifting their comfort preference from a lower temperature (eg, 68F) in winter to a higher temperature (eg, 75F) in summer. They may change their clothing from sweaters and long pants to shorts and teeshirts, further shifting them from one region of comfort to another as discussed in the previous section.

Occupants can extend the width of the deadband (region 2) by opening and closing windows, which improves comfort by making use of outdoor conditions when they are "nicer" than indoor ambient conditions. Opening windows and "smart" ventilation systems, such as the CERV, with automated "free cooling" algorithms can maintain comfort in a home with very low energy usage. Few people seem to regularly open and close windows due to the effort required, health concerns (asthma triggers), or perhaps security concerns. Considering the value of a human's time, a person spending 5 to 10 minutes per day opening and closing windows costs $2 to $4 per day, or two to three times a person's daily energy cost. When the outdoor ambient reaches a sufficiently high temperature where it can no longer keep the interior comfortable, some type of air conditioning is required if comfort is to be maintained.

For a home with average daily energy requirements similar to the Region 1 blue line in Figure 1, energy usage due to home heating will increase 1kWh per day per degree Fahrenheit decrease. Likewise, a home with cooling characteristics similar to the Region 3 red line would require an extra 1kWh per day per degree Fahrenheit increase above the high balance point temperature.

The plot in Figure 1 is one of the most important figures for analyzing a home's energy characteristics. The lines drawn on Figure 1 for a particular home are not arbitrary. They are directly related to a home's insulation, infiltration/exfiltration, ventilation, windows, and house energy usage. We can answer many questions with a set of data plotted as in Figure 1:

- What are my home's balance point temperatures?
- How does my home's heating and cooling change throughout the year
- Can I improve its energy requirements in a cost effective manner?
- How do windows, insulation, and infiltration sealing impact the gross home energy usage characteristics?
- How does comfort conditioning efficiency impact energy usage trends?
- How will the home perform in other climate locations?
- How does the thermostat temperature setting affect my home's energy usage?

Appendix C provides additional information related to building energy versus outdoor ambient temperature.

Energy data for "identical" Vermod Houses 6 and 7 are shown in Figures 3-6. Although the homes are identical, their energy usage is not. House 6 does not use air conditioning during the summer and experiences indoor temperatures that reach 90F. House 7 maintains a comfortable temperature in the home throughout the year. The baseload energy for House 6 is only 2kWh/day, indicating very little occupant energy usage (and perhaps very low actual occupancy?), while House 7 has a very reasonable 15kWh/day base energy usage. At 0F, both homes require approximately 50kWh/day. Because of the occupant activity level in House 7, larger variability in day-to-day energy usage occurs while House 6 with very inactive occupants displays very little day-to-day energy fluctuations.

Figure 7 is a bar chart showing the heating season and cooling season average daily energy per degree outdoor temperature (line slope of a best fit linear least squares of the energy data) for each of the 13 Vermod-CERV homes in the study. Daily energy plots (both raw house energy data and data divided into Regions 1 (heating), 2 (baseload), and 3 (cooling)) for all study homes are included in Appendix F. Some of the homes did not have sufficient data for determining cooling slopes (Houses 19, 20, 21). Some homes did not use air conditioning during the summer which often resulted in high indoor temperatures during the summer.

Figure 7 shows that House 17 has the lowest heating slope (0.2kWh/F-day) while House 6 has the highest heating slope (0.9kWh/F-day). For homes that displayed cooling, House 9 has the lowest cooling slope (0.2kWh/F-day) while House 14 has the highest cooling slope (0.8kWh/F-day). The broad variation of heating characteristics and cooling characteristics for "identical" homes shows how occupant behavior impacts home energy usage. The next section will examine home energy usage in a detailed manner in order to assess how the occupants use energy as well as how much energy per occupant is used in each home.

Although the wide variation of energy usage seems quite large, relative to energy usage of conventional homes, the variation is actually quite small. For example, the difference between a value of 1 and 2 may seem large (2 is twice as large as 1). The difference between 101 and 102, although the same as the difference between 1 and 2, does not seem so great because 101 and 102 are only 1% different in value. Our study homes should be viewed with a similar perspective. Bar 22 in Figure 7 shows the average study home heating and cooling season slopes, and bars 23 and 24 show the heating and cooling slopes for conventional homes 3 and 4 included in Figure 2. All of the study homes are less than half of the heating slopes and most are less than half of the cooling slopes.

Figure 8 uses the best fit line data for the study homes in order to examine the daily house electric energy usage when it is 0F outside. 0F is the intercept value of the best fit heating season data and forms a convenient reference for examining extreme weather energy usage. Also shown in Figure 8 are Region 2 (baseload) house daily energy. The difference between the 0F energy use and baseload energy use represents the energy for comfort conditioning and ventilation at 0F.

Bars 23 and 24 in Figure 8 show data for conventional homes 3 and 4 included in the Figure 2 plot for comparison. All homes in the Vermont study use less than half of the conventional home energy for outdoor temperatures of 0F. The conventional homes, as described in the introduction section, are modern, all electric homes with reasonable levels of insulation. House 19 has the highest 0F energy use

(78kWh/day) while House 17 only requires 24kWh/day. The average 0F energy usage for the study homes (bar 22) is 47kWh/day. If an entire month consisted of 0F ambient temperature, the study homes would use 1410kWh for the month, with a utility bill of $200 (utility cost of 14 cents per kWh). By comparison, the conventional homes require 160 to 200kWh/day when it is 0F with a monthly utility bill that would be 3 to 4 times that of the study homes during extreme cold weather.

The conventional homes have a baseload energy of approximately 30kWh/day. The average baseload energy usage for the Vermod-CERV homes is 13.3kWh/day, which is equivalent to an average power of 550Watts. The next section will examine how 550Watts of average power is used within the Vermod-CERV homes.

Figure 9 displays the balance temperatures at the high and low ends of Region 2. Temperatures below the low temperature require heating and temperatures above the high temperature require cooling (for those homes that use cooling). Bars 23 and 24 are for conventional homes 3 and 4 while bar 22 shows the average low and high balance temperature of the study homes. In general, the study homes have an average low balance temperature of 56F in comparison to the conventional homes with 60F. A high efficiency home would be expected to have a somewhat lower balance temperature, which indicates that internal load generation from daily activities, such as lights, cooking, computers, etc, provide sufficient heat that keeps a home comfortable to lower outdoor ambient temperatures. Conventional homes, however, with higher internal heat generation (for the example homes, a baseload daily energy of 30kWh/day versus the study home average of 13kWh/day) have more internal heat generation that also allows them to be comfortable at relatively low ambient temperatures (in this case, as 60F or 4 degrees higher than the Vermod home temperature).

On the other end of Region 2, the study homes that use air conditioning tend to begin cooling when outdoor ambient temperature is 62F in comparison to the conventional homes with 65F temperature. The difference is not so significant, but points to the fact that highly insulated and sealed homes that may stay comfortable at relatively low outdoor temperature conditions are generally hotter and require some type of cooling (automated venting and/or air conditioning) at lower ambient temperatures than more poorly insulated and sealed conventional homes. The average temperature difference between heating and cooling seasons is 10F for the study homes compared to a 5F temperature difference between heating and cooling of the conventional homes.

The Vermod-CERV homes as a whole are significantly more energy efficient than conventional homes. Among the Vermod homes is a wide variation of energy usage that is due to occupant and their activities. In fact, as discussed in the next section that outlines the sub-system energy usage within the homes, Vermod homes are equally impacted by its occupants as they are by the climate, one of the most challenging climates in the U.S. In almost any other region in the U.S., occupant behavior is the dominant factor in energy usage with climate of secondary importance.

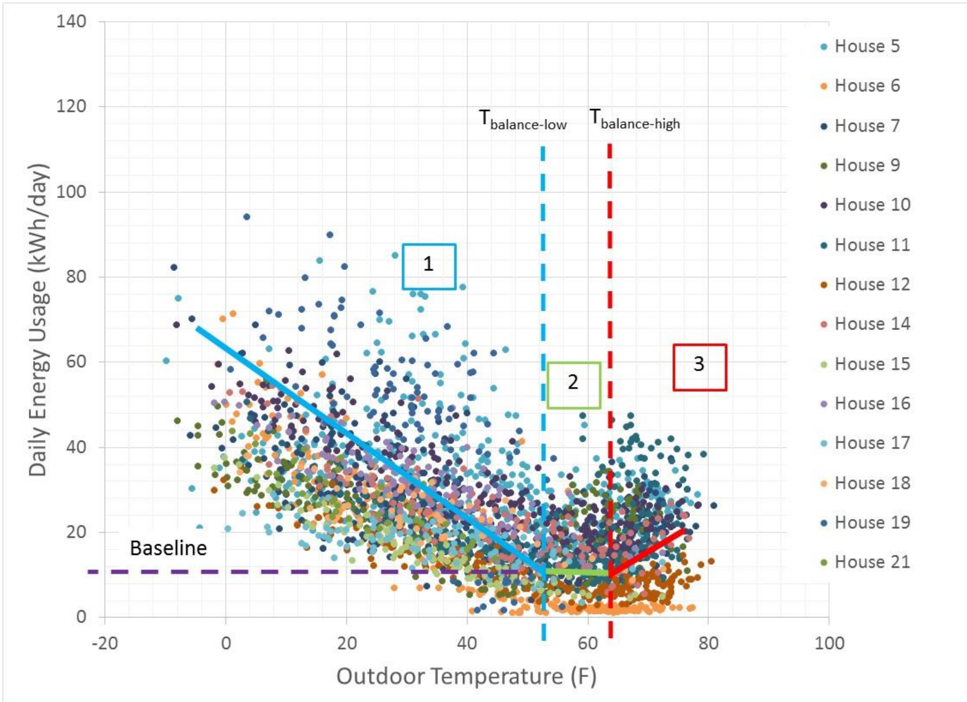


Figure 1 Daily household energy usage for 13 Vermod study homes with CERV® preventilation systems.

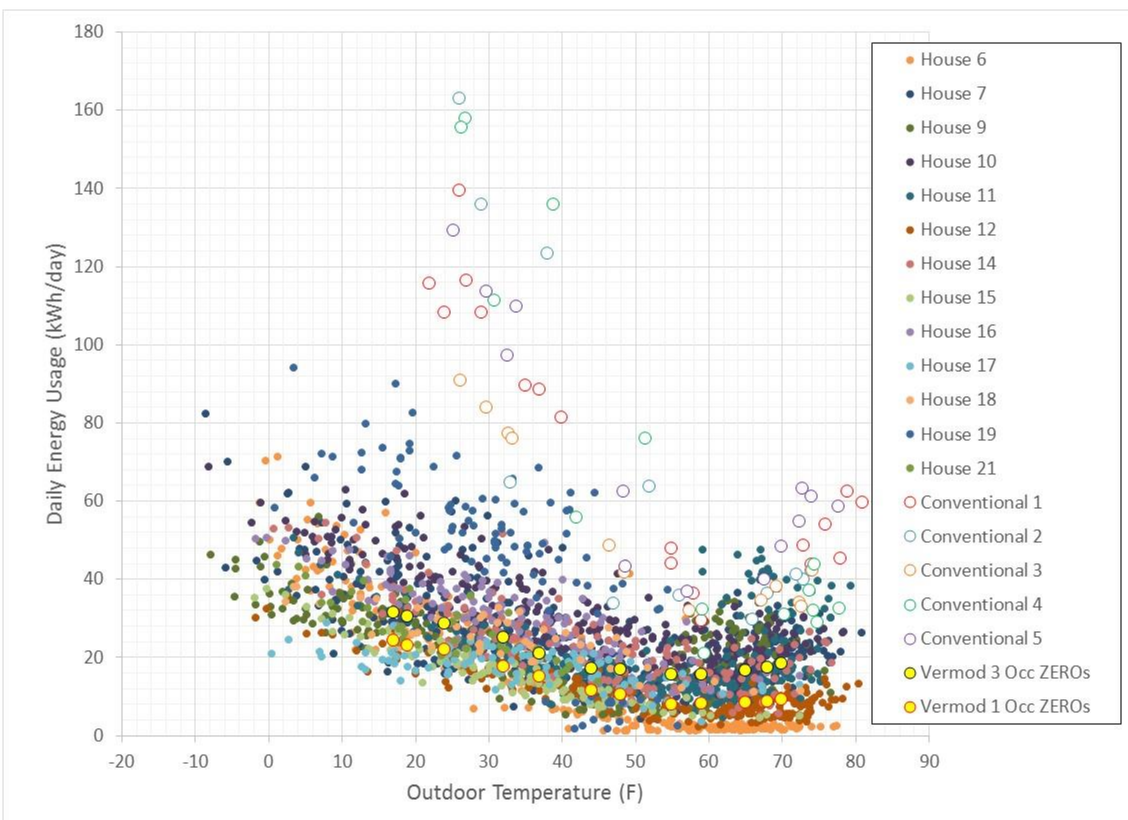


Figure 2 Energy data for 13 Vermod houses with ZEROs predictions for 1 occupant and 3 occupants.

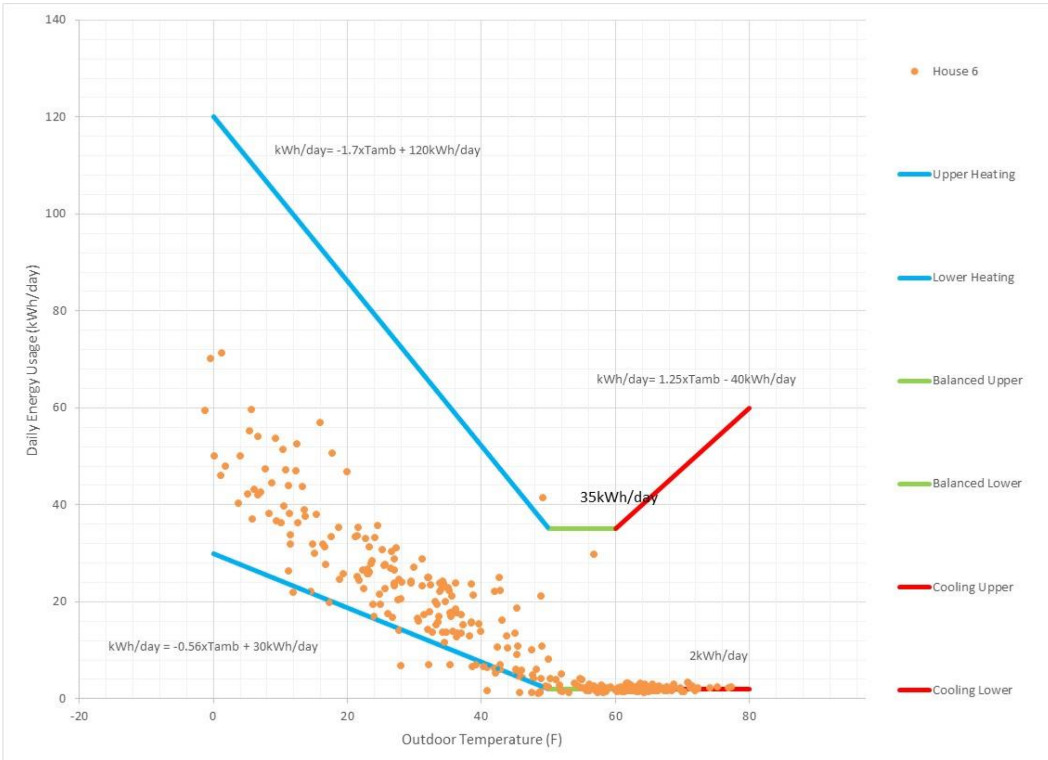


Figure 3 House 6 (Vermod) daily energy characteristics.

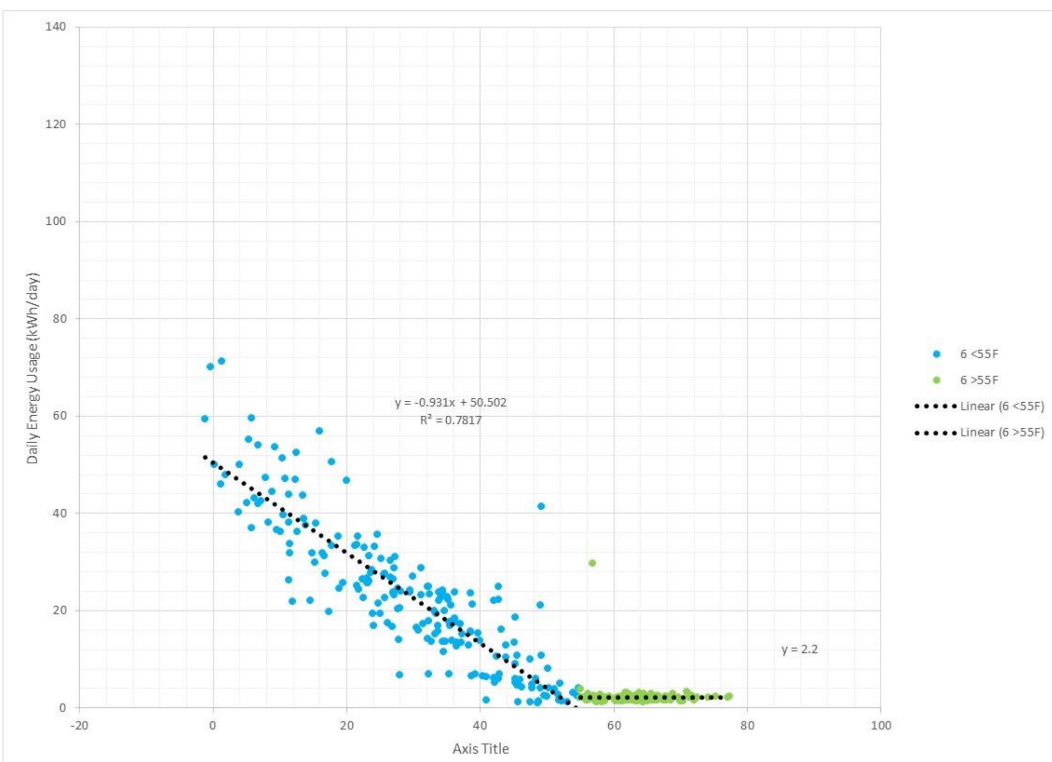


Figure 4 House 6 (Vermod) daily energy characteristics divided into regions.

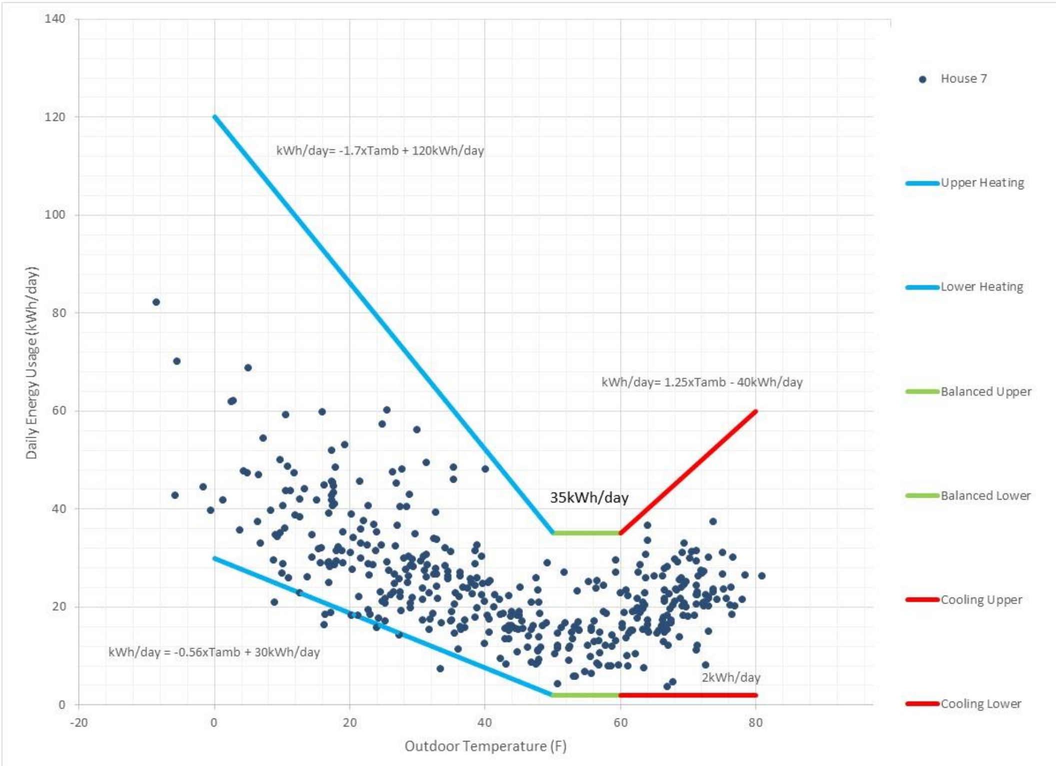


Figure 5 House 7 (Vermod) daily energy characteristics.

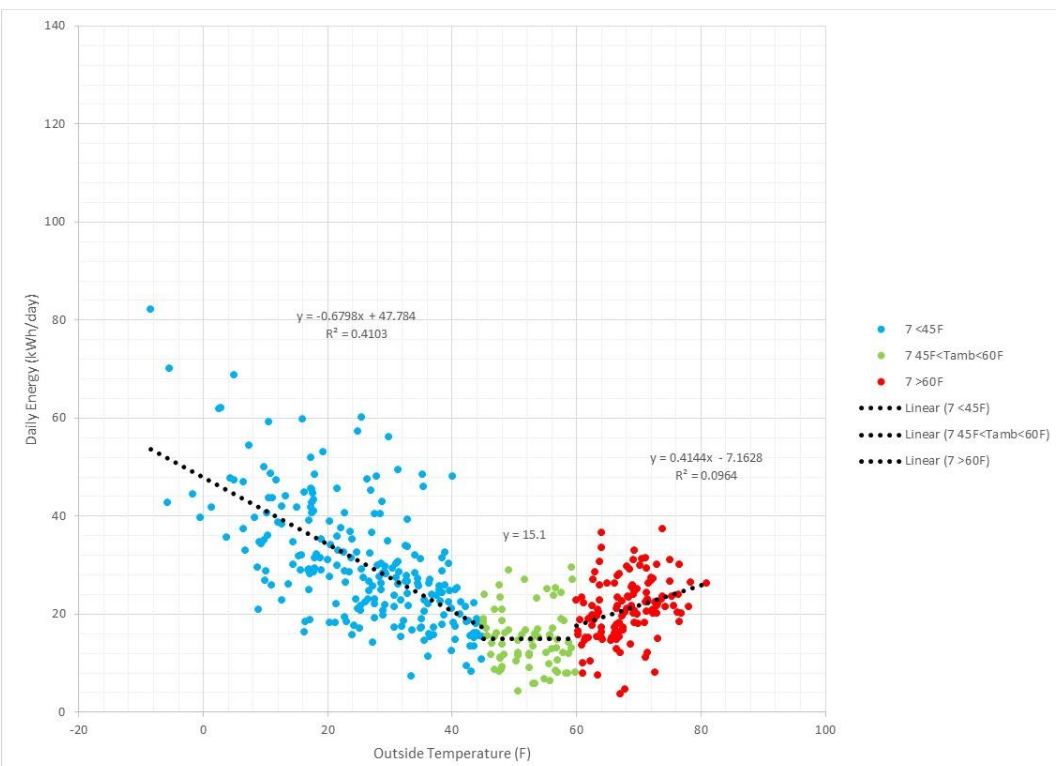


Figure 6 House 7 (Vermod) daily energy characteristics divided into regions.

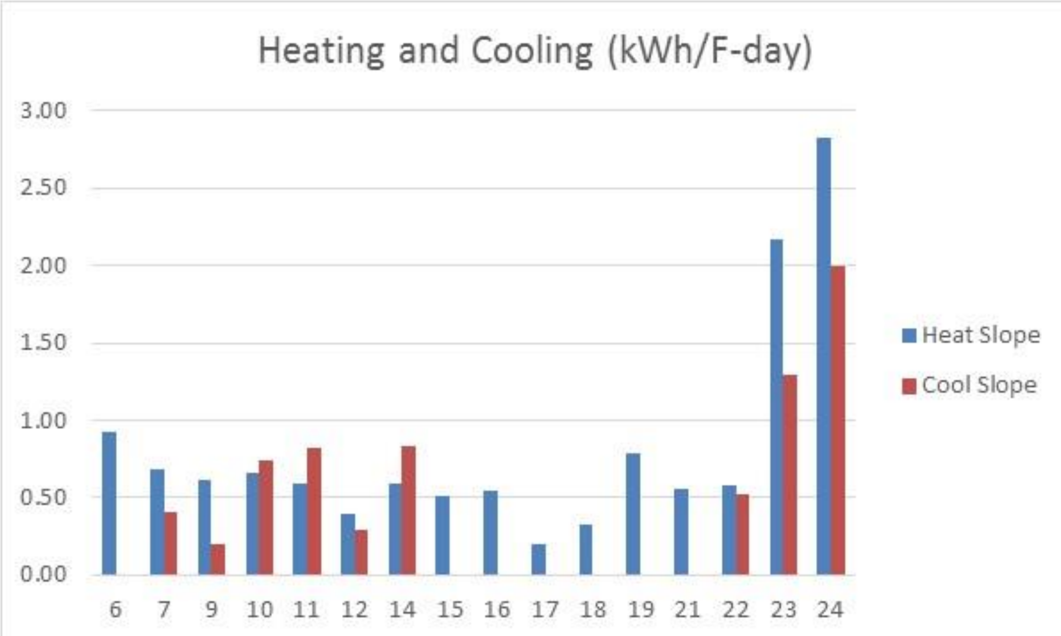


Figure 7 Heating and cooling slopes for study homes. Bars 23 and 24 are Conventional Homes 3 and 4 shown in Figure 2. Bar 22 is the average of thestudy homes.

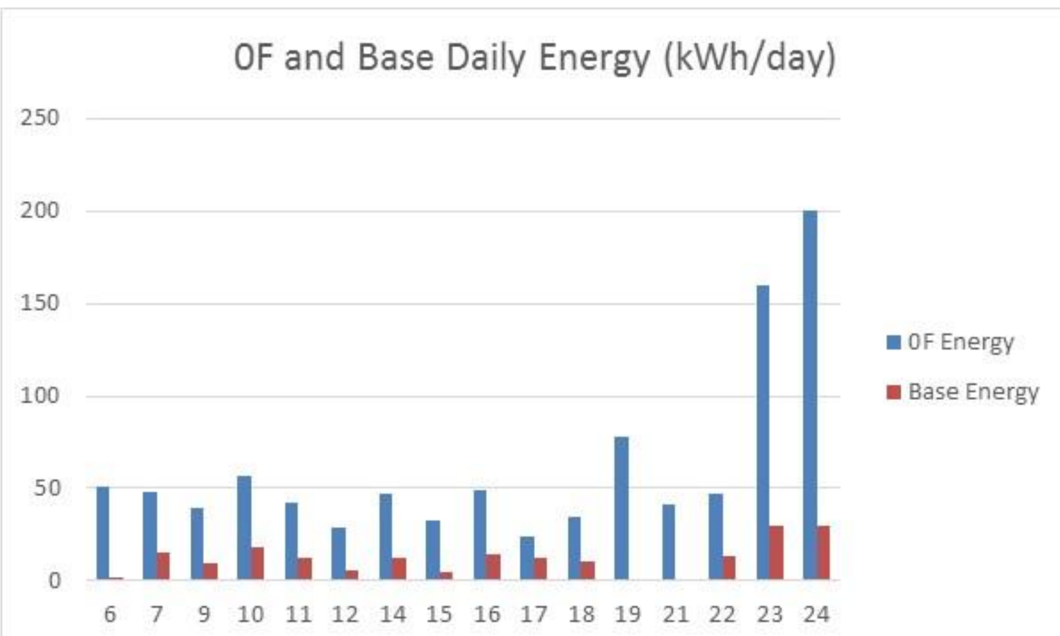


Figure 8 Average daily house energy at 0F and during baseload (swing season) period. Bars 23 and 24 are Conventional Houses 3 and 4 in Figure 2. Bar 22 is the average of the 21 study homes.

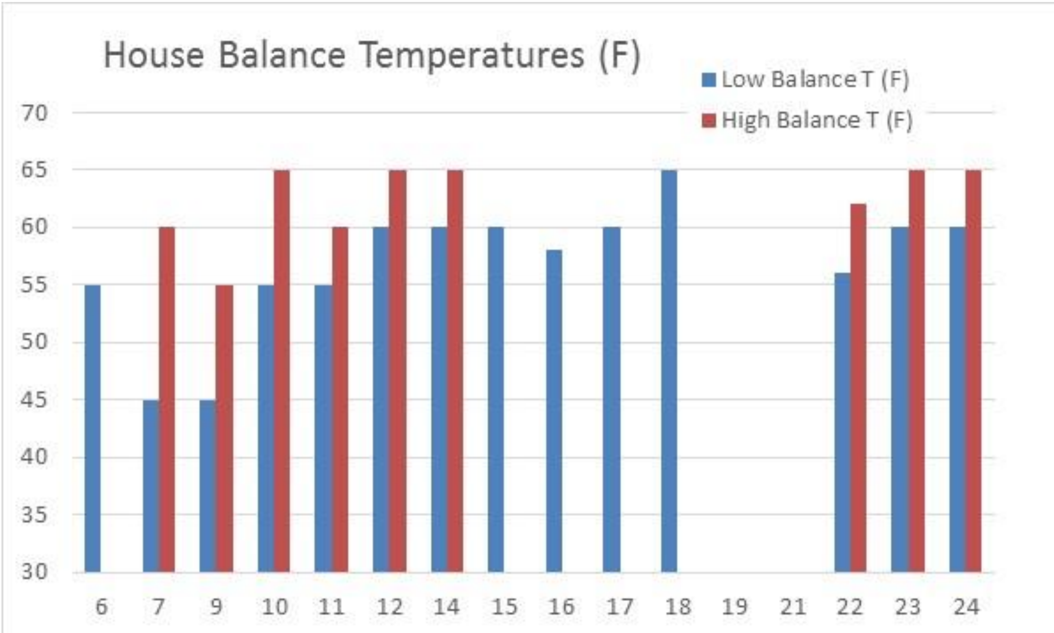


Figure 9 Low and high house balance (swing season) temperatures. Bars 23 and 24 are for Conventional Houses 3 and 4 in Figure 2. Houses 15-18 had not been in the study sufficiently long for high balance temperature. Houses 19-21 had not been in the sufficiently long for low and high balance temperatures. Bar 22 is the average of the 21 study homes.

Sub-System Energy

We investigate energy use on a fine scale in this section in order to understand where energy in the study homes is used. Tables 1 and 2 list daily average energy usage for each home. Table 1 lists the daily energy usage per house while Table 2 lists the daily energy per occupant. The data is averaged regardless of the time period, which in the case of homes with only a few winter months of data collection prior to this study, energy usage is skewed to winter usage. Also, even though there are undoubtedly seasonal variations, such as lighting or cooking that may be reduced with the longer, hotter days of summer, we ignore the seasonal variations because the overall energy consumption of these homes is quite small.

Figures 1 and 2 divide household energy use into three categories:

- Comfort conditioning
- Water heating
- Non-comfort conditioning

Comfort conditioning includes energy for the CERV fresh air ventilation system in addition to energy for the mini-split heat pump because the CERV contributes significantly to comfort conditioning in addition to providing fresh air. Water heating is a major energy use, however, as described in Appendix D, it is integrally connected to the Vermod-CERV home's heating and cooling loads. Non-comfort conditioning are all the other energy categories. Non-comfort energy categories are divided into:

- Miscellaneous (lighting and plug loads such as televisions, coffee makers, aquariums, etc)
- Cooking (stove/oven, microwave oven)
- Clothes Washing
- Clothes Drying
- Refrigerator
- Dishwasher

Figure 1 compares comfort conditioning, water heating and non-comfort conditioning average daily energy usage against the occupancy of each study home. Figure 2 compares comfort conditioning, water heating and non-comfort conditioning on an average daily energy usage "per occupant" against the occupancy of each study home. These two viewpoints allow us to determine the significance of occupants on each energy category.

In Figure 1, a least squares linear curve fit has been applied to each data set. Comfort is found to be relatively independent of the number of occupants, as evidenced by the very small slope (horizontal line). The variation of the comfort data is quite great. A smaller set of data could skew one's opinion quite markedly. On average, the study homes require 12.5kWh/day for comfort conditioning and fresh air ventilation.

Water heating and non-comfort conditioning energy usage both display a strong relation to occupancy as one would expect. Note that one house (House 9) was unoccupied during the course of the data collection. This house is a model home that is periodically visited by groups of people, but otherwise has insignificant uses of almost all non-comfort conditioning energy categories. Water heating energy for House 9 is primarily for standby losses, with 0.65kWh/day average, which is less than 30Watts continuous power draw.

Figure 2 illustrates that both non-comfort energy and water heating energy are linearly related to the number of occupants. While this is not surprising, other results could have occurred. For example, as occupants increase, non-comfort energy per occupant might have decreased. If television were an important factor (and it may be), and if only one television is in a home, one television can be watched by one or several people. On the other hand, multiple televisions are common in homes these days, and each occupant may have their own television (or computer), which increases this energy term in proportion to the occupancy. Water heating is also found to be relatively constant on an occupancy basis, indicating that each person's hot water usage is relatively constant. On average, our study homes used 1.2kWh/day-occupant for hot water.

In the United States, approximately 18 gallons of hot water per day per person is common, which requires 3kWh/day for heating 50F (10C) to 122F (50C) with a conventional electric water heater, whether tank or tankless. The study homes used "hybrid" or heat pump water heaters, which reduce electric energy required for heating water by 50% or more for homes in which the "eco mode" (heat pump only) is used. Because we do not have hot water consumption data, we are not able to definitively state that the low water heating energy usage is due to the heat pump water heaters. Instead, the low energy usage may be attributed to occupants using less than 18 gallons of hot water per day.

Energy used for comfort conditioning is not significantly affected by the number of occupants, as observed in Figure 1. From Figure 2, we see diminishing comfort energy usage on an occupancy basis. That is, as more people are added to a house, comfort conditioning energy is more economically utilized. Comfort energy drops below energy required for water heating and non-comfort conditioning between 2 and 3 occupants (the study average is 2.4 occupants per home, near the US national average). An exponential curve fit is included in Figure 2 because the drop in house comfort conditioning energy is not truly linear, but instead asymptotically decays toward zero energy per occupant as occupancy increases. House comfort conditioning energy is essentially a non-factor relative to occupancy related energy as occupancy increases beyond 6 to 8 people.

Figures 3 and 4 present the average daily energy usage for each sub-category for the non-comfort energy usage. As before, Figure 3 is the average daily energy usage versus the occupancy while Figure 4 is the average daily energy per person plotted against the occupancy. The six sub-categories listed for non-comfort conditioning energy are plotted in Figures 3 and 4. An additional sub-category listed in Tables 1 and 2 is "other", which is generally made up of heat tape and water well pumping. The energy usage for these is generally small.

Figure 3 shows us that only refrigerator energy is insensitive to occupancy, while all other sub-categories increase as occupancy increases. These trends make sense as more occupants result in more dishes, more laundry, more lights and plug loads. A refrigerator might show some occupancy dependency due to door openings, however, the amount of time a refrigerator door is open as well as its impact on refrigerator energy is apparently quite small. On average, the refrigerators used 0.97kWh/day or an average power draw of 40Watts. Average annual refrigerator energy usage is 350kWh per year, which indicates that most of the refrigerators are very efficient. Refrigerators used four times more energy two decades ago.

Occupancy effects are mostly linear for the other sub-categories as seen by the relatively flat (horizontal) lines in Figure 4. Miscellaneous energy loads (television, lights, plug loads, etc) increases at

0.2kWh/day per occupant basis. The reason for this trend is not clear, however, it may be some bias in the data or a higher order occupancy effect. The effect is not as significant as the basic occupancy effect on miscellaneous energy usage. With 2 occupants, for example, twice as much of the miscellaneous sub-category energy usage per occupant is from the constant term of the Figure 4 best fit line rather than the higher order (slope) occupancy effect. The other energy sub-categories in Figure 4 are relatively flat, indicating linear occupancy effects. Cooking and clothes drying are the most significant energy uses after the miscellaneous energy sub-category. Dishwashing and clothes washing are the least significant energy uses. Note that hot water for dishwashing and clothes washing are not included in the energy terms for dishwashing and clothes washing.

Figures 5 through 14 display the house energy usage for all study homes for each of the categories listed in Table 1. Bar 22 in Figures 5-14 represents the average daily energy use for the study homes. Figure 15 is a bar chart showing the total daily average energy usage for the study homes. Bar 22 shows the average daily energy usage for this collection of homes is a very low 24kWh/day.

Figure 16 divides Table 1 data into comfort and non-comfort energy amounts. Comfort energy in Figure 16 is the sum of comfort conditioning (eg, mini-split heat pump) and ventilation (CERV) energy. Non-comfort energy in Figure 16 is all other energy (including water heating energy). From Figure 16, it is very clear that occupant behavior is as significant as energy related to climate. On average, as shown with bar 22 (average of 21 home data), household energy is split nearly 50/50 with 12kWh/day due to comfort and 12kWh/day due to non-comfort energy usage activities.

Table 1 Vermod-CERV House Average Daily Energy Data (kWh/day)

House	Occupants	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other	Total	NonComf	TotComf
6	4	3.78	0.06	0.67	0.00	0.01	0.15	0.40	7.75	10.63	0.00	23.46	5.08	18.38
7	1.5	3.86	0.99	1.16	0.07	0.08	1.52	4.14	7.40	8.13	0.00	27.34	11.81	15.53
9	0	0.38	0.00	0.58	0.00	0.00	0.01	0.65	6.75	5.97	0.00	14.34	1.62	12.72
10	5	7.08	1.77	0.86	0.29	0.00	3.24	4.69	7.19	6.11	0.12	31.35	18.05	13.30
11	1	5.84	0.45	0.75	0.06	0.04	0.54	1.11	5.33	4.97	0.00	19.08	8.78	10.30
12	1	4.46	1.08	0.76	0.35	0.07	0.97	1.43	5.34	3.26	0.00	17.72	9.13	8.60
14	4	6.33	1.39	0.81	0.00	0.16	2.54	2.47	5.39	4.06	1.28	24.44	14.98	9.45
15	1	3.41	0.51	0.79	0.00	0.03	0.02	0.80	2.69	6.20	0.02	14.48	5.58	8.90
16	1	3.82	2.00	0.81	0.54	0.22	4.00	3.47	7.41	6.84	1.13	30.25	16.00	14.25
17	1	3.95	0.06	0.60	0.00	0.01	0.00	0.73	6.34	2.44	0.24	14.38	5.59	8.78
18	4	3.36	1.81	0.73	0.59	0.17	2.39	2.03	9.62	2.91	0.08	23.69	11.17	12.52
19	5	5.23	8.37	1.34	0.67	0.20	2.67	7.25	6.82	13.15	0.02	45.74	25.77	19.97
21	2	2.72	0.40	0.84	0.24	0.04	0.49	1.59	9.59	14.96	0.29	31.16	6.62	24.55
Average		4.17	1.45	0.82	0.22	0.08	1.43	2.37	6.74	6.89	0.25	24.42	10.78	13.63

Table 2 Vermod-CERV House Average Daily Energy Data (kWh/day) per Occupant

House	Occupants	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other	Total	NonComf	TotComf
6	4	0.94	0.02	0.17	0.00	0.00	0.04	0.10	1.94	2.66	0.00	5.86	1.27	4.59
7	1.5	2.57	0.66	0.77	0.05	0.05	1.01	2.76	4.93	5.42	0.00	18.23	7.87	10.35
9	1	0.38	0.00	0.58	0.00	0.00	0.01	0.65	6.75	5.97	0.00	14.34	1.62	12.72
10	5	1.42	0.35	0.17	0.06	0.00	0.65	0.94	1.44	1.22	0.02	6.27	3.61	2.66
11	1	5.84	0.45	0.75	0.06	0.04	0.54	1.11	5.33	4.97	0.00	19.08	8.78	10.30
12	1	4.46	1.08	0.76	0.35	0.07	0.97	1.43	5.34	3.26	0.00	17.72	9.13	8.60
14	4	1.58	0.35	0.20	0.00	0.04	0.64	0.62	1.35	1.02	0.32	6.11	3.75	2.36
15	1	3.41	0.51	0.79	0.00	0.03	0.02	0.80	2.69	6.20	0.02	14.48	5.58	8.90
16	1	3.82	2.00	0.81	0.54	0.22	4.00	3.47	7.41	6.84	1.13	30.25	16.00	14.25
17	1	3.95	0.06	0.60	0.00	0.01	0.00	0.73	6.34	2.44	0.24	14.38	5.59	8.78
18	4	0.84	0.45	0.18	0.15	0.04	0.60	0.51	2.40	0.73	0.02	5.92	2.79	3.13
19	5	1.05	1.67	0.27	0.13	0.04	0.53	1.45	1.36	2.63	0.00	9.15	5.15	3.99
21	2	1.36	0.20	0.42	0.12	0.02	0.24	0.79	4.79	7.48	0.15	15.58	3.31	12.27
Average	2.42	1.72	0.60	0.34	0.09	0.03	0.59	0.98	2.78	2.85	0.10	10.08	4.45	5.63

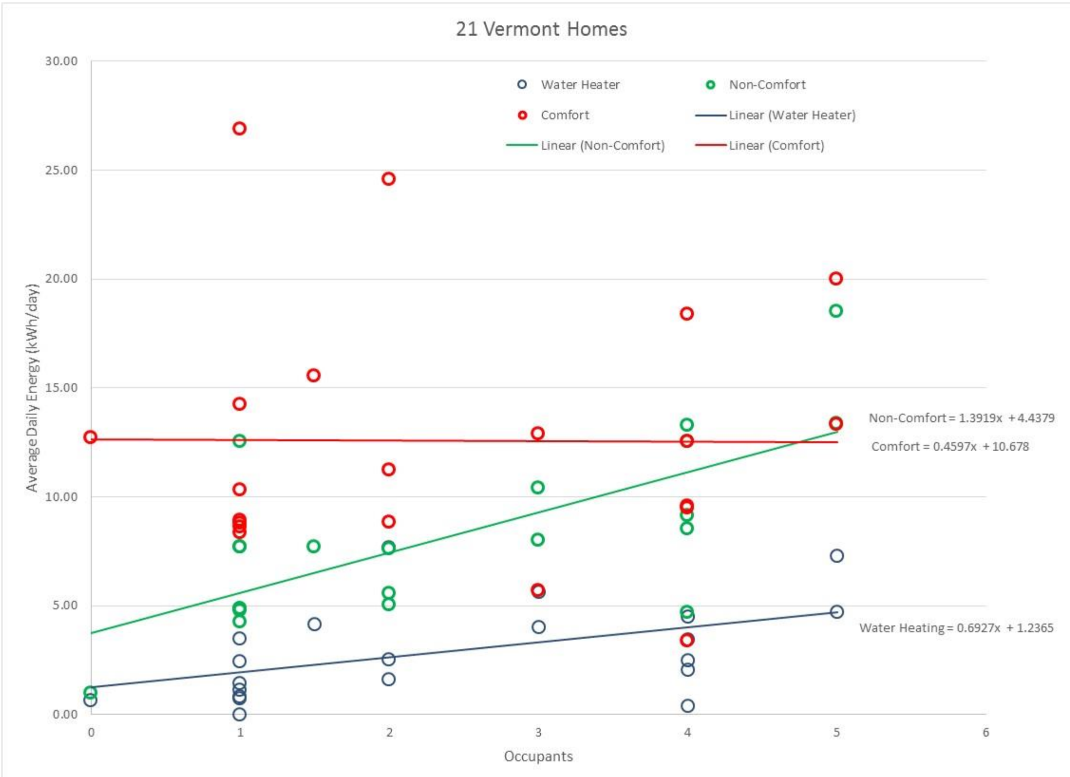


Figure 1 Average daily energy for Comfort, Non-Comfort and Water Heating.

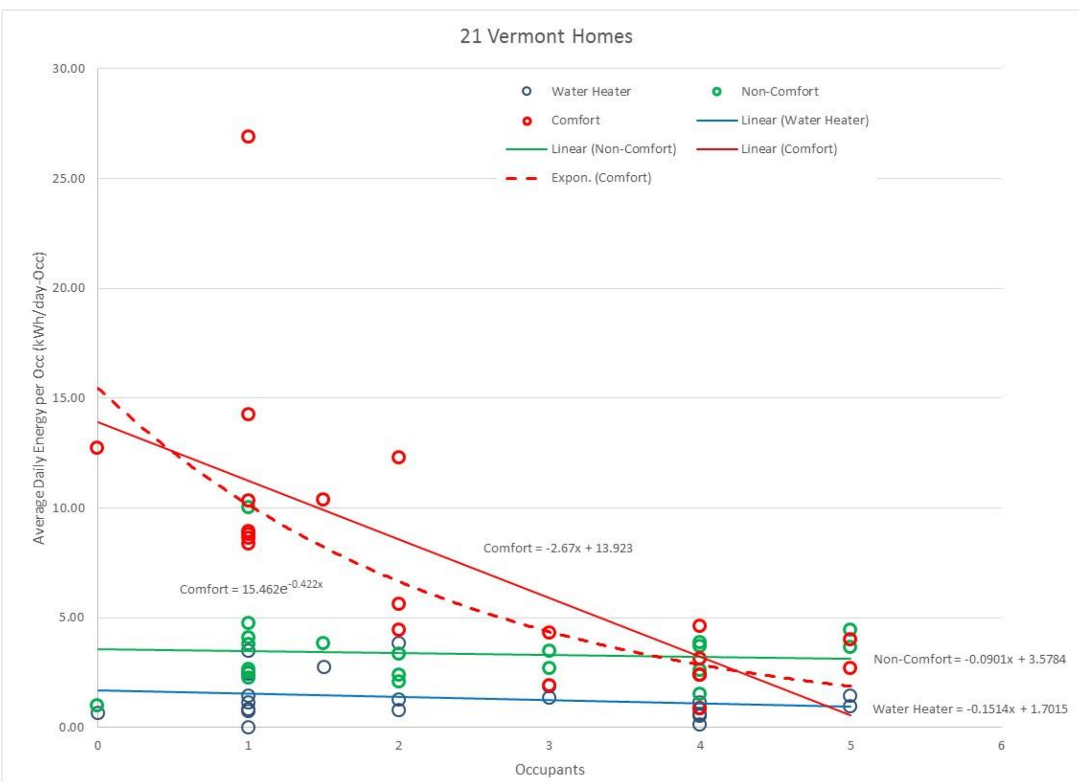


Figure 2 Average daily energy per Occupant for Comfort, Non-Comfort and Water Heating.

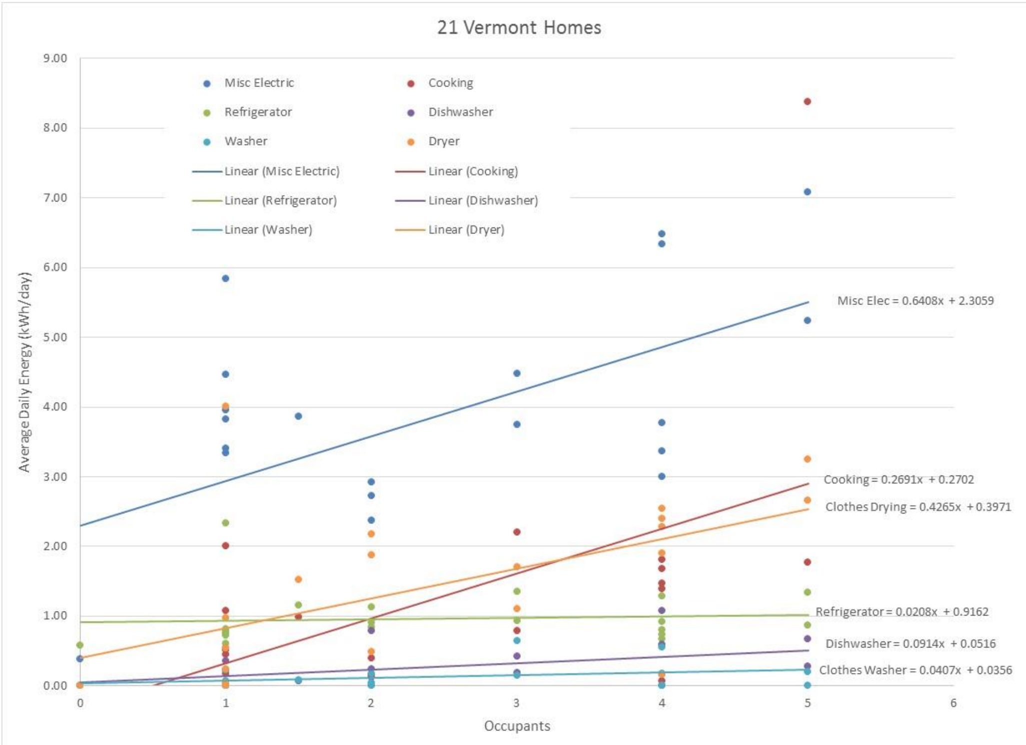


Figure 3 Average daily energy for Non-Comfort energy usage.

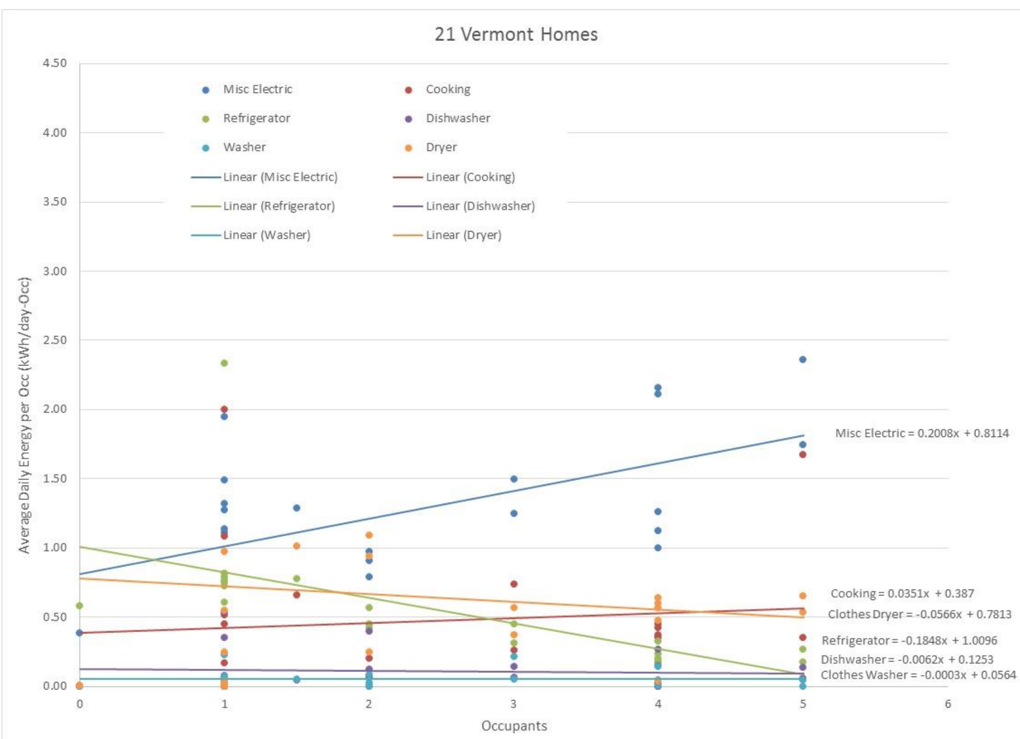


Figure 4 Average daily energy per Occupant for Non-Comfort energy usage.

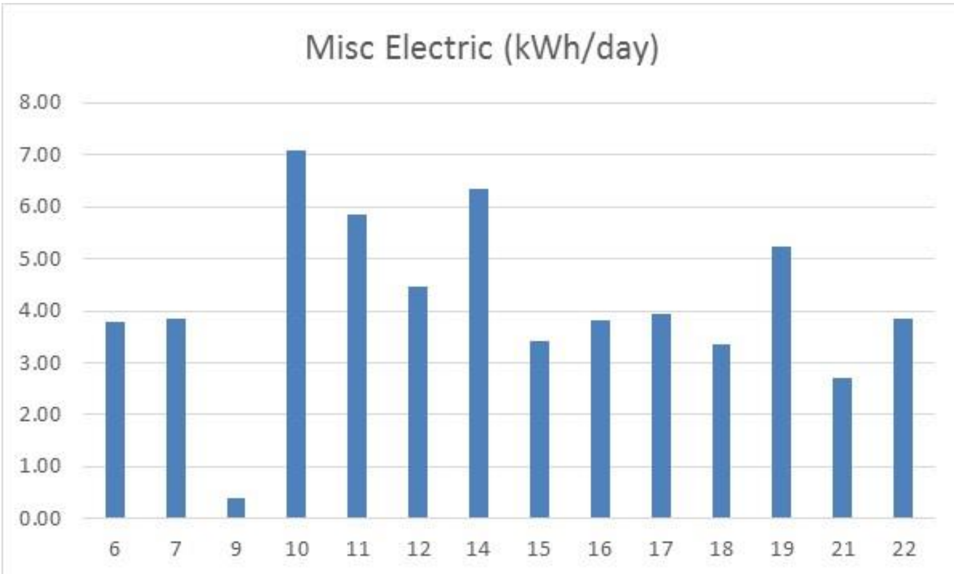


Figure 5 Miscellaneous electric energy usage for each study house (bar 22 = average).

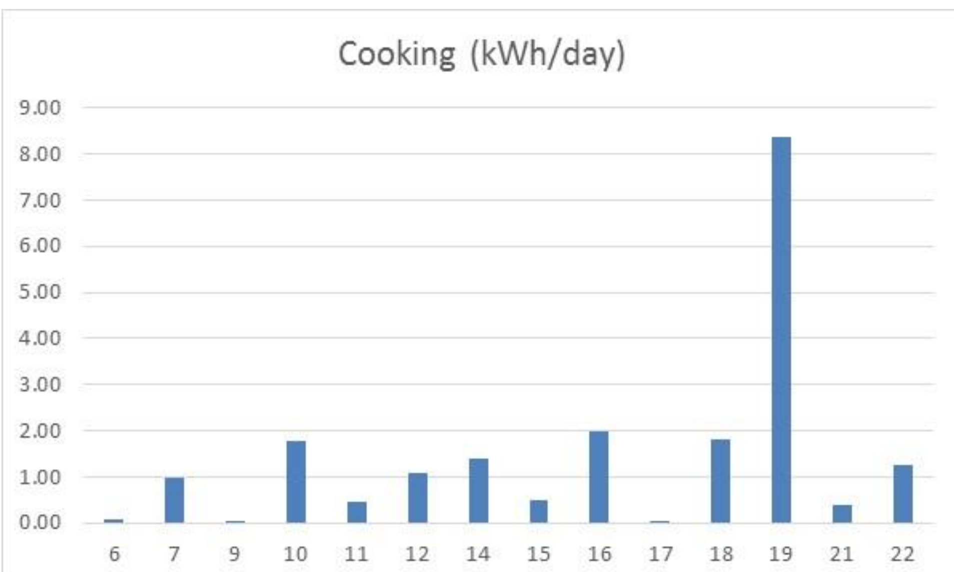


Figure 6 Cooking electric energy usage for each study house (bar 22 = average).

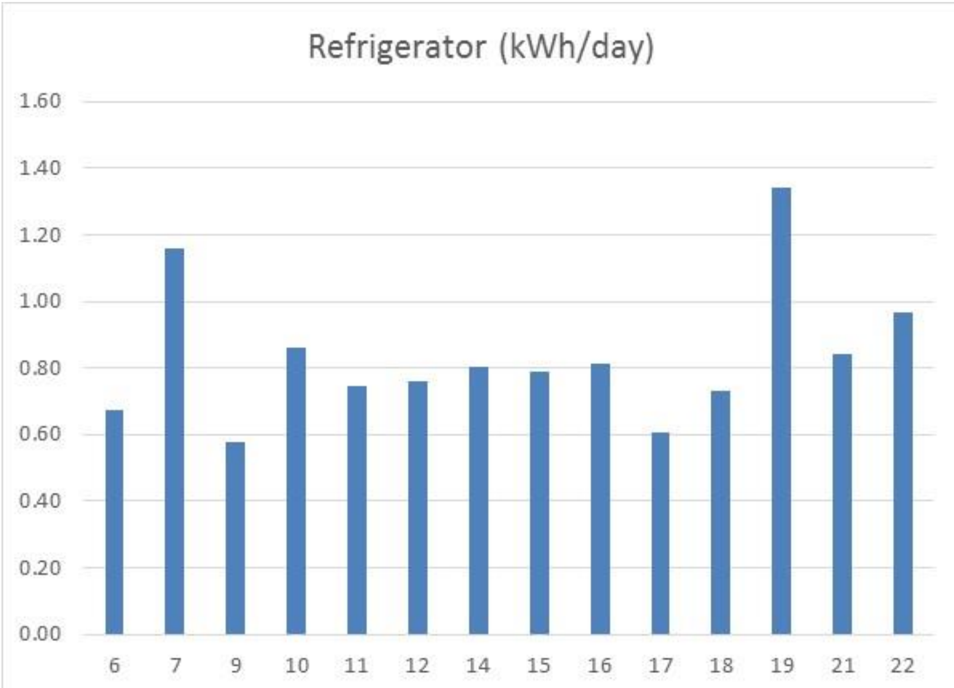


Figure 7 Refrigerator electric energy usage for each study house (bar 22 = average).

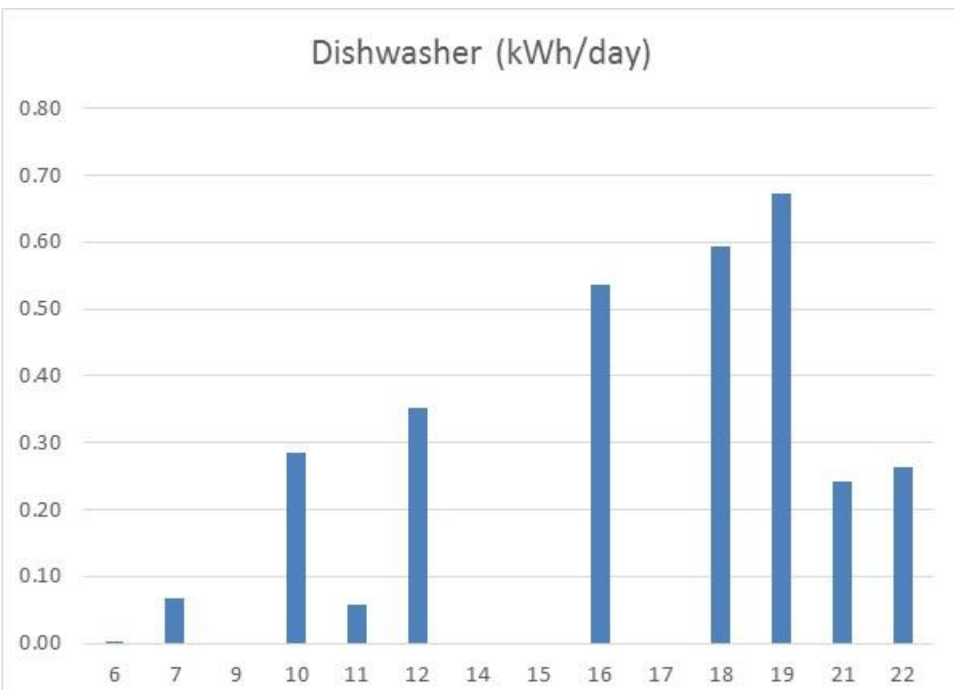


Figure 8 Dishwasher electric energy usage for each study house (bar 22 = average).

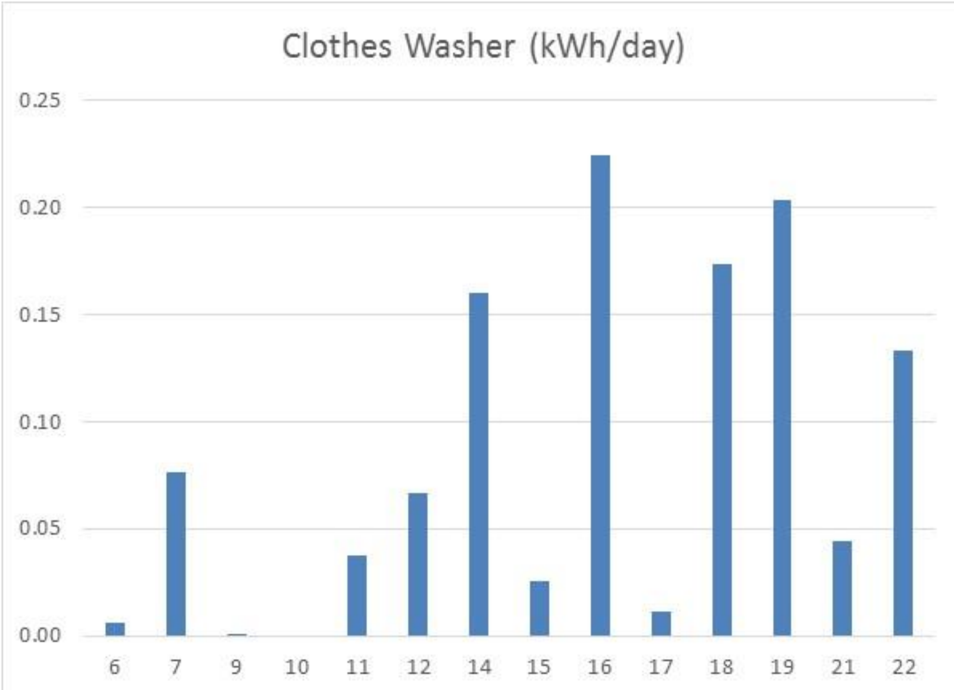


Figure 9 Clothes washer electric energy usage for each study house (bar 22 = average).

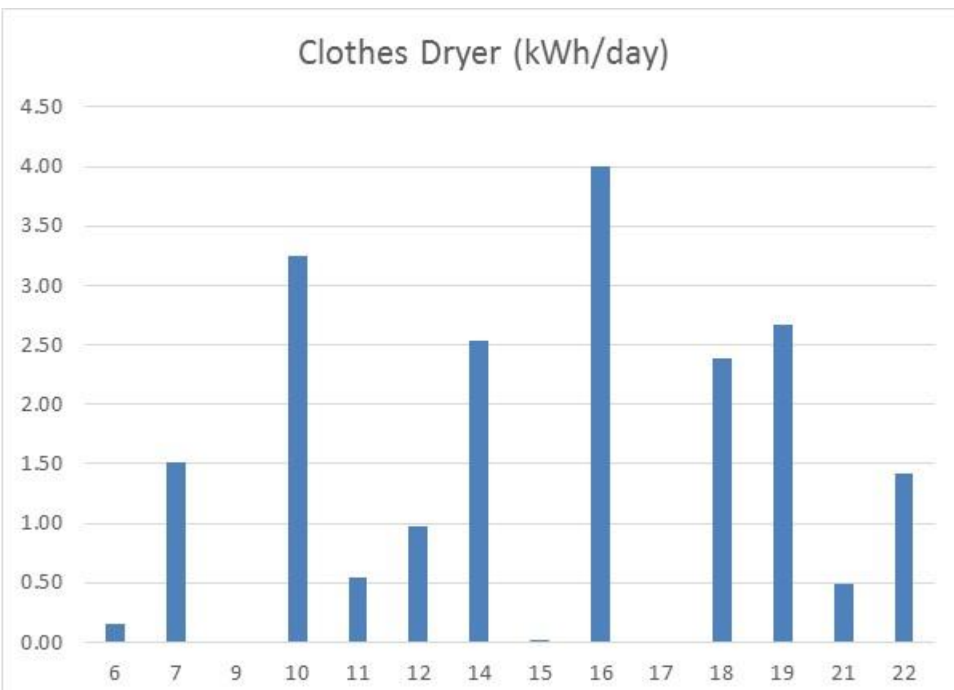


Figure 10 Clothes Dryer electric energy usage for each study house (bar 22 = average).

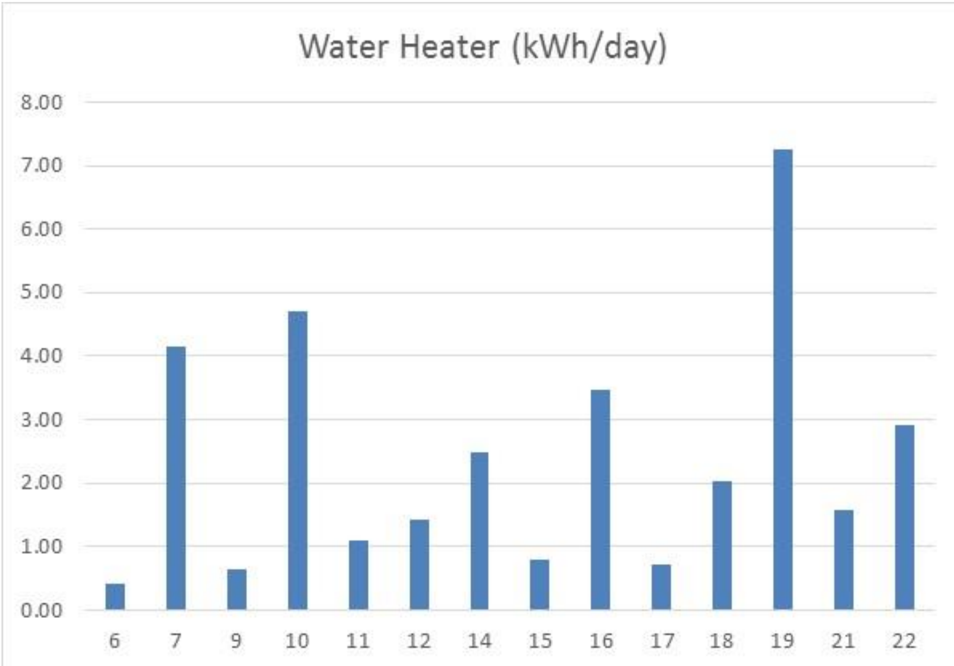


Figure 11 Water Heater electric energy usage for each study house (bar 22 = average).

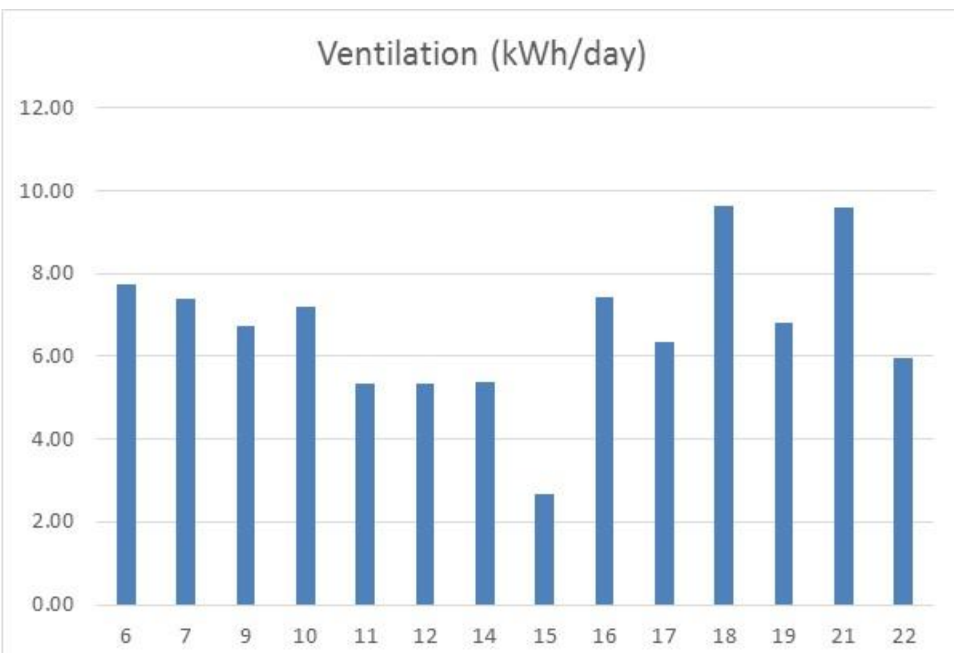


Figure 12 Ventilation electric energy usage for each study house (bar 22 = average).

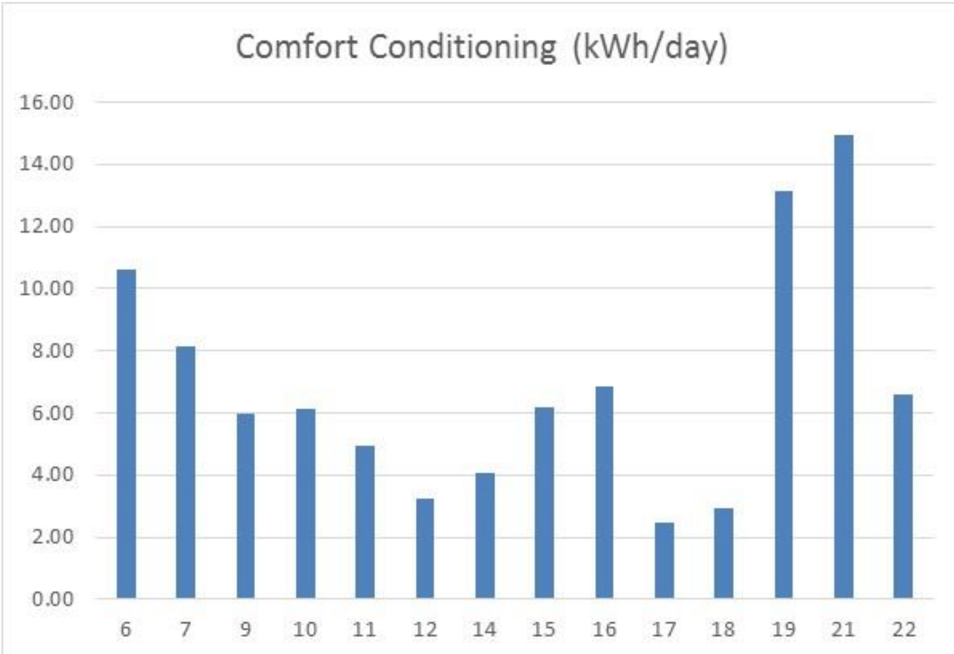


Figure 13 Comfort Conditioning electric energy usage for each study house (bar 22 = average).

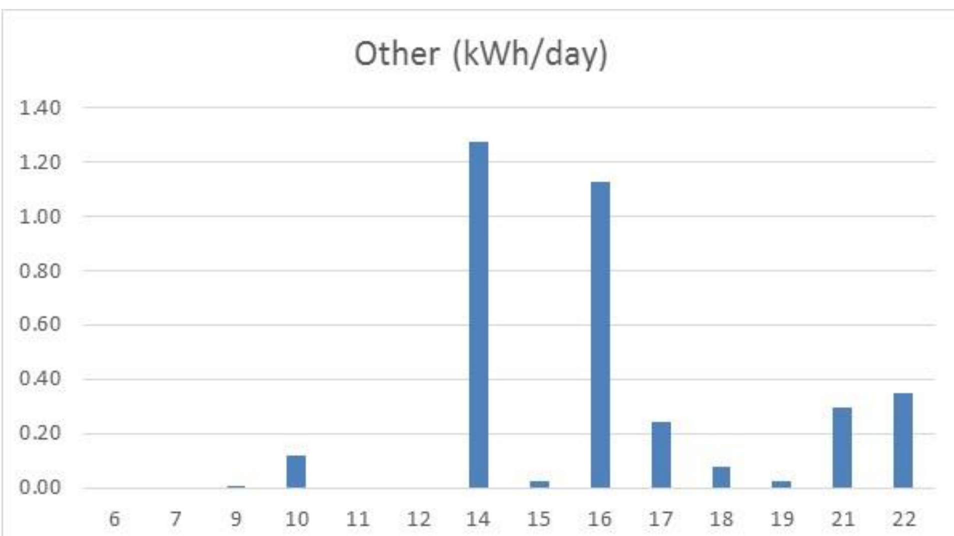


Figure 14 Other electric energy usage for each study house (bar 22 = average).

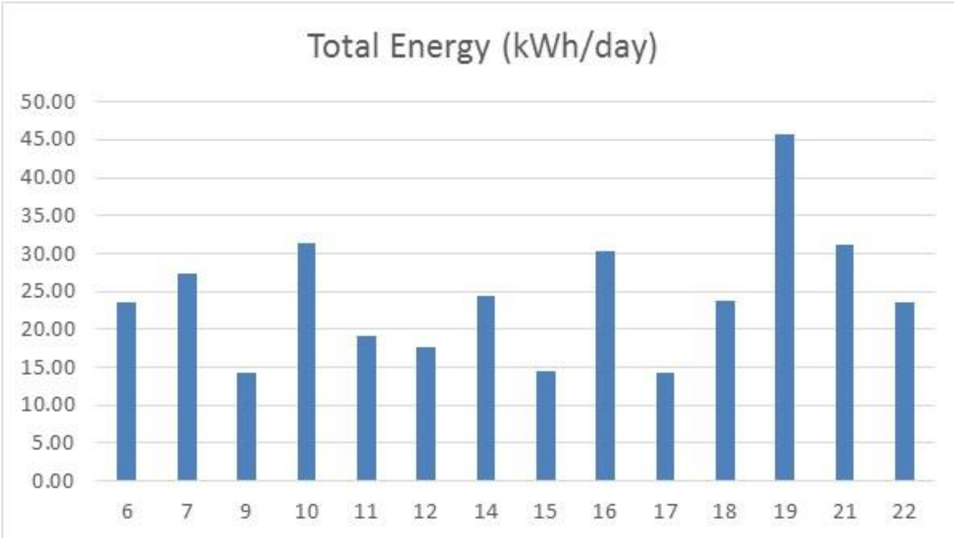


Figure 15 Total electric energy usage for each study house (bar 22 = average).

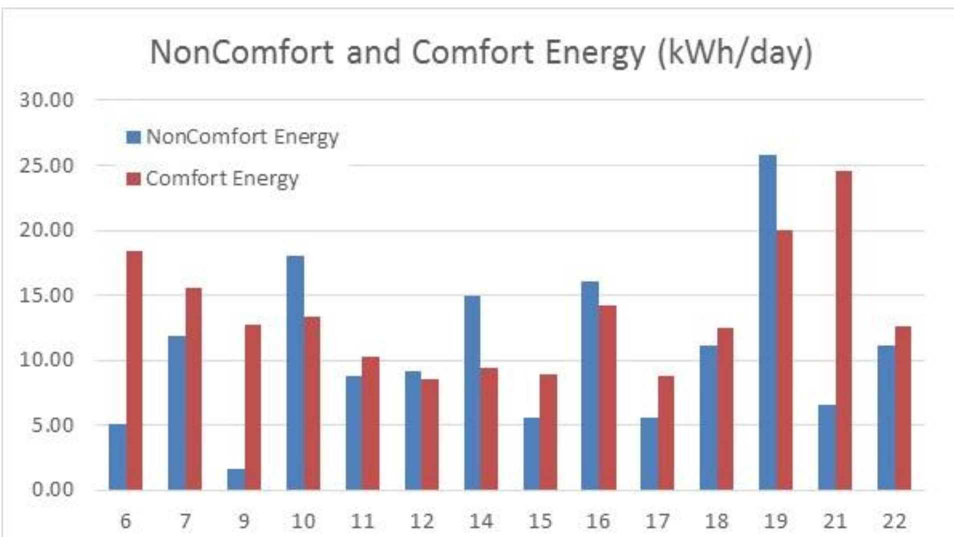


Figure 16 Comfort (total of comfort conditioning and ventilation) electric energy usage and non-comfort (all other energy including water heating) electric energy usage for each study house (bar 22 = average).

Conclusions

The Vermod-CERV house energy and air quality monitoring program has produced an extremely valuable and remarkable set of data that clearly illustrates many important results:

1) Properly insulating and sealing homes effectively reduces energy consumption relative to today's conventional home construction.
2) Air quality can be maintained at excellent levels in combination with maintaining comfort in an energy efficient manner.
3) Comfort can be maintained at occupant desired levels throughout the year.
4) Occupant behavior is as significant as climate related energy in high performance homes in challenging (Vermont) climates.

Although further reduction in energy usage is possible, continued reductions in Vermod-CERV house energy by further insulating and sealing beyond the levels used in the study homes is not economically efficient. With an average house daily energy usage of 12kWh/day (4400kWh/year) for climatic effects, the associated energy cost does not have much potential for further savings. For example, approximately 1/3 of the climatic energy cost is due to wall and roof insulation. If the wall and roof insulation levels are doubled from 12 inches to 24 inches, at a cost of $15,000 (assuming $5/cuft for insulation with R3 per inch and 3000sqft of wall and roof area), the climatic energy would be reduced to 10kWh/day. The 2kWh/day savings is worth $75 per year for a 200 year payback. Installed solar PV system cost is dropping below $3/Watt ($1/W for solar panels, $0.5/W for inverters, and $1.5/W for installation labor and balance of system components), a 5000W solar array could be purchased for $15,000 instead of increased insulation. The energy production of the solar PV array would be nearly 6000kWh per year for an annual energy value of $720 (assuming 12 cents/kWh electricity displace), or more than 10 times the potential savings of additional insulation.

And finally, as discussed at the beginning of this report, designing a healthy, comfortable home has potential energy savings that outweigh further savings from any of the energy related categories. For a family of 3, an uncomfortable home can easily reduce occupant productivity by 10% at a cost that is more than 10 times the total cost of energy for the home. A child who cannot effectively concentrate and study due to discomfort will have a future cost on society. A person who cannot easily breathe because of respiratory sensitivities cannot be productive. Increased sick days due to poor air and discomfort have similar economic consequences. We can reverse these impacts while decreasing our energy needs, and realize savings and increased value by utilizing the design and quality construction practices of the Vermod-CERV homes.

Appendices

Appendix A – Generalized Fractional Time Indoor Air Pollution Plot

Field IAQ data collected by Build Equinox from approximately 40 homes and commercial businesses indicated poor air quality (defined as average air quality greater than 1000ppm of carbon dioxide or VOCs) exists in 25% of the buildings. Our field studies show that "fractional time functions" can be defined that describe the time distribution of a building's pollutant levels in relation to the building's average air exchange rate. We divide CO2 and VOC pollutants into three bands:

1) Fraction of time pollutants (CO2 and VOC) are less than 1000ppm (Good)
2) Fraction of time pollutants are between 1000ppm and 2000ppm (Satisfactory)
3) Fraction of time pollutants are greater than 2000ppm (Unsatisfactory)

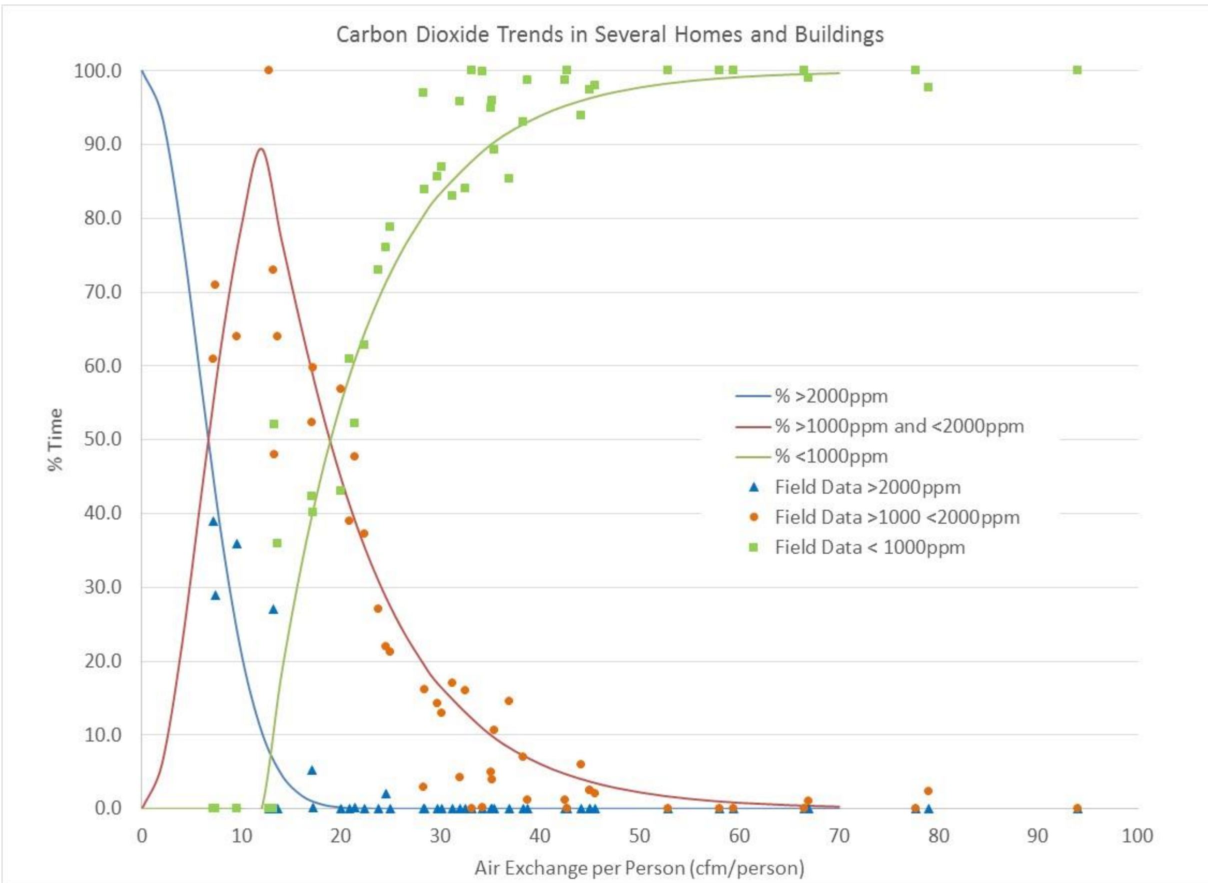
The figure below shows field data for CO2 in the study buildings plotted in the above terms. Mathematical relations have been developed that describe these trends, and are plotted as well. The fraction of time spent at different levels of pollution is related to the air flow exchange rate (ventilation plus infiltration) per person.

A "person" is a convenient unit of pollutant generation determined from analysis algorithms developed by Build Equinox. For example, a gas burner on a stove will produce CO2 at a level equivalent to 5 or 6 people. Cooking odors, perfumes, cleansers, furnishing off-gassing may contribute to VOC generation rates that are several times that of actual occupant metabolic VOC generation. If a human occupant is the only source of indoor air pollutants, and if they never leave the residence, then the air flow per person value from the experimental monitoring would be similar to the actual air flow per occupant. A person who is out of the house for 12 hours per day would be equivalent to "half a person" of pollutant generation (either CO2 or VOCs).

In the attached plot, at an air flow rate of 20 cfm/person, the building is between 1000 and 2000ppm for 50% of the time, and less than 1000ppm for the other 50% of the time. There is negligible time when the indoor air has pollutant levels above 2000ppm. This is an average indoor pollutant level of 1000ppm, which is the approximate target level for indoor air quality level based on ASHRAE ventilation standards (ASHRAE target = 700ppm + outside air level ~1100ppm). At 1000ppm, approximately 80% of the population are satisfied with the air quality.

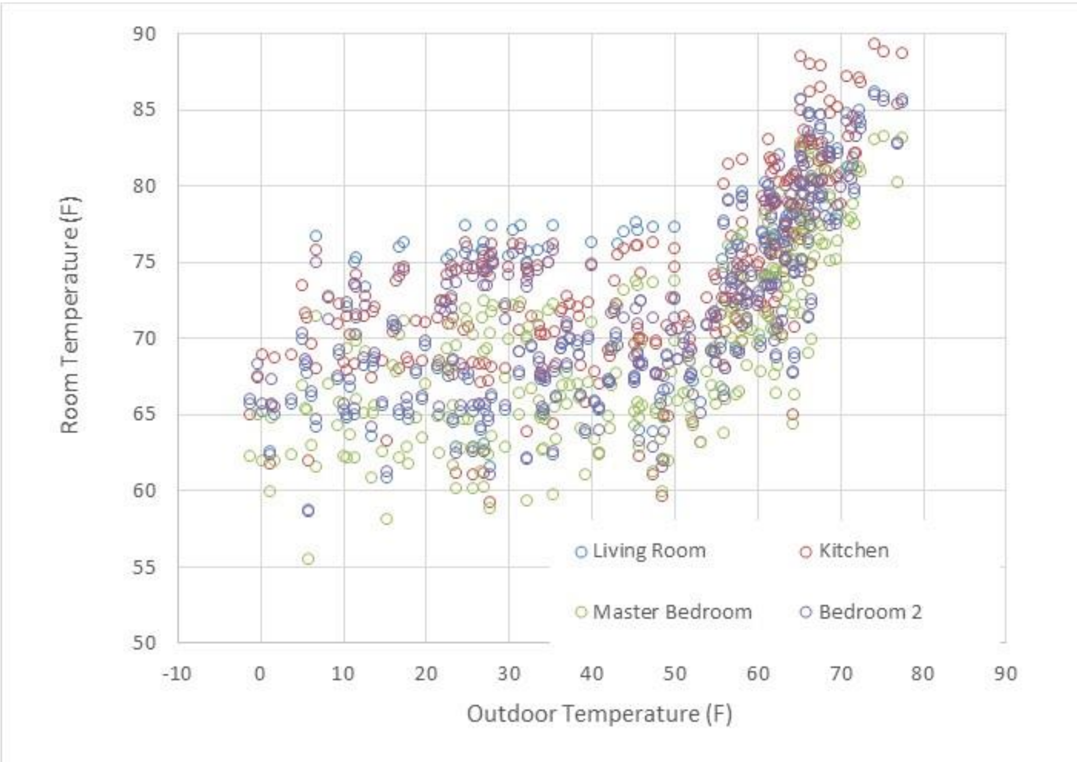
The change of air quality is very sensitive to air flow. For example, a house with a ventilation system operating at 40cfm with two occupants of pollutant generation rates (20cfm/person) would be reduced to 10cfm/person with the addition of two more occupant pollutant generators. At 10cfm/person, indoor air is never below 1000ppm. 70% of the time is spent in air that is satisfactory (1000 to 2000ppm) and 30% of the time is spent in air that is unsatisfactory (pollutants greater than 2000ppm).

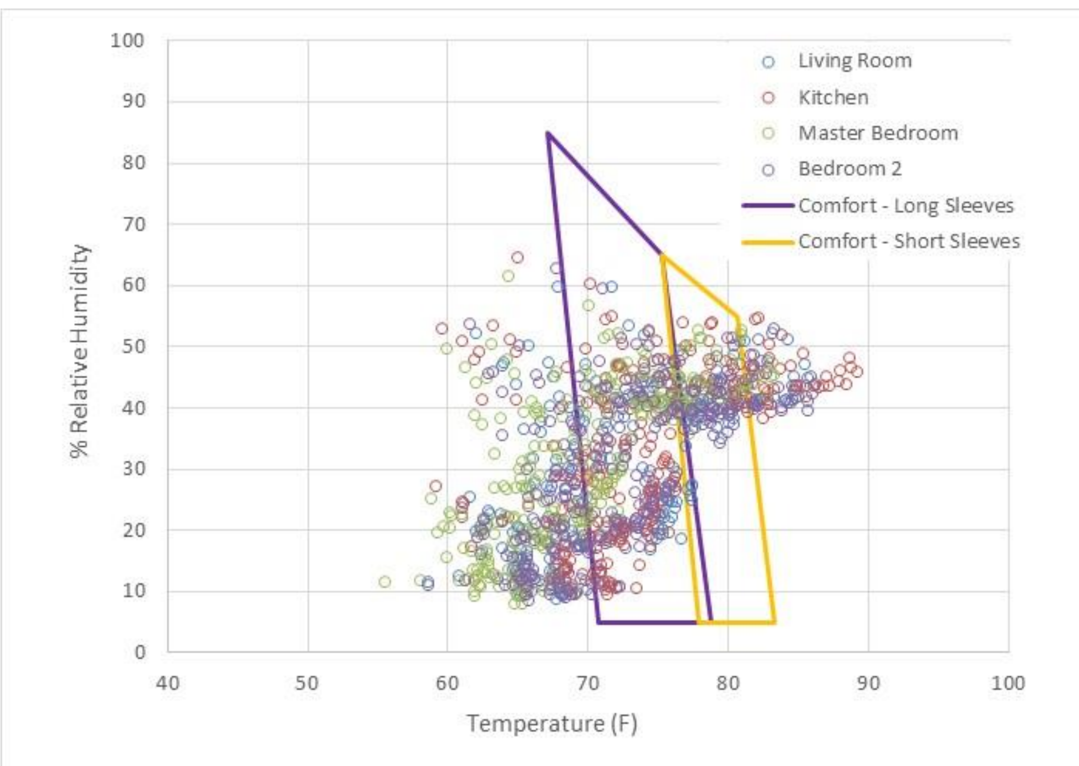
The fractional time characteristic curves are not "physical laws", but instead are simply correlation characteristics reflective of how people occupy and pollute their indoor environment. We can envision a home where periodically, someone might instantaneously have very high pollutant levels (eg, using model airplane cement or spraying some cleanser) followed by a high ventilation period to flush the pollutant out, and the rest of the time spent at relatively low pollutant levels. One could have a situation where 50% of the time is at high pollutant levels (greater than 2000ppm) and 50% is at low pollutant levels (less than 1000ppm) with insignificant time in between the two extremes. The characteristic indoor air pollutant curves do not allow for this situation. Our indoor environmental research, however, does not indicate such occurrences are common in most homes and buildings.



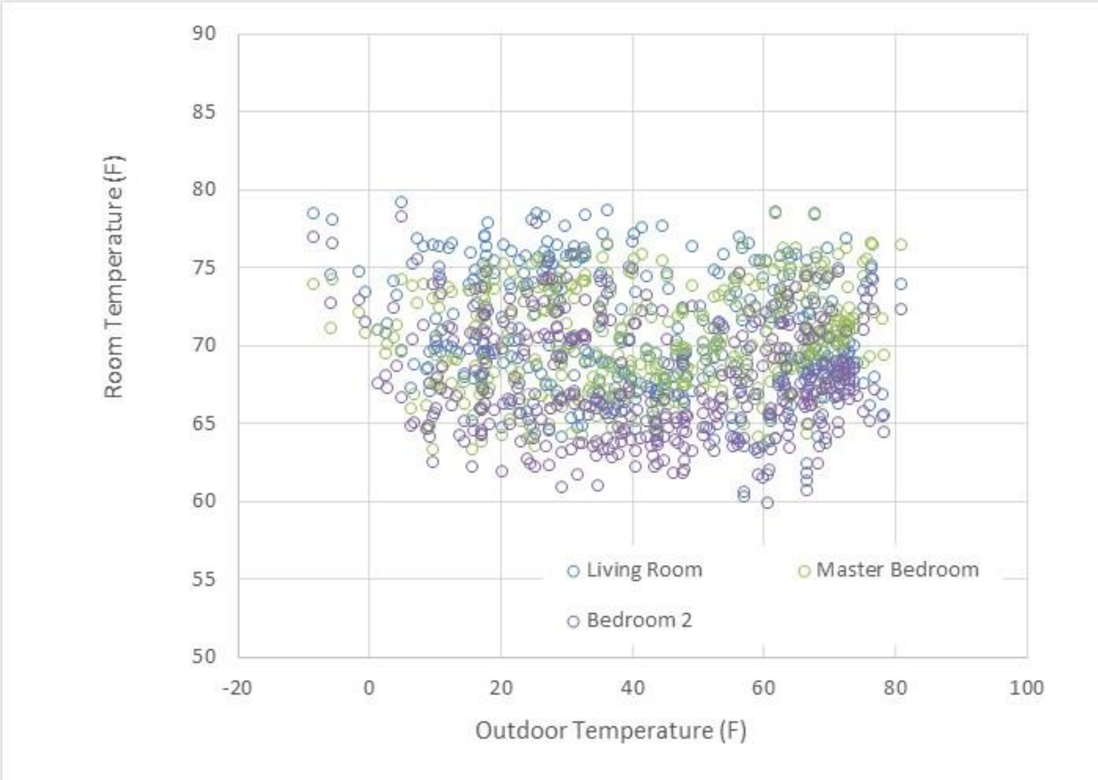
Appendix B – Seasonal Indoor Temperature and Comfort Charts

House 6:

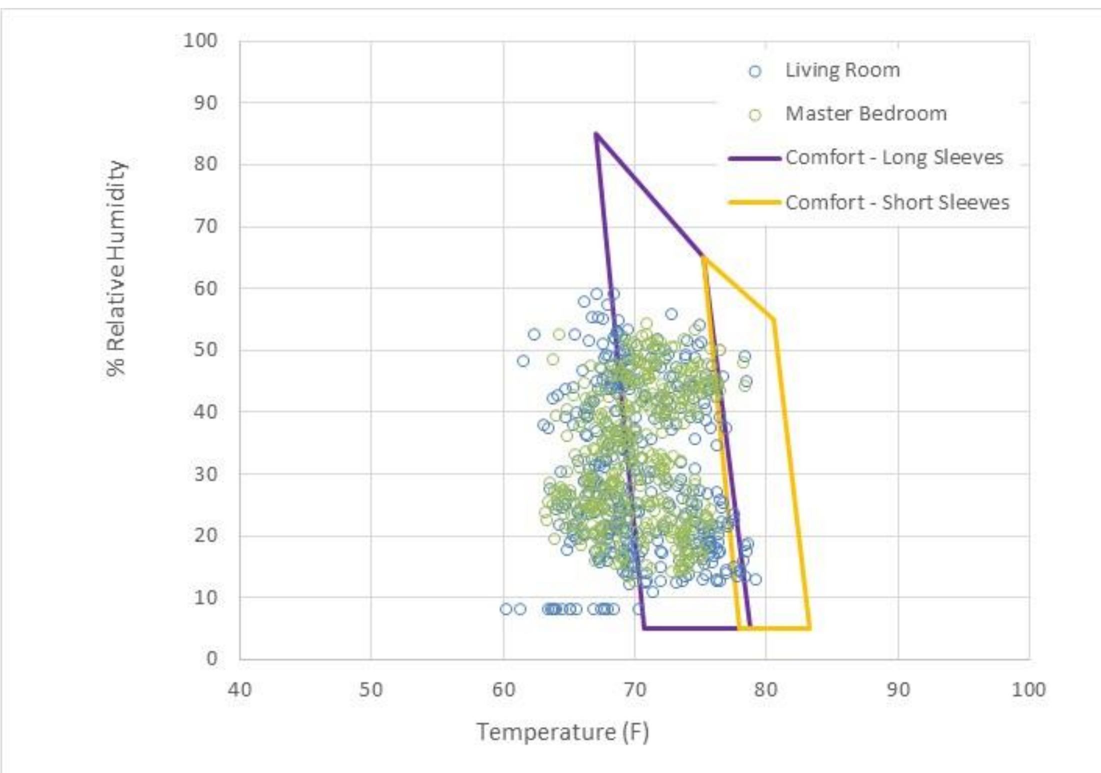




House 7:

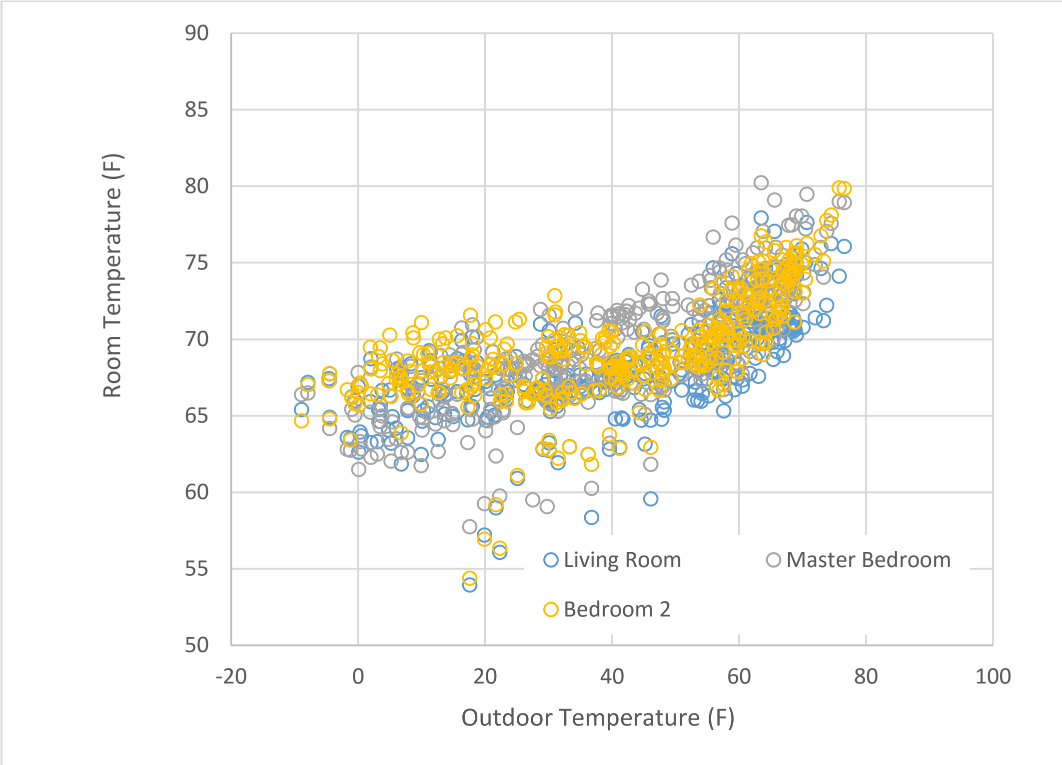


Room Temperature (F)
Outdoor Temperature (F)
Living Room
Master Bedroom
Bedroom 2

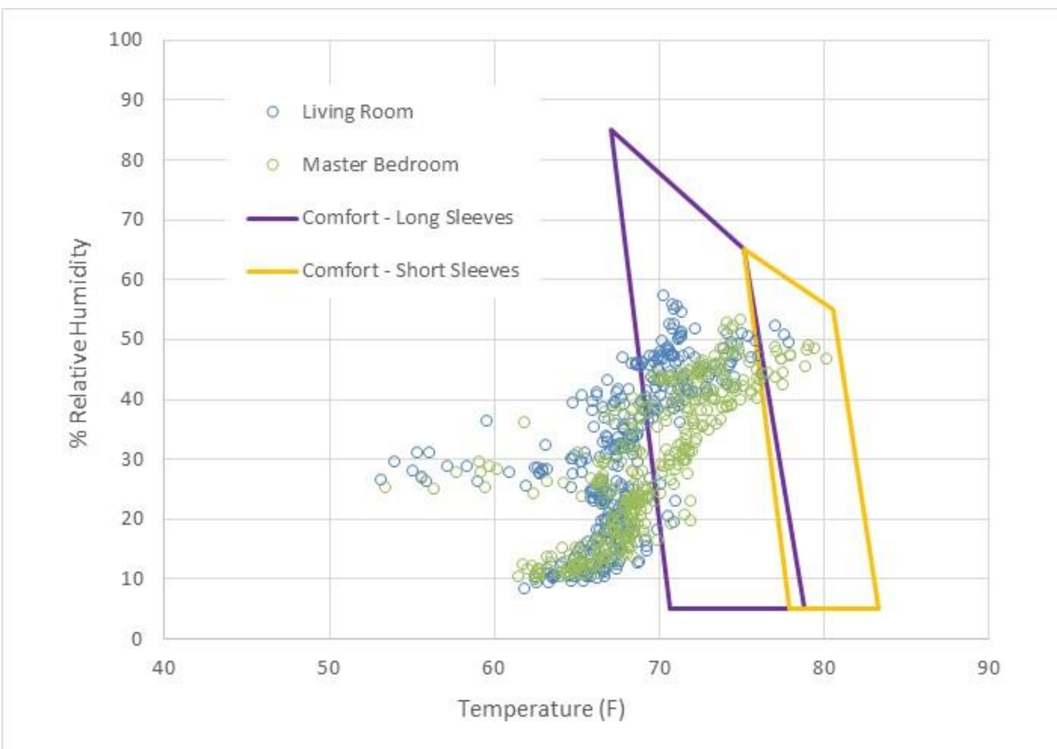


% Relative Humidity
Temperature (F)
Living Room
Master Bedroom
Comfort - Long Sleeves
Comfort - Short Sleeves

House 9:

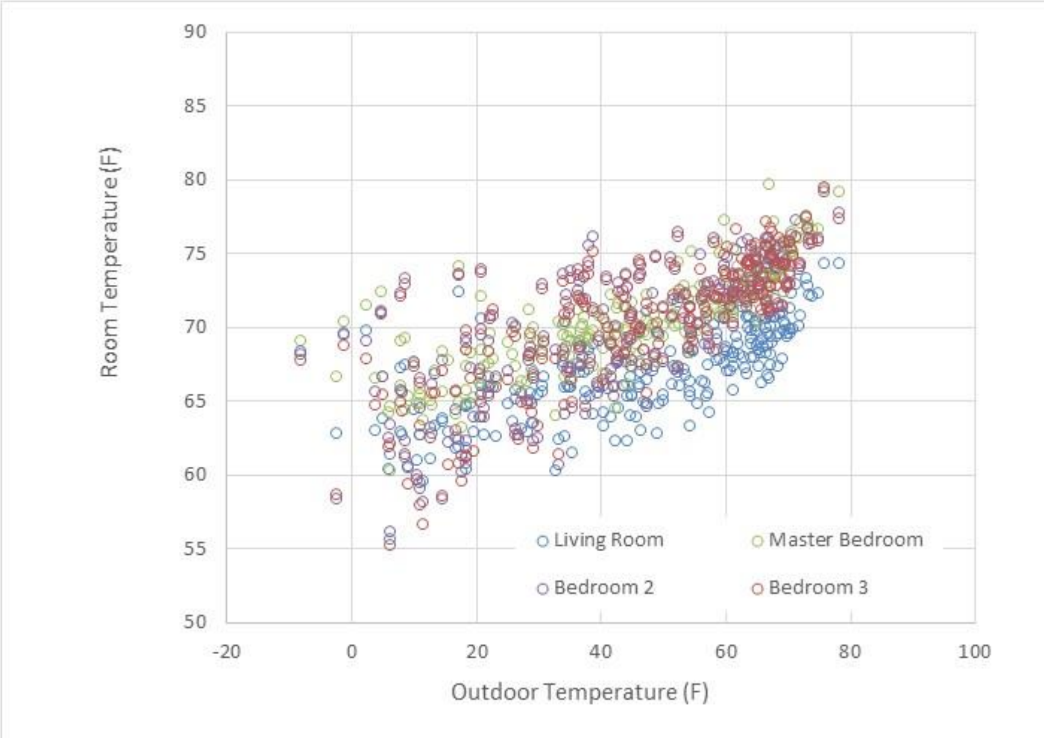


Room Temperature (F)
Outdoor Temperature (F)
Living Room
Master Bedroom
Bedroom 2
90
85
80
75
70
65
60
55
50
-20
0
20
40
60
80
100

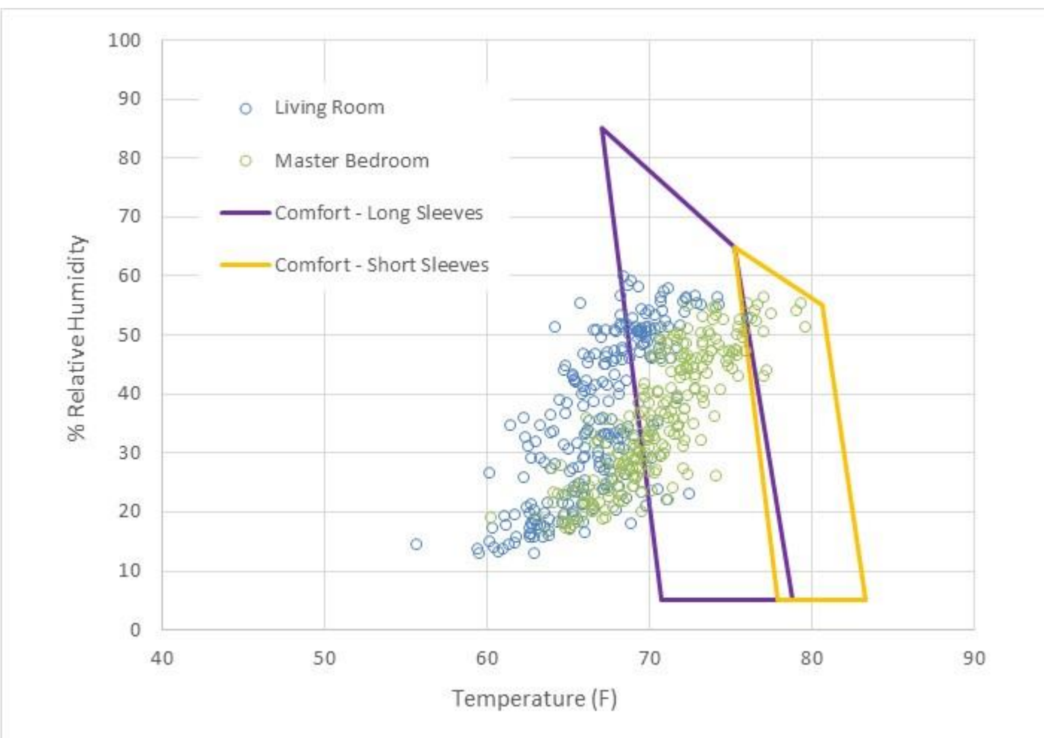


% Relative Humidity
Temperature (F)
Living Room
Master Bedroom
Comfort - Long Sleeves
Comfort - Short Sleeves
100
90
80
70
60
50
40
30
20
10
0
40
50
60
70
80
90

House 10:

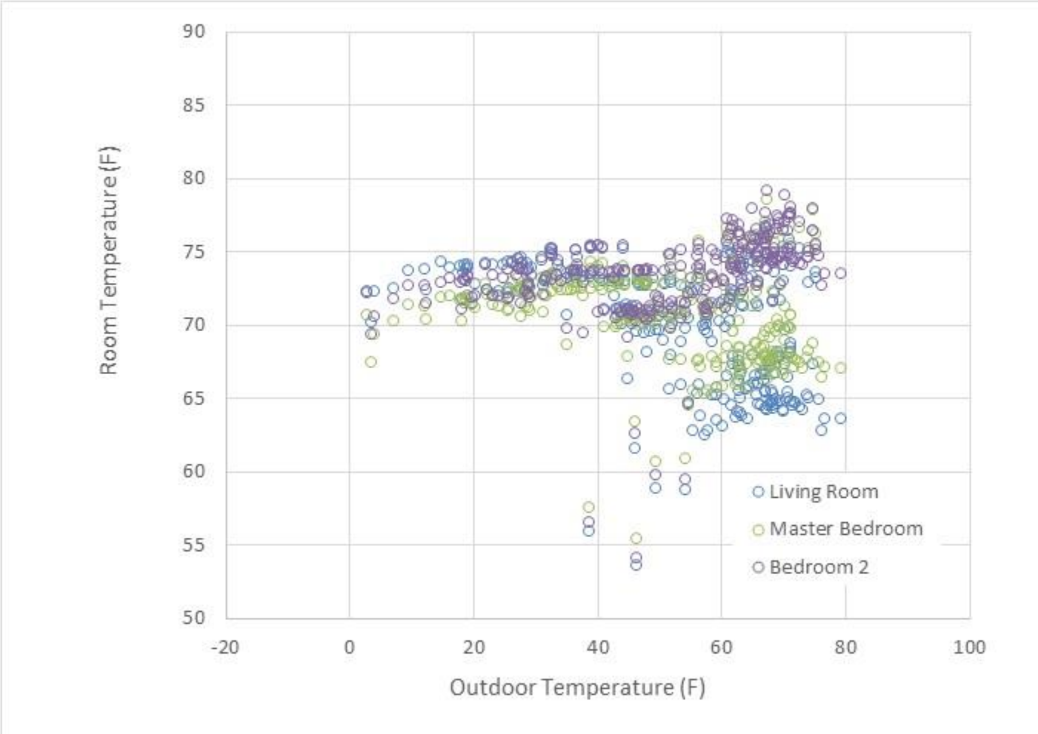


Room Temperature (F)
Outdoor Temperature (F)
Living Room
Master Bedroom
Bedroom 2
Bedroom 3

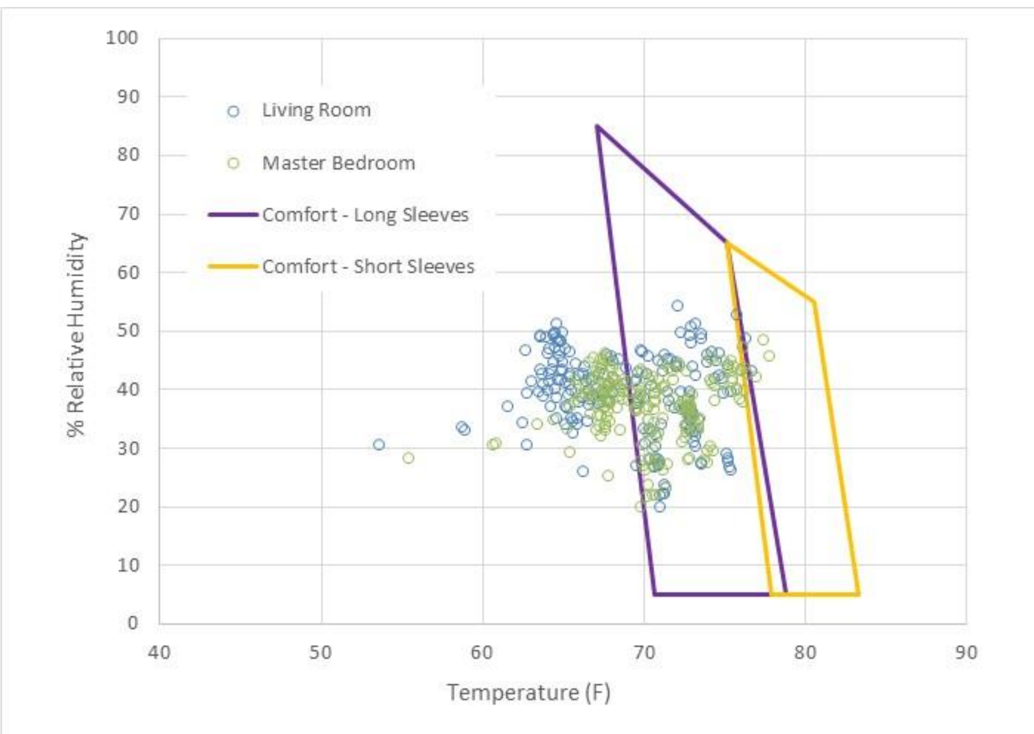


% Relative Humidity
Temperature (F)
Living Room
Master Bedroom
Comfort - Long Sleeves
Comfort - Short Sleeves

House 11:

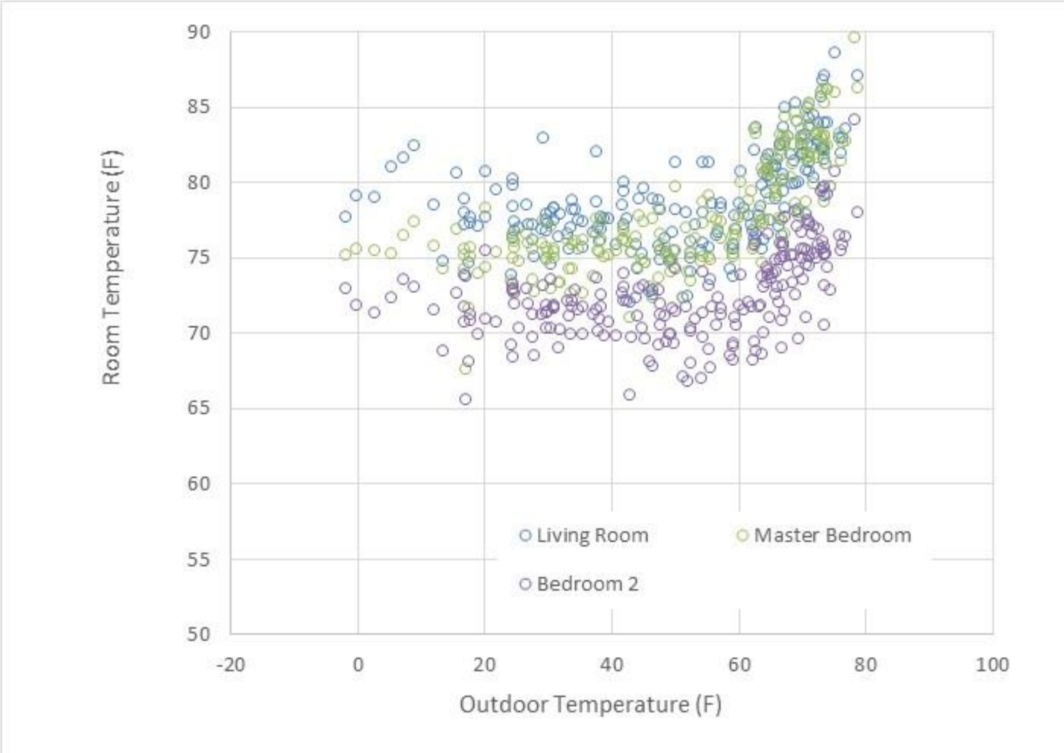


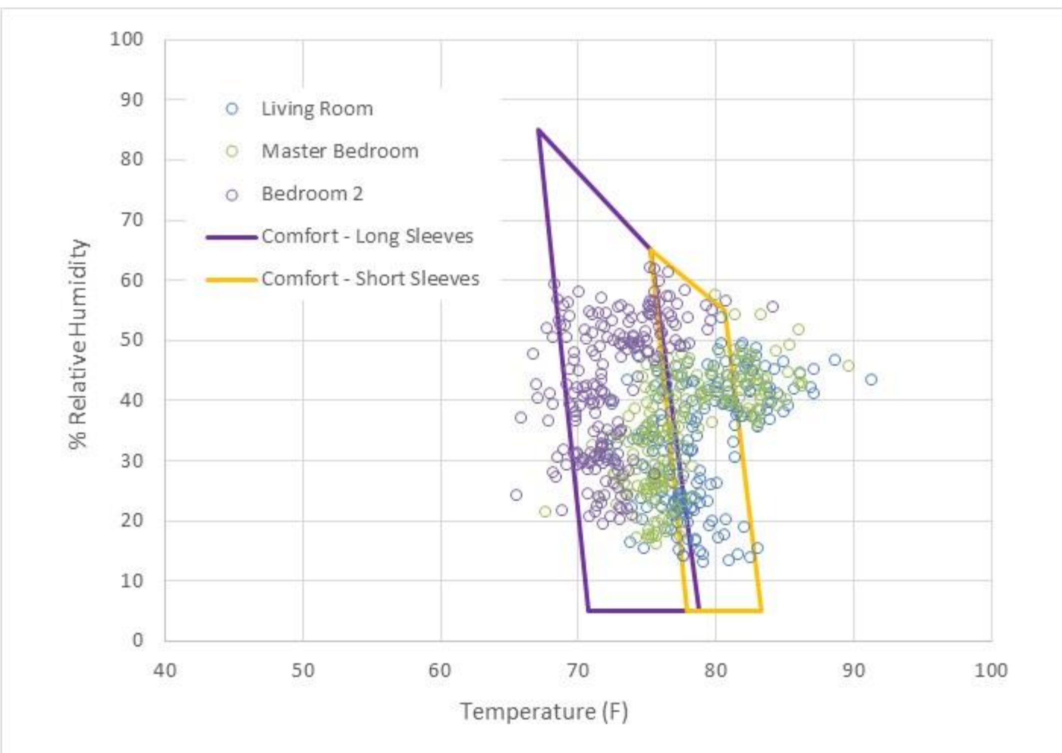
Room Temperature (F)
Outdoor Temperature (F)
Living Room
Master Bedroom
Bedroom 2



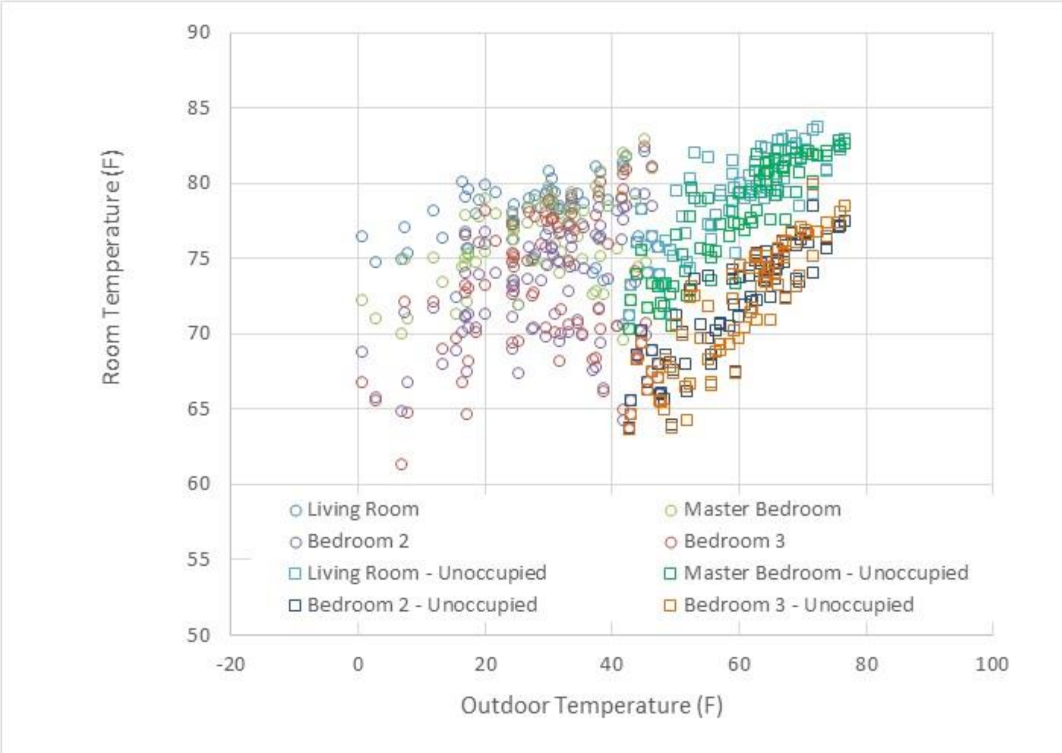
% Relative Humidity
Temperature (F)
Living Room
Master Bedroom
Comfort - Long Sleeves
Comfort - Short Sleeves

House 12:

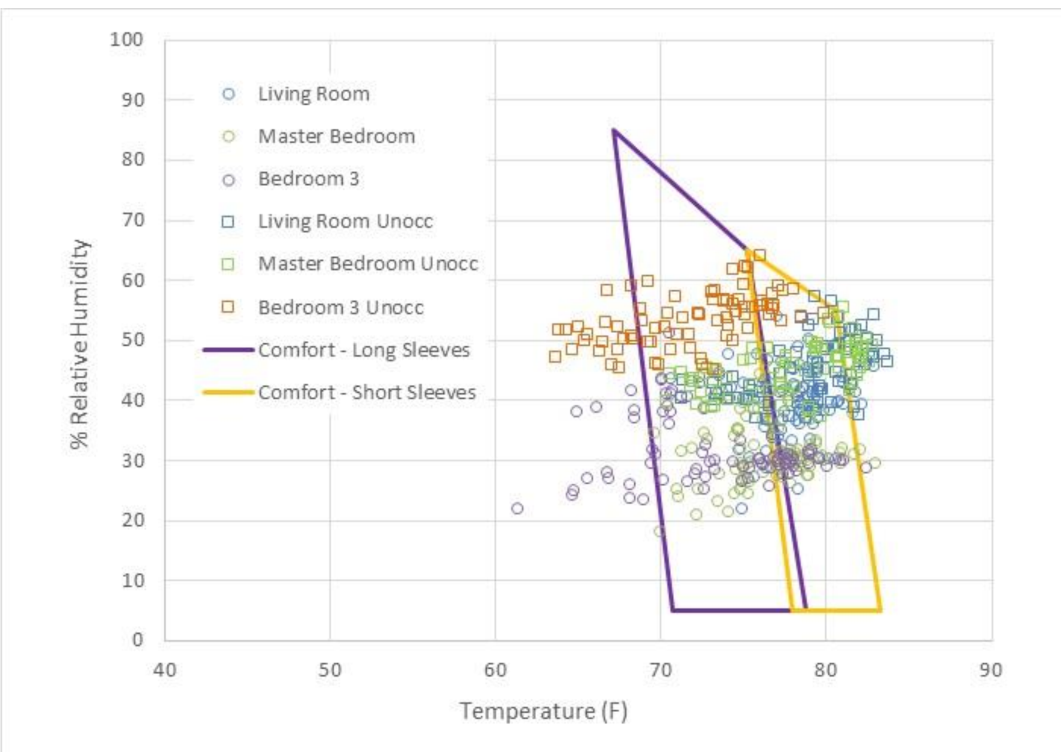

90
85
80
75
70
65
60
55
50
Room Temperature (F)
-20
0
20
40
60
80
100
Outdoor Temperature (F)
Living Room
Master Bedroom
Bedroom 2


100
90
80
70
60
50
40
30
20
10
0
% Relative Humidity
40
50
60
70
80
90
100
Temperature (F)
Living Room
Master Bedroom
Bedroom 2
Comfort - Long Sleeves
Comfort - Short Sleeves

House 14:

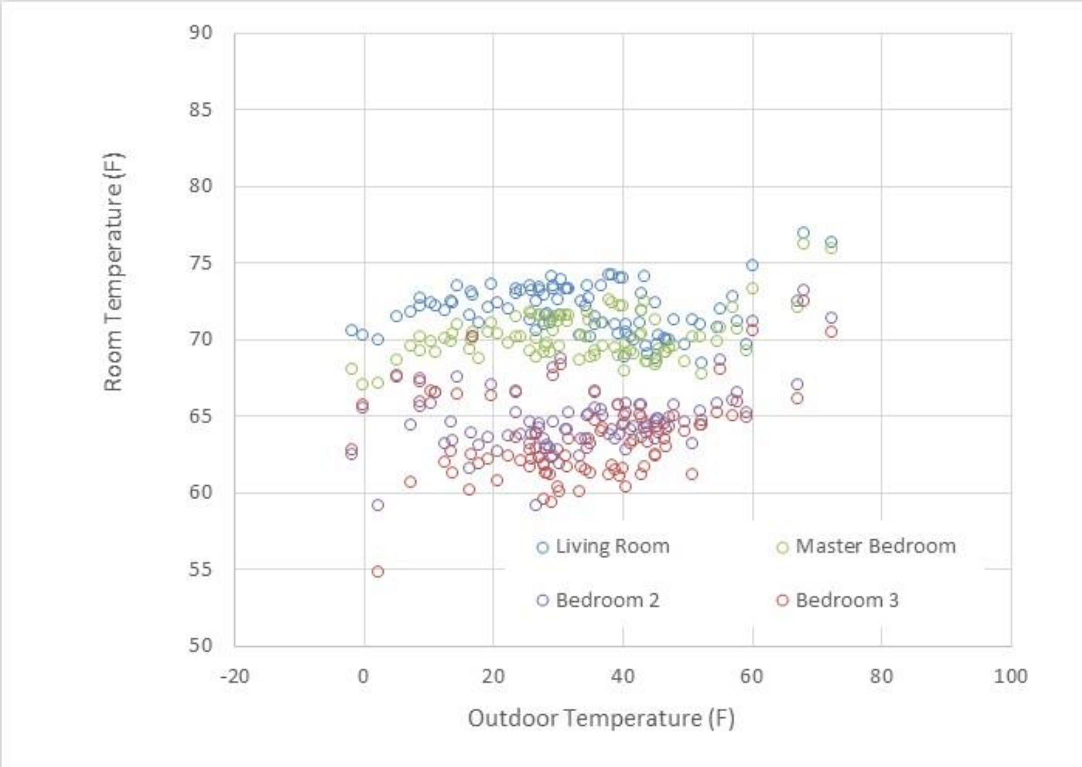


Room Temperature (F)
Outdoor Temperature (F)
Living Room
Master Bedroom
Bedroom 2
Bedroom 3
Living Room - Unoccupied
Master Bedroom - Unoccupied
Bedroom 2 - Unoccupied
Bedroom 3 - Unoccupied

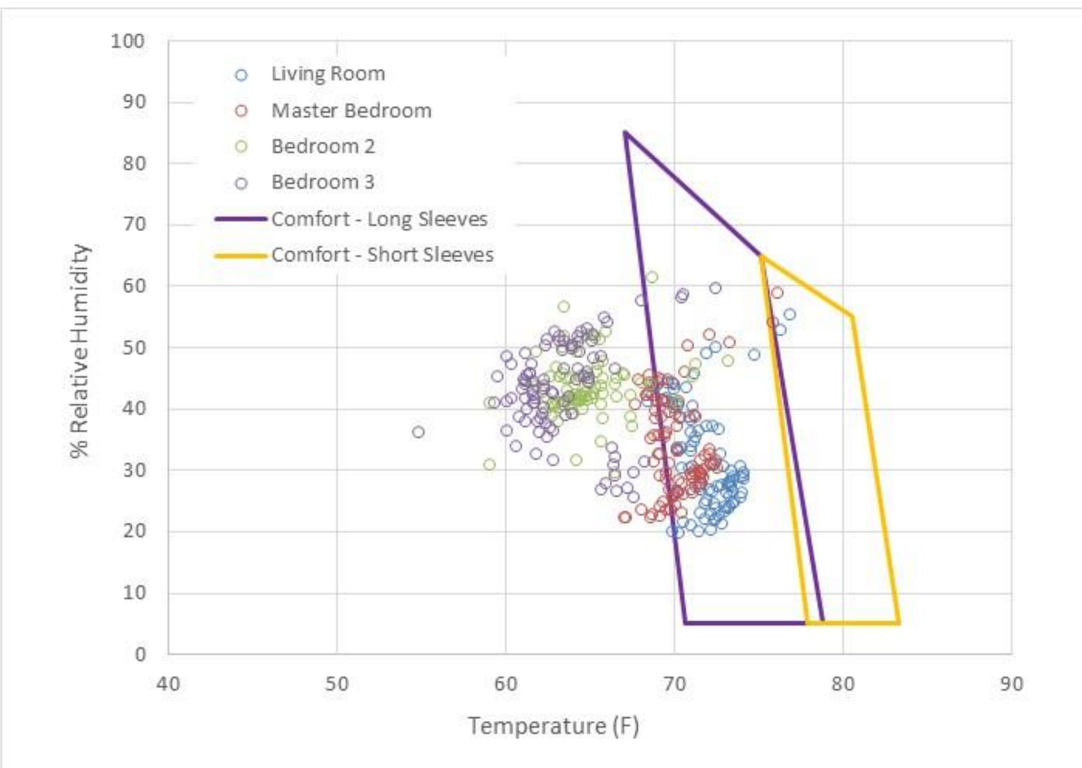


% Relative Humidity
Temperature (F)
Living Room
Master Bedroom
Bedroom 3
Living Room Unocc
Master Bedroom Unocc
Bedroom 3 Unocc
Comfort - Long Sleeves
Comfort - Short Sleeves

House 15:

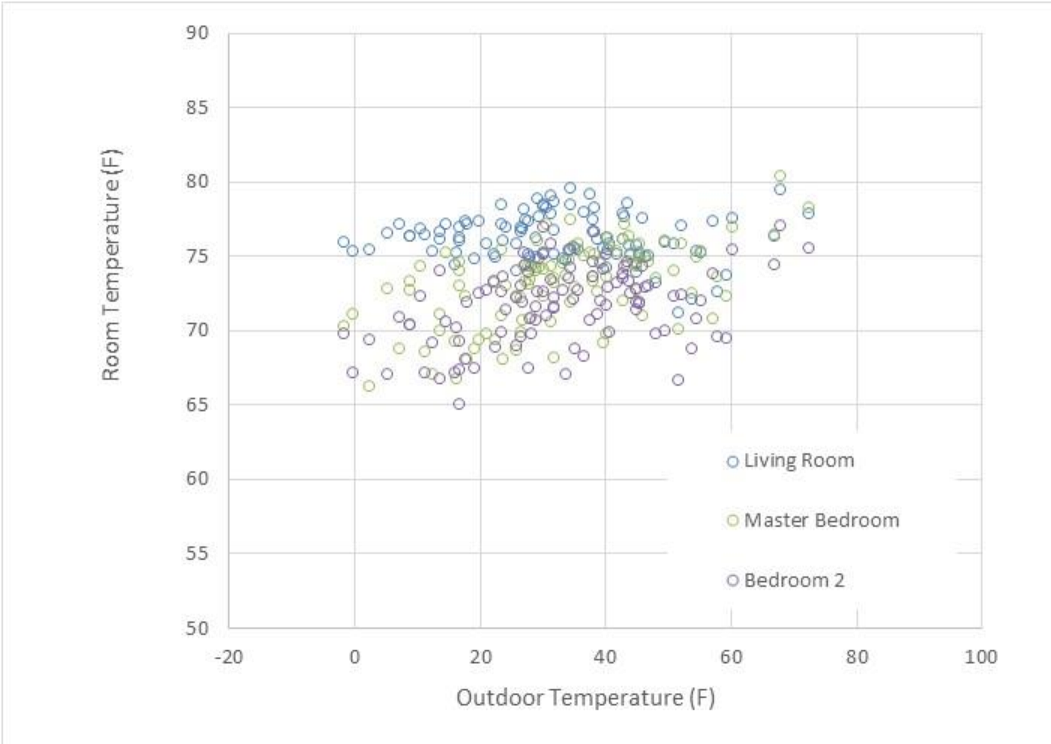


90
85
80
75
70
65
60
55
50
Room Temperature (F)
-20
0
20
40
60
80
100
Outdoor Temperature (F)
Living Room
Master Bedroom
Bedroom 2
Bedroom 3

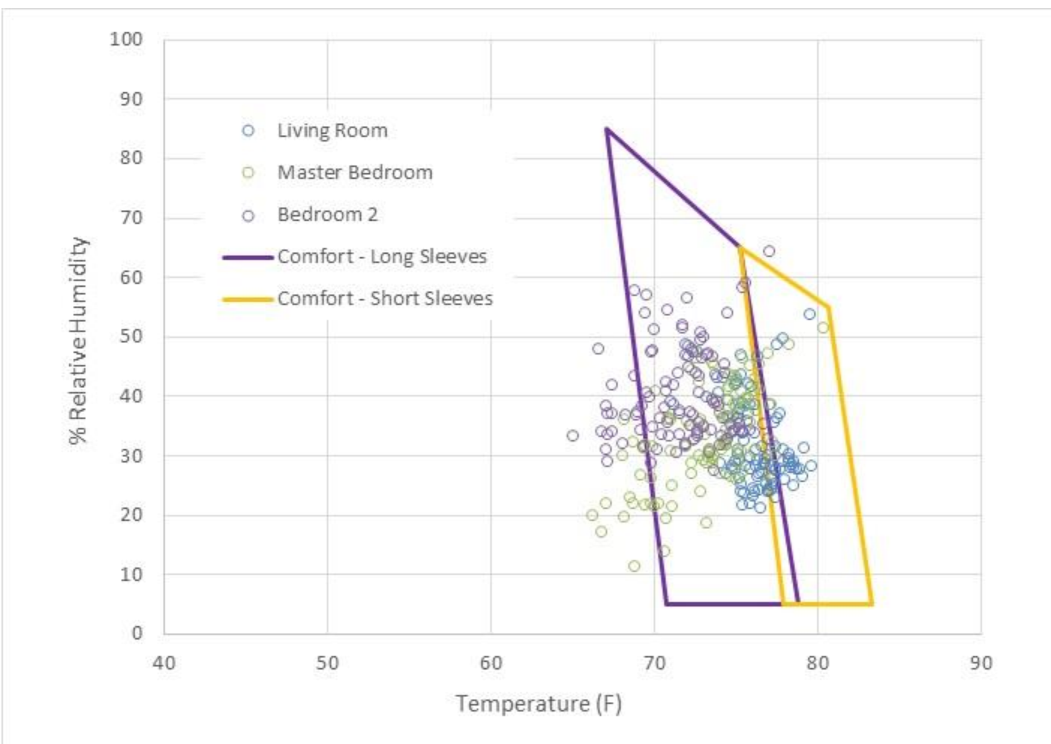


100
90
80
70
60
50
40
30
20
10
0
% Relative Humidity
40
50
60
70
80
90
Temperature (F)
Living Room
Master Bedroom
Bedroom 2
Bedroom 3
Comfort - Long Sleeves
Comfort - Short Sleeves

House 16:

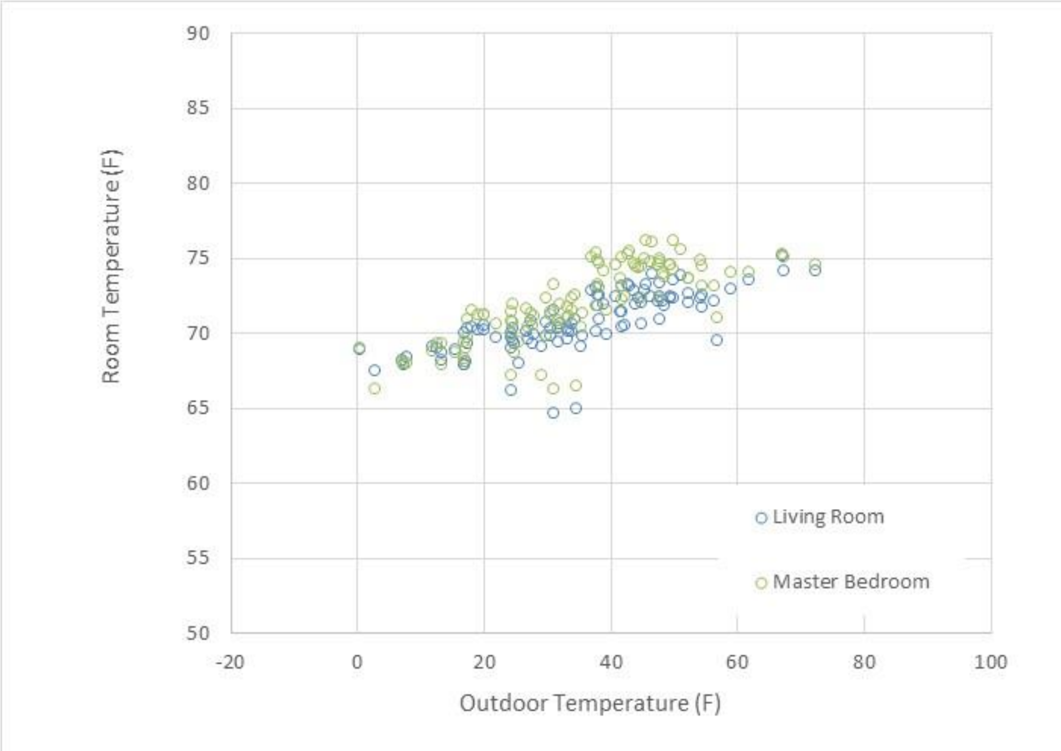


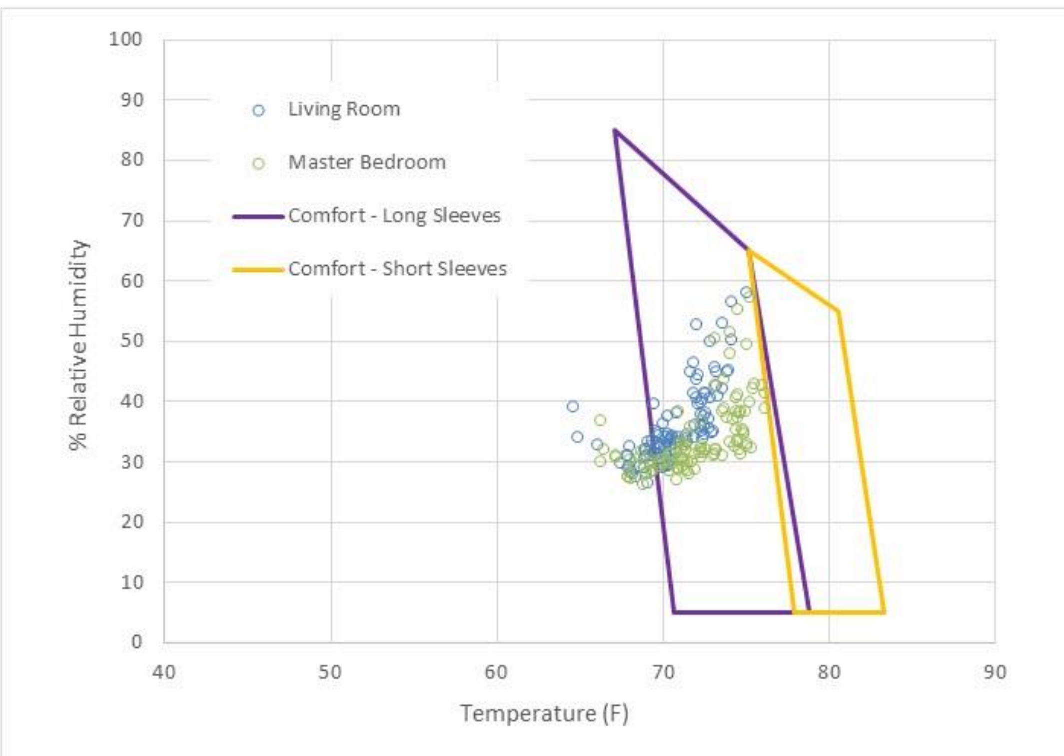
90
85
80
75
70
65
60
55
50
Room Temperature (F)
-20
0
20
40
60
80
100
Outdoor Temperature (F)
Living Room
Master Bedroom
Bedroom 2



100
90
80
70
60
50
40
30
20
10
0
% Relative Humidity
40
50
60
70
80
90
Temperature (F)
Living Room
Master Bedroom
Bedroom 2
Comfort - Long Sleeves
Comfort - Short Sleeves

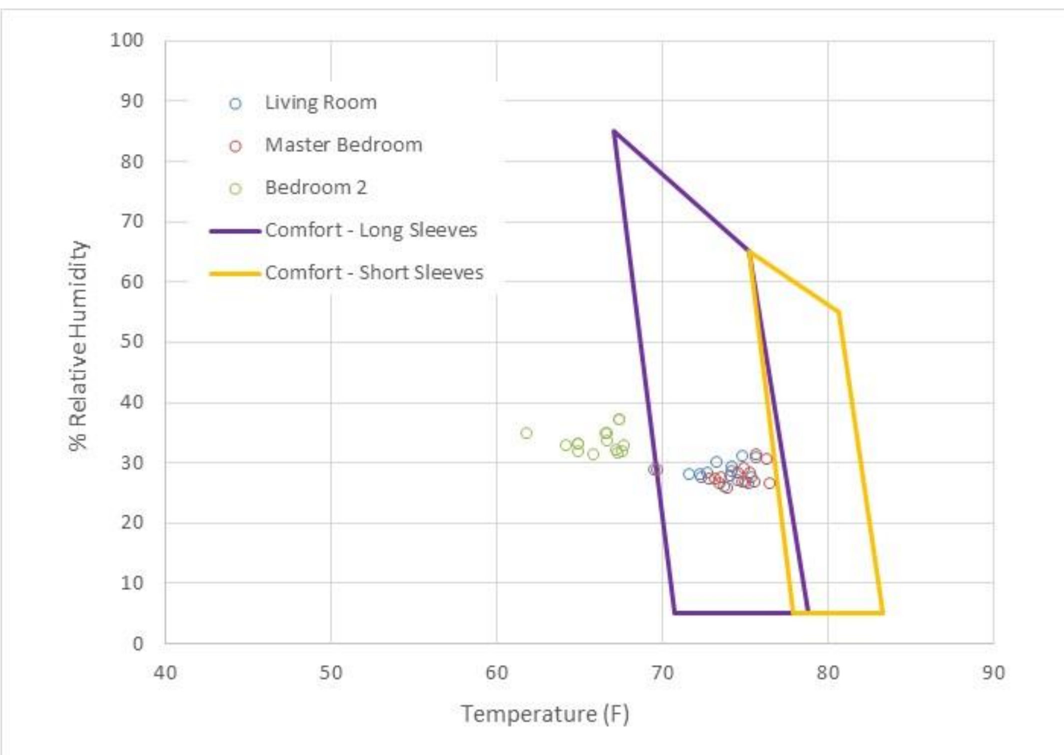
House 17:


90
85
80
75
70
65
60
55
50
Room Temperature (F)
-20
0
20
40
60
80
100
Outdoor Temperature (F)
Living Room
Master Bedroom


100
90
80
70
60
50
40
30
20
10
0
% Relative Humidity
40
50
60
70
80
90
Temperature (F)
Living Room
Master Bedroom
Comfort - Long Sleeves
Comfort - Short Sleeves

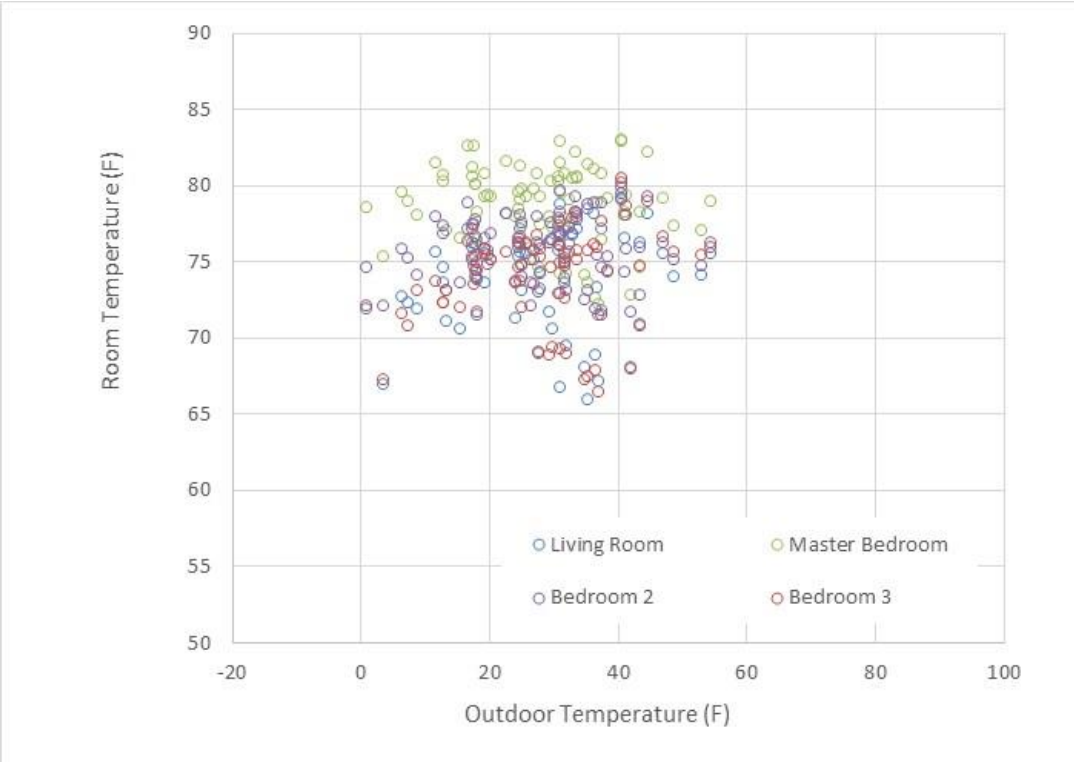
House 18:

90
85
80
75
70
65
60
55
50
Room Temperature (F)
-20
0
20
40
60
80
100
Outdoor Temperature (F)
Living Room
Master Bedroom
Bedroom 2
Bedroom 3

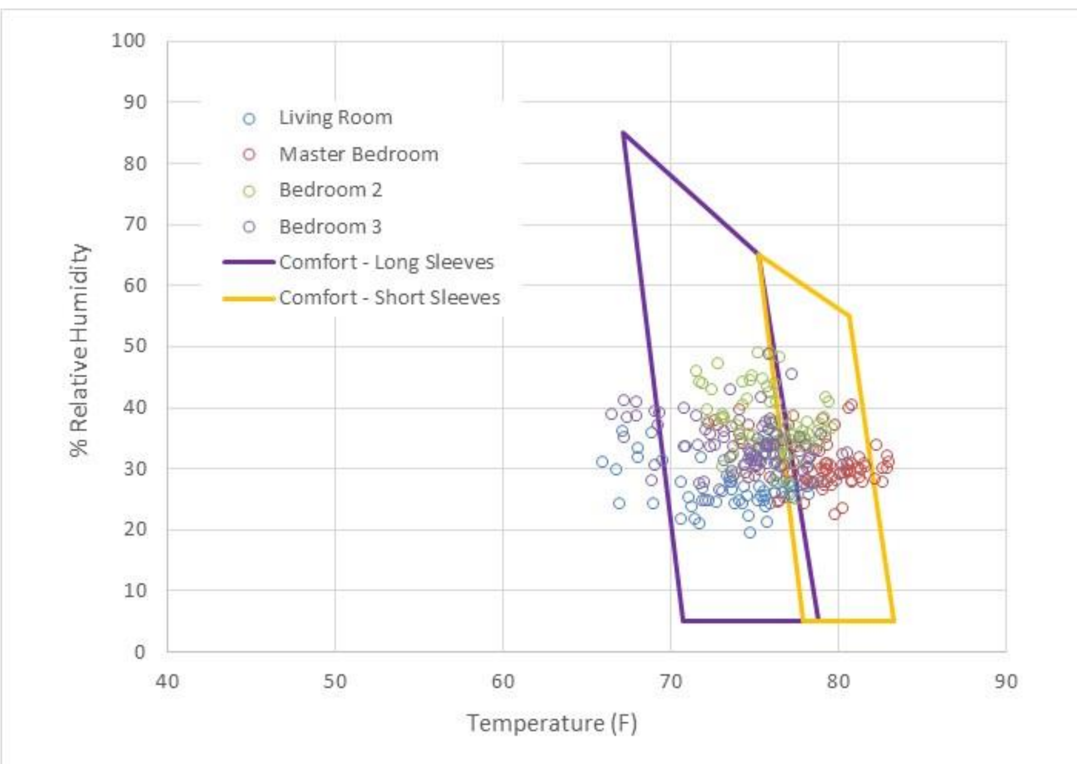


100
90
80
70
60
50
40
30
20
10
0
% Relative Humidity
40
50
60
70
80
90
Temperature (F)
Living Room
Master Bedroom
Bedroom 2
Comfort - Long Sleeves
Comfort - Short Sleeves

House 19:

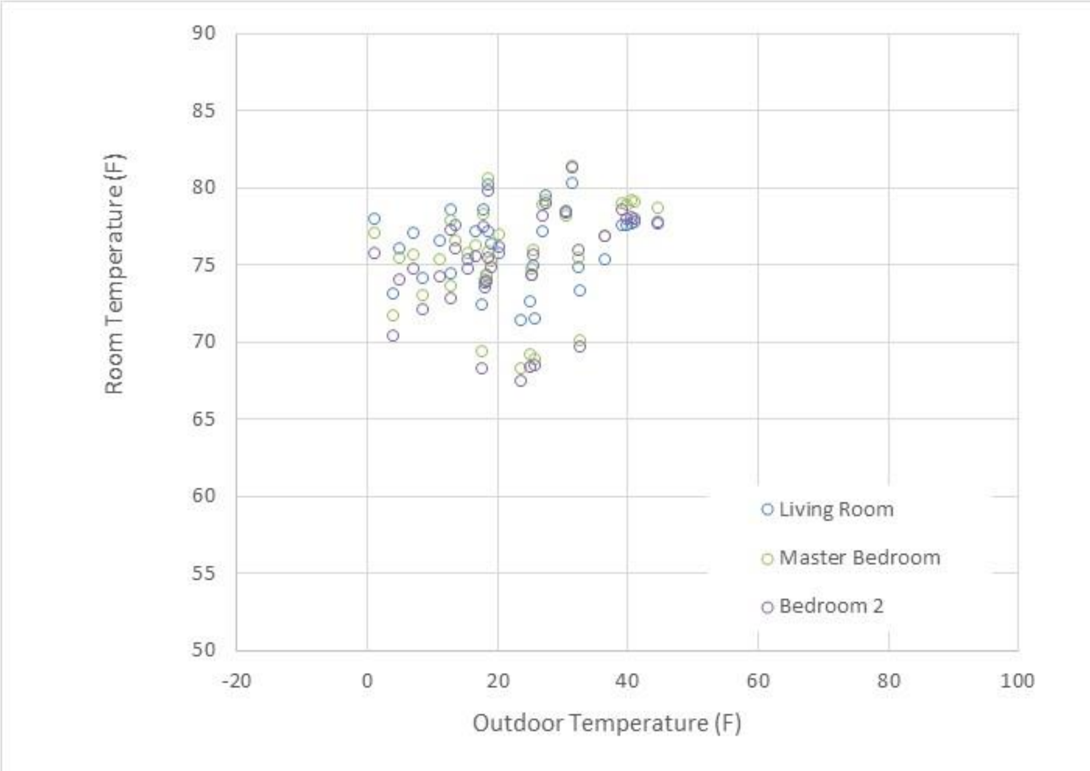


Room Temperature (F)
Outdoor Temperature (F)
Living Room
Master Bedroom
Bedroom 2
Bedroom 3
90
85
80
75
70
65
60
55
50
-20
0
20
40
60
80
100

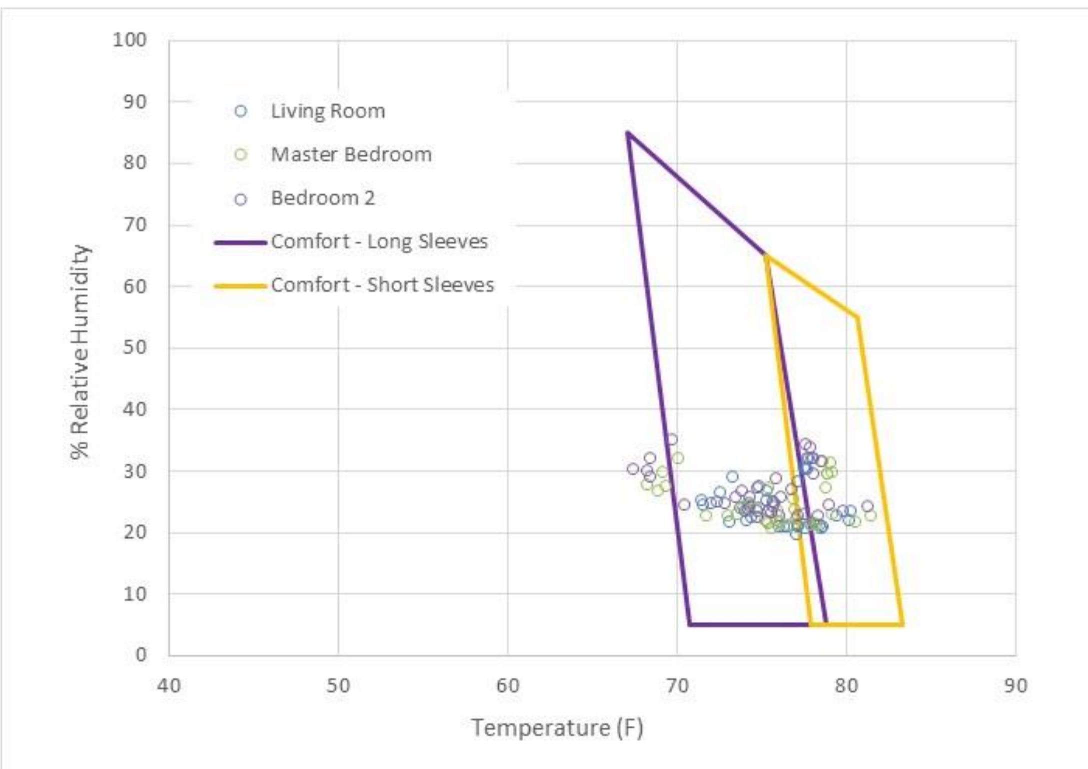


% Relative Humidity
Temperature (F)
Living Room
Master Bedroom
Bedroom 2
Bedroom 3
Comfort - Long Sleeves
Comfort - Short Sleeves
100
90
80
70
60
50
40
30
20
10
0
40
50
60
70
80
90

House 21:



90
85
80
75
70
65
60
55
50
Room Temperature (F)
-20
0
20
40
60
80
100
Outdoor Temperature (F)
Living Room
Master Bedroom
Bedroom 2



100
90
80
70
60
50
40
30
20
10
0
% Relative Humidity
40
50
60
70
80
90
Temperature (F)
Living Room
Master Bedroom
Bedroom 2
Comfort - Long Sleeves
Comfort - Short Sleeves

Appendix C - General House Energy Characteristics:

All homes, and buildings in general, have energy usage characteristics as shown in Figure 1. Heating (Region 1), cooling (Region 3) and spring/fall shoulder seasons (Region 2) may be more or less emphasized depending on a variety of factors. In addition, all buildings have a baseline level of energy consumption that is not dependent on climate. The shoulder seasons are a time when climate independent energy consumption processes can be identified. Plotting energy monitoring or utility data versus outdoor ambient temperature is a simple manner for observing a building's seasonal energy characteristics. As one gains experience, a brief glimpse of this curve reveals many features such as energy efficiency and occupant energy usage behavior.

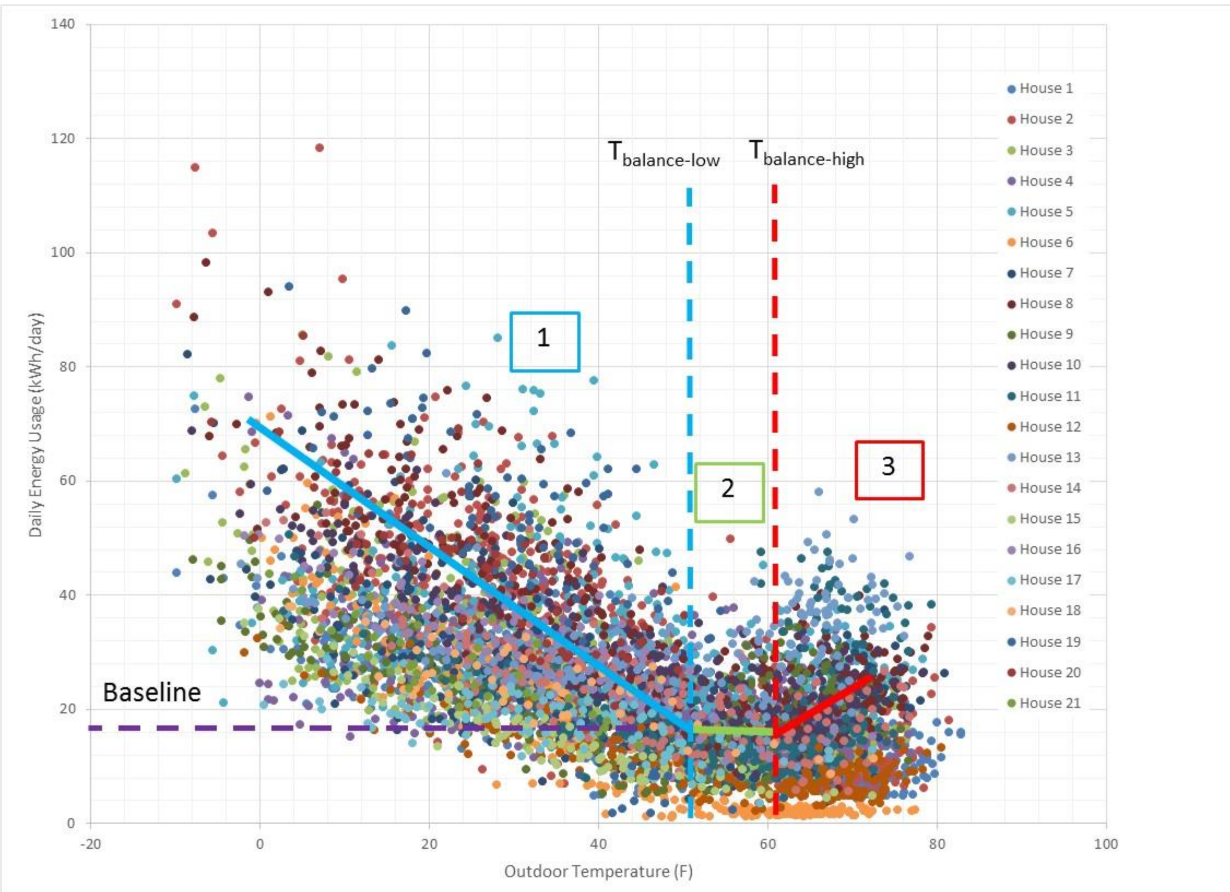


Figure 1 Characteristic daily energy usage trends for 21 homes in Vermont.

Figure 1 is the most important figure one can use for assessing the energy characteristics of a home. Without complex computations, detailed weather data or any knowledge of a home's design and construction, we are able to glance at Figure 1 and know many things about a house. For example, house energy data that falls along the blue/green/red lines sketched in Figure 1 indicates that this home requires 70kWh of electric energy per day when it is 0F. Approximately 50kWh per day of electric energy are required for heating…..either 50kWh (about 2kW or 7200Btu/h) of heat if the heating source is electric resistance, or 100kWh (about 4kW or 14,200Btu/h) of heat if the heating source is an air source heat pump. Heating season begins when the outdoor ambient is less than 50F and cooling season begins when the outdoor temperature is greater than 60F. When the average ambient temperature is 80F, 8kWh per day of electric energy are needed for cooling the house with a cooling load that is 4000Btu/h (assuming an air conditioning SEER value of 15).

The lines sketched on Figure 1 are a characteristic of a particular house and its occupants' behaviors. The lines can either be determined through statistical analysis ("best fit") or using a human's innate ability to sketch best fit lines through a home's utility data.

Once a home's energy lines are drawn, the home's characteristics can be transferred to other locations by plotting the new location's monthly average temperatures on the plot. The daily average energy usage per day for the home in the new climatic region will be the points on the lines that insects with each monthly average temperature.

Appendix D – Understanding the House as a System

A house is a complex system of components that must interact synergistically for achieving excellent performance. Too often, home designers select each component based on individual ratings, such as Energy Star or HVI performance values, without regard to the interaction among the components under actual operation. The Vermod-CERV homes have exceptional, year-long energy performance because of design of its interrelated comfort conditioning, fresh air ventilation, and water heater components.

Figures 1-4 illustrate a progression of "house efficiency" through common component choices for house space heating, water heating, and fresh air ventilation. Figure 1 depicts a home with electric resistance space heating and electric resistance water heating coupled with a CERV fresh air conditioner. Although heat pumps are more expensive than electric resistance heaters, they are much more efficient and generally pay for the extra capital cost through it lifetime energy savings.

A common misconception is that electric resistance heaters are more reliable than the "sophisticated" components of a heat pump. Heat pumps, however, are more reliable than electric resistance heaters. Electric resistance heaters must operate at very high temperatures (and thus are a source of many home fires) in order to transfer heat through the relatively small surface area of the heater. High electric resistance wire temperatures lead to oxidation and fatigue of the resistance heater, leading to its failure. The high temperatures also burn airborne particles and react them into undesirable pollutants while the low operation temperature of a heat pump's heat exchanger are well below temperatures that burn anything. A frequent cause of refrigerator failure is a broken electric defrost heater rather than the refrigeration system components. A common failure in clothes dryers and electric water heaters is also the electric resistance heater. In water heaters, the high temperature electric heater precipitates mineral salts (eg, calcium carbonate) on its surface, which eventually causes failure of the heater element.

In the Figure 1 house with electric heater and electric water heater, the one-to-one degradation of electrical energy into thermal energy is the most inefficient manner for obtaining heat, although manufacturers of electric heaters will proclaim an "efficiency" of 100% conversion of electricity into heat. The CERV's heat pump, is shown as operating with an "efficiency" of 2. Efficiency is called a "Coefficient of Performance", or COP, for air conditioners and heat pumps. For a heat pump with a COP of two, 2 units of heat are supplied by the CERV for each unit of electrical energy used to power the CERV. An overall house coefficient of performance can be determined by adding the amount of desired heating and cooling energy by the total amount of electrical energy used. For Figure 1, 4 units of house heat, 3 units of water heat, and 3 units of CERV heat are supplied to the home to keep it comfortable with adequate fresh air and the desired amount of hot water. The 10 units of desired heat required 8 units of electrical energy, for an overall house efficiency of 125% (or house COP of 1.25).

In Figure 2, we assume that someone decides to upgrade to a heat pump water heater while retaining their house electric resistance heater. During the winter, even though the heat pump water heater heats water much more efficiently than an electric resistance water heater (heat pump water heater COP=3, electric resistance water heater COP=1), the combination of electric resistance house heating, heat pump water heater and CERV is exactly the same house system efficiency as derived for Figure 1. Even though the heat pump water heater is efficient, because the additional heat supplied to the house is electric resistance heat, the heat pump water heater, in effect, is operating with the same efficiency as an electric resistance water heater.

Figure 3 shows the effect of substituting a heat pump for the house electric resistance heater while using an electric resistance water heater. We see that this combination is better than the electric space heater for the house with a heat pump water heater because we realize an efficiency gain through the house heat pump. The house system COP is 1.88 compared to 1.25, or 50% better house energy performance than the Figure 2 combination. Note that the cost for a heat pump water heater and a mini-split heat pump are similar enough that one might find designers and homeowners selecting between one or the other option.

Figure 4 shows the effect of using heat pumps for space heating, water heating and fresh air ventilation. The overall house efficiency doubles to 250% (house system COP of 2.5) from the electric resistance space and water heat case. Note that the component efficiencies and energy amounts depicted in the example plots are very reasonable, and the house system efficiency results of the examples are quite realistic.

Similar effects occur during cooling season, however, the situation is somewhat complicated by the need to dehumidify (condense) moisture from the inside air in order to maintain comfortable conditions. Because we do not have an electric resistance analog for cooling, a heat pump (air conditioner) must be used for cooling and dehumidifying the house. There are other analogous processes to the common vapor compression cooling system, such as solid state cooling, magnetic cooling, absorption cooling, and others. The system analyses and results will be the same as those shown for the vapor compression cooling systems.

Figure 5 depicts a home with an electric resistance water heater coupled with a house air conditioner and a CERV fresh air ventilator. The air conditioner removes heat (4 units shown in Figure 5) and moisture energy, or latent heat (2 units of energy) that requires 2 units of electrical energy. Note that energy is conserved, with 8 units of heat being exhausted outside. The electric water heater, as before, requires 3 units of electrical energy in order to produce 3 units of heated water. The CERV reverses itself to provide cooling and dehumidification. Adding the total house cooling energy (6 ½ units) and dehumidification energy (2 ½ units) with the energy of the hot water (3 units), and dividing the desired total energy quantity by the electrical energy (6 units) required to produce the desired heating and cooling yields a house system efficiency of 200% (house system COP = 2).

Figure 6 assumes heat pump water heating in addition to the house air conditioning and heat pump fresh air ventilation. Note that the heat pump water heater during the cooling season has a dual contribution to the house. The heat pump water heater removes heat and moisture from the house interior, which is desirable, while transferring that energy into the hot water tank. In effect, the heat pump water heat keeps you more comfortable, allowing you to shower and wash laundry with the waste heat before sending it out of your house through the drain. Note that the desired energy amounts are exactly the same as discussed with Figure 5. The amount of electrical energy has been further reduced with the use of heat pumps for space cooling and dehumidification, water heating and ventilation energy recovery. Overall, the Figure 6 house system has an efficiency of 360% in comparison with Figure 5's 200%! Again, the energy unit values have been selected to be realistic levels for space cooling and dehumidification coupled with water heating and ventilation requirements.

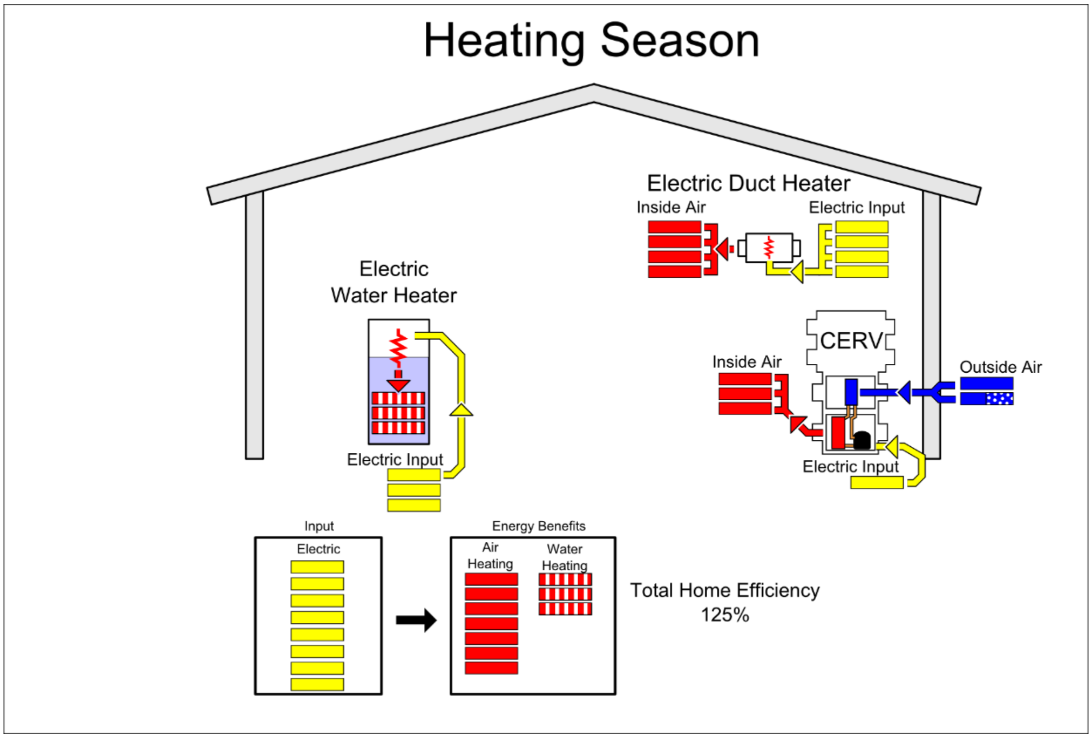


Figure 1 Winter with electric resistance heat, electric resistance water heat and CERV fresh air ventilation.

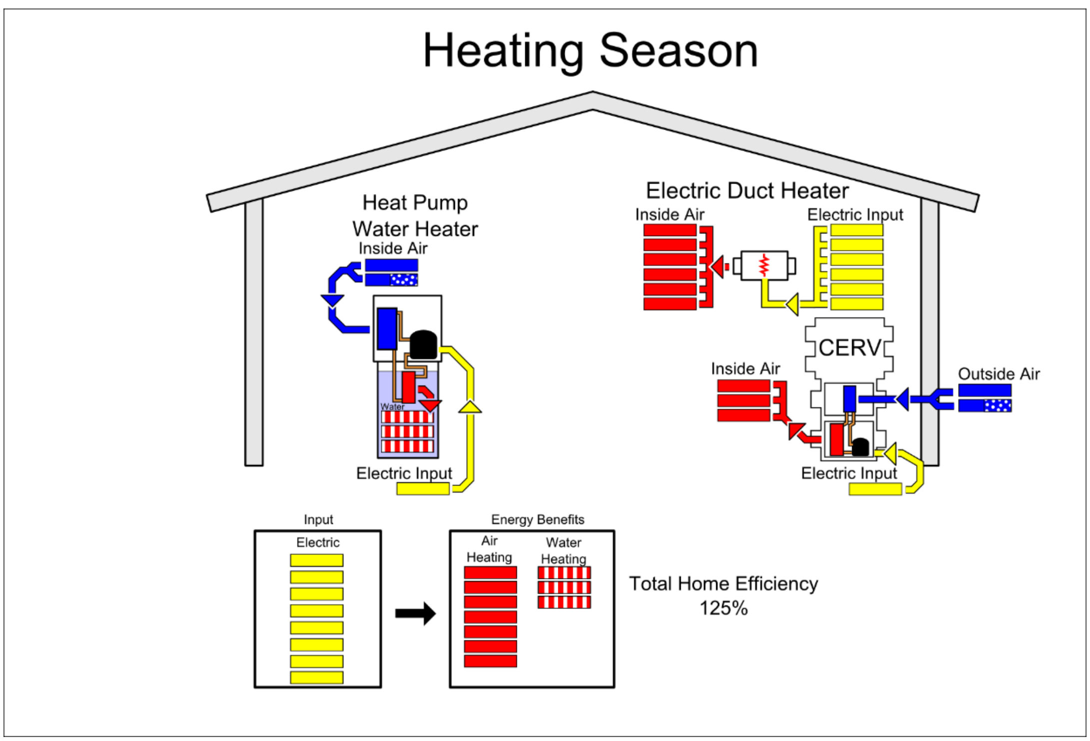


Figure 2 Winter with electric resistance heat, heat pump water heater, and CERV fresh air ventilation.

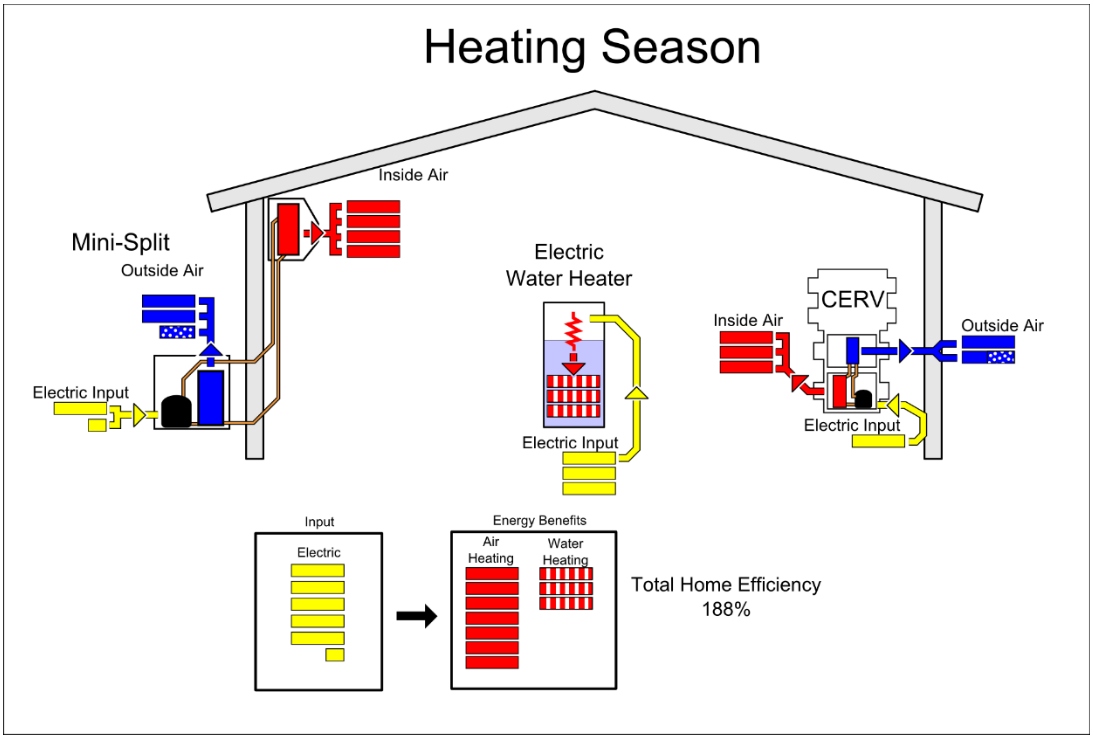


Figure 3 Winter house heat pump, electric resistance water heat, and CERV fresh air ventilation.

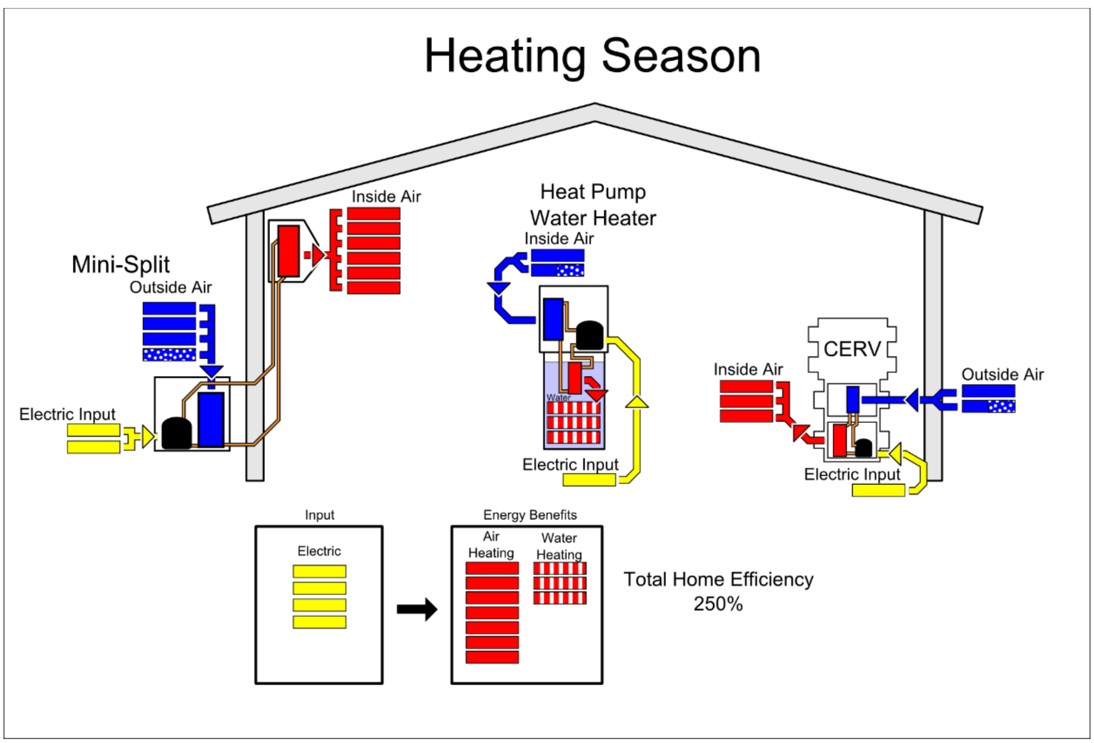


Figure 4 Winter with house heat pump, heat pump water heater and CERV fresh air ventilation.

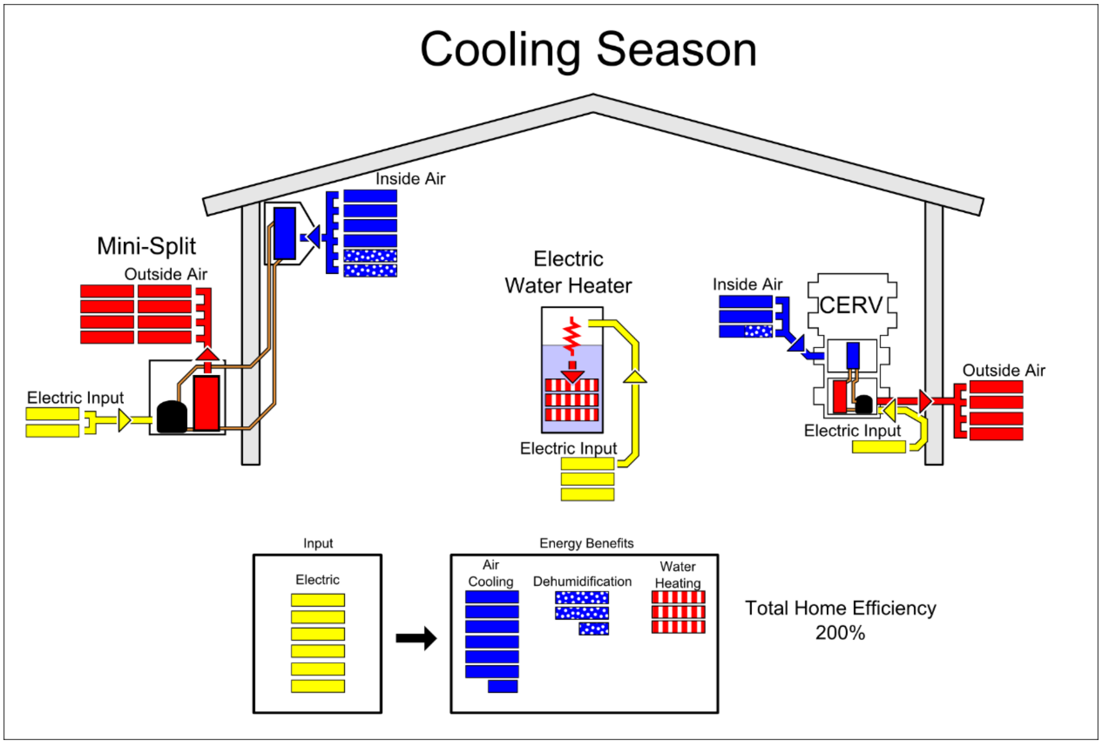


Figure 5 Summer with house air conditioning, electric resistance water heater, and CERV fresh air ventilation.

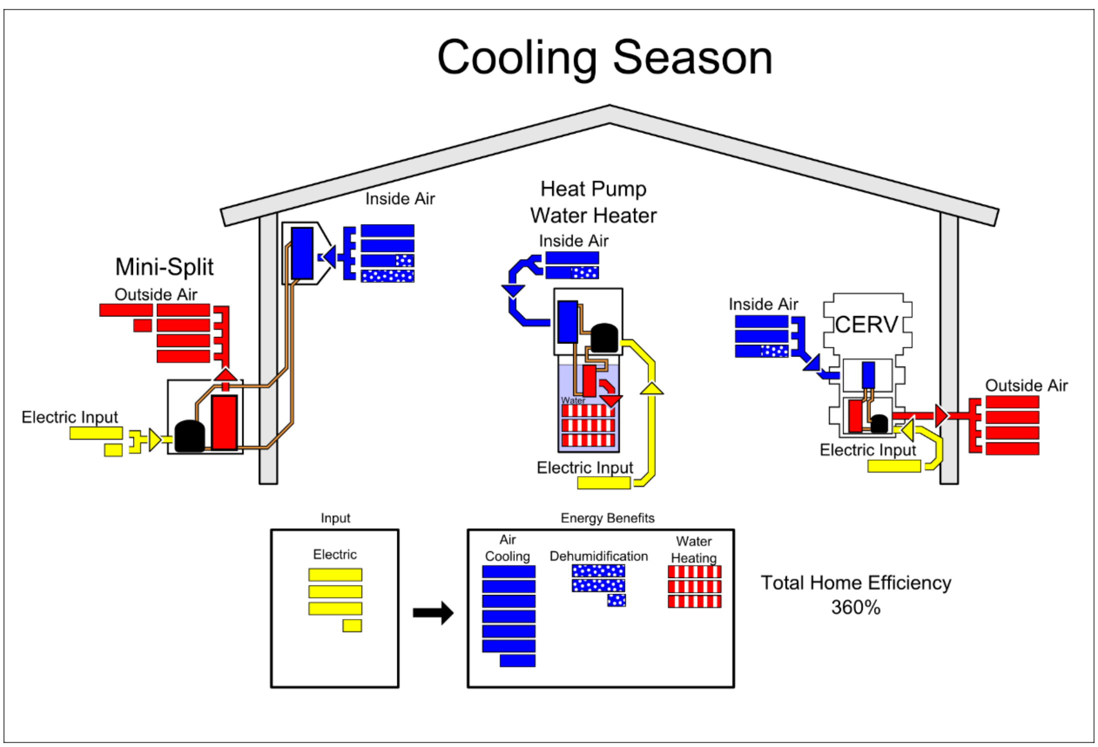


Figure 6 Summer with house air conditioner, heat pump water heater, and CERV fresh air ventilation system.

Appendix E – What can the CERV Smell?

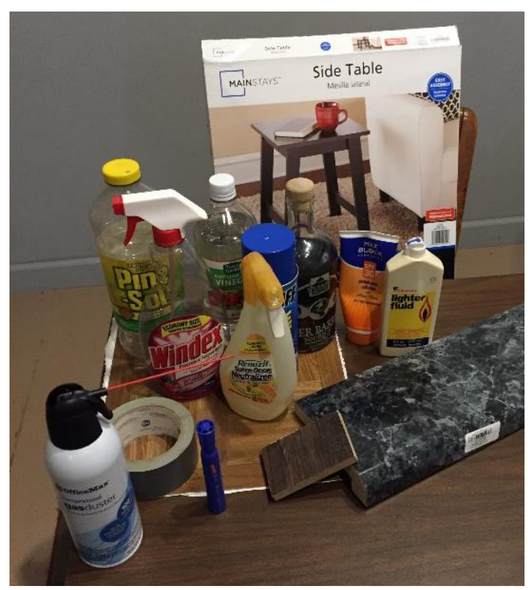
What Can the CERV™ Smell?

Build Equinox CERV VOC Library

We are continuously bombarded in our homes by a dizzying array of pollutants. Many of these substances are modern creations in which humans have never before been immersed. Our homes are deteriorating because of substances such as "Chinese drywall" that emits sulfurous fumes, and formaldehyde released by many of today's building materials and furnishings. Formaldehyde turns into formic acid that corrodes the copper tubing in air conditioners (web search "formicary corrosion"). If these substances can destroy our homes, what are they doing to our lungs, body, and mind? It is essential that we flush these substances from our homes in an energy efficient manner in order to minimize their impact on us.

We breathe 40 pounds of air into our lungs each day. In order to keep air inside a building fresh enough for our lungs, at least 2000 pounds of outdoor air per person must flow into a building daily! Have you ever moved a ton of anything? It takes a lot of work to effectively move a volume of 28,000 cubic feet of fresh air per person throughout a home's nook-n-crannies each day. This is why ventilation ductwork should become foremost in importance in home design rather than as an afterthought left to the whims of installers.

The CERV™ fresh air ventilation system, by Build Equinox, incorporates air pollution sensors (carbon dioxide and VOCs) that detect pollutants our noses cannot. Various hydrocarbon gases (methane, propane, butane) are odorless, and we will not smell them at any concentration, but the CERV can. Like our best friends, our dogs, your CERV is continually on guard and extends our sense of smell to keep us protected.



Our CERV's VOC (Volatile Organic Compound) sensor is a total VOC sensor that can detect minute amounts reactive compounds. Not all VOCs are bad, such as the wonderful odors of Grandma's chicken soup. Such beneficial odors release good feelings, love and accelerated healing. But, even good odors should not be allowed to stay so long that they become infused and absorbed in our furnishings and building surfaces.

Many people ask us which VOCs the CERV can detect. Perhaps it is better ask "Is there anything that the CERV cannot detect?" The CERV can detect "new car smell", pollutants in your breath, the citrus smell of limonene cleansers, hydrocarbons, various aldehydes, acetone (fingernail polish remover), and whatever it is in "magic" markers.

Build Equinox, the inventor and manufacturer of the CERV, has started a library that lists the CERV's sensitivity to VOCs emitted by various substances. A "high" or "low" rating is not an indication of toxicity or danger, but rather an indication of how strongly the CERV's total VOC sensor is able to detect something. For example, two brands of duct tape are listed. One brand was found to emit very little VOCs while the other emits a moderate levels of VOCs. We do not know whether the VOCs emitted by the "smelly" duct tape are harmful or not. That is a question for others to answer. But we do know that a typical mixture of VOCs in the modern home, office and school environment do impact our cognitive performance [1] as well as having the potential over time to produce health problems [2].

Table 1 is a listing of the substances Build Equinox has tested to date, ordered in terms of "High", "Medium", "Low", and "No" VOC detection by our CERV VOC sensor. The ranking of a substance as high, medium, low or no is based on our judgement. You should know our judgment is very good because we have measured VOCs in more homes for a longer time than almost anyone else.

We use a 41 quart size, covered polypropylene container to test substances. The container is intentionally not well-sealed in order to create a space with some level of infiltration and dilution during the test period. A CERV VOC sensor is placed in the container and connected to a data recorder. We tested the empty container, too. The polypropylene test box did not emit a VOC level detectable by the CERV, which is nice to know because polypropylene is a polymer commonly used for food containers (eg, plastic milk jug bottle caps) and toys (hula hoops).

A "High" rating occurs due to either a high peak VOC sensor reading, or a steep increase of the VOC sensor output after a sample is added to the test container. A sample of isobutane, for example, does not elevate the VOC sensor output to its highest level because we use a small sample (butane is highly flammable and can be explosive!). The steep rise of the VOC sensor output, however, indicates that the sensor is very sensitive to isobutane. What is isobutane? It is a common aerosol can propellant used to spray other chemicals (paints, cleansers, etc). Some test materials, such as liquids, have a very high VOC content that builds more slowly to a very high VOC sensor reading. A "Medium" level is less than a "High" level, while a "Low" level indicates there is some VOC detection, but either the pollutant emission rate from the sample is low, or the amount of pollutants in the sample that can be volatilized is low.

We hope this information is useful to you. Check back often to see new listings added to our list. We welcome suggestions from you, too. Are there some substances that you would like to know about? If so, we'll add it to our list and do our best to test it.

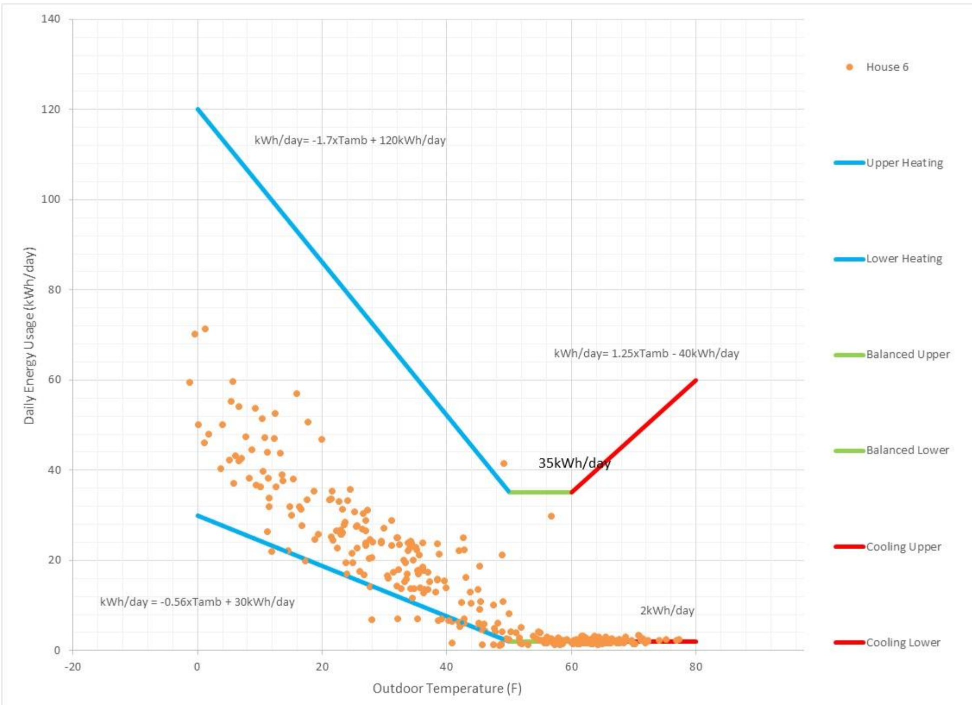
[1] Joseph G. Allen, Piers MacNaughton, Usha Satish, Suresh Santanam, Jose Vallarino, and John D. Spengler; "Associations of Cognitive Function Scores with Carbon Dioxide, Ventilation, and Volatile Organic Compound Exposures in Office Workers: A Controlled Exposure Study of Green and Conventional Office Environments";Env Health Perspectives; Oct 2015
[2] Formaldehyde Chemical Summary, US Environmental Protection Agency, Toxicity and Exposure for Children's Health; www.usepa.gov/teach/

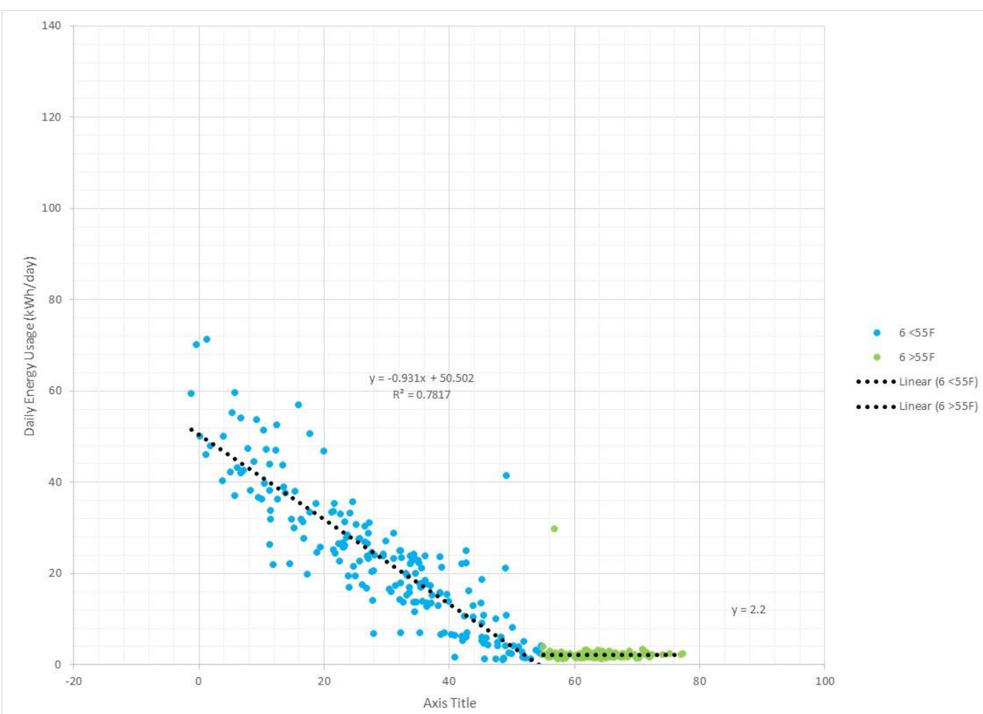
Table 1 “High” to “No” listing of VOC substances that the CERV can detect.

Substance	Form	VOC (N/L/M/H)	Comments
Acetone	liquid	H	4g in ceramic bowl
Ajax "triple action" dish detergent	liquid	H	4g in ceramic bowl
Bourbon 80 Proof	liquid	H	4g in ceramic bowl
Easy-Off No Fume Oven Cleaner	liquid	H	4g in ceramic bowl
Human Breath	gas	H	2 breaths exhaled into test box
Isobutane	gas	H	6" diameter balloon released into box; common aerosol propellant
Isopropyl Alcohol (50%)	liquid	H	4g in ceramic bowl
Murphy Oil Soap	liquid	H	4g in bowl, "Tall" Oil Fatty Acid and potasium hydroxide
Office Max "Gasduster"	gas	H	6" diameter balloon released into box; aersol for cleaning computer keyboards; also called 1,1-difluoro-ethane and refrigerant R152a
Pine-Sol	liquid	H	~ 4g of cleanser in a ceramic bowl
Renuzit Super Odor Neutralizer	liquid	H	~4g in ceramic bowl
Staples Blue Marker	liquid	H	cap removed from permanent marker
Walgreens Lighter Fluid	liquid	H	4g of lighter fluid (naptha; petroleum distillates) in ceramic bowl
Windex	liquid	H	~8g in ceramic bowl
Zep Heavy Duty Foam Degreaser	liquid	H	4g of foam in ceramic bowl
Chlorox (6% sodium hypochlorite)	liquid	M	4g in ceramic bowl
ipg Duct Tape	solid	M	30ft of 2" wide tape; noticeable odor
Sun "oxy" gen dish detergent	liquid	M	4g in ceramic bowl
White Vinegar	liquid	M	~4g in ceramic bowl
Dirty teeshirt and socks	solid	L	worn for one day
Laminate Countertop	solid	L	52g laminate covered particleboard
Max Block 30SPF Sunscreen	liquid	L	4g of sunscreen in ceramic bowl
Sauder Bookshelf "B"	solid	L	36g of low density particleboard from bookshelf
Sauder Bookshelf "C"	solid	L	50g of high density particle board; low reading but higher than part
Shaw Laminate Floor	solid	L	16g of glueless (floating) laminate floor materials
Vinyl Floor Tile	solid	L	12" x 12" Peel-n-stick vinyl tile with adhesive back exposed
Hydrogen Peroxide (3%)	liquid	N	4g in ceramic bowl
Polypropylene	solid	N	Empty plastic tub used for VOC measurements. No measurable TVOCs with CERV sensor.
Scotch 395 Duct Tape	solid	N	80 sq in of duct tape
Scotch Packaging Tape	solid	N	80 sq in of heavy duct packaging tape
Water	liquid	N	no noticeable reading, but humidity increase due to water can mobilize other VOCs

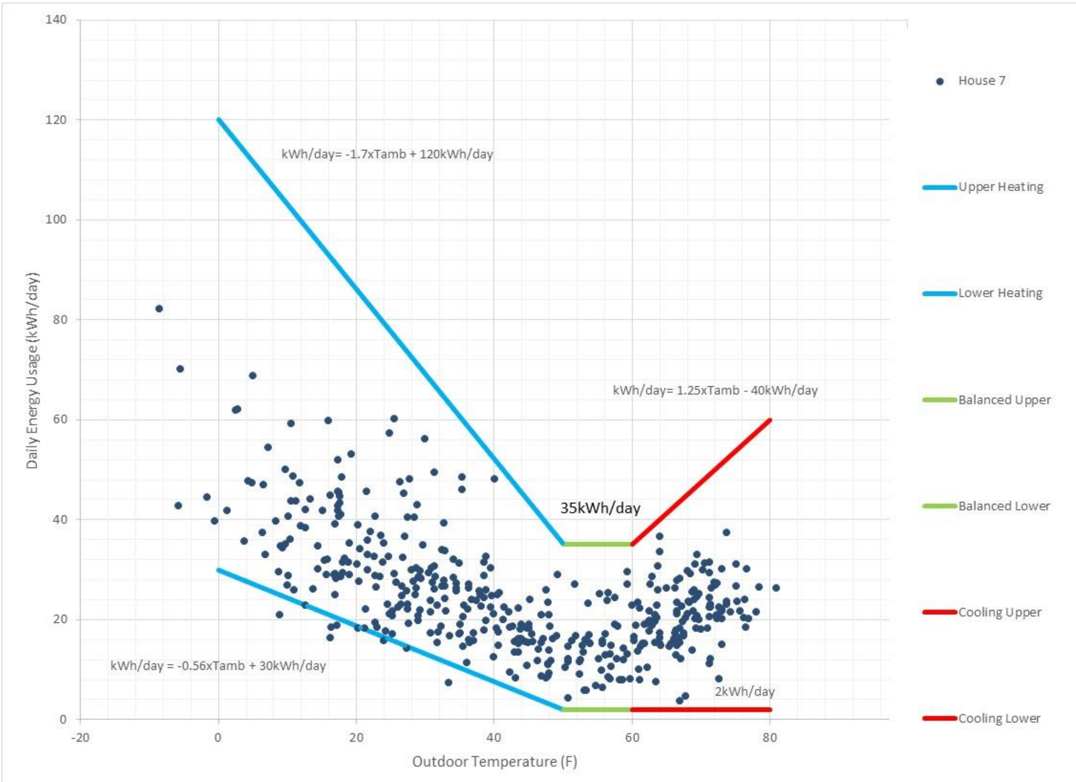
Appendix F – Specific House Energy Characteristics

House 6:

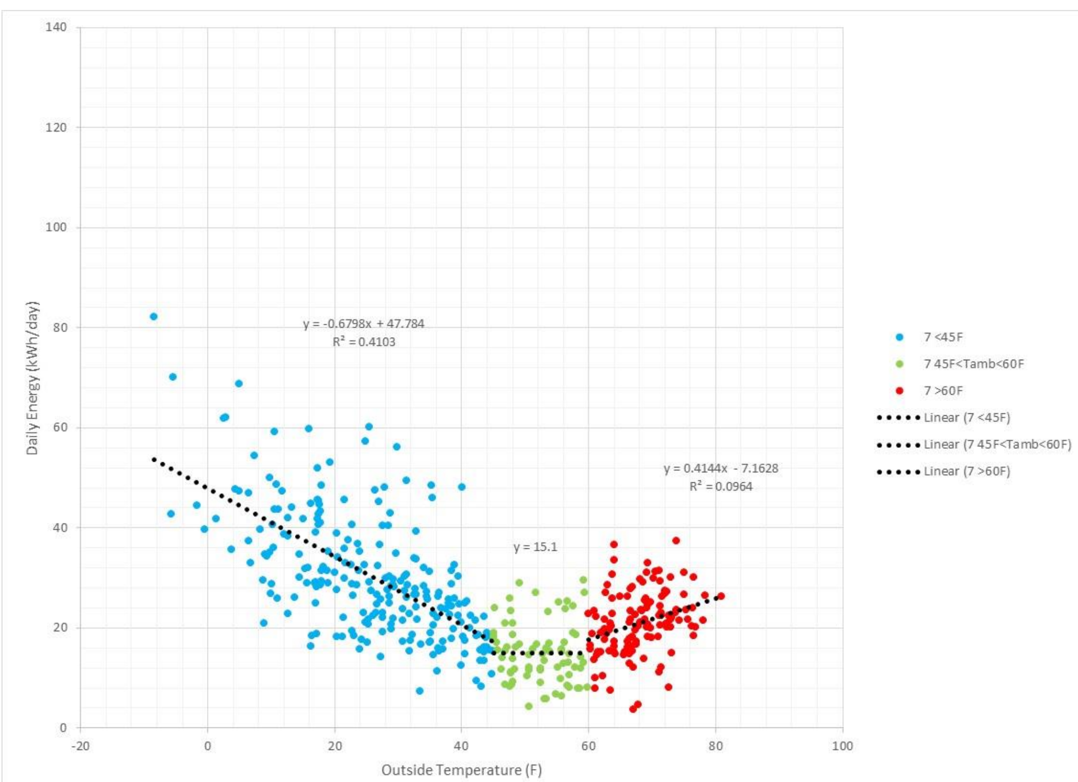




House 7:

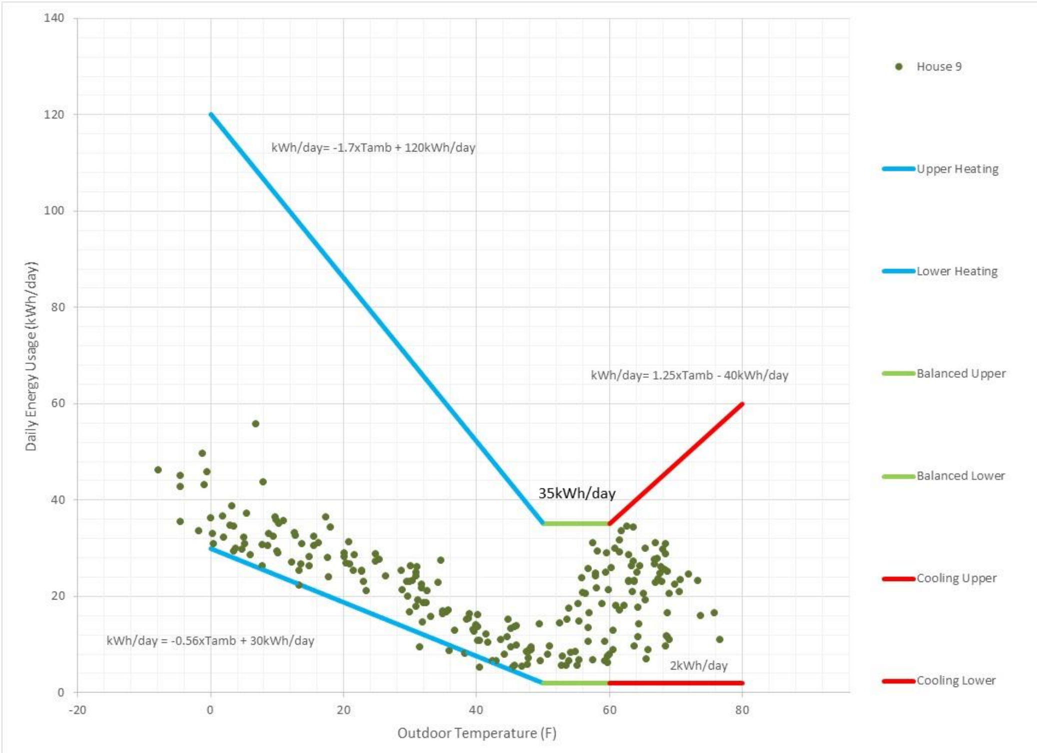


House 7
Upper Heating
Lower Heating
Balanced Upper
Balanced Lower
Cooling Upper
Cooling Lower
kWh/day= -1.7xTamb + 120kWh/day
kWh/day= 1.25xTamb - 40kWh/day
35kWh/day
kWh/day = -0.56xTamb + 30kWh/day
2kWh/day
Daily Energy Usage (kWh/day)
Outdoor Temperature (F)

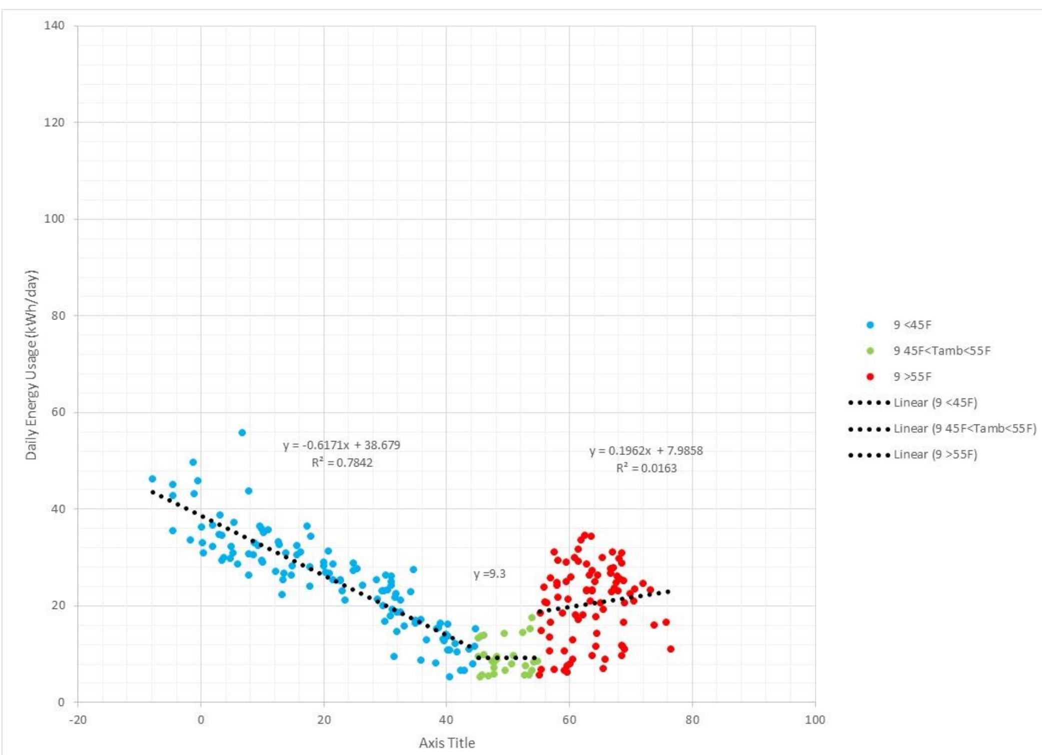


y = -0.6798x + 47.784
R² = 0.4103
y = 0.4144x - 7.1628
R² = 0.0964
y = 15.1
7 <45F
7 45F<Tamb<60F
7 >60F
Linear (7 <45F)
Linear (7 45F<Tamb<60F)
Linear (7 >60F)
Daily Energy (kWh/day)
Outside Temperature (F)

House 9:

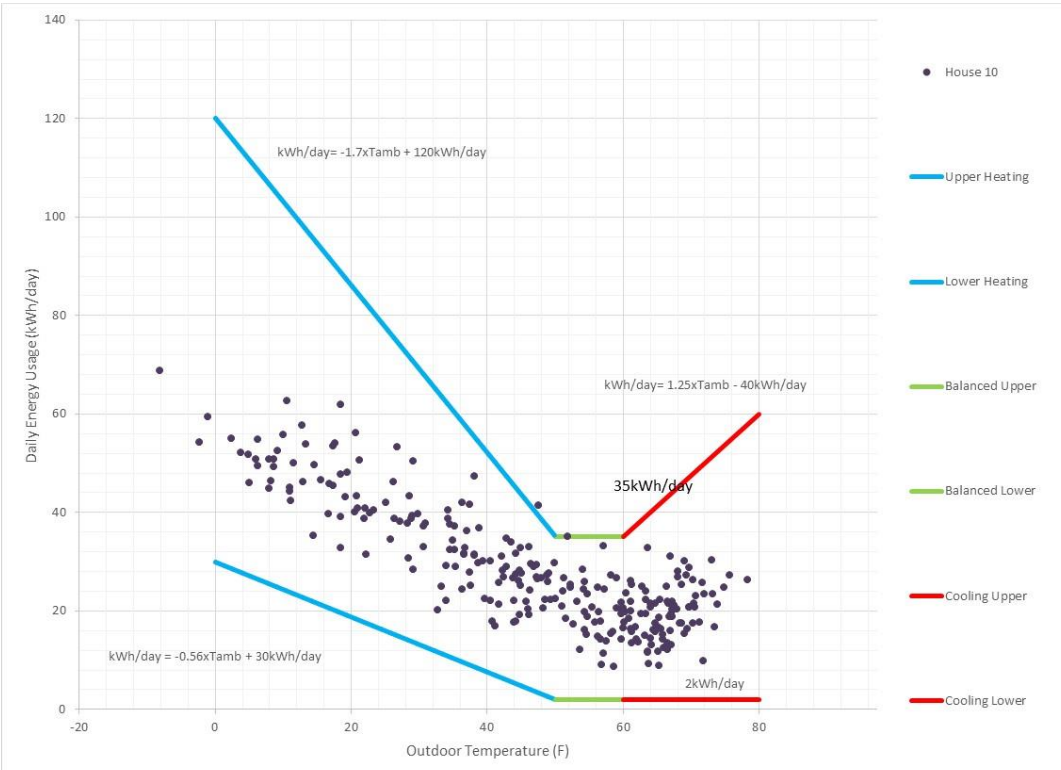


kWh/day= -1.7xTamb + 120kWh/day
kWh/day= 1.25xTamb - 40kWh/day
35kWh/day
kWh/day = -0.56xTamb + 30kWh/day
2kWh/day
Daily Energy Usage (kWh/day)
Outdoor Temperature (F)
House 9
Upper Heating
Lower Heating
Balanced Upper
Balanced Lower
Cooling Upper
Cooling Lower

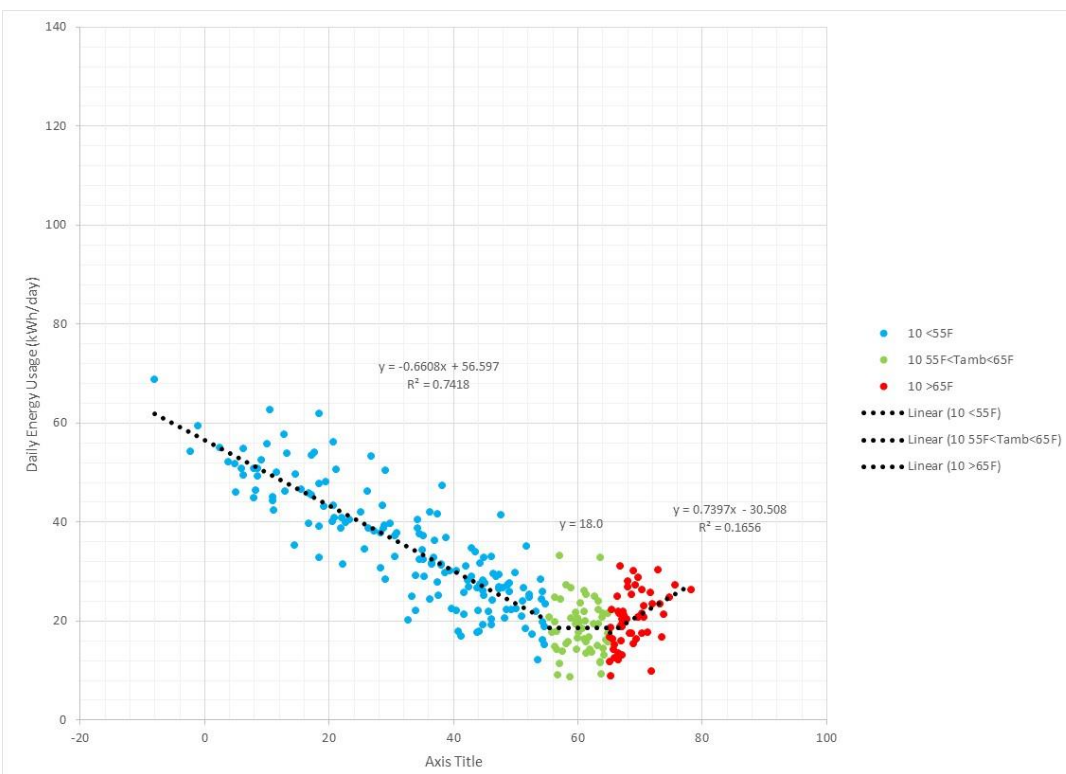


y = -0.6171x + 38.679
R² = 0.7842
y = 0.1962x + 7.9858
R² = 0.0163
y =9.3
Daily Energy Usage (kWh/day)
Axis Title
9 <45F
9 45F<Tamb<55F
9 >55F
Linear (9 <45F)
Linear (9 45F<Tamb<55F)
Linear (9 >55F)

House 10:

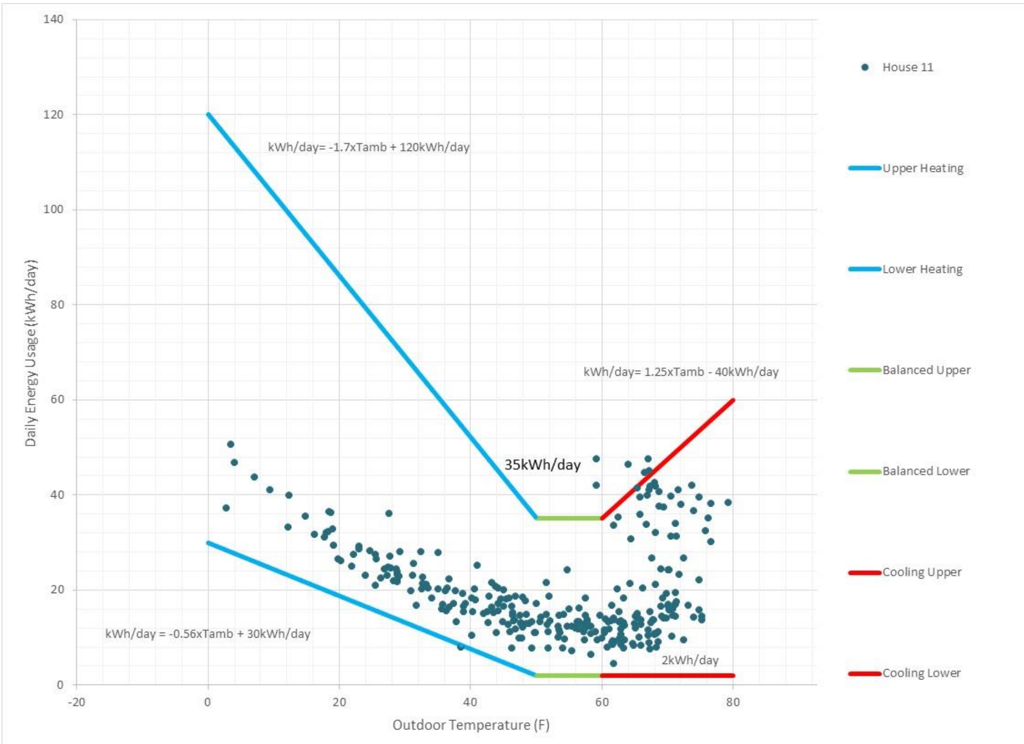


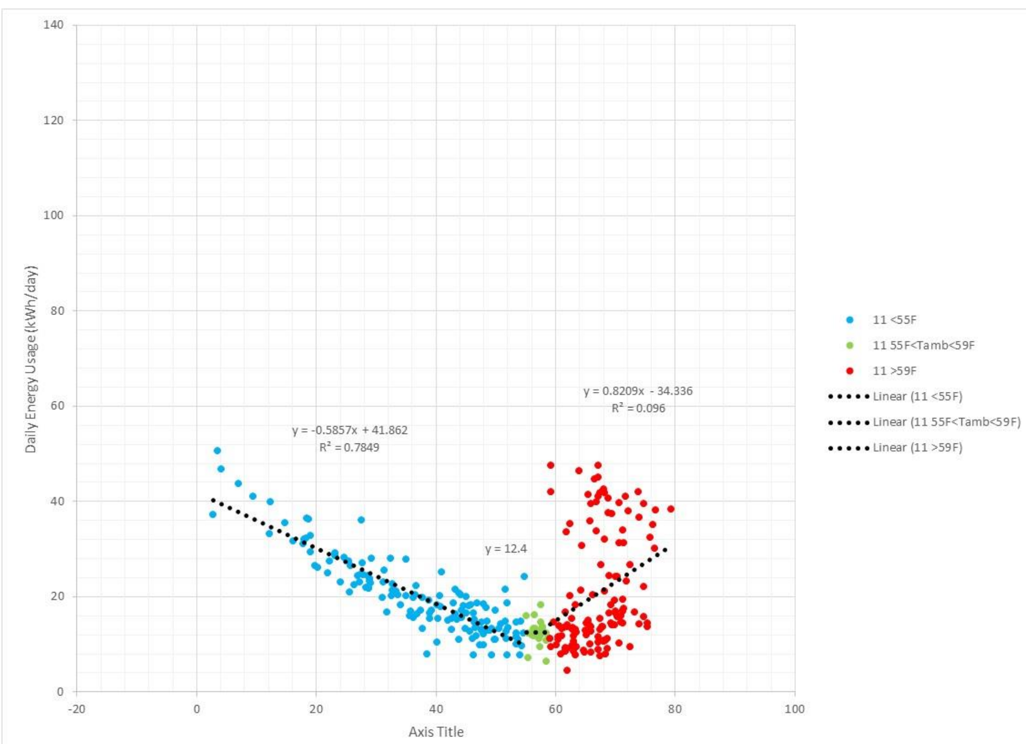
140
120
100
80
60
40
20
0
-20
0
20
40
60
80
Daily Energy Usage (kWh/day)
Outdoor Temperature (F)
kWh/day= -1.7xTamb + 120kWh/day
kWh/day= 1.25xTamb - 40kWh/day
35kWh/day
kWh/day = -0.56xTamb + 30kWh/day
2kWh/day
House 10
Upper Heating
Lower Heating
Balanced Upper
Balanced Lower
Cooling Upper
Cooling Lower



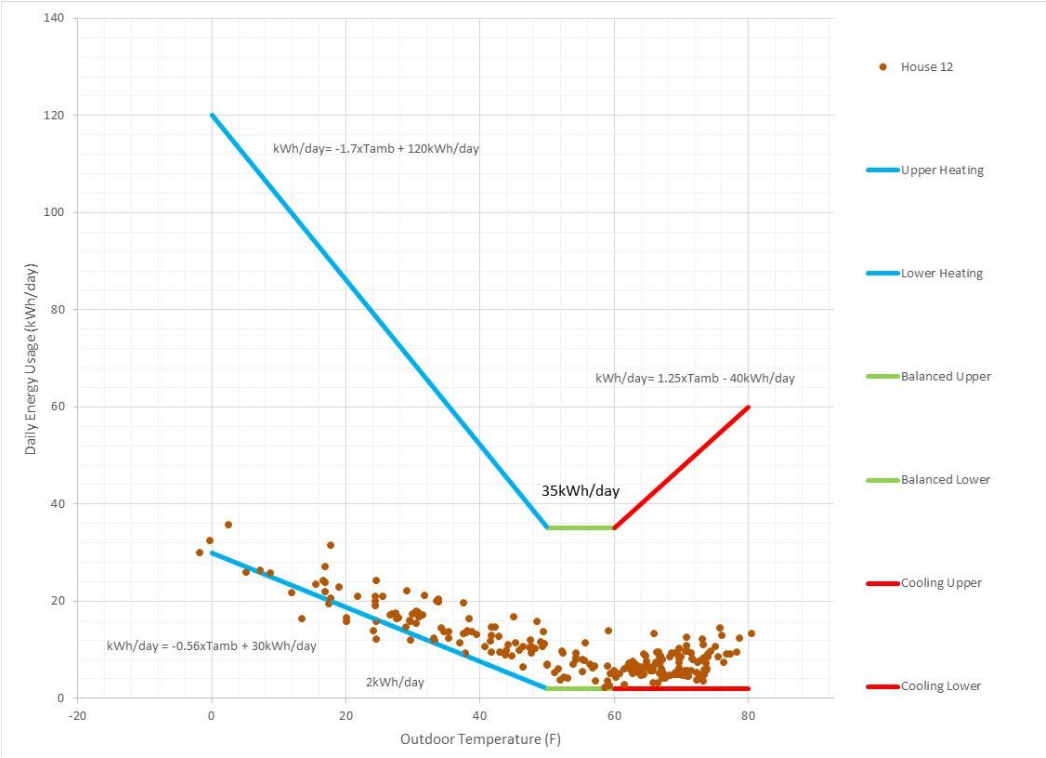
140
120
100
80
60
40
20
0
-20
0
20
40
60
80
100
Daily Energy Usage (kWh/day)
Axis Title
y = -0.6608x + 56.597
R² = 0.7418
y = 18.0
y = 0.7397x - 30.508
R² = 0.1656
10 <55F
10 55F<Tamb<65F
10 >65F
Linear (10 <55F)
Linear (10 55F<Tamb<65F)
Linear (10 >65F)

House 11:

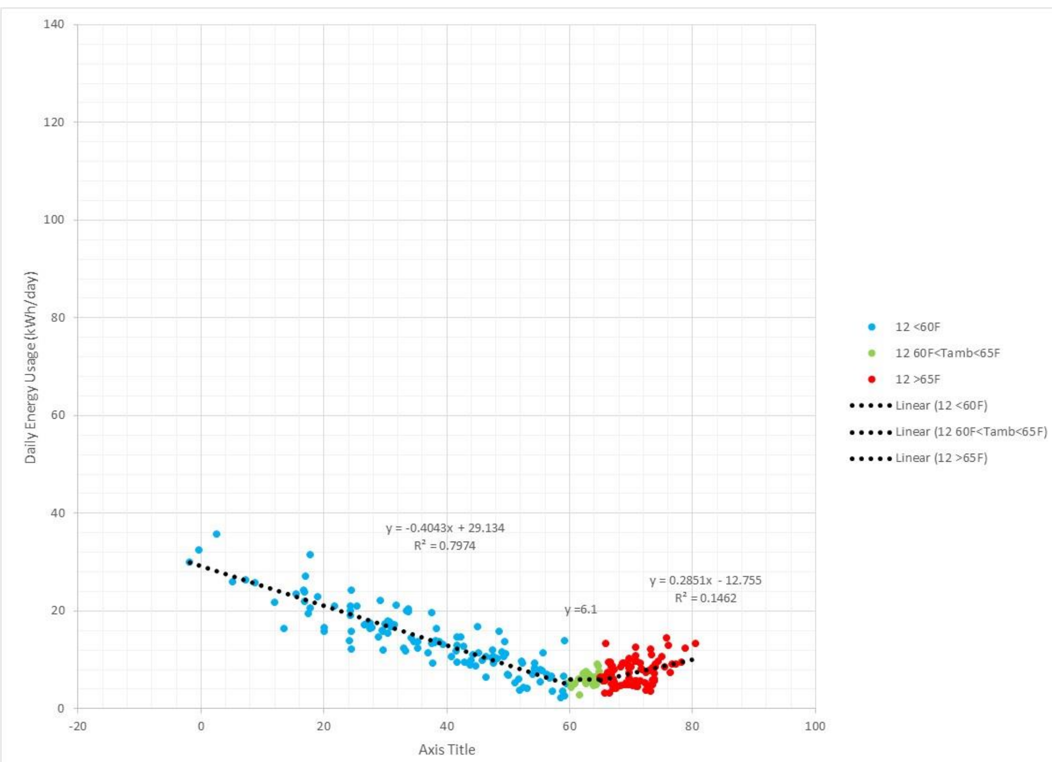

House 11
Upper Heating
Lower Heating
Balanced Upper
Balanced Lower
Cooling Upper
Cooling Lower
kWh/day= -1.7xTamb + 120kWh/day
kWh/day= 1.25xTamb - 40kWh/day
35kWh/day
kWh/day = -0.56xTamb + 30kWh/day
2kWh/day
Daily Energy Usage (kWh/day)
Outdoor Temperature (F)


11 <55F
11 55F<Tamb<59F
11 >59F
Linear (11 <55F)
Linear (11 55F<Tamb<59F)
Linear (11 >59F)
y = 0.8209x - 34.336
R² = 0.096
y = -0.5857x + 41.862
R² = 0.7849
y = 12.4
Daily Energy Usage (kWh/day)
Axis Title

House12:

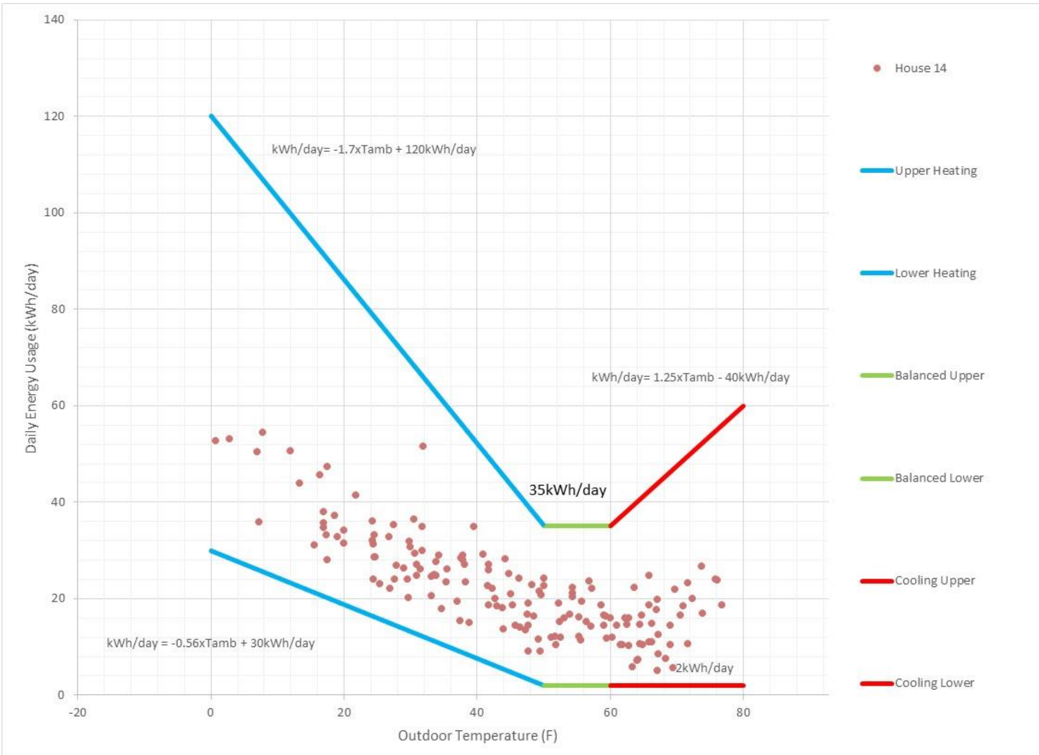


House 12
Upper Heating
Lower Heating
Balanced Upper
Balanced Lower
Cooling Upper
Cooling Lower
kWh/day= -1.7xTamb + 120kWh/day
kWh/day= 1.25xTamb - 40kWh/day
35kWh/day
kWh/day = -0.56xTamb + 30kWh/day
2kWh/day
Daily Energy Usage (kWh/day)
Outdoor Temperature (F)

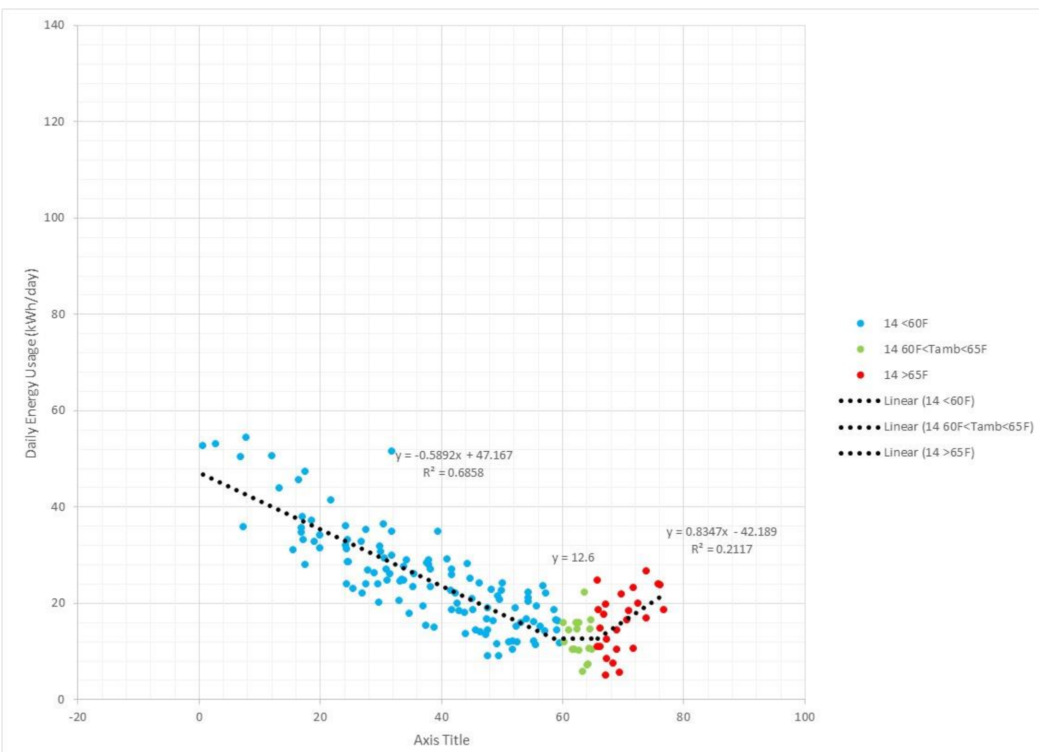


12 <60F
12 60F<Tamb<65F
12 >65F
Linear (12 <60F)
Linear (12 60F<Tamb<65F)
Linear (12 >65F)
y = -0.4043x + 29.134
R² = 0.7974
y = 0.2851x - 12.755
R² = 0.1462
y =6.1
Daily Energy Usage (kWh/day)
Axis Title

House 14:

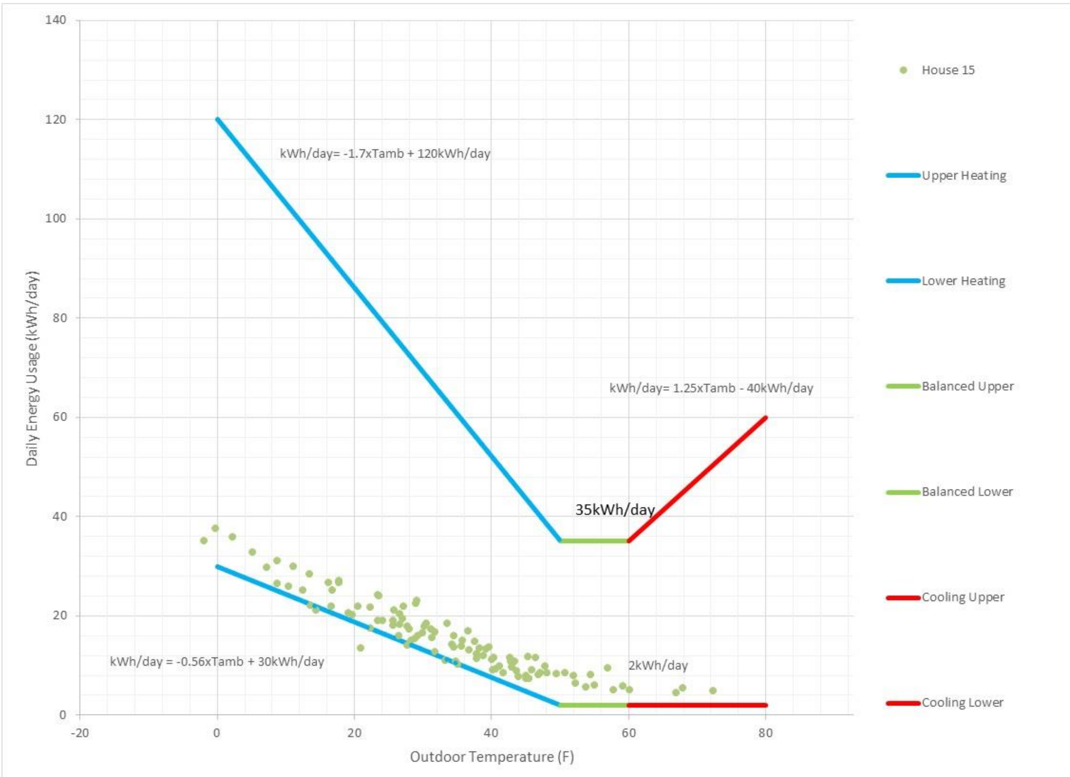


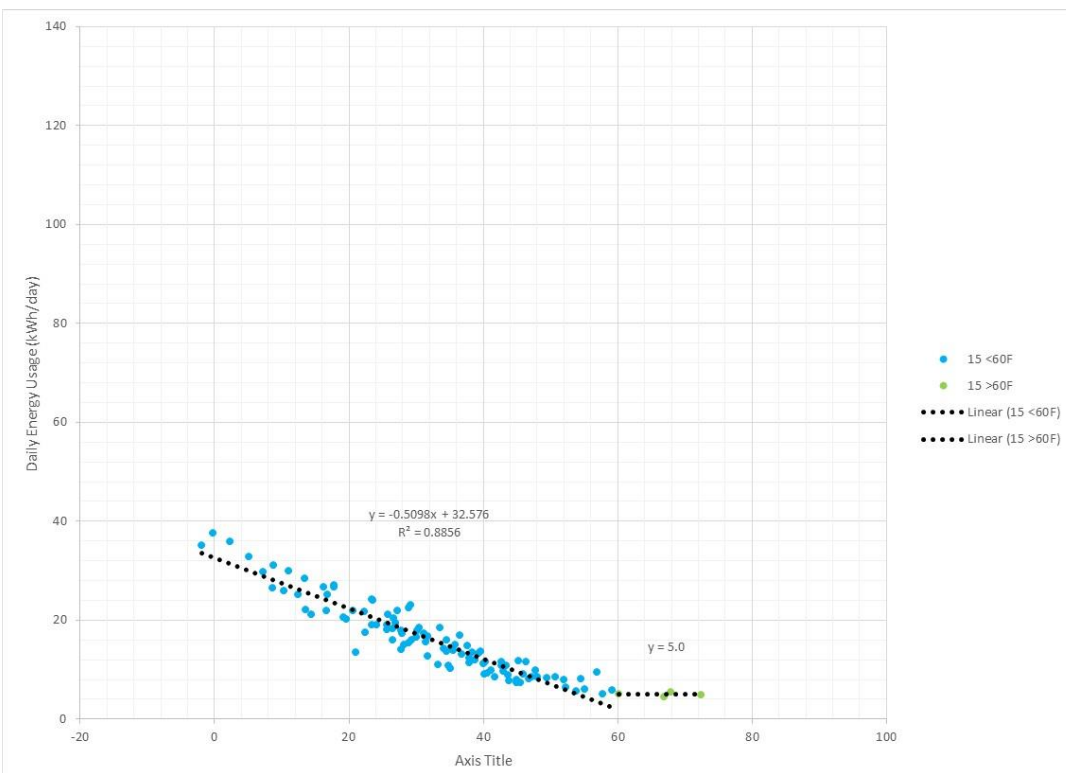
kWh/day= -1.7xTamb + 120kWh/day
kWh/day= 1.25xTamb - 40kWh/day
35kWh/day
kWh/day = -0.56xTamb + 30kWh/day
2kWh/day
Daily Energy Usage (kWh/day)
Outdoor Temperature (F)
House 14
Upper Heating
Lower Heating
Balanced Upper
Balanced Lower
Cooling Upper
Cooling Lower



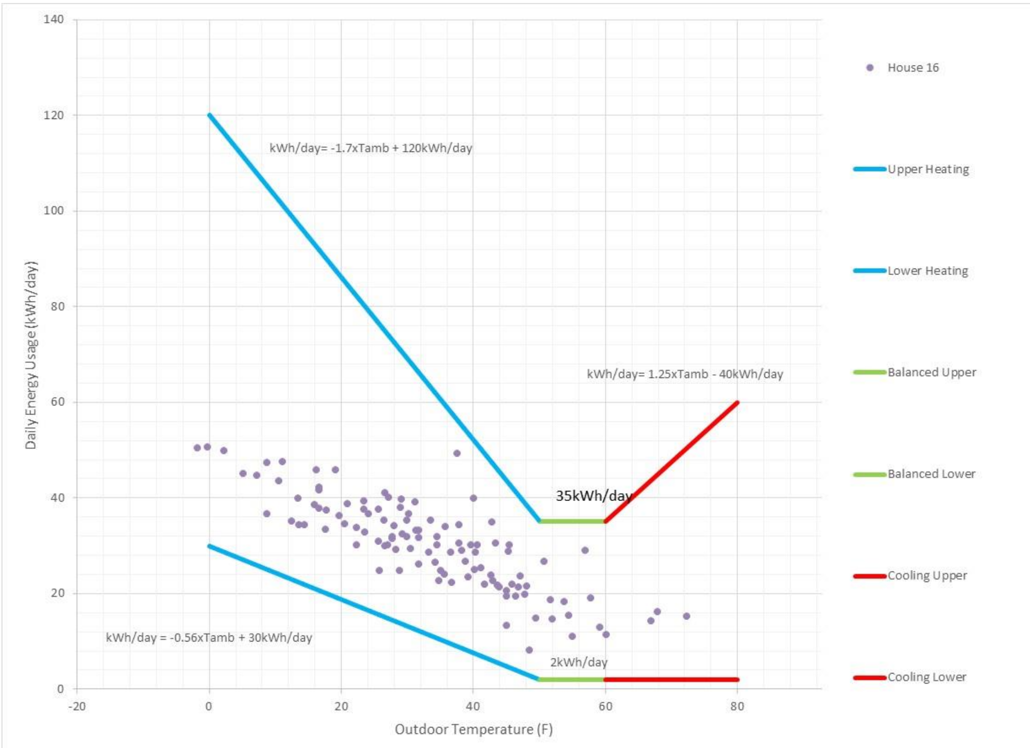
y = -0.5892x + 47.167
R² = 0.6858
y = 12.6
y = 0.8347x - 42.189
R² = 0.2117
Daily Energy Usage (kWh/day)
Axis Title
14 <60F
14 60F<Tamb<65F
14 >65F
Linear (14 <60F)
Linear (14 60F<Tamb<65F)
Linear (14 >65F)

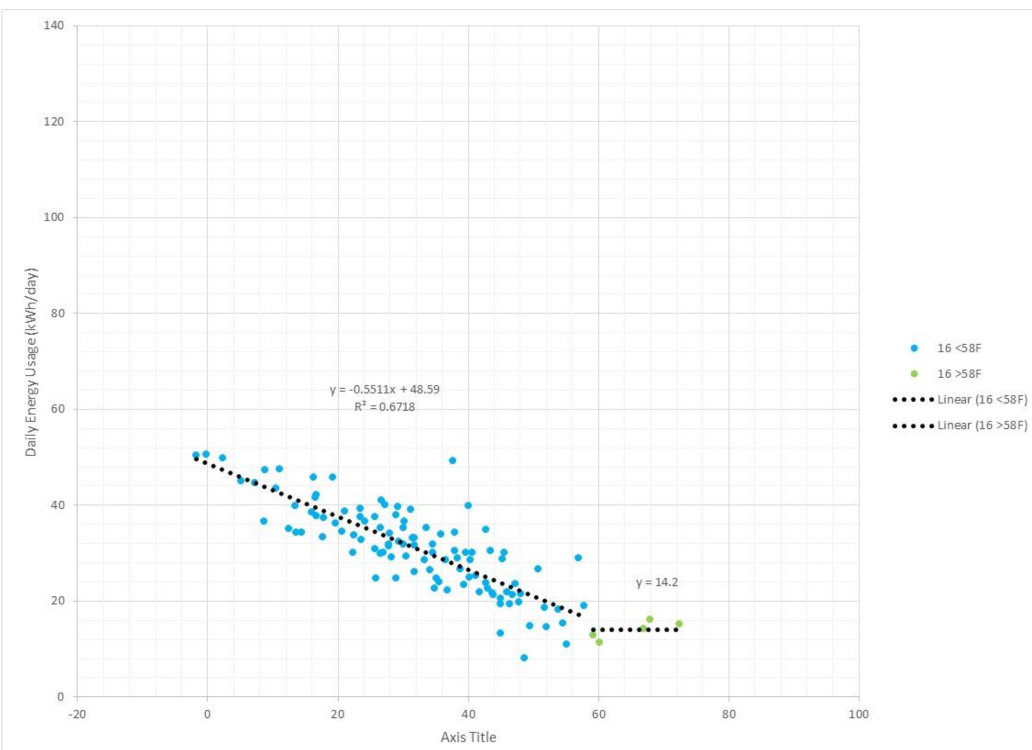
House 15:


House 15
kWh/day= -1.7xTamb + 120kWh/day
kWh/day= 1.25xTamb - 40kWh/day
35kWh/day
kWh/day = -0.56xTamb + 30kWh/day
2kWh/day
Upper Heating
Lower Heating
Balanced Upper
Balanced Lower
Cooling Upper
Cooling Lower
Daily Energy Usage (kWh/day)
Outdoor Temperature (F)

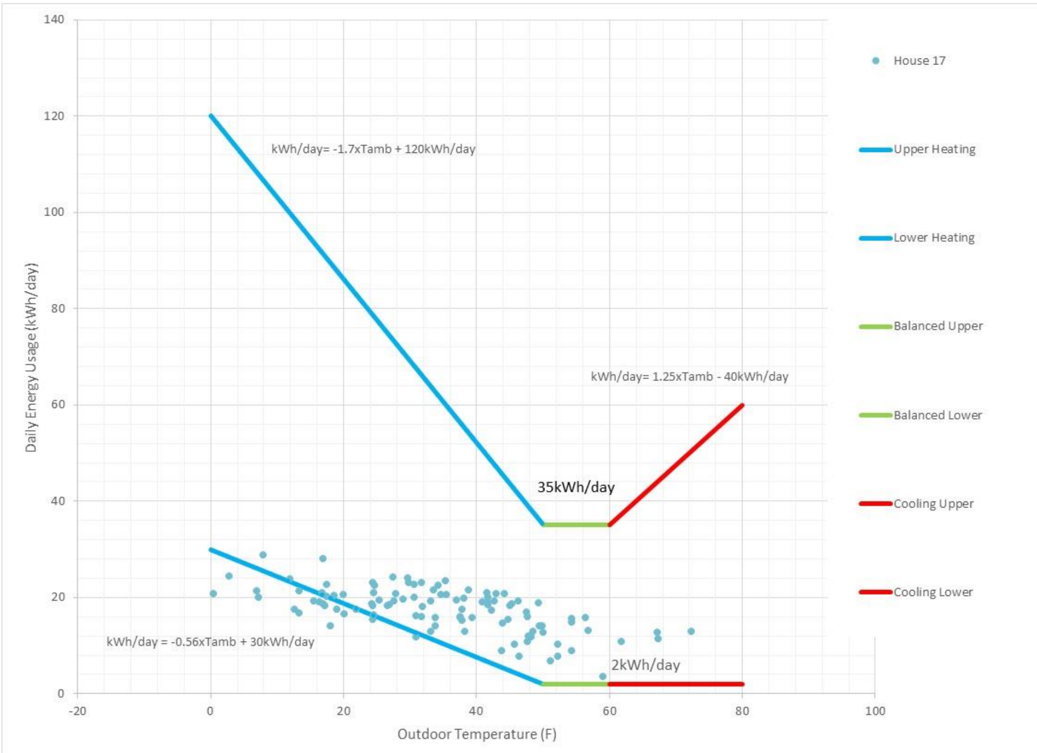

y = -0.5098x + 32.576
R² = 0.8856
y = 5.0
15 <60F
15 >60F
Linear (15 <60F)
Linear (15 >60F)
Daily Energy Usage (kWh/day)
Axis Title

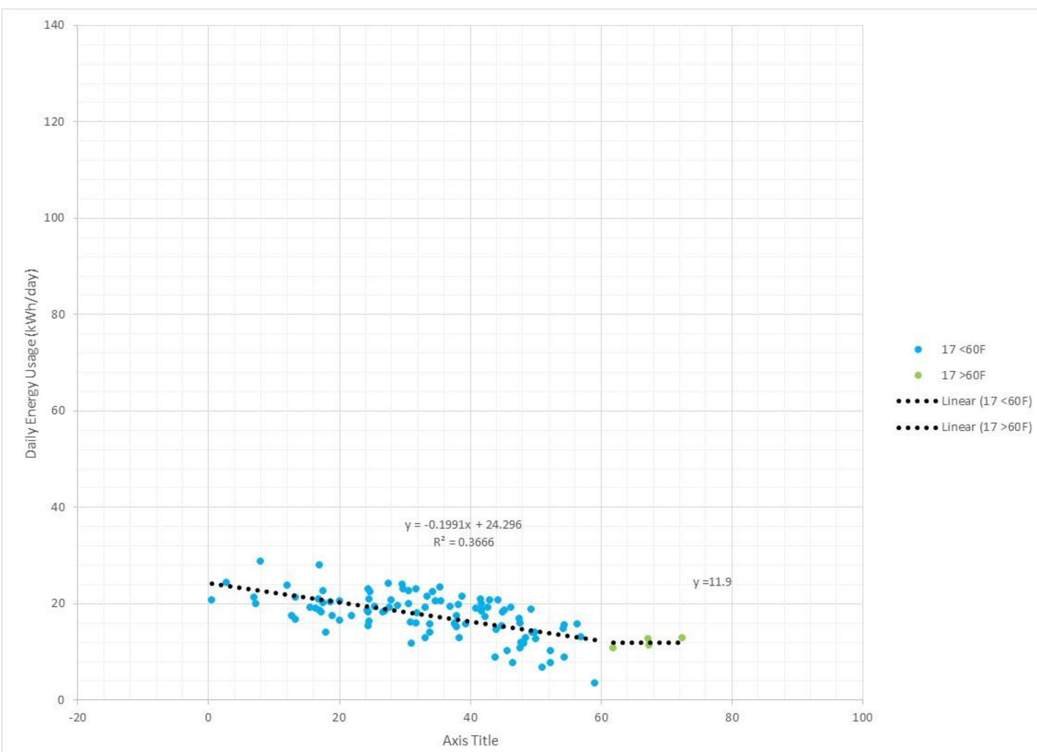
House 16:


kWh/day= -1.7xTamb + 120kWh/day
kWh/day= 1.25xTamb - 40kWh/day
35kWh/day
2kWh/day
kWh/day = -0.56xTamb + 30kWh/day
Daily Energy Usage (kWh/day)
Outdoor Temperature (F)
House 16
Upper Heating
Lower Heating
Balanced Upper
Balanced Lower
Cooling Upper
Cooling Lower

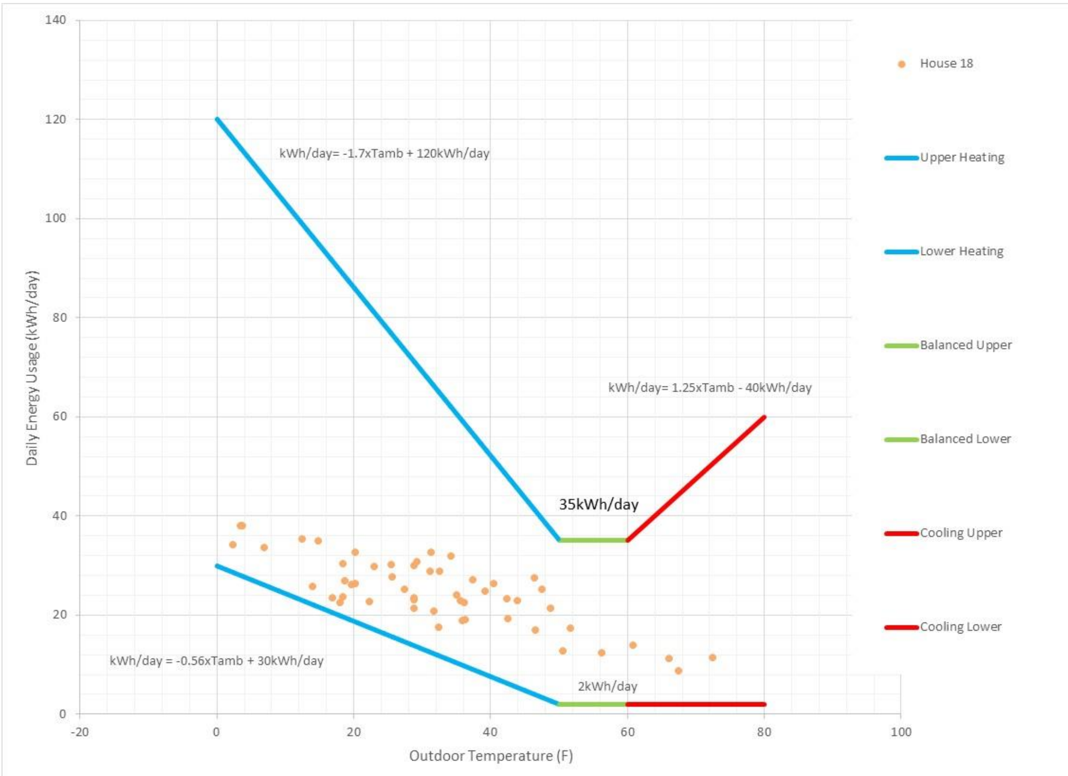

y = -0.5511x + 48.59
R² = 0.6718
y = 14.2
Daily Energy Usage (kWh/day)
Axis Title
16 <58F
16 >58F
Linear (16 <58F)
Linear (16 >58F)

House 17:

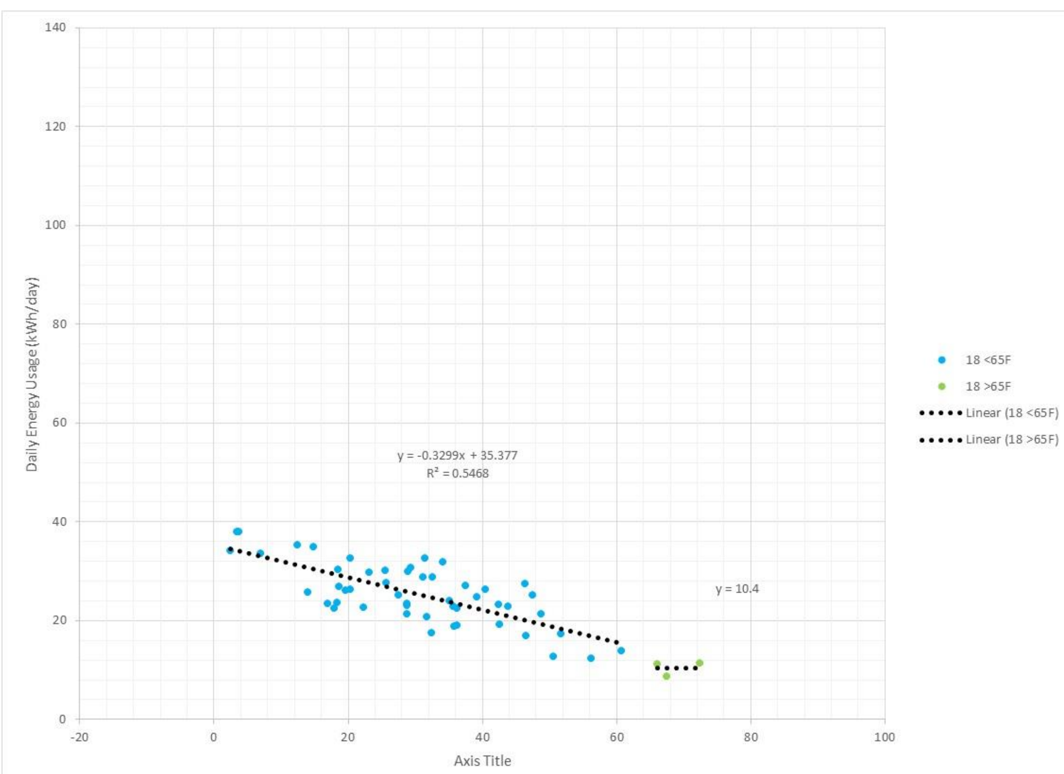

House 17
Upper Heating
Lower Heating
Balanced Upper
Balanced Lower
Cooling Upper
Cooling Lower
kWh/day= -1.7xTamb + 120kWh/day
kWh/day= 1.25xTamb - 40kWh/day
35kWh/day
kWh/day = -0.56xTamb + 30kWh/day
2kWh/day
Daily Energy Usage (kWh/day)
Outdoor Temperature (F)


17 <60F
17 >60F
Linear (17 <60F)
Linear (17 >60F)
y = -0.1991x + 24.296
R² = 0.3666
y =11.9
Daily Energy Usage (kWh/day)
Axis Title

House 18:

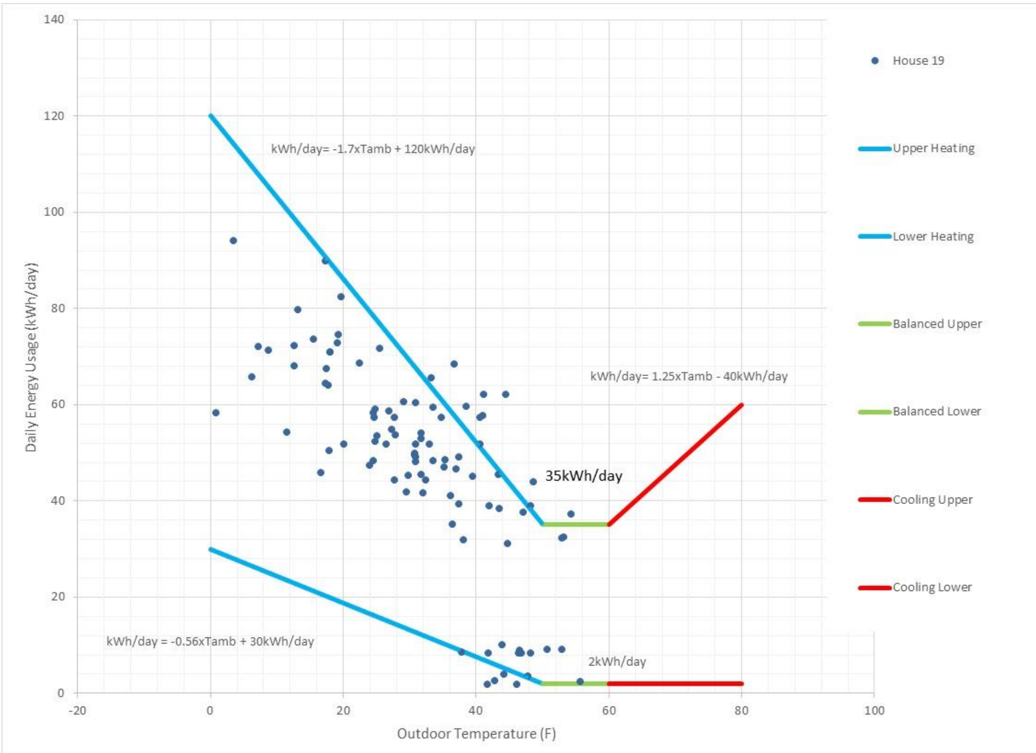


Daily Energy Usage (kWh/day)
Outdoor Temperature (F)
kWh/day= -1.7xTamb + 120kWh/day
kWh/day= 1.25xTamb - 40kWh/day
35kWh/day
kWh/day = -0.56xTamb + 30kWh/day
2kWh/day
House 18
Upper Heating
Lower Heating
Balanced Upper
Balanced Lower
Cooling Upper
Cooling Lower

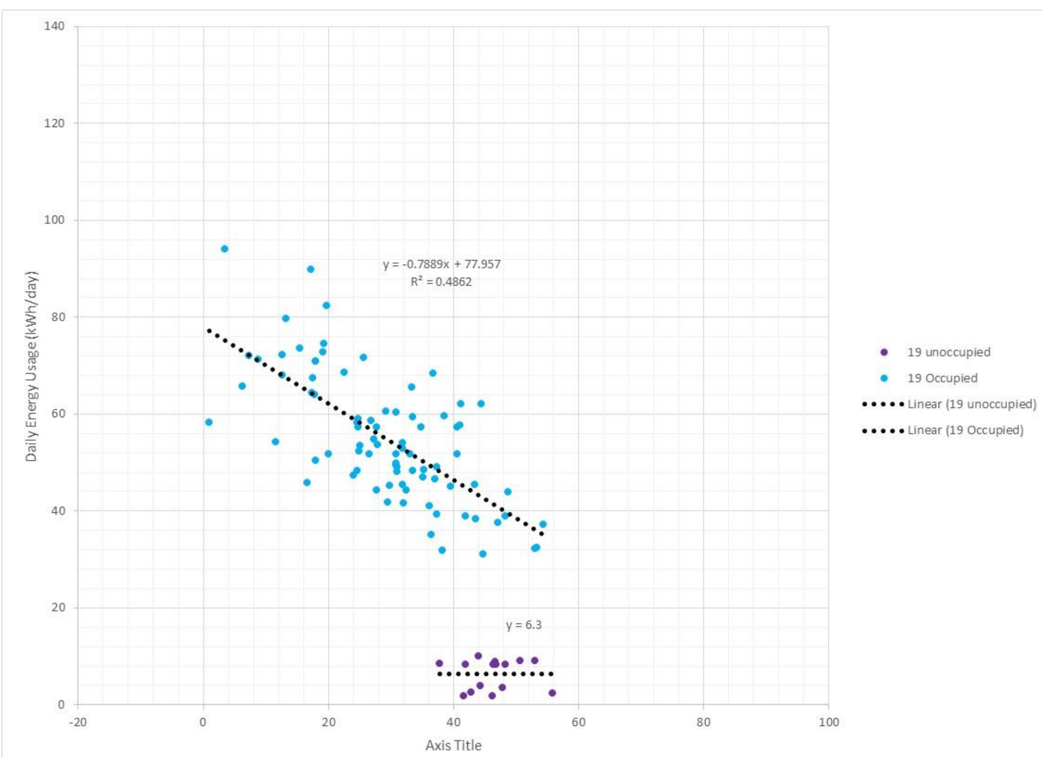


Daily Energy Usage (kWh/day)
Axis Title
y = -0.3299x + 35.377
R² = 0.5468
y = 10.4
18 <65F
18 >65F
Linear (18 <65F)
Linear (18 >65F)

House 19:

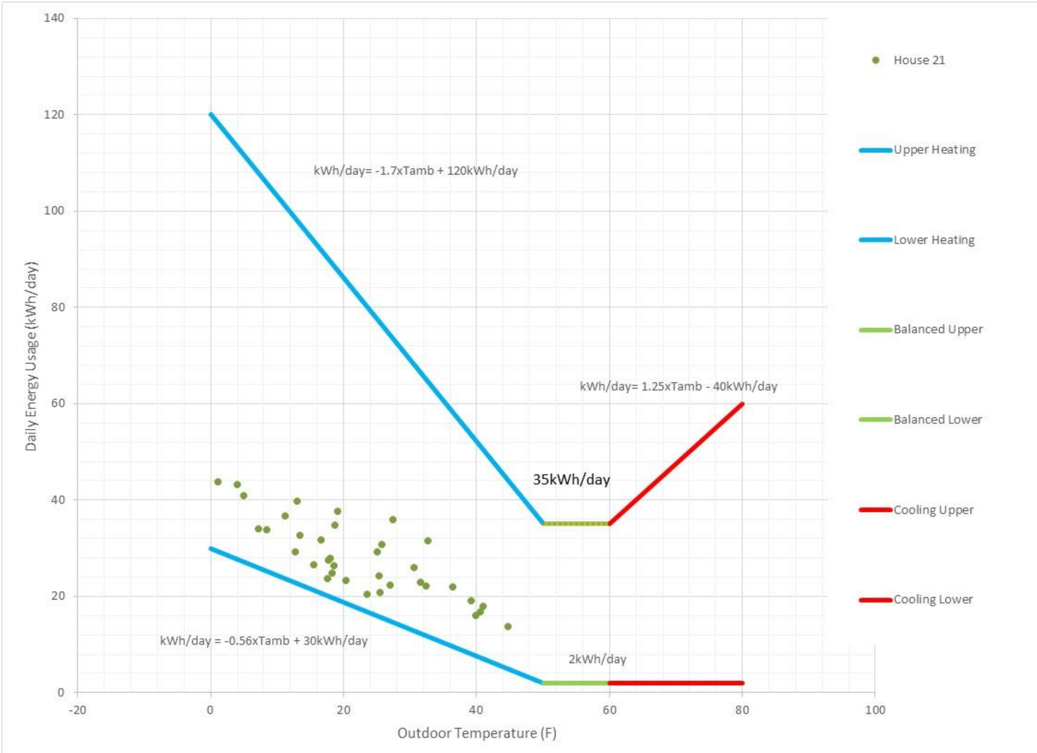


House 19
Upper Heating
Lower Heating
Balanced Upper
Balanced Lower
Cooling Upper
Cooling Lower
kWh/day= -1.7xTamb + 120kWh/day
kWh/day= 1.25xTamb - 40kWh/day
35kWh/day
kWh/day = -0.56xTamb + 30kWh/day
2kWh/day
Daily Energy Usage (kWh/day)
Outdoor Temperature (F)

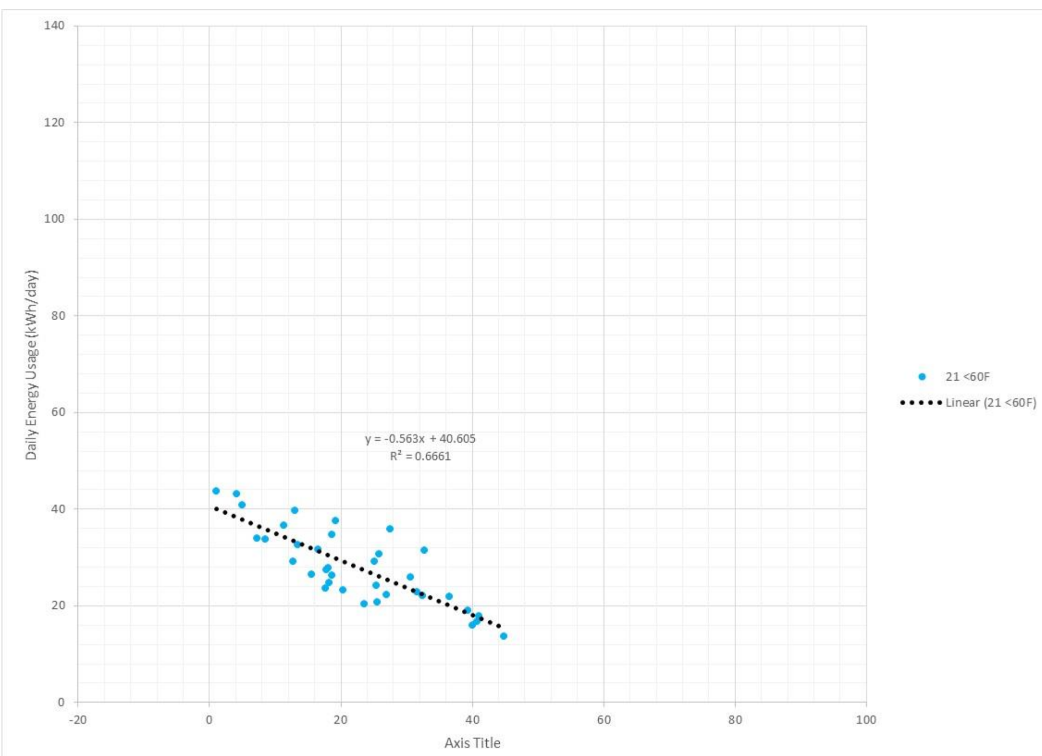


y = -0.7889x + 77.957
R² = 0.4862
y = 6.3
19 unoccupied
19 Occupied
Linear (19 unoccupied)
Linear (19 Occupied)
Daily Energy Usage (kWh/day)
Axis Title

House 21:



House 21
Upper Heating
Lower Heating
Balanced Upper
Balanced Lower
Cooling Upper
Cooling Lower
kWh/day= -1.7xTamb + 120kWh/day
kWh/day= 1.25xTamb - 40kWh/day
35kWh/day
kWh/day = -0.56xTamb + 30kWh/day
2kWh/day
Daily Energy Usage (kWh/day)
Outdoor Temperature (F)



21 <60F
Linear (21 <60F)
y = -0.563x + 40.605
R² = 0.6661
Daily Energy Usage (kWh/day)
Axis Title

Appendix G – House Energy Usage

House 6	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other	Total	NonComf	TotComf
kWh/day	3.78	0.06	0.67	0.00	0.01	0.15	0.40	7.75	10.63	0.00	23.46	5.08	18.38
	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other	Total		
kWh/Occ-	0.94	0.02	0.17	0.00	0.00	0.04	0.10	1.94	2.66	0.00	5.86	1.27	4.59
	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other			
%	16.1	0.3	2.9	0.0	0.0	0.7	1.7	33.0	45.3	0.0	100.0	21.7	78.3

House 7	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other	Total	NonComf	TotComf
kWh/day	3.86	0.99	1.16	0.07	0.08	1.52	4.14	7.40	8.13	0.00	27.34	11.81	15.53
	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other	Total		
kWh/Occ-day	2.57	0.66	0.77	0.05	0.05	1.01	2.76	4.93	5.42	0.00	18.23	7.87	10.35
	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other			
%	14.1	3.6	4.2	0.3	0.3	5.6	15.1	27.1	29.7	0.0	100.0	43.2	56.8

House 9	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other	Total	NonComf	TotComf
kWh/day	0.38	0.00	0.58	0.00	0.00	0.01	0.65	6.75	5.97	0.00	14.34	1.62	12.72
	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other	Total		
kWh/Occ-	0.38	0.00	0.58	0.00	0.00	0.01	0.65	6.75	5.97	0.00	14.34	1.62	12.72
	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other			
%	2.7	0.0	4.0	0.0	0.0	0.0	4.5	47.1	41.7	0.0	100.0	11.3	88.7

House 10	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other	Total	NonComf	TotComf
kWh/day	7.08	1.77	0.86	0.29	0.00	3.24	4.69	7.19	6.11	0.12	31.35	18.05	13.30
	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other	Total		
kWh/Occ-	1.42	0.35	0.17	0.06	0.00	0.65	0.94	1.44	1.22	0.02	6.27	3.61	2.66
	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other			
%	22.6	5.6	2.7	0.9	0.0	10.3	15.0	22.9	19.5	0.4	100.0	57.6	42.4

House 11	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other	Total	NonComf	TotComf
kWh/day	5.84	0.45	0.75	0.06	0.04	0.54	1.11	5.33	4.97	0.00	19.08	8.78	10.30
	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other	Total		
kWh/Occ-	5.84	0.45	0.75	0.06	0.04	0.54	1.11	5.33	4.97	0.00	19.08	8.78	10.30
	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other			
%	30.6	2.3	3.9	0.3	0.2	2.9	5.8	27.9	26.0	0.0	100.0	46.0	54.0

House 12	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other	Total	NonComf	TotComf
kWh/day	4.46	1.08	0.76	0.35	0.07	0.97	1.43	5.34	3.26	0.00	17.72	9.13	8.60
	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other	Total		
kWh/Occ-	4.46	1.08	0.76	0.35	0.07	0.97	1.43	5.34	3.26	0.00	17.72	9.13	8.60
	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other			
%	25.2	6.1	4.3	2.0	0.4	5.5	8.1	30.1	18.4	0.0	100.0	51.5	48.5

House 14	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other	Total	NonComf	TotComf
kWh/day	6.33	1.39	0.81	0.00	0.16	2.54	2.47	5.39	4.06	1.28	24.44	14.98	9.45
	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other	Total		
kWh/Occ-	1.58	0.35	0.20	0.00	0.04	0.64	0.62	1.35	1.02	0.32	6.11	3.75	2.36
	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other			
%	25.9	5.7	3.3	0.0	0.7	10.4	10.1	22.1	16.6	5.2	100.0	61.3	38.7

House 15	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other	Total	NonComf	TotComf
kWh/day	3.41	0.51	0.79	0.00	0.03	0.02	0.80	2.69	6.20	0.02	14.48	5.58	8.90
	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other	Total		
kWh/Occ-	3.41	0.51	0.79	0.00	0.03	0.02	0.80	2.69	6.20	0.02	14.48	5.58	8.90
	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other			
%	23.5	3.5	5.4	0.0	0.2	0.1	5.5	18.6	42.8	0.2	100.0	38.6	61.4

House 16	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other	Total	NonComf	TotComf
kWh/day	3.82	2.00	0.81	0.54	0.22	4.00	3.47	7.41	6.84	1.13	30.25	16.00	14.25
	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other	Total		
kWh/Occ-	3.82	2.00	0.81	0.54	0.22	4.00	3.47	7.41	6.84	1.13	30.25	16.00	14.25
	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other			
%	12.6	6.6	2.7	1.8	0.7	13.2	11.5	24.5	22.6	3.7	100.0	52.9	47.1

House 17	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other	Total	NonComf	TotComf
kWh/day	3.95	0.06	0.60	0.00	0.01	0.00	0.73	6.34	2.44	0.24	14.38	5.59	8.78
	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other	Total		
kWh/Occ-	3.95	0.06	0.60	0.00	0.01	0.00	0.73	6.34	2.44	0.24	14.38	5.59	8.78
	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other			
%	27.5	0.4	4.2	0.0	0.1	0.0	5.0	44.1	17.0	1.7	100.0	38.9	61.1

House 18	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other	Total	NonComf	TotComf
kWh/day	3.36	1.81	0.73	0.59	0.17	2.39	2.03	9.62	2.91	0.08	23.69	11.17	12.52
	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other	Total		
kWh/Occ-	0.84	0.45	0.18	0.15	0.04	0.60	0.51	2.40	0.73	0.02	5.92	2.79	3.13
	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other			
%	14.2	7.6	3.1	2.5	0.7	10.1	8.5	40.6	12.3	0.3	100.0	47.1	52.9

House 19 Occupied

House 19	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other	Total	NonComf	TotComf
kWh/day	5.23	8.37	1.34	0.67	0.20	2.67	7.25	6.82	13.15	0.02	45.74	25.77	19.97
	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other	Total		
kWh/Occ-	1.05	1.67	0.27	0.13	0.04	0.53	1.45	1.36	2.63	0.00	9.15	5.15	3.99
	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other			
%	11.4	18.3	2.9	1.5	0.4	5.8	15.9	14.9	28.8	0.0	100.0	56.3	43.7

House 19 Unoccupied

House 19	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other	Total	NonComf	TotComf
kWh/day	0.22	0.00	0.45	0.00	0.00	0.00	0.00	2.63	0.13	0.00	3.43	0.67	2.76
	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other	Total		
kWh/Occ-	0.22	0.00	0.45	0.00	0.00	0.00	0.00	2.63	0.13	0.00	3.43	0.67	2.76
	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other			
%	6.5	0.0	13.2	0.0	0.0	0.0	0.0	76.6	3.8	0.0	100.0	19.6	80.4

House 21	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other	Total	NonComf	TotComf
kWh/day	2.72	0.40	0.84	0.24	0.04	0.49	1.59	9.59	14.96	0.29	31.16	6.62	24.55
	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other	Total		
kWh/Occ-	1.36	0.20	0.42	0.12	0.02	0.24	0.79	4.79	7.48	0.15	6.23	3.31	12.27
	Misc Elec	Cooking	Refrig	Dish	Washer	Dryer	WaterH	Vent	Comf	Other			
%	8.7	1.3	2.7	0.8	0.1	1.6	5.1	30.8	48.0	0.9	100.0	21.2	78.8