Energy - Docket Optical System

From:	Roger LeBrun [roger.lebrun@velux.com]
Sent:	Thursday, July 24, 2014 9:15 AM
To:	Shirakh, Maziar@Energy
Cc:	Energy - Docket Optical System
Subject:	Docket #2014-BSTD-01 - CEC - 2016 Building Energy Efficiency Standards - Proposed Energy Efficiency Measures - Residential Ventilation Compliance Credit
Attachments:	VELUX Skylight Ventilation Study - Boston.pdf
Categories:	Waiting for Reply

Dear Mr. Shirakh,

Thank you for the opportunity, during yesterday's Staff Workshop, to ask a question during the closing session. Recall that I had inquired about whether the Commission has considered the use of venting skylights as an alternative to the whole house fan credit, which is being proposed as an efficiency measure.

VELUX would like to make you aware of a recent study we commissioned, through Group14 Engineering, that examined the benefits and cost savings of venting skylights vis-à-vis whole house fans in two house configurations and two home performance levels in one city. I am attaching the full report of that study so you can see the methodology and modeling tools the consultant thought were most appropriate.

Based on the encouraging results in Boston, we authorized Group14 to extend the study to many additional cities across the US climate zone map, including Los Angeles. We expect a preliminary report in a matter of days, which we are told will show similar rankings of the two ventilation methods across the board, but with different degrees of savings.

This was a groundbreaking effort to measure, for the first time, the known benefits of natural ventilation when intelligently deployed. We would like the Commission to take a longer look at whether the builder industry should be afforded the flexibility of choosing a natural solution instead of a power-consuming one that is more effective for bringing in fresher, cooler air, and brings other benefits beyond what the fan option can offer.

If this is an option the Commission will seriously consider, we will forward the extended study report when it becomes available.

Best Regards,

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A Study of Venting Skylights in Homes in Boston, Massachusetts

Prepared for

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April 4, 2014

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Executive Summary

This study analyzes the energy cost, indoor air quality and thermal comfort impacts of VELUX venting skylights and compares them with those of whole house fans in residential homes. A vaulted ceiling 2,000ft^2 2-story house located in Boston, Massachusetts is modeled with two levels of energy efficiency: Code Base Home and High Performance Home. The modeled house has a partial 2-story high space with skylights above to investigate the stack effect impact.

EnergyPlus v8.0 along with Contam, LoopDA and BEopt were used to analyze the coupling effects of air flow, contaminant flow and energy flow.

ENERGY COST: The study reveals that adding venting skylights will result in energy cost savings compared to a home without skylights. In the Code Base Home, the venting skylights generate $35 of annual energy cost savings from the home without skylights or natural ventilation. In the High Performance home with reduced cooling loads, the venting skylights result in $17 of annual energy cost savings compared to the case without skylights. The savings are based on intelligent placement of the venting skylights for wind effects, a natural ventilation setpoint temperature of 75°F and an integral rain sensor control.

INDOOR ENVIRONMENTAL QUALITY (IEQ): In both the Code Base Home and High Performance Home, indoor air quality is significantly improved when the venting skylights are used leading to a very quick dilution of predictable indoor contaminant concentrations. (With the known physiological and psychological benefits of daylight, especially from the sky, IEQ is further enhanced.)

HUMAN COMFORT: Both Fanger and Adaptive ASHRAE 55 thermal comfort models were used to analyze home comfort conditions. When the Adaptive ASHRAE 55 model is used to account for occupant's behavior and expectations adaptation during the natural ventilation mode, the study predicts slightly improved comfort conditions in both the Code Base Home and High Performance Home with venting skylights.

A whole house fan behaves similarly to venting skylights in terms of indoor air quality and thermal comfort improvements. However, contrary to claims by most whole house fan advocates, a whole house fan does not always reduce a home's energy cost. The natural ventilation savings are offset by fan energy in the study homes located in Boston, Massachusetts, even with an efficient fan motor.

The study was further extended to a one-story 2,000 square feet house to examine the energy cost impact of venting skylights. The analysis reveals a similar trend: in the 1-story Code Base Home, adding venting skylights results in $27 of annual energy cost savings from the base case without skylights or natural ventilation. And in the 1-story High Performance Home, adding venting skylights results in $13 of energy cost savings from the base case without skylights or natural ventilation. The savings are also based on thoughtful placement of the venting skylights, a natural ventilation setpoint temperature of 75°F and an integral rain sensor control. Further studies are recommended that can account for shaded skylights, with both manual and automated controls, to reflect additional energy cost savings as well as glare control that may be realized at low initial added cost when specified at the time of skylight procurement.

Table of Contents

List of Tables & Figures

1 Introduction

This study analyzes the energy and certain use-phase environmental impacts of venting skylights in residential homes in cold climates. The study home is located in Boston, MA (climate zone 5). Energy cost, indoor air quality (IAQ) and thermal comfort are analyzed for the homes with venting skylights against the baselines of the homes with no skylights. An alternate technology, whole house fans, are also analyzed for comparison.

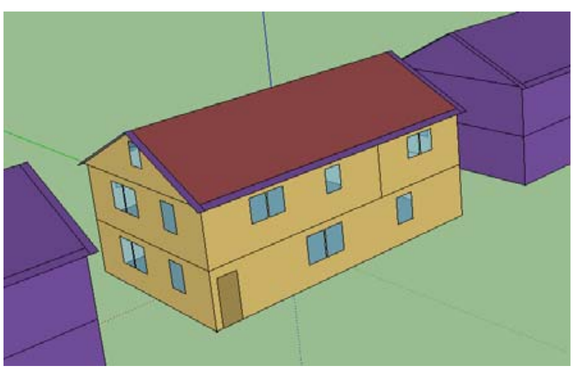
EnergyPlus V8.0, along with BEopt (Building Energy Optimization software), Contam (a multizone indoor air quality and ventilation analysis program) and LoopDA (Loop Design and Analysis tool) are used in the study. EnergyPlus V8.0 can predict thermal comfort and account for the coupling effects of air flow, contaminant flow and energy flow in a building.

Daylight benefits of skylights are not part of this study. Refer to other recent studies for energy cost impacts of this skylight feature.

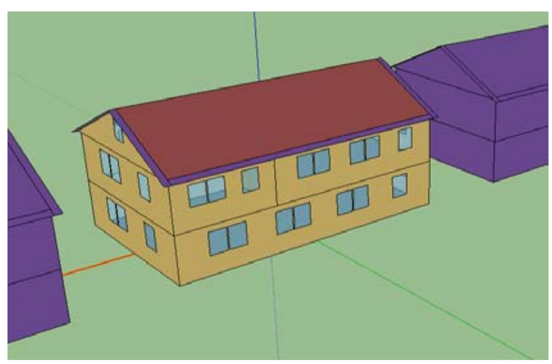
1.1 House Model (Bi-level)

A 2-story, slab-on-grade, 2,000 ft^2 house is modeled in EnergyPlus V8.0 with 3 bedrooms and 2 bathrooms. The house is east facing with 15% window-to-wall ratio (18% window-to-floor ratio) distributed at 20% front (east), 40% back, 20% left and 20% right. The large amount of west facing glass (40% back) makes it the worst cooling case for the analysis purpose. The house has gable roofs (6:12 roof pitch), 1 foot eaves and a vaulted ceiling (Figure 1). The average window sizes are 3’-0” wide by 4’-0” high. The house is modeled with its north space as a 2-story high space above which the venting skylights will be placed. This configuration also permits evaluation of the stack effect for the natural ventilation analysis.

Figure 1: House East and West Views



East view (front)



West view (back)

Two levels of house efficiencies are listed below (Table 1) with a code level (ICC 2009) base home and high performance home at (~20% energy cost savings level) using BEopt v2.0 /EnergyPlus v7.2. Code base home internal loads on lighting, appliances, domestic hot water and miscellaneous electrical and gas loads are generated following Building America House Simulation Protocol (Hendron and Engrebrecht, 2011). State wide average utility rate from BEopt is used:

- Electricity: $0.1639/kWh with $8 monthly charge.
- Gas: $1.2319/therm, $8 monthly charge

Table 1: Code Base and High Performance Home Features

	Code Base	High Performance
Wall	R13 fiberglass + R5 XPS	R21 fiberglass + R10XPS
Roof	R30 fiberglass vaulted ceiling	R48 vaulted ceiling
Slab	2ft R10 Exterior	2ft R10 Exterior
Window	Double pane low-e vinyl frame assembly U=0.38, SHGC=0.44	Double pane low e low SHGC vinyl frame assembly, air (U=0.29, SHGC=0.31)
Air Leakage	4ACH50 (SLA=0.00036)	2ACH50 (SLA=0.00018)
Mechanical Ventilation	ASHRAE 62.2 (50cfm continuous)	ASHRAE 62.2 (50cfm continuous)
Natural Ventilation	None	None
Heating/Cooling setpoints	68°F /78°F	68°F /78°F
Appliances	ENERGY STAR (refrigerator 348kWh/yr, Clothes washer ENERGY STAR, Dishwasher ENERGY STAR 318kWh)	ENERGY STAR (refrigerator 348kWh/yr, clothes washer ENERGY STAR, Dishwasher ENERGY STAR 318kWh)
Miscellaneous Electric / Gas / Hot Water Loads (Fraction of Benchmark Use)	0.25 /1/1	0.25 /1/1
Lighting	80% FL hardwired and plugin 1,254kWh/yr	100% fluorescent hardwired and plugin 1,103kWh/yr
DX AC	SEER 13	SEER 15
Furnace	80% AFUE	92.5% AFUE
Duct	In finished space	In finished space
Water Heater	Gas Standard 0.57 EF	Gas premium 0.69 EF
DW Piping	Uninsulated trunk branch, copper	Uninsulated trunk branch, copper

Files generated from BEopt v2.0 were further processed in EnergyPlus v8.0 to:

- Add skylights
- Use AirFlow Network (AFN) to analyze infiltration, mechanical ventilation and natural ventilation interactions
- Use EMS (Energy Management System) to control vent openings with a rain sensor and indoor-outdoor air temperature differences.
- Add the contaminant flow balance model and contaminant decay source
- Add thermal comfort parameters and customize data post-processing

To first validate EnergyPlus model inputs on AFN crack sizes, building effective leakage area (ELA) was calculated from specific leakage area (SLA) listed in Table 1, and the leakage areas were distributed evenly to every wall and roof surface. The resulting total house leakage was cross checked with Contam using blower door test at @50Pa.

1.2 VELUX Solar Powered Venting Skylight

Venting skylights save energy because they can open to ventilate and cool homes naturally when the outside air temperature is lower than the indoor air temperature and there is cooling load in homes. Using venting skylights will reduce air conditioning (A/C) run time and save electrical consumption during the cooling season.

The skylight selected in the study is VELUX model VSS (#VEL-N-17-00016-00001), an ENERGY STAR qualified operable skylight with the following NFRC-rated whole-unit characteristics and its product information screenshot from NFRC (National Fenestration Rating Council). The skylight is constructed with an aluminum/wood composite frame and high performance ¾" double glazing using Cardinal LoĒ^{3}-366® with argon/air (95/5).

Table 2: Skylight Energy Performance Ratings

Total U-factor	0.43
Solar Heat Gain Coefficient	0.23
Total Visible Transmittance	0.54 clear

Figure 2: NFRC List Product Information

CPD #	U-factor	SHGC	VT	Condensation Resistance	Air Leakage
VEL-N-17-00016-00001	0.43	0.23	0.54	52	-

Close

Group ID	Manufacturer Product Code	Frame/Sash Type	Glazing Layers	Low-E	Gap Widths	Spacer	Gap Fill	Grid	Divider	Tint
1	05: 3mm Cardinal E366 / 95% Argon / 3mm Clear	WA/WA	2	0.022(2)	0.433	SS-D	Fill 1: ARG/AIR (95/5)	N	-	CL

VELUX VSS is a solar powered "fresh air" skylight with its remote control and integral rain sensor to automatically close the skylight in case of rain events. VELUX VSS skylight can also come with factory installed blinds to prevent overheating on sunny days, and lower heat loss at night. Note the current study does not have window or skylight shading effect taken into account as shading schedule is generally hard to predict in a residential home setting.

Figure 3: VELUX VSS Skylight

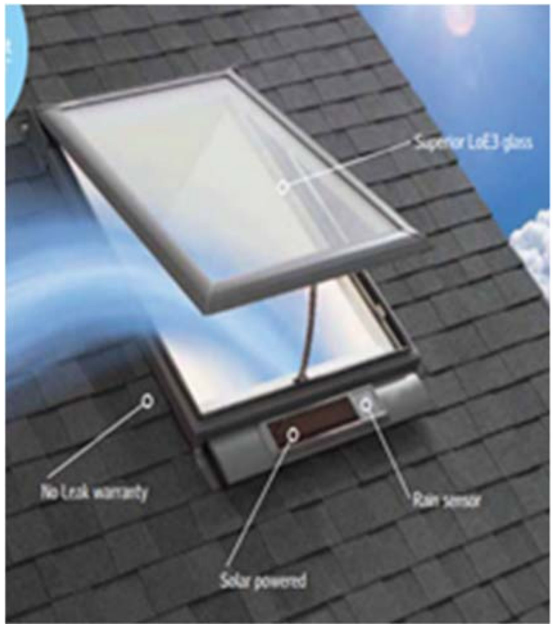


Figure 4: VELUX VSS Skylight Available below shows VSS deck mounted skylight available model sizes with corresponding ventilation areas.

Figure 4: VELUX VSS Skylight Available Model Size Chart

Size code		C01	C04	C06	C08	M02	M04	M06	M08	S01	S06
Outside frame	in.	21 1/2 x 27 3/8	21 1/2 x 38 3/8	21 1/2 x 46 1/4	21 1/2 x 54 15/16	30 9/16 x 30 1/2	30 9/16 x 38 3/8	30 9/16 x 46 1/4	30 9/16 x 54 15/16	44 3/4 x 27 3/8	44 3/4 x 46 1/4
Rough opening	in.	21 x 26 7/8	21 x 37 7/8	21 x 45 3/4	21 x 54 7/16	30 1/16 x 30	30 1/16 x 37 7/8	30 1/16 x 45 3/4	30 1/16 x 54 7/16	44 1/4 x 26 7/8	44 1/4 x 45 3/4
Daylight Area	in.	16 x 20.44	16 x 31.5	16 x 39.38	16 x 48	25.125 x 23.56	25 x 31.5	25 x 39.38	25 x 48	39.25 x 20.44	39.25 x 39.38
Ventilation Area	sq. ft.	2.60	3.56	4.14	4.71	4.11	4.17	4.75	5.32	4.31	5.84

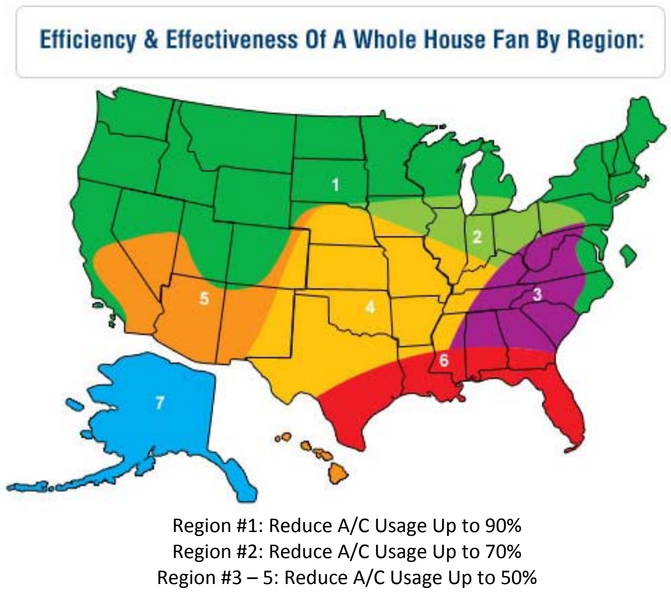
1.3 Whole House Fan

A whole house fan is a powerful exhaust fan that's designed to pull air out of the house and quickly cool the house. It is a popular strategy used to effectively cool / pre-cool homes reducing the air conditioner (A/C) mechanical cooling time. To cool the house fastest, whole house fans are generally sized at 3 cfm/ft^2 as a general rule-of-thumb, though there is some belief in reducing the flow rate to 2 cfm/ft^2 in order to save the fan energy. The study home has vaulted ceilings which increase the volume/area ratio of the house, so 3 cfm/ft^2 is used in this case for effective cooling / pre-cooling.

Figure 5: Whole House Fans

A Quiet Cool QC6400 whole house fan was selected with its high speed at 6,418 cfm and 658 watts (0.1025 W/cfm) and low speed at 3,226 cfm and 329 watts (0.1020 W/cfm). The fan is very efficient and operates quietly with a sound level of 50 db. in operation. Figure 6 below is a US regional map showing efficiency and effectiveness of a whole house fan (picture from www.wholehousefan.com). In region 1 (mostly climate zones 5,6 and 7) highlighted in green below, whole house fans are claimed to save up to 90% A/C usage with its powerful cooling / pre-cooling capability.

Figure 6: Efficiency & Effectiveness of a Whole House Fan



2 Natural Ventilation Analysis and Energy Cost Impacts (Bi-level Home)

2.1 Code Base Home

2.1.1 Natural Ventilation Opening Sizing

LoopDA is used in the study to properly size the natural ventilation (NV) openings. Natural ventilation can operate based upon stack-and-wind effect or stack effect only. Obviously, with stack-and-wind effect, the required opening sizes will be smaller than with stack effect only. To demonstrate the natural ventilation opening sizing procedure, Code Base home is used.

Figure 7 below is a plot of EnergyPlus output showing hourly house cooling load vs. outside air temperature for the Code Base Home. The green dashed line boxes the region where the natural ventilation opportunity exists, i.e. OAT <=77°F. The corresponding time period for natural ventilation goes from May 29 to October 1, spanning the entire summer. When the entire house cooling load peaks at 4,700W (orange arrow) with OAT at 95°F, the peak cooling load that can be handled by natural ventilation is at ~2,500W. Thus 2,500W is used as input in LoopDA.

Figure 7: Code Base Home Cooling Load vs. OAT

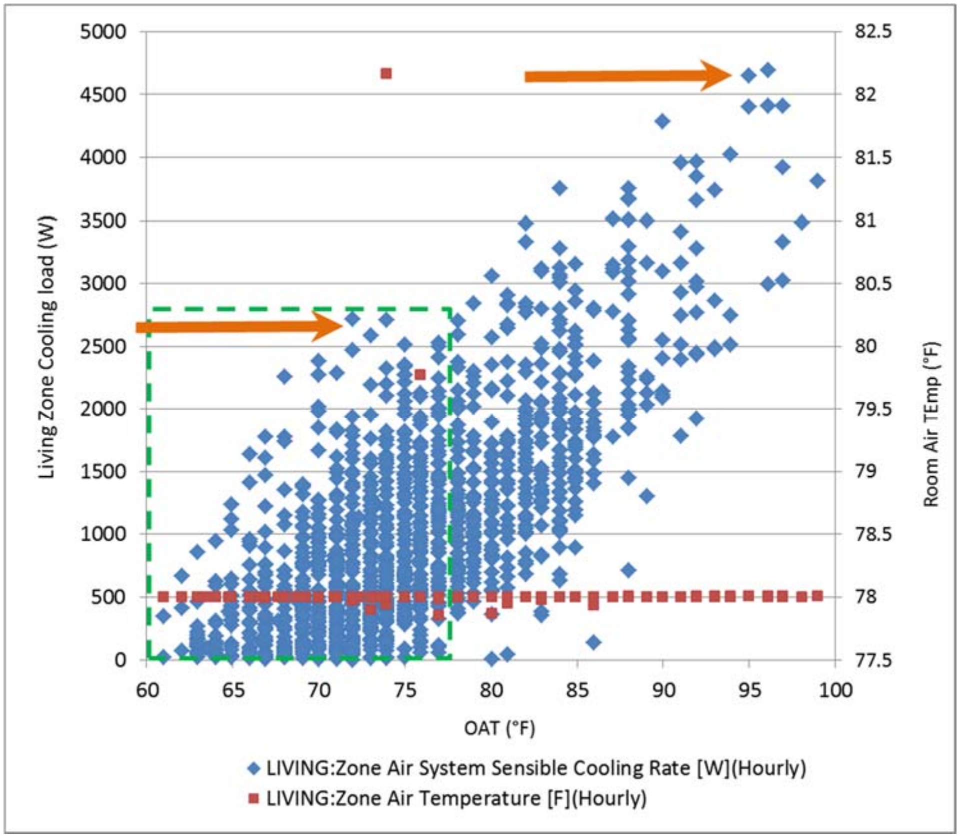
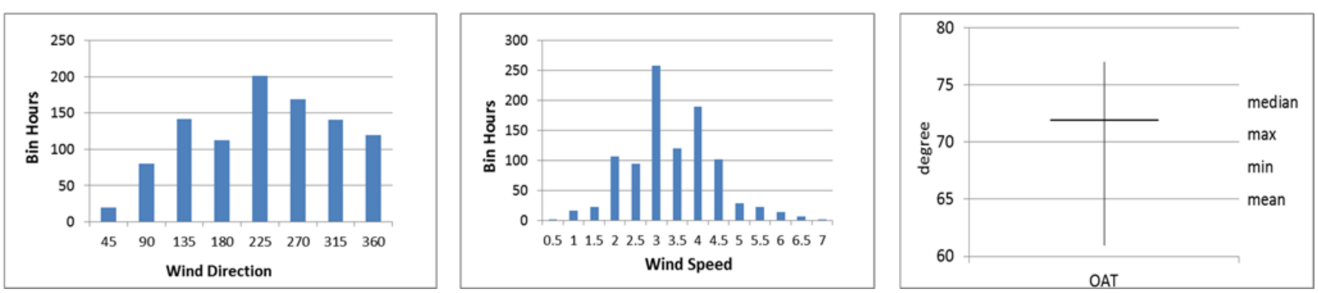


Figure 8 plots the corresponding histograms for wind direction and wind speed and the statistical data on outside air temperature during the time period for natural ventilation opportunity.

Figure 8: Statistical Plots of Wind Direction, Speed and OAT During NV period



The average values of 3 m/s (590 fpm) wind speed and 72°F OAT are also used as input parameters for LoopDA. The prevailing wind is from the south-south west direction (208 degree). The prevailing wind direction is used to guide the placement of venting skylights and corresponding inlet window openings in the homes.

Figure 9: LoopDA Setup and Results Window

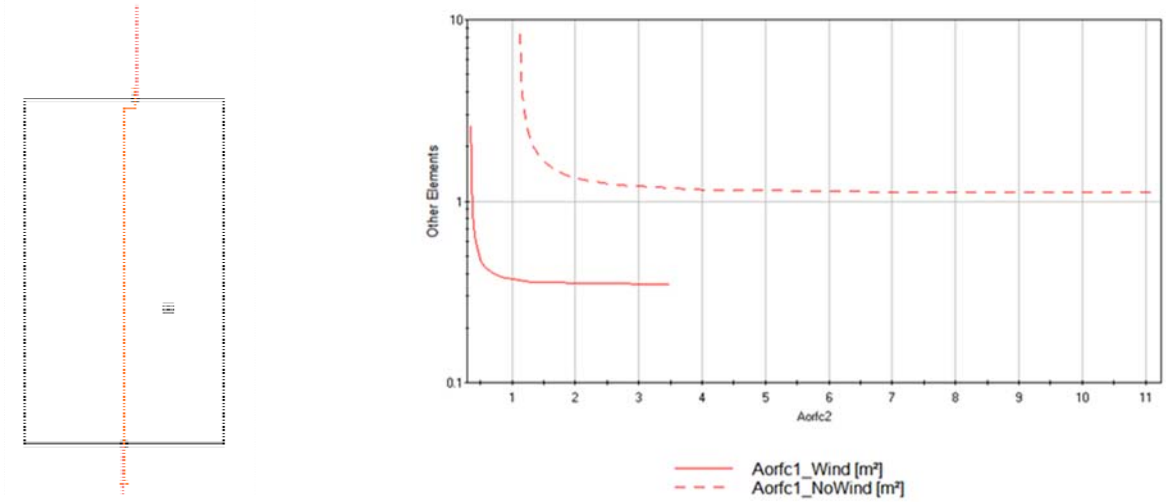
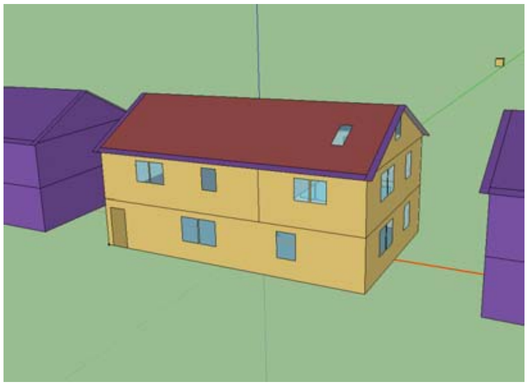


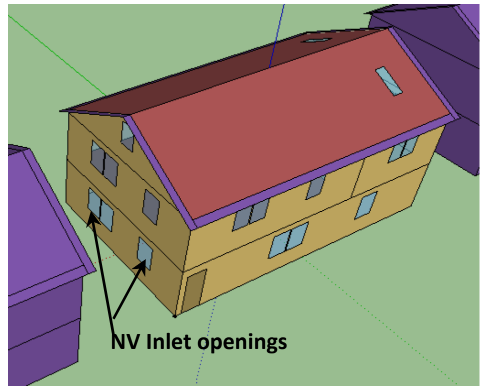
Figure 9 shows a simple house in LoopDA with the ventilation path configuration. The bottom side has a window opening placed 3ft above slab and top (north) side has a clerestory window 18ft above slab. The clerestory window was used because LoopDA does not offer detailed skylight configuration. An average wind pressure coefficient of Cp = 0.5 is used for the lower window, and Cp = -0.4 is used for the clerestory (ASHRAE 2005). With the average wind direction almost parallel along the gable roof, the impact of roof slope and associated wind pressure coefficient distributions are relatively small and are not included in the study. (ASHRAE 2005)

For the 2-story home with 2,000ft^2 of floor area and 29,169ft^3 of house volume, the required natural ventilation opening size for the skylight is 0.35m^2 (3.767ft^2) with stack-and-wind effect and 1.12m^2(12.56ft^2) with stack effect only. The required natural ventilation opening size for the first floor window is about the same 0.35m^2 (3.767ft^2) with stack-and-wind effect and 1.11m^2(11.95ft^2) with stack effect only. Notice the opening sizes are calculated at the average wind speed and outside air temperature. In other words, if the OAT is lower than 72°F, opening areas required will be smaller, and if the OAT is higher than 72°F, the home cooling load cannot be met with natural ventilation alone and supplemental A/C cooling is needed.

Two VSS C08 skylights were selected and added to the Code Base home with one on the east, and one on the west gable roof with a total ventilation area of 9.42ft^2 as the middle value between the stack-and-wind effect and stack effect only. With the prevailing wind in the south-southwest direction, two windows (wall1-window1 and wall1-window3) on the first floor (Figure 10) below are designated as natural ventilation inlet openings, and the two skylights are placed toward the north side above the 2-story high space. This configuration maximizes natural ventilation effect.

Figure 10: Code Base Home w/Skylights





2.1.2 Natural Ventilation Openings and Controls

Environmental factors such as rain, noise, security concerns and occupant schedules all impact the venting skylights operation. In this study, only rain sensors and operation schedules are analyzed.

The natural ventilation openings (venting skylights and corresponding window inlet openings) are operated based on the following rules:

- Natural ventilation openings shall close when the rain precipitation is detected
- Natural ventilation openings shall open when the indoor air temperature is above 24°C [1](75.2°F) AND the outdoor air temperature is less than the indoor air temperature
- When open, natural ventilation openings shall modulate based on the following schedule[1]:

$$OpenSizeFactor = \begin{cases} 0.0 & \Delta T >= 10°C\ (18°F) \\ 1.0 & \Delta T <= 5°C\ (9°F) \\ \frac{10-\Delta T}{5} & \Delta T > 5°C\ (9°F)\ \&\ \Delta T < 10°C\ (18°F) \end{cases}$$

Where: $\Delta T = Tin - Tout$,

This modulation reduces the potential for overcooling the home and triggering unnecessary heating. Occupant is assumed available to operate the skylights when conditions call for it. Automatic sensor-driven control is another means to ensure the same response. Sensitivity on occupant schedule is also discussed in the next section.

2.1.3 Venting Skylights Energy Cost Impacts

Figure 11 shows the annual energy cost comparison for the Code Base home for the cases of:

- Code Base Home w/o skylights,
- Code Base Home w/venting skylights,
- Code Base Home w/venting skylights, venting is only available during daytime (6am -11pm)

When venting skylights are added with natural ventilation enabled, with the optimized natural ventilation flow direction (windward) and specified controls, venting skylights save $36 from the Code Base Home

[1] The indoor-air-temperature setpoint and modulation schedule were also optimized for energy cost savings potential.

without skylights (Figure 11). The venting skylights introduce natural ventilation in the Code Base Home, both cooling energy and fan energy are reduced, with a slight penalty on heating energy.

Figure 11: Code Base Home Energy Cost Comparison on Skylights

Figure 11 also indicates that when the venting skylights operation by the homeowner only happens during the daytime (6am - 11pm), the energy cost increases to $1,840, resulting <u>$31</u> of energy cost savings from the Code Base Home. This indicates for venting skylights, majority of the savings potential is during the daytime.

2.1.4 Whole House Fan Energy Cost Impacts

A whole house fan consumes large amount of fan energy when it's operating. We modeled three fan operation schedules to test the sensitivity of energy cost impacts with the whole house fan operation schedule:

- Whole house fan is enabled whenever there exists opportunity for natural ventilation,
- Whole house fan is only allowed to operate during 6:00-10:00am and 5:00-9:00pm (8hrs) for natural ventilation,
- Whole house fan is only allowed to operate during 6:00-8:00am and 5:00-7:00pm (4hrs) for natural ventilation.

The time step in the EnergyPlus is reduced to 15min for the whole house fan cases to mimic real life operation and to capture more fan energy savings. Additionally, indoor natural ventilation temperature setpoint is raised to 25°C (77°F) as opposed to 24°C (75°F) in the skylight case. Raising the setpoint by one degree Celsius reduces heating energy penalty caused by whole house fan overcooling. The whole house fan speed / flow fraction is modulated as below to allow efficient low-speed operation.

$$\begin{cases} 0.0 & \Delta T >= 10°C\ (18°F) \end{cases}$$

WHFanFlowFraction = 1.0 *ΔT <= 5°C (9°F)*
0.5 *ΔT>5°C (9°F) & ΔT<10°C (18°F)*

Corresponding window openings (wall1-window1 and wall1-window3) still operate as defined in the venting skylight section above. Similar to the venting skylights case, the fan is turned off and the inlet window openings are closed with rain precipitation detection.

Figure 12: Code Base Home Energy Cost Comparison on Whole House Fans

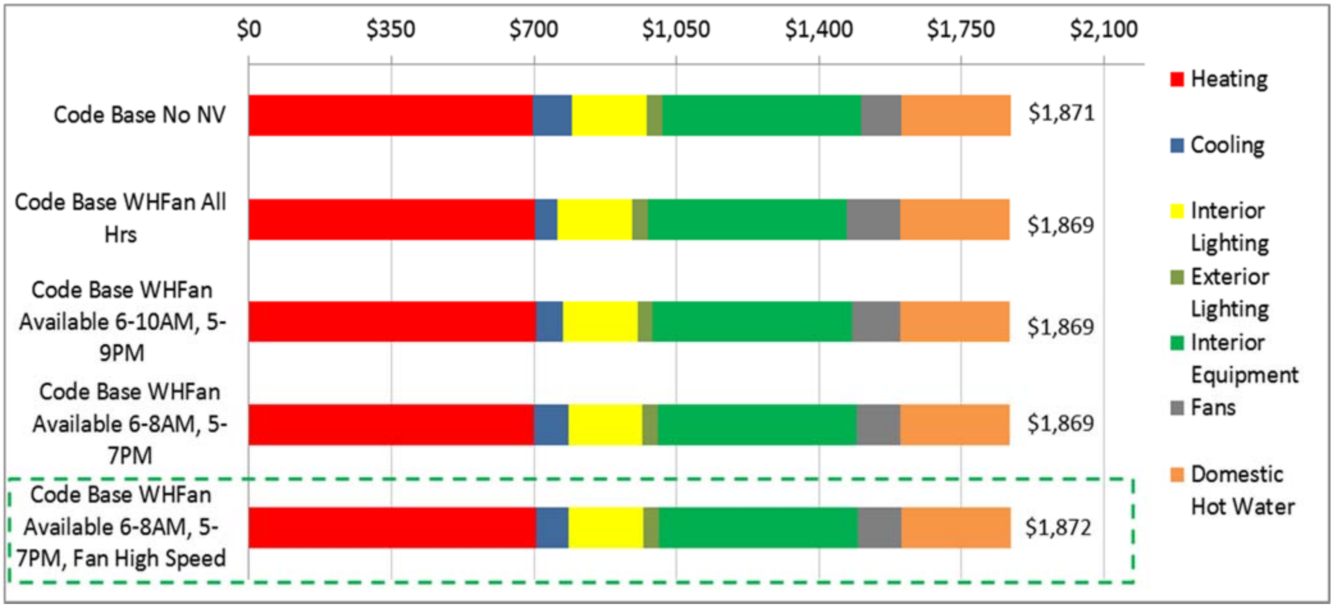


Figure 12 shows that with a very efficient fan and a low-speed operation rule, a whole house fan barely saves any energy. The reduced cooling energy in the Code Base Home is offset by the increased fan energy. When a whole house fan is allowed to operate whenever there exists natural ventilation opportunity, energy cost is only reduced by $2 from the Code Base Home without skylights. The trade-off between the cooling energy and fan energy is also shown in the 8-hour vs. 4-hour operation cases. The 4-hour fan operation saves less cooling energy than the 8-hour operation case. But the 4-hour fan operation consumes less fan energy than the 8-hour operation case. The overall energy cost impact is the same with the 4-hour or 8-hour whole house fan operation with both at $2 energy cost savings from the Code Base Home without skylights.

Figure 12 has a fourth run in the dashed green box with the whole house fan always operating at high speed in the 4 hour window, assuming the homeowner wants to quickly cool the house in 15 minutes in the morning or evening. The energy cost with the high-speed fan operation increased to $1,872 resulting in $1 of energy cost penalty from the Code Base Home.

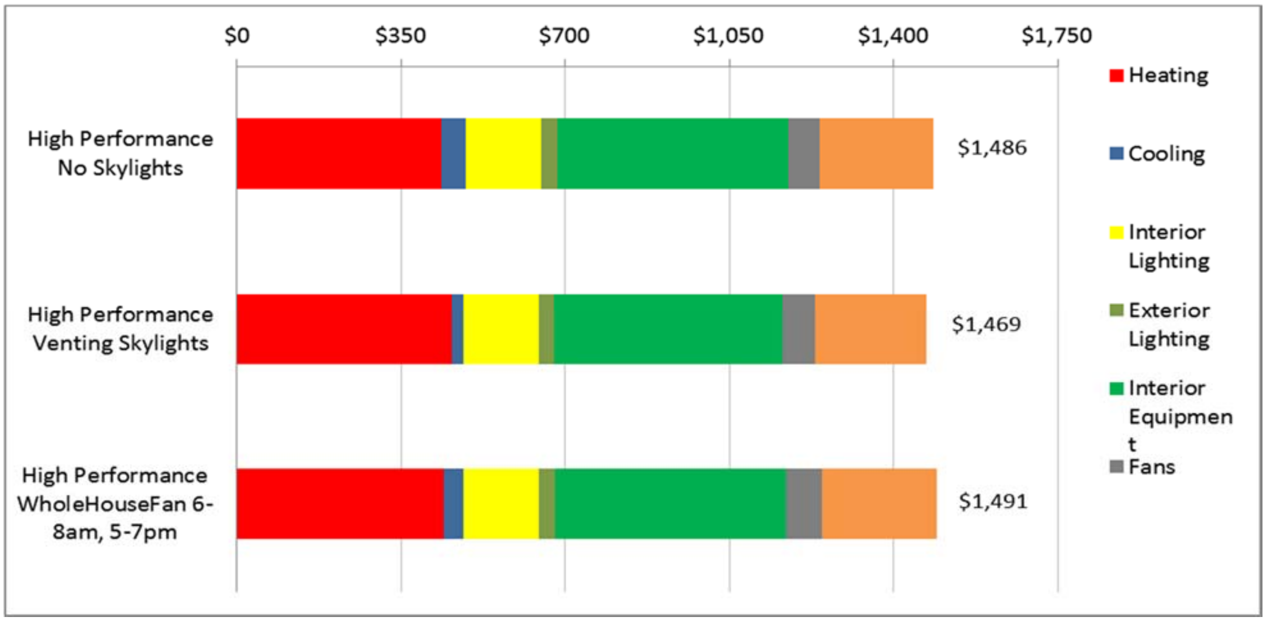
Contrary to the product marketing claims, this study shows a whole house fan DOES NOT save energy.

2.2 High Performance Home

The maximum cooling load in the High Performance Home for natural ventilation to handle is 2,000W, with the average wind speed at 3.3 m/s and average wind direction at 230 degree. This would result in smaller ventilation areas on the venting skylights required for natural ventilation. To simplify the process, the same two VSS C08 venting skylights are selected and placed the same as shown in Figure 10.

In the High Performance Home, which has tighter construction and decreased lighting and appliance loads, the cooling loads are reduced from the Code Base Home leaving less room for natural ventilation to save energy. Figure 13 shows adding venting skylights saves $17 is saved from the High Performance Home without skylights. Figure 13 also shows adding a whole house fan with 4 hours operation increases the energy cost by $5 from the High Performance Home without skylights.

Figure 13: High Performance Home Energy Cost Comparisons on Venting Skylights and Whole House Fans



3 Indoor Air Quality (IAQ) Analysis

Indoor air quality (IAQ) is important in evaluating healthy homes. Every material in a home is a potential pollutant source. Examples of pollutants generated in a typical home by the following are:

- Household cleaning products that release vapors from hard floors, carpets, furniture etc.
- New carpet or paint
- A cat litter box
- Bathrooms and kitchen ranges without any no local exhaust fans running

Additionally EPA (Environmental Protection Agency) provides basic information on pollutants and sources for indoor air pollution (http://www.epa.gov/ia-intro.html). For instance: average house carbon monoxide levels are around 5 to 15ppm near a properly adjusted gas stove, OSAHA (Occupational Safety and Health Administration) permissible exposure limit for CO is 50ppm as an 8-hour time weighted average etc.

Without the dilution of outside air, these pollutants can stay in a household for a long time and the room air can become stale.) In other words, the “age of air” becomes old, or the “reciprocal age-of-air” (RAoA) is small

(C.D. Barley, et. al, 2007). Indoor air quality (IAQ) in a single family house has been evaluated using single-tracer gas decay tests (Fang and Hancock. 2009). The test begins with injecting a tracer gas to the well-mixed house, then injection is ceased and the concentrations of the tracer gas at sampling points are monitored. Obviously the quicker the concentration decay, the younger the "age-of-air" (or bigger the RAoA), and the healthier the home is. For a single-well mixed home, RAoA is equal to air-change rate (ACR). ACR is calculated as:

$$ACR = \frac{\ln(C_B / C_A)}{T_A - T_B}$$

Where:

ACR – air-change rates
C_A *- contaminant initial concentration*
C_B *- contaminant final concentration*
T_A *- initial time stamp*
T_B *- final time stamp*

EnergyPlus V8.0 is used to evaluate the concentration decay rate on both the Code Base Home and High Performance Home without natural ventilation, with venting skylights and with whole house fans.

3.1 Code Base Home

A contaminant source was introduced to the house May 29th starting at 4:00PM at a constant injection rate of 0.00114683m3/s for one hour in the house continuously. Ideally, without any dilution from the outside air, the contaminant concentration should go up to 5,000ppm at the end of the hour or the beginning of the next hour.

$$Concentration\ PPM = {V_{contam}}/{V_{House}}$$

Where: V_{contam} *- contaminant volume -* m^3, V_{contam} *= Injection Rate x 3600s*

V_{House} *– Volume of the House (826*m^3 *or 29,169*ft^3*)*

The time stamp was purposely picked due to:

- The weather conditions allow natural ventilation openings for effective cooling in the next two hours
- Outside wind conditions are relatively mild to reduce fluctuations on the amount of outside air introduced into the home.

Figure 14 shows both the venting skylights and whole house fan quickly dilute the contaminant concentration to normal levels in 3 hours. And the contaminant dilution without natural ventilation takes 1.75 days.

Figure 14: Code Base Home Contaminant Concentration Decay Rate Comparisons

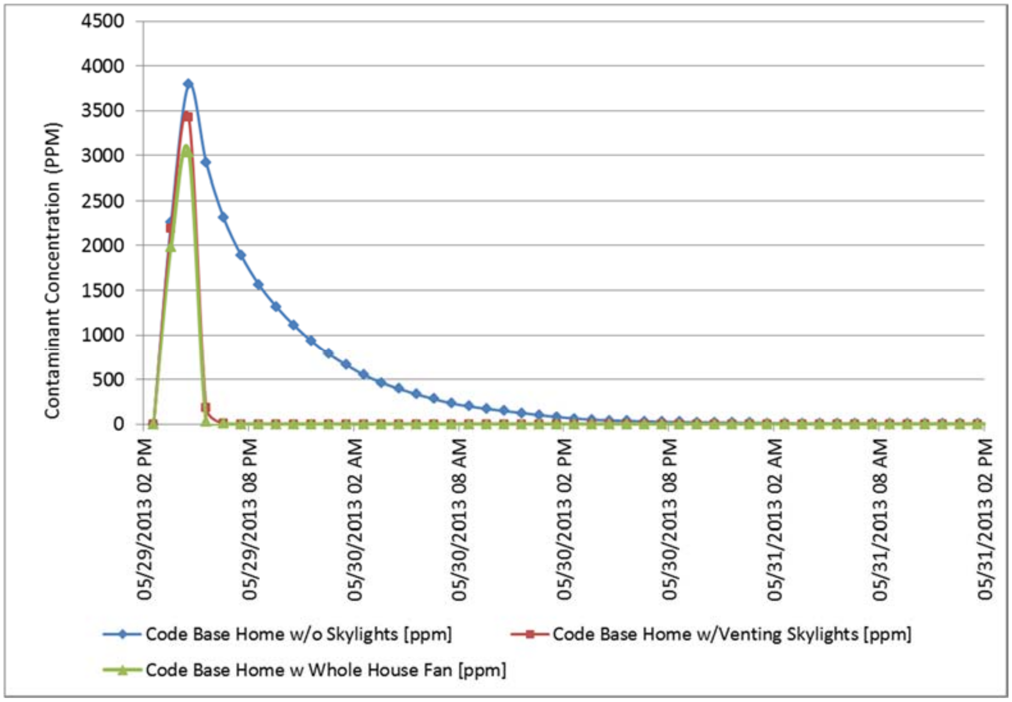


Table 3: ACR Comparisons

	ACR (hr^{-1})
Code Base Home w/o NV	*0.16*
Code Base Home w/Venting Skylights	*2.68*
Code Base Home w/Whole House Fan	*2.31*

The ACR value for the Code Base Home without natural ventilation is acceptable at 0.16 referring to past field tests (Barley C.D. et.al 2007). With mechanical ventilation running continuously, the home design ACH is 0.13 under normal operating conditions. Having an ACR of 0.16 indicates slightly more envelope leakage under the simulation test condition. Both venting skylights and whole house fans boost ACR values significantly. Contaminant sources dilution becomes 15 times quicker and the home becomes healthier.

3.2 High Performance Home

With a tighter construction in the High Performance Home, the contaminant concentrations in the High Performance Home peak around 4,200ppm (second hour average) as opposed to 3,800ppm in the Code Base Home. The ACR value for the Code Base Home without natural ventilation is lower but still decent at 0.13 with the exhaust fan acting as a means for mechanical ventilation.

In the High Performance Home, both the venting skylights and whole house fan again quickly dilute the contaminant as in the Code Base Home. Very high ACRs are calculated.

Figure 15: Code Base Home Contaminant Concentration Decay Rate Comparisons

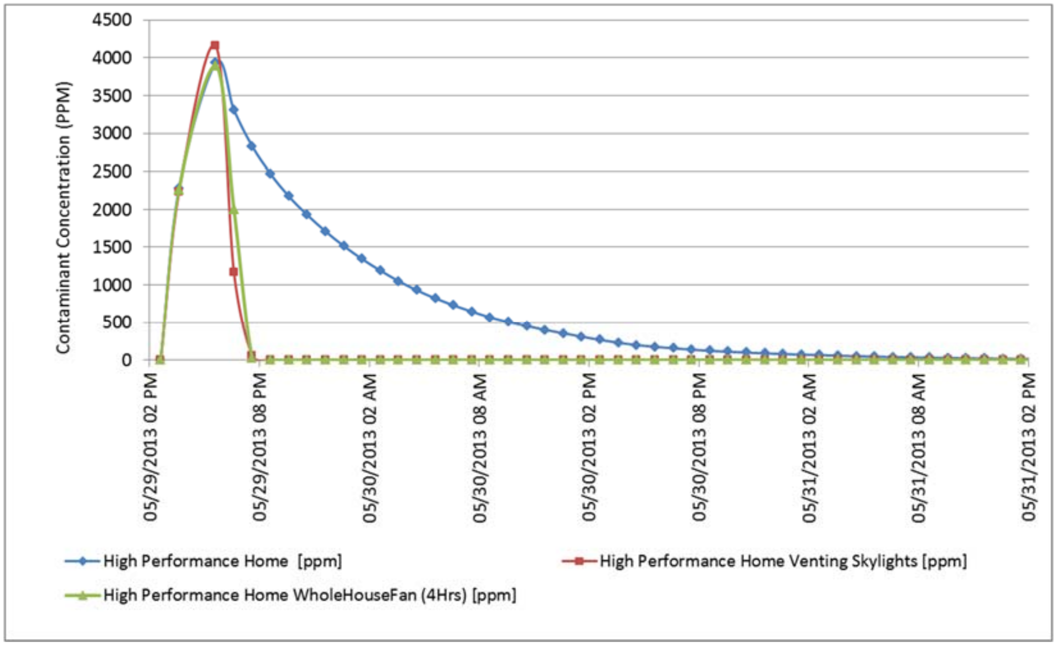


Table 4: ACR Comparisons

	ACR (hr^{-1})
High Performance Home w/o Skylights	*0.13*
High Performance Home w/Venting Skylights	*2.31*
High Performance Home w/Whole House Fan	*2.08*

4 Thermal Comfort Analysis

In this study, Fanger thermal comfort index and Adaptive ASHRAE 55 model were both used. (ASHRAE 2010) Fanger model was first used in all the homes. During the natural ventilation mode, when the occupants comfort conditions are associated with different thermal expectations and adaptive clothing adjustment etc., Adaptive ASHRAE 55 model was used in lieu of Fanger model.

4.1 Fanger Model

Fanger thermal comfort PPD-PMV (Predicted Percent Dissatisfied, and Predicted Mean Vote) scale captures the mean response of a large group. In a residential setting, clothing levels and metabolic rates can change with daily activities, and an individual homeowner may prefer a comfort index that significantly deviates from the mean response. However, using PPD-PMV on a large community scale, regional scale, or climate zone scale to analyze residential home thermal comfort can be adequate. (Fang, et. al, 2012) This large-scale characterization is applicable in Building America House Simulation Protocol (Hendron and Engebrecht, 2010) for home appliance, miscellaneous electric loads, lighting, domestic hot water, etc.

Table 5 shows the PMV index spanning from -3(cold) to +3(hot), with 0 indicating neutral. Generally speaking a PMV index from -0.5 to 0.5 is a neutral thermal sensation region (ASHRAE 2010).

Table 5: PMV Index

-3	-2	-1	0	+1	+2	+3
(cold)	(cool)	(slightly cool)	(neutral)	(slightly warm)	(warm)	(hot)

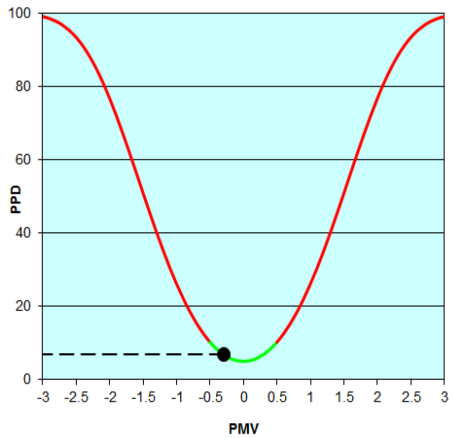
Of the six primary factors affecting thermal comfort (ASHRAE 2010), thermal comfort is highly sensitive to clothing levels and metabolic rates. A heavily dressed active person can feel hot when a lightly dressed sitting person in the same environment can feel cool. This study used a constant metabolic rate / occupant activity or a constant occupant sensible and latent heat gain as prescribed by the Building America House Simulation Protocol. This in turn leads to a simplified constant daily clothing level assumption. Because the combined comfort effect of night sleeping (lower metabolic rates at higher clothing level) vs. daytime sitting (higher metabolic rates at normal clothing level) is very much the same. We adjusted the occupant clothing level with some seasonal variations based on monthly average temperatures (see Table 6).

Table 6: Clothing Level (clo) Assumption

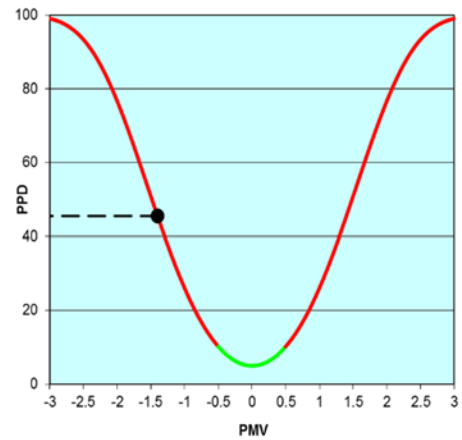
Average Outside Monthly Temperature	< 35°F	≤80°F & ≥35°F	> 80°F
Clothing Level	1.0	0.75	0.5

When a home is under mechanical air conditioning, air is evenly distributed to each room by ducts, and the air velocity that a person experiences is assumed to be 0.1m/s (ASHRAE 2010). When a living space is under natural ventilation mode, the study assumes the person body surface area is fully exposed to the ventilation air flow stream. The large amount of air flow blowing on the person will make him/her feel drafty and trigger a strong cooling sensation. PPD-PMV sensitivity to air speed is shown in Figure 16:

Figure 16: PMV-PPD Plots on Air Speed Comparison



Air Speed = 0.1 m/s (20fpm)



Air Speed = 1.5 m/s (300fpm)

Parameter	Input
Clothing (clo)	0.75
Air temp. (°C)	24.0
Mean radiant temp. (°C)	23.0
Activity (met)	1.0
Relative humidity (%)	50.0

The green curves (-0.5<PMV<0.5) in Figure 16 indicate the region where the thermal sensation is neutral. When the air speed is increased from 0.1m/s to 1.5m/s, the thermal sensation drops from neutral to between slightly cool and cool with 45% people dissatisfied. A human body surface area assumed in the study is 1.8m^2 for a 150 pound, 5'9" tall person using Mosteller formula (from http://www.halls.md/body-surface-area/bsa.htm). The study assumes the person is fully facing the natural ventilation air stream during the natural ventilation mode. The study also assumes a well-mixed steady-state condition; any cyclic variations caused by PMV controls, local draft, and radiant asymmetry are not great concerns in a home; thus, contributed to a PPD < 10%.

Figure 17: Code Base Home PPD Bin Hours Comparisons

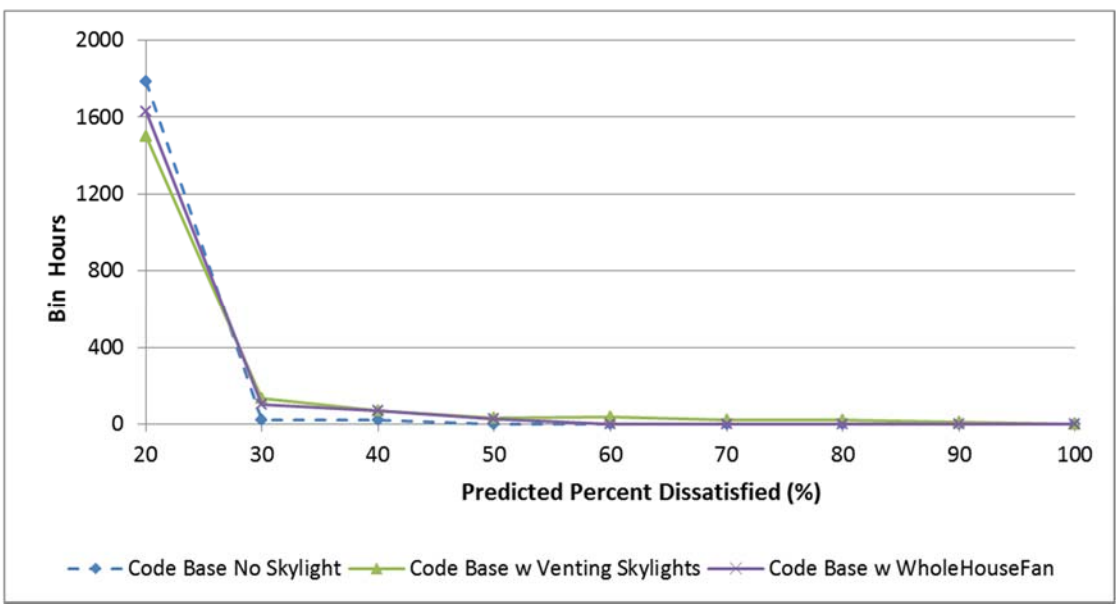
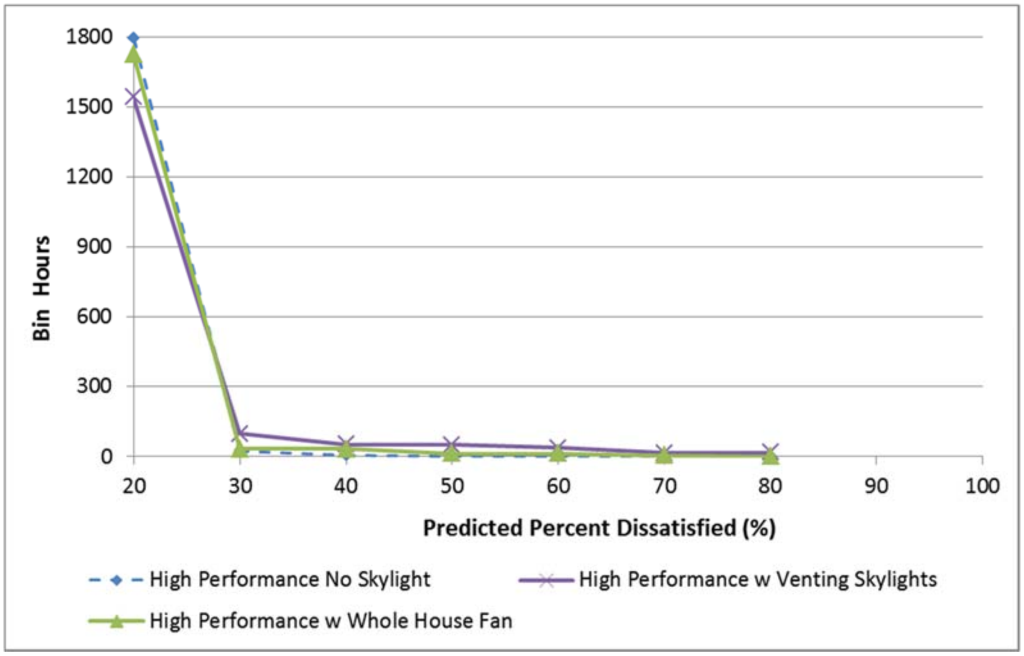


Figure 17 uses PPD bins during daytime hours (7:00am to 11:00pm) in the summer months (June to September) to examine various comfort levels. This assumes that maintaining comfort levels at night is less critical, since most people adjust their bedding levels to stay comfortable. Given the assumed metabolic rate, clothing level and air speed, the High Performance Home (Figure 17) shows slightly improved thermal comfort conditions than the Code Base Home (Figure 18) as a general trend. This is expected with the improved building envelopes resulting in improved radiant comfort in the High Performance Home. Figure 17 and Figure 18 also show that with the air speed adjustment only, adding natural ventilation with venting skylights or a whole house fan increases an occupant cooling sensations during the natural ventilation mode, i.e. more hours of occupant feeling uncomfortable.

Figure 18: High Performance Home PPD Bin Hours Comparisons



4.2 Adaptive ASHRAE 55 Model

Studies have found that occupants tend to have a different thermal experience with shifts in expectations, and changes in clothing (ASHRAE 2010) during the natural ventilation mode. The Fanger model tends to underestimate the thermal comfort conditions with natural ventilation, so Adaptive ASHRAE 55 model is used to account for people's clothing and comfort expectation adaptation by relating the acceptable range of indoor temperatures to the outdoor climate.

Figure 19: Acceptable Operative Temperature Ranges for Naturally Conditioned Spaces (ASHRAE 55)

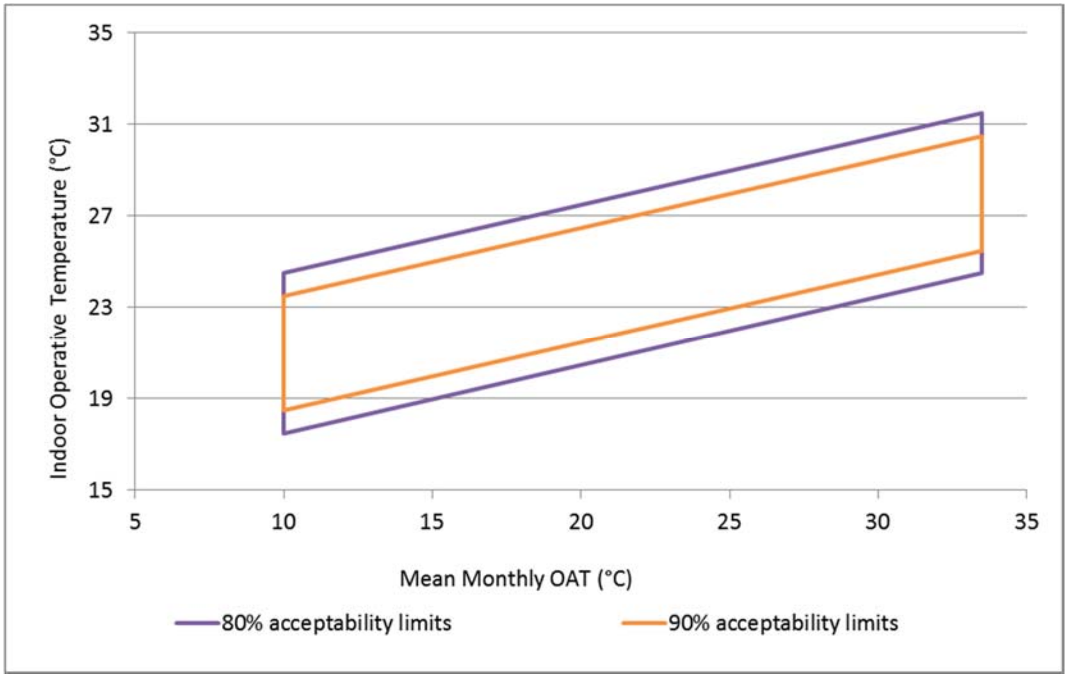


Figure 19 is a plot of Adaptive ASHRAE 55 range, with the orange polygon indicating the 90% acceptability limits, and the purple polygon indicating the 80% acceptability limits. Notice Adaptive ASHRAE 55 model is purely relating the indoor operative temperature to the outdoor average climates.

Figure 20: Code Base Home Indoor Operative Temperatures vs. Mean Monthly OAT

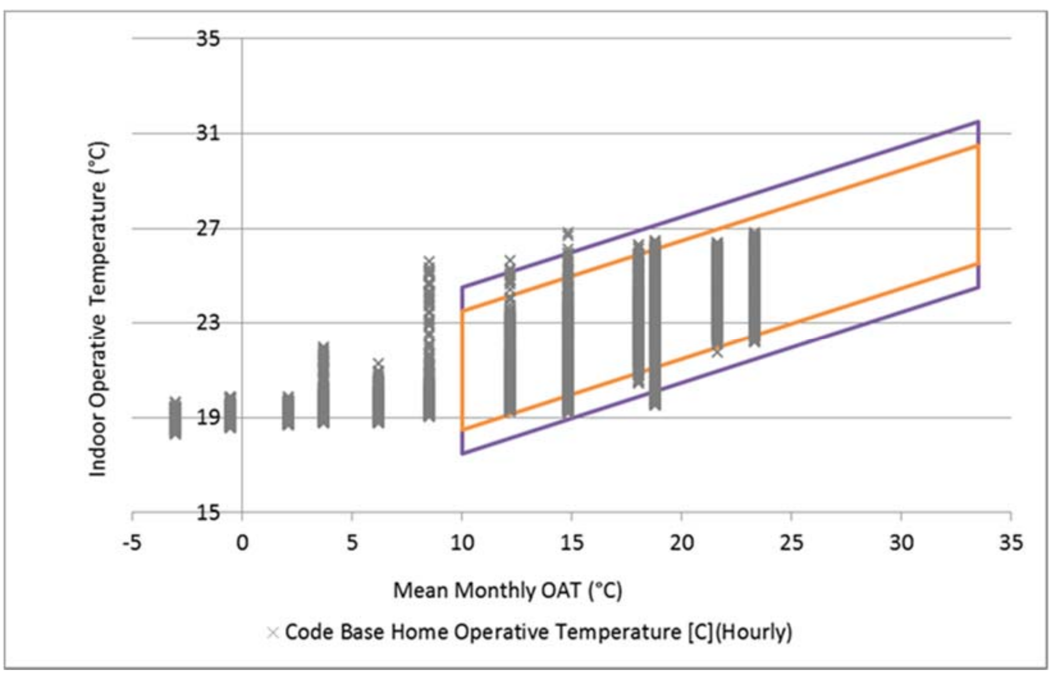


Figure 20 is a plot of the annual indoor operative temperatures vs. mean monthly outside air temperature on the adaptive comfort chart for the Code Base Home with venting skylights. The amount of hours where the 80% acceptability limit is not met is minimal. Note that 90% acceptability is indicating a high level of expectation is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped etc. 80% acceptability indicates a normal level of expectation is used here. Similarly 20% PPD is used in lieu of 10% PPD.

Table 7 lists the unmet hours for the 80% acceptability limits in both the Code Base Home and High Performance Home. Fanger model is used in the homes without natural ventilation, and Adaptive ASHRAE 55 model is used in the home with natural ventilation (highlighted green).

Table 7: Comfort Unmet Hours for Code Base and High Performance Homes

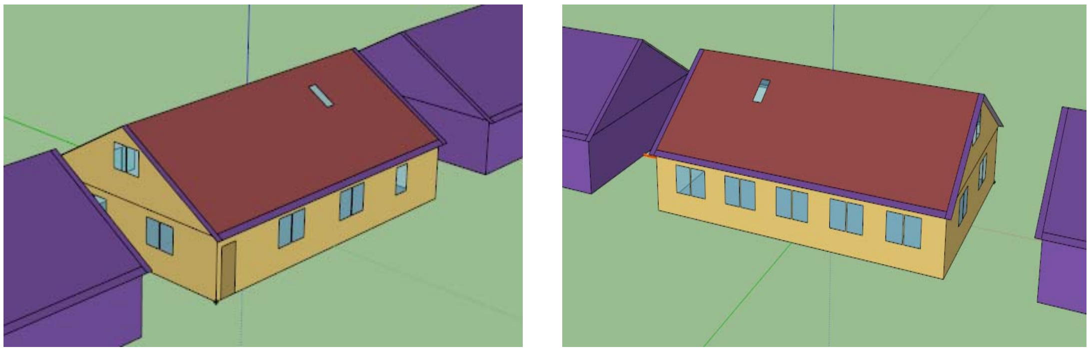
		Unmet Hours	
Description		**Fanger (PPD>20%)**	**AdaptiveASH55 (<80% acceptability)**
Code Base Home	No Skylight	46	NA
	w/ Venting Skylights	328	30
	Whole House Fan	201	33
High Performance Home	No Skylight	32	NA
	w/ Venting Skylights	284	21
	Whole House Fan	102	27

Using 80% acceptability (Fanger PPD>20%, AdaptiveASH55 <80% acceptability), adding natural ventilation slightly increases thermal comfort conditions while providing the homes a connection to the outdoor environment.

5 One-Story House Energy Cost Impact

A 2,000sf one-story house was created in BEopt with 2-levels of efficiency to further study the venting skylights energy cost impacts. Two levels of efficiencies are analyzed: 1-story Code Base Home and 1-story High Performance Home. The features of the house are the same as listed in Table 1.

Figure 21: One-Story House East and West Views



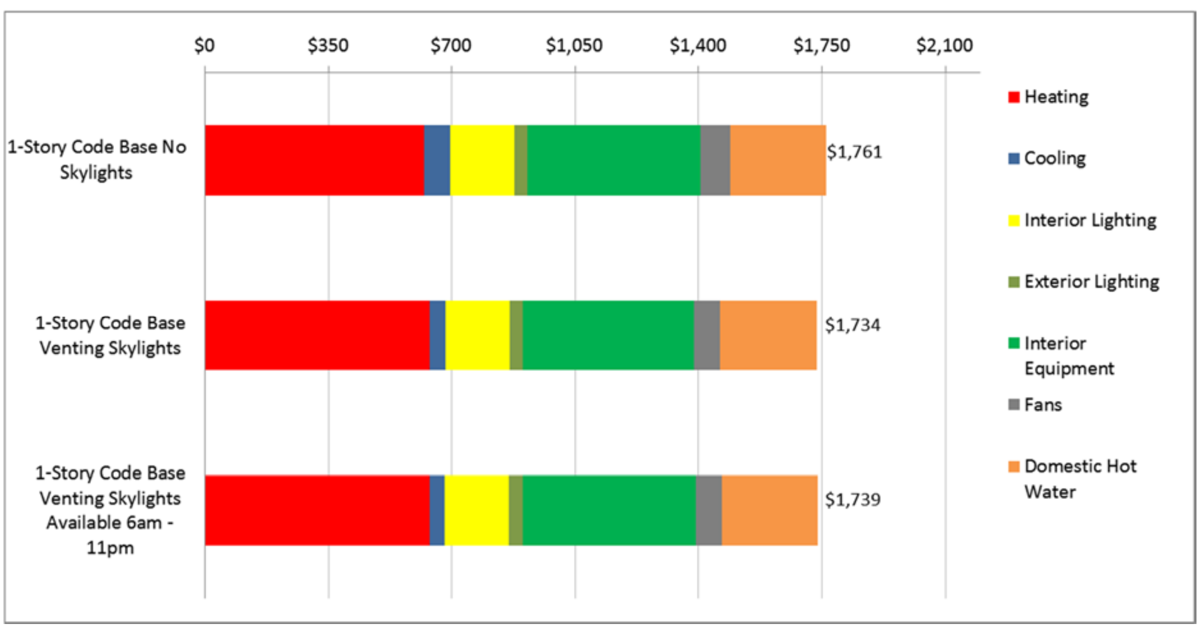
East view (front) West view (back)

Two venting skylights (VELUX VSS-C08) are placed on the gable roof toward the north end to maximize the wind effect as the prevailing wind comes in the southwest direction.

5.1 One-Story Code Base Home

The natural ventilation openings also operate per the rules prescribed above in Section 2. Figure 21 below lists the energy cost comparison on the one-story Code Base Home.

Figure 22: One-Story Code Base Home Energy Cost Savings on Venting Skylights



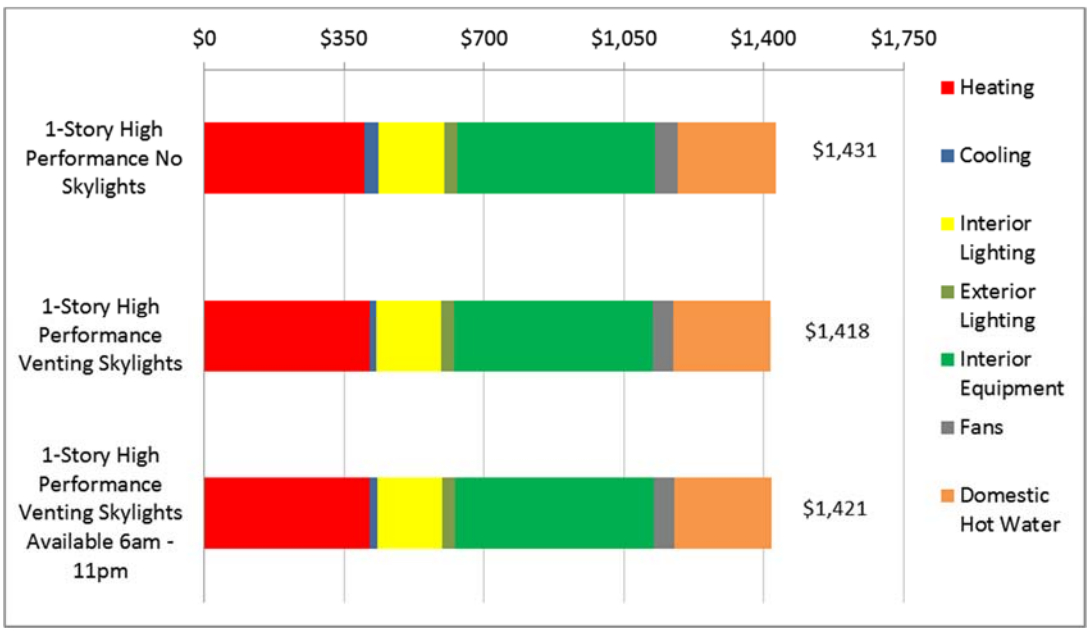
A few points are summarized from Figure 22 above:

1. One-story 2,000sf Code Base Home has slightly lower energy cost than the 2-story 2,000sf Code Base Home with a 2-story high family room.
2. Adding the two venting skylights in the 1-story Code Base Home generates $27 energy cost savings from the 1-story Code Base Home without skylights. The amount of saving is less than in the 2-story Code Base Home ($35).
3. When the venting skylights are only enabled in the daytime from (6am to 11pm), the amount of energy cost savings are slightly reduced to $22 a year. This indicates majority of energy cost savings opportunity is in the daytime window.

5.2 One-Story High Performance Home

Figure 23 below shows the venting skylights impact on the one-story High Performance home. Adding venting skylights on the one-story High Performance home generates $13 of energy cost savings from the High Performance home without skylight or natural ventilation. When the venting skylights are only enabled in the daytime from (6am to 11pm), the amount of energy cost savings are slightly reduced to $10 a year. This indicates majority of energy cost savings opportunity is in the daytime window.

Figure 23: One-Story High Performance Home Energy Cost Savings on Venting Skylights



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www.WholeHouseFan.com

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