

MODELING ENERGY IMPACTS OF PASSIVE ATTIC VENTILATION IN THE SOUTHWESTERN U.S.

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ABSTRACT

Minimum levels of attic ventilation have been required by residential building codes in the United States for years, but the precise attic temperature reductions of “poking holes in the roof” and corresponding energy impacts have rarely been robustly quantified. This study investigates electric energy and demand impacts from passive attic ventilation using field study measurements and building energy simulations for homes in the American Southwest. The results of the parametric simulations are used to determine qualitative and statistical trends for attic ventilation energy impacts, provide insight on the main drivers of changes in energy use, validate simplified models from the field study, and explore cost effectiveness and program design topics.

INTRODUCTION

A large electric utility in the Southwest region of the United States currently offers a weatherization program for targeted residential customers. For this target market, many homes are older than the average building stock and have little or no attic ventilation. Most of these homes had wood shingle roofs at construction but later had asphalt shingles applied, which sealed off the attic almost entirely. Since current building codes (IBC, 2009) stipulate a minimum 1:150 ratio of net free ventilating area to the area of ventilated space (and a ratio of 1:300 with active ventilation or a Class I or II vapour barrier), the utility has been adding passive attic ventilation wherever feasible. The specific leakage area (SLA) ratio of 1:300 was first selected as a U.S. property standard in 1942 without much explanation or basis in previous research (Rose, 1995), but has since been implemented as a commonly recommended installation practice and code requirement.

Literature Review

Moisture control, minimization of ice dams, extended shingle life, and reduced cooling load have all been cited as advantages of attic ventilation (Rose et al., 2002). Although there has been increased interest in recent years in studying residential passive attic ventilation as a possible source of energy savings,

most research to date has focused on reducing condensation on the underside of roof sheathing. In hot, humid climates such as Oklahoma in the summer, however, moisture control could actually be a reason to avoid attic ventilation. In such conditions, ventilation tends to increase moisture in the attic and may increase the risk of condensation on air conditioning (AC) ductwork as well as insulation and wood damage. (Parker, 2005). Additionally, the effect of attic ventilation on ice dam formation is expected to be minimal in the American Southwest due to low annual snowfall levels.

Though high roof surface temperatures have been shown to accelerate the degradation of asphalt shingles (Terrenzio, 1997), attic ventilation has been found to have a minimal impact on shingle temperatures compared to other factors such as geographic location, roof direction, and shingle color (Cash, et al., 2002; Rose, 2001). However, shingle manufacturers still specifically denote “adequate attic ventilation” as requisites in their warranties (Rose et al., 2002).

Although there appears to be a consensus in the literature that passive attic ventilation can decrease attic dry-bulb temperatures over the cooling season, there is no agreement on the magnitude of this reduction nor the effect that these temperature reductions have on overall cooling load. Multiple studies in the State of Florida showed varied results, with up to a 37% decrease in the attic to ambient air temperature difference for high profile ridge vent additions to existing soffit vents (Parker, 2005). Another study showed that attic ventilation resulted in up to a 25% reduction in heat flow through the ceiling, though the subsequent energetic effect was not calculated (Rose et al., 2002). Regardless of the temperature difference, the impact on the overall heat flux across the ceiling was projected to be minimal in homes with satisfactory attic insulation (Dutt et al., 1978). This effect is further limited by the portion of the total cooling load gained through the ceiling and roof. An LBNL study found that heat gains through the roof account for about 17% and 9% of cooling load for old and new vintage (respectively) residential homes in the American South (Huang, 1999). Others have found that, although attics are indeed cooler due

to attic ventilation, any resultant energy savings cannot be distinguished from the variability of cooling loads between homes (Cash et al., 2002).

There are also a number of caveats regarding attic ventilation performance in humid climates with cold winters. Contrary to HVAC design best practices, ductwork is often placed in unconditioned spaces such as attics. While attic ventilation may reduce the dry bulb temperature and therefore the sensible heat load, performance in humid climates remains a concern due to increased latent heat load from added humidity (Rose et al., 2002). Additionally, attic temperature reduction in the winter would result in greater heat loss through the ceiling.

Research to date indicates that while passive attic ventilation may reduce attic temperature and sensible heat gain through ceilings, resulting in a modicum of cooling savings, the latent heat load in Oklahoma's humid summers may offset these gains and lead to other problems if the attic space and ductwork is not properly sealed. Increased energy use in winter months is also a concern. According to the literature, the most effective measures to reduce attic-influenced heat gain and loss are properly sealing and insulating the ceiling and AC ducts. Although forced attic ventilation is a possibility, it was beyond the scope of this investigation. This study focused on the impact on electrical energy use from increased passive attic ventilation in homes in the service territory of an electric utility. Though many studies question the efficacy of this measure, none have been done in the West South Central U.S. census region. The effects of attic ventilation were investigated first for the cooling season with a field study and then for a typical year using whole-building energy simulation.

FIELD STUDY

In the first phase of this study, six (6) homes with pre-existing roof vents were chosen to investigate the impacts of passive attic ventilation during the cooling season. These homes were one-story, single-family homes with central air conditioning (CAC). Temperature sensors were installed to record air temperatures within each home, in each attic, and outdoors for a period of 21 days while the roof vents were closed and opened in four alternating and approximately equal intervals. A regression analysis was done for the open and closed cases to predict the variation of attic temperatures based on outside air temperature (OAT), typical solar insolation, and a peak-coincident indicator variable. This approach made it possible to normalize the results with weather conditions and to compare closed and open cases.

The field study did not find significant difference between attic temperatures in closed and open cases, even for the largest observed temperature differences between average temperature profiles (see Figure 1). Nevertheless the field study did provide insight into the behavior of attic temperatures with changes in ventilation and external factors such as weather.

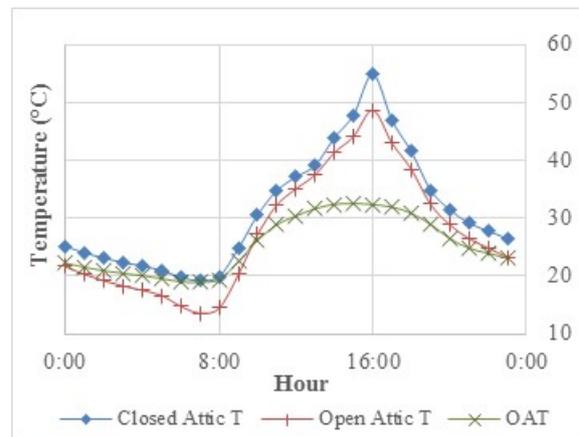


Figure 1 Average Measured Temperature Profile

The conductive heat transfer across the ceiling was then calculated for both cases with the standard heat transfer equation of $Q = UA\Delta T$. Average AC savings over the cooling season were estimated assuming the AC system would remove all heat transferred across the ceiling when the OAT was above the indoor temperature. Energy savings calculated for the examined homes varied between 6 kWh and 100 kWh for the cooling season (May 1 through October 15). Savings were also estimated based on conductive heat transfer across ducts in the attic space, resulting in a combined savings range of 21 to 352 kWh. A representative sample could not be selected for the utility service territory, due to time and monetary constraints, so results were not extrapolated to the population.

SIMULATION

To expand the analysis to the customer population, whole-building energy simulations were done using prototype models for typical homes in the utility service territory. This approach was considered more cost-effective for estimating whole-year impacts of attic ventilation on a wider range of homes than an expanded field study. An expansive field study was expected to require more intrusion at customer sites, require more expensive sensors and loggers, and require a greater amount of labor.

BEoptTM was used as the front-end modeling tool; EnergyPlusTM as the simulation engine. BEopt and EnergyPlus use a reasonable approach to model the effect of passive attic ventilation on attic temperature and resulting changes in home energy use. Although the model does not account for various attic ventilation designs (e.g. turtle and ridge vents as opposed to soffit vents), the EnergyPlus simulation bases its infiltration analysis on the widely accepted AIM-2 and Sherman-Grimsrud infiltration models. These approaches, which offer explicit algebraic solutions for wind and stack driven ventilation across the building envelope boundary, are incorporated into the EnergyPlus model (Sherman, et al., 1980; Walker et al., 1998). However, this approach does not include

infiltration between the attic and indoor space; the analysis assumes a perfectly sealed ceiling boundary. Prototypes were created based on typical construction characteristics and other data collected from the utility's existing weatherization program and national surveys (RECS, 2009) to accurately represent detached single-family homes in the utility's territory. A sensitivity analysis was completed prior to the full set of simulations to determine key parameters to take into account in the full simulation runs. This exploration was conducted by individually varying BEopt inputs with a change in attic ventilation and determining the coefficient of variation (CV) for percent change in electricity use. The CV was used to determine the significance of the parameter's impact on ventilation savings, with a threshold for sensitivity set at 30% to balance sufficient granularity with practical limits for simulation and analysis.

The baseline SLA of 1:1500 was chosen to reflect a realistic baseline ventilation level that is 20% of the minimum code ventilation level for attics with a vapour barrier (1:300) as well as 10% of the default code ventilation level (1:150). Building geometries were simplified as square homes without attached garages, with average conditioned areas of 36.7 m² for single-story homes and 53.8 m² for two-story homes. Whole-house infiltration and duct leakage were set at 12.5 ACH₅₀ and 17.5%, respectively, to represent the conditions of the home after implementing air and duct sealing measures. Heating and cooling setpoints were fixed at temperatures of 68°F and 78°F (20°C and 25.6°C), respectively (RESNET, 2014). Eight (8) final parameter types were varied in the study:

1. *Number of Stories*: One and Two
2. *Unfinished Attic Insulation Level*: R-0, R-11, R-19, and R-38*
3. *HVAC Type*: Combinations of CAC, Room AC (RAC), Air-Source Heat Pump (ASHP) Forced Air Furnace (FAF), Electric Baseboard Heat (BB)
4. *HVAC Efficiency*: Efficiency levels of SEER 10 and SEER 13 for CAC systems, EER 8.5 and EER 9.8 for RAC systems, SEER 10/HSPF 6.2 and SEER 13/HSPF 7.7 for ASHP systems reflected pre- and post-2006 standard efficiencies for electric HVAC equipment (U.S. DOE, 2006). Gas furnaces were assumed to have an AFUE of 78%
5. *Duct Location*: Attic and Interior
6. *Duct Insulation*: R-0, R-2, R-4
7. *Climate Zone*: Based on five (5) representative cities in Oklahoma and Arkansas
8. *SLA Ratio*: 1:1500, 1:300, 1:150

Twenty (20) prototypes were created representing each type of home (single or two-story), presence of ducts, and climate zone. The above parameters were

then varied in BEopt's parametric analysis mode, where multiple variables could be iterated against each other to result in unique permutations used for savings analysis. Typical meteorological year (TMY3) data was used for each climate zone to simulate the energy use of a home during a typical year.

Post-Processing

After the batch parametric simulations, hourly outputs were post-processed. The hourly output files were analysed to obtain annual total electricity and heating end use consumption for each iteration. Annual electricity consumption values for iterations vented at SLAs of 1:300 and 1:150 were then subtracted from the annual consumption of the corresponding baseline iteration. Estimates of electricity savings for homes with Central Gas Heat (CGH) and Gas Space Heat (GSH) were accounted for without further simulation by subtracting electric heating end use from the annual electricity consumption. This method was manually confirmed to provide the same annual electrical energy consumption as a home modeled with gas heat: furnace fan energy was accounted for with a separate HVAC fan end use. Including these homes resulted in a total of 4,000 iterations for energy savings. Peak-coincident electric demand reductions were also investigated; the utility system peak period is between 16:00 and 17:00 in the last week of July and first week of August. Hourly output files for each iteration were analysed to obtain average peak demand values (in kW), and the reduction in average peak demand was calculated by subtracting corresponding cases.

RESULTS AND DISCUSSION

Single-story homes comprised the bulk (95%) of the studied population and thus were the main focus of this investigation. Once annual electricity savings were calculated for each iteration, they could be re-organized and analysed for trends. The box plot in Figure 2 depicts the ranges of savings for single-story homes over all climate zones separated by the HVAC system type for an increase in attic ventilation to a code-mandated level of 1:150. The savings range for single-story homes ventilated to an SLA of 1:300 was narrower than the corresponding range for 1:150 ventilation savings. A smaller area of installed attic ventilation resulted in a lower change in attic temperatures and subsequent energy impacts.

After further parsing of the data, the following observations were made:

1. *A large contingent[†] of homes with electric heating systems had increased electricity use.* In most iterations, cooling savings from adding attic ventilation were outweighed by increased electric heating. Homes with uninsulated attics and uninsulated ducts located in the attic showed the largest increase in electricity consumption, and

** R-values are given in ft²-°F-hr/Btu

[†] 74% of 2,320 single- and two-story iterations with electric heat resulted in negative savings.

- uninsulated attics resulted in increased electricity use for all homes with electric heating systems.
2. *Only 33% of single-story homes with electric heat had electricity savings.* CAC-BB, ASHP, and ductless RAC-BB homes tended to have more instances of savings, while only 18% and 12% of CAC-FAF and RAC-FAF (respectively) home iterations had savings. This could be explained by the lack of ductwork and corresponding lack of heat loss through ductwork for baseboard heating systems, as well as the higher efficiencies of ASHP heating systems.
 3. *Most savings for homes with electric heat were low, averaging 59 kWh/yr for 1:150 ventilation and 37 kWh/yr for 1:300 ventilation across all climate zones.* The overall CV for savings across all homes with electric heat and both levels of ventilation was 78%, indicating significant variability. Separating these savings by HVAC system and weather zone, each range still had significantly high CV values ($\geq 30\%$). This level of variation made each average less likely to be acceptable as a deemed (or prescribed) savings. The maximum savings for a home with electric heat was 1.9% of the baseline.
 4. *More efficient cooling systems tended to have lower savings than less efficient counterparts, and thus more savings for units with pre-2006 standard efficiency.* However, this was only true for systems where heating efficiency was constant (e.g. systems with electric resistance heating and not ASHP). Additionally, all iterations of homes with no attic insulation resulted in increased use. While there were more instances of savings for interior duct locations, savings were lower on average than the average savings when ducts were in the attic. Furthermore, savings for 1:150 ventilation cases were greater than their 1:300 ventilation counterparts. Iterations with 1:150 code ventilation are the primary focus of the following discussion unless otherwise noted; iterations with 1:300 ventilation followed the same general trends.
 5. *For two-story homes with electric heating, only 18% of iterations resulted in savings.* This could be explained by the relatively lower impact that heat transfer through the ceiling had on the overall energy consumption of a two-story home. Another reason was the exclusion of non-central heating systems in two-story homes. While the overwhelming majority of the savings instances for two-story homes were for ASHP HVAC systems, these comprised only 2% of the examined population due to the currently limited penetration of this technology. Furthermore, savings for homes with ASHP systems were most common for interior duct configurations, which eliminated heat loss through ductwork.
 6. *All homes with gas heating systems exhibited annual electricity savings.* With no electrical penalty during the heating season besides an increase in furnace fan usage, homes with natural gas heating systems showed savings across the board. Electricity savings for homes with gas-fired heating systems tended to decrease with increasing attic insulation. In the best-case scenario, this resulted in a maximum of 4% electrical energy savings from the original baseline for single-story homes and a maximum of 2% savings for two-story homes. These electricity savings do not necessarily mean overall energy use is reduced; the gas cost in the heating season is still increased. This study focused only on the electrical consumption impacts.
- In the field study, cooling season savings for single-story homes with CAC were found to vary from 21 to 352 kWh (for an average real SLA ratio of 1:133). This was based on simplified engineering calculations for conductive heat transfer across ceilings and ducts without taking heating penalties into account. This range is consistent with the annual savings range of 36 to 369 kWh/yr found for simulated single-story homes with CAC and central gas heat systems and an SLA ratio of 1:150.
- Since the system peak occurs during the cooling season, demand reductions were all positive. For homes with central cooling systems, interior ducts, efficient AC equipment, and high attic insulation levels resulted in the lowest demand reductions; uninsulated ducts in the attic and R-11 attic insulation resulted in the highest. Peak demand reductions were low overall, with an average reduction of 0.11 kW (maximum reduction of 0.39 kW) for all single-story homes and 0.07 kW (maximum of 0.20 kW) for all two-story homes with 1:150 attic ventilation levels.

Statistical Analysis

Though most variables in this study were quite discrete, numerous regression models were run in an attempt to develop an algorithm for attic ventilation electrical energy savings. The statistical analysis was conducted with StatwingTM, a web-based regression analysis tool that allows for ordinary least squares (OLS) as well as more robust M-estimation methods. Both techniques were applied to the full 4,000-point dataset from single- and two-story homes.

All eight (8) investigated variables were statistically significant, which confirmed the findings of the sensitivity analysis. To get a more accurate regression, the analysis was filtered for only positive energy savings in ducted homes; the inverses of attic and duct insulation R-values were also used to better reflect

their thermodynamic impact.[‡] While the transformation of attic and duct insulation R-values improved the curve fit, this reduced the scope of application. Climate zones were used as discrete string variables instead of their constituent parameters such as degree-days due to the annualized nature of the analysis. The final regression models were built on a sample of 1,371 datapoints and resulted in R-squared values of 0.77 for the OLS method. Thus, the variation in investigated variables could explain 77% of the variation in savings from attic ventilation.

The resultant algorithm from the OLS method can be seen in Equation 1 below, where all variable names except for R-values, SLA (as a mathematical ratio), and cooling efficiency are binary indicators (1 = True, 0 = False) for the presence of that particular parameter.

$$\begin{aligned}
 kWh \text{ savings} = & 95.6 + 609.6*(Attic \ R\text{-value})^{-1} + \\
 & 0*(One \ Story) - 33.3*(Two \ Stories) + \\
 & 0*(RAC\text{-}Gas) + 34.7*(CAC\text{-}GCH) + \\
 & 47.2*(CAC\text{-}GSH) - 16.7*(ASHP) - \\
 & 25.4*(CAC\text{-}BB) - 42.9*(CAC\text{-}FAF) - \\
 & 40.5*(RAC\text{-}FAF) + 0*(Ducts \ in \ Attic) - \\
 & 25.9*(Interior \ Ducts) + 26.1*(Duct \ R\text{-} \\
 & value)^{-1} - 7.9*(Cooling \ Eff.) + 0*(CZ6) - \\
 & 13.8*(CZ7) - 21.5*(CZ8a) - 20.3*(CZ8b) - \\
 & 18.5*(CZ9) + 8464.3*(SLA) \quad (1)
 \end{aligned}$$

The above equation provides a descriptive estimation for annual electricity savings from attic ventilation; it also indicates the relative influence of each parameter on the final savings values. However, the regression's predictive capability is limited due to odd residual trends at higher and lower levels of the savings spectrum. The coefficients for the regression can also be found in Table 1.

Other Parameters

In the field study temperature loggers were installed at multiple points in the attic as well as outdoors to gauge the effect of an increase in attic ventilation on attic temperature. Though a temperature difference could be discerned at times, the statistical significance was questionable. Humidity and latent heat considerations were identified as of interest but could not be taken into account in the quantitative analysis due to lack of data. Since BEopt can output hourly temperatures and other parameters like humidity, these parameters were explored for further effects and to validate the model.

A single-story home with a SEER 13 CAC and FAF system, R-19 attic insulation, and R-2 ducts in the attic in Zone 8a was used to explore temperature and humidity effects. The simulation with added 1:150 ventilation resulted in an annual cooling end use savings value of 104 kWh, an annual heating end use penalty of -308 kWh, and overall negative energy savings of -182 kWh.[§] Temperatures were taken for a representative hot day in July. As shown in Figure 3,

the ventilated attic option follows the variation in OAT much more closely.

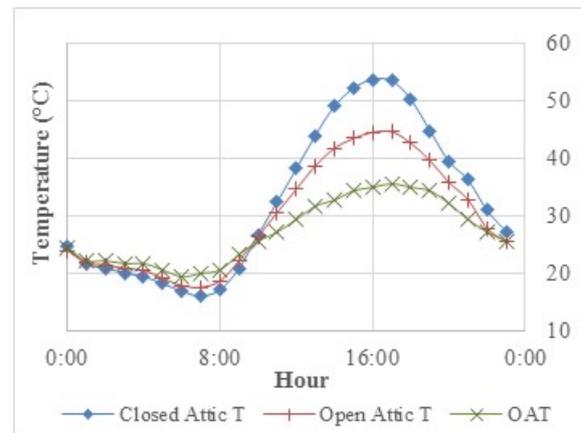


Figure 3 Simulated Peak Day Temperatures

These temperature differences persisted over the utility-defined cooling season from May 1 to October 15. For this home, the average temperature difference between the attic and OAT over the cooling season decreased by 55% from 4°C to 1.8°C from the unvented to vented attic case. The average temperature difference for peak hours between 12:00 and 20:00 over the cooling season decreased by 53% from 10.5°C to 4.9°C from the unvented to vented attic case. Temperature differences between the attic and OAT were reduced by of 61% for the rest of the year as well, explaining the large heating penalty. Attic temperature reductions were found to directly result in differences for sensible heat gain during the investigated time period.

Humidity effects were also investigated with an hourly profile for an average day over a typical year (see Figure 4), since single-day humidity variations were non-uniform.

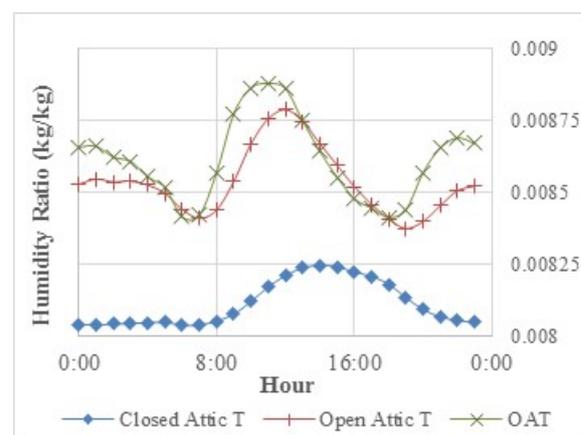


Figure 4 Simulated Humidity Ratio Averages

[‡] While transforming the R-value variables to an inverse function reflected the U-value and resulted in a better curve fit, it effectively removed R-values of 0 from the regression analysis.

[§] Energy savings for cooling and heating end uses do not add up to total annual savings due to other end uses, such as HVAC fans.

Though the relative humidity ratio in the attic did tend to follow the outdoor humidity ratio much more closely, there were no such clear-cut relationships for the HVAC system latent heat gains or losses. In the investigated peak day dataset, some hours (2:00 and 20:00) exhibited higher latent heat loads with a ventilated attic. This would increase AC use when ducts are in the attic even though the overall cooling effect is energy saving. The increase in humidity could cause non-energy related issues such as condensation on ductwork and attic damage.

The parametric simulation also allowed comparison of savings from different measure packages offered by the weatherization program and a simple savings-to-investment ratio (SIR) cost-effectiveness test. Other measures investigated included attic and duct insulation using parametric run results; duct sealing and whole-house infiltration reduction were modelled in a separate simulation to produce a full package of measures. The SIR results for different baseline attic insulation levels and various measure packages in a single-story home with a SEER 13 CAC and FAF system are depicted in Figure 5; an SIR level of 1 is considered cost-effective. These effects were further explored for homes with gas furnace systems, which increased the measure package cost-effectiveness. Expanding the parameter space with building energy simulations provided useful insights on program design and possible packages of measures.

SUMMARY AND CONCLUSIONS

This paper investigated electric energy and demand impacts from passive attic ventilation using field study measurements and parametric building energy simulations for homes in the American Southwest. The whole-building simulation analysis expanded on the field study results with hourly simulations that accounted for relevant physical models for infiltration, heat transfer, and various sources of sensible and latent heat gains. The results of the parametric simulations were used to determine trends for energy impacts based on a wider array of parameters, provide insight on the main drivers of changes in energy consumption, validate earlier models from the field study, and explore cost effectiveness and program design. This approach was less costly, less intrusive to homeowners, and more comprehensive than an expanded field study. This study showed that attic ventilation results in non-trivial differences in attic temperature and accompanying energy impacts, with heating system penalties often outweighing cooling system benefits in the climate of interest. The results also pointed to practices such as attic insulation and interior duct re-location that result in higher savings and lower penalties from code-required ventilation levels. Although this study focused on ventilation impacts in the American Southwest, the approach can be generalized for similar research in other warm climates. Building energy simulations allowed for a robust analysis of a rarely studied measure with results

that could be applied to identify home characteristics that result in attic ventilation electricity savings and estimate typical savings magnitudes when they occur.

NOMENCLATURE

A	= Area of heat transfer, in ft ² or m ²
ACH ₅₀	= Air changes per hour at 50 Pa
AFUE	= Annual fuel utilization efficiency, in units of Btu/Btu
BB	= Electric baseboard heating
CAC	= Central air conditioner
CZ6	= Climate zone represented by El Dorado, Arkansas USA
CZ7	= Climate zone represented by Lawton, Oklahoma USA
CZ8a	= Climate zone represented by Oklahoma City, Oklahoma USA
CZ8b	= Climate zone represented by Tulsa, Oklahoma USA
CZ9	= Climate zone represented by Fayetteville, Arkansas USA
EER	= Energy efficiency ratio, in units of Btu/Wh
FAF	= Electric forced air furnace
GCH	= Gas, central heat
GSH	= Gas, space heat
HSPF	= Heating seasonal performance factor, in units of Btu/Wh
OAT	= Outside air temperature
Q	= Heat, in Btu or W
RAC	= Room air conditioner
R-value	= Thermal resistance, in units of ft ² -°F-hr/Btu
SEER	= Seasonal energy efficiency ratio, in units of Btu/Wh
SLA	= Specific leakage area
ΔT	= Temperature gradient, in °F or °C
U	= Heat transfer coefficient, in units of Btu/ft ² -°F-hr or W/m ² -°C

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REFERENCES

- Burch, D. M., Treado, S. 1978. Ventilating Residences and their Attics for Energy Conservation - An Experimental Study. Workshop at Center for Building Technology, National Bureau of Standards. Washington, D.C. USA.
- Cash, C.G., Lyon, E.G. 2002. What's the Value of Ventilation? Professional Roofing, March.
- Dutt, G., Harrje, D. 1978. Forced Ventilation for Cooling attics in Summer. Summer Attic and Whole-House Ventilation, NBS Special Publication 548.
- International Building Code (IBC), 2009. International Code Council, Inc., Illinois USA.
- Huang, J. 1999. Residential Heating and Cooling Loads Component Analysis. Building Technologies Department, Lawrence Berkeley National Laboratory. California USA.
- Parker, D. 2005. Literature Review of the Impact and Need for Attic Ventilation in Florida Homes. Florida Solar Energy Center. Florida USA.
- Residential Energy Consumption Survey (RECS), 2009. US Energy Information Administration. Washington, D.C. USA.
- Residential Energy Services Network (RESNET). 2014. Standard for the Calculation and Labeling of the Energy Performance of Low-Rise Residential Buildings using the HERS Index. Residential Energy Services Network, Inc. California USA.
- Rose, W. 1995. The History of Attic Ventilation Regulation and Research. Thermal Envelopes VI/Moisture and Air Leakage Control II – Practices, ASHRAE/DOE/BTECC, p. 125, December.
- Rose, W. 2001. Measured Values of Temperature and Sheathing Moisture Content in Residential Attic Assemblies. Performance of Exterior Envelopes of Whole Buildings VIII: Integration of Building Envelopes.
- Rose, W., TenWolde, A. 2002. Venting of Attics and Cathedral Ceilings. ASHRAE Journal, 26-33. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. October.
- Sherman, M.H., Grimsrud, D.T. 1980. Measurement of Infiltration Using Fan Pressurization and Weather Data. Lawrence Berkeley Laboratory, October. California USA
- Terrenzio, L.E. 1997. Natural v. Artificial Aging: Use of Diffusion Theory to Model Asphalt and Fiberglass-reinforced Shingle Performance. Fourth International Symposium on Roofing Technology. National Roofing Contractors of America.
- United States Department of Energy (U.S. DOE). Appliance and Equipment Standards, Building Technologies Office. Washington D.C. USA.
- Walker, I.S., Wilson, D.J., 1998. Field Validation of Algebraic Equations for Stack and Wind Driven Air Infiltration Calculations. ASHRAE HVAC&R Research Vol. 4 No. 2, p. 119.

Table 1
Regression Results for Annual Electric Energy Savings

PARAMETER	COEFFICIENT	P-VALUE	PARAMETER	COEFFICIENT	P-VALUE
Intercept	95.6	3E-52	Interior Ducts	-25.9	4E-53
1 / Attic R-Value	609.6	2E-115	1 / Duct R-value	26.1	7E-05
Two Story Home	-33.3	1E-99	Cooling Efficiency	-7.9	5E-53
CAC-GCH System	34.7	2E-56	CZ7	-13.8	1E-13
CAC-GSH System	47.2	2E-69	CZ8a	-21.5	4E-25
ASHP System	-16.7	6E-12	CZ8b	-20.3	4E-23
CAC-BB System	-25.4	2E-20	CZ9	-18.5	8E-20
CAC-FAF System	-42.9	2E-35	Final SLA	8,464.3	1E-94
RAC-FAF System	-40.5	5E-35			

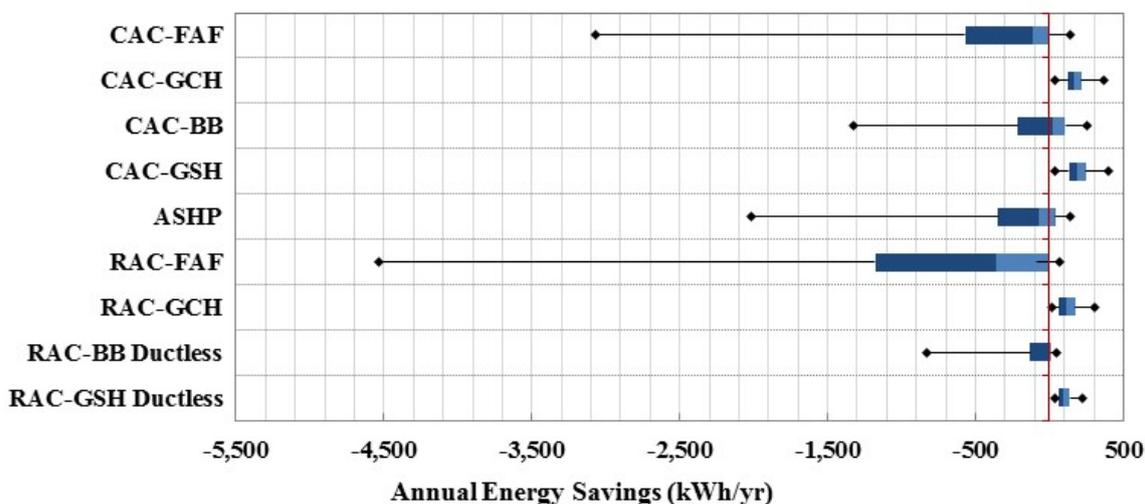


Figure 2 Ranges of Savings for Single-Story Homes, Vented from SLA of 1:1500 to 1:150

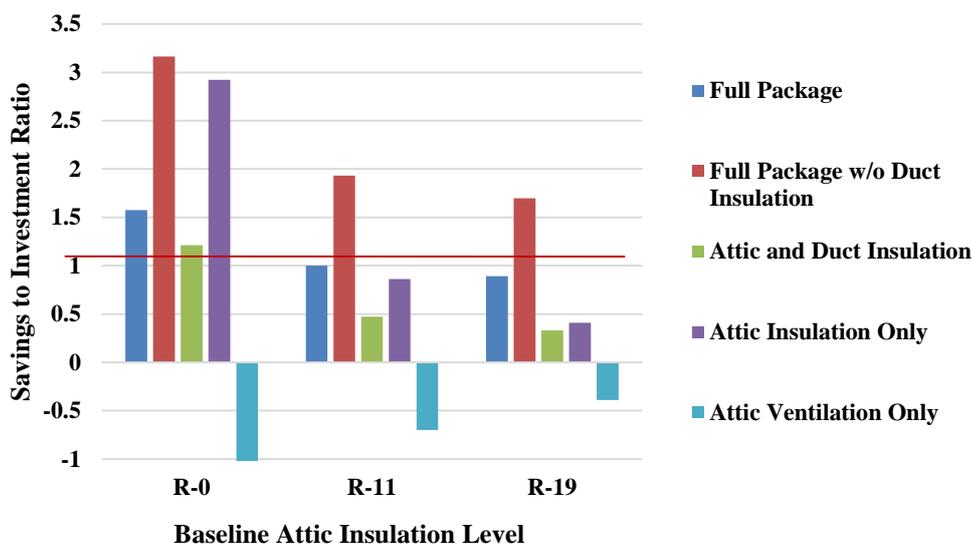


Figure 5 SIR Comparison for Various Measure Packages, by Insulation Level