

# A WEB-BASED SIMULATION TOOL ON THE PERFORMANCE OF DIFFERENT ROOFING SYSTEMS

Yu Joe Huang<sup>1</sup>, Joshua R New<sup>2</sup>, William A Miller<sup>2</sup>, Kenneth W Childs<sup>2</sup>, Ronnen Levinson<sup>3</sup>

<sup>1</sup>White Box Technologies, Moraga CA, United States of America;

<sup>2</sup>Oak Ridge National Laboratory, Oak Ridge TN, United States of America;

<sup>3</sup>Lawrence Berkeley National Laboratory, Berkeley CA, United States of America

## ABSTRACT

The *Roof Savings Calculator* ([www.roofcalc.com](http://www.roofcalc.com)) provides the general public with a web-based program for calculating the energy savings of different roofing and attic systems on four different building types (residential, office, retail, and warehouse) in 239 US TMY2 locations. The core simulation engine of the *RSC* is *doe2attic*, which couples the *AtticSim* program developed by Oak Ridge National Laboratory with the *DOE-2.1E* program originally developed by Lawrence Berkeley National Laboratory in the early 1980's and maintained through the late 1990's.

Although simulating heat flows through the roof may seem at first to be easy, modeling the net impact of roofing strategies on building heating and cooling energy use can be challenging. Few simulation programs can model reliably thermal conditions in an attic that has large day-night temperature swings, high ventilation rates, significant radiant exchange between the roof and the attic floor, as well as the complex thermal interactions between the ducts and the attic air and inside surfaces.

The *doe2attic* program has been tested against detailed measurements gathered in two residential buildings in Fresno, California from cooling energy use to air and surface temperatures, and heat fluxes of the roof and attic floor. The focus of this paper is on the *doe2attic* simulation program, and not the *RSC* user interface that has been described in other papers..

## INTRODUCTION

The *Roof Savings Calculator (RSC)* is a web-accessible tool that leverages the *AtticSim* program for advanced modeling of modern attic and cool roofing technologies, in combination with hour-by-hour whole building energy performance provided by *DOE-2.1E*, to provide simulations that quantify annual energy and cost savings between a customizable baseline building and a cool-roof building. *RSC* was developed beginning in 2009 through collaborations among Oak Ridge National Laboratory (ORNL), White Box Technologies (WBT), Lawrence Berkeley National Laboratory (LBNL), and the Environmental Protection Agency (EPA) in the context of a California Energy Commission (CEC) Public Interest Energy Research (PIER) project to make cool-color roofing materials a

market reality. The *RSC* was developed to replace DOE's *Cool Roof Calculator* (DOE 2015) and EPA's *Energy Star Roofing Calculator* (EPA 2012).

The primary objective in developing *RSC* was to provide a web-based tool with which users can easily estimate realistic cooling energy savings that can be achieved by installing Cool Roofing products on the most common residential and commercial building types in the US stock. Other goals included educating the public with regard to cool roofing options, helping manufacturers of cool-color materials deploy their products, and assisting utilities and public interest organizations to refine incentive programs for Cool Roofs. The first version of the *RSC* was completed in 2012, but the validation described in this paper was not done until 2014.

## THE DOE2ATTIC PROGRAM

The *RSC* uses *doe2attic* as its simulation engine, which is a coupling of two simulation programs, each well-established in its domain – *AtticSim* for modeling attics, and *DOE-2.1E* for modeling whole buildings. By combining the two programs, the *RSC* is able to model in detail the thermal processes in the attic, including the effects of the duct system, and then calculate the impact these processes would have on the thermal comfort and energy usage of the entire building. In *doe2attic*, *AtticSim* has been modified into a large subroutine within *DOE-2.1E* that is called during the SYSTEMS module and returns to the main program the heat flows through the ceiling to the space below, as well as the heat losses or gains for any ducts that pass through the attic space. All the input data needed by *AtticSim*, such as the ambient outside conditions, the physical descriptions of the attic and the duct system, the air temperature of the room below, the supply air temperature, flowrate, and fraction ontime of the duct system, etc., are all extracted from or calculated by *DOE-2.1E*. The following three subsections briefly describe *AtticSim* and *DOE-2.1E*, and how the two programs have been coupled.

### *a. Description of AtticSim*

*AtticSim* is a computer tool for predicting the thermal performance of residential attics. The code is publicly available as ASTM Standard C1340 (ASTM 2004). It mathematically describes the conduction through the gables, eaves, roof deck, and ceiling; the convection at the exterior and interior surfaces; the radiant heat exchange between surfaces within the

attic enclosure; the heat transfer to the ventilation air stream; and the latent heat effects due to sorption and desorption of moisture at the wood surfaces. Each of these heat flow paths is solved separately using methods either based on the literature or developed at ORNL. Conduction is calculated using conduction transfer functions, convection using correlations in the literature, radiative exchange with the enclosure method using first principles equations, as is ventilation using a method by Peavy.

To simplify the simulation of radiant heat exchange, *AtticSim* assumes fixed view factors between seven attic surfaces (2 roofs, 2 gables, 2 eaves, and 1 floor/ceiling) and the ducts (if they are located in the attic). Thus, *AtticSim* is limited to modeling only flat (e.g. commercial), open gable, saltbox, or shed roofs. Heat balance equations are used to combine the heat flows at the inside and outside surfaces and on the attic air mass. For a thorough description of the equations and their implementation in *AtticSim*, please refer to ASTM 2004.

Because of the strong interaction between the attic and any ducts located there, *AtticSim* also has an algorithm for predicting the effect of air-conditioning ducts in the attic (Petrie et al. 2004). Typical construction places ductwork within the attic, which can triple the loads for the attic assembly for moderately leaky ducts (Petrie et al. 2004, Parker et al. 1993). *AtticSim* models the impact of conduction, leakage, surface convection, and radiative exchange between the ducts and the attic surfaces, even when the HVAC system is turned off, but does not calculate pressure or air loop connections. Petrie et al. 1998 validated the duct algorithm in *AtticSim* against experimental data for an attic assembly tested first without and then with a radiant barrier attached to the underside of the roof deck. Validations showed the duct algorithm predicted the duct air temperature change (inlet-to-outlet of the supply duct) within  $\pm 0.2^\circ\text{C}$  ( $\pm 0.3^\circ\text{F}$ ) of the test results.

*AtticSim* was the subject of an extensive field validation conducted by Ober and Wilkes (1997) for ASHRAE, which provides mathematical documentation of the code and validation results for low-slope and steep-slope field data collected from seven different field sites. The code was later validated for steep-slope asphalt shingle and stone-coated metal roofs (Miller 2006). *AtticSim* was also benchmarked against clay and concrete tile and painted metal roof and attic assemblies that exhibit above-sheathing ventilation (i.e., roof on a roof) where heat in an inclined air space is carried by buoyant air away from the roof deck and out the roof ridge (Miller et al. 2007).

#### **b. Description of DOE-2.1E**

*DOE-2.1E* is a whole-building energy simulation program that was originally developed by Lawrence Berkeley National Laboratory in the early 1980s (Version 2.1A) (LASL 1980, LBL 1982), with

continued development through 1993 (Versions 2.1B through 2.1E) (Winkelmann et al. 1993). *DOE-2.1E* is the most recent version in the public domain, although there have been later efforts and user-interfaces developed by private companies.

*DOE-2* operates on an hourly time-step, and uses Response Factors to model the dynamic heat flows through the building envelope. At the zone level, *DOE-2* uses Weighting Factors (also called Zone Response Factors) to model the dynamic response of the space, taking into account its thermal mass or capacitance, heat loss through radiation and or convection. *DOE-2* is made up of two programs, an input processing program called *doebdl* and a simulation program called *doesim*, which in turn contains four separate modules that are invoked sequentially. The LOADS module simulates the heat flows in and out of the building and calculates the net balance at a fixed reference temperature, where negative is interpreted as a heating load and positive as a cooling load. The SYSTEMS module takes the results from LOADS, simulates the operation of the HVAC system, and derives the actual zone temperatures, amount of heating and cooling provided by the system, and the energy consumed. If the building has a central plant, the heating and cooling demands from SYSTEMS are passed to the PLANT module that simulates the energy consumed by the plant to meet the SYSTEMS demands. The version used for *doe2attic* is *DOE-2.1E* Version 124, released by LBNL in April 2004.

#### **c. Combining AtticSim with DOE-2.1E**

*DOE-2.1E* and *AtticSim* are both written in FORTRAN and the method of integration primarily relies upon the idea of using the attic floor/ceiling as a boundary condition for interaction between the two programs, except that heat losses and gains in the duct systems are added directly to the zone air below. For all simulations, the attic floor/ceiling is assumed sealed with no air leakage crossing from the conditioned space into the attic. The heat flows at the attic's roof, gables, eaves, and floor are calculated in *AtticSim* using the thermal response factor technique by Mitalas and Stephenson (1981), whereby the dynamic response of a layer is modeled using Conduction Transfer Functions (CTF), while the heat gain to the space is modeled using the heat balance technique. *DOE-2.1E* uses a similar technique of Response Factors (RF) to calculate heat flows through the building envelope, but uses Weighting Factors (WF), which is a parameterization of a heat balance solution, to model the heat gain to the space.

In *doe2attic*, new subroutines have been added to *doebdl* and *doesim* (now called *doe2atticbdl* and *doe2atticsim*) to extract the descriptions of the attic space and surfaces and reformat them as *AtticSim* inputs. For example, the attic surface RFs calculated by *doe2atticbdl* are transformed to CTFs before they are passed to *AtticSim*. Since there are many

*AtticSim* inputs, especially for the duct system, that do not appear in *DOE-2.1E*, a number of new keywords have been added to *doe2atticbdl*. Since *AtticSim* can only handle a fixed rectilinear attic geometry with 7 surfaces (2 roofs, 2 gables, 2 eaves, 1 floor), the inputs for the attic in *doe2attic* have also been constrained to accept only length, width, and pitch, and not flexible geometry with user-defined coordinates or vertices.<sup>1</sup> Lastly, to simplify programming requirements, it was decided to allow only one attic, require that it be listed first in both the LOADS and SYSTEMS inputs, and be identified by the name ATTICSIM.

In *doe2atticsim*, *AtticSim* has been converted to a subroutine that is called in the SYSTEMS module, in effect overwriting the attic loads calculated by LOADS, and replacing it with the heat flows, surface and air temperatures, ventilation rates, and (if ducts are in the attic) the heat losses or gains to the duct system. To calculate the ceiling heat flows and the duct losses, *AtticSim* uses the room air temperature below, and the HVAC and fan ontimes from the previous time step. *AtticSim* then returns to the main program the attic temperature, the heat flows through the ceiling, and the heat gains or losses to the HVAC ducts, which are used by *doe2atticsim* in calculating the room air temperature below, the heat addition or extraction provided by the HVAC system, and finally its energy consumption.

During the course of the project, new insights were gained and improvements made in modeling of duct losses. These are described in detail in Miller et al. 2014, and summarized below:

- 1) *Correction to HVAC Loads due to ducts*  
Any net mass gain or loss in the conditioned space due to leakage in the ducts has to be compensated. If leaks from the supply ducts exceed leaks into the return ducts then air is drawn into the conditioned space from the outdoors to make up the net difference.

$$\dot{Q}_{ducts} = \sum_{i=1}^{N_{ducts}} (\dot{m}_{in} c_p T_{in} - \dot{m}_{out} c_p T_{out})_i + \dot{m}_{net} c_p T_{outdoor} \quad (1)$$

If leaks into the return ducts exceed leaks from the supply ducts then indoor air has to be exhausted from the conditioned space to make up the net difference.

$$\dot{Q}_{ducts} = \sum_{i=1}^{N_{ducts}} (\dot{m}_{in} c_p T_{in} - \dot{m}_{out} c_p T_{out})_i - \dot{m}_{net} c_p T_{indoor} \quad (2)$$

- 2) *Correction to HVAC "on Time" Fraction*  
When *AtticSim* calls the transient duct subroutine (DUCTTR) to calculate performance for an hour

it supplies a variable (ONTIME) giving the fraction of time during the hour that the HVAC system is on. *AtticSim* calculates the number of cycles per hour using Eq. 3. A plot of the number of cycles per hour versus the specified on time is shown in Fig 1.

$$N_{cycles} = 3 * 4 * ONTIME * (1 - ONTIME) \quad (3)$$

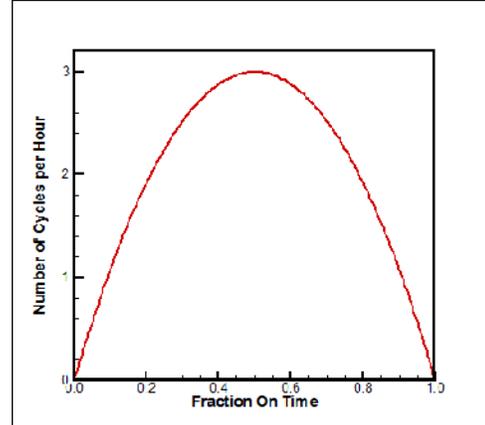


Figure 1. Cycles per hours as a function of ONTIME

The time that the HVAC is on during a cycle is given by Eq. 4, and the time that it is off is given by Eq. 5

$$t_{on} = ONTIME / N_{cycles} \quad (4)$$

$$t_{off} = (1 - ONTIME) / N_{cycles} \quad (5)$$

Unfortunately, this procedure did not guarantee that the specific on time is achieved for the hour, because a cycle might not be complete during the hour. To correct this discrepancy, *AtticSim* was modified to always have an integer number of cycles per hour as illustrated in Figure 2.

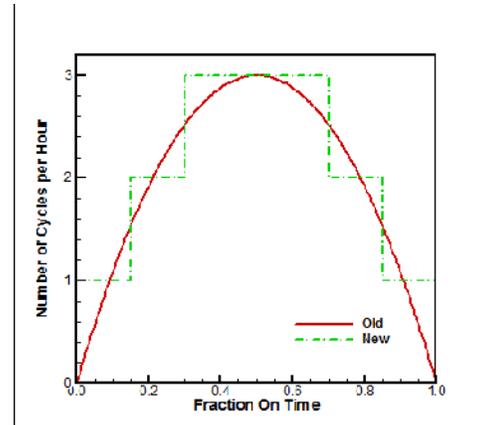


Figure 2. Modified method for calculating cycles per hour

- 3) *Change in Duct Length for Large Buildings*  
When performing its energy balance calculation on a duct *AtticSim* divides the duct length into a number of equal-length segments. Each segment has a maximum length of 1 foot, and there are a

<sup>1</sup> The reason for this fixed attic geometry has to do with the heat balance solution in *AtticSim*. There has been some exploratory work with having flexible attic geometry, which is beyond the scope of this project.

maximum of 100 segments. Thus the maximum length for any duct was 100 feet. However commercial buildings commonly have duct runs much greater than 100 feet in length, so there was a need to remove this restriction from *AtticSim* in order to simulate large buildings. Two alternatives were considered: (1) keep the 1 foot segment length but increase the number of segments or (2) keep a maximum of 100 but increase the segment length. Both approaches have shortcomings. Increasing the number of segments will drastically increase the time required to run a simulation. Increasing the segment length can introduce inaccuracies in the calculations – particularly near the duct entrance where temperatures may be changing rapidly along the duct length. Thus, a third hybrid approach was implemented where the segment length is 1 foot at the duct entrance but each segment along the duct is progressively longer than the previous segment. This allows the code to handle the rapidly changing condition near the entrance, while limiting the number of segments by having longer segments further down the duct where change is much more gradual. Figure 3 shows the required growth factor to obtain the desired duct length using 100 segments. Also shown in the figure is the equation used by *AtticSim* to calculate the growth factor.<sup>2</sup> This modification was tested by comparing results from a version of *AtticSim* where the number of 1-foot segments was increased to give the desired length to a version with 100 segments with increasing length down the duct. For the cases tested the two versions gave essentially the same results for duct lengths up to 1000 feet, but the case with 100 increasing-length segments runs much faster.

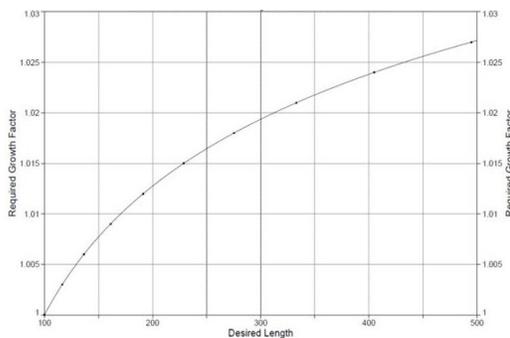


Fig 3. Equation used for model growth factor

## VALIDATION OF DOE2ATTIC

Although there have been multiple studies comparing *AtticSim* and *DOE-2.1E* separately to measured data (Parker 2005, Sullivan and Winkelmann 1998), there is still a need to validate the combined *doe2attic*

<sup>2</sup> The equation was obtained by curve fit using the commercial software package TableCurve 2D.

program, particularly for the impact of roof measures on HVAC energy use. This is particularly true for building energy modeling, since input parameters and in this case, the “handshaking” between two complex programs, can cause large discrepancies between the simulated results and measured data even if the fundamental algorithms are sound.

Empirical validation of *doe2attic* addressing not only the simulation program, but also the modeling methodology, was done using measured data obtained by one of the co-authors for two similar houses in Fresno CA with different roof conditions that were monitored for a year from May 2012 through April 2013 (Rosado et al. 2014). Since the objective of that monitoring effort was to measure the thermal performance and energy usage for two roofing systems, the data set was particularly detailed for the attics, making it particularly useful for validating the *doe2attic* program.

Detailed descriptions of the two houses, their operations and indoor conditions, monitoring instrumentation, and a summary of the monitored results are provided in Rosado et al. 2014. To use the measured data to validate *doe2attic*, the lead author created detailed computer models of both houses based on the information in Rosado et al. 2014, supplemented by additional information provided by a co-author. These models were then simulated in *doe2attic* using the onsite weather data, and the results compared to the monitored data that included the surface temperatures of the roof, attic and room air temperatures, ceiling heat flux, return air temperature and relative humidity, and electricity use (Rosado et al. 2014)

### a. Description of the two houses

The two monitored houses are typical new construction located in a residential development on the outskirts of Fresno California. They were actually “show homes” during the monitoring period that were unoccupied but kept on a fixed operating schedule for space conditioning and lighting, with no other internal loads except for intermittent customer foot traffic. In the computer models of the houses, the metered non-HVAC electricity was converted into internal loads schedules. As indicated in Table 1, the main difference between the two houses is in their roofing systems, where the Standard Home has asphalt shingles with an albedo of 0.07, while the Cool Home has light-colored concrete tiles with an albedo of 0.51.

### b. Onsite weather data

Fresno has a subtropical climate characterized by relatively mild winters, but hot moderately humid summers with large diurnal swings. An onsite weather station had been installed that recorded temperature, humidity, and global horizontal solar radiation. For many technical reasons, there were

Table 1. Summary of house characteristics

Property	Standard Home	Cool Home
Living floor area (m <sup>2</sup> )	187	189
Number of stories	1	Same
Ceiling height (m)	2.74	3.05
Frame construction	Wood	Same
Roof		
Type	Asphalt shingle	Concrete tile
Initial albedo	0.07	0.51
Mass (kg/m <sup>2</sup> )	17.3	47.4
Thermal capacity (kJ/m <sup>2</sup> -K)	21.8	39.8
Waterproofing layer and deck	black felt over plywood sheathing	Same
Slope	18.4°	22.6°
Air gap height (cm)	No gap	1.9 - 4.4
Attic		
Total ventilation area (m <sup>2</sup> )	1.66	1.62
Gable end vent - qty. x area (m <sup>2</sup> )	2 x 0.25	4 x 0.17
Eave vent - qty. x area (m <sup>2</sup> )	20 x 0.04	19 x 0.04
Dormer vent - qty. x area (m <sup>2</sup> )	6 x 0.06	3 x 0.06
Radiant barrier	None	Same
Insulation (m <sup>2</sup> -K/W)		
Roof	3.3	Same
Exterior wall	3.3	Same
Ducts	1.1	Same
Windows		
Construction	2-pane, low- E	Same
U-factor (W/m <sup>2</sup> -K)	1.9 - 2.0	1.6 - 1.7
Area (m <sup>2</sup> )		
South	3.25	4.74
East	1.86	3.40
West	11.90	11.00
North	9.38	2.32
Total	26.30	21.50
HVAC system		
Air conditioner		
Estimated COP (Wh/Wh)	3.5	3.5
Cooling capacity (kW)	12.3	14
Gas furnace		
AFUE (%)	92.1	Same

Ref: Rosado et al. 2014

significant amounts of missing data. Since this weather station did not contain an anemometer, wind speed data were obtained from the nearest California Irrigation Management Information System (CIMIS) station located 2 km to the west. Data from the nearest major weather station (Fresno Yosemite International Airport, WMO 723890) were also obtained to be used for filling missing data and evaluating the quality of the onsite weather data.

The differences in temperature and wind speed seemed explainable due to the local terrain factors (see Figure 4 for dry-bulb and dewpoint temperatures, Figure 5 left for wind speeds). However, the locally measured global solar radiation under clear skies was found to be consistently 9% higher than that calculated using the 2009 ASHRAE Clear Sky Model (ACSM09, Gueymard and Thevenard 2013).

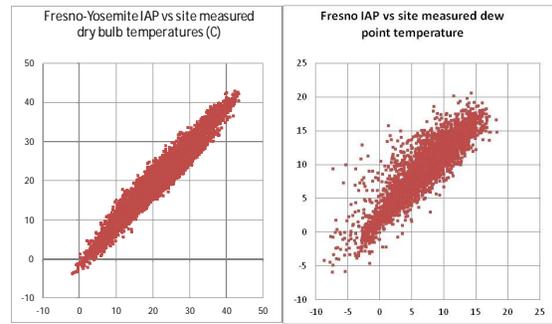


Figure 4. Comparison of dry-bulb and dewpoint temperatures from onsite weather station and Fresno Yosemite Airport

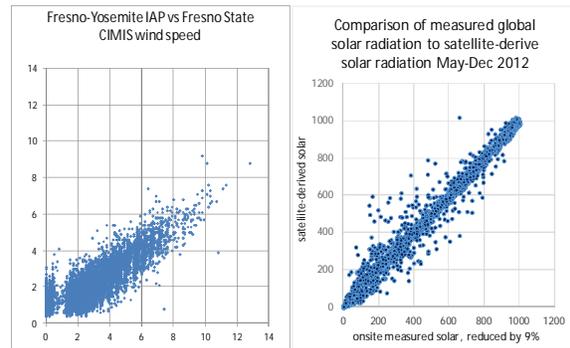


Figure 5. Comparisons of wind speed from CIMIS station to Fresno Yosemite Airport (left) and onsite measured solar\*0.91 to satellite-derived solar (right)

According to the co-author, the radiation sensor (Li-Cor) had not been calibrated, so it was felt that the ACSM09 was more likely to be correct, and the measured solar lowered by 9% when used to produce the final weather file. This modification was further corroborated when satellite-derived solar data was obtained for the same time (May – Dec 2012) and location from CPR 2015, and found to correlate very well with no visible bias (see Figure 5 right). From this analysis, the weather data is judged to be quite reliable for the site.

### c. Comparison of simulated and measured attic air temperatures

Figures 6 and 7 show the simulated and measured attic air temperatures in the Standard Home during the summer and the winter, while Figures 8 and 9 show the same in the Cool Home. The simulated temperatures were found to be extremely close to the measured temperatures, although the simulated nighttime minima were a few degrees lower.

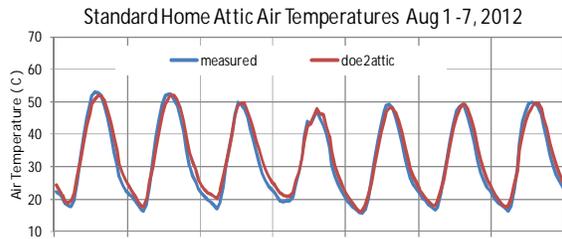


Figure 6. Simulated and measured attic air temps. in the Standard Home during the summer

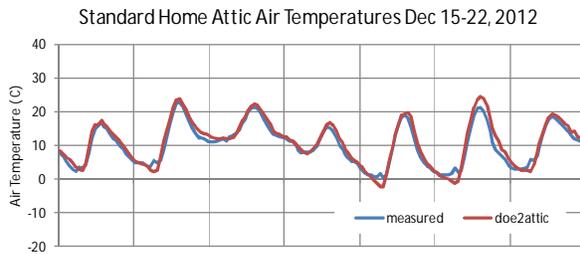


Figure 7. Simulated and measured attic air temps. in the Standard Home during the winter

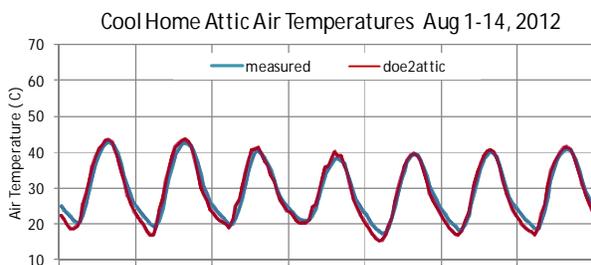


Figure 8. Simulated and measured attic air temps. in the Cool Home during the summer

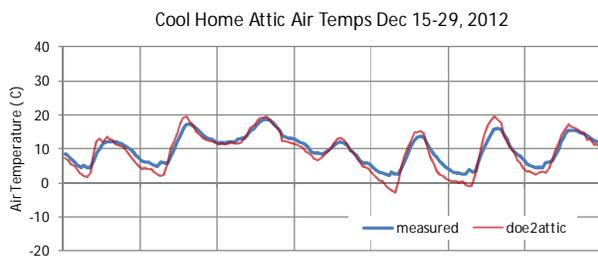


Figure 9. Simulated and measured attic air temps. in the Cool Home during the winter

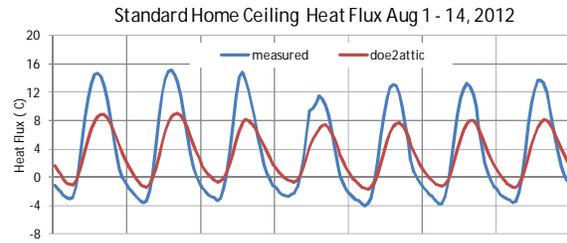


Figure 10. Simulated and measured ceiling heat fluxes in the Standard Home during the summer

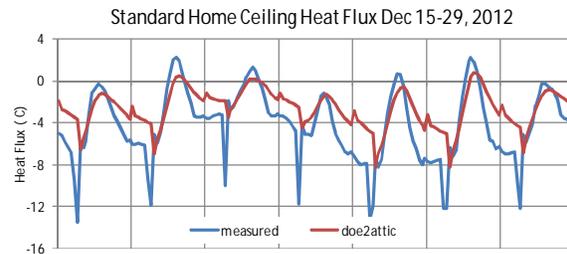


Figure 11. Simulated and measured ceiling heat fluxes in the Standard Home during the winter

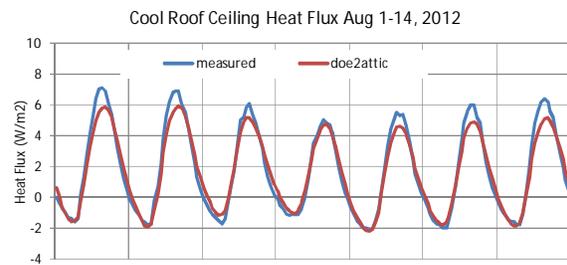


Figure 12. Simulated and measured ceiling heat fluxes in the Cool Home during the summer

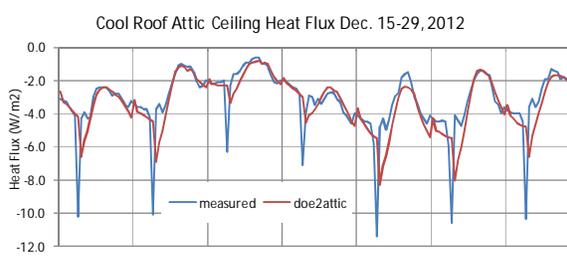


Figure 13. Simulated and measured ceiling heat fluxes in the Cool Home during the winter

**d. Comparison of simulated and measured ceiling heat fluxes**

Figures 10 and 11 show the simulated and measured ceiling heat fluxes in the Standard Home during the summer and the winter, while Figures 12 and 13 show the same in the Cool Home. Although the simulated agreed well with the measured heat fluxes in the Cool Home attic, they were noticeably dampened in the Standard Home attic. The contribution of radiant exchange is being evaluated.

**e. Comparison of simulated and measured room air temperatures**

Figures 14 and 15 show the simulated and measured room air temperatures in the Standard Home during the summer and the spring. Since the room temperatures are simulated not by *AtticSim* but by *DOE-2.1E*, these plots are in fact a validation of the *DOE-2* room model. Figure 15 shows that during the swing season the *DOE-2* room model is floating a degrees or more higher than shown in the measured data.

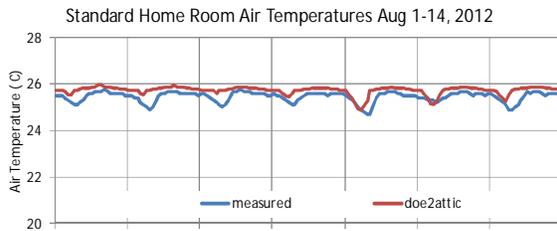


Figure 14. Simulated and measured room air temps. in the Standard Home during the summer

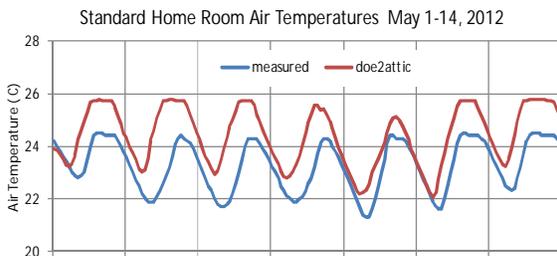


Figure 15. Simulated and measured room air temps. in the Standard Home during the spring

**f. Comparison of simulated and measured A/C electricity consumption**

Figures 16 and 17 show the simulated and measured A/C electricity usage in the Standard Home during the summer and the spring. Despite the higher floating temperatures shown in Fig. 15, the modeled A/C electricity usage during the spring is actually lower than that the measured usage.

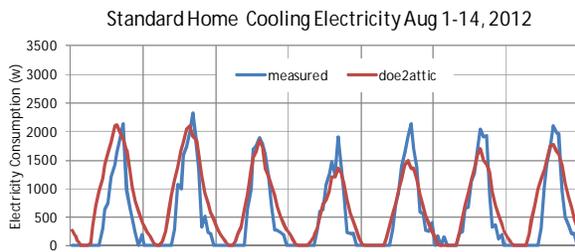


Figure 16. Simulated and measured A/C electricity in the Standard Home during the summer

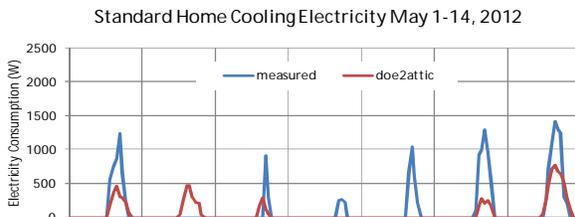


Figure 17. Simulated and measured A/C electricity. in the Standard Home during the spring

Figures 18 and 19 compare the simulated and measured A/C electricity usage for the entire monitoring period. The simulated usages are 8% and 13% lower than the measured usages for the Standard Home and Cool Home, respectively.

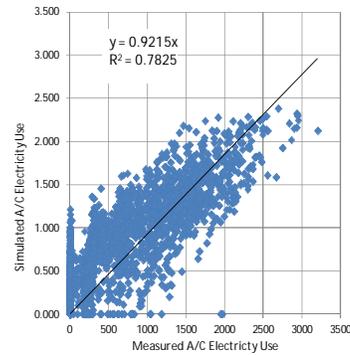


Figure 18. Simulated vs measured A/C electricity use for Standard Home

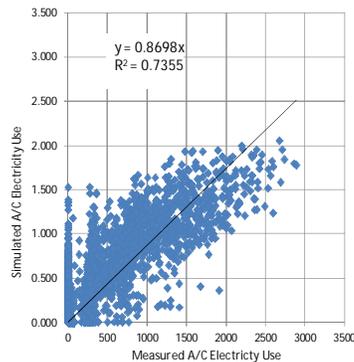


Figure 19. Simulated vs measured A/C electricity use for Cool Home

Figures 20 and 21 show the measured and simulated monthly electricity usage. Because there are gaps in the monitored data, the monthly totals are based on the utility bills, and thus could not be disaggregated by end-use. The simulated annual totals are 38% and 50% larger than measured for the Standard Home and Cool Home, respectively, which suggests substantial overestimation of the non-HVAC load.

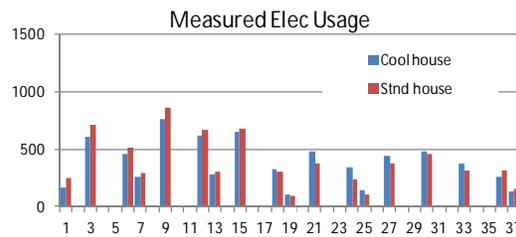


Figure 20. Monthly elec. usage from utility bills

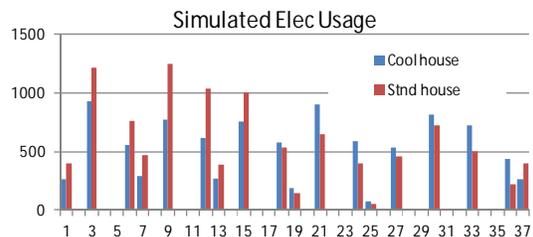


Figure 21. Monthly elec. usage from simulations

## CONCLUSIONS

The first version of the *RSC* went online in late 2012, although the testing and validation described in this paper was not started until 2014 and is still ongoing.

The wealth of monitored data permitted a level of detail in the validation that helped justify algorithmic behaviour but also raised additional complexities and challenges. Although the calculator shows close correlation with attic air temperatures, indicating that *AtticSim* is modeling correctly attic heat transfer, the discrepancy in the Standard Home ceiling heat fluxes remains unexplained. Since many of the boundary conditions (roof surface temperatures and heat flows, etc.) have been defined, efforts are focused on ensuring proper physics rather than empirical correction factors.

For *RSC* users interested in cool roofs, the comparison of simulated to measured cooling electricity consumption indicates relatively small underpredictions of 8-13%. Although it is easy to further reduce this difference by slight adjustments to uncertain parameters such as thermostat setpoint, internal-loads intensity, or window shading schedule, current efforts are focused on modeling and expected trends between sets of measured data.

Thus, the main objective of this validation is to verify that *doe2attic* is working as designed, and that the results are in accordance with the authors' understanding of building physics.

## REFERENCES

- American Society for Testing and Materials (ASTM), 2004. "Standard practice for estimation of heat gain or loss through ceilings under attics containing radiant barriers by use of a computer program". Standard C 1340-04. West Conshohocken PA: ASTM.
- Clean Power Research (CPR) 2015. [www.solaranywhere.com](http://www.solaranywhere.com) (accessed May 2015)
- Department of Energy (DOE) 2015. "DOE Cool Roof Calculator". Oak Ridge National Laboratory, <http://www.ornl.gov/sci/roofs+walls/facts/CoolCalcEnergy.htm>
- Environmental Protection Agency (EPA) 2012. "Roofing Comparison Calculator" (no longer available). <http://www.roofcalc.com/RoofCalcBuildingInput.aspx>.
- Gueymard, C and D Thevenard 2013. "Revising ASHRAE climatic data for design and standards - Part II, Clear-Sky Solar Radiation Model (1613-RP)", *ASHRAE Trans*, June 2013, Denver CO.
- Los Alamos Scientific Laboratory 1980. *DOE-2 Reference Manual, Parts 1 and 2, Version 2.1*. LA-7689-M Ver. 2.1, LBL-8706 Rev. 1, Berkeley: LBNL and Los Alamos: LASL.
- Lawrence Berkeley Laboratory (1982). *DOE-2 Engineers Manual*, Version 2.1A. Berkeley: LBNL.
- Miller, WA, S Shrestha, L Gu, K Childs, and J New 2014. "A comparison of simulation capabilities for ducts", ORNL/LTR-2014/283. Oak Ridge, Tenn.: ORNL.
- Miller, WA 2006. "The effects of infrared-blocking pigments and deck venting on stone-coated metal residential roofs". ORNL/TM-2006/9. Oak Ridge, Tenn.: ORNL.
- Ober, DG and KE Wilkes 1997. "An energy calculation method for attics, Including radiant barriers". ASHRAE Research Project RP717, Feb. 1997.
- Parker, D 2005. "Technical Support for development of an attic simulation model for the California Energy Commission", FSEC-CR-1526-05, Cocoa FL: Florida Solar Energy Center.
- Parker, D, P Fairey, and L Gu. 1993. "Simulation of the effects of duct leakage and heat transfer on residential space cooling energy use". *Energy and Buildings*, 20(2): 97-113.
- Petrie, TW, TK Stovall, and AO Desjarlais. 2004. "Comparison of cathedralized attics to conventional attics: where and when do cathedralized attics save energy and operating costs?" *Thermal Performance of the Exterior Envelopes of Buildings IX*, Atlanta: ASHRAE.
- Petrie, TW., KE Wilkes, PW Childs, and JE Christian. 1998. "Effect of radiant barriers and attic ventilation on residential attics and attic duct systems: New tools for measuring and modeling". *ASHRAE Trans.*, Vol. 104, 1175-1192.
- Rosado, P, D Faulkner, D Sullivan, and R Levinson 2014. "Measured temperature reductions and energy savings from a cool tile roof on a central California home", *Energy & Buildings* Vol. 80, p. 57-71.
- Sullivan, R. and F. Winkelmann 1998. "Validation studies of the DOE-2 building energy simulation program", Final Report LBNL-42241, Berkeley CA: LBNL.
- Stephenson, DG and GP Mitalas 1981. "Calculation of heat conduction transfer functions for multi-layer slabs". *ASHRAE Trans.* 77, Part II, 117.
- Winkelmann, FC, B Birdsall, WF Buhl, K Ellington, E Erdem, JJ Hirsch, and S Gates. 1993. *DOE-2 Supplement, Version 2.1E*. LBL-34947, LBNL, Berkeley CA.