Comparison of Software Models for Energy Savings from Cool Roofs

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ABSTRACT

A web-based Roof Savings Calculator (RSC) has been deployed for the United States Department of Energy as an industry-consensus tool to help building owners, manufacturers, distributors, contractors and researchers easily run complex roof and attic simulations. RSC simulates multiple roof and attic technologies for side-by-side comparison including reflective roofs, different roof slopes, above sheathing ventilation, radiant barriers, low-emittance roof surfaces, duct location, duct leakage rates, multiple substrate types, and insulation levels. Annual simulations of hour-by-hour, whole-building performance are used to provide estimated annual energy and cost savings from reduced HVAC use.

While RSC reported similar cooling savings to other simulation engines, heating penalty varied significantly. RSC results show reduced cool roofing cost-effectiveness, thus mitigating expected economic incentives for this countermeasure to the urban heat island effect. This paper consolidates comparison of RSC's projected energy savings to other simulation engines including DOE-2.1E, AtticSim, Micropas, and EnergyPlus. Also included are comparisons to previous simulation-based studies, analysis of RSC cooling savings and heating penalties, the role of radiative heat exchange in an attic assembly, and changes made for increased accuracy of the duct model. Radiant heat transfer and duct interaction not previously modeled is considered a major contributor to heating penalties.

Keywords

Energy efficiency; building energy modeling; cool roofs; urban heat island

Introduction

The Roof Savings Calculator (RSC) was initially developed 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 colored roofing materials a market reality. The RSC website (Miller et al. 2010) and a simulation engine validated against demonstration homes were developed to replace the DOE Roofing Calculator (DOE 1998) and the EPA Energy Star Roofing Calculator (EPA 2001). The DOE Roofing Calculator tended to report higher annual energy and annual energy cost savings than did the EPA calculator.

The primary objective with the RSC was to develop a web-based tool with which users can easily estimate the annual energy cost savings achieved by installing cool (higher than normal albedo) roofing products on the most common residential and commercial building types in the US stock. Goals included development of a fast simulation engine benchmarked against cool-colored roofing materials, educating the public with regard to cool roofing options and savings, helping manufacturers of cool-colored materials deploy their products, and assisting utilities and public interest organizations to refine incentive programs for cool roofs. Recent emphasis on domestic building energy use, market penetration for cool roofing products, and job creation has made the work a top priority of the Department of Energy's (DOE) Building Technologies Office (BTO).

The simulation engine used in the RSC leverages the modeling capabilities of two well-established computer programs: AtticSim, developed by ORNL for advanced modeling of modern attic and cool roofing technologies (ASTM 2004), and DOE-2.1E, a whole-building simulation program developed by LBNL for modeling the hourly energy performance and thermal conditions in residential or commercial buildings. Source code for AtticSim was incorporated as a subroutine within a module of DOE-2.1E and then compiled into an executable we refer to as doe2attic. The primary objective of this paper is to compare the results using doe2attic with the building models and modeling methodology in the RSC against previous studies done by the authors using DOE-2.1E or EnergyPlus, along with a validation study against detailed measured data of roof performance in two test houses in Fresno that was concluded in 2013 (New et al. 2014).

Background

This report compares results from several different simulation engines and calculators including Micropas, DOE-2.1E, AtticSim, Roof Savings Calculator, and EnergyPlus. We briefly discuss the history and capabilities of the most relevant software tools used in this study.

DOE-2.1E

DOE-2.1E (LASL 1980) is a whole-building energy simulation program that was originally developed by Lawrence Berkeley National Laboratory in the early 1980s with Version 2.1A (LBNL 1982), continued development for version 2.1B through 2.1E (Winkelmann et al. 1993), and new versions created by James J. Hirsch & Associates (JJH 2014). The core simulation engine is a Fortran-based engineering program which takes a text input description of a physical building, space conditioning systems, internal conditions, operation schedules, and weather data to produce a text output of the energy consumption (or other variables of interest). DOE-2 uses an hourly time-step and "response factors" to model the dynamic heat flows through the building envelope. DOE-2 is composed of four separate modules called sequentially at each time-step: (1) LOADS – simulates heat flow of the building and calculates net balance for fixed thermostat temperature (negative meaning heating load and positive meaning cooling load); (2) SYSTEMS – uses results from LOADS to simulate operation of the space conditioning system, deriving temperatures for each zone, amount of heating/cooling required, and energy consumed;

(3) PLANT – simulates energy consumed by a central plant (if present) to meet SYSTEMS demands; and (4) ECONOMICS – computes energy costs. Typical runtime is on the order of seconds for an annual energy simulation.

AtticSim

AtticSim is a computer simulation program which predicts thermal performance of advanced roof and attic technologies. It mathematically describes conduction, convection, and radiation heat transfer at all interior and exterior surfaces such as gables, eaves, roof deck, ceiling, etc. This includes radiation heat transfer among all surfaces within the attic enclosure (fixed geometries and view factors are assumed), heat transfer with the ventilation air stream, turbulent air flow over different roof material profiles, and latent heat effects due to sorption/desorption of moisture at material surfaces.

AtticSim has an advanced algorithm which accounts for most of the computational time for predicting the effect of air-conditioned ducts placed in an 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 (Parker 1993). The duct algorithms used have been validated in field demonstration facilities for radiant barriers where the algorithm predicted temperature change in a duct (inlet-to-outlet of the supply duct) to within ±0.2°C (±0.3°F) over all tests which included an insulated duct system (Petrie et al. 1998). *AtticSim* can either use a fixed HVAC on-time, or on-time can be computed by a whole building code and hour-by-hour data passed to *AtticSim* along with hourly indoor boundary temperatures. Sizing of the duct system to match HVAC capacity is also very important for proper airflow distribution. The inlet air temperatures and airflow rates in each duct section can be fixed inputs, or parameters computed by a whole building model and read by *AtticSim* to better simulate attic thermal performance in a whole building.

AtticSim has been thoroughly validated for low-slope and steep-slope roofs using field data from seven field sites (Ober and Wilkes 1997); steep-slope asphalt shingle and stone-coated metal roofs (Miller 2006); and clay, concrete, or painted metal tile roofs with above sheathing ventilation (Miller et al 2007). *AtticSim* has been established as ASTM Standard C1340 (ASTM 2004) and ASTM makes publicly available an older version of the *AtticSim* software. Typical runtime is on the order of seconds for an annual energy simulation without ducts in the attic, and approximately two minutes with ducts in the attic.

Roof Savings Calculator

The *Roof Savings Calculator (RSC)* was developed by integrating *AtticSim* with *DOE-2.1E*. Doing so allows simulation of modern roof and attic technologies (*AtticSim*) that transfer load and energy savings all the way to the whole-building space conditioning (*DOE-2.1E*) so energy and cost savings can be calculated. *RSC* (v 0.92) is currently on the web at http://rsc.ornl.gov. While *AtticSim* has undergone thorough validation, a project for RSC's integration of *AtticSim* with *DOE-2.1E* was necessary. This project consists of the software comparisons to other simulation engines reported in this study, and is also currently undergoing empirical validation.

AtticSim has been incorporated as a subroutine within the SYSTEMS module of *DOE-2.1E* that is called at every time step to simulate the attic based on the conditions outdoors, in the space below, and in the air ducts if installed in the attic. *AtticSim* then returns to *DOE-2.1E* the heat transfer through the attic floor to the space below as the primary hand-shaking mechanism between the two simulation engines. In addition, heating or cooling to be provided by the *DOE-2.1E* HVAC system is provided, taking into account the conductive and convective heat flows through the ducts as reported by *AtticSim*. *DOE-2.1E* then combines this information with the rest of the building model to derive the building's indoor conditions and total energy consumption. This combined program is called *doe2attic*, and works just like *DOE-2.1E* except for the additional inputs needed by *AtticSim*. More information on how they have been linked and the web-interface for the *RSC* can be found in New et al. (2011). Typical runtime is approximately 30 seconds for an annual energy simulation without ducts in the attic, and approximately two minutes with ducts in the attic.

EnergyPlus

EnergyPlus began in 1995 to replace DOE-2 and is currently DOE's flagship whole-building energy simulation program. Since that time, DOE has invested over $65 million in adding new building technologies and modern simulation capabilities. Many algorithms of varying fidelity exist for modeling certain phenomena within the simulation engine, allowing the user to occasionally define the tradeoff between more accurate simulations and longer runtime. EnergyPlus consists of ~600,000 lines of Fortran code and has recently been cross-compiled to ~750,000 lines of C for version 8.2. The typical runtime of EnergyPlus is on the order of a few minutes to run an annual energy simulation.

Benchmarking the RSC

At the time of the research project, one study (Dodge 2002) shows tile roofs comprise ~30% of the new and retrofit roof markets in California. A more recent study (Western Roofing 2014) states that tile makes up 14% of the western U.S. roofing market. Therefore, field experiments were conducted in Southern California to benchmark both AtticSim as a stand-alone tool and the new RSC. AtticSim has a history of validations against several different profiles of tile, stone-coated metal, asphalt shingle and standing seam metal roofs, all of which were field tested at ORNL's Envelope System Research Apparatus (ESRA) through measurement of temperatures and heat flows for each of the attic types. However, AtticSim was also benchmarked against two of the Ft. Irwin homes to assist White Box Technology with its benchmark of the RSC. For brevity, the benchmarking effort for one house (House N5 with a tile roof attached to the deck and monitored in August 2008) is described in this paper.

Heat flux transducers (HFTs) were attached to the roof sheathing to measure the heat flux crossing the north- and south-facing roof decks. The contractor insulated the attic floor with RSI-6.7 (R-38) fiberglass batt. Type T thermocouples were placed across the insulation at three different ceiling locations and used to deduce the ceiling heat flux from the product of thermal conductance of the batt and temperature difference across the batt. Samples of the RSI-6.7 batt insulation were retrieved from the demonstration site and measured for thermal conductivity in ORNL's heat flow metering apparatus. Prior experience showed an HFTs sensitivity to be too low to accurately measure the flux across an RSI-6.7 batt.

Pyranometers were attached to the north- and south-facing roof surfaces to measure the global irradiance on the respective sloped surfaces. Outdoor air temperature and relative humidity (measured under the soffits of the north- and south-facing exterior walls) and indoor air temperature (measured at the thermostat) were used as boundary conditions by AtticSim. AtticSim computed the surface temperature of the tile, the air temperature in the inclined air space made by the tile, the heat flux crossing the roof decks, the attic air temperature, and the heat flux crossing the attic floor.

Estimates had to be made of the airflow induced by a solar powered attic ventilation fan installed on the south facing roof. All homes had these fans that energized whenever the photovoltaic panel generated enough current to drive the fan. The heat flux crossing the south facing roof deck computed by AtticSim closely matched the flux measured by the HFTs installed on underside of roof deck (see Figure 1). Benchmarks for the attic floor (Figure 2) show that the AtticSim heat flux predictions lead the measured flux by about two hours. Results show a thermal capacitance effect between the measured flux reduced from thermometry and AtticSim predictions. The shift is most evident during periods of peak irradiance. However, measurement and prediction are in better agreement during the late evening and early morning hours (Figure 2).

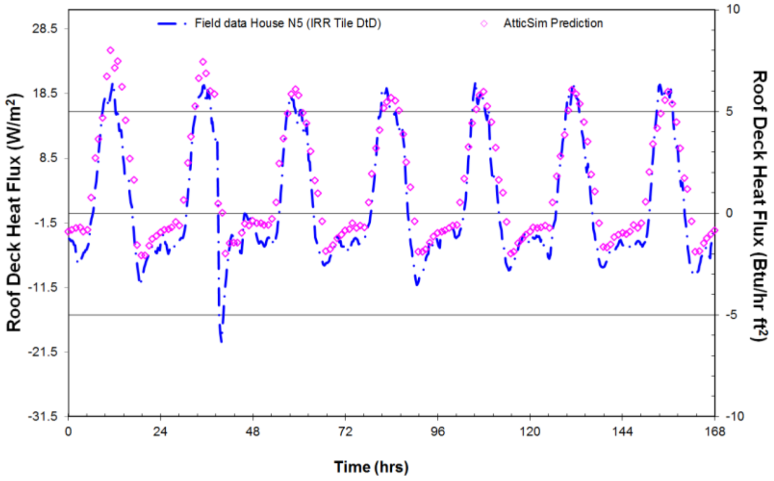

Figure 1. The heat flux through the south-facing roof deck for House N5 in August 2008 having cool color tile laid directly to the deck.

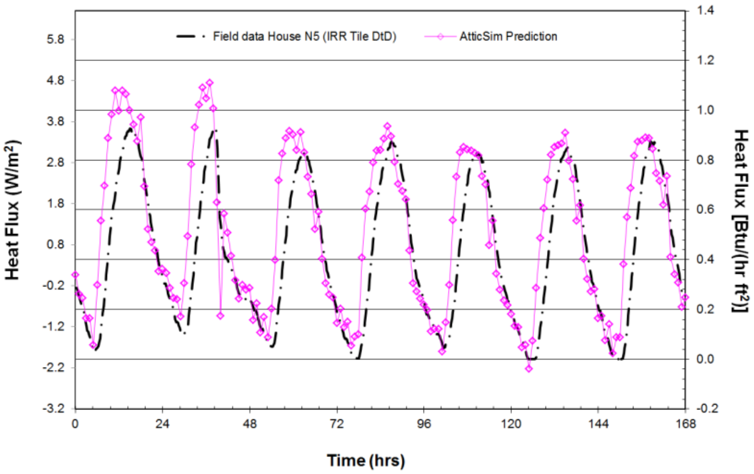

Figure 2. The heat flux across the attic floor for House N5 in August 2008 having cool color tile laid directly to the deck.

doe2attic Simulation of Benchmark Houses

Simulations were repeated for House N5 using the August 8th week of field data and for House N8 using the February 8th data. The combined doe2attic program was used with this empirical data to test whether AtticSim was working properly as a subroutine within DOE-2.1E for the thermal exchange through the attic floor (i.e., house ceiling) and the data exchange about HVAC operations and duct losses. Both of these issues are complex, since they are nonlinear as well as interrelated. The heat flows through the attic floor, which are critical for determining the energy savings from attic conservation measures, are further complicated by the fact that *DOE-2* uses several sequential steps to derive net zone heat flows, so that in coupling *DOE-2* with AtticSim, it has been necessary to disable some of these steps to prevent double counting. Duct losses, particularly those placed in an attic, can strongly depend on HVAC sizing and partial load ratios. DOE-2 assumes that the HVAC system is "right-sized" (i.e. sized based on the simulated building load) (LBNL 1982). To calculate the duct losses, AtticSim needs to know the on-time for the HVAC system, but that is not known until further into the simulation process. Ultimately, it was found necessary to model the attic twice, once with *DOE-2* and then again with AtticSim.

Figure 3 shows the measured attic air temperatures benchmarked against the modeled air temperature computed by the stand-alone AtticSim code and by doe2attic. Both codes predict the measurements temperatures to within ±1.1°C (2°F) with exception of the early morning hours from about 2:00am until 8:00am. The results of the benchmark show that doe2attic is predicting the attic air temperature to about the same accuracy as the standalone AtticSim code. Hence the integration of AtticSim into DOE-2.1E appears to be working adequately**.**

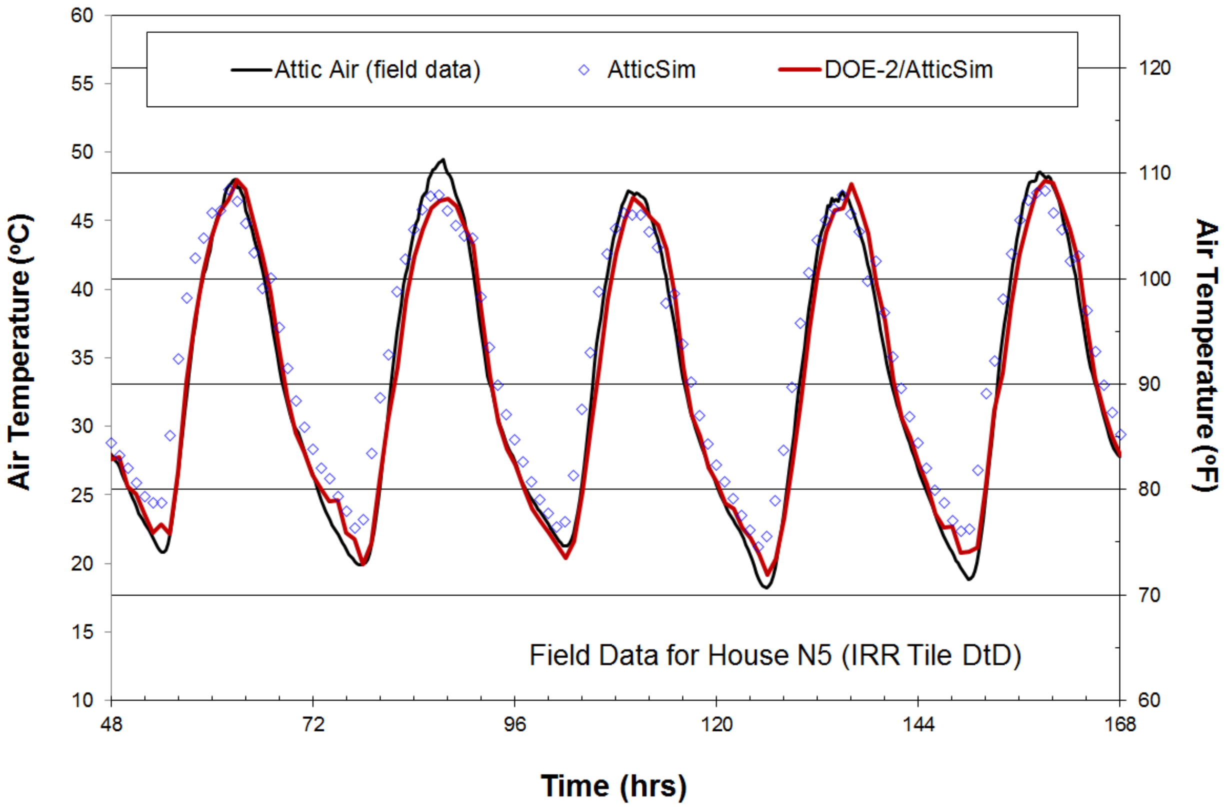

Figure 3. Comparison of AtticSim before and after integration with DOE-2 (doe2attic).

Comparison of RSC to previous studies

From 2009-2011, WBT worked with ORNL to create the RSC as an easy-to-use Web-based calculator for estimating the effects of various roof and attic strategies on the heating and cooling energy uses of four building types—residential, office, retail, and warehouse—in 239 U.S. locations. WBT's main responsibility was to develop the doe2attic engine by linking the DOE-2.1E whole-building simulation program with ORNL's AtticSim program. After the initial roll-out of the RSC in mid-2011, questions were raised because the results produced by the RSC for "cool roofs" differed from those of previous studies, particularly those by LBNL. While the RSC predicted annual cooling savings similar to those from previous LBNL studies, it computed annual heating energy penalties that were much larger than those reported in LBNL studies.

To better understand and evaluate these differences, a thorough comparison was conducted of the RSC doe2attic simulations against those using two other programs—DOE-2.1E and EnergyPlus v7.0. EnergyPlus is a whole-building simulation program currently supported by DOE, while DOE-2.1E was used in the previous LBNL studies for roofs in commercial and residential buildings.

Comparison of RSC to previous LBNL studies

After the RSC went online on April 22, 2010, LBNL researchers compared RSC to previous reports for an old office building prototype. This old office building prototype was for a 455 m^2 (4900 ft^2) 1-floor, pre-1980 building with a low slope built up roof, no radiant barrier, no above-sheathing ventilation, RSI-40 (R-7) ceiling, gas furnace with 70% heating efficiency, 8.4 SEER (2.3 COP, 8 EER), uninspected ducts, and a roof thermal emittance of 90%. Comparing a cool roof with a solar reflectance of 60% to a traditional roof with 20% solar reflectance, RSC calculations of annual cooling energy savings were typically within about 20% of those predicted in earlier studies by LBNL (Akbari and Konopacki 2005a, 2005b, Akbari et al. 2006). However, the RSC annual heating penalties were 6-12 times larger than those calculated by LBNL (Figure 4 and Figure 5).

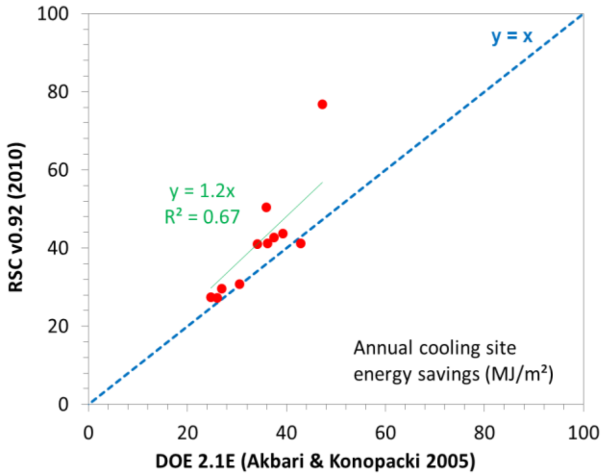

Figure 4. RSC vs. LBNL cooling energy savings from cool roofs on old office buildings in 14 U.S. cities

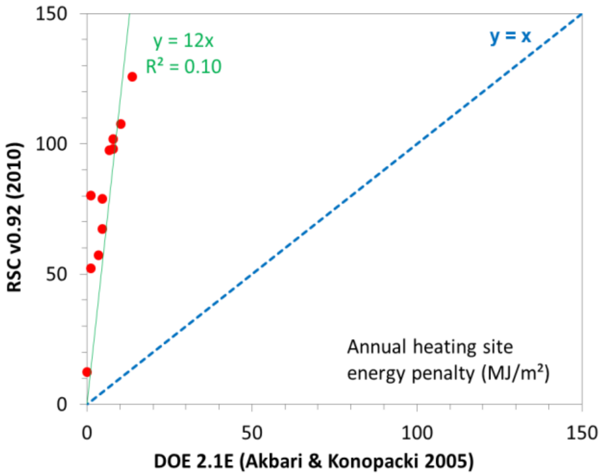

Figure 5. RSC vs. LBNL heating energy penalties from cool roofs on old office building in 14 U.S. cities.

The difficulty with this discrepancy is that, whereas LBNL's previous study showed that cool roofs were beneficial for an old office prototype in all 14 US climates studied, the RSC now showed them to be detrimental in colder locations such as Chicago, New York, Philadelphia, and Baltimore (Figure 6). It also appears that the RSC shows greater sensitivity to the energy impacts due to cool roof changes in general, since the RSC shows larger cooling savings in hot locations such as Phoenix. Our initial assessment of these differences in cooling savings and heating penalties was that they may have resulted from differences between how the DOE-2.1E program used in the previous LBNL work and AtticSim handles radiant heat exchange in interior spaces.

Since doe2attic is a modified version of DOE-2, the input files can be used with either doe2attic or DOE-2.1E. In the preliminary assessment, WBT took the RSC input files for a set of 40 test runs done by LBNL and used them with doe2attic as well as standard DOE-2.1E, progressively eliminating the duct model, attic ventilation, etc., to produce a simple model of an unvented attic with no interaction with the HVAC system. When this basic attic model was run with doe2attic and DOE-2.1E, the differences in heating penalties were reduced, but still significant with doe2attic showing double the heating penalties as shown by DOE-2.1E (Table 1). It is anticipated that duct heat gain/loss and attic ventilation are scalar factors that multiply both the cooling savings and heating penalties, but do not affect their relative magnitudes.

From an algorithmic perspective, the differences in the attic model of DOE-2.1E and AtticSim are easy to explain. AtticSim does a detailed heat balance of the attic heat flows taking into account radiation, convection, and conduction, whereas the weighting factor method in DOE-2.1E, derives only the room air temperature, with no explicit solution of the interzone radiative transfer between different room surfaces, such as between the bottom of the roof and the top of the ceiling. Heat flow through the attic floor is calculated as pure conduction between the air temperatures of the attic and the space below. Therefore, in DOE-2.1E the only impact of a cool roof on heating and cooling loads is by lowering the attic air temperature, whereas in doe2attic there is also the impact of reducing the radiative heat transfer between the roof bottom and the attic floor, which may explain why doe2attic shows larger cooling savings as well as heating penalties than does DOE-2.1E.

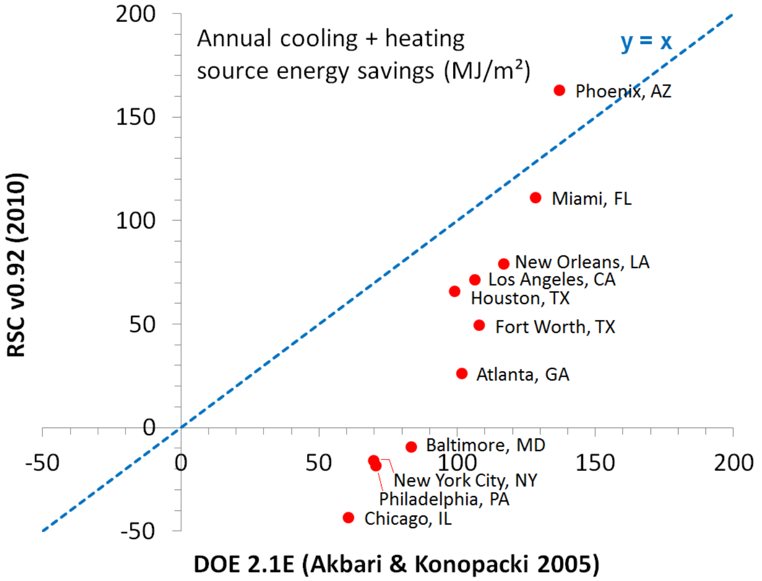

Figure 6. Comparison of annual source energy savings (cooling savings – heating penalty) from cool roofs between LBNL 2005 study and the RSC

Table 1. Comparison of site energy use for test simulations of the same attic model for multiple simulation engines.

	DOE-2.1E unmodified						DOE-2.1E + AtticSim (doe2attic)						EnergyPlus V7.0					
	Heat	Heat Penalty		Cool	Cool savings		Heat	Heat Penalty		Cool	Cool savings		Heat	Heat Penalty		Cool	Cool savings	
Location	GJ	GJ	%	kWh	kWh	%	GJ	GJ	%	kWh	kWh	%	GJ	GJ	%	kWh	kWh	%
Miami	7.8	0.1	1	31673	802	3	7.7	0.1	1	32576	1432	4	0.3	0.1	41	29726	1533	5
Los Angeles	16.3	1.6	10	10623	894	8	15.1	2.6	18	11573	1639	14	7.1	2.4	34	12442	1509	12
Phoenix	22.7	2.4	11	29133	1538	5	21.6	4.1	19	29868	2586	9	10.2	2.3	22	27218	2118	8
New Orleans	29.7	1.8	6	22116	849	4	27.9	3.0	11	22881	1391	6	10.1	1.9	19	21931	1456	7
Houston	34.3	1.9	6	23154	801	4	32.0	3.1	10	23970	1392	6	14.4	1.8	12	22729	1415	6
Fort Worth	55.4	2.6	5	19973	759	4	52.6	4.8	9	20702	1331	6	22.5	3.1	14	20147	1449	7
Atlanta	81.6	3.8	5	15308	831	5	78.0	6.5	8	16088	1416	9	37.6	4.1	11	15696	1325	8
Baltimore	99.7	3.7	4	12575	634	5	95.8	6.5	7	13165	1111	8	46.6	5.1	11	13053	1140	9
New York	110.5	3.2	3	11198	519	5	106.5	6.0	6	11792	959	8	42.5	4.3	10	12316	1108	9
Philadelphia	112.5	3.8	3	11729	592	5	108.4	6.7	6	12310	1033	8	54.6	5.2	10	12125	1043	9
Chicago	149.8	4.1	3	10188	573	6	144.5	7.2	5	10740	1006	9	70.6	6.4	9	10852	1017	9

Results of DOE-2.1E unmodified shown in Table 4 are similar to those by (Akbari and Konopacki 2005). A backup of raw data from Konopacki's 2005 work, believed to include the simulation and data files used for this 2005 study, was analyzed to attempt to identify the appropriate files, resolve the extent of reported radiant modeling by the Gartland method (Gartland et al. 1996), and reconcile the similarity with the DOE-2.1E unmodified runs which have no radiant barrier. Upon further analysis, it was concluded from the original simulation files that the previous study's simulations did not use the Gartland function or any other to model the radiation heat transfer in the attic. There is also no documentation of how Micropas models intrazone radiant heat transfer. Ken Nittler, author of Micropas, has conveyed that the simulation runs performed for (Akbari and Konopacki 2005) used a preliminary version of the Unconditioned Zone Model (UZM) (Wilcox et al. 2006).

Another check of this modeling difference has been done by converting the RSC input files to EnergyPlus, which also uses the heat balance method to derive the room heat flows. These results appear in the columns on the right of Table 4. There is a significant discrepancy in the house heating energies as calculated by EnergyPlus, but the percent heating penalties agreed closely with doe2attic and not with DOE-2.1E (Figure 7).

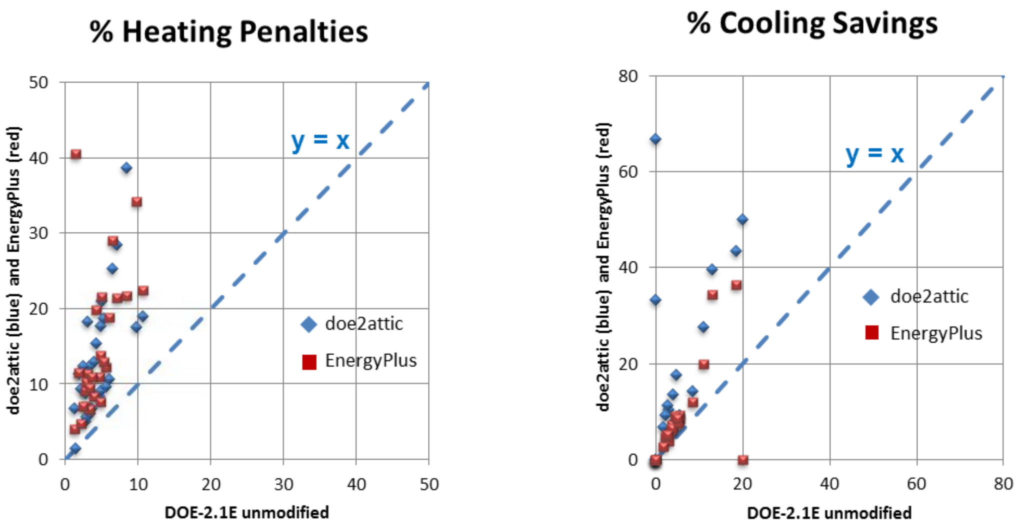

Figure 7. Percent heating penalties and cooling savings calculated by EnergyPlus and doe2attic compared to standard DOE-2.1E

This preliminary analysis is aimed at providing a tentative explanation for why the RSC results differed from the previous LBNL studies. The authors are now working on a much more thorough evaluation of the RSC as well as validating the RSC against detailed measured data obtained by LBNL and ORNL at test houses in California and North Carolina. In the course of this ongoing evaluation, some problems were found in both the linkage between AtticSim and doe2attic, as well as the modeling of the office and residential buildings. Since both of these activities are still ongoing, it is unclear how much of this preliminary assessment will be affected.

Conclusions and Future Work

In conclusion, the Roof Savings Calculator provides an approachable portal for both industry experts and residential homeowners to leverage the best available whole-building energy simulation packages and determine energy and cost savings for modern roof technologies and related retrofits. The tool uses the DOE-2.1E whole-building energy simulation program and calls AtticSim from the SYSTEMS module where AtticSim computes the temperatures and heat flows of all surfaces in the attic and passes back to DOE-2.1E the attic air temperature, the HVAC duct gains and losses, and the ceiling heat flow. Combined, the two codes, benchmarked against field data including California demonstration homes at Ft. Irwin, were shown to yield credible results and are now usable online at www.roofcalc.com.

The preliminary analysis arrived at tentative explanations for why the RSC results differed from the previous LBNL studies which includes RSC bug fixes and the lack of use of the Gartland model for simulating radiant heat transfer in previous studies. Comparative analysis has been shown involving four simulation programs (RSC, DOE-2.1E, EnergyPlus, and MicroPas) including heat exchange between the attic surfaces (principally the roof and ceiling), and the resultant heat flows through the ceiling to the building below.

Further analysis has been completed involving statistical summaries of simulation ensembles for surface variables throughout the roof and attic assembly, domain expert validation of patterns observed from the simulation engine's physics, and is nearing completion for empirical validation of RSC in comparison to an instrumented building in Fresno, CA. Work has begun on a publication which will summarize the analysis with a side-by-side comparison of the pre- and post-validation version of RSC.

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