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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.

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1. 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 [2] and a simulation engine validated against demonstration homes were developed to replace the DOE Roofing Calculator [3] and the EPA Energy Star Roofing Calculator [4]. 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 [16], and DOE-2.1E, a whole-building simulation program developed by LBNL for modeling the hourly energy performance and thermal conditions in residential or

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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 [9].

2. 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.

2.1. DOE-2.1E

DOE-2.1E [5] is a whole-building energy simulation program that was originally developed by Lawrence Berkeley National Laboratory in the early 1980s with Version 2.1A [6], continued development for version 2.1B through 2.1E [7], and new versions created by James J. Hirsch & Associates [8]. 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.

2.2. 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 [17]. Typical construction places ductwork within the attic, which can triple the loads for the attic assembly for moderately leaky ducts [11]. 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 [12]. *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 [13]; steep-slope asphalt shingle and stone-coated metal roofs [14]; and clay, concrete, or painted metal tile roofs with above sheathing ventilation [15]. *AtticSim* has been established as ASTM Standard C1340 [16] 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 2 min with ducts in the attic.

2.3. 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 [10]. Typical runtime is approximately 30 s for an annual energy simulation without ducts in the attic, and approximately 2 min with ducts in the attic.

2.4. 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.

2.5. Benchmarking the RSC

At the time of the research project, one study [18] shows tile roofs comprise ~30% of the new and retrofit roof markets in