Trade-Off Between Cool Roofs and Attic Insulation in New Single-Family Residential Buildings

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ABSTRACT

This paper summarizes a comparative analysis of the impact of roof surface solar absorptance and attic insulation on simulated residential annual cooling and heating energy use in sixteen sunbelt climates. The buildings are single-story, single-family, new construction residences with either a gas furnace or an electric heat pump and with ducts in the attic or conditioned zone. Annual energy use is simulated with DOE-2 for dark and cool roofs and eleven attic insulation R-values ranging from 1 through 60. The simulations are regressed as a function of roof system conductance and roof absorptance for each heating system, duct location / insulation level, and climate. An equivalent change in conductance is calculated for a given change in absorptance from a dark to a cool roof. Equivalent attic insulation R-values are found from the conductance of the cool roof. Reductions in R-value are observed in all buildings and climates. The analysis demonstrates that a roof system with a cool roof and low attic insulation can be used as an alternative to the more conventional dark-colored roof with a high level of insulation, with a zero net change in the annual energy bill. Similar work was previously done in support of revisions to ASHRAE commercial building standard 90.1.

Introduction

Cool roofs have a lower solar absorptance (higher albedo [1]) and contribute less to the cooling load of a building than dark-colored roofs, and thus, save energy and money by reducing cooling electricity use. In some climates, a heating energy penalty may occur due to the reduced solar load on the roof. Energy savings from cool roofs have been documented with computer simulations and measured data in residential and commercial buildings. The magnitude of the savings are dependent upon the reduction in roof absorptance, levels of attic and duct insulation, duct location, and climate.

Computer simulations of residential and commercial building cooling and heating energy use in climatically diverse locations throughout the United States have shown the impact of cool roofs in reducing energy use (Akbari et al. 1998; Gartland et al. 1996; Konopacki et al. 1997; Parker et al. 1998). Cooling electricity savings have been measured in Florida from the application of white-roof coatings on several residences (Parker et al. 1998) and on a strip mall (Parker et al. 1997). Similarly, savings were measured in California in two medical office buildings, a retail store (Konopacki et al. 1998), a residence, and two school bungalows (Akbari et al. 1997).

This paper summarizes a recent study conducted by Konopacki and Akbari (1998) on a comparative analysis of the impact of roof solar absorptance and attic insulation on simulated residential annual cooling and heating energy use in sixteen sunbelt climates: Albuquerque, NM, Atlanta, GA, Austin, TX, Fort Worth, TX, Houston, TX, Las Vegas, NV, Lexington, KY, Long Beach, CA, Nashville, TN, Phoenix, AZ, Raleigh, NC, Sacramento, CA, Salt Lake City, UT, Sterling, VA (represents Washington, DC), Tampa, FL, and Tucson, AZ. These locations cover a wide range of climates where cool roofs are expected to save energy and money, and are areas with high growth rates in new residential construction. The residences are single-story,

[1] When sunlight hits a surface some of the energy is reflected (this fraction is called the albedo = a) and the rest is absorbed ($\alpha = 1 - a$). Low-a surfaces become much hotter than high-a surfaces.

single-family of new construction with either a gas furnace or an electric heat pump and with ducts in the attic or conditioned zone.

Annual energy use is simulated with DOE-2 for dark and cool roofs and eleven attic insulation R-values ranging from 1 through 60. The results are then regressed as a function of roof system conductance and roof absorptance for each heating system, duct location / insulation level, and climate. An equivalent change in conductance is calculated for a given change in absorptance from a dark to a cool roof. Equivalent attic insulation R-values are then found from the conductance of the cool roof.

The Envelope Subcommittee of the ASHRAE Standing Standard Project Committee (SSPC) has recently voted for inclusion of reflective roofs in public review drafts for commercial building standard 90.1. Their decision was based on evidence of savings obtained from DOE-2 simulations as reported by Akbari et al. (1998). The results presented in this paper can be used towards proposing modifications to building standard 90.2 for new residences, and in support of the US Environmental Protection Agency's (EPA) Energy Star® Homes Program.

Residential Building Model

A single-story, single-family residential building was modeled with typical characteristics found in new constructions (Aktinson 1997) and DOE national appliance energy standards (NAECA 1987), as shown in **Table 1**. The model has two zones arranged in a non-directional floor plan: a conditioned living zone with a floor area of $1600ft^2$ and an unconditioned attic zone above. The building characteristics were selected to be uniform for all locations, since the focus was on the effects of roof absorptance and attic insulation, and since, most roof, wall, and window parameters did not exhibit much local variation.

The attic model was recently developed by Parker et al. (1998). It calculates attic temperature, supply and return duct losses, and temperature-dependent heat conduction through the attic insulation. The roof system is composed of asphalt shingles (infrared emittance 0.9) attached to a 20° sloped roof deck, over a naturally ventilated unconditioned attic space (15% ceiling frame fraction [2]), with fiberglass insulation and 1/2" drywall comprising the ceiling. The attic ventilation to floor area ratio was set at 1:300, and variable air infiltration was modeled by the Sherman-Grimsrud algorithm (Sherman 1986).

The cooling and heating system(s) were sized automatically by DOE-2 (including a sizing-ratio of 1.25), and the equipment efficiencies were defined by the national energy standards as: air conditioner SEER=10, gas furnace η=78%, and heat pump HSPF=6.8. Modified part-load-ratio curves for a typical air conditioner, heat pump, and furnace were used in place of the standard DOE-2 curves, since they model low-load energy use more accurately (Henderson 1998).

DOE-2 Annual Cooling and Heating Energy Use Estimates

Annual cooling and heating energy use were estimated with the DOE-2.1E building energy simulation program (BESG 1990). The simulations were performed with the residential building model for both dark (α=0.9) and cool (α=0.3) roofs [3], attic insulation R-values of 1, 3, 5, 7, 11, 13, 19, 22, 30, 38, and 60, insulated (R-2, 4, 6, and 8) attic ducts, uninsulated attic ducts, and uninsulated conditioned zone ducts, and with Typical Meteorological Year (TMY2) weather data for the sixteen previously listed locations. Local 1995 residential average prices for electricity and gas (EIA 1997) are shown in **Table 2** and were used to calculate total annual

[2] The ceiling frame fraction accounts for joists, electrical junction boxes, access doors, insulation voids, etc.

[3] The albedos selected for these simulations cover a wide range of materials, both fresh and aged. An on-line database characterizing some of these materials can be found at http://eetd.lbl.gov/coolroof.

Table 1. Typical construction, equipment, and interior load characteristics for a new residence.

construction	
floors	single-story
zones	living: conditioned, attic: unconditioned
floor area	1600ft^2: conditioned
orientation	non-directional floor plan
roof construction	1/4" asphalt shingle, 3/4" plywood decking: 20° slope
ceiling construction	2"x4" studded frame (15%), variable fiberglass insulation, 1/2" drywall insulation R-value = 1, 3, 5, 7, 11, 13, 19, 22, 30, 38, 60
wall construction	brick, 2"x4" studded frame (15%), R-11 fiberglass insulation, 1/2" drywall
foundation	slab-on-grade
windows	320ft^2: clear with double glazing and operable shades
equipment	
sizing-ratio	1.25
cooling	direct expansion: SEER = 10
heating	gas furnace: η = 0.78, heat pump: HSPF = 6.8
distribution	constant-volume forced air system with ducts located in attic (R-1, 2, 4, 6, 8) and living zone (no duct insulation): η = 0.36 W/cfm supply duct area = 370ft^2, return duct area = 69ft^2, duct leakage = 10%
thermostat	cooling setpoint = 78°F, heating setpoint = 70°F (7am - 10pm), setback = 64°F
natural ventilation	window operation available
interior load	
infiltration	Sherman-Grimsrud: fla = 0.0005 (living) fla = 0.0025 (attic)
lighting & equipment	0.4 W/ft^2 & 0.8 W/ft^2
occupants	3

Table 2. Local 1995 residential average prices for electricity and gas (EIA 1997).

location	electricity [$/kWh]	gas [$/therm]
Albuquerque, NM	0.095	0.561
Atlanta, GA	0.077	0.609
Austin, TX	0.073	0.504
Fort Worth, TX	0.080	0.636
Houston, TX	0.081	0.600
Las Vegas, NV	0.067	0.777
Lexington, KY	0.049	0.400
Long Beach, CA	0.129	0.649
Nashville, TN	0.058	0.670
Phoenix, AZ	0.098	0.777
Raleigh, NC	0.080	0.758
Sacramento, CA	0.082	0.628
Salt Lake City, UT	0.068	0.476
Sterling, VA	0.083	0.714
Tampa, FL	0.072	0.546
Tucson, AZ	0.094	0.777

energy use in dollars.

Annual cooling and heating electricity, gas, and total energy use for dark roofs and savings resulting from cool roofs are displayed in **Table 3** for residences with R-19 attic insulation, R-4 attic ducts, and both gas furnaces and electric heat pumps [4]. The effect of the cool roof was greatest in the gas heated Phoenix residence with an annual total energy savings of 5.9¢/ft^2 (12%), followed by Tucson 4.5 (13), Tampa 3.5 (14), Houston 3.0 (11), Austin 2.9 (11), Las Vegas 2.6 (8), Fort Worth 2.5 (8), Long Beach 2.5 (21), Albuquerque 2.4 (8), Atlanta 1.8 (7), Sacramento 1.7 (8), Raleigh 1.5 (5), Nashville 0.9 (3), Salt Lake City 0.6 (2), Sterling 0.6 (1), and Lexington 0.4 (2). Although the savings were estimated with a single-story residential model, they can be applied to the top story of multi-story residences. Energy use in gas heated Phoenix, Tampa, and Sterling residences with R-4 attic ducts are plotted in **Figure 1** as a function of roof albedo and attic insulation R-value.

The dark roof has an albedo of 0.1 and the savings (penalties) were estimated for a cool roof with an albedo of 0.7, a net change of 0.6. Linear interpolation can be used to estimate savings (penalties) for other net changes in albedo regardless of the initial or final albedo for a given residence (Konopacki et al. 1997: Attachment 2). Simply adjust the value given by the ratio $\Delta a/0.6$. As an example, the savings (penalties) associated with a cool roof with an albedo of 0.55 would be 75% of those with an albedo of 0.7.

Regression Analysis

The simulated annual cooling and heating energy use was expressed as a function of the overall roof system conductance and roof surface solar absorptance of the form in equation 1,

$$E = C_0 + C_1 U + C_2 U^2 + C_3 U \alpha \qquad [1]$$

where, E is the annual cooling and heating energy use: electricity [kWh/ft^2], gas [therms/ft^2], and total [\$/ft^2], U is the overall roof system conductance including outdoor air film [Btu/h·ft^2·°F], α is the roof surface solar absorptance, and C_n are regression parameter estimates. The conductance is related to the attic insulation R-value through equation 2 [5],

$$U = 0.011 + \frac{0.85}{4.8 + R} \qquad [2]$$

where, 0.011 is frame resistive element [6] inverted [Btu/h·ft^2·°F], 0.85 is the cavity fraction, 4.8 is the cavity resistive element [7] [h·ft^2·°F/Btu] excluding insulation, and R is the attic insulation R-value [h·ft^2·°F/Btu].

Linear regressions using eq. 1 were completed for sets of electricity, gas, and total energy use by heating system, duct location / insulation level, and climate. The analysis of variance (standard deviation of the error and R^2) and parameter estimates (C_0, C_1, C_2, and C_3) for new residences with R-4 attic ducts are shown for total (\$) energy in **Table 4**. The R^2 values for this curve-fit ranged from 0.97 - 1.00 for all data sets analyzed except for the uninsulated attic duct case, where R^2 ranged from 0.91 - 1.00 (Konopacki & Akbari 1998). Fig. 1 compares the simulated estimates with those of eq. 1 for electricity, gas, and total energy use in Phoenix, Tampa, and Sterling for a new residence with gas heating and R-4 attic ducts.

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[4] Electric resistance supplemental heating was available for the heat pump.

[5] $U = 1 / (A\ R_{tot})$ where, $R_{tot} = (1 / R_{frame} + 1 / R_{cavity})^{-1}$ total resistance of the roof system modeled with a parallel thermal circuit.

[6] R_{frame} (15%): outdoor air film 0.25 (ASHRAE 1989: table 1: summer 7.5 mph), 1/4" asphalt shingle 0.32, 3/4" plywood 0.93, 2"x4" joist 4.37, naturally ventilated attic 2.1 (ASHRAE 1989: table 5: reduced for roof deck), 2"x4" joist 4.37, drywall 0.45, and indoor air film 0.77 (ASHRAE 1989: table 1: average of cooling and heating).

[7] R_{cavity} (85%): outdoor air film 0.25, 1/4" asphalt shingle 0.32, 3/4" plywood 0.93, naturally ventilated attic 2.1, fiberglass insulation (R), 1/2" drywall 0.45, and indoor air film 0.77.

Table 3. Simulated impact of roof albedo on annual cooling and heating energy use in a single-family new residence with R-19 attic insulation and R-4 attic ducts. Dark roof albedo is 10%. Savings (penalties) are calculated for increasing roof albedo from 0.1 to 0.7 (Δa = 0.6). To estimate savings (penalties) for other Δa multiply savings (penalties) in this table by the ratio of $\Delta a/0.6$. Total energy use is expressed in dollars and was calculated with local electricity and gas prices.

location	electricity [kWh/ft²]			gas [therms/ft²]			total [$/ft²]		
	dark	savings		dark	savings		dark	savings	
	roof	Δ	%	roof	Δ	%	roof	Δ	%
gas furnace									
Albuquerque	1.336	0.343	26	0.305	-0.016	-5	0.298	0.024	8
Atlanta	1.515	0.309	20	0.229	-0.009	-4	0.256	0.018	7
Austin	2.999	0.424	14	0.113	-0.004	-4	0.276	0.029	11
Fort Worth	2.569	0.365	14	0.153	-0.007	-5	0.303	0.025	8
Houston	2.748	0.395	14	0.100	-0.004	-4	0.283	0.030	11
Las Vegas	3.314	0.443	13	0.116	-0.005	-4	0.312	0.026	8
Lexington	1.077	0.209	19	0.435	-0.015	-3	0.227	0.004	2
Long Beach	0.614	0.213	35	0.065	-0.003	-5	0.121	0.025	21
Nashville	1.798	0.304	17	0.315	-0.012	-4	0.315	0.009	3
Phoenix	4.399	0.622	14	0.058	-0.003	-5	0.476	0.059	12
Raleigh	1.334	0.281	21	0.262	-0.011	-4	0.306	0.015	5
Sacramento	1.059	0.273	26	0.183	-0.009	-5	0.202	0.017	8
Salt Lake City	1.263	0.218	17	0.435	-0.018	-4	0.293	0.006	2
Sterling	1.169	0.206	18	0.430	-0.016	-4	0.404	0.006	1
Tampa	3.217	0.499	16	0.037	-0.001	-3	0.252	0.035	14
Tucson	3.004	0.503	17	0.088	-0.003	-3	0.351	0.045	13
heat pump									
Albuquerque	5.577	0.109	2	-	-	-	0.530	0.011	2
Atlanta	4.579	0.190	4	-	-	-	0.353	0.015	4
Austin	4.511	0.368	8	-	-	-	0.329	0.027	8
Fort Worth	4.625	0.283	6	-	-	-	0.370	0.023	6
Houston	4.093	0.342	8	-	-	-	0.331	0.027	8
Las Vegas	4.942	0.374	8	-	-	-	0.331	0.025	8
Lexington	6.991	0.030	1	-	-	-	0.343	0.002	1
Long Beach	1.366	0.178	13	-	-	-	0.176	0.023	13
Nashville	6.438	0.145	2	-	-	-	0.373	0.008	2
Phoenix	5.185	0.595	11	-	-	-	0.508	0.058	11
Raleigh	4.802	0.138	3	-	-	-	0.384	0.011	3
Sacramento	3.417	0.162	5	-	-	-	0.280	0.013	5
Salt Lake City	7.391	-0.034	0	-	-	-	0.503	-0.002	0
Sterling	7.178	0.000	0	-	-	-	0.596	0.000	0
Tampa	3.679	0.482	13	-	-	-	0.265	0.035	13
Tucson	4.201	0.460	11	-	-	-	0.395	0.043	11

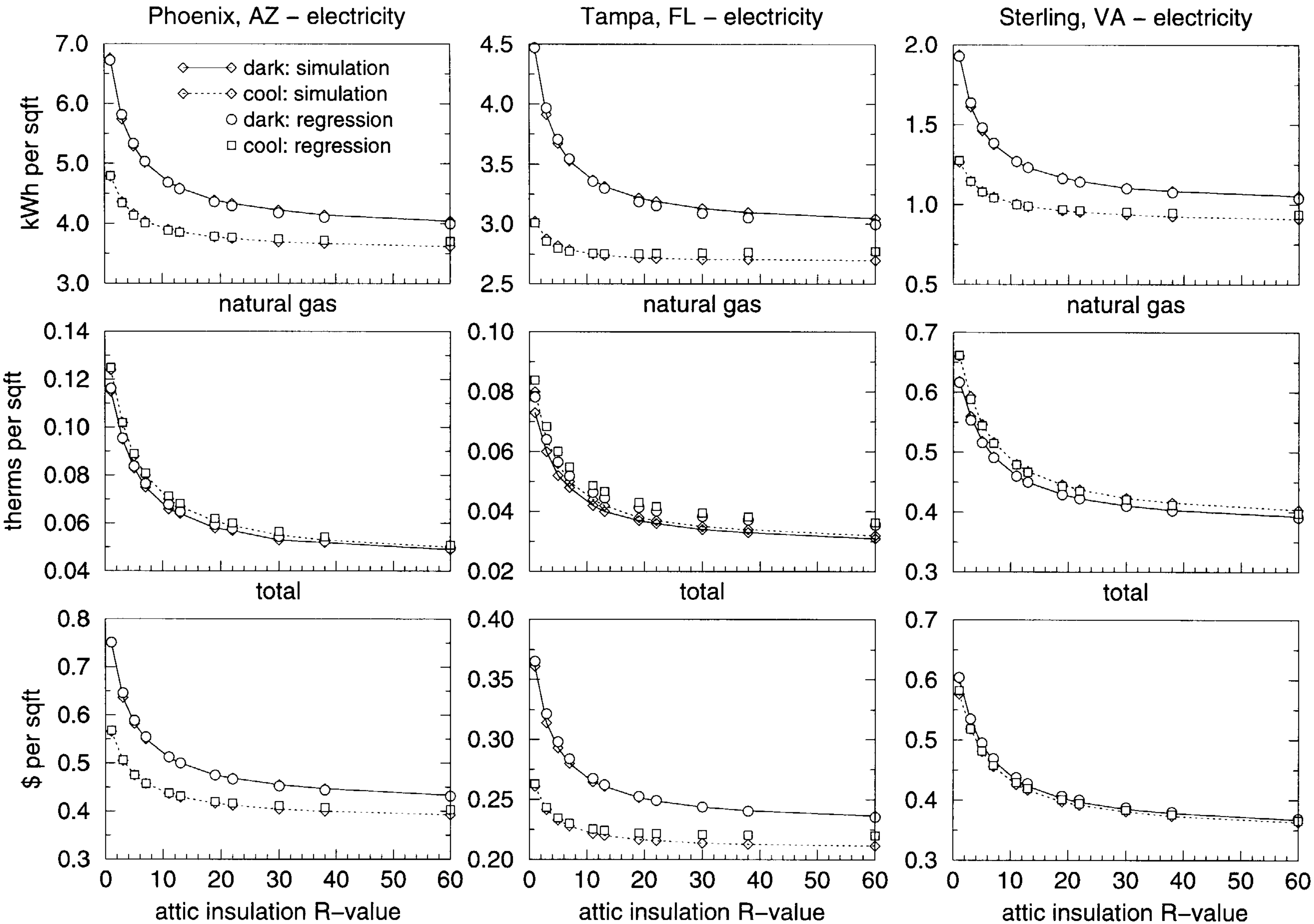

Figure 1. Simulation and regression estimates of annual cooling and heating energy use for a new residence with a gas furnace and R–4 attic ducts in Phoenix, Tampa, and Sterling. Electricity, gas and total energy use per sqft are presented for dark (albedo 0.1) and cool (albedo 0.7) roofs vs. attic insulation R–values of 1, 3, 5, 7, 11, 13, 19, 22, 30, 38, and 60.

Table 4. Analysis of variance and parameter estimates from regressions of annual total ($) cooling and heating energy use (E) versus roof system conductance (U) and roof surface solar absorptance (α) for a new residence with R-4 attic ducts.

$$E(\$) = C_0 + C_1\,U + C_2\,U^2 + C_3\,U\alpha$$

location	variance		parameter estimates			
	σ	R^2	C_0	C_1	C_2	C_3
gas furnace						
Albuquerque	0.002	1.00	0.22	0.81	1.31	0.78
Atlanta	0.001	1.00	0.20	0.52	1.35	0.60
Austin	0.003	1.00	0.23	-0.00	1.92	0.89
Fort Worth	0.002	1.00	0.25	0.30	1.98	0.77
Houston	0.003	1.00	0.24	-0.01	1.80	0.92
Las Vegas	0.002	1.00	0.25	0.44	2.59	0.82
Lexington	0.001	1.00	0.18	0.85	0.05	0.17
Long Beach	0.002	1.00	0.08	0.07	1.71	0.87
Nashville	0.001	1.00	0.26	0.93	0.97	0.33
Phoenix	0.004	1.00	0.39	-0.12	4.23	1.94
Raleigh	0.001	1.00	0.24	0.93	1.16	0.45
Sacramento	0.001	1.00	0.15	0.60	1.66	0.58
Salt Lake City	0.001	1.00	0.23	1.05	0.65	0.22
Sterling	0.001	1.00	0.33	1.41	0.80	0.23
Tampa	0.003	0.99	0.22	-0.37	2.03	1.08
Tucson	0.003	1.00	0.28	0.04	3.12	1.44
heat pump						
Albuquerque	0.002	1.00	0.43	1.77	-1.83	0.47
Atlanta	0.001	1.00	0.29	0.87	0.03	0.51
Austin	0.002	1.00	0.28	0.30	1.11	0.83
Fort Worth	0.002	1.00	0.31	0.63	1.06	0.70
Houston	0.002	1.00	0.28	0.23	1.30	0.86
Las Vegas	0.002	1.00	0.27	0.52	2.26	0.81
Lexington	0.002	1.00	0.30	0.85	-1.00	0.14
Long Beach	0.001	1.00	0.11	0.54	1.96	0.75
Nashville	0.001	1.00	0.31	1.00	-0.18	0.33
Phoenix	0.004	1.00	0.41	0.09	4.28	1.90
Raleigh	0.001	1.00	0.32	1.11	-0.65	0.41
Sacramento	0.001	1.00	0.21	1.07	1.06	0.46
Salt Lake City	0.003	1.00	0.43	1.59	-2.00	0.08
Sterling	0.003	1.00	0.51	1.88	-2.03	0.15
Tampa	0.003	1.00	0.23	-0.27	1.97	1.06
Tucson	0.003	1.00	0.31	0.32	2.78	1.39

Equivalent Attic Insulation R-Values

The objective of this work was to correlate energy savings from cool roofs to an equivalent reduction in the level of attic insulation. First, the total derivative (dE) of eq. 1 was found. Next, the condition of a zero net change in annual cooling and heating energy use (dE=0) was applied. Then, an equivalent change in roof-system conductance (ΔU) from a dark to cool roof was found from equation 3,

$$\Delta U = -K\,\Delta\alpha \qquad [3]$$

with decreasing absorptance (dark to cool roof: $\Delta\alpha<0$) the equivalent conductance will increase ($\Delta U>0$) proportionally by the constant K defined in equation 4 (for K>0),

$$K = \frac{C_3\,U_1}{C_1 + 2\,C_2\,U_1 + C_3\,\alpha_1} \qquad [4]$$

where, K is dependent upon initial values of U and α. The constant K is identified in **Table 5** for a new residence with R-4 attic ducts and R_1 of 7, 11, 19, 30, 38, and 60.

Finally, by rearranging eq. 2 the equivalent attic insulation R-values (R_2) were determined and are reported together with K in Tbl. 5. Reductions in R-value were observed for all climates, duct locations / insulation levels, and in both heating systems (Konopacki & Akbari 1998). The highest impact for a residence with R-4 attic ducts was in Tampa with gas heating, where the equivalent R-value dropped from 38 to 13 (14 w/ heat pump), followed by Phoenix 17 (18), Houston 17 (20), Tucson 18 (20), Austin 18 (20), Long Beach 18 (23), Fort Worth 21 (24), Las Vegas 22 (23), Atlanta 24 (27), Sacramento 25 (29), Albuquerque 25 (31), Raleigh 28 (29), Nashville 30 (30), Lexington 32 (33), Salt Lake City 32 (36), and Sterling 33 (35).

Example 1. A gas heated new residence in Tampa with R-4 ducts located in the attic is planned for construction with a dark roof [8] of α_1=0.9 and R_1=38 attic insulation. This residence could alternately incorporate a cool roof [9] of α_2=0.3 and a lower level of attic insulation with a zero net change in the annual energy bill.

step 1: Table 5 ⇒ R_2 = 13

Example 2. The same residence in Tampa instead incorporates a cool roof [10] of α_2=0.45 ($\Delta\alpha$=-0.45 U_1=0.031).

step 1: Table 5 ⇒ K = 0.046, *step 2*: Equation 3 ⇒ ΔU = 0.021, *step 3*: Equation 2 ⇒ R_2 = 16

Example 3. The same residence in Tampa is planned with a dark roof [11] of α_1=0.8 and a cool roof of α_2=0.45 ($\Delta\alpha$=-0.35 U_1=0.031).

step 1: Substitute parameter estimates from Table 4 into Equation 4 ⇒ K = 0.054, *step 2*: Equation 3 ⇒ ΔU = 0.019, *step 3*: Equation 2 ⇒ R_2 = 17

The effect of duct location and insulation on equivalent R-values can be observed in **Table 6**. These R_2 were based on total ($) energy use. The residence with uninsulated (R-1) attic ducts had the largest reduction in R_2 and the most energy savings, where the smallest reduction and least savings were in the residence with conditioned zone ducts (Konopacki & Akbari 1998). By comparing these two cases across climates, R_2 decreased

[8] A typical new black asphalt shingle has a measured albedo of 0.05 and dark brown 0.08 (Berdahl & Bretz 1997).

[9] (CRMD 1998).

[10] Several recently developed white-roof coating have measured albedos of 0.51 - 0.58 (Konopacki et al. 1997: Att. 1).

[11] A typical new green asphalt shingle has a measured albedo of 0.19 and white 0.25 (Berdahl & Bretz 1997).

Table 5. The constant K and equivalent attic insulation R-values (R_2) based on annual total ($) cooling and heating energy use for a new residence with R-4 attic ducts and initial attic insulation R-values of 7, 11, 19, 30, 38, and 60.

dark roof $\alpha_1 = 0.9$ --- *cool roof* $\alpha_2 = 0.3$

location	K						R_2					
$R_1 \rightarrow$	7	11	19	30	38	60	7	11	19	30	38	60
gas furnace												
Albuquerque	0.037	0.030	0.022	0.017	0.015	0.012	4	7	13	20	25	37
Atlanta	0.039	0.031	0.024	0.018	0.016	0.013	4	7	12	19	24	36
Austin	0.066	0.055	0.042	0.034	0.030	0.024	3	5	9	14	18	26
Fort Worth	0.048	0.040	0.031	0.024	0.021	0.017	4	6	11	17	21	32
Houston	0.068	0.057	0.044	0.034	0.031	0.025	3	5	9	14	17	26
Las Vegas	0.042	0.035	0.027	0.021	0.019	0.015	4	7	12	18	22	33
Lexington	0.014	0.011	0.008	0.006	0.005	0.004	6	9	16	26	32	50
Long Beach	0.064	0.052	0.040	0.032	0.028	0.022	3	5	9	15	18	27
Nashville	0.020	0.016	0.012	0.009	0.008	0.006	5	9	15	24	30	46
Phoenix	0.069	0.058	0.045	0.036	0.032	0.026	3	5	9	14	17	25
Raleigh	0.024	0.020	0.015	0.011	0.010	0.008	5	8	14	22	28	43
Sacramento	0.034	0.028	0.021	0.017	0.015	0.012	4	7	13	20	25	37
Salt Lake City	0.013	0.011	0.008	0.006	0.005	0.004	6	9	16	26	32	50
Sterling	0.011	0.009	0.006	0.005	0.004	0.003	6	10	17	26	33	51
Tampa	0.095	0.081	0.064	0.051	0.046	0.037	2	4	7	11	13	19
Tucson	0.064	0.054	0.041	0.033	0.029	0.023	3	5	9	14	18	27
heat pump												
Albuquerque	0.021	0.016	0.011	0.008	0.007	0.005	5	9	15	24	31	47
Atlanta	0.032	0.025	0.018	0.014	0.012	0.009	5	8	14	21	27	41
Austin	0.056	0.045	0.034	0.026	0.023	0.018	3	6	10	16	20	31
Fort Worth	0.040	0.032	0.024	0.019	0.016	0.013	4	7	12	19	24	36
Houston	0.059	0.048	0.036	0.028	0.024	0.019	3	6	10	16	20	29
Las Vegas	0.041	0.034	0.026	0.020	0.018	0.014	4	7	12	18	23	34
Lexington	0.014	0.011	0.007	0.005	0.005	0.004	6	9	16	26	33	51
Long Beach	0.040	0.033	0.025	0.020	0.017	0.014	4	7	12	19	23	35
Nashville	0.022	0.017	0.012	0.009	0.008	0.006	5	9	15	24	30	46
Phoenix	0.063	0.052	0.040	0.032	0.028	0.023	3	5	9	15	18	27
Raleigh	0.025	0.019	0.014	0.010	0.009	0.007	5	8	15	23	29	45
Sacramento	0.023	0.018	0.014	0.010	0.009	0.007	5	8	15	23	29	44
Salt Lake City	0.005	0.004	0.003	0.002	0.002	0.001	7	10	18	28	36	57
Sterling	0.007	0.006	0.004	0.003	0.002	0.002	6	10	18	28	35	55
Tampa	0.087	0.073	0.057	0.046	0.041	0.033	2	4	7	12	14	21
Tucson	0.057	0.047	0.035	0.028	0.025	0.020	3	6	10	16	20	29

Table 6. Equivalent attic insulation R-values (R_2) based on annual total ($) cooling and heating energy use for a new residence with initial attic insulation R-values (R_1) of 19 and 38, and attic duct R-values of 1, 2, 4, 6, and 8 and conditioned zone duct R-value of 1.

dark roof $\alpha_1 = 0.9$ --- *cool roof* $\alpha_2 = 0.3$

location	R-1		R-2		R-4		R-6		R-8		R-1 cond	
$R_1 \rightarrow$	19	38	19	38	19	38	19	38	19	38	19	38
gas furnace												
Albuquerque	11	22	12	23	13	25	13	25	13	25	13	26
Atlanta	11	21	12	23	12	24	12	24	13	25	13	25
Austin	7	15	8	17	9	18	9	18	10	18	10	19
Fort Worth	9	18	10	20	11	21	11	22	11	22	12	23
Houston	7	15	8	16	9	17	9	18	9	18	10	19
Las Vegas	10	19	11	21	12	22	12	23	12	23	12	24
Lexington	16	32	16	32	16	32	16	32	16	32	16	32
Long Beach	8	17	9	18	9	18	10	19	10	19	10	19
Nashville	14	28	15	29	15	30	15	30	15	30	16	31
Phoenix	7	14	8	16	9	17	9	17	9	18	9	18
Raleigh	13	26	14	27	14	28	14	28	15	29	15	29
Sacramento	11	22	12	24	13	25	13	25	13	25	13	26
Salt Lake City	15	30	16	31	16	32	16	32	17	33	17	33
Sterling	16	32	17	33	17	33	17	33	17	33	17	33
Tampa	5	11	6	13	7	13	7	14	7	13	7	14
Tucson	7	15	9	17	9	18	9	18	10	19	10	19
heat pump												
Albuquerque	14	28	15	30	15	31	15	31	16	31	16	31
Atlanta	11	23	13	25	14	27	14	27	14	27	14	27
Austin	8	17	10	19	10	20	11	21	11	21	11	22
Fort Worth	10	20	11	22	12	24	12	24	13	25	13	25
Houston	8	17	9	19	10	20	10	20	10	20	11	21
Las Vegas	10	20	11	22	12	23	12	23	12	24	12	24
Lexington	16	32	16	33	16	33	16	33	16	32	16	32
Long Beach	11	22	11	23	12	23	12	24	12	24	12	24
Nashville	13	27	15	29	15	30	15	30	15	30	15	30
Phoenix	8	15	9	17	9	18	10	19	10	19	10	19
Raleigh	13	26	14	28	15	29	15	29	15	29	15	29
Sacramento	13	27	14	28	15	29	15	29	15	29	15	29
Salt Lake City	19	37	18	37	18	36	18	36	18	36	18	35
Sterling	18	35	18	35	18	35	17	35	17	35	17	34
Tampa	6	12	7	14	7	14	8	15	8	15	8	15
Tucson	8	17	9	19	10	20	10	20	10	20	11	21

slightly (ΔR_{max}=3 at R_1=19 and ΔR_{max}=5 at R_1=38) as would be expected with a decrease in energy savings. An exception was the electric heated residence in Salt Lake City where ΔR increased by 2 (R_1=38) due to a high demand during the heating season.

Conclusion

This paper summarized a comparative analysis of the impact of roof surface solar absorptance and attic insulation on simulated residential annual cooling and heating energy use in sixteen sunbelt climates. The residences were single-story, single-family of new construction with either a gas furnace or an electric heat pump and with ducts in the attic or conditioned zone. Annual energy use was simulated with DOE-2 for dark and cool roofs and eleven attic insulation R-values ranging from 1 through 60. The simulations were regressed as a function of roof system conductance and roof absorptance for each heating system, duct location / insulation level, and climate. An equivalent change in conductance was calculated for a given change in absorptance from a dark to a cool roof. Equivalent attic insulation R-values were found from the conductance of the cool roof.

The analysis demonstrated that a roof system with a cool roof and low attic insulation can be used as an alternative to the more conventional dark-colored roof with a high level of insulation, with a zero net change in the annual energy bill. Reductions in R-value were observed for all climates, duct locations / insulation levels, and in both heating systems. The highest impact for a residence with R-4 attic ducts was in Tampa with gas heating, where the equivalent R-value dropped from 38 to 13 (14 w/ heat pump), followed by Phoenix 17 (18), Houston 17 (20), Tucson 18 (20), Austin 18 (20), Long Beach 18 (23), Fort Worth 21 (24), Las Vegas 22 (23), Atlanta 24 (27), Sacramento 25 (29), Albuquerque 25 (31), Raleigh 28 (29), Nashville 30 (30), Lexington 32 (33), Salt Lake City 32 (36), and Sterling 33 (35).

The Envelope Subcommittee of the ASHRAE Standing Standard Project Committee (SSPC) has recently voted for inclusion of reflective roofs in public review drafts for commercial building standard 90.1. The results presented in this paper can be used towards proposing modifications to building standard 90.2 for new residences, and in support of the US Environmental Protection Agency's (EPA) Energy Star® Homes Program.

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References

Akbari, H., Bretz, S., Kurn, D., and Hanford, J. 1997. "Peak Power and Cooling Energy Savings of High-Albedo Roofs". *Energy and Buildings* 25:117-126. Lawrence Berkeley National Laboratory Report LBL-34411. Berkeley, CA.

Akbari, H., Konopacki, S., Eley, C., Wilcox, B. Van Geem, M., and Parker, D. 1998. "Calculations for Reflective Roofs in Support of Standard 90.1". *In ASHRAE Transactions* vol. 104, pt. 1. Lawrence Berkeley National Laboratory Report LBNL-40260. Berkeley, CA.

Aktinson, C. 1997. Lawrence Berkeley National Laboratory. "New Residential Construction Characteristics". Personal communication to author.

American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE). 1989. *ASHRAE Handbook 1989 Fundamentals.* chapter 22. Atlanta, GA.

Berdahl, P. and Bretz, S. 1997. "Preliminary Survey of the Solar Reflectance of Cool Roofing Materials". *Energy and Buildings* 25:149-158. Lawrence Berkeley National Laboratory Report LBL-36020. Berkeley, CA.

Building Energy Simulation Group (BESG). 1990. "Overview of the DOE-2 Building Energy Analysis Program, Version 2.1D". Lawrence Berkeley National Laboratory Report LBL- 19735, Rev. 1. Berkeley, CA.

Cool Roofing Materials Database (CRMD).1998. http://eetd.lbl.gov/coolroof. Lawrence Berkeley National Laboratory. Berkeley, CA.

Energy Information Administration (EIA). 1997. *Electric Sales and Revenue 1995.* DOE/EIA- 0540(95). Web version. Washington, DC.

Gartland, L., Konopacki, S., and Akbari, H. 1996. "Modeling the Effects of Reflective Roofing". *In Proceedings of the 1996 ACEEE Summer Study on Energy Efficiency in Buildings* 4:117. Lawrence Berkeley National Laboratory Report LBL-38580. Berkeley, CA.

Henderson, H. 1998. "Part Load Curves for Use in DOE-2" Draft report prepared for Lawrence Berkeley National Laboratory and Florida Solar Energy Center. CDH Energy Corp., Cazenovia, NY. January 16, 1998.

Konopacki, S. and Akbari, H. 1998. "Simulated Impact of Roof Solar Absorptance, Attic and Duct Insulation, and Climate on Cooling and Heating Energy Use in New Construction Single- Family Residential Buildings". Lawrence Berkeley National Laboratory Report LBNL-41834. Berkeley, CA.

Konopacki, S., Akbari, H., Gartland, L., and Rainer, L. 1998. "Demonstration of Energy Savings of Cool Roofs". Lawrence Berkeley National Laboratory Report LBNL-40673. Berkeley, CA.

Konopacki, S., Akbari, H., Pomerantz, M., Gabersek, S., and Gartland, L. 1997. "Cooling Energy Savings Potential of Light-Colored Roofs for Residential and Commercial Buildings in 11 U.S. Metropolitan Areas". Lawrence Berkeley National Laboratory Report LBNL-39433. Berkeley, CA.

National Appliance Energy Conservation Act of 1987 (NAECA). 1987.

Parker, D., Huang, J., Konopacki, S., Gartland, L., Sherwin, J., and Gu, L. 1998. "Measured and Simulated Performance of Reflective Roofing Systems in Residential Buildings". *In ASHRAE Transactions* vol. 104, pt. 1. Atlanta, GA.

Parker, D., Sonne, J., and Sherwin, J. 1997. "Demonstration of Cooling Savings of Light Colored Roof Surfacing in Florida Commercial Buildings: Retail Strip Mall". Florida Solar Energy Center Report FSEC-CR-964-97. Cocoa, Fl.

Sherman, M., Wilson, D., and Kiel, D. 1986. "Variability in Residential Air Leakage". Measured Air Leakage in Buildings ASTM STP-904. Philadelphia, PA.