Title

Simulated Impact of Roof Surface Solar Absorptance, Attic, and Duct Insulation, and Duct Insulation on Cooling and Heating Energy Use in Single-Family Residential Buildings

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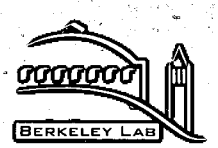

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S. Konopacki and H. Akbari

Environmental Energy Technologies Division

October 1998

DISCLAIMER

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Abstract

This report summarizes a comparative analysis of the impact of roof surface solar absorptance, attic, and duct insulation on simulated residential annual cooling and heating energy use in sixteen sunbelt climates. 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, single-family of new construction with either a gas furnace or an electric heat pump, and with ducts in the attic or conditioned zone. The objective is to demonstrate that a residence with a cool roof could utilize a lower level of attic insulation than one with a dark roof with a zero net change in the annual energy bill.

Annual energy use is simulated with DOE-2.1E, which was adapted with a validated residential duct-attic function, for dark and cool roofs and eleven attic insulation R-values ranging from 1 through 60. Analysis of the simulated energy savings from the light-colored roofs show that the savings can be transformed into an equivalent reduction in the level of attic insulation. Reductions in R-value are observed in varying degrees for residences with both gas and electric heat, all duct configurations, and all climates. In some cooling dominated climates there are cases where a cool roof could be implemented without attic insulation.

Executive Summary

Cool or light-colored roofs have a lower solar absorptance (higher albedo †) 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 solar absorptance, levels of attic and duct insulation, duct location, and climate.

This report summarizes a comparative analysis of the impact of roof surface solar absorptance, attic, and duct 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 (represents Los Angeles), 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, single-family of new construction with either a gas furnace or an electric heat pump, and with ducts in the attic or conditioned zone. The objective is to demonstrate that a residence with a cool roof could utilize a lower level of attic insulation than one with a dark roof with a zero net change in annual energy use.

Annual energy use is simulated with DOE-2, adapted with a validated residential duct-attic function, for dark and cool roofs and eleven attic insulation R-values ranging from 1 through 60. The simulations are then regressed as a function of roof system conductance and roof solar absorptance for each heating system, duct- insulation level / location, and climate. From the regressions an equivalent change in conductance is calculated for a given change in absorptance under the condition of equal dark- and cool-roof annual energy costs. Finally, equivalent attic insulation R-values are found from the conductance of the cool roof. Highlighted below are the major findings of the study, which are based on a dark-roof absorptance of 0.9 and a cool-roof absorptance of 0.3 ‡.

- Annual savings in total dollars were observed in all but a few simulations, with the highest of 28.2 ¢/ft^2 in the gas heated Phoenix residence with R-1 attic insulation and uninsulated attic ducts. This residence also had savings of 16.0 ¢/ft^2 (uninsulated conditioned zone ducts and R-1 attic insulation), 12.8 ¢/ft^2 (uninsulated attic ducts and R-60 attic insulation), and 2.3 ¢/ft^2 (uninsulated conditioned zone ducts and R-60 attic insulation). Those with small deficits were some electric heated residences in Lexington (-0.1 to -0.2 ¢/ft^2), Salt Lake City (-0.1 to -0.9 ¢/ft^2), and Sterling (-0.1 to -0.6 ¢/ft^2).
- For a residence with R-30 attic insulation and R-4 attic ducts the effect of the light-colored roof on energy savings was greatest in Phoenix with a gas heating system, which had annual combined cooling and heating energy savings of 5.1 ¢/ft^2 (or 12% of the dark-roof annual electric bill), followed by Tucson 3.8 (14), Tampa 3.0 (13), Houston 2.6 (12), Austin 2.5 (12), Fort Worth 2.2 (11), Las Vegas 2.2 (10), Long Beach 2.1 (29), Albuquerque 2.0 (17), Atlanta 1.6 (14), Sacramento 1.4

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

‡ The savings are estimated based on initial and modified roof reflectances of 0.1 and 0.7, respectively. Studies have shown that the modified roof reflectance may degrade to 0.55 over time, thus the energy savings would decrease by the ratio of 0.45 / 0.6.

(17), Raleigh 1.1 (11), Nashville 0.8 (8), Salt Lake City 0.5 (6), Sterling 0.4 (4), and Lexington 0.3 (6). Energy savings for this residence are illustrated in **Figure EX.1** and for all duct configurations in **Table EX.1**.

- 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 annual energy costs. Reductions in R-value were observed in varying degrees for residences with both gas and electric heat, all duct configurations, and all climates. The highest impact for a residence with R-30 attic insulation and R-4 attic ducts was in Tampa with a gas heating system, where the attic insulation R-value decreased to 3 (4 w/ heat pump), followed by Phoenix 8 (9), Houston 8 (11), Austin 8 (12), Tucson 9 (11), Long Beach 9 (16), Fort Worth 13 (16), Las Vegas 15 (15), Atlanta 16 (19), Albuquerque 17 (23), Sacramento 18 (22), Raleigh 21 (22), Nashville 23 (23), Lexington 25 (25), Salt Lake City 25 (28), and Sterling 26 (28). Equivalent R-values for this residence are displayed in **Figure EX.1**.
- In general, the uninsulated attic duct case was shown to have the largest reduction in R-value, where the smallest reduction was found with the conditioned zone ducts. In the gas heated Tampa residence with a dark-roof attic insulation R-value of 30, the cool-roof equivalent ranged from 0 (for uninsulated attic duct case) to 5 (for uninsulated conditioned zone duct case), in Phoenix and Houston it ranged from 2 to 10, Austin and Tucson 3 to 11, Long Beach 5 to 11, Fort Worth 8 to 15, Las Vegas 10 to 17, Atlanta 12 to 18, Albuquerque 13 to 19, Sacramento 14 to 19, Raleigh 19 to 22, Nashville 21 to 24, Salt Lake City 23 to 26, Lexington 24 to 25, and Sterling 25 to 26. In the heating dominated climates of Lexington and Sterling the effect of duct insulation and location was negligible. Equivalent R-values for all duct configurations are shown in **Table EX.2**.
- In the cooling dominated climates of Austin, Houston, Long Beach, Phoenix, Tampa, and Tucson there were some cases (predominantly those with uninsulated attic ducts and dark-roof attic insulation of R-7 or R-11) where a cool roof could be implemented without attic insulation. This also applies to Tampa residences with uninsulated attic ducts, either gas or electric heat, and all dark-roof attic R-values evaluated, and for those with gas heat, insulated attic ducts (R-2 to R-8), and dark-roof attic insulation of R-7.

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 report 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.

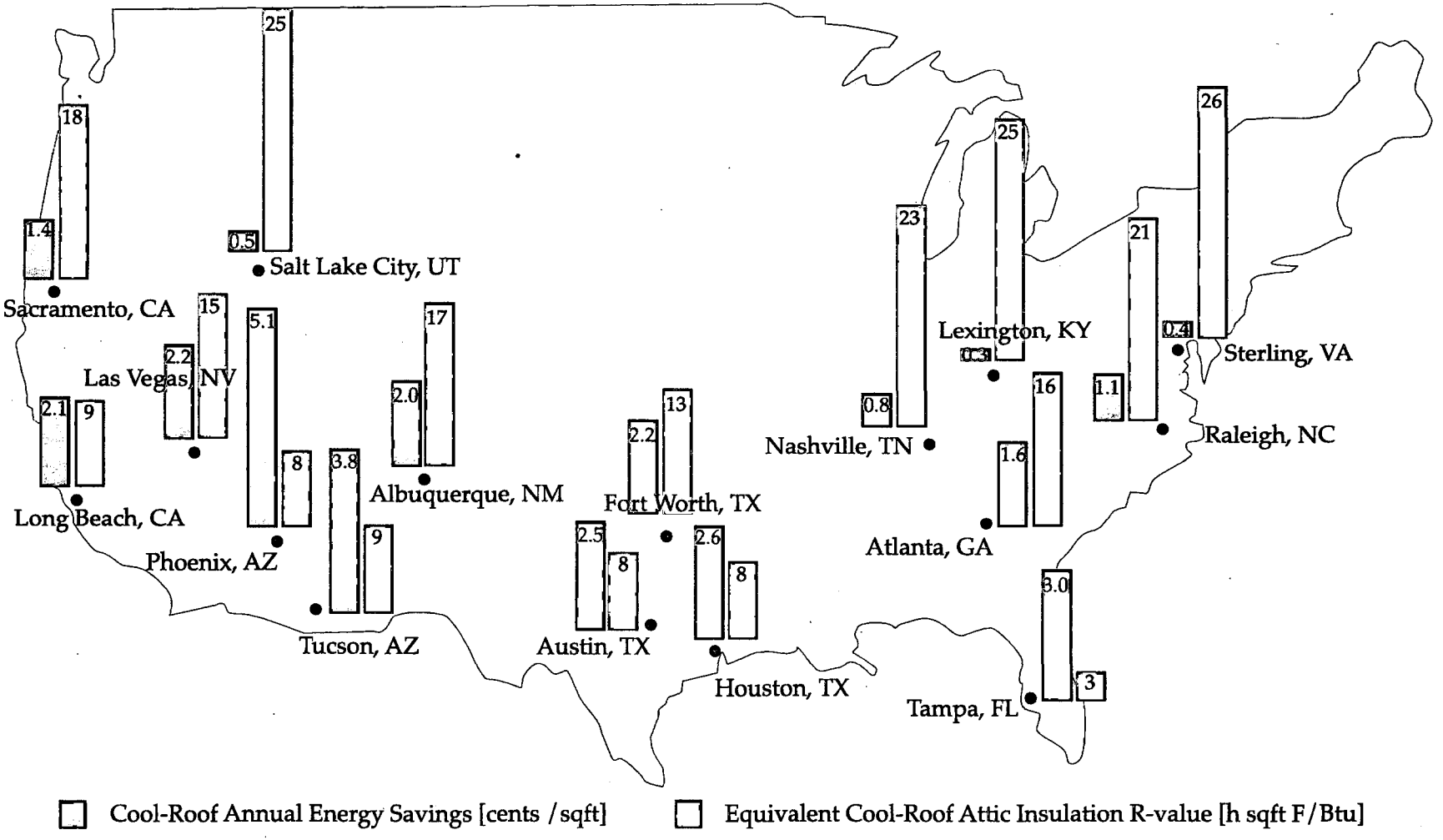

Figure EX.1. Simulation estimates of cool-roof annual total cooling and heating energy savings and equivalent cool-roof attic insulation R-values for a single-family new residence with gas heat, R-30 attic insulation, and R-4 attic ducts. Dark-roof absorptance is 0.9 and cool-roof absorptance is 0.3.

Table EX.1. Simulated impact of roof surface solar absorptance (α) on annual total cooling and heating energy use compared by duct configuration for a single-family new residence with R-30 attic insulation and a gas furnace. Dark-roof α is 0.9 and cool-roof α is 0.3. Total percent savings are calculated relative to the dark-roof annual electricity bill.

climate	**cool-roof annual total cooling and heating energy savings**											
duct location →	attic										living	
duct R-value →	R-1		R-2		R-4		R-6		R-8		R-1	
	¢/ft^2	%	¢/ft^2	%	¢/ft^2	%	¢/ft^2	%	¢/ft^2	%	¢/ft^2	%
Albuquerque, NM	6.4	29	3.3	22	2.0	17	1.6	15	1.4	13	1.1	11
Atlanta, GA	4.8	26	2.4	18	1.6	14	1.3	12	1.2	12	0.9	9
Austin, TX	7.3	22	4.0	16	2.5	12	2.1	10	1.8	9	1.4	8
Fort Worth, TX	6.4	21	3.5	15	2.2	11	1.8	10	1.6	9	1.1	6
Houston, TX	7.5	22	4.0	16	2.6	12	2.1	10	1.9	9	1.5	8
Las Vegas, NV	6.6	20	3.4	14	2.2	10	1.8	9	1.7	9	1.2	6
Lexington, KY	0.9	11	0.4	7	0.3	6	0.3	6	0.3	7	0.2	5
Long Beach, CA	6.4	46	3.3	36	2.1	29	1.9	28	1.8	27	1.4	23
Nashville, TN	2.4	15	1.3	11	0.8	8	0.7	7	0.6	6	0.5	6
Phoenix, AZ	14.1	23	7.6	16	5.1	12	4.3	11	4.1	11	3.2	9
Raleigh, NC	3.6	21	1.9	16	1.1	11	1.0	10	0.9	10	0.7	8
Sacramento, CA	4.3	30	2.3	23	1.4	17	1.2	16	1.1	15	0.9	13
Salt Lake City, UT	1.8	13	1.0	10	0.5	6	0.4	5	0.3	4	0.2	3
Sterling, VA	1.3	9	0.7	7	0.4	4	0.4	5	0.4	5	0.3	4
Tampa, FL	9.0	25	4.8	18	3.0	13	2.5	12	2.3	11	1.7	9
Tucson, AZ	11.3	26	5.9	19	3.8	14	3.1	12	3.0	12	2.3	10

Table EX.2. Equivalent cool-roof attic insulation R-values compared by duct configuration for a single-family new residence with R-30 attic insulation and a gas furnace. Dark-roof solar absorptance (α) is 0.9 and cool-roof α is 0.3.

climate	**equivalent cool-roof attic insulation R-value** [h·ft^2·°F/Btu]					
duct location ⇒	attic					living
duct R-value ⇒	R-1	R-2	R-4	R-6	R-8	R-1
Albuquerque, NM	13	16	17	18	18	19
Atlanta, GA	12	15	16	17	17	18
Austin, TX	3	6	8	9	10	11
Fort Worth, TX	8	11	13	14	14	15
Houston, TX	2	6	8	9	9	10
Las Vegas, NV	10	13	15	15	16	17
Lexington, KY	24	25	25	25	25	25
Long Beach, CA	5	8	9	10	10	11
Nashville, TN	21	22	23	23	23	24
Phoenix, AZ	2	6	8	8	9	10
Raleigh, NC	19	20	21	22	22	22
Sacramento, CA	14	16	18	18	18	19
Salt Lake City, UT	23	24	25	25	26	26
Sterling, VA	25	26	26	26	26	26
Tampa, FL	0	1	3	4	4	5
Tucson, AZ	3	7	9	10	10	11

1.0 Introduction

1.1 Background

Cool or light-colored 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. Computer simulations of residential and commercial building cooling and heating energy use in diverse climates 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). The magnitude of the savings are dependent upon the reduction in roof solar absorptance, levels of attic and duct insulation, duct location, and climate.

1.2 Project Objective

The objective of this study was to perform a comparative analysis of the impact of roof surface solar absorptance, attic, and duct 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 (represents Los Angeles), 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, single-family of new construction with either a gas furnace or an electric heat pump and with ducts in the attic or conditioned zone.

1.3 Methodology

As depicted in **Figure 1.1**, annual energy use is simulated with DOE-2, adapted with a validated residential duct-attic function, for dark and cool roofs and eleven attic insulation R-values ranging from 1 through 60. The simulations are then regressed as a function of roof system conductance and roof solar absorptance for each heating system, duct- insulation level / location, and climate. From the regressions an equivalent change in conductance is calculated for a given change in absorptance under the condition of equal dark- and cool-roof annual energy costs. Finally, equivalent attic insulation R-values are found from the conductance of the cool roof.

2.0 Residential Building Model

A single-story, single-family residential building was modeled with typical characteristics found in new constructions (Atkinson 1997) and DOE national appliance energy standards (NAECA 1987) as shown in **Table 2.1**. 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 climates, since the focus was on the influence of roof solar absorptance and attic insulation, and since most roof, wall, and window parameters did not exhibit much local variation.

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

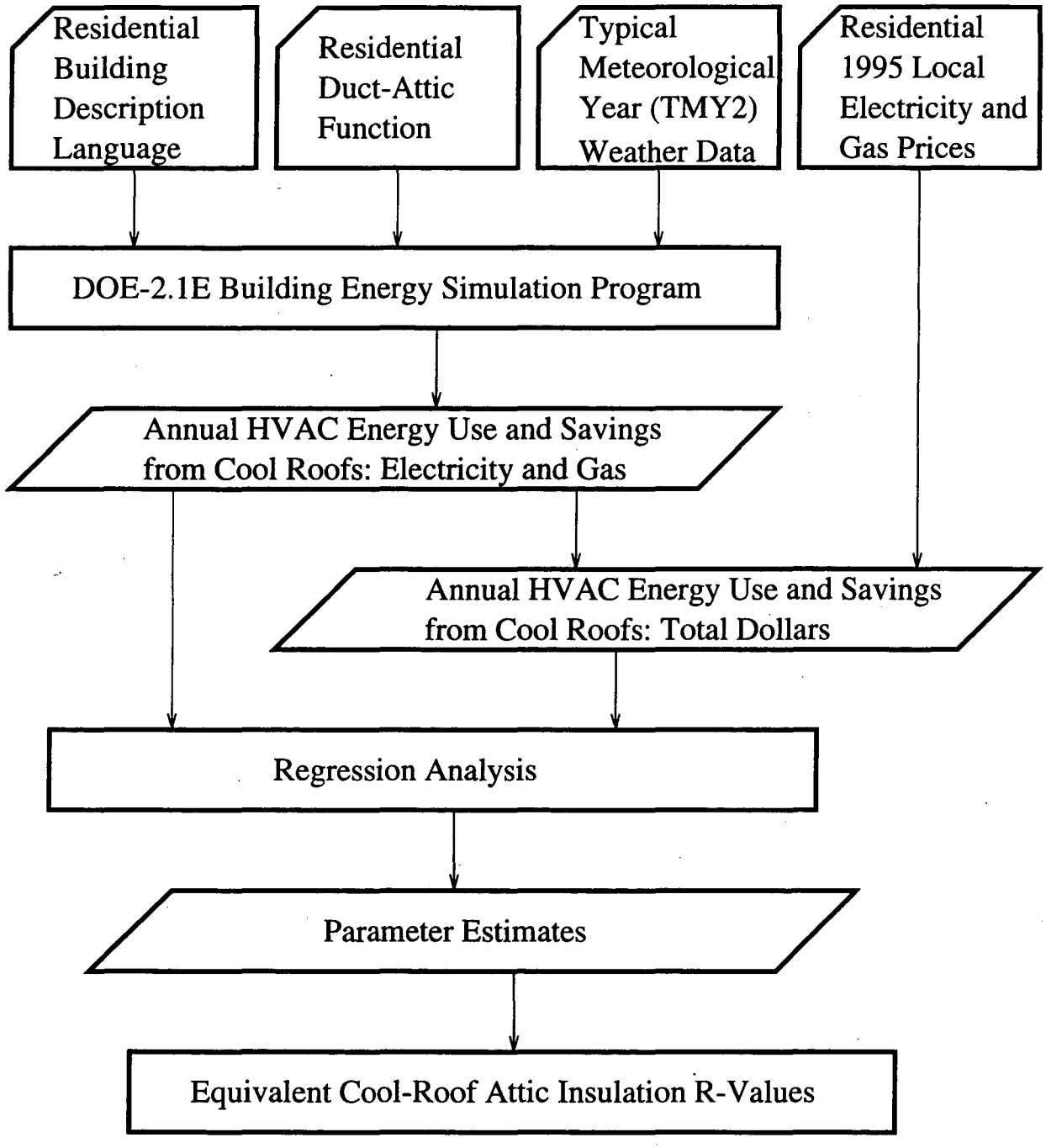

Figure 1.1. Project methodology.

The roof system was modeled with 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).

A residential duct-attic function was recently developed by Parker et al. (1998) for implementation into DOE-2 for the purpose of better estimating the thermal interactions between the ducts and the attic space. The model calculates attic temperature, supply and return duct losses, and temperature-dependent heat conduction through the attic insulation. It was documented to provide reasonable agreement with measured attic temperature and air-conditioning energy use data taken from Florida test homes. The function was incorporated into the roof system model.

The cooling and heating system(s) were sized automatically by DOE-2, which included an over sizing-ratio of 1.25 to allow for the additional load contributed by the ducts. 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).

Table 2.1. 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

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

3.0 Data Analysis and Results

3.1 Simulated Annual Cooling and Heating Energy Use

Annual cooling and heating energy use were estimated with the DOE-2.1E building energy simulation program (BESG 1990), which was adapted with a validated residential duct-attic function (Parker et al. 1998). The simulations were performed with the residential building model for both dark (α=0.9) and cool (α=0.3) roofs, 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 (R-1), uninsulated conditioned zone ducts (R-1C), gas furnaces and electric heat pumps [3], and Typical Meteorological Year (TMY2) weather data for the sixteen previously listed climates. Cooling and heating degree-days at 65 °F extracted from the TMY2 hourly temperature data are identified in **Table 3.1**. The table indicates that Phoenix recorded the highest number of cooling degree-days at 3814, and the lowest, Long Beach at 942, and Salt Lake City with the most heating degree-days with 5636, where Tampa only had 697. Local 1995 residential average prices for electricity and gas (EIA 1997) were used to calculate total annual energy use in dollars and are shown in **Table 3.2**. The cost of electricity ranged from a low of 4.9¢/kWh in Lexington to 12.9¢/kWh in Long Beach, and the cost of gas spanned from a low of 40.0¢/therm in Lexington to 77.7¢/therm in Las Vegas, Phoenix, and Tucson.

Annual cooling and heating electricity, gas, and total energy use for dark roofs and savings resulting from cool roofs are displayed in **Tables 3.3-18** for attic insulation R-values of 1, 7, 11, 19, 30, and 60, all duct configurations, both heating systems, and all climates. Annual total cooling and heating energy use are plotted for all simulations in **Figures A.1-16**. The total percent savings were calculated relative to the dark roof electricity use in dollars, which enables the rate-payer to estimate total dollar savings based on the annual electric bill. Annual savings in total dollars were observed in all but a few simulations, with the highest of 28.2 ¢/ft^2 in the gas heated Phoenix residence with R-1 attic insulation and uninsulated attic ducts. This residence also had savings of 16.0 ¢/ft^2 (uninsulated conditioned zone ducts and R-1 attic insulation), 12.8 ¢/ft^2 (uninsulated attic ducts and R-60 attic insulation), and 2.3 ¢/ft^2 (uninsulated conditioned zone ducts and R-60 attic insulation). Those with small deficits were some electric heated residences in Lexington (-0.1 to -0.2 ¢/ft^2), Salt Lake City (-0.1 to -0.9 ¢/ft^2), and Sterling (-0.1 to -0.6 ¢/ft^2).

For a residence with R-30 attic insulation and R-4 attic ducts the effect of the light-colored roof on energy savings was greatest in Phoenix with a gas heating system, which had annual combined cooling and heating energy savings of 5.1 ¢/ft^2 (or 12% of the dark-roof annual electric bill), followed by Tucson 3.8 (14), Tampa 3.0 (13), Houston 2.6 (12), Austin 2.5 (12), Fort Worth 2.2 (11), Las Vegas 2.2 (10), Long Beach 2.1 (29), Albuquerque 2.0 (17), Atlanta 1.6 (14), Sacramento 1.4 (17), Raleigh 1.1 (11), Nashville 0.8 (8), Salt Lake City 0.5 (6), Sterling 0.4 (4), and Lexington 0.3 (6). Energy use in Phoenix, Tampa, and Sterling residences with gas heat and R-4 attic ducts is plotted in **Figure 3.1** as a function of roof albedo and attic insulation R-value.

The dark roof has an absorptance (α) of 0.9 and the savings (penalties) were estimated for a cool roof with an α of 0.3, a net change of 0.6 [4]. Bretz and Akbari (1997) report that the albedo of white-coated roof surfaces can degrade up to 20% over a period of several years as a result of weathering and accumulation of dirt and debris (microbial growth can contribute to degradation in humid climates), and by washing the roof, the albedo can be restored to 90-100% of the initial value. Linear interpolation can be used to estimate savings (penalties) for other net changes in α regardless of the initial or final α for a given

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

[4] 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 (CRMD 1998).

residence (Konopacki et al. 1997: Attachment 2). The results can be simply adjusted by the ratio $\Delta a/0.6$ to account for depreciation in roof albedo. As an example, the savings (penalties) associated with a cool roof with an α of 0.45 (a 20% degradation in albedo) would be 75% of those with an α of 0.3. Although the savings were estimated with a single-story residential model, they can be applied to the top story of multi-story residences.

Table 3.1. Cooling and heating degree-days from Typical Meteorological Year 2 (TMY2) weather files.

TMY2 weather file	degree-days [65 °F]	
	cooling	heating
Albuquerque, NM	1211	4361
Atlanta, GA	1611	3090
Austin, TX	2965	1630
Fort Worth, TX	2414	2304
Houston, TX	2810	1552
Las Vegas, NV	3066	2293
Lexington, KY	1005	4994
Long Beach, CA	942	1308
Nashville, TN	1672	4031
Phoenix, AZ	3814	1154
Raleigh, NC	1313	3547
Sacramento, CA	1144	2794
Salt Lake City, UT	1054	5636
Sterling, VA	1044	5232
Tampa, FL	3311	697
Tucson, AZ	2762	1554

Table 3.2. 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

Table 3.3. Simulated impact of roof surface solar absorptance (α) and duct / attic insulation on annual cooling and heating energy use for a single-family new residence in **Albuquerque, NM**. Dark roof α is 90%. Savings (penalties) are calculated for decreasing α from 0.9 to 0.3 ($\Delta\alpha = 0.6$). To estimate savings (penalties) for other $\Delta\alpha$ multiply savings (penalties) in this table by the ratio of $\Delta\alpha/0.6$. Total percent savings are calculated relative to dark roof electricity use in $/ft^2.

duct / attic insulation	gas furnace							electric heat pump				
	electricity [kWh/ft^2]		gas [therms/ft^2]		total [$/ft^2]			electricity [kWh/ft^2]		total [$/ft^2]		
R-value	dark roof	svgs Δ	dark roof	svgs Δ	dark roof	svgs Δ	%	dark roof	svgs Δ	dark roof	svgs Δ	%
R-1 attic												
R-1	3.66	1.73	0.758	-0.080	0.773	0.119	34	12.04	0.80	1.144	0.076	7
R-7	2.83	1.19	0.634	-0.051	0.624	0.084	31	10.90	0.40	1.036	0.038	4
R-11	2.64	1.06	0.597	-0.045	0.586	0.076	30	10.53	0.34	1.001	0.033	3
R-19	2.45	0.94	0.561	-0.037	0.547	0.069	30	10.12	0.28	0.962	0.027	3
R-30	2.33	0.86	0.538	-0.032	0.523	0.064	29	9.85	0.24	0.935	0.023	2
R-60	2.18	0.76	0.514	-0.028	0.496	0.057	27	9.53	0.20	0.906	0.020	2
R-2 attic												
R-1	2.84	1.28	0.550	-0.055	0.579	0.091	34	9.13	0.66	0.867	0.062	7
R-7	2.00	0.73	0.437	-0.032	0.435	0.052	27	7.75	0.26	0.736	0.025	3
R-11	1.83	0.62	0.407	-0.027	0.402	0.044	25	7.38	0.21	0.701	0.020	3
R-19	1.66	0.52	0.378	-0.021	0.370	0.038	24	6.99	0.16	0.664	0.015	2
R-30	1.55	0.45	0.360	-0.018	0.350	0.033	22	6.74	0.12	0.640	0.012	2
R-60	1.44	0.38	0.342	-0.015	0.329	0.028	20	6.47	0.10	0.614	0.009	1
R-4 attic												
R-1	2.47	1.06	0.464	-0.045	0.495	0.076	32	7.76	0.58	0.737	0.055	7
R-7	1.64	0.53	0.358	-0.025	0.357	0.037	24	6.31	0.20	0.600	0.019	3
R-11	1.48	0.43	0.331	-0.020	0.327	0.030	21	5.95	0.15	0.565	0.015	3
R-19	1.34	0.34	0.305	-0.016	0.298	0.024	19	5.58	0.11	0.530	0.011	2
R-30	1.24	0.28	0.290	-0.012	0.281	0.020	17	5.34	0.08	0.508	0.008	2
R-60	1.15	0.23	0.274	-0.010	0.263	0.016	15	5.10	0.06	0.485	0.006	1
R-6 attic												
R-1	2.35	0.99	0.439	-0.041	0.469	0.070	31	7.33	0.56	0.696	0.053	8
R-7	1.54	0.47	0.335	-0.023	0.334	0.032	22	5.87	0.18	0.557	0.017	3
R-11	1.39	0.38	0.309	-0.018	0.305	0.025	19	5.51	0.14	0.523	0.013	2
R-19	1.24	0.29	0.285	-0.013	0.278	0.020	17	5.15	0.10	0.489	0.009	2
R-30	1.16	0.24	0.270	-0.011	0.261	0.016	15	4.92	0.07	0.467	0.006	1
R-60	1.07	0.18	0.255	-0.009	0.245	0.013	13	4.69	0.05	0.445	0.004	1
R-8 attic												
R-1	2.29	0.95	0.427	-0.040	0.457	0.068	31	7.11	0.55	0.676	0.052	8
R-7	1.49	0.44	0.325	-0.021	0.324	0.030	21	5.65	0.18	0.537	0.017	3
R-11	1.34	0.35	0.299	-0.017	0.295	0.023	18	5.29	0.13	0.503	0.013	3
R-19	1.20	0.27	0.275	-0.013	0.269	0.019	17	4.94	0.09	0.469	0.009	2
R-30	1.12	0.22	0.261	-0.010	0.252	0.014	13	4.72	0.07	0.448	0.006	1
R-60	1.03	0.17	0.246	-0.008	0.236	0.011	11	4.49	0.05	0.427	0.005	1
R-1 cond.												
R-1	2.14	0.86	0.393	-0.037	0.424	0.061	30	6.51	0.52	0.618	0.049	8
R-7	1.36	0.37	0.296	-0.019	0.295	0.024	19	5.05	0.16	0.480	0.016	3
R-11	1.22	0.28	0.272	-0.015	0.269	0.019	16	4.70	0.12	0.447	0.011	2
R-19	1.09	0.21	0.249	-0.011	0.244	0.014	13	4.37	0.08	0.415	0.008	2
R-30	1.01	0.17	0.236	-0.009	0.229	0.011	11	4.16	0.06	0.395	0.005	1
R-60	0.94	0.12	0.223	-0.006	0.214	0.008	9	3.95	0.04	0.375	0.004	1

Table 3.4. Simulated impact of roof surface solar absorptance (α) and duct / attic insulation on annual cooling and heating energy use for a single-family new residence in **Atlanta, GA**. Dark roof α is 90%. Savings (penalties) are calculated for decreasing α from 0.9 to 0.3 ($\Delta\alpha$ = 0.6). To estimate savings (penalties) for other $\Delta\alpha$ multiply savings (penalties) in this table by the ratio of $\Delta\alpha$/0.6. Total percent savings are calculated relative to dark roof electricity use in $/ft^2.

duct / attic insulation	gas furnace							electric heat pump				
	electricity [kWh/ft^2]		gas [therms/ft^2]		total [$/ft^2]			electricity [kWh/ft^2]		total [$/ft^2]		
R-value	dark roof	svgs Δ	dark roof	svgs Δ	dark roof	svgs Δ	%	dark roof	svgs Δ	dark roof	svgs Δ	%
R-1 attic												
R-1	3.48	1.54	0.558	-0.049	0.608	0.089	33	9.66	1.03	0.744	0.080	11
R-7	2.79	1.05	0.459	-0.030	0.495	0.063	29	8.45	0.66	0.651	0.051	8
R-11	2.65	0.95	0.432	-0.026	0.467	0.057	28	8.12	0.59	0.625	0.046	7
R-19	2.51	0.84	0.406	-0.021	0.440	0.052	27	7.77	0.53	0.598	0.041	7
R-30	2.41	0.77	0.390	-0.018	0.423	0.048	26	7.54	0.49	0.581	0.038	7
R-60	2.31	0.70	0.373	-0.016	0.405	0.044	25	7.29	0.43	0.561	0.033	6
R-2 attic												
R-1	2.77	1.15	0.413	-0.034	0.465	0.068	32	7.51	0.79	0.578	0.061	11
R-7	2.06	0.65	0.324	-0.018	0.356	0.039	25	6.19	0.41	0.476	0.031	7
R-11	1.93	0.55	0.301	-0.015	0.332	0.034	23	5.87	0.34	0.452	0.027	6
R-19	1.80	0.46	0.280	-0.012	0.309	0.028	20	5.54	0.28	0.427	0.022	5
R-30	1.71	0.40	0.267	-0.010	0.294	0.024	18	5.34	0.25	0.411	0.019	5
R-60	1.63	0.34	0.254	-0.008	0.280	0.021	17	5.13	0.20	0.395	0.016	4
R-4 attic												
R-1	2.45	0.96	0.353	-0.027	0.404	0.058	31	6.52	0.68	0.502	0.052	10
R-7	1.76	0.47	0.268	-0.015	0.299	0.028	21	5.19	0.30	0.400	0.024	6
R-11	1.63	0.39	0.248	-0.011	0.277	0.023	18	4.88	0.25	0.376	0.019	5
R-19	1.51	0.31	0.229	-0.009	0.256	0.018	15	4.58	0.19	0.353	0.015	4
R-30	1.44	0.26	0.218	-0.007	0.244	0.016	14	4.39	0.16	0.338	0.012	4
R-60	1.37	0.21	0.206	-0.006	0.231	0.013	12	4.20	0.12	0.324	0.010	3
R-6 attic												
R-1	2.36	0.90	0.335	-0.025	0.385	0.054	30	6.21	0.65	0.479	0.050	10
R-7	1.67	0.43	0.253	-0.013	0.282	0.025	19	4.88	0.27	0.376	0.021	6
R-11	1.55	0.35	0.233	-0.010	0.261	0.020	17	4.58	0.22	0.353	0.017	5
R-19	1.44	0.27	0.215	-0.007	0.241	0.016	14	4.29	0.17	0.330	0.013	4
R-30	1.37	0.22	0.204	-0.006	0.229	0.013	12	4.11	0.14	0.317	0.011	3
R-60	1.30	0.18	0.193	-0.005	0.218	0.011	11	3.93	0.10	0.302	0.008	3
R-8 attic												
R-1	2.31	0.87	0.326	-0.025	0.376	0.052	29	6.07	0.63	0.467	0.048	10
R-7	1.63	0.41	0.245	-0.013	0.275	0.024	19	4.74	0.26	0.365	0.020	5
R-11	1.51	0.33	0.226	-0.010	0.254	0.019	16	4.44	0.21	0.342	0.016	5
R-19	1.40	0.25	0.208	-0.007	0.234	0.014	13	4.15	0.16	0.320	0.012	4
R-30	1.33	0.20	0.197	-0.006	0.222	0.012	12	3.98	0.13	0.306	0.010	3
R-60	1.27	0.16	0.186	-0.005	0.211	0.009	9	3.80	0.10	0.292	0.007	2
R-1 cond.												
R-1	2.19	0.80	0.302	-0.023	0.352	0.048	29	5.65	0.59	0.435	0.046	11
R-7	1.52	0.35	0.225	-0.011	0.254	0.020	17	4.33	0.23	0.334	0.018	5
R-11	1.40	0.27	0.206	-0.009	0.234	0.016	15	4.05	0.18	0.312	0.014	4
R-19	1.30	0.20	0.189	-0.007	0.215	0.011	11	3.77	0.13	0.290	0.010	3
R-30	1.24	0.16	0.179	-0.005	0.204	0.009	9	3.61	0.10	0.278	0.008	3
R-60	1.18	0.12	0.170	-0.003	0.194	0.007	8	3.44	0.07	0.265	0.006	2

Table 3.5. Simulated impact of roof surface solar absorptance (α) and duct / attic insulation on annual cooling and heating energy use for a single-family new residence in **Austin, TX**. Dark roof α is 90%. Savings (penalties) are calculated for decreasing α from 0.9 to 0.3 ($\Delta\alpha$ = 0.6). To estimate savings (penalties) for other $\Delta\alpha$ multiply savings (penalties) in this table by the ratio of $\Delta\alpha$/0.6. Total percent savings are calculated relative to dark roof electricity use in $/ft^2.

duct / attic insulation	gas furnace							electric heat pump				
	electricity [kWh/ft^2]		gas [therms/ft^2]		total [$/ft^2]			electricity [kWh/ft^2]		total [$/ft^2]		
R-value	dark roof	svgs Δ	dark roof	svgs Δ	dark roof	svgs Δ	svgs %	dark roof	svgs Δ	dark roof	svgs Δ	svgs %
R-1 attic												
R-1	5.82	1.94	0.289	-0.026	0.571	0.129	30	9.12	1.66	0.666	0.121	18
R-7	4.97	1.37	0.226	-0.015	0.477	0.092	25	7.84	1.17	0.572	0.085	15
R-11	4.80	1.25	0.210	-0.012	0.456	0.084	24	7.53	1.07	0.550	0.078	14
R-19	4.63	1.13	0.195	-0.009	0.436	0.077	23	7.23	0.98	0.527	0.071	13
R-30	4.53	1.05	0.185	-0.008	0.424	0.073	22	7.03	0.92	0.513	0.067	13
R-60	4.41	0.98	0.175	-0.007	0.411	0.068	21	6.82	0.86	0.498	0.063	13
R-2 attic												
R-1	4.75	1.47	0.216	-0.018	0.456	0.098	28	7.28	1.27	0.531	0.092	17
R-7	3.83	0.87	0.161	-0.010	0.361	0.059	21	5.92	0.75	0.432	0.055	13
R-11	3.66	0.76	0.148	-0.007	0.342	0.052	19	5.62	0.65	0.410	0.048	12
R-19	3.49	0.64	0.136	-0.005	0.323	0.044	17	5.33	0.56	0.389	0.041	11
R-30	3.39	0.57	0.128	-0.005	0.312	0.040	16	5.15	0.50	0.376	0.037	10
R-60	3.28	0.50	0.121	-0.004	0.300	0.034	14	4.96	0.44	0.362	0.032	9
R-4 attic												
R-1	4.26	1.23	0.186	-0.015	0.405	0.082	26	6.43	1.07	0.469	0.078	17
R-7	3.33	0.64	0.136	-0.007	0.311	0.043	18	5.07	0.55	0.370	0.040	11
R-11	3.16	0.53	0.124	-0.006	0.293	0.036	16	4.78	0.45	0.349	0.033	9
R-19	3.00	0.42	0.113	-0.004	0.276	0.029	13	4.51	0.37	0.329	0.027	8
R-30	2.91	0.36	0.107	-0.003	0.266	0.025	12	4.35	0.32	0.317	0.023	7
R-60	2.81	0.30	0.100	-0.003	0.256	0.021	10	4.18	0.26	0.305	0.019	6
R-6 attic												
R-1	4.11	1.16	0.178	-0.014	0.389	0.077	26	6.17	1.01	0.450	0.073	16
R-7	3.18	0.57	0.128	-0.007	0.297	0.039	17	4.81	0.49	0.351	0.036	10
R-11	3.01	0.46	0.117	-0.005	0.279	0.031	14	4.53	0.40	0.331	0.029	9
R-19	2.86	0.36	0.107	-0.003	0.262	0.024	12	4.27	0.31	0.312	0.023	7
R-30	2.77	0.30	0.100	-0.003	0.253	0.021	10	4.11	0.26	0.300	0.019	6
R-60	2.68	0.25	0.094	-0.002	0.243	0.017	9	3.95	0.21	0.288	0.015	5
R-8 attic												
R-1	4.04	1.12	0.173	-0.014	0.382	0.075	25	6.05	0.98	0.441	0.071	16
R-7	3.11	0.54	0.125	-0.006	0.290	0.036	16	4.69	0.46	0.342	0.033	10
R-11	2.94	0.43	0.114	-0.005	0.272	0.029	13	4.42	0.37	0.322	0.027	8
R-19	2.79	0.34	0.103	-0.004	0.256	0.023	11	4.16	0.29	0.303	0.021	7
R-30	2.70	0.28	0.097	-0.003	0.246	0.018	9	4.00	0.24	0.292	0.017	6
R-60	2.62	0.22	0.091	-0.003	0.237	0.015	8	3.84	0.19	0.281	0.014	5
R-1 cond.												
R-1	3.84	1.03	0.162	-0.012	0.362	0.069	25	5.70	0.90	0.416	0.066	16
R-7	2.92	0.46	0.115	-0.006	0.271	0.030	14	4.36	0.39	0.318	0.028	9
R-11	2.76	0.35	0.105	-0.004	0.254	0.023	11	4.09	0.30	0.299	0.022	7
R-19	2.61	0.26	0.095	-0.003	0.239	0.018	9	3.85	0.23	0.281	0.017	6
R-30	2.53	0.21	0.090	-0.002	0.230	0.014	8	3.70	0.18	0.270	0.013	5
R-60	2.44	0.16	0.084	-0.002	0.221	0.011	6	3.55	0.13	0.259	0.009	3

Table 3.6. Simulated impact of roof surface solar absorptance (α) and duct / attic insulation on annual cooling and heating energy use for a single-family new residence in **Fort Worth, TX**. Dark roof α is 90%. Savings (penalties) are calculated for decreasing α from 0.9 to 0.3 ($\Delta\alpha = 0.6$). To estimate savings (penalties) for other $\Delta\alpha$ multiply savings (penalties) in this table by the ratio of $\Delta\alpha/0.6$. Total percent savings are calculated relative to dark roof electricity use in $/ft^2.

duct / attic insulation R-value	gas furnace							electric heat pump				
	electricity [kWh/ft^2]		gas [therms/ft^2]		total [$/ft^2]			electricity [kWh/ft^2]		total [$/ft^2]		
	dark roof	svgs Δ	dark roof	svgs Δ	dark roof	svgs Δ	svgs %	dark roof	svgs Δ	dark roof	svgs Δ	svgs %
R-1 attic												
R-1	5.03	1.65	0.385	-0.035	0.647	0.109	27	9.50	1.25	0.760	0.099	13
R-7	4.27	1.16	0.302	-0.020	0.534	0.080	23	8.14	0.87	0.651	0.070	11
R-11	4.12	1.06	0.280	-0.017	0.507	0.073	22	7.80	0.82	0.624	0.065	10
R-19	3.97	0.96	0.260	-0.013	0.483	0.068	21	7.46	0.75	0.597	0.060	10
R-30	3.88	0.89	0.247	-0.012	0.467	0.064	21	7.24	0.70	0.579	0.056	10
R-60	3.78	0.84	0.235	-0.009	0.451	0.061	20	7.02	0.67	0.562	0.054	10
R-2 attic												
R-1	4.12	1.25	0.289	-0.025	0.513	0.084	25	7.55	0.97	0.604	0.078	13
R-7	3.30	0.75	0.217	-0.013	0.402	0.052	20	6.12	0.57	0.490	0.046	9
R-11	3.14	0.65	0.200	-0.010	0.378	0.045	18	5.80	0.50	0.464	0.040	9
R-19	2.99	0.55	0.183	-0.008	0.356	0.039	16	5.48	0.43	0.439	0.035	8
R-30	2.90	0.49	0.173	-0.007	0.342	0.035	15	5.28	0.38	0.423	0.031	7
R-60	2.81	0.44	0.164	-0.005	0.329	0.032	14	5.09	0.35	0.407	0.028	7
R-4 attic												
R-1	3.69	1.05	0.250	-0.021	0.455	0.071	24	6.65	0.82	0.532	0.066	12
R-7	2.86	0.55	0.184	-0.010	0.346	0.037	16	5.23	0.41	0.418	0.033	8
R-11	2.71	0.45	0.168	-0.008	0.324	0.031	14	4.92	0.35	0.394	0.028	7
R-19	2.57	0.36	0.153	-0.007	0.303	0.025	12	4.62	0.28	0.370	0.023	6
R-30	2.48	0.31	0.145	-0.005	0.291	0.022	11	4.44	0.23	0.355	0.019	5
R-60	2.40	0.26	0.136	-0.004	0.279	0.019	10	4.26	0.21	0.341	0.016	5
R-6 attic												
R-1	3.56	0.98	0.239	-0.019	0.437	0.066	23	6.38	0.78	0.510	0.062	12
R-7	2.73	0.49	0.174	-0.010	0.329	0.033	15	4.96	0.37	0.397	0.030	8
R-11	2.58	0.40	0.159	-0.007	0.308	0.027	13	4.66	0.30	0.373	0.025	7
R-19	2.45	0.31	0.145	-0.006	0.288	0.022	11	4.37	0.24	0.350	0.020	6
R-30	2.36	0.26	0.137	-0.004	0.276	0.018	10	4.19	0.19	0.335	0.015	4
R-60	2.28	0.21	0.128	-0.004	0.264	0.014	8	4.03	0.17	0.322	0.013	4
R-8 attic												
R-1	3.50	0.96	0.233	-0.019	0.429	0.065	23	6.24	0.76	0.500	0.061	12
R-7	2.67	0.46	0.169	-0.010	0.322	0.031	14	4.83	0.35	0.386	0.027	7
R-11	2.52	0.37	0.155	-0.007	0.300	0.025	12	4.53	0.28	0.363	0.023	6
R-19	2.39	0.29	0.141	-0.005	0.281	0.020	10	4.25	0.22	0.340	0.018	5
R-30	2.31	0.23	0.133	-0.004	0.269	0.016	9	4.08	0.18	0.326	0.014	4
R-60	2.23	0.19	0.125	-0.003	0.258	0.014	8	3.91	0.15	0.313	0.012	4
R-1 cond.												
R-1	3.33	0.88	0.218	-0.018	0.405	0.059	22	5.87	0.70	0.470	0.056	12
R-7	2.51	0.39	0.157	-0.008	0.300	0.025	12	4.48	0.29	0.358	0.023	6
R-11	2.36	0.30	0.143	-0.006	0.280	0.020	11	4.19	0.23	0.335	0.018	5
R-19	2.23	0.22	0.130	-0.005	0.261	0.015	8	3.92	0.17	0.314	0.014	4
R-30	2.16	0.18	0.122	-0.004	0.250	0.011	6	3.76	0.13	0.301	0.011	4
R-60	2.08	0.14	0.115	-0.003	0.240	0.009	5	3.60	0.10	0.288	0.008	3

Table 3.7. Simulated impact of roof surface solar absorptance (α) and duct / attic insulation on annual cooling and heating energy use for a single-family new residence in **Houston, TX**. Dark roof α is 90%. Savings (penalties) are calculated for decreasing α from 0.9 to 0.3 ($\Delta\alpha$ = 0.6). To estimate savings (penalties) for other $\Delta\alpha$ multiply savings (penalties) in this table by the ratio of $\Delta\alpha$/0.6. Total percent savings are calculated relative to dark roof electricity use in $/ft^2.

duct / attic insulation	gas furnace							electric heat pump				
	electricity [kWh/ft^2]		gas [therms/ft^2]		total [$/ft^2]			electricity [kWh/ft^2]		total [$/ft^2]		
R-value	dark roof	svgs Δ	dark roof	svgs Δ	dark roof	svgs Δ	svgs %	dark roof	svgs Δ	dark roof	svgs Δ	svgs %
R-1 attic												
R-1	5.27	1.82	0.265	-0.024	0.586	0.133	31	8.29	1.55	0.672	0.126	19
R-7	4.54	1.28	0.208	-0.014	0.493	0.095	26	7.15	1.09	0.579	0.089	15
R-11	4.40	1.17	0.193	-0.012	0.472	0.087	24	6.87	1.00	0.557	0.081	15
R-19	4.26	1.05	0.178	-0.010	0.452	0.080	23	6.60	0.91	0.535	0.074	14
R-30	4.17	0.98	0.169	-0.009	0.439	0.075	22	6.42	0.85	0.520	0.069	13
R-60	4.07	0.91	0.160	-0.007	0.426	0.070	21	6.23	0.79	0.504	0.064	13
R-2 attic												
R-1	4.28	1.37	0.196	-0.016	0.464	0.101	29	6.58	1.19	0.533	0.096	18
R-7	3.48	0.81	0.146	-0.009	0.370	0.061	22	5.36	0.69	0.434	0.056	13
R-11	3.33	0.70	0.134	-0.007	0.350	0.052	19	5.09	0.60	0.413	0.049	12
R-19	3.19	0.59	0.122	-0.006	0.332	0.045	17	4.84	0.51	0.392	0.042	11
R-30	3.11	0.53	0.115	-0.005	0.321	0.040	16	4.68	0.46	0.379	0.037	10
R-60	3.02	0.47	0.108	-0.004	0.310	0.036	15	4.51	0.40	0.365	0.032	9
R-4 attic												
R-1	3.84	1.15	0.167	-0.014	0.411	0.085	27	5.81	1.00	0.470	0.081	17
R-7	3.02	0.60	0.121	-0.007	0.318	0.044	18	4.58	0.51	0.371	0.041	11
R-11	2.88	0.49	0.111	-0.005	0.300	0.037	16	4.33	0.42	0.351	0.034	10
R-19	2.75	0.40	0.100	-0.004	0.283	0.030	13	4.09	0.34	0.331	0.027	8
R-30	2.67	0.34	0.094	-0.004	0.273	0.026	12	3.94	0.29	0.320	0.024	8
R-60	2.59	0.28	0.088	-0.003	0.263	0.022	10	3.80	0.24	0.308	0.020	7
R-6 attic												
R-1	3.70	1.08	0.159	-0.013	0.395	0.080	27	5.57	0.95	0.451	0.077	17
R-7	2.89	0.53	0.114	-0.007	0.303	0.040	17	4.35	0.46	0.352	0.037	11
R-11	2.75	0.43	0.104	-0.005	0.285	0.032	14	4.10	0.37	0.332	0.030	9
R-19	2.62	0.34	0.094	-0.004	0.269	0.026	12	3.87	0.29	0.314	0.024	8
R-30	2.54	0.28	0.088	-0.003	0.259	0.021	10	3.73	0.24	0.302	0.019	6
R-60	2.47	0.23	0.083	-0.002	0.249	0.017	9	3.59	0.20	0.291	0.016	6
R-8 attic												
R-1	3.63	1.05	0.155	-0.012	0.387	0.077	26	5.45	0.92	0.442	0.075	17
R-7	2.83	0.51	0.111	-0.006	0.295	0.037	16	4.24	0.43	0.343	0.035	10
R-11	2.69	0.41	0.101	-0.004	0.278	0.030	14	4.00	0.34	0.324	0.028	9
R-19	2.56	0.32	0.091	-0.004	0.262	0.023	11	3.77	0.27	0.305	0.022	7
R-30	2.48	0.26	0.086	-0.002	0.252	0.019	9	3.63	0.22	0.294	0.018	6
R-60	2.41	0.21	0.080	-0.002	0.243	0.016	8	3.49	0.18	0.283	0.014	5
R-1 cond.												
R-1	3.45	0.96	0.144	-0.011	0.366	0.071	25	5.13	0.85	0.415	0.068	16
R-7	2.65	0.43	0.102	-0.005	0.276	0.032	15	3.93	0.37	0.319	0.030	9
R-11	2.51	0.33	0.092	-0.004	0.259	0.024	12	3.70	0.28	0.300	0.023	8
R-19	2.39	0.25	0.083	-0.003	0.244	0.018	9	3.49	0.21	0.282	0.017	6
R-30	2.32	0.20	0.078	-0.002	0.235	0.015	8	3.36	0.17	0.272	0.014	5
R-60	2.25	0.15	0.073	-0.002	0.226	0.011	6	3.23	0.13	0.261	0.010	4

Table 3.8. Simulated impact of roof surface solar absorptance (α) and duct / attic insulation on annual cooling and heating energy use for a single-family new residence in **Las Vegas, NV**. Dark roof α is 90%. Savings (penalties) are calculated for decreasing α from 0.9 to 0.3 ($\Delta\alpha$ = 0.6). To estimate savings (penalties) for other $\Delta\alpha$ multiply savings (penalties) in this table by the ratio of $\Delta\alpha$/0.6. Total percent savings are calculated relative to dark roof electricity use in $/ft^2.

duct / attic insulation	gas furnace							electric heat pump				
	electricity [kWh/ft^2]		gas [therms/ft^2]		total [$/ft^2]			electricity [kWh/ft^2]		total [$/ft^2]		
R-value	dark roof	svgs Δ	dark roof	svgs Δ	dark roof	svgs Δ	%	dark roof	svgs Δ	dark roof	svgs Δ	%
R-1 attic												
R-1	6.73	2.12	0.285	-0.029	0.672	0.120	27	10.57	1.74	0.708	0.117	17
R-7	5.49	1.44	0.207	-0.015	0.529	0.085	23	8.50	1.22	0.569	0.081	14
R-11	5.24	1.30	0.188	-0.011	0.497	0.078	22	8.03	1.12	0.538	0.075	14
R-19	5.00	1.16	0.170	-0.008	0.467	0.071	21	7.56	1.02	0.507	0.069	14
R-30	4.85	1.07	0.159	-0.007	0.448	0.066	20	7.27	0.95	0.487	0.064	13
R-60	4.69	0.99	0.148	-0.005	0.429	0.062	20	6.97	0.89	0.467	0.059	13
R-2 attic												
R-1	5.60	1.64	0.229	-0.022	0.552	0.091	24	8.62	1.35	0.578	0.091	16
R-7	4.29	0.92	0.162	-0.011	0.413	0.053	18	6.56	0.77	0.439	0.052	12
R-11	4.04	0.79	0.146	-0.008	0.384	0.046	17	6.12	0.67	0.410	0.045	11
R-19	3.81	0.66	0.131	-0.006	0.357	0.039	15	5.70	0.56	0.382	0.038	10
R-30	3.66	0.58	0.122	-0.005	0.340	0.034	14	5.45	0.50	0.365	0.034	9
R-60	3.52	0.50	0.113	-0.004	0.324	0.030	13	5.19	0.44	0.348	0.029	8
R-4 attic												
R-1	5.08	1.40	0.206	-0.020	0.500	0.078	23	7.77	1.16	0.520	0.078	15
R-7	3.77	0.69	0.144	-0.009	0.364	0.039	15	5.74	0.57	0.385	0.039	10
R-11	3.53	0.56	0.129	-0.008	0.337	0.032	14	5.33	0.47	0.357	0.031	9
R-19	3.31	0.44	0.116	-0.005	0.312	0.026	12	4.94	0.37	0.331	0.025	8
R-30	3.18	0.37	0.108	-0.004	0.297	0.022	10	4.71	0.32	0.316	0.022	7
R-60	3.05	0.31	0.100	-0.003	0.282	0.018	9	4.48	0.26	0.300	0.017	6
R-6 attic												
R-1	4.93	1.33	0.199	-0.019	0.484	0.074	22	7.50	1.10	0.503	0.074	15
R-7	3.62	0.62	0.138	-0.009	0.350	0.035	14	5.50	0.51	0.368	0.034	9
R-11	3.39	0.50	0.124	-0.007	0.324	0.029	13	5.10	0.41	0.342	0.028	8
R-19	3.17	0.39	0.111	-0.005	0.299	0.022	10	4.72	0.32	0.316	0.021	7
R-30	3.04	0.32	0.104	-0.003	0.284	0.018	9	4.50	0.27	0.301	0.017	6
R-60	2.92	0.26	0.096	-0.003	0.270	0.015	8	4.28	0.21	0.287	0.015	5
R-8 attic												
R-1	4.85	1.30	0.195	-0.020	0.477	0.072	22	7.38	1.07	0.494	0.071	14
R-7	3.55	0.59	0.136	-0.009	0.343	0.033	14	5.39	0.48	0.361	0.033	9
R-11	3.32	0.47	0.122	-0.007	0.317	0.026	12	4.99	0.39	0.334	0.026	8
R-19	3.11	0.36	0.109	-0.005	0.293	0.020	10	4.62	0.30	0.309	0.019	6
R-30	2.98	0.29	0.102	-0.003	0.279	0.017	9	4.40	0.24	0.295	0.017	6
R-60	2.86	0.23	0.094	-0.003	0.265	0.014	7	4.18	0.19	0.280	0.013	5
R-1 cond.												
R-1	4.64	1.20	0.186	-0.018	0.455	0.066	21	7.02	0.99	0.471	0.067	14
R-7	3.35	0.51	0.129	-0.008	0.324	0.027	12	5.07	0.41	0.340	0.028	8
R-11	3.13	0.40	0.115	-0.007	0.299	0.021	10	4.69	0.32	0.314	0.021	7
R-19	2.93	0.29	0.103	-0.005	0.276	0.016	8	4.34	0.23	0.291	0.016	6
R-30	2.80	0.23	0.096	-0.003	0.262	0.012	6	4.13	0.18	0.277	0.013	5
R-60	2.69	0.17	0.089	-0.002	0.249	0.009	5	3.92	0.14	0.263	0.009	3

Table 3.9. Simulated impact of roof surface solar absorptance (α) and duct / attic insulation on annual cooling and heating energy use for a single-family new residence in **Lexington, KY**. Dark roof α is 90%. Savings (penalties) are calculated for decreasing α from 0.9 to 0.3 ($\Delta\alpha$ = 0.6). To estimate savings (penalties) for other $\Delta\alpha$ multiply savings (penalties) in this table by the ratio of $\Delta\alpha$/0.6. Total percent savings are calculated relative to dark roof electricity use in $/ft^2.

duct / attic insulation	gas furnace							electric heat pump				
	electricity [kWh/ft^2]		gas [therms/ft^2]		total [$/ft^2]			electricity [kWh/ft^2]		total [$/ft^2]		
R-value	dark roof	svgs Δ	dark roof	svgs Δ	dark roof	svgs Δ	%	dark roof	svgs Δ	dark roof	svgs Δ	%
R-1 attic												
R-1	2.68	1.12	1.012	-0.072	0.536	0.026	20	13.11	0.55	0.642	0.027	4
R-7	2.06	0.71	0.877	-0.052	0.452	0.014	14	12.27	0.16	0.601	0.008	1
R-11	1.91	0.63	0.834	-0.046	0.427	0.012	13	11.96	0.10	0.586	0.004	1
R-19	1.76	0.54	0.790	-0.040	0.402	0.010	12	11.60	0.04	0.569	0.002	0
R-30	1.66	0.47	0.763	-0.037	0.387	0.009	11	11.36	-0.01	0.556	-0.001	-0
R-60	1.56	0.41	0.735	-0.033	0.371	0.007	9	11.10	-0.03	0.544	-0.001	-0
R-2 attic												
R-1	2.09	0.82	0.747	-0.050	0.402	0.021	20	10.20	0.45	0.500	0.022	4
R-7	1.50	0.44	0.617	-0.032	0.321	0.009	12	9.08	0.10	0.445	0.005	1
R-11	1.39	0.36	0.579	-0.026	0.299	0.007	10	8.76	0.06	0.429	0.002	0
R-19	1.27	0.30	0.542	-0.022	0.279	0.006	10	8.42	0.02	0.413	0.001	0
R-30	1.19	0.25	0.519	-0.019	0.266	0.004	7	8.20	-0.01	0.402	0.000	0
R-60	1.12	0.21	0.497	-0.016	0.254	0.004	7	7.97	-0.02	0.390	-0.002	-1
R-4 attic												
R-1	1.84	0.69	0.626	-0.038	0.340	0.018	20	8.84	0.41	0.433	0.020	5
R-7	1.28	0.33	0.501	-0.022	0.263	0.007	11	7.62	0.10	0.373	0.004	1
R-11	1.18	0.26	0.467	-0.019	0.245	0.006	10	7.32	0.06	0.358	0.003	1
R-19	1.08	0.21	0.435	-0.015	0.227	0.004	8	6.99	0.03	0.343	0.002	1
R-30	1.01	0.17	0.416	-0.013	0.216	0.003	6	6.78	0.01	0.332	0.000	0
R-60	0.96	0.14	0.398	-0.010	0.206	0.003	6	6.57	-0.00	0.322	0.000	0
R-6 attic												
R-1	1.76	0.65	0.589	-0.035	0.322	0.018	21	8.41	0.40	0.412	0.020	5
R-7	1.21	0.30	0.467	-0.020	0.246	0.006	10	7.17	0.10	0.351	0.005	1
R-11	1.12	0.24	0.435	-0.016	0.229	0.006	11	6.87	0.07	0.336	0.003	1
R-19	1.02	0.18	0.405	-0.012	0.212	0.004	8	6.55	0.04	0.321	0.002	1
R-30	0.96	0.15	0.387	-0.010	0.202	0.003	6	6.34	0.01	0.311	0.001	0
R-60	0.91	0.12	0.369	-0.009	0.192	0.002	4	6.14	0.01	0.301	0.001	0
R-8 attic												
R-1	1.72	0.63	0.571	-0.034	0.313	0.018	21	8.20	0.40	0.402	0.020	5
R-7	1.18	0.28	0.451	-0.018	0.238	0.006	10	6.95	0.10	0.340	0.005	1
R-11	1.09	0.23	0.420	-0.015	0.221	0.005	9	6.65	0.07	0.326	0.004	1
R-19	1.00	0.17	0.390	-0.012	0.205	0.004	8	6.34	0.04	0.310	0.002	1
R-30	0.94	0.14	0.373	-0.010	0.195	0.003	7	6.13	0.02	0.301	0.001	0
R-60	0.89	0.11	0.356	-0.008	0.186	0.002	5	5.93	0.01	0.291	0.001	0
R-1 cond.												
R-1	1.62	0.58	0.522	-0.029	0.288	0.016	20	7.59	0.39	0.372	0.019	5
R-7	1.10	0.24	0.407	-0.015	0.217	0.006	11	6.32	0.11	0.310	0.006	2
R-11	1.01	0.19	0.378	-0.013	0.201	0.004	8	6.03	0.08	0.296	0.004	1
R-19	0.93	0.14	0.352	-0.009	0.186	0.003	7	5.73	0.05	0.281	0.003	1
R-30	0.88	0.11	0.336	-0.007	0.177	0.002	5	5.54	0.03	0.272	0.002	1
R-60	0.83	0.08	0.320	-0.006	0.169	0.002	5	5.36	0.03	0.262	0.001	0

Table 3.10. Simulated impact of roof surface solar absorptance (α) and duct / attic insulation on annual cooling and heating energy use for a single-family new residence in **Long Beach, CA**. Dark roof α is 90%. Savings (penalties) are calculated for decreasing α from 0.9 to 0.3 ($\Delta\alpha = 0.6$). To estimate savings (penalties) for other $\Delta\alpha$ multiply savings (penalties) in this table by the ratio of $\Delta\alpha/0.6$. Total percent savings are calculated relative to dark roof electricity use in $/ft^2.

duct / attic insulation	gas furnace							electric heat pump				
	electricity [kWh/ft^2]		gas [therms/ft^2]		total [$/ft^2]			electricity [kWh/ft^2]		total [$/ft^2]		
R-value	dark roof	svgs Δ	dark roof	svgs Δ	dark roof	svgs Δ	%	dark roof	svgs Δ	dark roof	svgs Δ	%
R-1 attic												
R-1	1.96	1.22	0.211	-0.025	0.390	0.141	56	4.30	0.92	0.555	0.119	21
R-7	1.41	0.77	0.147	-0.011	0.277	0.093	51	3.13	0.63	0.404	0.081	20
R-11	1.29	0.68	0.131	-0.008	0.251	0.082	49	2.84	0.56	0.367	0.073	20
R-19	1.16	0.58	0.115	-0.006	0.224	0.070	47	2.55	0.49	0.329	0.063	19
R-30	1.08	0.52	0.106	-0.004	0.209	0.064	46	2.38	0.45	0.306	0.058	19
R-60	0.99	0.45	0.096	-0.003	0.190	0.055	43	2.17	0.39	0.280	0.050	18
R-2 attic												
R-1	1.50	0.89	0.156	-0.018	0.296	0.104	54	3.22	0.68	0.416	0.088	21
R-7	0.97	0.47	0.103	-0.008	0.192	0.056	45	2.16	0.38	0.279	0.049	18
R-11	0.87	0.39	0.091	-0.005	0.171	0.047	42	1.93	0.32	0.249	0.042	17
R-19	0.77	0.31	0.079	-0.004	0.150	0.038	39	1.70	0.27	0.220	0.034	15
R-30	0.71	0.27	0.072	-0.003	0.138	0.033	36	1.57	0.23	0.202	0.029	14
R-60	0.64	0.22	0.065	-0.002	0.125	0.027	33	1.42	0.19	0.183	0.024	13
R-4 attic												
R-1	1.30	0.74	0.134	-0.015	0.255	0.085	51	2.76	0.57	0.356	0.073	21
R-7	0.79	0.35	0.086	-0.006	0.158	0.041	40	1.77	0.28	0.228	0.036	16
R-11	0.70	0.28	0.075	-0.005	0.140	0.034	37	1.56	0.23	0.201	0.029	14
R-19	0.61	0.21	0.065	-0.003	0.121	0.025	32	1.37	0.18	0.176	0.023	13
R-30	0.57	0.18	0.059	-0.002	0.111	0.021	29	1.25	0.15	0.161	0.019	12
R-60	0.51	0.14	0.053	-0.002	0.100	0.017	26	1.13	0.12	0.146	0.015	10
R-6 attic												
R-1	1.24	0.69	0.128	-0.014	0.243	0.080	50	2.62	0.53	0.338	0.069	20
R-7	0.74	0.31	0.081	-0.006	0.149	0.037	39	1.65	0.25	0.213	0.032	15
R-11	0.66	0.25	0.071	-0.004	0.131	0.030	35	1.45	0.20	0.188	0.026	14
R-19	0.57	0.19	0.061	-0.003	0.114	0.023	31	1.27	0.15	0.164	0.020	12
R-30	0.53	0.15	0.055	-0.002	0.104	0.019	28	1.16	0.13	0.150	0.017	11
R-60	0.48	0.12	0.050	-0.001	0.094	0.015	24	1.05	0.10	0.135	0.013	10
R-8 attic												
R-1	1.21	0.67	0.125	-0.014	0.237	0.077	49	2.55	0.51	0.329	0.066	20
R-7	0.72	0.30	0.079	-0.006	0.144	0.035	38	1.60	0.23	0.206	0.030	15
R-11	0.64	0.24	0.069	-0.004	0.127	0.028	34	1.40	0.19	0.181	0.024	13
R-19	0.55	0.17	0.059	-0.003	0.110	0.021	29	1.23	0.14	0.158	0.019	12
R-30	0.51	0.14	0.054	-0.002	0.101	0.018	27	1.12	0.12	0.145	0.016	11
R-60	0.46	0.11	0.048	-0.002	0.091	0.014	24	1.01	0.09	0.130	0.012	9
R-1 cond.												
R-1	1.13	0.61	0.116	-0.013	0.222	0.071	49	2.37	0.47	0.305	0.061	20
R-7	0.66	0.26	0.073	-0.005	0.132	0.030	35	1.45	0.20	0.187	0.026	14
R-11	0.58	0.20	0.063	-0.004	0.116	0.024	32	1.27	0.16	0.164	0.020	12
R-19	0.50	0.14	0.054	-0.003	0.100	0.017	26	1.10	0.12	0.142	0.015	11
R-30	0.46	0.12	0.049	-0.002	0.092	0.014	23	1.01	0.09	0.130	0.012	9
R-60	0.42	0.08	0.044	-0.001	0.082	0.010	19	0.91	0.07	0.117	0.009	8

Table 3.11. Simulated impact of roof surface solar absorptance (α) and duct / attic insulation on annual cooling and heating energy use for a single-family new residence in **Nashville, TN**. Dark roof α is 90%. Savings (penalties) are calculated for decreasing α from 0.9 to 0.3 ($\Delta\alpha$ = 0.6). To estimate savings (penalties) for other $\Delta\alpha$ multiply savings (penalties) in this table by the ratio of $\Delta\alpha$/0.6. Total percent savings are calculated relative to dark roof electricity use in $/ft^2.

duct / attic insulation	gas furnace							electric heat pump				
	electricity [kWh/ft^2]		gas [therms/ft^2]		total [$/ft^2]			electricity [kWh/ft^2]		total [$/ft^2]		
R-value	dark roof	svgs Δ	dark roof	svgs Δ	dark roof	svgs Δ	%	dark roof	svgs Δ	dark roof	svgs Δ	%
R-1 attic												
R-1	3.87	1.50	0.725	-0.060	0.711	0.047	21	12.64	0.89	0.733	0.052	7
R-7	3.13	1.00	0.614	-0.041	0.593	0.031	17	11.21	0.50	0.650	0.029	4
R-11	2.98	0.90	0.583	-0.036	0.563	0.028	16	10.80	0.43	0.626	0.025	4
R-19	2.83	0.79	0.552	-0.031	0.534	0.026	16	10.38	0.36	0.602	0.021	3
R-30	2.72	0.73	0.533	-0.027	0.515	0.024	15	10.11	0.32	0.586	0.018	3
R-60	2.61	0.65	0.513	-0.024	0.495	0.021	14	9.82	0.28	0.569	0.016	3
R-2 attic												
R-1	3.13	1.12	0.542	-0.041	0.545	0.038	21	10.06	0.71	0.584	0.041	7
R-7	2.37	0.63	0.437	-0.026	0.431	0.020	15	8.45	0.32	0.490	0.019	4
R-11	2.23	0.54	0.410	-0.021	0.404	0.017	13	8.04	0.26	0.466	0.015	3
R-19	2.09	0.44	0.384	-0.017	0.379	0.015	12	7.63	0.20	0.443	0.012	3
R-30	2.00	0.39	0.368	-0.015	0.363	0.013	11	7.38	0.17	0.428	0.010	2
R-60	1.91	0.33	0.352	-0.013	0.347	0.011	10	7.12	0.13	0.413	0.008	2
R-4 attic												
R-1	2.80	0.94	0.463	-0.033	0.473	0.033	20	8.88	0.62	0.515	0.036	7
R-7	2.06	0.47	0.364	-0.019	0.363	0.015	13	7.22	0.25	0.419	0.015	4
R-11	1.92	0.39	0.339	-0.015	0.338	0.012	11	6.83	0.19	0.396	0.011	3
R-19	1.80	0.30	0.315	-0.012	0.315	0.009	9	6.44	0.14	0.373	0.008	2
R-30	1.72	0.26	0.301	-0.010	0.301	0.008	8	6.20	0.12	0.360	0.007	2
R-60	1.64	0.20	0.286	-0.009	0.287	0.006	6	5.96	0.09	0.346	0.005	1
R-6 attic												
R-1	2.70	0.89	0.440	-0.031	0.451	0.031	20	8.52	0.60	0.494	0.035	7
R-7	1.97	0.43	0.342	-0.017	0.343	0.013	11	6.85	0.23	0.397	0.013	3
R-11	1.84	0.35	0.318	-0.014	0.319	0.010	9	6.46	0.18	0.375	0.011	3
R-19	1.71	0.27	0.295	-0.011	0.297	0.008	8	6.08	0.13	0.353	0.008	2
R-30	1.64	0.22	0.281	-0.009	0.284	0.007	7	5.85	0.10	0.339	0.006	2
R-60	1.56	0.17	0.268	-0.007	0.270	0.005	6	5.62	0.07	0.326	0.005	2
R-8 attic												
R-1	2.65	0.87	0.429	-0.029	0.441	0.030	20	8.34	0.58	0.484	0.034	7
R-7	1.92	0.41	0.332	-0.016	0.334	0.013	12	6.67	0.22	0.387	0.013	3
R-11	1.79	0.33	0.308	-0.013	0.311	0.011	11	6.29	0.17	0.365	0.010	3
R-19	1.68	0.25	0.286	-0.010	0.289	0.008	8	5.91	0.12	0.343	0.007	2
R-30	1.60	0.20	0.272	-0.008	0.275	0.006	6	5.68	0.10	0.329	0.005	2
R-60	1.53	0.15	0.259	-0.007	0.262	0.005	6	5.45	0.07	0.316	0.004	1
R-1 cond.												
R-1	2.52	0.80	0.397	-0.027	0.412	0.028	19	7.83	0.56	0.454	0.032	7
R-7	1.81	0.35	0.304	-0.015	0.309	0.011	10	6.18	0.20	0.358	0.012	3
R-11	1.68	0.28	0.282	-0.011	0.286	0.008	8	5.80	0.15	0.336	0.009	3
R-19	1.57	0.20	0.261	-0.008	0.266	0.007	8	5.44	0.11	0.315	0.006	2
R-30	1.50	0.16	0.248	-0.007	0.253	0.005	6	5.22	0.08	0.303	0.005	2
R-60	1.43	0.12	0.236	-0.005	0.241	0.004	5	5.00	0.06	0.290	0.003	1

Table 3.12. Simulated impact of roof surface solar absorptance (α) and duct / attic insulation on annual cooling and heating energy use for a single-family new residence in **Phoenix, AZ**. Dark roof α is 90%. Savings (penalties) are calculated for decreasing α from 0.9 to 0.3 ($\Delta\alpha$ = 0.6). To estimate savings (penalties) for other $\Delta\alpha$ multiply savings (penalties) in this table by the ratio of $\Delta\alpha$/0.6. Total percent savings are calculated relative to dark roof electricity use in $/ft^2.

duct / attic insulation	gas furnace							electric heat pump				
	electricity [kWh/ft^2]		gas [therms/ft^2]		total [$/ft^2]			electricity [kWh/ft^2]		total [$/ft^2]		
R-value	dark roof	svgs Δ	dark roof	svgs Δ	dark roof	svgs Δ	%	dark roof	svgs Δ	dark roof	svgs Δ	%
R-1 attic												
R-1	8.85	2.98	0.156	-0.014	0.989	0.282	33	10.85	2.80	1.063	0.275	26
R-7	7.19	2.01	0.107	-0.007	0.788	0.192	27	8.66	1.93	0.849	0.189	22
R-11	6.84	1.79	0.096	-0.004	0.745	0.172	26	8.18	1.72	0.802	0.169	21
R-19	6.50	1.58	0.085	-0.003	0.703	0.152	24	7.71	1.53	0.755	0.150	20
R-30	6.30	1.46	0.078	-0.003	0.678	0.141	23	7.42	1.42	0.727	0.139	19
R-60	6.06	1.32	0.071	-0.003	0.650	0.128	22	7.11	1.28	0.697	0.126	18
R-2 attic												
R-1	7.39	2.28	0.127	-0.011	0.823	0.215	30	8.99	2.14	0.881	0.210	24
R-7	5.66	1.29	0.084	-0.005	0.620	0.122	22	6.79	1.23	0.666	0.121	18
R-11	5.33	1.08	0.075	-0.003	0.580	0.103	20	6.34	1.04	0.622	0.102	16
R-19	5.00	0.89	0.066	-0.002	0.541	0.085	17	5.91	0.86	0.579	0.084	15
R-30	4.82	0.79	0.060	-0.002	0.519	0.076	16	5.66	0.76	0.555	0.075	14
R-60	4.62	0.67	0.055	-0.002	0.495	0.064	14	5.39	0.65	0.528	0.063	12
R-4 attic												
R-1	6.76	1.97	0.115	-0.009	0.752	0.186	28	8.19	1.84	0.803	0.181	23
R-7	5.02	0.98	0.075	-0.005	0.551	0.093	19	6.01	0.93	0.589	0.091	15
R-11	4.70	0.79	0.066	-0.004	0.512	0.075	16	5.58	0.76	0.547	0.074	14
R-19	4.40	0.62	0.058	-0.003	0.476	0.059	14	5.18	0.59	0.508	0.058	11
R-30	4.23	0.53	0.053	-0.002	0.456	0.051	12	4.95	0.51	0.485	0.049	10
R-60	4.04	0.42	0.049	-0.001	0.434	0.041	10	4.71	0.41	0.462	0.040	9
R-6 attic												
R-1	6.57	1.87	0.111	-0.009	0.730	0.176	27	7.95	1.76	0.779	0.172	22
R-7	4.83	0.90	0.073	-0.004	0.530	0.084	18	5.78	0.85	0.567	0.083	15
R-11	4.52	0.71	0.064	-0.003	0.493	0.068	15	5.37	0.68	0.526	0.067	13
R-19	4.22	0.55	0.056	-0.002	0.457	0.051	12	4.97	0.52	0.487	0.051	10
R-30	4.06	0.46	0.051	-0.002	0.437	0.043	11	4.75	0.44	0.466	0.043	9
R-60	3.88	0.36	0.047	-0.001	0.416	0.034	9	4.52	0.34	0.443	0.034	8
R-8 attic												
R-1	6.48	1.83	0.109	-0.009	0.720	0.173	27	7.83	1.72	0.767	0.168	22
R-7	4.75	0.86	0.071	-0.004	0.521	0.081	17	5.68	0.81	0.556	0.079	14
R-11	4.43	0.67	0.063	-0.003	0.483	0.063	15	5.26	0.64	0.516	0.063	12
R-19	4.14	0.51	0.055	-0.002	0.449	0.049	12	4.88	0.49	0.478	0.048	10
R-30	3.98	0.42	0.050	-0.002	0.429	0.041	11	4.66	0.40	0.456	0.039	9
R-60	3.80	0.33	0.046	-0.001	0.408	0.031	8	4.42	0.31	0.434	0.031	7
R-1 cond.												
R-1	6.22	1.71	0.104	-0.009	0.690	0.160	26	7.50	1.60	0.735	0.156	21
R-7	4.50	0.75	0.068	-0.004	0.494	0.071	16	5.38	0.71	0.527	0.069	13
R-11	4.20	0.57	0.060	-0.002	0.458	0.054	13	4.97	0.54	0.488	0.054	11
R-19	3.92	0.42	0.052	-0.002	0.424	0.039	10	4.60	0.40	0.451	0.039	9
R-30	3.76	0.34	0.048	-0.001	0.405	0.032	9	4.39	0.32	0.430	0.031	7
R-60	3.59	0.24	0.043	-0.002	0.385	0.023	7	4.17	0.23	0.409	0.023	6

Table 3.13. Simulated impact of roof surface solar absorptance (α) and duct / attic insulation on annual cooling and heating energy use for a single-family new residence in **Raleigh, NC**. Dark roof α is 90%. Savings (penalties) are calculated for decreasing α from 0.9 to 0.3 ($\Delta\alpha$ = 0.6). To estimate savings (penalties) for other $\Delta\alpha$ multiply savings (penalties) in this table by the ratio of $\Delta\alpha$/0.6. Total percent savings are calculated relative to dark roof electricity use in $/ft^2.

duct / attic insulation	gas furnace							electric heat pump				
	electricity [kWh/ft^2]		gas [therms/ft^2]		total [$/ft^2]			electricity [kWh/ft^2]		total [$/ft^2]		
R-value	dark roof	svgs Δ	dark roof	svgs Δ	dark roof	svgs Δ	%	dark roof	svgs Δ	dark roof	svgs Δ	%
R-1 attic												
R-1	3.17	1.39	0.650	-0.060	0.746	0.065	26	10.10	0.80	0.808	0.064	8
R-7	2.53	0.94	0.543	-0.039	0.614	0.045	22	9.01	0.46	0.721	0.037	5
R-11	2.39	0.84	0.513	-0.034	0.580	0.041	21	8.70	0.41	0.696	0.033	5
R-19	2.26	0.75	0.483	-0.029	0.547	0.038	21	8.35	0.36	0.668	0.028	4
R-30	2.17	0.68	0.464	-0.025	0.526	0.036	21	8.12	0.32	0.650	0.026	4
R-60	2.07	0.61	0.445	-0.022	0.503	0.032	19	7.88	0.29	0.630	0.023	4
R-2 attic												
R-1	2.50	1.03	0.474	-0.041	0.560	0.052	26	7.77	0.64	0.622	0.051	8
R-7	1.85	0.59	0.377	-0.023	0.434	0.029	20	6.53	0.30	0.523	0.024	5
R-11	1.72	0.50	0.351	-0.020	0.404	0.025	18	6.22	0.25	0.497	0.020	4
R-19	1.60	0.42	0.327	-0.015	0.376	0.022	17	5.89	0.20	0.471	0.016	3
R-30	1.53	0.36	0.312	-0.013	0.358	0.019	16	5.68	0.17	0.454	0.013	3
R-60	1.45	0.31	0.296	-0.012	0.341	0.017	15	5.47	0.15	0.438	0.012	3
R-4 attic												
R-1	2.20	0.86	0.400	-0.032	0.479	0.044	25	6.70	0.56	0.536	0.045	8
R-7	1.56	0.43	0.307	-0.018	0.358	0.021	17	5.42	0.23	0.433	0.018	4
R-11	1.44	0.35	0.284	-0.014	0.331	0.018	16	5.11	0.18	0.409	0.015	4
R-19	1.33	0.28	0.262	-0.011	0.306	0.015	14	4.80	0.14	0.384	0.011	3
R-30	1.27	0.23	0.249	-0.009	0.290	0.011	11	4.61	0.11	0.368	0.008	2
R-60	1.20	0.19	0.236	-0.007	0.275	0.010	10	4.42	0.09	0.353	0.007	2
R-6 attic												
R-1	2.11	0.81	0.378	-0.030	0.455	0.042	25	6.36	0.53	0.509	0.043	8
R-7	1.48	0.39	0.287	-0.016	0.336	0.019	16	5.08	0.21	0.406	0.016	4
R-11	1.36	0.31	0.265	-0.013	0.310	0.015	14	4.77	0.16	0.382	0.013	3
R-19	1.26	0.24	0.244	-0.010	0.286	0.012	12	4.47	0.12	0.358	0.010	3
R-30	1.19	0.20	0.232	-0.007	0.271	0.010	10	4.28	0.10	0.343	0.008	2
R-60	1.13	0.15	0.219	-0.006	0.256	0.007	8	4.10	0.08	0.328	0.006	2
R-8 attic												
R-1	2.07	0.78	0.367	-0.029	0.444	0.041	25	6.20	0.52	0.496	0.042	8
R-7	1.44	0.37	0.278	-0.015	0.326	0.018	16	4.91	0.20	0.393	0.016	4
R-11	1.32	0.29	0.256	-0.012	0.300	0.014	13	4.61	0.16	0.369	0.013	4
R-19	1.22	0.23	0.236	-0.009	0.276	0.011	11	4.31	0.12	0.345	0.009	3
R-30	1.16	0.18	0.223	-0.008	0.262	0.009	10	4.13	0.09	0.330	0.007	2
R-60	1.10	0.14	0.211	-0.006	0.248	0.007	8	3.95	0.07	0.316	0.006	2
R-1 cond.												
R-1	1.95	0.72	0.338	-0.026	0.412	0.037	24	5.73	0.49	0.459	0.040	9
R-7	1.33	0.31	0.252	-0.014	0.298	0.015	14	4.45	0.18	0.356	0.014	4
R-11	1.22	0.24	0.232	-0.010	0.273	0.011	11	4.16	0.14	0.333	0.011	3
R-19	1.13	0.18	0.213	-0.007	0.251	0.008	9	3.88	0.10	0.310	0.008	3
R-30	1.07	0.14	0.201	-0.006	0.238	0.007	8	3.70	0.08	0.296	0.006	2
R-60	1.01	0.10	0.190	-0.005	0.225	0.005	6	3.53	0.06	0.283	0.005	2

Table 3.14. Simulated impact of roof surface solar absorptance (α) and duct / attic insulation on annual cooling and heating energy use for a single-family new residence in **Sacramento, CA**. Dark roof α is 90%. Savings (penalties) are calculated for decreasing α from 0.9 to 0.3 ($\Delta\alpha = 0.6$). To estimate savings (penalties) for other $\Delta\alpha$ multiply savings (penalties) in this table by the ratio of $\Delta\alpha/0.6$. Total percent savings are calculated relative to dark roof electricity use in $/ft^2.

duct / attic insulation	gas furnace							electric heat pump				
	electricity [kWh/ft^2]		gas [therms/ft^2]		total [$/ft^2]			electricity [kWh/ft^2]		total [$/ft^2]		
R-value	dark roof	svgs Δ	dark roof	svgs Δ	dark roof	svgs Δ	%	dark roof	svgs Δ	dark roof	svgs Δ	%
R-1 attic												
R-1	2.95	1.47	0.464	-0.048	0.533	0.090	37	8.55	0.85	0.701	0.070	10
R-7	2.18	0.95	0.357	-0.027	0.403	0.061	34	6.83	0.54	0.560	0.044	8
R-11	2.01	0.84	0.329	-0.022	0.372	0.055	33	6.39	0.49	0.524	0.041	8
R-19	1.84	0.71	0.302	-0.018	0.341	0.048	32	5.93	0.43	0.486	0.035	7
R-30	1.74	0.65	0.285	-0.015	0.321	0.043	30	5.63	0.38	0.462	0.031	7
R-60	1.62	0.57	0.268	-0.013	0.301	0.039	29	5.32	0.34	0.436	0.028	6
R-2 attic												
R-1	2.34	1.09	0.354	-0.034	0.414	0.068	35	6.60	0.67	0.541	0.055	10
R-7	1.58	0.60	0.260	-0.019	0.293	0.038	29	4.92	0.35	0.403	0.028	7
R-11	1.43	0.50	0.238	-0.014	0.267	0.032	27	4.53	0.30	0.371	0.024	6
R-19	1.28	0.40	0.216	-0.012	0.241	0.026	25	4.15	0.24	0.340	0.020	6
R-30	1.20	0.35	0.203	-0.009	0.226	0.023	23	3.90	0.20	0.320	0.016	5
R-60	1.10	0.29	0.190	-0.007	0.210	0.019	21	3.66	0.17	0.300	0.014	5
R-4 attic												
R-1	2.06	0.92	0.309	-0.030	0.364	0.057	34	5.74	0.58	0.471	0.048	10
R-7	1.33	0.45	0.223	-0.015	0.249	0.028	26	4.12	0.26	0.338	0.021	6
R-11	1.19	0.36	0.203	-0.011	0.225	0.022	23	3.76	0.21	0.309	0.018	6
R-19	1.06	0.27	0.183	-0.009	0.202	0.017	20	3.42	0.16	0.280	0.013	5
R-30	0.98	0.23	0.172	-0.007	0.188	0.014	17	3.20	0.13	0.263	0.011	4
R-60	0.90	0.18	0.160	-0.006	0.175	0.012	16	2.99	0.10	0.245	0.008	3
R-6 attic												
R-1	1.98	0.87	0.296	-0.028	0.349	0.054	33	5.48	0.55	0.449	0.044	10
R-7	1.25	0.40	0.212	-0.014	0.236	0.024	23	3.88	0.23	0.319	0.019	6
R-11	1.12	0.32	0.193	-0.010	0.213	0.020	22	3.54	0.19	0.290	0.015	5
R-19	1.00	0.24	0.174	-0.008	0.191	0.014	17	3.21	0.14	0.263	0.012	5
R-30	0.92	0.20	0.163	-0.006	0.178	0.012	16	3.00	0.11	0.246	0.009	4
R-60	0.85	0.15	0.152	-0.005	0.165	0.009	13	2.80	0.08	0.229	0.006	3
R-8 attic												
R-1	1.94	0.85	0.290	-0.028	0.342	0.053	33	5.36	0.53	0.439	0.043	10
R-7	1.22	0.38	0.207	-0.013	0.230	0.023	23	3.77	0.22	0.310	0.018	6
R-11	1.09	0.30	0.188	-0.010	0.207	0.018	20	3.43	0.17	0.282	0.015	5
R-19	0.97	0.22	0.170	-0.007	0.186	0.013	16	3.11	0.13	0.255	0.011	4
R-30	0.90	0.18	0.159	-0.006	0.173	0.011	15	2.91	0.10	0.238	0.008	3
R-60	0.82	0.14	0.148	-0.005	0.160	0.008	12	2.71	0.08	0.222	0.006	3
R-1 cond.												
R-1	1.84	0.78	0.273	-0.025	0.322	0.048	32	5.01	0.49	0.411	0.041	10
R-7	1.13	0.33	0.193	-0.012	0.214	0.020	22	3.47	0.19	0.285	0.016	6
R-11	1.01	0.26	0.175	-0.009	0.192	0.015	18	3.15	0.15	0.258	0.012	5
R-19	0.89	0.18	0.157	-0.007	0.172	0.011	15	2.84	0.10	0.233	0.009	4
R-30	0.82	0.14	0.147	-0.006	0.160	0.009	13	2.65	0.08	0.217	0.006	3
R-60	0.75	0.11	0.137	-0.004	0.148	0.006	10	2.47	0.06	0.202	0.004	2

Table 3.15. Simulated impact of roof surface solar absorptance (α) and duct / attic insulation on annual cooling and heating energy use for a single-family new residence in **Salt Lake City, UT**. Dark roof α is 90%. Savings (penalties) are calculated for decreasing α from 0.9 to 0.3 ($\Delta\alpha = 0.6$). To estimate savings (penalties) for other $\Delta\alpha$ multiply savings (penalties) in this table by the ratio of $\Delta\alpha/0.6$. Total percent savings are calculated relative to dark roof electricity use in $/ft^2.

duct / attic insulation	gas furnace							electric heat pump				
	electricity [kWh/ft^2]		gas [therms/ft^2]		total [$/ft^2]			electricity [kWh/ft^2]		total [$/ft^2]		
R-value	dark roof	svgs Δ	dark roof	svgs Δ	dark roof	svgs Δ	%	dark roof	svgs Δ	dark roof	svgs Δ	%
R-1 attic												
R-1	3.07	1.11	1.009	-0.088	0.689	0.034	16	14.23	0.27	0.968	0.018	2
R-7	2.43	0.76	0.862	-0.061	0.576	0.023	14	13.35	-0.03	0.908	-0.002	-0
R-11	2.28	0.68	0.819	-0.054	0.545	0.020	13	13.01	-0.07	0.885	-0.004	-0
R-19	2.14	0.61	0.776	-0.047	0.515	0.019	13	12.65	-0.10	0.860	-0.007	-1
R-30	2.06	0.56	0.749	-0.042	0.496	0.018	13	12.40	-0.12	0.843	-0.008	-1
R-60	1.96	0.51	0.721	-0.037	0.477	0.017	13	12.12	-0.14	0.824	-0.009	-1
R-2 attic												
R-1	2.44	0.83	0.743	-0.060	0.519	0.028	17	11.03	0.27	0.750	0.018	2
R-7	1.79	0.48	0.605	-0.037	0.409	0.015	12	9.79	0.00	0.666	0.001	0
R-11	1.65	0.41	0.568	-0.031	0.382	0.012	11	9.42	-0.03	0.640	-0.002	-0
R-19	1.52	0.34	0.532	-0.025	0.357	0.011	11	9.04	-0.06	0.614	-0.004	-1
R-30	1.44	0.29	0.510	-0.022	0.341	0.010	10	8.79	-0.08	0.597	-0.006	-1
R-60	1.36	0.25	0.488	-0.018	0.325	0.008	9	8.52	-0.09	0.579	-0.006	-1
R-4 attic												
R-1	2.15	0.69	0.632	-0.049	0.447	0.024	16	9.53	0.27	0.648	0.018	3
R-7	1.51	0.34	0.501	-0.028	0.341	0.010	10	8.15	0.01	0.554	0.001	0
R-11	1.38	0.28	0.467	-0.023	0.316	0.008	9	7.77	-0.01	0.528	-0.001	-0
R-19	1.26	0.22	0.435	-0.018	0.293	0.006	7	7.39	-0.03	0.503	-0.002	-0
R-30	1.19	0.18	0.415	-0.015	0.279	0.005	6	7.15	-0.05	0.486	-0.004	-1
R-60	1.12	0.15	0.396	-0.012	0.265	0.004	5	6.89	-0.06	0.469	-0.004	-1
R-6 attic												
R-1	2.06	0.65	0.600	-0.045	0.426	0.023	16	9.05	0.26	0.615	0.018	3
R-7	1.43	0.31	0.471	-0.025	0.321	0.008	8	7.64	0.02	0.519	0.001	0
R-11	1.30	0.24	0.438	-0.021	0.297	0.006	7	7.26	-0.01	0.493	-0.001	-0
R-19	1.19	0.18	0.407	-0.016	0.275	0.005	6	6.88	-0.02	0.468	-0.002	-0
R-30	1.12	0.15	0.388	-0.014	0.261	0.004	5	6.64	-0.04	0.452	-0.002	-0
R-60	1.06	0.12	0.370	-0.011	0.248	0.003	4	6.39	-0.05	0.435	-0.003	-1
R-8 attic												
R-1	2.02	0.63	0.584	-0.044	0.415	0.021	15	8.81	0.26	0.599	0.018	3
R-7	1.39	0.29	0.457	-0.024	0.312	0.008	8	7.39	0.02	0.503	0.002	0
R-11	1.27	0.23	0.425	-0.019	0.288	0.005	6	7.01	-0.00	0.477	0.000	0
R-19	1.16	0.17	0.394	-0.015	0.266	0.004	5	6.64	-0.02	0.451	-0.002	-0
R-30	1.09	0.14	0.376	-0.012	0.253	0.003	4	6.40	-0.04	0.435	-0.003	-1
R-60	1.03	0.11	0.358	-0.010	0.240	0.002	3	6.16	-0.04	0.419	-0.002	-0
R-1 cond.												
R-1	1.90	0.57	0.541	-0.040	0.387	0.020	15	8.14	0.26	0.553	0.018	3
R-7	1.29	0.24	0.418	-0.022	0.287	0.006	7	6.69	0.04	0.455	0.003	1
R-11	1.17	0.18	0.388	-0.017	0.265	0.005	6	6.31	0.02	0.429	0.001	0
R-19	1.07	0.13	0.359	-0.013	0.244	0.003	4	5.95	0.00	0.405	0.000	0
R-30	1.01	0.10	0.342	-0.011	0.231	0.002	3	5.72	-0.01	0.389	-0.001	-0
R-60	0.95	0.07	0.325	-0.008	0.219	0.001	2	5.49	-0.02	0.374	-0.001	-0

Table 3.16. Simulated impact of roof surface solar absorptance (α) and duct / attic insulation on annual cooling and heating energy use for a single-family new residence in **Sterling, VA**. Dark roof α is 90%. Savings (penalties) are calculated for decreasing α from 0.9 to 0.3 ($\Delta\alpha$ = 0.6). To estimate savings (penalties) for other $\Delta\alpha$ multiply savings (penalties) in this table by the ratio of $\Delta\alpha$/0.6. Total percent savings are calculated relative to dark roof electricity use in $/ft^2.

duct / attic insulation	gas furnace							electric heat pump				
	electricity [kWh/ft^2]		gas [therms/ft^2]		total [$/ft^2]			electricity [kWh/ft^2]		total [$/ft^2]		
R-value	dark roof	svgs Δ	dark roof	svgs Δ	dark roof	svgs Δ	%	dark roof	svgs Δ	dark roof	svgs Δ	%
R-1 attic												
R-1	2.72	1.07	0.989	-0.078	0.932	0.033	15	13.71	0.37	1.138	0.030	3
R-7	2.12	0.69	0.854	-0.055	0.786	0.019	11	12.65	0.05	1.050	0.004	0
R-11	1.99	0.61	0.814	-0.049	0.747	0.016	10	12.29	0.00	1.020	0.000	0
R-19	1.86	0.53	0.775	-0.042	0.708	0.014	9	11.90	-0.04	0.988	-0.003	-0
R-30	1.77	0.47	0.750	-0.038	0.683	0.013	9	11.64	-0.06	0.966	-0.005	-1
R-60	1.69	0.43	0.725	-0.034	0.658	0.012	9	11.36	-0.08	0.943	-0.006	-1
R-2 attic												
R-1	2.17	0.80	0.730	-0.053	0.702	0.028	16	10.77	0.32	0.894	0.027	3
R-7	1.59	0.43	0.599	-0.033	0.560	0.012	9	9.42	0.04	0.782	0.003	0
R-11	1.47	0.36	0.564	-0.028	0.525	0.010	8	9.03	0.00	0.750	0.001	0
R-19	1.36	0.29	0.531	-0.022	0.492	0.008	7	8.64	-0.03	0.717	-0.002	-0
R-30	1.29	0.25	0.510	-0.019	0.471	0.007	7	8.39	-0.04	0.696	-0.003	-0
R-60	1.23	0.22	0.489	-0.017	0.451	0.006	6	8.12	-0.05	0.674	-0.004	-1
R-4 attic												
R-1	1.94	0.67	0.619	-0.042	0.603	0.026	16	9.40	0.31	0.780	0.025	3
R-7	1.38	0.33	0.493	-0.024	0.466	0.010	9	7.95	0.05	0.660	0.004	1
R-11	1.27	0.27	0.461	-0.019	0.434	0.008	8	7.56	0.02	0.628	0.002	0
R-19	1.17	0.21	0.430	-0.016	0.404	0.006	6	7.18	0.00	0.596	0.000	0
R-30	1.11	0.17	0.411	-0.013	0.385	0.004	4	6.94	-0.01	0.576	-0.001	-0
R-60	1.05	0.14	0.393	-0.011	0.368	0.004	5	6.69	-0.02	0.555	-0.002	-0
R-6 attic												
R-1	1.87	0.64	0.586	-0.039	0.574	0.026	17	8.97	0.30	0.744	0.025	3
R-7	1.31	0.30	0.462	-0.022	0.439	0.009	8	7.50	0.05	0.622	0.004	1
R-11	1.21	0.24	0.431	-0.017	0.408	0.007	7	7.11	0.03	0.590	0.002	0
R-19	1.11	0.18	0.401	-0.014	0.379	0.005	5	6.73	0.01	0.559	0.001	0
R-30	1.05	0.15	0.383	-0.011	0.361	0.004	5	6.50	0.00	0.539	0.000	0
R-60	1.00	0.12	0.366	-0.009	0.344	0.003	4	6.25	-0.01	0.519	-0.001	-0
R-8 attic												
R-1	1.84	0.62	0.570	-0.038	0.560	0.025	16	8.75	0.30	0.727	0.026	4
R-7	1.29	0.28	0.447	-0.021	0.426	0.009	8	7.28	0.06	0.604	0.005	1
R-11	1.19	0.23	0.417	-0.016	0.396	0.007	7	6.89	0.03	0.572	0.003	1
R-19	1.09	0.17	0.388	-0.012	0.367	0.005	6	6.52	0.01	0.541	0.001	0
R-30	1.03	0.14	0.370	-0.011	0.350	0.004	5	6.28	0.01	0.522	0.001	0
R-60	0.98	0.11	0.353	-0.008	0.333	0.003	4	6.05	-0.00	0.502	0.000	0
R-1 cond.												
R-1	1.74	0.57	0.526	-0.034	0.520	0.023	16	8.15	0.31	0.676	0.025	4
R-7	1.21	0.25	0.408	-0.018	0.391	0.008	8	6.66	0.07	0.553	0.006	1
R-11	1.11	0.19	0.379	-0.014	0.362	0.005	5	6.28	0.05	0.521	0.003	1
R-19	1.02	0.14	0.351	-0.011	0.335	0.004	5	5.92	0.03	0.491	0.002	0
R-30	0.96	0.11	0.335	-0.008	0.319	0.003	4	5.69	0.02	0.473	0.002	0
R-60	0.92	0.09	0.319	-0.006	0.304	0.003	4	5.47	0.01	0.454	0.001	0

Table 3.17. Simulated impact of roof surface solar absorptance (α) and duct / attic insulation on annual cooling and heating energy use for a single-family new residence in **Tampa, FL**. Dark roof α is 90%. Savings (penalties) are calculated for decreasing α from 0.9 to 0.3 ($\Delta\alpha$ = 0.6). To estimate savings (penalties) for other $\Delta\alpha$ multiply savings (penalties) in this table by the ratio of $\Delta\alpha$/0.6. Total percent savings are calculated relative to dark roof electricity use in $/ft^2.

duct / attic insulation	gas furnace							electric heat pump				
	electricity [kWh/ft^2]		gas [therms/ft^2]		total [$/ft^2]			electricity [kWh/ft^2]		total [$/ft^2]		
R-value	dark roof	svgs Δ	dark roof	svgs Δ	dark roof	svgs Δ	%	dark roof	svgs Δ	dark roof	svgs Δ	%
R-1 attic												
R-1	6.19	2.31	0.113	-0.011	0.507	0.160	36	7.49	2.17	0.539	0.156	29
R-7	5.37	1.63	0.080	-0.005	0.430	0.115	30	6.36	1.57	0.458	0.113	25
R-11	5.21	1.50	0.072	-0.003	0.414	0.105	28	6.11	1.44	0.440	0.104	24
R-19	5.05	1.36	0.064	-0.003	0.399	0.097	27	5.87	1.32	0.423	0.096	23
R-30	4.96	1.28	0.059	-0.003	0.389	0.090	25	5.72	1.24	0.412	0.089	22
R-60	4.85	1.18	0.055	-0.001	0.379	0.084	24	5.56	1.15	0.400	0.082	20
R-2 attic												
R-1	5.00	1.73	0.084	-0.008	0.406	0.120	33	5.98	1.63	0.430	0.117	27
R-7	4.08	1.02	0.057	-0.003	0.325	0.072	24	4.78	0.98	0.344	0.070	20
R-11	3.91	0.88	0.050	-0.003	0.309	0.062	22	4.54	0.85	0.327	0.061	19
R-19	3.75	0.76	0.045	-0.001	0.295	0.054	20	4.32	0.73	0.311	0.053	17
R-30	3.66	0.67	0.041	-0.001	0.286	0.048	18	4.18	0.65	0.301	0.047	16
R-60	3.56	0.59	0.038	-0.001	0.277	0.042	16	4.05	0.57	0.291	0.041	14
R-4 attic												
R-1	4.46	1.44	0.073	-0.007	0.361	0.100	31	5.30	1.36	0.382	0.098	26
R-7	3.53	0.74	0.048	-0.002	0.280	0.052	20	4.11	0.71	0.296	0.052	18
R-11	3.37	0.62	0.042	-0.002	0.265	0.043	18	3.88	0.59	0.280	0.043	15
R-19	3.22	0.50	0.037	-0.001	0.252	0.035	15	3.68	0.48	0.265	0.035	13
R-30	3.13	0.43	0.034	-0.001	0.244	0.030	13	3.56	0.41	0.256	0.029	11
R-60	3.05	0.35	0.031	-0.001	0.237	0.025	11	3.44	0.34	0.248	0.025	10
R-6 attic												
R-1	4.30	1.35	0.070	-0.006	0.348	0.095	31	5.10	1.28	0.367	0.092	25
R-7	3.37	0.66	0.045	-0.003	0.267	0.046	19	3.91	0.64	0.282	0.046	16
R-11	3.21	0.54	0.040	-0.002	0.253	0.038	16	3.69	0.52	0.266	0.037	14
R-19	3.06	0.43	0.035	-0.001	0.240	0.031	14	3.50	0.41	0.252	0.030	12
R-30	2.98	0.36	0.032	-0.001	0.232	0.025	12	3.38	0.35	0.243	0.025	10
R-60	2.90	0.29	0.029	-0.001	0.225	0.020	10	3.27	0.28	0.235	0.020	8
R-8 attic												
R-1	4.22	1.31	0.068	-0.006	0.341	0.091	30	5.00	1.24	0.360	0.090	25
R-7	3.29	0.63	0.044	-0.002	0.261	0.044	19	3.82	0.60	0.275	0.043	16
R-11	3.13	0.51	0.039	-0.001	0.247	0.036	16	3.60	0.48	0.259	0.034	13
R-19	2.99	0.40	0.034	-0.001	0.234	0.028	13	3.41	0.38	0.245	0.027	11
R-30	2.91	0.33	0.031	-0.001	0.227	0.023	11	3.30	0.32	0.237	0.022	9
R-60	2.83	0.26	0.028	-0.001	0.220	0.019	9	3.19	0.25	0.229	0.018	8
R-1 cond.												
R-1	4.00	1.20	0.063	-0.006	0.323	0.084	29	4.72	1.14	0.340	0.082	24
R-7	3.08	0.53	0.041	-0.002	0.244	0.037	17	3.56	0.51	0.257	0.037	14
R-11	2.93	0.41	0.036	-0.001	0.230	0.028	13	3.36	0.39	0.242	0.029	12
R-19	2.79	0.31	0.031	-0.001	0.218	0.022	11	3.17	0.30	0.229	0.022	10
R-30	2.72	0.25	0.029	-0.001	0.211	0.017	9	3.07	0.24	0.221	0.017	8
R-60	2.65	0.18	0.026	-0.001	0.205	0.013	7	2.97	0.18	0.214	0.013	6

Table 3.18. Simulated impact of roof surface solar absorptance (α) and duct / attic insulation on annual cooling and heating energy use for a single-family new residence in **Tucson, AZ**. Dark roof α is 90%. Savings (penalties) are calculated for decreasing α from 0.9 to 0.3 ($\Delta\alpha$ = 0.6). To estimate savings (penalties) for other $\Delta\alpha$ multiply savings (penalties) in this table by the ratio of $\Delta\alpha$/0.6. Total percent savings are calculated relative to dark roof electricity use in $/ft^2.

duct / attic insulation	gas furnace							electric heat pump				
	electricity [kWh/ft^2]		gas [therms/ft^2]		total [$/ft^2]			electricity [kWh/ft^2]		total [$/ft^2]		
R-value	dark roof	svgs Δ	dark roof	svgs Δ	dark roof	svgs Δ	%	dark roof	svgs Δ	dark roof	svgs Δ	%
R-1 attic												
R-1	6.45	2.41	0.237	-0.020	0.790	0.211	35	9.46	2.15	0.889	0.203	23
R-7	5.27	1.64	0.171	-0.009	0.628	0.148	30	7.63	1.50	0.717	0.141	20
R-11	5.02	1.48	0.154	-0.008	0.592	0.133	28	7.21	1.37	0.678	0.129	19
R-19	4.80	1.34	0.139	-0.005	0.559	0.122	27	6.80	1.25	0.640	0.118	18
R-30	4.65	1.24	0.130	-0.004	0.538	0.113	26	6.54	1.16	0.615	0.109	18
R-60	4.48	1.12	0.120	-0.004	0.514	0.103	24	6.26	1.06	0.588	0.099	17
R-2 attic												
R-1	5.25	1.84	0.184	-0.015	0.636	0.162	33	7.56	1.66	0.711	0.156	22
R-7	3.99	1.05	0.127	-0.007	0.474	0.093	25	5.72	0.96	0.538	0.090	17
R-11	3.75	0.89	0.114	-0.006	0.442	0.080	23	5.33	0.82	0.501	0.077	15
R-19	3.53	0.75	0.102	-0.004	0.411	0.068	21	4.96	0.70	0.466	0.065	14
R-30	3.39	0.66	0.095	-0.003	0.392	0.059	19	4.73	0.61	0.445	0.058	13
R-60	3.24	0.56	0.088	-0.002	0.373	0.052	17	4.49	0.52	0.422	0.049	12
R-4 attic												
R-1	4.71	1.57	0.162	-0.013	0.568	0.137	31	6.72	1.41	0.631	0.133	21
R-7	3.44	0.78	0.111	-0.005	0.410	0.069	21	4.90	0.70	0.461	0.066	14
R-11	3.21	0.63	0.099	-0.004	0.379	0.056	19	4.54	0.57	0.427	0.054	13
R-19	3.00	0.50	0.088	-0.003	0.351	0.045	16	4.20	0.46	0.395	0.043	11
R-30	2.88	0.42	0.082	-0.002	0.334	0.038	14	4.00	0.39	0.376	0.037	10
R-60	2.75	0.34	0.075	-0.002	0.316	0.030	12	3.78	0.31	0.356	0.029	8
R-6 attic												
R-1	4.54	1.48	0.156	-0.012	0.547	0.129	30	6.45	1.33	0.607	0.126	21
R-7	3.28	0.70	0.106	-0.005	0.391	0.062	20	4.66	0.63	0.438	0.059	13
R-11	3.06	0.55	0.094	-0.005	0.361	0.049	17	4.31	0.51	0.405	0.047	12
R-19	2.85	0.43	0.084	-0.003	0.334	0.039	15	3.98	0.40	0.374	0.037	10
R-30	2.73	0.36	0.078	-0.002	0.317	0.031	12	3.79	0.32	0.356	0.031	9
R-60	2.61	0.28	0.072	-0.001	0.301	0.025	10	3.58	0.25	0.337	0.024	7
R-8 attic												
R-1	4.45	1.44	0.153	-0.012	0.537	0.125	30	6.33	1.29	0.595	0.122	21
R-7	3.21	0.66	0.103	-0.006	0.382	0.058	19	4.55	0.60	0.428	0.056	13
R-11	2.98	0.52	0.092	-0.004	0.352	0.045	16	4.20	0.47	0.395	0.044	11
R-19	2.78	0.40	0.082	-0.003	0.325	0.035	13	3.88	0.37	0.365	0.035	10
R-30	2.67	0.33	0.076	-0.002	0.310	0.030	12	3.69	0.30	0.347	0.028	8
R-60	2.54	0.25	0.070	-0.002	0.293	0.022	9	3.49	0.23	0.328	0.021	6
R-1 cond.												
R-1	4.23	1.32	0.144	-0.012	0.509	0.115	29	5.98	1.19	0.562	0.112	20
R-7	3.00	0.57	0.097	-0.005	0.357	0.049	17	4.24	0.51	0.399	0.048	12
R-11	2.79	0.43	0.086	-0.004	0.329	0.038	15	3.91	0.39	0.367	0.036	10
R-19	2.60	0.32	0.077	-0.002	0.304	0.029	12	3.60	0.29	0.339	0.028	8
R-30	2.48	0.25	0.071	-0.002	0.289	0.023	10	3.42	0.23	0.321	0.021	7
R-60	2.37	0.18	0.065	-0.002	0.273	0.016	7	3.23	0.16	0.304	0.015	5

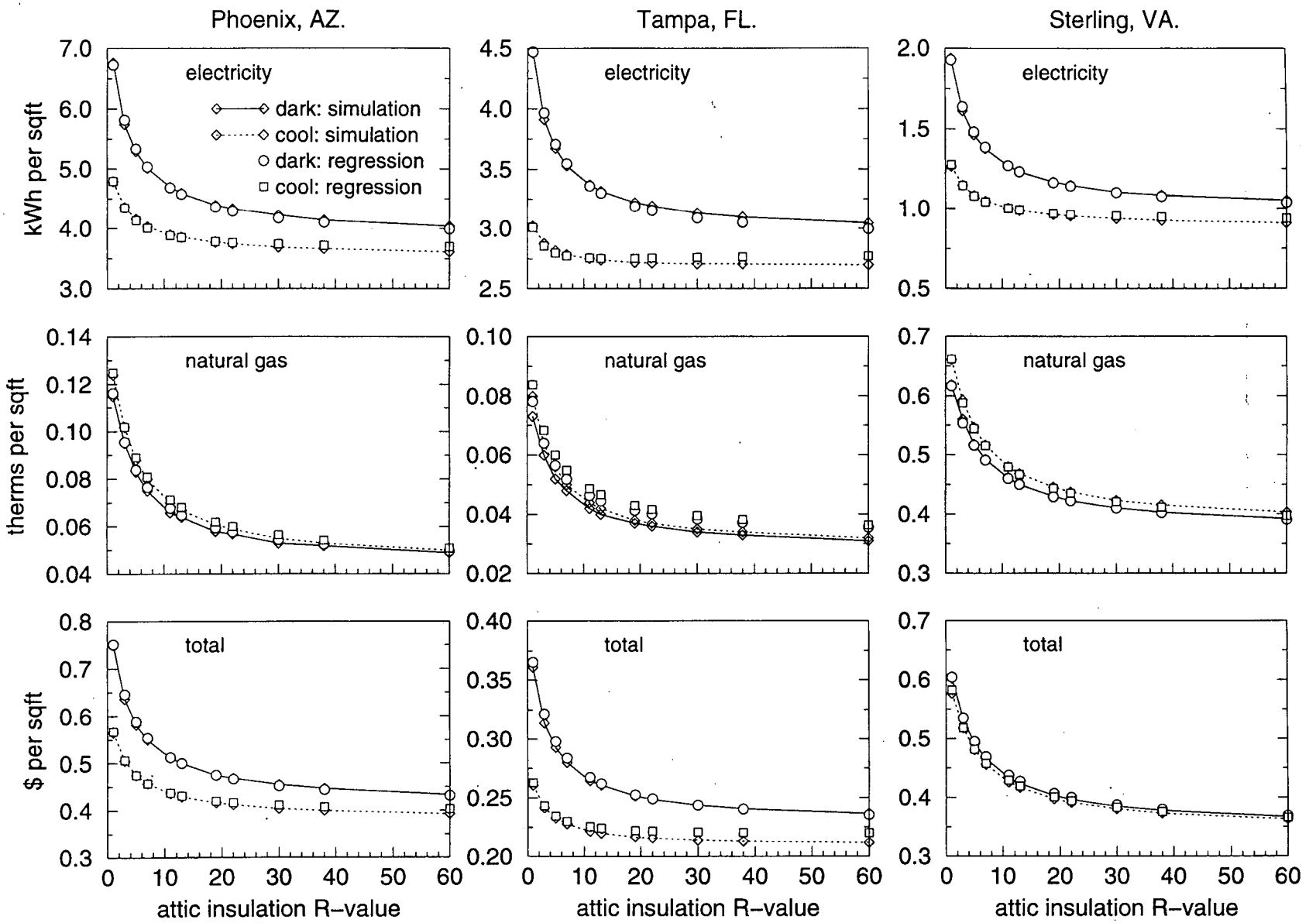

Figure 3.1. Simulation and regression estimates of annual cooling and heating energy use for a new residence with a gas furnace and R–4 attic ducts in Phoenix, Tampa, and Sterling. Electricity, gas and total energy use per sqft are presented for dark (albedo 0.1) and cool (albedo 0.7) roofs vs. attic insulation R–values of 1, 3, 5, 7, 11, 13, 19, 22, 30, 38, and 60.

3.2 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,

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

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_i are regression parameter estimates. The conductance is related to the attic insulation R-value through equation 2[5],

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

where, 0.011 is frame resistance[6] inverted [Btu/h·ft^2·°F], 0.85 is the cavity fraction, 4.8 is the cavity resistance[7] [h·ft^2·°F/Btu] excluding insulation, and R is the attic insulation R-value [h·ft^2·°F/Btu]. The roof system resistance by layer for the frame and cavity sections is illustrated in **Figure 3.2**.

Linear regressions using eq. 1 were completed for sets of electricity, gas, and total energy use by heating system, duct- insulation level / location, and climate. The parameter estimates (C_0, C_1, C_2, and C_3) are shown in **Tables 3.19** and **3.20** for gas and electric heated residences, respectively. The regression statistics (σ: standard deviation of the error and R^2) are listed in **Table B.1**. The R^2 values for this curve-fit ranged from 0.97 to 1.00 for all data sets analyzed except for the uninsulated attic duct case, where R^2 ranged from 0.91 to 1.00. **Figure 3.1** 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.

3.3 Equivalent Cool-Roof 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 condition of a zero net change in annual cooling and heating energy use ($\Delta E=0$) from a dark to cool roof was applied to eq. 1. Then, an equivalent change in roof-system conductance (ΔU) was found from the solution of equation 3,

$$C_2 \Delta U^2 + (C_1 + 2 C_2 U_1 + C_3 \alpha_2) \Delta U + C_3 U_1 \Delta\alpha = 0 \quad [3]$$

Finally, by rearranging eq. 2 the equivalent cool-roof attic insulation R-values (R_2) were determined and are reported in **Table. 3.21**. These R_2 were based on total ($) energy use and a dark-roof absorptance of 0.9 and a cool-roof absorptance of 0.3. Reductions in R-value were observed in varying degrees for residences with both gas and electric heat, all duct configurations, and all climates. The highest impact for a residence with R-30 attic insulation and R-4 attic ducts was in Tampa with a gas heating system, where the attic insulation R-value decreased to 3 (4 w/ heat pump), followed by Phoenix 8 (9), Houston 8 (11), Austin 8 (12), Tucson 9 (11), Long Beach 9 (16), Fort Worth 13 (16), Las Vegas 15 (15), Atlanta 16 (19), Albuquerque 17 (23), Sacramento 18 (22), Raleigh 21 (22), Nashville 23 (23), Lexington 25 (25), Salt Lake City 25 (28), and Sterling 26 (28).

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[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, 1/2" 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.

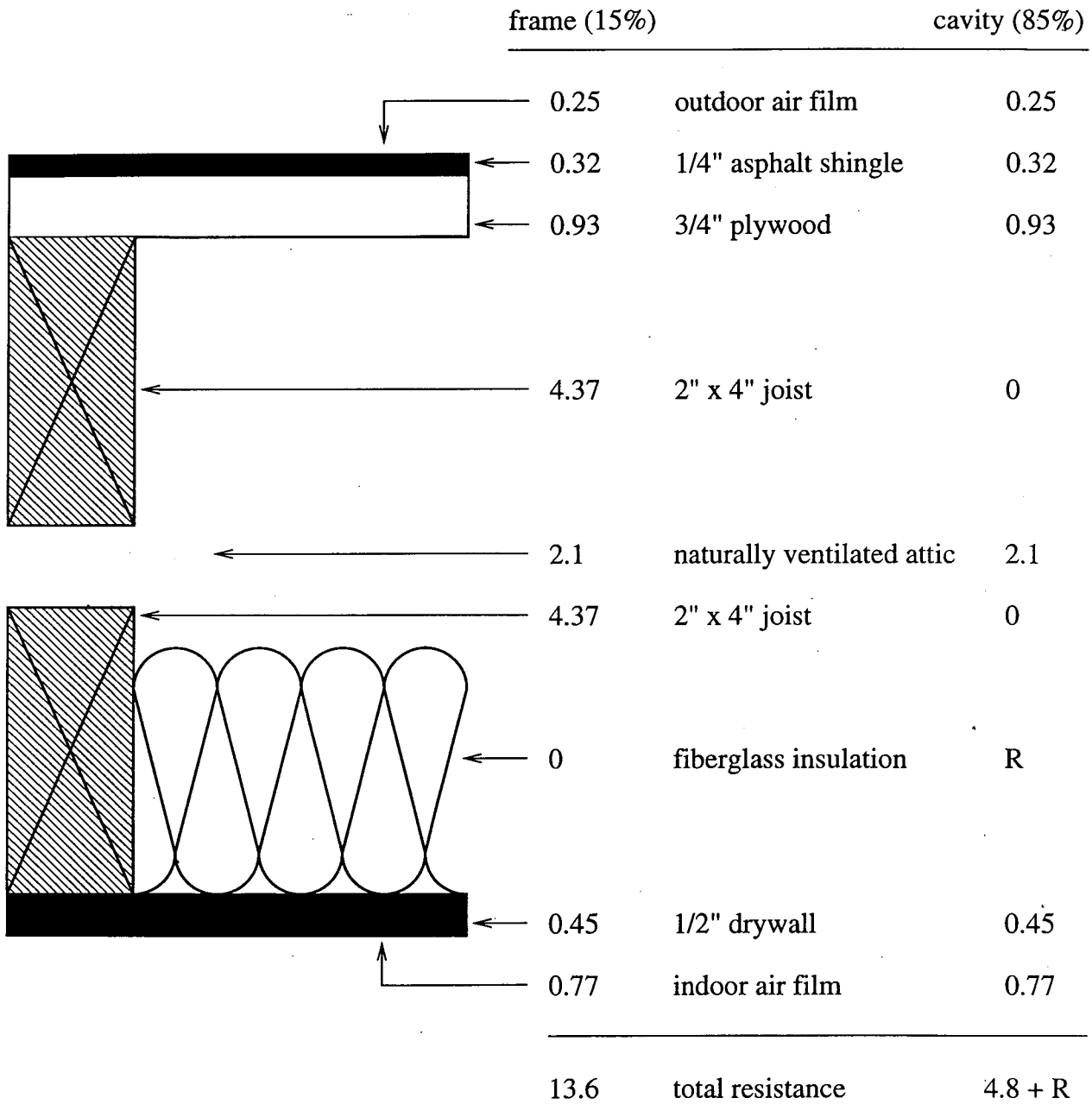

Figure 3.2. Roof system resistance by layer for frame and cavity sections [hr sqft F/Btu].

Table 3.19. Parameter estimates from regressions of annual cooling and heating energy use (E) versus roof system conductance (U in Btu/h·ft^2·°F) and roof surface solar absorptance (α for $0<\alpha<1$) for a single-family new residence with a **gas furnace**. (Duct configurations: uninsulated attic ducts R-1, insulated attic ducts R-2, R-4, R-6, and R-8, and uninsulated conditioned zone ducts R-1C).

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

climate	electricity [kWh/ft^2]				gas [therms/ft^2]				total [$/ft^2]			
	C_0	C_1	C_2	C_3	C_0	C_1	C_2	C_3	C_0	C_1	C_2	C_3
Albuquerque, NM												
R-1	1.65	-6.77	2.58	22.70	0.47	3.18	-2.97	-0.99	0.42	1.14	-1.40	1.60
R-2	1.13	-3.70	10.27	14.69	0.30	2.27	-0.88	-0.63	0.28	0.92	0.51	1.04
R-4	0.94	-2.56	14.03	11.07	0.24	1.89	-0.12	-0.50	0.22	0.81	1.31	0.78
R-6	0.89	-2.24	14.99	9.98	0.22	1.77	0.14	-0.45	0.21	0.78	1.49	0.69
R-8	0.86	-2.12	15.53	9.49	0.21	1.71	0.22	-0.43	0.20	0.78	1.50	0.65
R-1C	0.80	-1.79	16.65	8.18	0.19	1.57	0.42	-0.40	0.18	0.72	1.78	0.55
Atlanta, GA												
R-1	1.86	-7.69	5.83	20.24	0.34	2.08	-1.11	-0.59	0.35	0.67	-0.20	1.20
R-2	1.38	-4.57	11.98	13.04	0.23	1.51	0.11	-0.38	0.24	0.57	0.95	0.78
R-4	1.20	-3.40	14.39	9.98	0.18	1.26	0.62	-0.29	0.20	0.52	1.35	0.60
R-6	1.15	-3.10	15.09	9.11	0.17	1.18	0.69	-0.26	0.19	0.49	1.54	0.54
R-8	1.13	-2.96	15.44	8.70	0.16	1.17	0.67	-0.26	0.19	0.49	1.53	0.51
R-1C	1.07	-2.59	16.08	7.64	0.15	1.06	0.84	-0.23	0.17	0.46	1.67	0.45
Austin, TX												
R-1	3.82	-10.93	11.05	26.17	0.16	1.13	-0.13	-0.29	0.36	-0.23	0.78	1.76
R-2	2.93	-6.34	17.42	17.39	0.11	0.81	0.44	-0.19	0.27	-0.05	1.51	1.17
R-4	2.58	-4.48	20.71	13.22	0.09	0.68	0.59	-0.15	0.23	-0.00	1.92	0.89
R-6	2.48	-4.04	22.09	11.98	0.08	0.63	0.71	-0.14	0.22	0.03	1.93	0.80
R-8	2.43	-3.82	22.62	11.41	0.08	0.63	0.66	-0.14	0.22	0.04	1.97	0.77
R-1C	2.30	-3.27	23.99	9.90	0.07	0.56	0.75	-0.12	0.20	0.05	2.11	0.66
Fort Worth, TX												
R-1	3.26	-9.10	11.11	22.18	0.21	1.50	-0.13	-0.40	0.39	0.24	0.70	1.52
R-2	2.50	-5.16	15.93	14.86	0.14	1.09	0.50	-0.27	0.29	0.28	1.57	1.02
R-4	2.19	-3.59	18.89	11.30	0.12	0.93	0.69	-0.22	0.25	0.30	1.98	0.77
R-6	2.10	-3.22	20.10	10.23	0.11	0.88	0.73	-0.20	0.24	0.30	2.11	0.69
R-8	2.06	-3.04	20.56	9.75	0.11	0.86	0.74	-0.19	0.23	0.30	2.13	0.66
R-1C	1.95	-2.60	21.90	8.45	0.10	0.78	0.89	-0.18	0.22	0.29	2.30	0.56
Houston, TX												
R-1	3.53	-11.07	10.18	24.49	0.14	1.10	-0.40	-0.28	0.37	-0.23	0.57	1.81
R-2	2.71	-6.69	16.39	16.12	0.09	0.79	0.16	-0.18	0.28	-0.07	1.41	1.20
R-4	2.39	-4.99	19.51	12.33	0.08	0.65	0.43	-0.15	0.24	-0.01	1.80	0.92
R-6	2.30	-4.53	20.52	11.20	0.07	0.61	0.50	-0.13	0.23	0.00	1.92	0.83
R-8	2.25	-4.35	21.00	10.68	0.07	0.59	0.49	-0.12	0.22	0.00	2.01	0.79
R-1C	2.13	-3.80	22.10	9.29	0.06	0.53	0.59	-0.11	0.21	0.02	2.11	0.68
Las Vegas, NV												
R-1	4.03	-9.21	18.45	27.76	0.12	1.24	0.38	-0.30	0.37	0.36	1.47	1.63
R-2	3.12	-4.93	26.71	18.62	0.09	0.97	0.60	-0.23	0.28	0.42	2.29	1.06
R-4	2.77	-3.39	30.73	14.55	0.08	0.85	0.76	-0.20	0.25	0.44	2.59	0.82
R-6	2.67	-2.97	31.75	13.36	0.08	0.80	0.83	-0.19	0.24	0.45	2.65	0.75
R-8	2.62	-2.79	32.28	12.80	0.08	0.81	0.76	-0.19	0.24	0.43	2.79	0.71
R-1C	2.49	-2.29	33.41	11.29	0.07	0.77	0.72	-0.18	0.22	0.44	2.86	0.61

Table 3.19(cont). Parameter estimates from regressions of annual cooling and heating energy use (E) versus roof system conductance (U in Btu/h·ft^2·°F) and roof surface solar absorptance (α for $0<\alpha<1$) for a single-family new residence with a **gas furnace**. (Duct configurations: uninsulated attic ducts R-1, insulated attic ducts R-2, R-4, R-6, and R-8, and uninsulated conditioned zone ducts R-1C).

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

climate	electricity [kWh/ft^2]				gas [therms/ft^2]				total [$/ft^2]			
	C_0	C_1	C_2	C_3	C_0	C_1	C_2	C_3	C_0	C_1	C_2	C_3
Lexington, KY												
R-1	1.21	-2.04	-2.95	13.89	0.68	3.75	-4.96	-0.97	0.33	1.40	-2.13	0.29
R-2	0.92	-1.46	5.64	8.99	0.44	2.89	-2.63	-0.61	0.22	1.07	-0.73	0.20
R-4	0.82	-1.33	8.94	6.99	0.35	2.26	-0.79	-0.45	0.18	0.85	0.05	0.17
R-6	0.79	-1.31	9.80	6.42	0.33	2.07	-0.30	-0.39	0.17	0.76	0.37	0.16
R-8	0.77	-1.27	10.03	6.16	0.32	1.98	-0.09	-0.38	0.16	0.72	0.48	0.16
R-1C	0.74	-1.23	10.91	5.45	0.28	1.74	0.42	-0.32	0.15	0.63	0.75	0.14
Long Beach, CA												
R-1	0.68	-5.21	2.55	15.06	0.07	1.08	0.05	-0.24	0.14	0.04	0.33	1.79
R-2	0.47	-3.29	7.57	9.67	0.05	0.74	0.56	-0.17	0.09	0.05	1.35	1.14
R-4	0.40	-2.59	9.49	7.44	0.04	0.61	0.74	-0.14	0.08	0.07	1.71	0.87
R-6	0.38	-2.40	10.01	6.80	0.04	0.57	0.81	-0.13	0.07	0.07	1.74	0.80
R-8	0.37	-2.30	10.16	6.51	0.04	0.56	0.78	-0.13	0.07	0.06	1.82	0.76
R-1C	0.34	-2.04	10.50	5.74	0.03	0.51	0.82	-0.12	0.07	0.06	1.95	0.67
Nashville, TN												
R-1	2.17	-6.61	6.24	19.39	0.47	2.57	-1.97	-0.78	0.44	1.32	-0.86	0.61
R-2	1.66	-3.88	12.41	12.74	0.32	1.93	-0.46	-0.49	0.31	1.07	0.41	0.42
R-4	1.47	-2.87	14.98	9.90	0.25	1.66	0.02	-0.37	0.26	0.93	0.97	0.33
R-6	1.41	-2.61	15.71	9.08	0.24	1.54	0.33	-0.34	0.24	0.89	1.08	0.29
R-8	1.38	-2.48	15.98	8.71	0.23	1.51	0.34	-0.32	0.23	0.87	1.18	0.28
R-1C	1.31	-2.13	16.60	7.71	0.21	1.39	0.52	-0.29	0.21	0.81	1.28	0.25
Phoenix, AZ												
R-1	5.16	-12.56	20.65	38.59	0.06	0.68	0.44	-0.14	0.55	-0.70	2.37	3.68
R-2	4.07	-6.85	32.32	25.84	0.04	0.52	0.64	-0.10	0.43	-0.26	3.63	2.45
R-4	3.65	-4.89	38.11	20.47	0.04	0.47	0.61	-0.09	0.39	-0.12	4.23	1.94
R-6	3.53	-4.36	39.72	18.93	0.04	0.46	0.60	-0.09	0.37	-0.07	4.40	1.78
R-8	3.47	-4.13	40.44	18.22	0.04	0.45	0.61	-0.09	0.37	-0.05	4.40	1.72
R-1C	3.31	-3.52	42.36	16.27	0.03	0.43	0.58	-0.08	0.35	0.00	4.55	1.53
Raleigh, NC												
R-1	1.67	-6.59	5.42	18.02	0.41	2.50	-1.91	-0.75	0.44	1.38	-1.06	0.87
R-2	1.22	-3.91	10.74	11.77	0.26	1.82	-0.43	-0.47	0.30	1.07	0.48	0.59
R-4	1.04	-2.88	13.14	8.99	0.21	1.51	0.22	-0.36	0.24	0.93	1.16	0.45
R-6	1.00	-2.60	13.79	8.18	0.19	1.42	0.41	-0.32	0.22	0.88	1.33	0.41
R-8	0.97	-2.47	14.08	7.80	0.18	1.38	0.43	-0.31	0.22	0.85	1.46	0.39
R-1C	0.91	-2.16	14.83	6.82	0.16	1.25	0.66	-0.27	0.20	0.78	1.69	0.33
Sacramento, CA												
R-1	1.21	-5.51	5.48	18.33	0.23	2.03	-0.50	-0.55	0.25	0.83	0.06	1.16
R-2	0.86	-3.22	11.48	12.08	0.16	1.47	0.48	-0.37	0.17	0.66	1.25	0.76
R-4	0.73	-2.36	14.02	9.38	0.14	1.27	0.75	-0.31	0.15	0.60	1.66	0.58
R-6	0.70	-2.15	14.77	8.60	0.13	1.20	0.83	-0.29	0.14	0.57	1.78	0.52
R-8	0.68	-2.03	14.99	8.25	0.13	1.15	0.98	-0.28	0.13	0.56	1.82	0.50
R-1C	0.64	-1.77	15.79	7.29	0.12	1.08	1.01	-0.26	0.13	0.52	1.96	0.44

Table 3.19(cont). Parameter estimates from regressions of annual cooling and heating energy use (E) versus roof system conductance (U in Btu/h·ft^2·°F) and roof surface solar absorptance (α for $0<\alpha<1$) for a single-family new residence with a **gas furnace**. (Duct configurations: uninsulated attic ducts R-1, insulated attic ducts R-2, R-4, R-6, and R-8, and uninsulated conditioned zone ducts R-1C).

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

climate	electricity [kWh/ft^2]				gas [therms/ft^2]				total [$/ft^2]			
	C_0	C_1	C_2	C_3	C_0	C_1	C_2	C_3	C_0	C_1	C_2	C_3
Salt Lake City, UT												
R-1	1.59	-3.51	4.14	14.55	0.67	3.72	-3.55	-1.16	0.43	1.53	-1.43	0.44
R-2	1.14	-1.55	8.96	9.54	0.44	2.75	-1.24	-0.72	0.29	1.20	0.04	0.30
R-4	0.96	-0.81	11.45	7.20	0.35	2.32	-0.31	-0.56	0.23	1.05	0.65	0.22
R-6	0.92	-0.64	12.20	6.50	0.33	2.19	-0.03	-0.51	0.22	1.00	0.80	0.20
R-8	0.90	-0.54	12.39	6.18	0.32	2.12	0.10	-0.49	0.21	0.98	0.85	0.18
R-1C	0.84	-0.34	13.16	5.32	0.29	1.96	0.34	-0.44	0.19	0.92	1.00	0.15
Sterling, VA												
R-1	1.37	-3.54	4.03	13.45	0.68	3.38	-3.21	-1.04	0.60	2.11	-1.92	0.37
R-2	1.04	-2.02	8.94	8.77	0.44	2.55	-1.10	-0.64	0.40	1.66	-0.05	0.27
R-4	0.92	-1.48	10.70	6.89	0.35	2.15	-0.15	-0.48	0.33	1.41	0.80	0.23
R-6	0.88	-1.32	11.01	6.36	0.33	2.04	0.07	-0.43	0.31	1.34	0.98	0.22
R-8	0.86	-1.24	11.14	6.11	0.31	1.97	0.22	-0.41	0.30	1.30	1.12	0.21
R-1C	0.82	-1.06	11.61	5.44	0.28	1.81	0.46	-0.36	0.27	1.20	1.31	0.19
Tampa, FL												
R-1	4.18	-15.26	11.89	31.27	0.05	0.49	0.28	-0.10	0.33	-0.83	1.00	2.19
R-2	3.20	-9.38	19.57	20.36	0.03	0.34	0.42	-0.08	0.25	-0.48	1.59	1.43
R-4	2.82	-7.17	23.72	15.46	0.03	0.27	0.57	-0.06	0.22	-0.37	2.03	1.08
R-6	2.71	-6.56	24.82	14.02	0.02	0.27	0.49	-0.06	0.21	-0.32	2.03	0.98
R-8	2.65	-6.29	25.35	13.36	0.02	0.26	0.51	-0.05	0.20	-0.33	2.19	0.93
R-1C	2.51	-5.55	26.63	11.58	0.02	0.24	0.46	-0.05	0.19	-0.27	2.20	0.80
Tucson, AZ												
R-1	3.75	-11.83	14.04	31.67	0.10	0.99	0.39	-0.20	0.43	-0.33	1.55	2.82
R-2	2.81	-6.68	22.44	21.13	0.07	0.72	0.77	-0.15	0.32	-0.05	2.59	1.87
R-4	2.45	-4.85	27.27	16.33	0.06	0.64	0.71	-0.13	0.28	0.04	3.12	1.44
R-6	2.35	-4.35	28.58	14.91	0.06	0.61	0.74	-0.12	0.27	0.06	3.27	1.30
R-8	2.31	-4.13	29.12	14.25	0.06	0.58	0.84	-0.12	0.26	0.08	3.29	1.24
R-1C	2.18	-3.54	30.50	12.50	0.05	0.55	0.81	-0.11	0.25	0.10	3.45	1.09

Table 3.20. Parameter estimates from regressions of annual total ($) cooling and heating energy use (E) versus roof system conductance (U in Btu/h·ft^2·°F) and roof surface solar absorptance (α for $0<\alpha<1$) for a single-family new residence with an **electric heat pump**. (Duct configurations: uninsulated attic ducts R-1, insulated attic ducts R-2, R-4, R-6, and R-8, and uninsulated conditioned zone ducts R-1C).

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

climate	R-1				R-2				R-4			
	C_0	C_1	C_2	C_3	C_0	C_1	C_2	C_3	C_0	C_1	C_2	C_3
Albuquerque, NM	0.83	2.27	-6.49	0.80	0.56	1.97	-3.33	0.57	0.43	1.77	-1.83	0.47
Atlanta, GA	0.51	1.02	-2.37	1.01	0.36	0.94	-0.69	0.66	0.29	0.87	0.03	0.51
Austin, TX	0.44	0.12	-0.37	1.64	0.32	0.25	0.72	1.09	0.28	0.30	1.11	0.83
Fort Worth, TX	0.50	0.65	-0.81	1.35	0.36	0.64	0.50	0.92	0.31	0.63	1.06	0.70
Houston, TX	0.45	0.09	-0.51	1.70	0.33	0.21	0.72	1.13	0.28	0.23	1.30	0.86
Las Vegas, NV	0.40	0.53	0.61	1.57	0.30	0.52	1.85	1.05	0.27	0.52	2.26	0.81
Lexington, KY	0.52	1.15	-3.56	0.20	0.37	0.99	-1.89	0.15	0.30	0.85	-1.00	0.14
Long Beach, CA	0.21	0.97	-0.53	1.55	0.14	0.68	1.23	0.99	0.11	0.54	1.96	0.75
Nashville, TN	0.53	1.16	-2.28	0.59	0.38	1.07	-0.82	0.40	0.31	1.00	-0.18	0.33
Phoenix, AZ	0.59	-0.36	1.97	3.61	0.46	0.01	3.42	2.41	0.41	0.09	4.28	1.90
Raleigh, NC	0.58	1.34	-3.36	0.75	0.40	1.20	-1.46	0.51	0.32	1.11	-0.65	0.41
Sacramento, CA	0.37	1.63	-1.85	0.87	0.25	1.25	0.25	0.59	0.21	1.07	1.06	0.46
Salt Lake City, UT	0.79	1.90	-5.15	0.03	0.54	1.72	-3.08	0.06	0.43	1.59	-2.00	0.08
Sterling, VA	0.89	2.26	-5.55	0.15	0.63	2.07	-3.33	0.14	0.51	1.88	-2.03	0.15
Tampa, FL	0.34	-0.67	0.74	2.15	0.26	-0.35	1.45	1.40	0.23	-0.27	1.97	1.06
Tucson, AZ	0.50	0.12	0.54	2.71	0.36	0.29	2.07	1.80	0.31	0.32	2.78	1.39

climate	R-6				R-8				R-1C			
	C_0	C_1	C_2	C_3	C_0	C_1	C_2	C_3	C_0	C_1	C_2	C_3
Albuquerque, NM	0.40	1.69	-1.37	0.43	0.38	1.65	-1.10	0.42	0.33	1.51	-0.47	0.39
Atlanta, GA	0.27	0.83	0.29	0.48	0.26	0.82	0.36	0.45	0.24	0.76	0.68	0.41
Austin, TX	0.26	0.28	1.39	0.76	0.26	0.27	1.53	0.72	0.24	0.28	1.67	0.62
Fort Worth, TX	0.29	0.60	1.32	0.63	0.28	0.59	1.42	0.60	0.26	0.56	1.68	0.52
Houston, TX	0.27	0.22	1.52	0.78	0.26	0.22	1.59	0.75	0.24	0.23	1.68	0.65
Las Vegas, NV	0.26	0.50	2.46	0.74	0.25	0.51	2.48	0.70	0.24	0.49	2.64	0.62
Lexington, KY	0.28	0.81	-0.77	0.14	0.27	0.77	-0.54	0.15	0.24	0.71	-0.23	0.15
Long Beach, CA	0.11	0.53	2.01	0.69	0.10	0.52	2.07	0.65	0.09	0.46	2.23	0.57
Nashville, TN	0.30	0.96	0.04	0.31	0.29	0.94	0.15	0.30	0.26	0.87	0.49	0.28
Phoenix, AZ	0.40	0.12	4.46	1.75	0.39	0.15	4.43	1.68	0.37	0.17	4.68	1.50
Raleigh, NC	0.29	1.05	-0.31	0.38	0.28	1.03	-0.17	0.37	0.25	0.95	0.23	0.34
Sacramento, CA	0.19	1.03	1.23	0.42	0.19	1.01	1.30	0.40	0.17	0.92	1.61	0.36
Salt Lake City, UT	0.40	1.55	-1.74	0.08	0.38	1.53	-1.63	0.09	0.34	1.41	-1.03	0.10
Sterling, VA	0.47	1.82	-1.70	0.16	0.46	1.77	-1.46	0.16	0.41	1.66	-0.93	0.17
Tampa, FL	0.22	-0.23	2.01	0.96	0.21	-0.22	2.05	0.91	0.20	-0.21	2.26	0.79
Tucson, AZ	0.30	0.32	3.05	1.27	0.29	0.32	3.09	1.21	0.27	0.34	3.25	1.05

Table 3.21. Equivalent cool-roof attic insulation R-values (R_2) based on simulated annual total cooling and heating energy use ($) for a single-family new residence with a dark-roof solar absorptance (α_1) of 0.9, a cool-roof solar absorptance (α_2) of 0.3, and dark-roof attic insulation R-values (R_1) of 7, 11, 19, 30, 38, and 60. (Duct configurations: uninsulated attic ducts R-1, insulated attic ducts R-2, R-4, R-6, and R-8, and uninsulated conditioned zone ducts R-1C).

climate	gas furnace						electric heat pump					
$R_1 \rightarrow$	7	11	19	30	38	60	7	11	19	30	38	60
Albuquerque, NM												
R-1	2	4	8	13	17	25	3	7	13	21	27	41
R-2	3	5	10	16	19	29	5	8	14	23	29	44
R-4	4	6	11	17	21	32	5	8	15	23	30	46
R-6	4	6	11	18	22	33	5	8	15	24	30	46
R-8	4	7	12	18	23	34	5	9	15	24	30	46
R-1C	4	7	12	19	24	35	5	9	15	24	30	46
Atlanta, GA												
R-1	2	4	7	12	16	23	1	4	9	15	19	29
R-2	3	5	9	15	19	28	3	6	11	18	23	34
R-4	3	6	11	16	20	30	4	7	12	19	24	37
R-6	4	6	11	17	21	31	4	7	13	20	25	37
R-8	4	6	11	17	21	32	4	7	13	20	25	38
R-1C	4	7	12	18	22	33	4	7	13	20	26	39
Austin, TX												
R-1	0	0	1	3	4	6	0	0	2	5	7	11
R-2	1	2	4	6	8	11	1	3	6	9	12	17
R-4	2	3	6	8	10	15	2	4	7	12	15	21
R-6	2	3	6	9	11	16	2	4	8	12	15	22
R-8	2	4	6	10	12	17	3	4	8	13	16	23
R-1C	2	4	7	11	13	18	3	5	9	14	17	25
Fort Worth, TX												
R-1	1	2	5	8	10	15	1	3	6	11	14	21
R-2	2	4	7	11	14	20	2	5	9	14	18	26
R-4	3	5	9	13	16	24	3	6	10	16	20	30
R-6	3	5	9	14	17	25	4	6	11	17	21	31
R-8	3	5	9	14	17	25	4	6	11	17	21	32
R-1C	3	6	10	15	19	27	4	7	12	18	22	33
Houston, TX												
R-1	0	0	1	2	3	6	0	0	2	4	6	10
R-2	0	2	4	6	7	11	1	2	5	9	11	16
R-4	1	3	5	8	10	14	2	4	7	11	14	20
R-6	2	3	6	9	11	15	2	4	7	12	14	21
R-8	2	3	6	9	11	15	2	4	8	12	15	21
R-1C	2	4	7	10	12	17	3	5	8	13	16	23
Las Vegas, NV												
R-1	1	3	6	10	12	18	1	3	6	10	13	20
R-2	3	5	8	13	16	23	3	5	9	13	17	24
R-4	3	5	10	15	18	27	3	6	10	15	19	28
R-6	3	6	10	15	19	28	3	6	10	16	20	29
R-8	4	6	10	16	19	28	4	6	11	16	20	30
R-1C	4	6	11	17	21	30	4	6	11	17	21	31

Table 3.21(cont). Equivalent cool-roof attic insulation R-values (R_2) based on simulated annual total cooling and heating energy use ($) for a single-family new residence with a dark-roof solar absorptance (α_1) of 0.9, a cool-roof solar absorptance (α_2) of 0.3, and dark-roof attic insulation R-values (R_1) of 7, 11, 19, 30, 38, and 60. (Duct configurations: uninsulated attic ducts R-1, insulated attic ducts R-2, R-4, R-6, and R-8, and uninsulated conditioned zone ducts R-1C).

climate	gas furnace						electric heat pump					
$R_1 \rightarrow$	7	11	19	30	38	60	7	11	19	30	38	60
Lexington, KY												
R-1	5	9	15	24	31	48	5	8	15	25	31	49
R-2	6	9	16	25	32	49	5	9	16	26	32	50
R-4	6	9	16	25	32	49	6	9	16	25	32	50
R-6	6	9	16	25	31	49	6	9	16	25	32	50
R-8	6	9	16	25	31	48	6	9	16	25	31	49
R-1C	6	9	16	25	31	48	6	9	16	25	31	48
Long Beach, CA												
R-1	0	1	3	5	7	10	2	4	8	13	16	24
R-2	1	2	5	8	9	14	3	5	9	15	18	27
R-4	2	3	6	9	11	16	3	6	10	16	19	29
R-6	2	3	6	10	12	17	4	6	10	16	20	30
R-8	2	4	6	10	12	17	4	6	11	17	20	30
R-1C	2	4	7	11	13	18	4	6	11	17	21	31
Nashville, TN												
R-1	4	7	13	21	26	40	3	6	12	19	24	37
R-2	5	8	14	22	28	42	5	8	14	22	27	42
R-4	5	8	15	23	29	44	5	8	14	23	29	44
R-6	5	9	15	23	29	45	5	8	15	23	29	44
R-8	5	9	15	23	29	45	5	8	15	23	29	44
R-1C	5	9	15	24	30	45	5	8	15	23	29	44
Phoenix, AZ												
R-1	0	0	1	2	3	5	0	0	2	4	5	7
R-2	1	2	4	6	7	10	1	2	5	7	9	13
R-4	1	3	5	8	9	13	2	3	6	9	11	16
R-6	2	3	6	8	10	14	2	4	6	10	12	17
R-8	2	3	6	9	11	15	2	4	7	10	12	18
R-1C	2	4	6	10	12	16	2	4	7	11	13	19
Raleigh, NC												
R-1	4	6	12	19	23	36	3	6	11	18	23	36
R-2	4	7	13	20	25	38	4	7	13	21	26	40
R-4	5	8	14	21	27	40	5	8	14	22	28	42
R-6	5	8	14	22	27	41	5	8	14	22	28	43
R-8	5	8	14	22	27	41	5	8	14	22	28	43
R-1C	5	8	14	22	28	42	5	8	14	22	28	43
Sacramento, CA												
R-1	2	4	9	14	18	26	4	7	12	19	24	37
R-2	3	6	10	16	20	30	4	7	13	21	26	40
R-4	4	6	11	18	22	33	5	8	14	22	27	41
R-6	4	7	12	18	23	33	5	8	14	22	28	42
R-8	4	7	12	18	23	34	5	8	14	22	28	43
R-1C	4	7	12	19	23	35	5	8	14	23	28	43

Table 3.21(cont). Equivalent cool-roof attic insulation R-values (R_2) based on simulated annual total cooling and heating energy use ($) for a single-family new residence with a dark-roof solar absorptance (α_1) of 0.9, a cool-roof solar absorptance (α_2) of 0.3, and dark-roof attic insulation R-values (R_1) of 7, 11, 19, 30, 38, and 60. (Duct configurations: uninsulated attic ducts R-1, insulated attic ducts R-2, R-4, R-6, and R-8, and uninsulated conditioned zone ducts R-1C).

climate	**gas furnace**						**electric heat pump**					
$R_1 \rightarrow$	7	11	19	30	38	60	7	11	19	30	38	60
Salt Lake City, UT												
R-1	5	8	15	23	29	45	7	11	19	29	37	59
R-2	5	9	15	24	30	47	7	11	18	29	37	57
R-4	6	9	16	25	32	49	7	10	18	28	36	56
R-6	6	9	16	25	32	49	7	10	18	28	36	56
R-8	6	9	16	26	32	50	6	10	18	28	36	56
R-1C	6	10	17	26	33	51	6	10	18	28	35	55
Sterling, VA												
R-1	6	9	16	25	32	50	6	10	18	28	35	55
R-2	6	9	16	26	33	51	6	10	18	28	35	55
R-4	6	10	17	26	33	51	6	10	17	28	35	55
R-6	6	10	17	26	33	51	6	10	17	27	35	54
R-8	6	10	17	26	33	51	6	10	17	27	35	54
R-1C	6	10	17	26	33	51	6	10	17	27	34	53
Tampa, FL												
R-1	0	0	0	0	0	0	0	0	0	0	0	0
R-2	0	0	0	1	1	2	0	0	1	2	3	4
R-4	0	1	2	3	4	5	0	1	3	4	5	7
R-6	0	1	2	4	4	6	1	2	3	5	6	8
R-8	0	1	3	4	5	6	1	2	3	5	6	8
R-1C	1	2	3	5	6	7	1	2	4	6	7	9
Tucson, AZ												
R-1	0	0	2	3	4	7	0	1	3	6	7	11
R-2	1	2	4	7	8	12	1	3	6	9	11	17
R-4	2	3	6	9	11	15	2	4	7	11	14	20
R-6	2	3	6	10	12	16	2	4	8	12	14	21
R-8	2	4	7	10	12	17	2	4	8	12	15	21
R-1C	2	4	7	11	13	18	3	5	9	13	16	23

Figure 3.3 shows simulation estimates of annual total cooling and heating energy use and equivalent cool-roof attic insulation R-values for a gas heated residence with R-8 attic ducts in Phoenix. For dark-roof insulation R-values of 7, 11, 19, 30, 38, and 60 the cool-roof equivalents are 2, 3, 6, 9, 11, and 15, respectively, which are the values listed in **Table 3.21**. Equivalent cool-roof R-values can be obtained graphically for all simulations in this way with **Figures A.1-16.**

The effect of duct insulation and location on equivalent R-values can be observed in **Table 3.21**. In general, the uninsulated attic duct case was shown to have the largest reduction in R-value, where the smallest reduction was found with the conditioned zone ducts. In the gas heated Tampa residence with a dark-roof attic insulation R-value of 30, the cool-roof equivalent ranged from 0 (for uninsulated attic duct case) to 5 (for uninsulated conditioned zone duct case), in Phoenix and Houston it ranged from 2 to 10, Austin and Tucson 3 to 11, Long Beach 5 to 11, Fort Worth 8 to 15, Las Vegas 10 to 17, Atlanta 12 to 18, Albuquerque 13 to 19, Sacramento 14 to 19, Raleigh 19 to 22, Nashville 21 to 24, Salt Lake City 23 to 26, Lexington 24 to 25, and Sterling 25 to 26. In the heating dominated climates of Lexington and Sterling the effect of duct insulation and location was negligible.

In the cooling dominated climates of Austin, Houston, Long Beach, Phoenix, Tampa, and Tucson there were some cases, listed in **Table 3.22** (and cross-checked graphically), where the equivalent R-value was calculated to be zero. These were predominantly with uninsulated attic ducts and dark-roof attic insulation of R-7 or R-11. In the Tampa residence with uninsulated attic ducts, either gas or electric heat, and all dark-roof attic R-values evaluated, and for those with gas heat, insulated attic ducts (R-2 to R-8), and dark-roof attic insulation of R-7, the annual energy bill would be equal to those with a cool roof and without attic insulation.

Table 3.22. Cases where residences with cool roofs and without attic insulation can replace a dark roof with attic insulation with a zero net change in the annual energy bill.

climate	attic duct R-value	heating system	dark-roof insulation (R_1)
Austin, TX	1 (uninsulated)	gas & electric	7 & 11
Houston, TX	1 (uninsulated) 2	gas & electric gas	7 & 11 7
Long Beach, CA	1 (uninsulated)	gas	7
Phoenix, AZ	1 (uninsulated)	gas & electric	7 & 11
Tampa, FL	1 (uninsulated) 2 4 6 & 8	gas & electric gas & electric gas gas & electric gas	7, 11, 19, 30, 38, & 60 7 & 11 19 7 7
Tucson, AZ	1 (uninsulated)	gas & electric gas	7 11

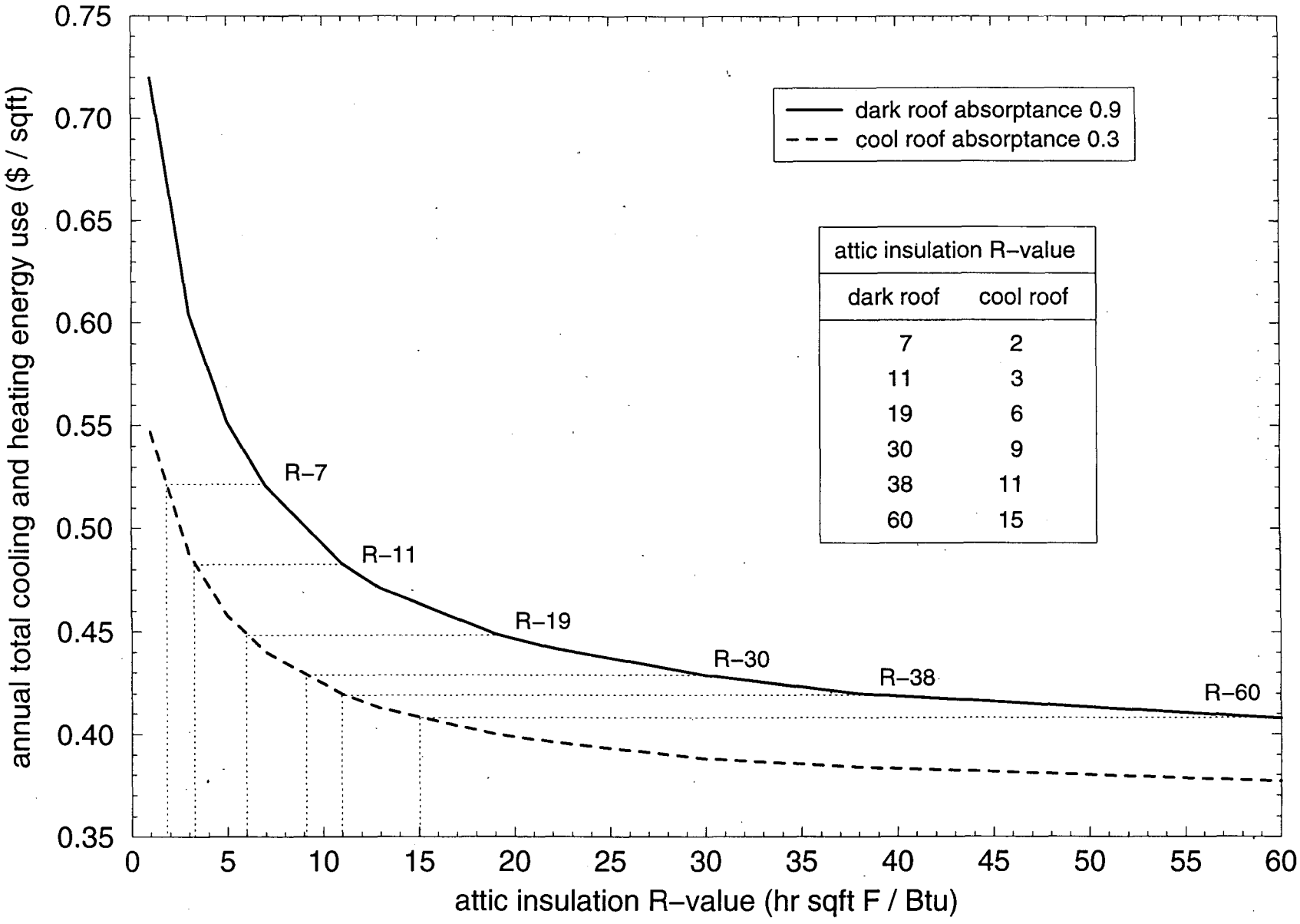

Figure 3.3. Simulation estimates of annual total cooling and heating energy use and equivalent cool–roof attic insulation R–values for a single–family new residence with R–8 attic ducts and a gas furnace in Phoenix, AZ.

4.0 Conclusion

This report summarized a comparative analysis of the impact of roof surface solar absorptance, attic, and duct 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. The objective was to demonstrate that a residence with a cool roof could utilize a lower level of attic insulation than one with a dark roof with a zero net change in annual energy use.

Annual energy use was simulated with DOE-2, which was adapted with a validated residential duct-attic function, for dark and cool roofs and eleven attic insulation R-values ranging from 1 through 60. The simulations were then regressed as a function of roof system conductance and roof solar absorptance for each heating system, duct- insulation level / location, and climate. From the regressions an equivalent change in conductance was calculated for a given change in absorptance under the condition of equal dark- and cool-roof annual energy costs. Finally, equivalent attic insulation R-values were found from the conductance of the cool roof. Highlighted below are the major findings of the study, which are based on a dark-roof absorptance of 0.9 and a cool-roof absorptance of 0.3 [8].

- Annual savings in total dollars were observed in all but a few simulations, with the highest of 28.2 ¢/ft^2 in the gas heated Phoenix residence with R-1 attic insulation and uninsulated attic ducts. This residence also had savings of 16.0 ¢/ft^2 (uninsulated conditioned zone ducts and R-1 attic insulation), 12.8 ¢/ft^2 (uninsulated attic ducts and R-60 attic insulation), and 2.3 ¢/ft^2 (uninsulated conditioned zone ducts and R-60 attic insulation). Those with small deficits were some electric heated residences in Lexington (-0.1 to -0.2 ¢/ft^2), Salt Lake City (-0.1 to -0.9 ¢/ft^2), and Sterling (-0.1 to -0.6 ¢/ft^2).
- For a residence with R-30 attic insulation and R-4 attic ducts the effect of the light-colored roof on energy savings was greatest in Phoenix with a gas heating system, which had annual combined cooling and heating energy savings of 5.1 ¢/ft^2 (or 12% of the dark-roof annual electric bill), followed by Tucson 3.8 (14), Tampa 3.0 (13), Houston 2.6 (12), Austin 2.5 (12), Fort Worth 2.2 (11), Las Vegas 2.2 (10), Long Beach 2.1 (29), Albuquerque 2.0 (17), Atlanta 1.6 (14), Sacramento 1.4 (17), Raleigh 1.1 (11), Nashville 0.8 (8), Salt Lake City 0.5 (6), Sterling 0.4 (4), and Lexington 0.3 (6).
- 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 annual energy costs. Reductions in R-value were observed in varying degrees for residences with both gas and electric heat, all duct configurations, and all climates. The highest impact for a residence with R-30 attic insulation and R-4 attic ducts was in Tampa with a gas heating system, where the attic insulation R-value decreased to 3 (4 w/ heat pump), followed by Phoenix 8 (9), Houston 8 (11), Austin 8 (12), Tucson 9 (11), Long Beach 9 (16), Fort Worth 13 (16), Las Vegas 15 (15), Atlanta 16 (19), Albuquerque 17 (23), Sacramento 18 (22), Raleigh 21 (22), Nashville 23 (23), Lexington 25 (25), Salt Lake City 25 (28), and Sterling 26 (28).
- In general, the uninsulated attic duct case was shown to have the largest reduction in R-value, where the smallest reduction was found with the conditioned zone ducts. In the gas heated Tampa residence with a dark-roof attic insulation R-value of 30, the cool-roof equivalent ranged from 0 (for uninsulated attic duct case) to 5 (for uninsulated conditioned zone duct case), in Phoenix and

[8] The savings are estimated based on initial and modified roof reflectances of 0.1 and 0.7, respectively. Studies have shown that the modified roof reflectance may degrade to 0.55 over time, thus the energy savings would decrease by the ratio of 0.45 / 0.6.

Houston it ranged from 2 to 10, Austin and Tucson 3 to 11, Long Beach 5 to 11, Fort Worth 8 to 15, Las Vegas 10 to 17, Atlanta 12 to 18, Albuquerque 13 to 19, Sacramento 14 to 19, Raleigh 19 to 22, Nashville 21 to 24, Salt Lake City 23 to 26, Lexington 24 to 25, and Sterling 25 to 26. In the heating dominated climates of Lexington and Sterling the effect of duct insulation and location was negligible.

- In the cooling dominated climates of Austin, Houston, Long Beach, Phoenix, Tampa, and Tucson there were some cases (predominantly those with uninsulated attic ducts and dark-roof attic insulation of R-7 or R-11) where a cool roof could be implemented without attic insulation. This also applies to Tampa residences with uninsulated attic ducts, either gas or electric heat, and all dark-roof attic R-values evaluated, and for those with gas heat, insulated attic ducts (R-2 to R-8), and dark-roof attic insulation of R-7.

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 report 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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Appendix A - Plots of Simulation Estimated Annual Total Cooling and Heating Energy Use

This appendix contains plots of DOE-2 simulated annual total cooling and heating energy use ($ per ft^2) for a single-family new residence with both gas furnace and electric heat pump heating systems, dark (absorptance = 0.9) and cool (absorptance = 0.3) roofs, uninsulated attic ducts (R-1), insulated attic ducts (R-2, R-4, R-6, and R-8), uninsulated conditioned zone ducts (R-1), and sixteen climates. Equivalent cool-roof attic insulation R-values can be determined graphically from **Figures A.1-16** for cases other than in **Table 3.21**.

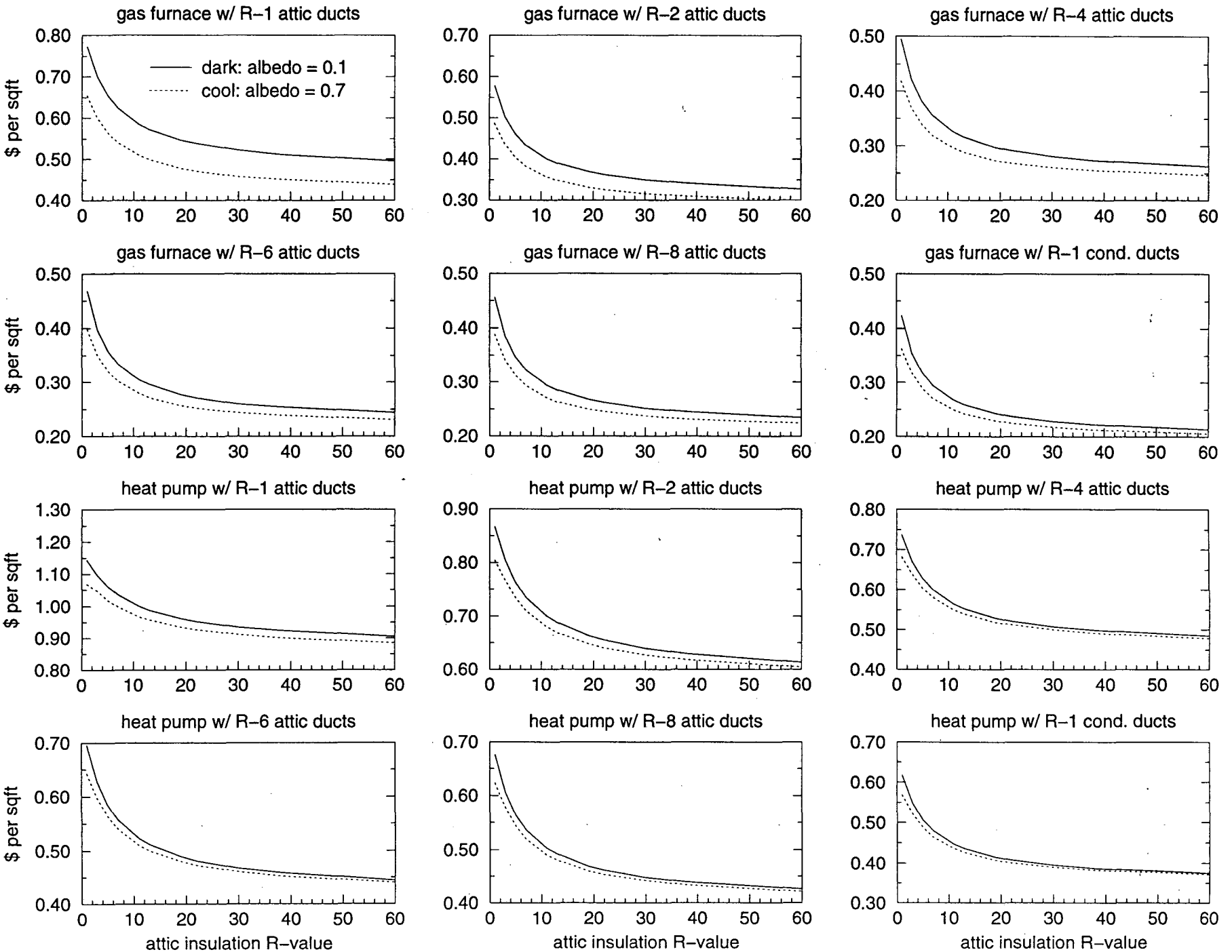

Figure A.1. Simulation estimates of annual total cooling and heating energy use ($ per sqft) for a new residence in Albuquerque, NM.

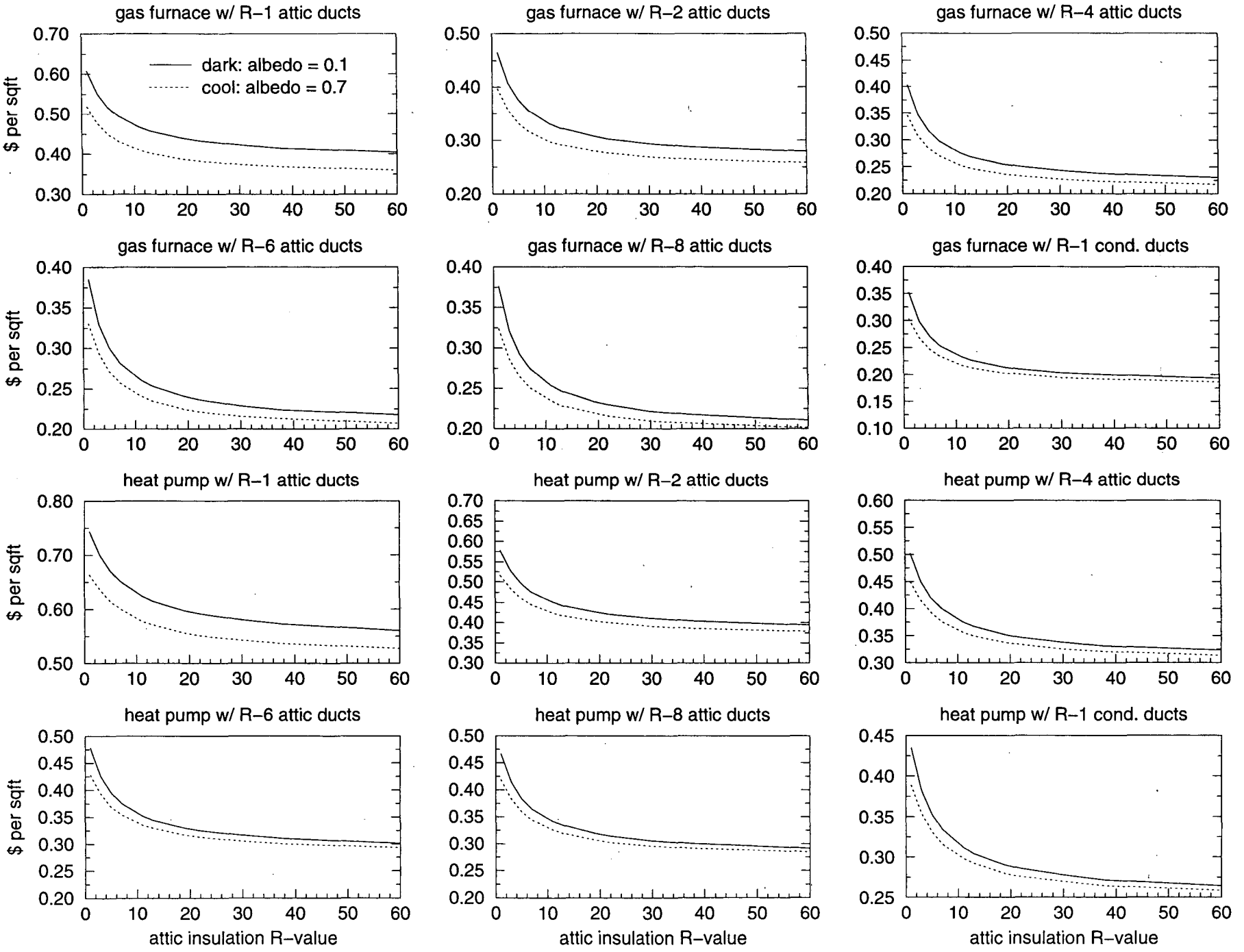

Figure A.2. Simulation estimates of annual total cooling and heating energy use ($ per sqft) for a new residence in Atlanta, GA.

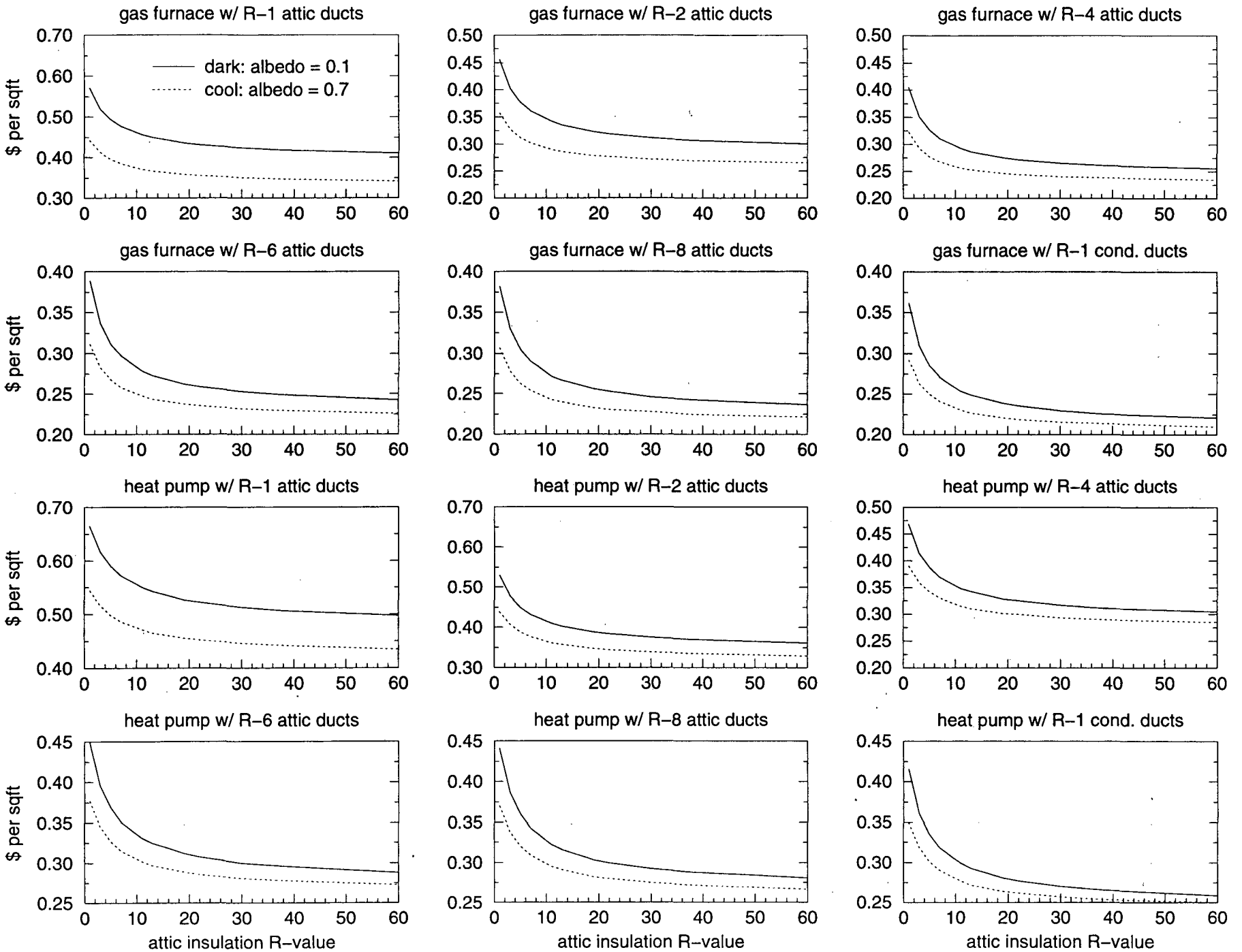

Figure A.3. Simulation estimates of annual total cooling and heating energy use ($ per sqft) for a new residence in Austin, TX.

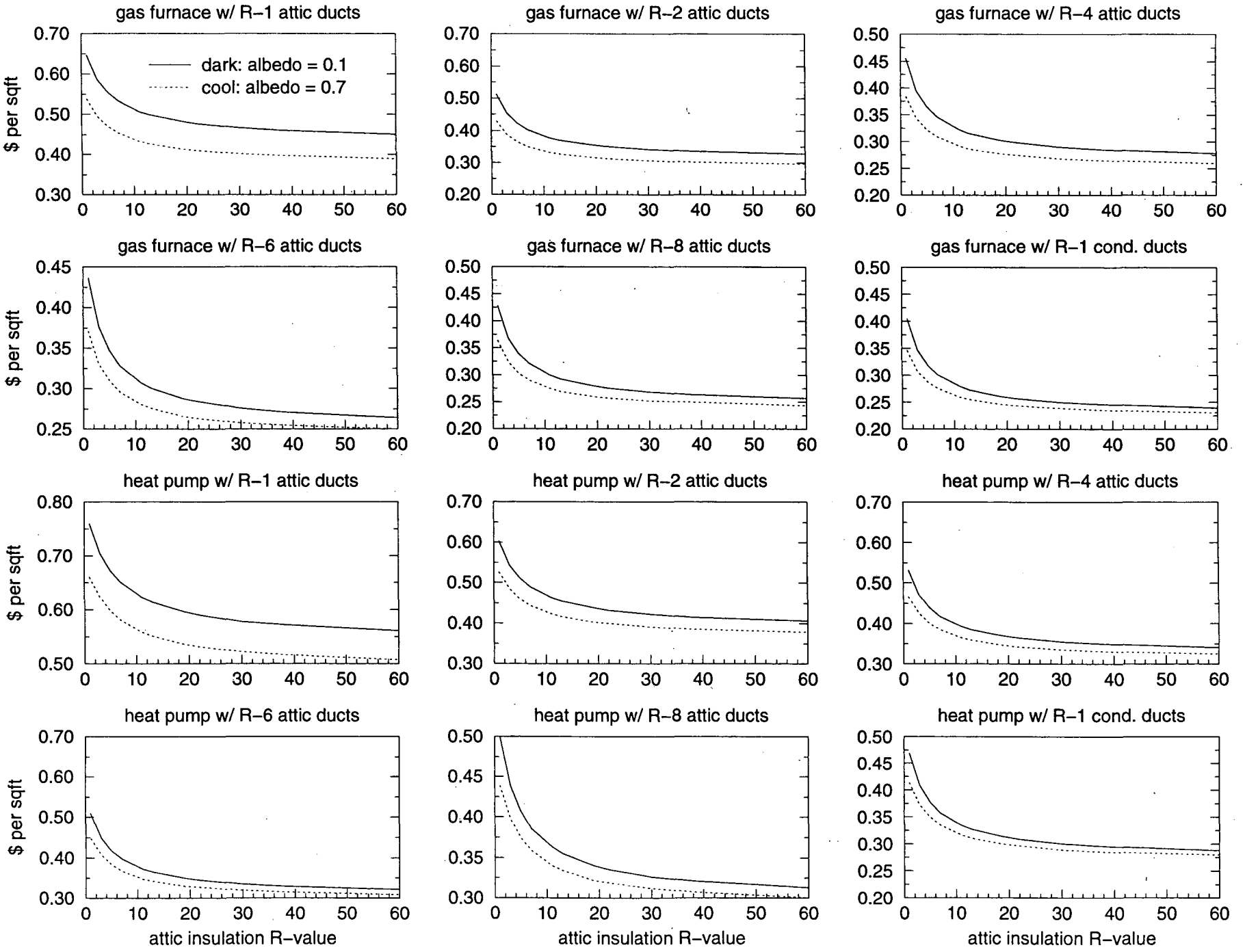

Figure A.4. Simulation estimates of annual total cooling and heating energy use ($ per sqft) for a new residence in Fort Worth, TX.

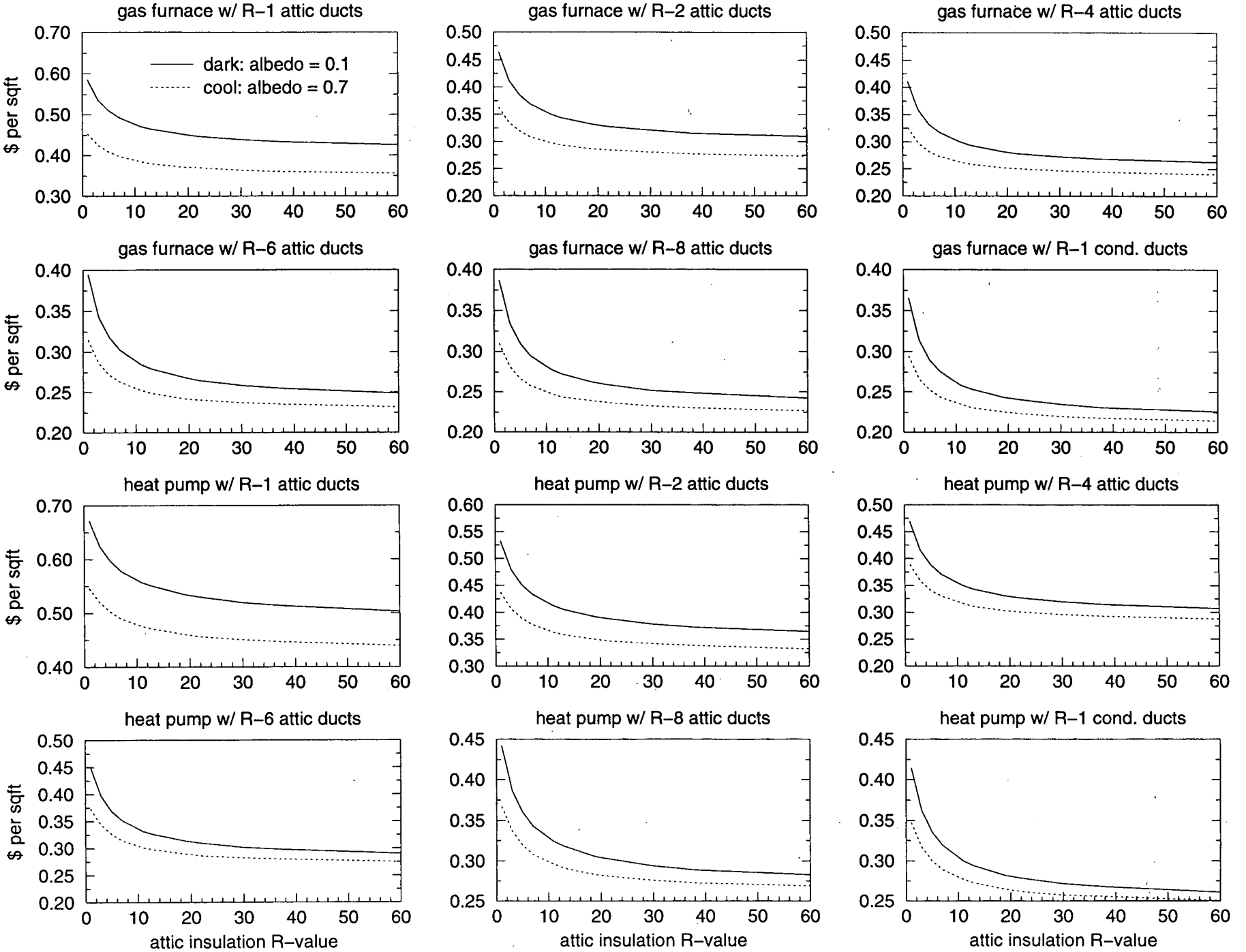

Figure A.5. Simulation estimates of annual total cooling and heating energy use ($ per sqft) for a new residence in Houston, TX.

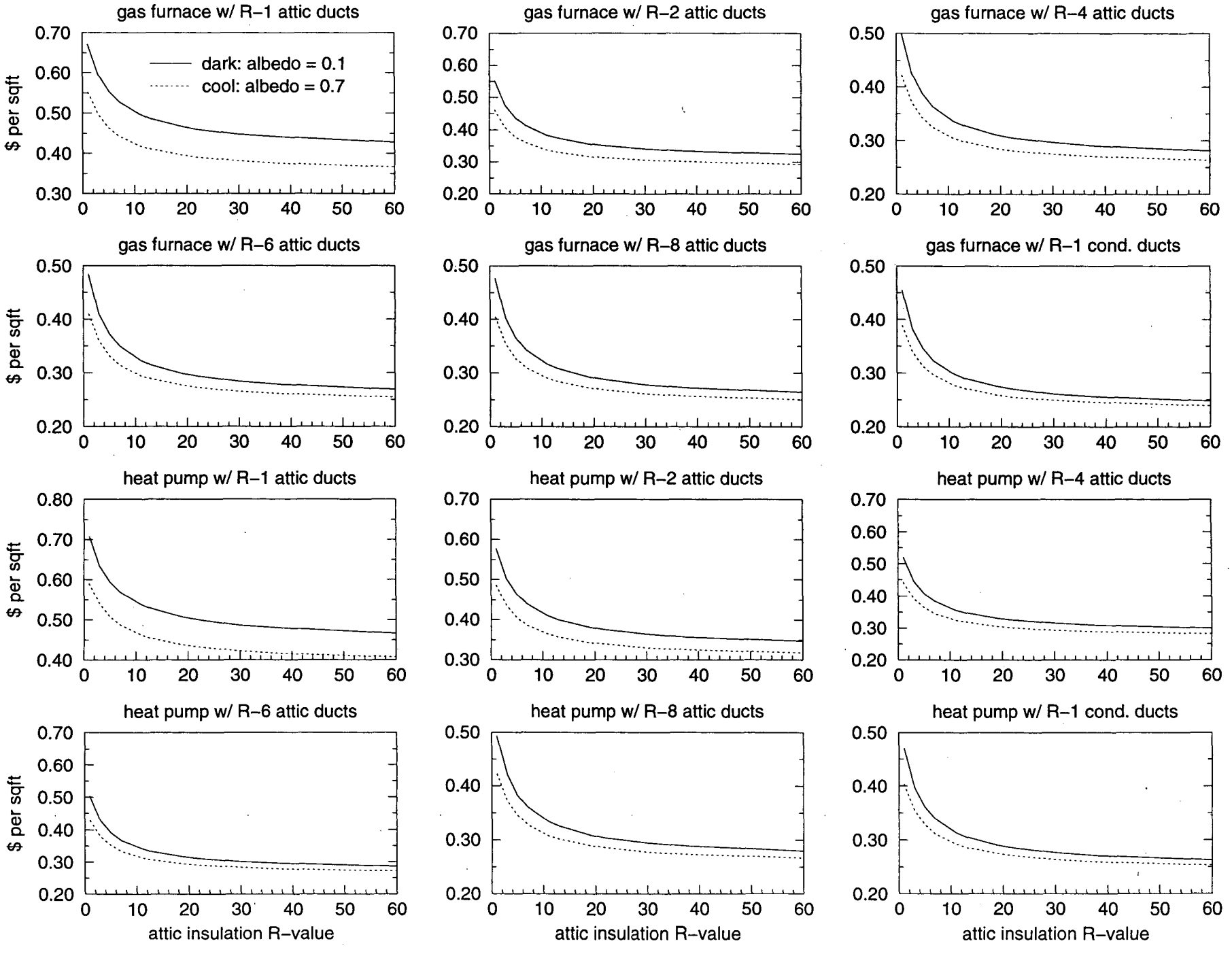

Figure A.6. Simulation estimates of annual total cooling and heating energy use ($ per sqft) for a new residence in Las Vegas, NV.

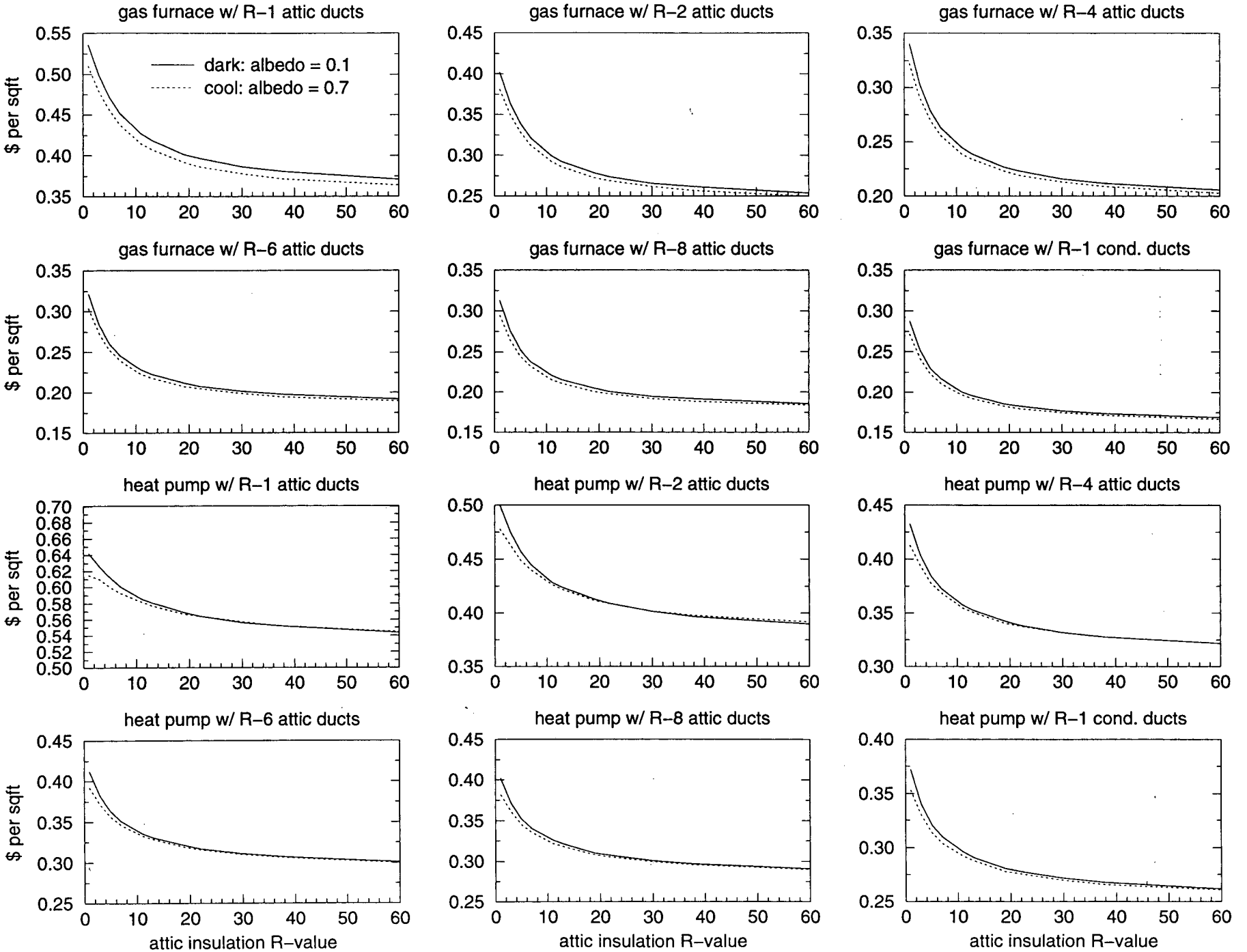

Figure A.7. Simulation estimates of annual total cooling and heating energy use ($ per sqft) for a new residence in Lexington, KY.

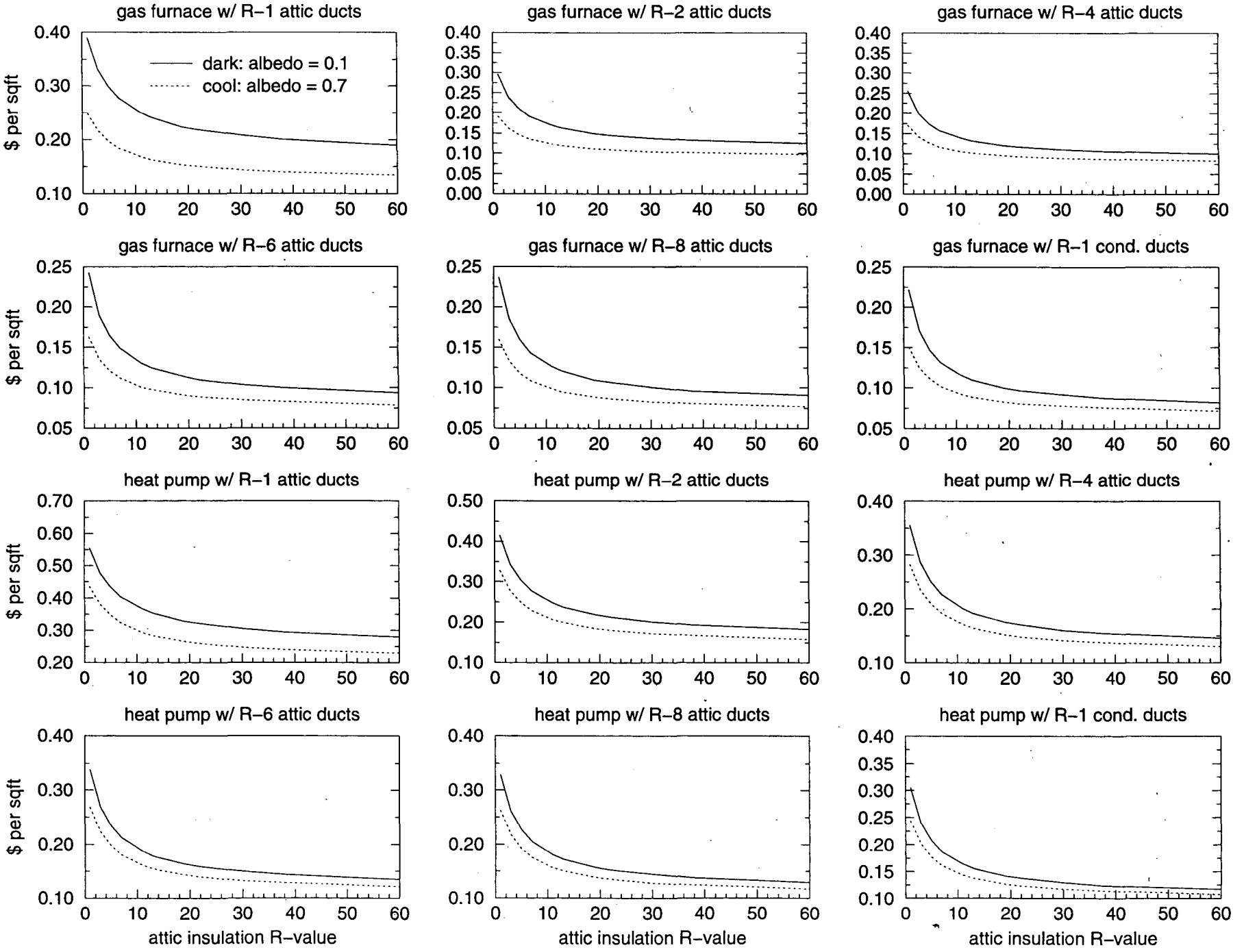

Figure A.8. Simulation estimates of annual total cooling and heating energy use ($ per sqft) for a new residence in Long Beach, CA.

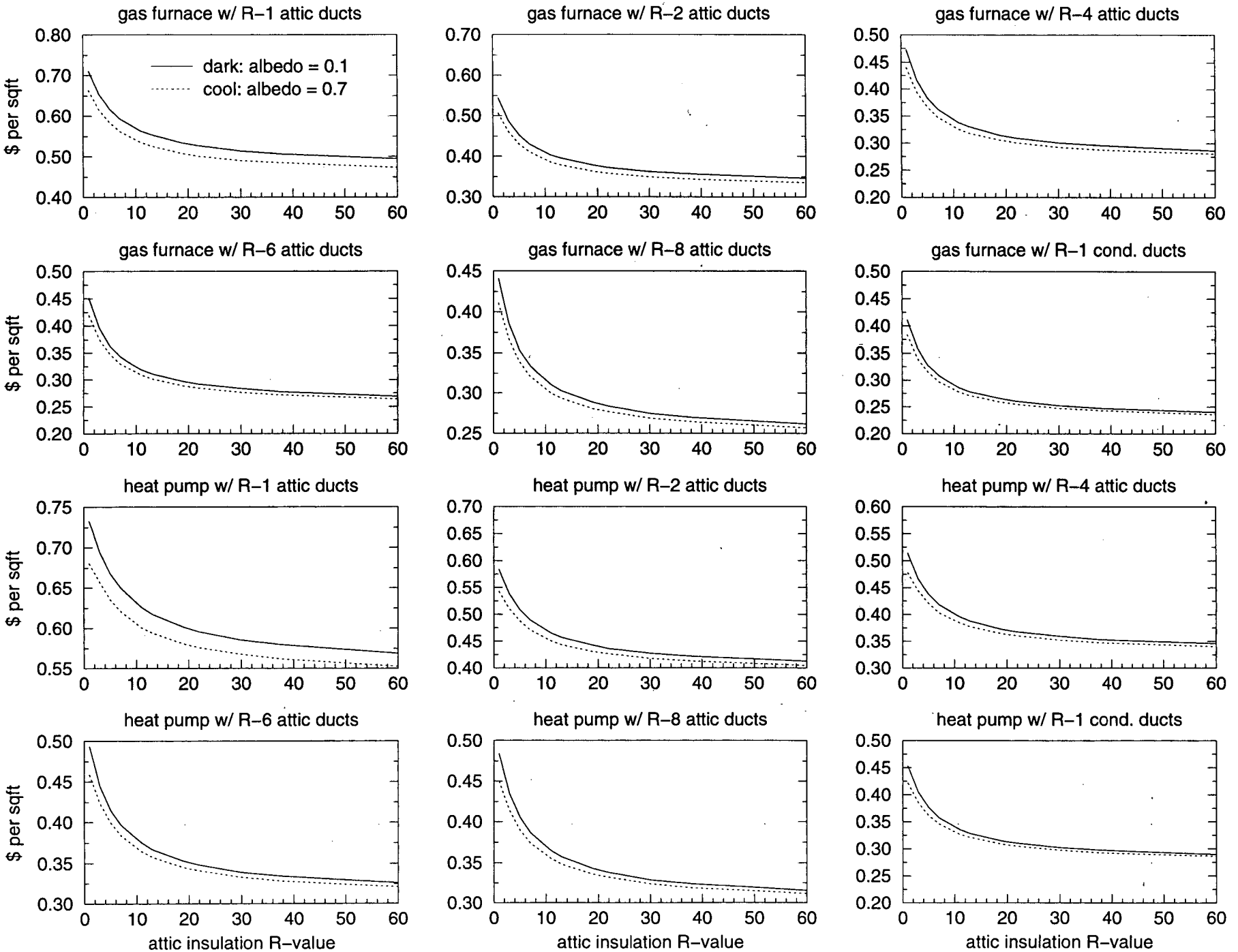

Figure A.9. Simulation estimates of annual total cooling and heating energy use ($ per sqft) for a new residence in Nashville, TN.

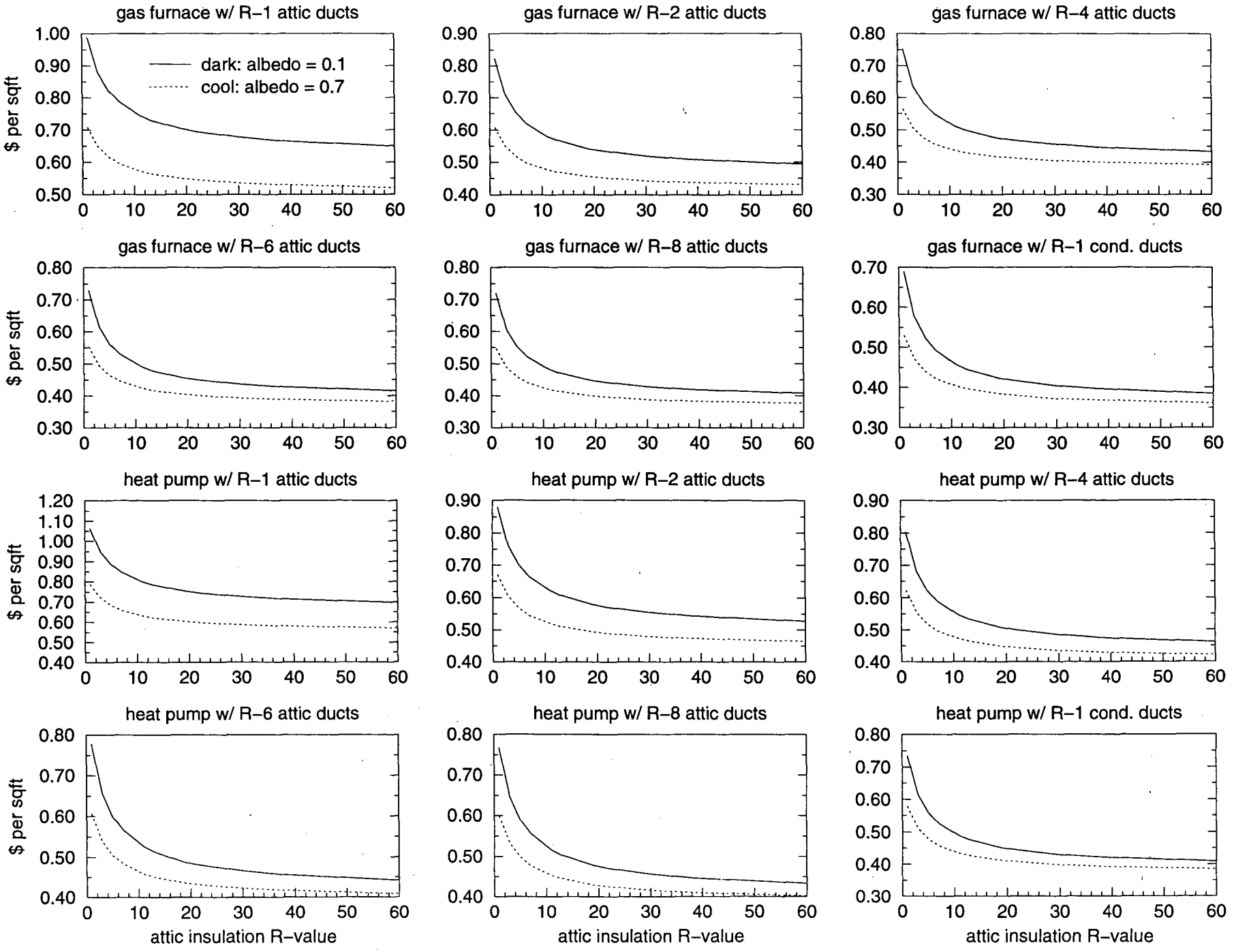

Figure A.10. Simulation estimates of annual total cooling and heating energy use ($ per sqft) for a new residence in Phoenix, AZ.

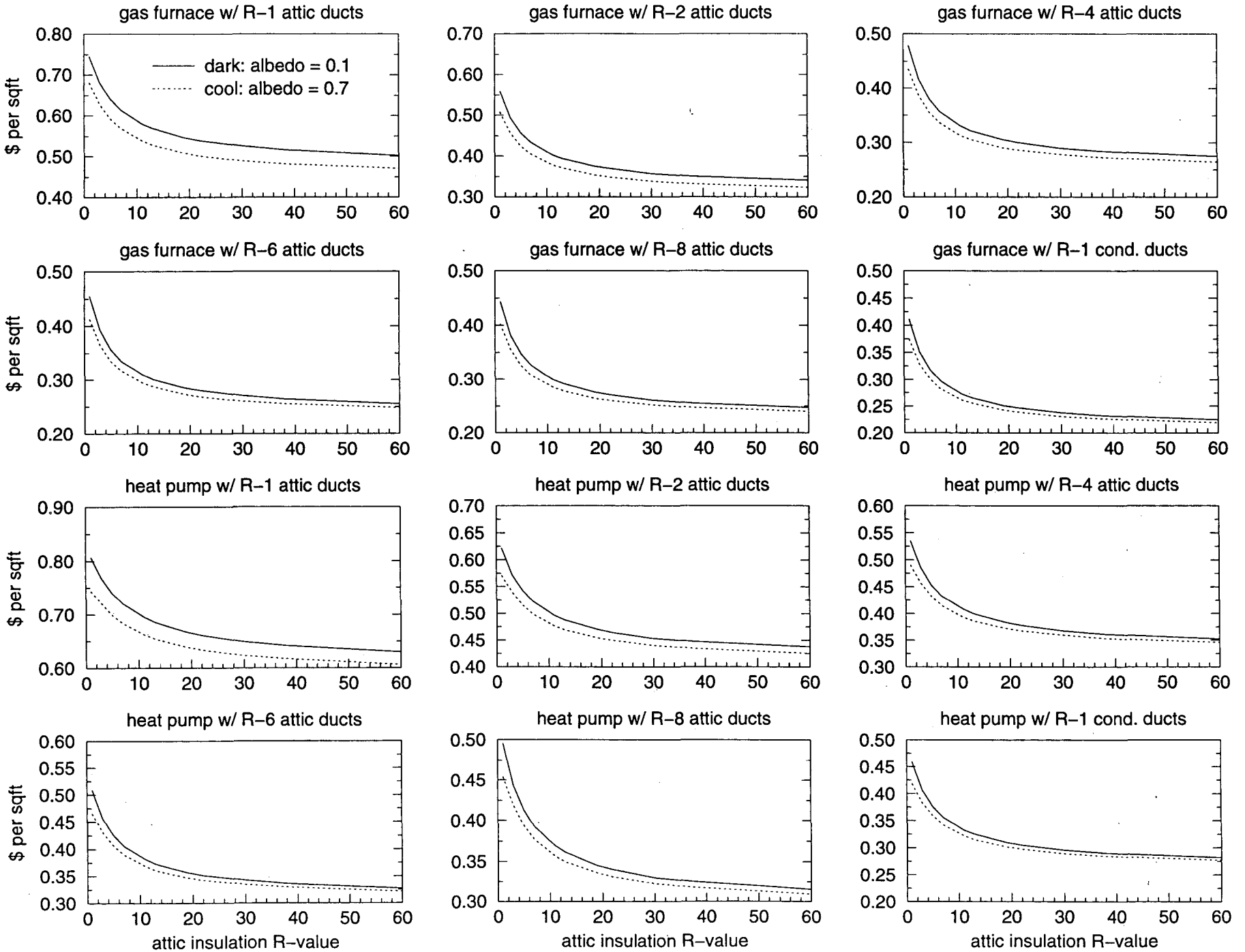

Figure A.11. Simulation estimates of annual total cooling and heating energy use ($ per sqft) for a new residence in Raleigh, NC.

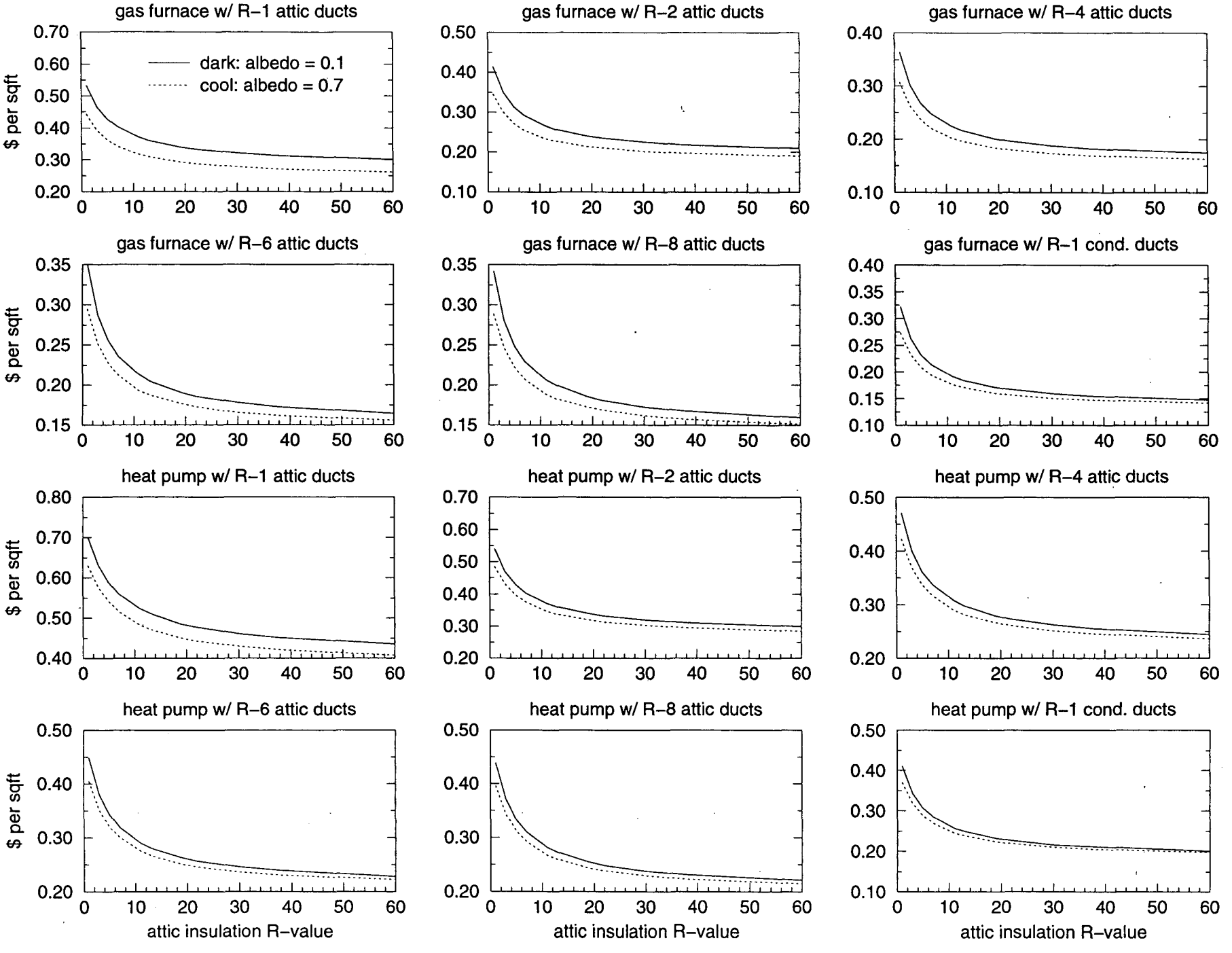

Figure A.12. Simulation estimates of annual total cooling and heating energy use ($ per sqft) for a new residence in Sacramento, CA.

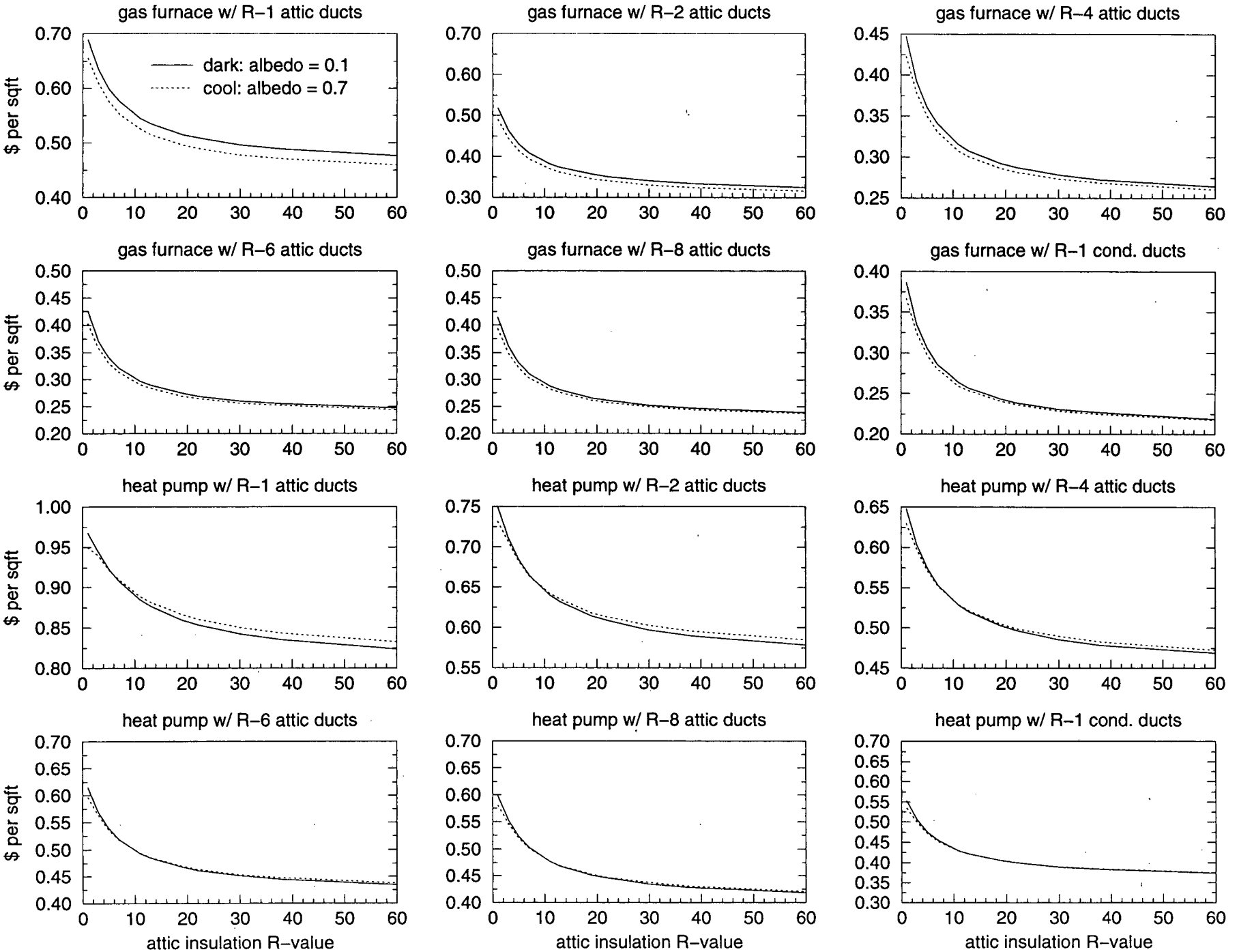

Figure A.13. Simulation estimates of annual total cooling and heating energy use ($ per sqft) for a new residence in Salt Lake City, UT.

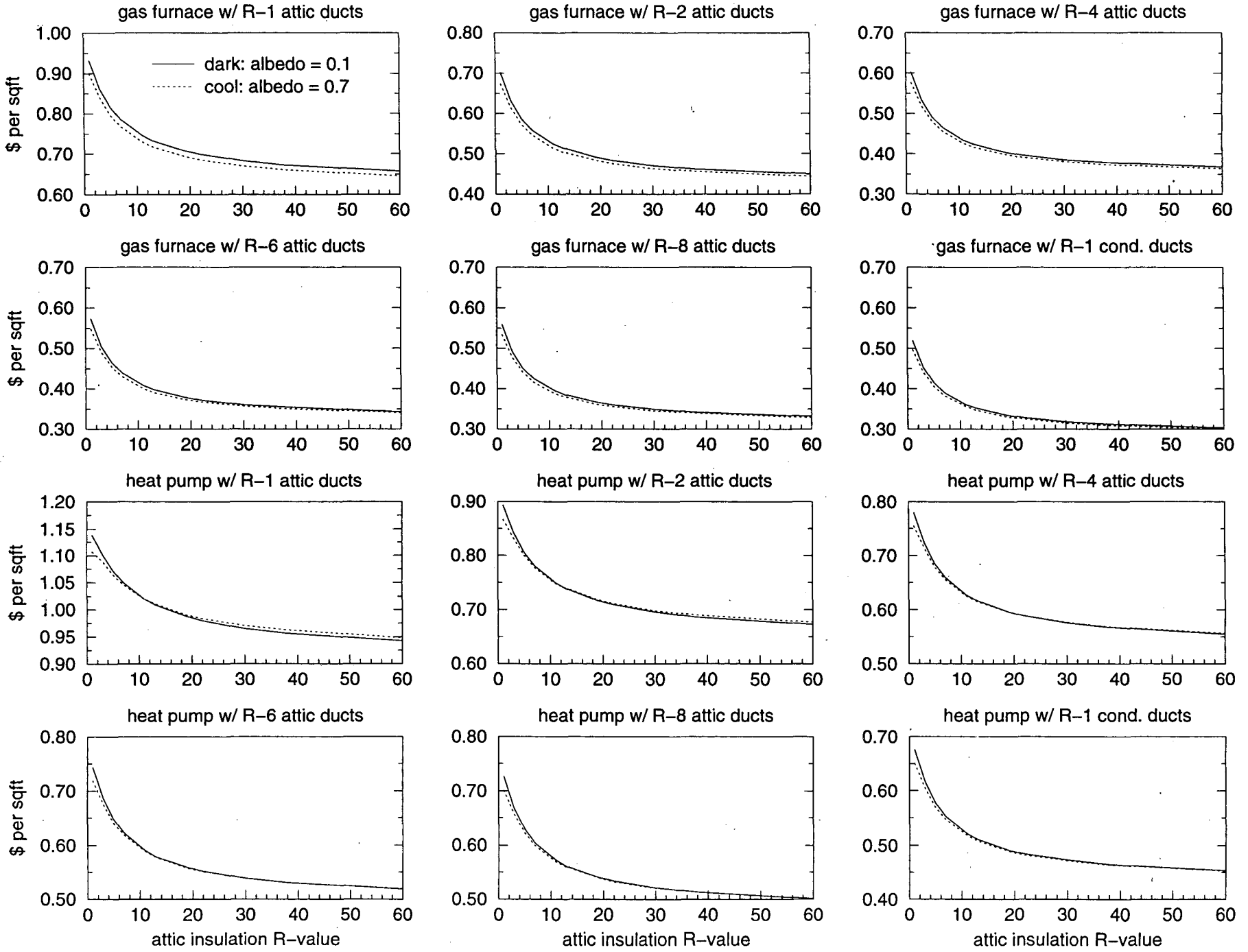

Figure A.14. Simulation estimates of annual total cooling and heating energy use ($ per sqft) for a new residence in Sterling, VA.

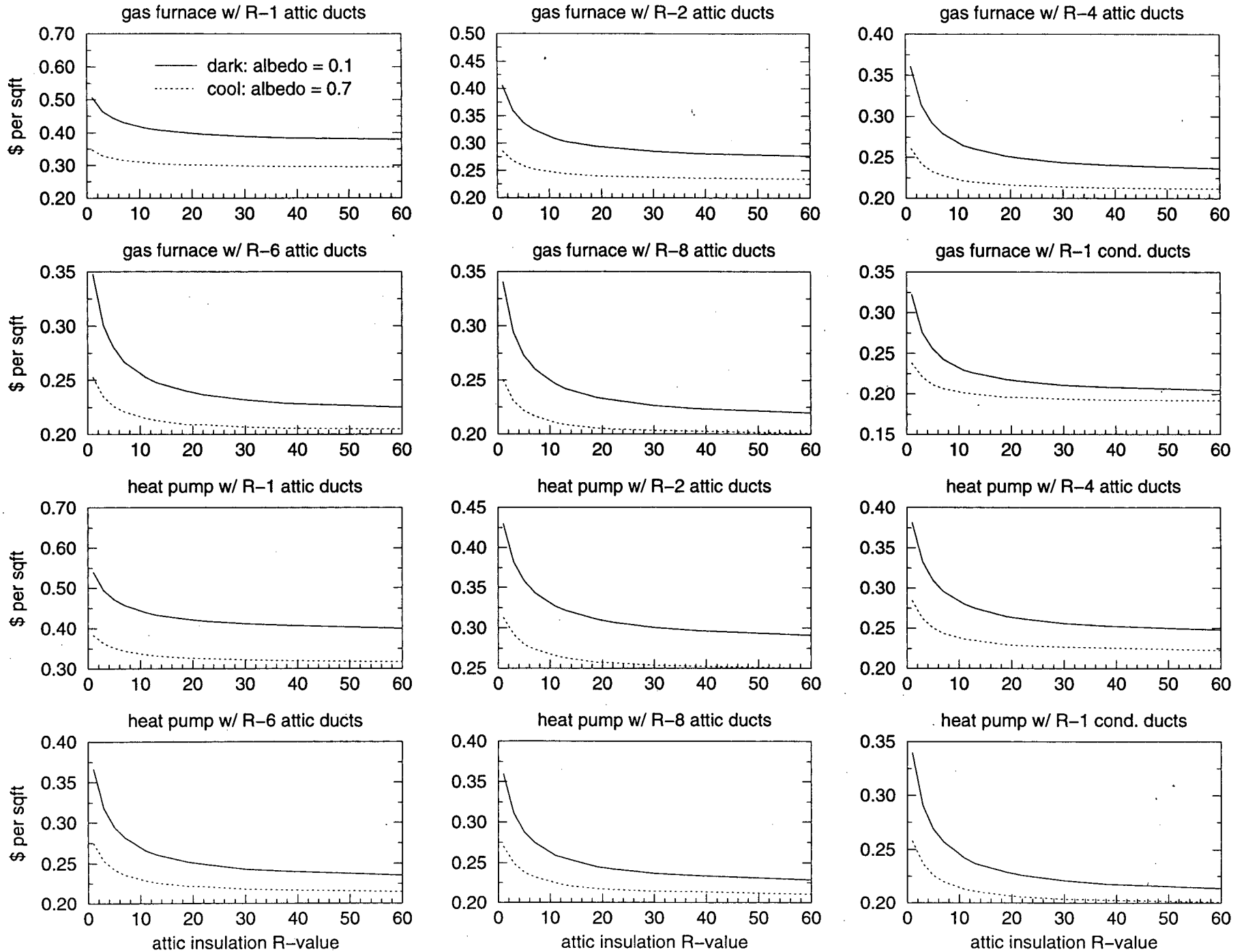

Figure A.15. Simulation estimates of annual total cooling and heating energy use ($ per sqft) for a new residence in Tampa, FL.

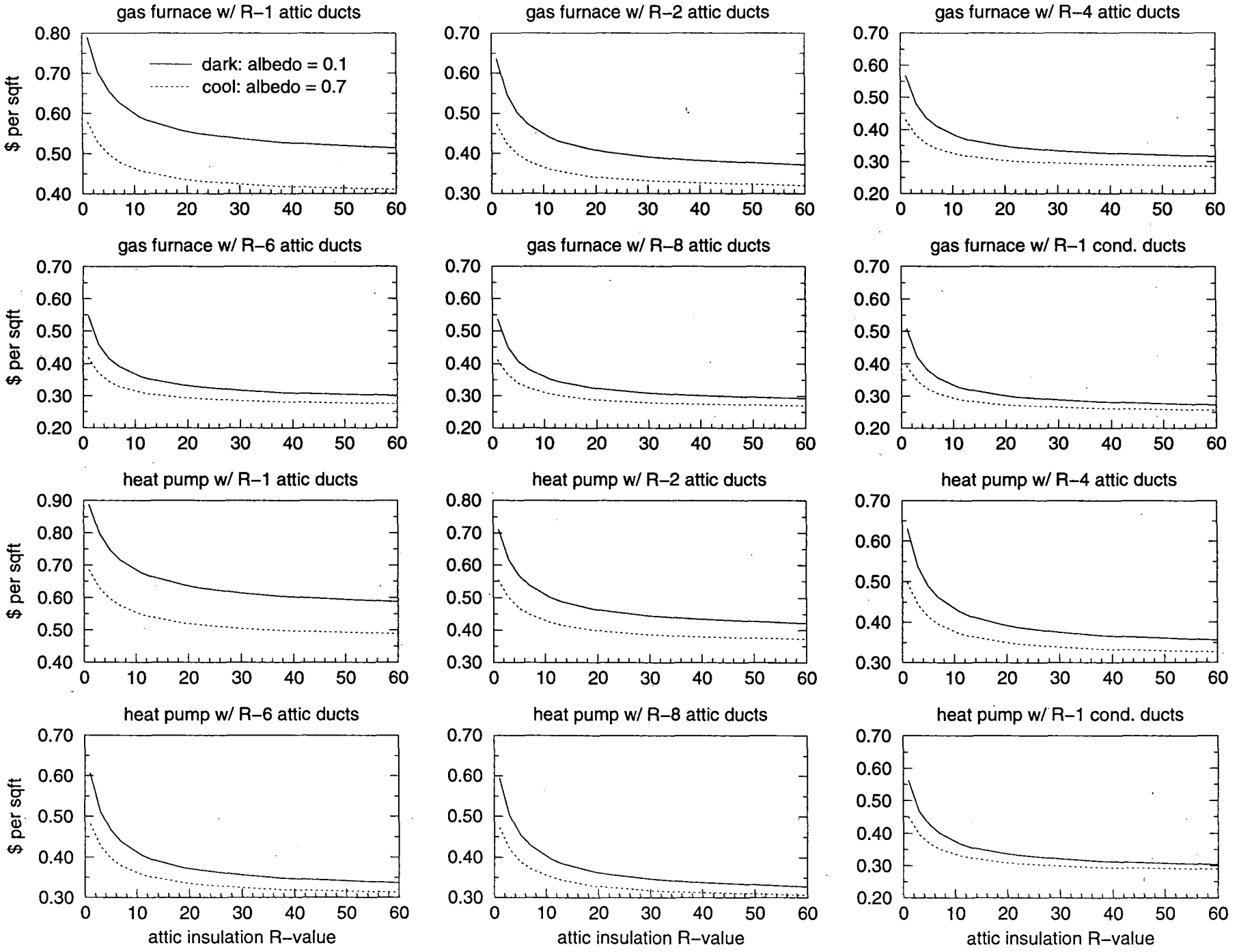

Figure A.16. Simulation estimates of annual total cooling and heating energy use ($ per sqft) for a new residence in Tucson, AZ.

Appendix B - Regression Statistics

This appendix contains the regression statistics (**Table B.1**) of annual cooling and heating energy use versus roof system conductance and roof surface solar absorptance for a single-family new residence with both gas furnace and electric heat pump heating systems, uninsulated attic ducts (R-1), insulated attic ducts (R-2, R-4, R-6, and R-8), uninsulated conditioned zone ducts (R-1C), and sixteen climates.

σ An estimate of the standard deviation of the error term, which is calculated as the square root of the mean square error.

R^2 A measure between 0 and 1 that indicates the portion of the total variation that is attributed to the fit rather than left to residual error (some values are equal to 1 due to rounding).

Table B.1. Statistics from regressions of annual cooling and heating energy use (E) versus roof system conductance (U in Btu/h·ft^2·°F) and roof surface solar absorptance (α for $0<\alpha<1$) for a single-family new residence. (Duct configurations: uninsulated attic ducts R-1, insulated attic ducts R-2, R-4, R-6, and R-8, and uninsulated conditioned zone ducts R-1C).

climate	gas furnace						electric heat pump			
	electricity		gas		total		electricity		total	
	σ	R^2	σ	R^2	σ	R^2	σ	R^2	σ	R^2
Albuquerque, NM										
R-1	0.167	0.94	0.005	1.00	0.013	0.98	0.030	1.00	0.003	1.00
R-2	0.060	0.99	0.002	1.00	0.005	1.00	0.021	1.00	0.002	1.00
R-4	0.022	1.00	0.002	1.00	0.002	1.00	0.027	1.00	0.002	1.00
R-6	0.017	1.00	0.002	1.00	0.001	1.00	0.028	1.00	0.003	1.00
R-8	0.017	1.00	0.001	1.00	0.001	1.00	0.029	1.00	0.003	1.00
R-1C	0.020	1.00	0.001	1.00	0.002	1.00	0.029	1.00	0.003	1.00
Atlanta, GA										
R-1	0.151	0.94	0.003	1.00	0.010	0.98	0.090	0.99	0.007	0.99
R-2	0.052	0.98	0.001	1.00	0.003	1.00	0.027	1.00	0.002	1.00
R-4	0.021	1.00	0.001	1.00	0.001	1.00	0.015	1.00	0.001	1.00
R-6	0.016	1.00	0.001	1.00	0.001	1.00	0.015	1.00	0.001	1.00
R-8	0.016	1.00	0.001	1.00	0.001	1.00	0.016	1.00	0.001	1.00
R-1C	0.018	1.00	0.001	1.00	0.001	1.00	0.019	1.00	0.002	1.00
Austin, TX										
R-1	0.219	0.92	0.001	1.00	0.016	0.94	0.195	0.95	0.014	0.95
R-2	0.088	0.98	0.001	1.00	0.006	0.99	0.078	0.99	0.006	0.99
R-4	0.035	0.99	0.001	1.00	0.003	1.00	0.030	1.00	0.002	1.00
R-6	0.024	1.00	0.000	1.00	0.002	1.00	0.021	1.00	0.002	1.00
R-8	0.021	1.00	0.001	1.00	0.001	1.00	0.018	1.00	0.001	1.00
R-1C	0.022	1.00	0.001	1.00	0.002	1.00	0.020	1.00	0.002	1.00
Fort Worth, TX										
R-1	0.188	0.92	0.002	1.00	0.014	0.96	0.152	0.97	0.012	0.97
R-2	0.077	0.98	0.001	1.00	0.006	0.99	0.061	0.99	0.005	0.99
R-4	0.031	0.99	0.001	1.00	0.002	1.00	0.024	1.00	0.002	1.00
R-6	0.021	1.00	0.001	1.00	0.002	1.00	0.016	1.00	0.001	1.00
R-8	0.018	1.00	0.001	1.00	0.001	1.00	0.015	1.00	0.001	1.00
R-1C	0.019	1.00	0.001	1.00	0.001	1.00	0.018	1.00	0.001	1.00
Houston, TX										
R-1	0.204	0.92	0.001	1.00	0.016	0.94	0.180	0.95	0.015	0.95
R-2	0.080	0.97	0.001	1.00	0.006	0.98	0.069	0.99	0.006	0.99
R-4	0.033	0.99	0.001	1.00	0.003	1.00	0.028	1.00	0.002	1.00
R-6	0.023	1.00	0.000	1.00	0.002	1.00	0.019	1.00	0.002	1.00
R-8	0.020	1.00	0.000	1.00	0.002	1.00	0.017	1.00	0.001	1.00
R-1C	0.020	1.00	0.001	1.00	0.002	1.00	0.019	1.00	0.001	1.00
Las Vegas, NV										
R-1	0.213	0.94	0.001	1.00	0.014	0.97	0.201	0.97	0.014	0.97
R-2	0.077	0.99	0.001	1.00	0.005	0.99	0.073	1.00	0.005	1.00
R-4	0.031	1.00	0.001	1.00	0.002	1.00	0.029	1.00	0.002	1.00
R-6	0.025	1.00	0.001	1.00	0.002	1.00	0.023	1.00	0.002	1.00
R-8	0.025	1.00	0.001	1.00	0.001	1.00	0.022	1.00	0.001	1.00
R-1C	0.030	1.00	0.001	1.00	0.002	1.00	0.026	1.00	0.002	1.00

Table B.1(cont). Statistics from regressions of annual cooling and heating energy use (E) versus roof system conductance (U in Btu/h·ft^2·°F) and roof surface solar absorptance (α for $0<\alpha<1$) for a single-family new residence. (Duct configurations: uninsulated attic ducts R-1, insulated attic ducts R-2, R-4, R-6, and R-8, and uninsulated conditioned zone ducts R-1C).

climate	gas furnace						electric heat pump			
	electricity		gas		total		electricity		total	
	σ	R^2	σ	R^2	σ	R^2	σ	R^2	σ	R^2
Lexington, KY										
R-1	0.080	0.97	0.008	0.99	0.002	1.00	0.047	0.99	0.002	0.99
R-2	0.025	0.99	0.004	1.00	0.001	1.00	0.042	1.00	0.002	1.00
R-4	0.012	1.00	0.003	1.00	0.001	1.00	0.035	1.00	0.002	1.00
R-6	0.012	1.00	0.002	1.00	0.001	1.00	0.032	1.00	0.002	1.00
R-8	0.012	1.00	0.002	1.00	0.001	1.00	0.030	1.00	0.001	1.00
R-1C	0.014	1.00	0.002	1.00	0.001	1.00	0.026	1.00	0.001	1.00
Long Beach, CA										
R-1	0.085	0.96	0.001	1.00	0.011	0.97	0.085	0.99	0.011	0.99
R-2	0.026	0.99	0.001	1.00	0.003	1.00	0.027	1.00	0.003	1.00
R-4	0.013	1.00	0.001	1.00	0.002	1.00	0.011	1.00	0.001	1.00
R-6	0.013	1.00	0.001	1.00	0.001	1.00	0.010	1.00	0.001	1.00
R-8	0.013	1.00	0.001	1.00	0.001	1.00	0.010	1.00	0.001	1.00
R-1C	0.016	0.99	0.001	1.00	0.002	1.00	0.011	1.00	0.002	1.00
Nashville, TN										
R-1	0.138	0.95	0.005	1.00	0.005	1.00	0.047	1.00	0.003	1.00
R-2	0.049	0.99	0.003	1.00	0.002	1.00	0.018	1.00	0.001	1.00
R-4	0.020	1.00	0.002	1.00	0.001	1.00	0.021	1.00	0.001	1.00
R-6	0.015	1.00	0.001	1.00	0.001	1.00	0.022	1.00	0.001	1.00
R-8	0.015	1.00	0.001	1.00	0.001	1.00	0.022	1.00	0.001	1.00
R-1C	0.017	1.00	0.001	1.00	0.001	1.00	0.024	1.00	0.001	1.00
Phoenix, AZ										
R-1	0.279	0.95	0.001	1.00	0.027	0.96	0.279	0.96	0.027	0.96
R-2	0.100	0.99	0.001	1.00	0.010	0.99	0.101	0.99	0.010	0.99
R-4	0.043	1.00	0.000	1.00	0.004	1.00	0.042	1.00	0.004	1.00
R-6	0.035	1.00	0.000	1.00	0.003	1.00	0.032	1.00	0.003	1.00
R-8	0.034	1.00	0.001	1.00	0.003	1.00	0.030	1.00	0.003	1.00
R-1C	0.040	1.00	0.001	1.00	0.004	1.00	0.035	1.00	0.003	1.00
Raleigh, NC										
R-1	0.132	0.94	0.004	1.00	0.007	0.99	0.053	0.99	0.004	0.99
R-2	0.049	0.98	0.002	1.00	0.003	1.00	0.019	1.00	0.002	1.00
R-4	0.019	1.00	0.001	1.00	0.001	1.00	0.016	1.00	0.001	1.00
R-6	0.015	1.00	0.001	1.00	0.001	1.00	0.018	1.00	0.002	1.00
R-8	0.014	1.00	0.001	1.00	0.001	1.00	0.018	1.00	0.002	1.00
R-1C	0.017	1.00	0.001	1.00	0.001	1.00	0.020	1.00	0.002	1.00
Sacramento, CA										
R-1	0.113	0.96	0.002	1.00	0.008	0.99	0.070	1.00	0.006	1.00
R-2	0.038	0.99	0.001	1.00	0.003	1.00	0.023	1.00	0.002	1.00
R-4	0.017	1.00	0.001	1.00	0.001	1.00	0.013	1.00	0.001	1.00
R-6	0.016	1.00	0.001	1.00	0.001	1.00	0.013	1.00	0.001	1.00
R-8	0.016	1.00	0.001	1.00	0.001	1.00	0.014	1.00	0.001	1.00
R-1C	0.020	1.00	0.001	1.00	0.001	1.00	0.018	1.00	0.002	1.00

Table B.1(cont). Statistics from regressions of annual cooling and heating energy use (E) versus roof system conductance (U in Btu/h·ft^2·°F) and roof surface solar absorptance (α for $0<\alpha<1$) for a single-family new residence. (Duct configurations: uninsulated attic ducts R-1, insulated attic ducts R-2, R-4, R-6, and R-8, and uninsulated conditioned zone ducts R-1C).

climate	gas furnace						electric heat pump			
	electricity		gas		total		electricity		total	
	σ	R^2	σ	R^2	σ	R^2	σ	R^2	σ	R^2
Salt Lake City, UT										
R-1	0.110	0.95	0.008	0.99	0.004	1.00	0.065	0.99	0.004	0.99
R-2	0.039	0.99	0.004	1.00	0.002	1.00	0.051	1.00	0.004	1.00
R-4	0.013	1.00	0.002	1.00	0.001	1.00	0.043	1.00	0.003	1.00
R-6	0.011	1.00	0.002	1.00	0.001	1.00	0.039	1.00	0.003	1.00
R-8	0.011	1.00	0.002	1.00	0.001	1.00	0.038	1.00	0.003	1.00
R-1C	0.015	1.00	0.002	1.00	0.001	1.00	0.032	1.00	0.002	1.00
Sterling, VA										
R-1	0.085	0.96	0.008	0.99	0.002	1.00	0.054	0.99	0.004	0.99
R-2	0.029	0.99	0.003	1.00	0.001	1.00	0.045	1.00	0.004	1.00
R-4	0.013	1.00	0.002	1.00	0.001	1.00	0.036	1.00	0.003	1.00
R-6	0.012	1.00	0.002	1.00	0.001	1.00	0.033	1.00	0.003	1.00
R-8	0.012	1.00	0.002	1.00	0.001	1.00	0.031	1.00	0.003	1.00
R-1C	0.013	1.00	0.002	1.00	0.001	1.00	0.028	1.00	0.002	1.00
Tampa, FL										
R-1	0.269	0.91	0.000	1.00	0.019	0.92	0.268	0.92	0.019	0.92
R-2	0.102	0.97	0.000	1.00	0.008	0.98	0.103	0.98	0.007	0.98
R-4	0.041	0.99	0.000	1.00	0.003	0.99	0.041	0.99	0.003	1.00
R-6	0.029	1.00	0.000	1.00	0.002	1.00	0.028	1.00	0.002	1.00
R-8	0.025	1.00	0.000	1.00	0.002	1.00	0.024	1.00	0.002	1.00
R-1C	0.025	1.00	0.000	1.00	0.002	1.00	0.022	1.00	0.002	1.00
Tucson, AZ										
R-1	0.245	0.94	0.001	1.00	0.023	0.95	0.239	0.96	0.022	0.96
R-2	0.088	0.98	0.001	1.00	0.008	0.99	0.086	0.99	0.008	0.99
R-4	0.034	1.00	0.001	1.00	0.003	1.00	0.032	1.00	0.003	1.00
R-6	0.027	1.00	0.001	1.00	0.002	1.00	0.024	1.00	0.002	1.00
R-8	0.026	1.00	0.001	1.00	0.002	1.00	0.023	1.00	0.002	1.00
R-1C	0.033	1.00	0.001	1.00	0.003	1.00	0.029	1.00	0.003	1.00

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