4838

Simulated Influence of Roof Reflectance on the Building Energy Balance in Two Northern Cities

Sebastian Freund **Daniel J. Dettmers** *Member ASHRAE* **Douglas T. Reindl, PhD** *Member ASHRAE*

ABSTRACT

Solar irradiation on the roof surfaces of buildings affects cooling and heating energy demand. In this study the effect of enhanced roof reflectance is investigated using computer simulations of a prototype large retail building with four roof insulation levels (R-4 through R-24) driven by hourly weather data for Minneapolis, MN. The dark roof surface temperatures in the summer reach more than 160ºF (71ºC); the white roof reaches about 100ºF (38ºC), leading to 6%-17% lower cooling energy consumption. Although the increased heating costs in the winter negate a portion of the cooling savings, the total energy cost savings of the white roof are still positive. Also, a reduction in the maximum hourly compressor power—responsible for the monthly billed electric peak demand—of 0.06 to 0.3 W/ft^2 (0.6 to 3 W/m^2) can be consistently attributed to the high albedo roof. The demand cost savings may be in excess of the energy cost savings. The total annual savings a white roof can attain are in a range between \$27/1,000 ft^2 (\$0.3/m^2) and \$10/1,000 ft^2 (\$0.1/m^2) for R-4 and R-24 insulation. For Denver, CO., which has a warmer climate and is located farther south than Minneapolis, limited simulation results indicate total savings twice as high. With higher insulation levels, savings of a white roof compared to a black roof are lower, but total cost savings of increased roof albedo can be higher than the cost savings of increased insulation. Also, the effects of snow cover and the operation of an outside air economizer on the energy savings of a reflective roof are investigated.

INTRODUCTION

Reflective roof coatings on commercial and residential buildings have the potential for decreasing cooling energy consumption and demand by lowering roof temperatures. The energy savings and potential for downsizing cooling equipment is due to the lower average roof temperatures obtained with roofing materials that have higher solar reflectance. During the heating season a reflective roof will also lower the roof temperature (relative to a non-reflective roof), thereby increasing the heating load and creating a trade-off between cooling energy savings and heating energy penalty. The effect is greatest on low-rise buildings with large flat or south-sloped roofs, typically commercial, institutional, and industrial facilities that would otherwise have dark bitumen or sheet metal roofing. Unconditioned attic spaces or high roof insulation values mitigate the effect.

The trade-off of cooling savings versus heating penalty had not been extensively studied in previously published literature for a northern climate such as Minneapolis. This study was conducted to determine the overall energy consumption in northern climates for heating and cooling when a reflective roof is used.

This paper summarizes the results of analysis using a computer simulation model built in TRNSYS, which is a simulation program specifically designed to model transient heat transfer processes and solar systems. The program includes all necessary routines to effectively calculate solar irradiation on buildings as well as models of building and HVAC components. Simulations are driven by TMY2 weather data for Minneapolis.

LITERATURE REVIEW

In previous studies on roof reflectance and building energy usage, authors agreed that roofs with higher reflectance could deliver space conditioning system energy savings in

Sebastian Freund is a graduate student at the Institute for Thermodynamics, Department of Mechanical Engineering, Helmut-Schmidt-University of the Federal Armed Forces, Hamburg, Germany. **Daniel J. Dettmers** is a research engineer and **Douglas T. Reindl** is center director at the HVAC&R Center, University of Wisconsin, Madison.

southern climates (Akbari et al. 1998; Akbari 1998; Parker, Sherwin et al. 1998). Prior simulation results were supplemented using experiments to demonstrate the significant roof surface temperature decreases with correspondingly lower cooling energy consumption in Florida (Akridge 1998; Parker, Huang et al. 1998). In warm climates, the savings in air-conditioning costs exceed the increased heating costs. For colder climates, it has been considered that the opposite may be the case. Akbari et al. (1998) conclude that highly reflective roofs have a negative impact on the annual building energy costs in Minneapolis. Positive net savings, however, may occur in those climates when the HVAC system size is reduced due to a smaller summer peak load, resulting in smaller fans and higher part-load ratio operation for a greater proportion of the year. From Parker, Huang et al. (1998) it can be concluded that reflective roofs on residential buildings in Minneapolis have a negative impact (if any) on annual energy costs. However, the different methods applied to analyze energy consumption do not yield consistent results (Hildebrandt et al. 1998) and DOE-2-based simulations may significantly underestimate the effect of roof reflectance on energy usage, including an underprediction of the savings by as much as twofold (Akbari 1998). In addition, the results may only be applicable to the certain type of analyzed building. For the northern climates, the question of whether or not reflective roofs offer positive net energy savings and, if so, for which types of buildings had not been conclusively determined.

INFLUENCING PARAMETERS

The relation of savings from enhanced roof reflectance in the summer versus losses in the winter is dependent upon the following factors:

- **Roof orientation:** Depending on the slope and the time of year, south-sloped roofs (in the northern hemisphere) can receive higher radiation intensity than flat roofs; plus, sloped roofs have less snow coverage.
- **Sunshine:** The number of sunshine hours in the winter and the summer affect the maximum heating benefit and cooling savings potential, respectively. When the roof is snow covered, the effect of the roof reflectance is negated. Consequently, the penalty of a reflective roof in the winter may be smaller for locations with a long snow season.
- **Roof construction and insulation:** The higher the R-value of the roof, the lower the transmission gains; therefore, there is less influence of the roof temperature on the building energy usage. A roof construction with high thermal capacity, such as thick concrete, will delay the solar heating effect and diminish the effect of roof reflectance.
- **Internal gains and length of cooling season:** During the cooling season, any additional heat gain (or reduction of heat loss) due to increased roof temperature increases the cooling load. If the cooling season is very long, either due to warm climate or to high internal gains (commercial and industrial buildings), a reflective roof will tend to provide higher savings.

MODEL SUMMARY

The building modeled is a large, single-story (i.e., "big-box") retail store with a height of 25 ft, a length of 316 ft, and a gross area of 100,000 ft^2. The four external walls have an R-value of 11 h-ft^2-F/Btu. A total of 5% of the wall area is composed of single-pane windows with internal shading of 80%.

The internal gains of the building originate from sources such as lights and other electric equipment, as well as humans, and are scheduled in accordance with the building occupancy. A lighting intensity of 2.5 W/ft^2 is used for the simulation. The electric equipment in the building other than lights is assumed to operate 24 hours a day at a rate of 0.3 W/ft^2.

The number of persons in the facility varies hourly and is different for weekdays and weekends. An occupancy schedule provided by a big box retailer was used in the simulation. The maximum number of people in the facility during the open hours is 400; a person density of 4/1,000 ft^2 is assumed. The heat generation per person for the activity level expected of a customer in a store is assumed to be 315 Btu/h sensible and 325 Btu/h latent, based on ISO Standard 7730 (ISO 1994).

The building modeled in this simulation has a large internal heat gain. Applying the results of this simulation to a building without a significant internal load, such as a residential building, may not yield similar results to those presented here. This analysis compares the modeled hourly energy consumption for heating and cooling. The parameters varied are the R-value of the insulation installed in the built-up roof (from R-0 to R-24), the roof albedo (black = 6% vs. white = 65%), and the presence of snow cover on the roof. The snow cover model is based on hourly weather data and also accounts for additional melting due to the heat flux through the roof.

It is important to emphasize our definition of an "R-24" roof as a sheet metal roof with an EPDM membrane and sufficient levels of an insulation material that adds an R-value of 24 h-ft^2-F/Btu (nominal value). The actual overall heat transfer resistance of the roof includes the variable inside and outside convective and radiative heat transfer coefficients; consequently, the overall R-value used is updated during each time step in the simulation based on prevailing outdoor and indoor conditions.

HVAC System

The mechanical systems serving the simulated facility are typical constant-volume packaged rooftop units. The heating stipend of the building is constant at 72ºF without humidification, while the cooling stipend is 76ºF with a maximum relative humidity of 60%. The supply air rate in the building is 1.5 cfm/ft^2, a typical value for large retail facilities to meet cooling peak demand. The outside airflow rate is 0.2 cfm/ft^2, a value in accordance with ASHRAE Standard 62-2001 for retail stores, malls, and arcades (ASHRAE 2001). During unoccupied hours, the outside air ventilation is set to a minimum value of 2.5% of the supply air, or 0.0375 cfm/ft^2.

The fan power is estimated based on the assumption of a total static pressure drop of 2 in. H_2O, a total supply flow rate of 150,000 cfm with a fan efficiency of 0.5 (motor 0.85, fan 0.6). These assumptions lead to a total fan power of 70 kW, which adds to the internal gains. Heat is provided by gas-fired units in the rooftop units. The heating units are assumed to have a constant efficiency of 0.8, based on the lower heating value.

The rooftop units assumed in this study operate with a full-load cooling EER of 9.0 (COP = 2.64). The EER includes the supply fan electric power as well as the degradation of the cooling capacity due to the heat added by the fan. The EER for rooftop units is established in accordance with ARI Standard 340/360 (ARI 2000). Under part-load conditions, when the cooling demand of the building is significantly lower than the capacity of the rooftop units, there are three options to meet the reduced demand: the compressors can be unloaded to a certain level, the compressors can be cycled on and off, or the total load can be split between the rooftop units servicing the same thermal zone so that only a few units operate under high load while others remain off. The first two options, unloading and cycling, compromise the compressor and refrigeration system efficiency. This, however, is partially compensated for by the general coincidence of lower outside air temperatures, leading to better heat rejection capacity and lower condensing pressure. The calculation of exact part-load efficiency requires detailed compressor and system modeling beyond the scope of this investigation, but this will not have any significant impact on the results. However, actual energy savings of a highly reflective roof could be somewhat lower than expected due to longer operation with lower part-load ratio when reducing cooling loads while leaving the equipment and design capacity the same.

The costs are evaluated based on the 2004 general service rate for commercial customers of the local utility in Minneapolis. The electric rate is \$0.031/kWh with demand charges of \$6.61/kW (October to May) and \$9.26/kW (June to September); the natural gas rate is \$0.481/therm.

Heat Transfer

The convective heat transfer coefficient on the outside surface of the roof is dependent on the wind speed. Limited research has been conducted in the area of building envelope convective heat transfer, and various existing correlations yield conflicting results (Beckman and Duffie 1991; ASHRAE 1997). The approach made here is the combination of a Nusselt number correlation for turbulent flow over a horizontal flat plate (Incropera and DeWitt 2002) and a constant term for natural convection at low wind speeds (Beckman and Duffie 1991). The Nusselt number is given as

$$\mathrm{Nu} = \mathrm{Re}^{0.8}\mathrm{Pr}^{0.33}, \tag{1}$$

while the free convection constant is estimated as 5 W/m^{2}K (0.88 Btu/h-ft^2-F). A curve fit of these equations using average air properties yields a convection coefficient of

$$h_W = \max[5, 2.5 + 1.19v] \tag{2}$$

with the convection coefficient h_W (W/m^{2}K) and the wind speed v (m/s).

The inside convective heat transfer coefficient on the roof surface is usually not of great significance since the thermal resistance of the wall is often very high compared to the added resistance of the convection coefficient. For simulations, the coefficient is often set to a default value of 0.5 Btu/h-ft^2-F (3 W/m^{2}K). However, since in this project a detailed analysis of the roof is desired, the inside convection coefficient is not constant but calculated based on airflow conditions and temperatures.

In an experimental investigation of heat transfer coefficients on the walls of a typical office room with ceiling ventilation, a correlation was developed that relates the convection coefficient solely to the ventilation rate (Fisher and Pedersen 1997). In that equation, h is the convection coefficient on the ceiling in W/m^{2}K and ACH is the air change rate per hour based on the supply airflow rate and the room volume:

$$h = 0.49\mathrm{ACH}^{0.8} \tag{3}$$

However, these results are assumed to have limited relevancy in a larger facility due to the special configuration of the room and diffuser and due to the negligence of free convection, the effect of different room and ceiling temperatures. Assuming undisturbed free convection dominates the heat transfer from the ceiling to the room, the coefficients will depend on the temperature difference of the ceiling surface and bulk room air. Furthermore, the coefficients will be different for a cool ceiling (winter) and a warm ceiling (summer). The buoyancy forces occurring with the density differences of colder and warmer air enhance convection when heavier, cooled air is sinking and warm air is rising toward the cooler ceiling (winter). When the ceiling is warmer than the room air (summer), the buoyancy suppresses convection, resulting in stratification disturbed only by the induced draft from supply air diffusers pending under the ceiling and the return air intakes. The application of Nusselt number correlations for free convection (Incropera and DeWitt 2002) on the bottom side of a horizontal plate are seen in Equations 4 and 5 for a cooled plate and a heated plate, respectively.

$$\mathrm{Nu} = 0.15Ra^{0.33} \tag{4}$$

$$\mathrm{Nu} = 0.27Ra^{0.25} \tag{5}$$

The length dimension used for the Nusselt number is 10 ft (3.05 m), an approximation for the distance between the support beams under the ceiling that disturb the flow.

For the simulations in this project, a superposition of the free convection approach and the diffuser-ventilation rate correlation is employed. Equations 4 and 5 are solved for actual temperatures and average air properties and then curve fitted for convenient use in the simulation program. The combination yields the mixed inside convection coefficients h_{in}:

$$h_{in} = 0.49\text{ACH}^{0.8} + 0.525(T_{roof,\,in} - T_{room})^{0.2446} \quad (6)$$

$$h_{in} = 0.49\text{ACH}^{0.8} + 4 - 0.0017T_{roof,\,in} + 0.0032T^2_{roof,\,in} - 0.0005T^3_{roof,\,in} \quad (7)$$

Equation 6 is for a warmer ceiling, Equation 7 for a cooler ceiling with respect to a bulk room temperature of the actual stipends T_{room} for heating and cooling.

Beside the convective heat transfer, the roof also exchanges radiation with the sky. The roof surface temperature, the sky temperature, and the infrared militance ε of the roof surface govern the radiative heat transfer. The sky temperature is the equivalent temperature of the sky acting as a blackbody that exchanges radiation with a surface on the earth. This temperature can be related to the dew-point and dry-bulb temperatures of the air and the time of the day. An empirical correlation of Berdahl and Martin (1984) is used here.

Roof Reflectance

For this model, the reflectance of the dark roof is set to 6%, a typical value for bituminous, asphalt roof coatings or black EPDM membrane (Cool Roofing Materials Database, 2000). Most reflective roofing materials available on the market are installed at 80% solar reflectance or higher. Despite this, a value of 65% is used as a conservative albedo for the light-roof simulations. Sixty-five percent is the minimum Energy Star level at the time of installation and allows for 15% degradation from an initial installation value of 80%.

Effect of Snow

A snow model considers the melting rate of snow accumulation on the roof. While the local snow height on the ground given in the hourly weather data accounts for the melting due to sublimation, radiation, convection, and rain, the additional melting rate of Equation 9 due to fusion on the warm roof surface also has to be considered. The melting rate is dependent on the heat flux through the roof, $\dot{q}_{roof}$, which is a function of the room temperature, T_{room}, and the overall thermal resistance of the roof with the outside convection coefficient:

$$\dot{q}_{roof} = \frac{1}{R_{roof}}(T_{room} - T_{out}) \quad (8)$$

$$\Delta h = \frac{\Delta E}{\rho h_{fw}} \quad (9)$$

Here Δh is the melting rate in feet per hour; ΔE denominates the change in energy in the snowpack on the roof. Only the base layer of the snowpack is considered, as conduction within the snow from the warmer snow at the roof surface into the colder snow is considered negligible. The change in energy of the snow, therefore, is set equal to the heat flux through the roof (Equation 8) integrated over a time step of one hour. The temperature of the base layer of the snow at the roof surface is a constant 32ºF (0ºC) since the snow is melting and equals T_{out}. The snow density, ρ, is assumed to equal the mean snow density of 5.05 lb/ft^3 (80.9 kg/m^3) from 1650 snowfall events over a 22-year period (1973–1994) measured at 28 weather stations within the climatic zones considered in this study (Roebber et al. 2002). The enthalpy of fusion, h_{fw} , for water at 32ºF (0°C) is 144 Btu/lb (335 kJ/kg). The heat transfer coefficient from the roof surface to the melting snow is set equal to the conductance of a water layer with a thickness of 20 mil (0.5 mm), i.e., 73000 Btu/h-ft^2-F (1100 W/m^{2}K).

SIMULATION RESULTS

The simulated data compared in this analysis include hourly energy consumption for heating and cooling (sensible and latent) and the roof surface temperature. The parameters varied are the roof insulation level (from R4 to R24), the roof albedo (black = 6% vs. white = 65%), and the presence of snow cover on the roof.

The origin of the difference in HVAC energy consumption of buildings with white and dark roofs lies in the roof surface temperature. In the summer months, from May until September, the daily peak temperature for the black roof is usually above 140ºF (60ºC), with a maximum peak value in June of 192ºF (89ºC), while the white roof peaks in the summer months around 100ºF (38ºC) with a June maximum of 122ºF (50ºC). An overview of the daily peak temperatures is given in Figure 1. We found it remarkable, compared to our assumptions prior to the start of this project, that the surface temperatures are largely independent of the insulation level. The magnitude of the heat loss/gain through the roof is insignificant compared to the incident solar load, even for the R-0 case.

As a consequence of the heating or cooling effect the roof temperature has on the building, the building load and the corresponding energy consumption for heating and cooling are different. A summary of the simulation results is given in Tables 1 and 2. These results reflect the use of an economizer and snow cover on the roof .

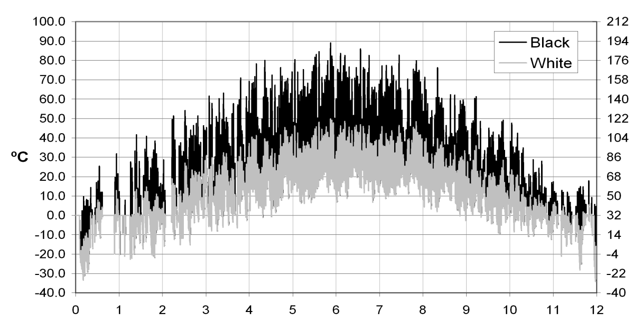

Figure 1   Roof surface temperature (R8 insulation).

Table 1. Summary of the Annual Heating Simulation Results[a]

R-value of Roof Insulation	R-0	R-4	R-8	R-16	R-24
Average Overall R-value of Roof	R3.82	R7.82	R11.82	R19.82	R27.82
Building Heating Load [Btu/ft²]					
Black	24,818	15,589	11,872	9,071	7,645
White	27,690	17,052	12,665	9,420	7,855
Difference	–2,871	–1,463	–793	–349	–210
Gas Consumption [Therm/1000 ft²]					
Black	310	195	148	113	96
White	346	213	158	118	98
Difference	–35.9	–18.3	–9.9	–4.4	–2.6
Peak Gas Consumption [Therm/h-1000 ft²]					
	0.31	0.27	0.24	0.21	0.18
Heating Cost [$/1000 ft²]					
Black	149	94	71	55	46
White	166	103	76	57	47
Difference	–17.3	–8.80	–4.77	–2.10	–1.26
	–12%	–9%	–7%	–4%	–3%

a. Economizer is used and roof is covered with snow at appropriate times.

Table 2. Summary of the Annual Cooling Simulation Results[a]

R-value of Roof Insulation	R-0	R-4	R-8	R-16	R-24
Average Overall R-value of Roof	R3.82	R7.82	R11.82	R19.82	R27.82
Building Cooling Load [Btu/ft²]					
Black	25,701	25,663	26,194	26,646	27,586
White	19,037	21,483	23,134	24,703	26,084
Difference	6,665	4,181	3,060	1,943	1,502
Cooling Consumption [kWh/1000 ft²]					
Black	2,545	2,541	2,593	2,638	2,731
White	1,885	2,127	2,291	2,446	2,583
Difference	660	414	303	192	149
Peak Cooling Power [kW/1000 ft²]					
Black	3.06	2.71	2.64	2.44	2.42
White	2.49	2.42	2.43	2.35	2.35
Difference	0.57	0.29	0.21	0.09	0.06
	19%	11%	8%	4%	3%
Cooling Cost [$/1000 ft²]					
Black	79	79	80	82	85
White	58	66	71	76	80
Difference	20	13	9	6	5
	26%	16%	12%	7%	5%
Annual Compressor Demand [$/1000 ft²]					
Cost Difference	$33.52	$17.55	$11.87	$5.82	$4.28

a. Economizer is used and roof is covered with snow at appropriate times.

The results show, as expected, higher heating load and lower cooling load for the white roof as opposed to the black roof. The annual heating load is strongly dependent on the insulation level of the roof. For example, the building with an R-24 insulated roof only consumes about 30% of the heating energy of an R-0 uninsulated building. The cooling energy usage does not follow this trend. Rather, it increases with the R-value due to the large internal load's inability to escape through the more highly insulated roof. This effect is reduced by the use of an outside air economizer in this case, but the difference will be more apparent later in this report when the simulation has been run without the outside air economizer.

The compressor peak demand is highest for the lowest R-value due to the higher transmission heat gains of the roof. Table 3 reflects only the differences between the two buildings with the black and the white roofs (difference = black – white). The data from this table should be less dependent on the specific assumptions made for the simulated buildings and henceforth rather universally applicable for similar building types.

In general, Tables 1, 2, and 3 show how increased roof insulation limits the impact the roof albedo has on the heating and the cooling load. While differences are considerable for low R-values, the simulations for R-24 show that heating penalty and cooling benefits both are roughly reduced by two-thirds, and a similar reduction applies for the peak demand difference. Although possible savings from increased albedo are smaller for higher R-values, the trend that cooling savings are greater than the heating penalty is independent of the insulation value.

During the summer months, the monthly compressor peak demand factors heavily into the monthly billed electric peak. The monthly reduction of compressor peak power due to the installation of a reflective roof is 10% to 15% during the summer months for an R-4 roof. The demand reduction drops to 3% to 5% during the summer months for an R-24 roof. The monthly reduction is plotted in Figure 2. Demand reduction can be of importance for building owners and utilities in demand side management (DSM) programs.

Table 3. Summary of Heating and Cooling Savings Per Year for a White Roof Compared to a Black Roof[a]

R-value of Roof Insulation		R-0	R-4	R-8	R-16	R-24
Average Overall R-value of Roof		R3.82	R-7.82	R-11.82	R-19.82	R-27.82
Heating Savings	Load, Btu/ft²	–2,871	–1,463	–793	–349	–210
	$/1000 ft²	–$17.30	–$8.80	–$4.77	–$2.10	–$1.26
Cooling Savings	Load, Btu/ft²	6,665	4,181	3,060	1,943	1,502
	$/1000 ft²	$53.98	$30.39	$21.26	$11.78	$8.89
Total Savings	Load, Btu/ft²	3,793	2,718	2,266	1,594	1,293
	$/1000 ft²	$36.71	$21.59	$16.49	$9.68	$7.63

a. White roof values subtracted from the black roof values.
Economizer is used and roof is covered with snow at appropriate times.

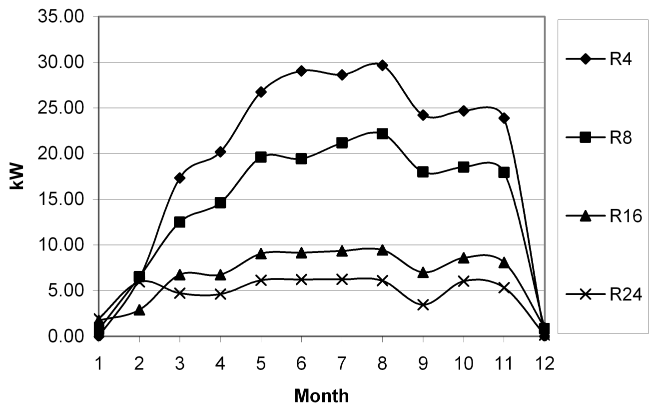

Figure 2 *Monthly reduction of compressor peak power demand.*

Table 4. Summary of Effects of Snow on the Simulation

R-value of Roof Insulation		R-4	R-24
Hours of Snow Cover		**615**	**1,511**
Building Heating Loads [Btu/ft^2]			
Black, With Snow		15,588	7,578
Black, Without Snow		16,054	8,115
	Difference	2.9%	6.6%
White, With Snow		17,052	7,798
White, Without Snow		17,859	8,610
	Difference	4.5%	9.4%
Building Cooling Loads [Btu/ft^2]			
Black, With Snow		33,988	38,974
Black, Without Snow		34,011	38,994
	Difference	0.1%	0.1%
White, With Snow		28,149	36,690
White, Without Snow		28,151	36,660
	Difference	0.0%	–0.1%

Snow Cover

Snow cover on the roof has the general effect of negating the impact of the color of the roof. When snow cover is present, all roofs are white. This removes the heating penalty of the light roof over the dark roof.

As mentioned in the previous section, a model was developed to determine an appropriate melting rate of the snow on roofs of varying insulation levels. This model was then applied to the simulation. The results reported thus far reflect this model.

The model was then re-run assuming the roof was snow-free the entire year. A comparison of the results is provided in Table 4.

At insulation value of R-4, the annual heating energy usage of the building simulated with snow is 2.9% and 4.5% lower, respectively, for the dark and the light roofs than the same building without snow. The total duration of snow cover with R-4 insulation is 615 h per year. For higher insulation values, the difference when considering the snow in the simulation becomes larger due to the longer duration the roof is covered. For a roof with an insulation of R-24, the annual heating energy is 6.6% and 9.4% higher for the dark and the light roof, respectively, without snow. The total time of the snow cover is 1,511 h per year.

Table 5. Effect of Snow Cover on White Roof Savings[a]

		With Snow		Without Snow	
R-value of Roof Insulation		**R-4**	**R-24**	**R-4**	**R-24**
Hours of Snow Cover		**615**	**1,511**	**0**	**0**
Heating Savings	**Load, Btu/ft^2**	–1,464	–220	–1,805	–495
	$/1000 ft^2	–$8.80	–$1.32	–$10.85	–$2.98
Cooling Savings	**Load, Btu/ft^2**	5,839	2,283	5,860	2,334
	$/1000 ft^2	$36.13	$11.36	$36.19	$11.36
Total Savings	**Load, Btu/ft^2**	4,375	2,064	4,055	1,839
	$/1000 ft^2	$27.33	$10.04	$25.34	$8.38

a. Neither case uses an economizer.

The energy cost savings for the white R-4 roof is 22% lower without the snow, but due to the addition of the demand cost savings, which are independent of the snow since they occur in the cooling season, the total cost savings of the white roof is only 7.5% lower when neglecting the snow cover. For an insulation value of R-24 where the influence of the snow is larger and the differences between the white and the dark roof are smaller, the energy savings without snow are 26% lower, while the overall savings are reduced by 17%.

Although one could imagine cases in which the snow cover would decide whether or not a reflective roof reduces overall yearly energy consumption or costs, the results for TMY2 data from Minneapolis show that even in the case of no snow cover the cooling energy savings are still higher than the heating energy penalty of a reflective roof. Thus, the inclusion of a snow model, as shown in Table 5, does not significantly alter the conclusions; i.e., even during a year with little snowfall, the white roof offers almost the same advantages.

Outside Air Economizer

The effect of operating without an economizer was also simulated. An outside air economizer provides a considerable reduction on the annual cooling energy consumption. Savings of 24% for an R-4 roof up to 29% for R-24 of the cooling cost were simulated for a black roof due to the addition of an economizer.

Without an economizer, there is a larger cooling load. This larger load results in considerably more energy savings for a non-economized building with a reflective roof, as can be seen in Table 6. The economizer does not affect the heating energy consumption.

Review the results presented in Table 6 with some scrutiny. The larger savings for the building without the economizer is because there is more room for improvement. For example, an R4 roof with an economizer improves from \$79/1,000 ft^2 to \$66/1,000 ft^2, while the same building without an economizer improves from \$104/1,000 ft^2 to \$86/1,000 ft^2. We recommend the installation of an economizer before money is spent on a reflective roof.

Effects of Increased Insulation

As a comparison point, the simulation also investigates the effects of increasing the roof insulation without changing the roof's reflectance. Table 7 shows the savings derived by incremental increases in the roof's insulation. In this simulation, the roof remained black, included snow cover, and used an economizer.

As expected, the incremental savings decrease as the level of insulation increases. Due to high internal loads, the heating season savings increase and cooling season savings decrease. This is because adding additional insulation extends the cooling season, but this is somewhat offset by the use of the economizer.

It is interesting to note that the savings from improving the reflectance at any given insulation level is higher than increasing the R-value of the roof by the increments chosen in this simulation, as can be seen by comparing Tables 3 and 7. For example, converting an R-16 roof to a white roof instead of increasing the R-value 8 h-ft^2-F/Btu to R-24 saves an additional \$3.99/1,000 ft^2. Even converting an R-4 roof to a reflective roof is half as effective as re-insulating it to the R-24 level. Further studies should investigate the return on investment for these two options.

Table 6. Effect of Economizer on White Roof Savings[a]

		With Economizer		Without Economizer	
R-value of Roof Insulation		R-4	R-24	R-4	R-24
Heating Savings	Load, Btu/ft^2	–1,463	–210	–1,464	–220
	\$/1000 ft^2	–\$8.80	–\$1.26	–\$8.80	–\$1.32
Cooling Savings	Load, Btu/ft^2	4,181	1,502	5,839	2,283
	\$/1000 ft^2	\$30.39	\$8.89	\$36.13	\$11.36
Total Savings	Load, Btu/ft^2	2,718	1,293	4,375	2,064
	\$/1000 ft^2	\$21.59	\$7.63	\$27.33	\$10.04

a. Both cases include snow cover.

Table 7. Savings for Incremental Increases in Roof Insulation[a]

Incremental Insulation Increase in R-value of Roof Insulation		R-4 to R-8	R-8 to R-16	R-16 to R-24	R-4 to R-24
Heating Savings	Load, Btu/ft^2	3,717	2,801	1,426	7,944
	\$/1000 ft^2	\$22.35	\$16.84	\$8.57	\$47.76
Cooling Savings	Load, Btu/ft^2	–531	–452	–940	–1,923
	\$/1000 ft^2	–\$1.63	–\$1.39	–\$2.89	–\$5.90
Total Savings	Load, Btu/ft^2	3,187	2,348	486	6,021
	\$/1000 ft^2	\$20.72	\$15.45	\$5.69	\$41.86

a. Roof is a black roof with snow cover and economizer in use.

Table 8. Annual CO_2 Savings of the White Roof[a]

R-value of Roof Insulation		R-4	R-8	R-16	R-24
CO_2 Savings	lb/ft^2	0.47	0.39	0.28	0.23
	kg/m^2	2.3	1.9	1.4	1.1

a. Economizer is used and roof is covered with snow at appropriate times

CO_2 REDUCTION

With increasing public awareness of global warming, it may be of interest to quantify possible CO_2 savings a reflective roof can achieve. The calculation is based on the assumption of 0.8 kg CO_2 per kWh electric generation predominantly from coal and 0.22 kg CO_2 per kWh of lower heating value of natural gas. Annual CO_2 savings are shown in Table 8.

INFLUENCE OF ALTERED PARAMETERS ON THE ANALYSIS

In this section, the influence of certain factors on the simulation results is studied. The base case will be the previously reported model with Minneapolis weather data. The factors investigated are energy prices, system efficiency, and TMY2 weather data from Denver.

Energy Prices

Lower natural gas, higher electricity costs, and demand charges would obviously increase the economic benefits of white roofs. In this analysis, break-even points of a high albedo roof depending on the energy costs but neglecting the electric demand charge are investigated for a range of electric and gas rates and shown in Figure 3. Savings occur whenever the point of the actual gas and electric rate lies below the respective line. Since the demand cost savings tend to be significant in many areas, this plot underestimates the total savings potential.

Efficiency of the HVAC System

The efficiencies of the components of the HVAC system, furnace, compressor/condenser, and fans, can affect the savings in a similar way as the energy costs outlined above. A doubling of the cooling efficiency corresponds to reducing by half the electric costs, with energy savings decreasing sharply

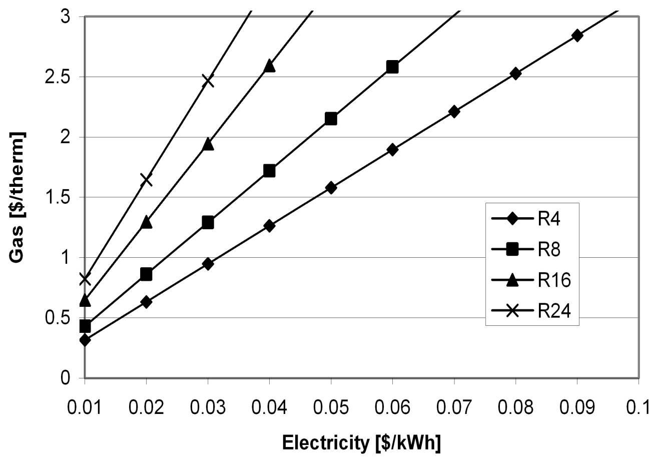

Figure 3 *Break-even energy cost. Savings below and losses above the respective lines.*

Table 9. Summary of Simulation Results for Denver, Co.

R-value of Roof Insulation			R4	R24
Heating Energy	Black	therm/1000 ft^2	88	24
		kWh/m^2	27.9	7.5
	White	therm/ft^2	102	25
		kWh/m^2	32.1	7.8
	Difference	%	–15.2%	–4.3%
	Difference	therm/1000 ft^2	–13.4	–1.0
	Difference	kWh/m^2	–4.24	–0.32
Cooling Energy	Black	kWh/1000 ft^2	3539	4162
		kWh/m^2	38.1	44.8
	White	kWh/ft^2	2736	3854
		kWh/m^2	29.4	41.5
	Difference	%	22.7%	7.4%
	Difference	kWh/1000 ft^2	803	307
	Difference	kWh/m^2	8.64	3.31
Compres-sor Peak Demand	Black	kW	210	169
	White	kW	169	159
	Difference	%	19%	6%
	Difference	kW/1000 ft^2	0.41	0.11
	Difference	kW/1000 m^2	4.5	1.2
Energy Cost	Difference	$/1000 ft^2	18.42	9.04
	Difference	$/m^2	0.198	0.097
Demand Cost	Difference	$/1000 ft^2	29.32	7.05
	Difference	$/m^2	0.316	0.076
Total Costs	Difference	$/1000 ft^2	47.74	16.09
	Difference	$/m^2	0.514	0.173

(approaching zero for low insulation levels) since heating losses are constant. Demand savings, however, although reduced by 50%, may still yield positive total savings. A highly efficient central cooling plant may reach almost twice the efficiency of the rooftop units assumed in the base case. On the heating side, only small differences in efficiency to the base case are likely, and, as evident from Figure 3, the effect is very limited. Overall, the influence of the system efficiency is very small at the current energy costs, especially at higher insulation values.

Denver Weather Data

The climate of Denver, as opposed to that of Minnesota, is characterized by warmer, shorter winters with more sunshine hours and less snow and by long, warm, and dry summers. Both the warmer winter and the longer summer increase the cooling load and, therefore, the advantages of a white roof. While the relative heating penalty is higher due to the increased sunshine in the winter and the smaller number of hours the roof is snow covered, the absolute heating penalty is lower; plus, the cooling savings, absolute and relative, are higher for Denver than for Minneapolis. Hence, as expected for a more southern location, the savings a white roof can offer are higher. A summary is given in Table 9, showing savings of $48/1000 ft^2 for R-4 insulation and $16/1000 ft^2 for R-24. These numbers are almost twice as high as for Minneapolis. The relation of demand cost savings to energy cost savings is similar, as is the relation of R-4 insulation total savings to R-24 total savings, a factor of approximately three. Despite increased solar radiation, the maximum roof temperatures are the same. However, the average roof temperatures in Denver are higher because of the milder winter.

CONCLUSION

High-albedo roofs lead to significantly lower daily roof temperatures of up to 72°F (40°C) lower than black roofs, hence reducing the cooling load and the compressor electric peak demand of the building. Despite a consistent heating penalty for the white roof in the winter, the savings of cooling energy for commercial buildings are higher than the additional heating energy, in terms of costs as well as CO_2. The savings of electric peak demand charges can be even higher than the energy savings. Total savings are dependent on the insulation level of the roof, with the highest savings potential for the lowest insulation. For R-4 insulation, expected savings are about three times higher than for R-24. Base case total savings are displayed in Figure 4.

The compressor peak demand savings from a white roof in the summer months range between 0.3 kW/1000 ft^2 (3.2 kW/1000m^2) for R-4 to 0.06 kW/1000 ft^2 (0.7 kW/1000m^2) for R-24. These savings may be interesting in association with demand side management (DSM) programs electric utilities offer their customers.

A sensitivity analysis shows that, for R-4 insulation, it would require only doubling of the current ratio of natural gas to electric costs or doubling of the cooling system efficiency

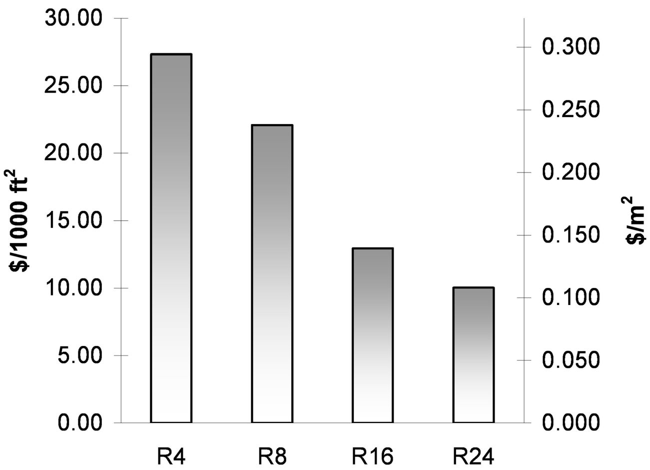

Figure 4 *Possible annual savings in the best case for the white roof in Minneapolis.*

to neutralize the energy cost savings. Also, electric energy savings are lower but still significant when an ideal outside air economizer is operated, whereas peak demand savings remain the same.

However, possible savings of high-albedo roofs in northern climate zones are small when compared to the total heating and cooling energy costs, in this case from 14% (for R-4) to 6% (for R-24 with economizer). If the total HVAC costs, including the fan energy and demand costs, were considered, the relative savings are only about half as much. When reduction of HVAC energy consumption is the goal, other measures may accomplish much higher savings (Freund et al. 2004), among them energy recovery systems such as enthalpy exchangers (up to 80% of the ventilation-dependent part of heating and cooling energy [Freund et al. 2003]) and more efficient central cooling systems instead of rooftop units.

For Denver, a warmer location than Minneapolis, the cost savings a high-albedo roof can achieve are approximately twice as high, the maximum temperatures and peak loads are almost the same, and all observed trends are similar.

Furthermore, the results show that the total cost savings between black and white roofs are higher than the HVAC cost differences when increasing the insulation level of the roof, e.g., from R-4 to R-8. This means that it can be more energy cost-effective to paint the roof white than to increase the insulation.

ACKNOWLEDGMENTS

Xcel Energy Corp. is gratefully acknowledged for funding this study. A word of appreciation is also due to Paul Riemer and Tom McDougall from The Weidt Group in Minneapolis for their cooperation.

REFERENCES

Akbari, H. 1998. Cool roofs save energy. *ASHRAE Transactions* 104(1):783–788.

Akbari, H., S.J. Konopacki, C.N. Eley, B.A. Wilcox, M.G. Van Geem, and D.S. Parker. 1998. Calculations for reflective roofs in support of Standard 90.1. *ASHRAE Transactions* 104(1):976–987.

Akridge J.M. 1998. High-albedo roof coatings—Impact on energy consumption. *ASHRAE Transactions* 104(1):957–962.

ARI. 2000. *ARI Standard 340/360, Standard for Commercial and Industrial Unitary Air-Conditioning and Heat Pump Equipment.* Arlington, VA: Air-Conditioning and Refrigeration Institute.

ASHRAE 1997. *ASHRAE Handbook—Fundamentals*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ASHRAE. 2001. *ASHRAE Standard 62-2001, Ventilation Requirements for Acceptable Indoor Air Quality.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Beckman, W.A., and J. Duffie. 1991. *Solar Engineering of Thermal Processes*, 2d ed. Hoboken, NJ: John Wiley & Sons.

Berdahl, P., and M. Martin. 1984. Characteristics of infrared sky radiation in the United States. *Solar Energy* 33(3).

Fisher, D.E., and C.O. Pedersen. 1997. Convective heat transfer in building energy and thermal load calculations. *ASHRAE Transactions* 103(2):137–148.

Freund, S., S.A. Klein, and D.T. Reindl. 2003. A semi-empirical method to estimate enthalpy exchanger performance and a comparison of alternative frost control strategies. *International Journal of Heating, Ventilating, Air-Conditioning and Refrigerating Research* 9(4):493–508.

Freund, S., S.A. Klein, and D.T. Reindl. 2004. Energy savings potential of energy recovery ventilation in an animal housing facility. *ASHRAE Transactions* 110(1):120–129.

Hildebrandt, E.W., W. Bos, and R. Moore. 1998. Assessing the impacts of white roofs on building energy loads. *ASHRAE Transactions* 104(1):810–818.

Incropera, F.P., and F. DeWitt. 2002. *Introduction to Heat Transfer*. Hoboken, NJ: John Wiley & Sons.

ISO. 1994. *ISO 7730, Moderate Thermal Environments-Determination of the PMV and PPD Indices and Specification of the Conditions for Thermal Comfort*. Geneva: International Organization for Standardization.

Klein, S.A., W.A. Beckman, and J.A. Duffie. 1976. TRNSYS—A transient simulation program. *ASHRAE Transactions* 82(1):623–633.

LBNL. 2000a. *Durability of high-albedo roof coatings*, http://eetd.lbl.gov/Buildings/RResearch/Albedo.html, Building Energy Analysis Group, Lawrence Berkeley National Laboratory.

LBNL. 2000b. Cool roofing materials database, http://eetd.lbl.gov/CoolRoofs/, Lawrence Berkeley National Laboratory.

Parker, D.S., J.R. Sherwin, and J.K. Sonne. 1998. Measured performance of a reflective roofing system in a Florida commercial building. *ASHRAE Transactions* 104(1):789–794.

Parker, D.S., Y.J. Huang, S.J. Konopacki, L.M. Gartland, J.R. Sherwin, and L. Gu. 1998. Measured and simulated performance of reflective roofing systems in residential buildings. *ASHRAE Transactions* 104(1):963–975.

Roebber, P.J., S.L. Bruening, D.M. Schultz, and J.V. Cortinas, Jr. 2002. Improving snowfall forecasting by diagnosing snow density *Weather and Forecasting* 18.

TRNSYS. 2002. TRNSYS Version 15, http://sel.me.wisc.edu.