A Guide for Estimating Potential Energy Savings from Increased Solar Reflectance of a Low-Sloped Roof

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ABSTRACT

A guidebook was developed that can be used to evaluate the net energy savings and resultant cost savings associated with changing the solar reflectance of low-sloped roofs. This paper presents an overview of the guide and excerpts to illustrate its use. The guide provides data and calculation procedures for estimating energy and cost savings. In most instances, the cooling cost savings associated with a change to a white roof surface (one with higher solar reflectance) exceed the heating cost penalty. If the difference between reduced cooling costs and increased heating costs is significant, it can affect the choice of membrane for a new roof or a re-roofed building. The guide helps the user estimate this energy cost difference and also describes how various factors influence potential energy savings and actual roof surface temperatures for different solar reflectances.

INTRODUCTION

This paper describes the methodology and limitations of an easy-to-use guide for calculating energy and cost savings resulting from a change in the solar reflectance of a low-slope roof.[1] The qualitative effects of solar reflectance are well understood.[2,3,4,5] Roof solar reflectance affects daytime roof surface temperature and hence impacts building heating and cooling costs. The biggest temperature effect occurs during the day, when the sun heats the roof and increases the heat flow into the building. Heat flow into a building is an asset when building heating is needed and a liability when building cooling is needed. Hence, roof reflectance can effect energy savings by impacting heating and cooling energy requirements. In terms of energy needs, a white (highly-reflective) roof is preferred during sunlit hours when building cooling is needed. Dark-colored roofs, which generally have low reflectances, are typically much hotter than white roofs during daytime hours and can easily reach temperatures of 165°F during clear, sunny conditions. Dark roofs are preferred during sunlit hours when building heating is needed. Thus, there is a counteracting influence of roof solar reflectance (color) on a building's heating and cooling energy requirements in many parts of the country.

The prevalence of asphaltic materials in built-up roofs means that many existing low-sloped roofs are black and have a low solar reflectance. Aggregate surfacing can increase the roof's reflectance. Roofs are also constructed using painted and unpainted metal roofs. Single-ply membranes are becoming more commonplace as a roof covering. With both painted roofs and single-ply membranes, a range of colors is available. Since low-sloped roofs constitute a significant portion of the overall thermal envelope of low-rise buildings and with the many available options for roof color, changing roof reflectance is now a viable option for reducing the energy costs of many buildings.

The most notable examples of reduced energy costs come from replacing black roofs by white roofs on buildings with high air conditioning loads. The prospects of reduced energy costs, along with the lower surface temperatures of white membranes, have been instrumental in creating a strong demand for high reflectance, white membranes. In general, white systems are more expensive. The cost differential is unique for a given situation and must be known by the decision maker.

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FACTORS THAT AFFECT THE ENERGY SAVINGS AVAILABLE FROM CHANGING ROOF SOLAR REFLECTANCE

The energy savings achievable by changing roof reflectance is predominantly influenced by:

- R-value of roof insulation
- Climate
- Building type and use
- Roof surface property changes

Each of these factors have varying degrees of influence on the potential for energy cost reductions resulting from reflectance change.

R-Value of Roof Insulation

The amount of roof insulation is a major factor influencing the energy savings potentially available from a change in roof reflectance. If a roof is well insulated, little heat is transported between the roof surface and the building interior. Thus, although a change in roof reflectance changes the roof surface temperature, the building energy use will experience little impact.

The influence of insulation on the savings from changes in roof reflectance is shown in Fig. 1. The values in Fig. 1 are derived from simulations with DOE-2.1B. Reflectance change will reduce energy costs the most for lower roof insulation levels. In cooling dominated climates, reductions in energy savings can also be significant for higher levels of roof insulation.

Climate

Climate has a strong influence on both building energy use and on the resulting energy savings available from changing roof reflectance. Since climate often dictates the size of the energy bill, it also affects the size of potential savings from reflectance change. Outdoor temperatures, solar radiation, and wind speed are significant climate factors.

Increasing roof reflectance results in a reduced summer cooling load and an increased winter heating load. Since there is a tradeoff, an increase in roof reflectance is typically most beneficial in hot climates where cooling load dominates most of the year. Climate effects on energy savings from reflectance change is illustrated in Fig. 2. This figure shows that potential savings are greatest in cooling season dominated climates. For the building configurations and climates examined for this work, the reduction in cooling load always exceeded the increase in heating load, but the distinction was small in northern climates. This trend does not imply that white is always better than black, because the benefits of savings must be compared to the relative costs of the white and black materials.

Building Type and Use

Different buildings use differing amounts of energy and, therefore, will benefit differently from roof reflectance change. Energy intensive buildings such as office or retail buildings often have large internal loads which extend the buildings cooling season. These building types could benefit even more from increasing roof reflectance since energy savings are most significant in cooling dominated climates.

In high-rise buildings, the roof makes up a small portion of the above-ground building shell. Although savings can justify a reflectance change for these buildings, the magnitude of savings will be small in comparison to the building's total energy bill. In low-rise buildings, however, the roof area can easily compose from 50 to 75% of the above-ground shell. Thus, the roof can be a major contributor to energy losses and gains, and savings from roof reflectance change may significantly reduce the building's total energy bill.

Roof Surface Property Changes

The solar reflectance of a roof changes over time, thus changing the performance of the roof as originally installed. Experience at Oak Ridge National Laboratory has shown that a black asphaltic surface becomes more reflective and that a white roof surface tends to become less reflective.[6] This change is likely due to surface contamination, chemical reactions, and other factors. These changes can be either beneficial or detrimental to a building's energy demands.

Quantifying the change in a roof's reflectance during its life can be very difficult. If this change can be quantified, then this guide provides a method for evaluating its impact on energy use. If a user wishes to make estimates of the degradation of roof reflectance, this guide can also be used to study energy use impacts of a range of estimated changes in reflectance.

METHODOLOGY

A guide was developed[1] that provides a simplified method for the user to estimate the cost savings from a change in roof reflectance. The method is based on factors developed from simulations of several building types in many climates.

Calculations were made of the decrease in energy required to cool a building and the increase in energy required to heat a building when the roof's solar reflectance is changed. The DOE 2.1B simulation program was used to make multiple simulations for five building configurations. Typical meteorological year (TMY) weather data files were used for all climate locations.

DOE 2.1B is structured with several subprograms.[7] Two of these are named LOADS and SYSTEMS. The LOADS subprogram calculates hourly heat gains and heat losses for each component of the building envelope. Space weighting factors are used to convert the predicted gains into loads. All calculations in the LOADS subprogram are made on the basis of a fixed, user-specified inside temperature for each conditioned space within the building. The SYSTEMS subprogram uses the output of the LOADS subprogram, user-specified HVAC system(s), operating schedules, and thermostat set points for conditioned zones to determine hourly values of heat which the cooling coil must remove during periods of cooling and the heating coil must provide during hours when heating is needed. Accumulative sums over the simulation period for each of these quantities are stored and reported as specified. The results presented here are derived from the SYSTEMS calculations.

Specific building and roof R-value configurations were simulated for different values of the roof's solar reflectance. The annual cooling energy and the annual heating energy values were found to vary linearly with the roof's solar reflectance, which made the method for calculating energy savings simpler and allowed easier extrapolation of results across climate locations.

The decrease in annual cooling energy divided by the product of the increase in roof solar reflectance and average daily solar radiation for the location is called the cooling factor here. Similarly, the increase in annual heating energy divided by the product of the increase in roof solar reflectance and average daily solar radiation for the location is called the heating factor.

The key to the method for calculating energy savings is determination of the cooling factor and heating factor for specific locations. These factors are multiplied by the annual average of daily solar radiation per unit area and the estimated increase in the roof's solar reflectance. The result of these two computations yields, respectively, the cooling energy savings and heating energy penalties for the building and location examined.

Heating and cooling factors were developed for five prototypical building cases. These cases were found to represent the range of interactive effects from different building configurations, combined with variations in roof solar reflectance, on heating and cooling energy changes. Building size was not found to significantly affect the results when other conditions were unchanged. Whether or not the building had a plenum space between the conditioned space and the roof and operating schedule and internal loading did influence the computed results. Summary descriptions of the five cases used to generate results for this document are given below.

For all the cases examined, the thermostat settings for cooling and heating were, respectively, 78°F and 72°F. Setback values were 84°F and 63°F for cooling and heating, respectively.

Building Ia:

The building for this case was 25 ft by 60 ft by 10 ft tall, providing a floor area of 1500 ft^2. The load schedule simulated office operation for weekdays only. Occupancy, lights, and equipment were specified for weekdays only. Peak loading included 10 people and 3 W/ft^2 for lights and equipment combined. Thermostat setback was used for nighttime and weekends. A suspended ceiling was included with the space between the roof and the suspended ceiling serving as a plenum.

Building Ib:

The building for this case was a two-story structure which simulated a retail store in a shopping mall. The building was not exactly rectangular. Gross floor area was 164,200 ft^2. The average floor-to-floor height was 19 ft. The exposed roof area was 76,240 ft^2. Peak loading on the first floor included 1102 people and 4.26 W/ft^2 for lighting. Peak loading on the second floor included 906 people, 4.26 W/ft^2 for lights, and 10 kW for equipment. There was a plenum between the conditioned top floor and the roof. A nighttime thermostat was used, but the building operated seven days a week.

Building IIa:

The building for this case consisted of two spaces. The large part was 120 ft by 322 ft by 24 ft tall. An adjacent office building was 32 ft by 66 ft by 12 ft tall. The combination has a gross area of 40,752 ft^2. The load schedule simulated a conditioned warehouse or light assembly plant. Occupancy, lights, and equipment were scheduled for weekdays and for Saturday morning in the office. Peak loading in the office included 16 people and combined 5.36 W/ft^2 for lights and equipment. Peak loading in the large building was less with 20 people and a combined 0.9 W/ft^2 for lights and equipment. Nighttime and weekend thermostat setback was used. The simulation did not include a plenum.

Building IIb:

The same building used for Building Ia was used in this case except the plenum was removed, internal loading was increased and operating time was extended. Loading schedule simulated office operation throughout the week and half a day on Saturday. No thermostat setback was used. Peak loading included 15 people and a combined 12.5 W/ft^2 for equipment and lights.

Building III:

The same building used for Building IIb was used in this case except internal loading and operating schedule were increased more. Loading schedule simulated a restaurant or fast-food operation. Peak loading included 30 people, 2.5 W/ft^2 for lights and 50 W/ft^2 for equipment. Occupancy, lights and equipment were scheduled for operation throughout the day and into late evening for every day of the week. No thermostat setback was used.

The five cases described above encompass buildings of different size, buildings with and without plenums, different schedules, and a range of internal loading. A few computations were made for Building Ia with the plenum removed. The results agreed almost exactly with computations made for Building IIa for the same locations and same roof R-value.

THE SIMPLIFIED METHOD

The simplified method for estimating potential cost savings from a change in roof solar reflectance is presented below. The method includes the following steps:

- Selection of building type and climate data
- Determination of roof insulation R-value
- Determination of local energy costs and HVAC system efficiencies
- Determination of the change in roof reflectance
- Selection of the heating and cooling factors
- Completing a savings worksheet to estimate annual energy and cost ($) savings

Selection of Building Type and Climate Data

The building type, Ia, Ib, IIa, IIb, or III, is selected to best represent the building being evaluated. The building choice determines which of the sets of Cooling/Heating Factors tables (or figures) should be used.

The appropriate climate data, heating and cooling degree days and solar radiation values, can be selected from available sources (data tables are provided in the guide). Solar radiation data typically do not consider the effects of water, snow, or shading on the annual global radiation received by a roof. The presence of snow tends to increase the benefits of a higher roof solar reflectance relative to a lower solar reflectance. Rain and shading tend to decrease the benefits. (See Interpreting Results section.)

Determination of Roof Insulation R-Value

The R-value required is the value for the roof insulation only since, in most cases, insulation R-value dominates the total R-value of a roof. Various sources are available that provide R-values for roofing materials. The *Roofing Materials Guide*[8] is a suggested source.

Determination of Local Energy Costs and HVAC System Efficiencies

The energy cost savings that result from a change in roof reflectance will vary with local energy rates. Doubling the local cost for energy would double the estimate of savings. Thus, savings will be dependent on local per unit energy costs and any reduction in (electric) demand-related charges.

If a building uses electricity for cooling and lower-cost gas for heating, increasing roof reflectance may be desirable even in an area where there is a substantial heating season. If there is a substantial difference between costs per unit of energy for cooling and heating, a building in a climate that is not dominated significantly by the heating or cooling season may still produce substantial savings from roof reflectance change.

Accurate energy costs should be obtained from local utilities. The guide provides costs for representative cities that can be used to develop a first estimate of savings. For electricity, the average cost per kWh should be obtained for the particular building size. This number is an average kWh cost based on standard kWh cost and typical demand costs for the particular building size. Cost histories may need to be examined here since projecting energy cost increases over long periods can lead to major errors.

Heating and cooling (HVAC) system operational costs are based on the amount of energy consumed by the heating or cooling system, but the increase in heating and decrease in cooling energy computed from the heating and cooling factors represent what the HVAC system must add or remove from the building space. Thus, the efficiency (heating) or COP (cooling) of these systems must also be estimated. The guide presents suggested values of efficiencies and COPs for cases where these values cannot be determined.

Determination of the Change in Roof Reflectance

The change in roof reflectance to be examined is determined based on manufacturer's data, values provided in the guide (in an appendix), or other estimates. Changes in surface infrared emittance are not considered in this guide for evaluating savings. This is done since surface infrared emittance has little dependence on surface color (solar reflectance) for presently available materials.

Selection of the Heating and Cooling Factors

Heating and cooling energy factors are selected from empirical data tables or figures generated from computer analyses using the DOE-2.1B program. The factors are provided by building type, roof R-value, and heating or cooling degree days.

The Savings Worksheet

The guide contains a worksheet for calculating energy cost savings as a result of roof reflectance change. The worksheet is completed by providing readily obtainable information on a particular building and climate and by selecting data from the data tables in the guide. Figure 3 shows a completed worksheet for the example calculation described below.

EXAMPLE: ROOF REFLECTANCE CHANGE FOR AN OFFICE BUILDING

A small office building in Albuquerque has 5,000 square feet of low-sloped roof. Re-roofing is being planned and use of a light-colored membrane having an estimated solar reflectance of 0.7 is being considered as opposed to a dark membrane with an estimated solar reflectance of 0.2. The lighter membrane will cost 20 cents more per sq. ft. ($1000 added). The insulation R-value of the new roof will be 4 ft^2-hr-°F/Btu. The building is electrically cooled and gas heated. The building has a ceiling plenum used to conceal air distribution ducts.

Part A

Will energy cost savings from the light-colored membrane pay back it's added cost within five years?

Solution. The building has a ceiling plenum and is not an intensive energy user. Thus, building Type Ia most nearly matches this building. Instead of obtaining current local energy costs, the user decides to use the energy cost rates provided in an appendix of the guide as approximations. The estimated change in solar reflectance is 0.7 - 0.2 = 0.5. The worksheet is completed as shown in Fig. 3.

Conclusions. The roof reflectance change reduces energy use by 26.9 MBtu/year providing a net annual energy cost savings of approximately $643/year (Fig. 3). Payback of the additional expense of the light membrane will occur in 1.6 years ($1000 / $643). Although Albuquerque ~~has a~~ heating-season dominated year, savings from increasing roof reflectance are still substantial, and the payback period is less than five years.

Part B

Assume that the roof insulation for this building was R-8 instead of R-4 as in Part A above. Will the energy cost savings from the light-colored membrane still pay back within five years?

Solution. The new values needed in Part A as a result of the increased R-value of the roof are:

R-Value = 8
Cooling Factor = 5.2
Heating Factor = 1.25

Conclusions. Changing these values on the worksheet results in a savings of $410 as a result of the reflectance change. Payback of the additional expense of the light membrane occurs in 2.5 years ($1000 / $410 = 2.5). The payback occurs within five years for a roof R-value of 8 as well.

LIMITATIONS

The principal purpose of the guide is to answer the question:

What is the net impact of increasing the solar reflectance of a roof on the energy use of a particular building?

The guide is intended to shed quantitative insight and aid in decision making; it is not intended to provide answers with scientific precision. The heating and cooling factors are based on computer simulations of annual building energy use with typical meterological year weather data as input. These simulations kept some values as constants which would normally vary throughout the year as the weather changes. Also, some factors that would affect energy use were not included so that the procedure presented here could be kept simple. The following limitations are noted:

1. The roof's reflectance of solar energy throughout the year is characterized by a single value of solar reflectance and the reflection of sunlight is the same from all parts of the roof for all seasons.

2. The roof is dry. Any effect due to the presence of accumulated water as a liquid, frost, or snow is not treated.

3. The roof is totally exposed to the sky. No external shading such as trees or other structures was considered.

4. The infrared emittance is assumed to be the same for all surfaces.

5. Reference to a roof indicates a near-flat roof. The construction consists of a metal deck, insulation, and an exterior waterproof covering. Pitched roofs and roofs over attic spaces are not considered. Cases presented do include that of a suspended ceiling below the roof assembly.

6. Changing roof reflectance can affect the energy use of a building and can also affect the size of heating or cooling equipment needed. A change in energy use or a change in equipment size can possibly lead to cost savings. Cost savings from a change in energy use could benefit both existing buildings and new building designs, while a cost savings from a change in equipment size would typically benefit new building designs. The savings evaluated here pertain only to the savings from changes in heating and cooling energy use, and potential equipment cost benefits would have to be evaluated separately.

A multitude of interrelated factors affect building energy use. Definition of periods of heating and cooling are determined by coupling of these factors. Correlations of computed results for selected conditions, such as those presented, are useful to show trends and help quantify effects; however, they cannot and should not be interpreted as exactly matching every unique setting.

The guide is intended to provide a straightforward aid to users in estimating the energy conservation potential offered by use of reflective roofs. The method is based on simulations using DOE-2.1B, which has been corroborated by some experimental measurements. However, many considerations emerge when applying the technology of higher reflectance roof surfaces, and the procedure presented in the guide is not intended to imply that analysis of changes in energy use from application of this technology is simple.

INTERPRETING RESULTS (CONCLUSIONS)

A method is presented for estimating the savings for a change in roof solar reflectance. Savings decrease with increased roof insulation R-value. The heating and cooling factors provided do not account for changes in heating or cooling energy use caused by changes in R-value of roof insulation. The factors do account for the interactive effect of roof insulation R-value on potential savings from a change in roof solar reflectance. Therefore, the data in the guide cannot be used to evaluate effects of insulation R-value on energy use or costs, and the user can only evaluate impacts from solar reflectance given a roof insulation R-value as a starting point.

In terms of dollar savings, increasing roof reflectance may or may not be cost effective. A positive dollar savings indicates reduced energy costs from the reflectance increase. A negative result indicates an increase in energy costs and thus a penalty for the increase in roof reflectance. Users must evaluate the benefits of the cost savings and the costs of achieving the increased roof reflectance to determine whether an investment in the increased reflectance is attractive.

Because the effects of snow, rain, and shading are not explicitly addressed in the heating and cooling factors or in the solar radiation data, some adjustments to the estimates of changes in heating and cooling energy due to increased roof reflectance may be required if snow, rain, or shading are judged to have a significant impact. Snow tends to increase benefits, and thus the savings estimates will be more conservative if snow is ignored. Rain will have an impact on savings, but if most of the daytime hours during the cooling season do not have rainfall, the effects of rain can usually be ignored. Significant shading on the roof (more than 10% shaded for most of the middle six hours of the day) by trees, buildings, or other causes must be considered, and the judgment of a professional is probably required to make an estimate of the impacts of significant shading.

ACKNOWLEDGMENTS

This work was conducted as part of the national program for Building Thermal Envelope Systems and Materials. This research was supported by the Office of Buildings and Community Systems, U.S. Department of Energy, under contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

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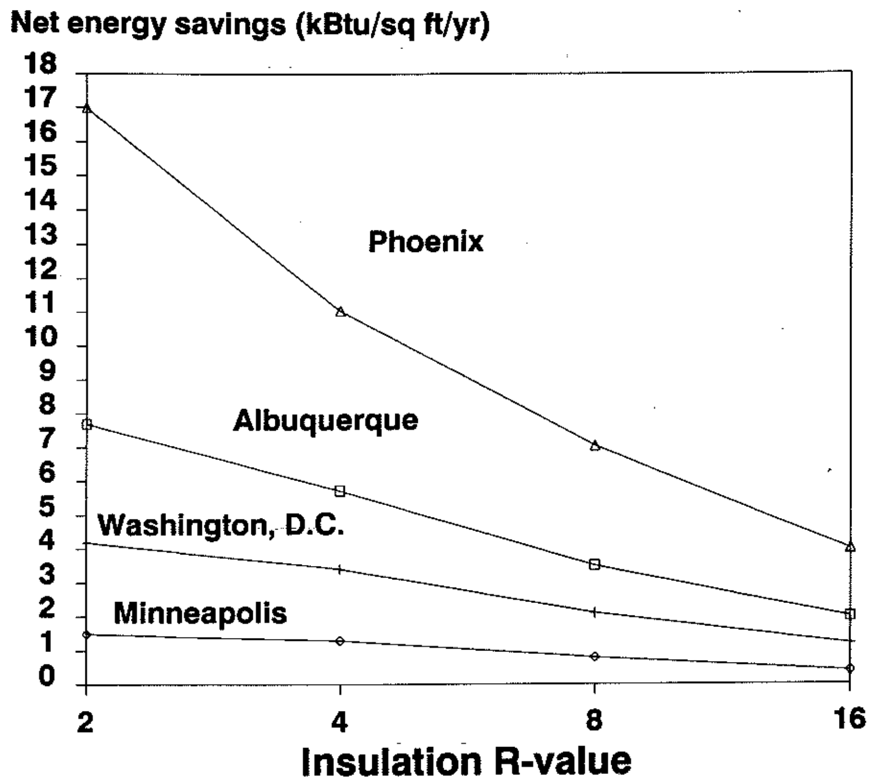

Figure 1. Effect of R-value on net energy savings for an increase of 0.5 in roof reflectance. The effect of R-value on the net energy savings (cooling savings minus heating penalty) due to changing roof reflectance is dramatic. These impacts are shown here for four diverse climates.

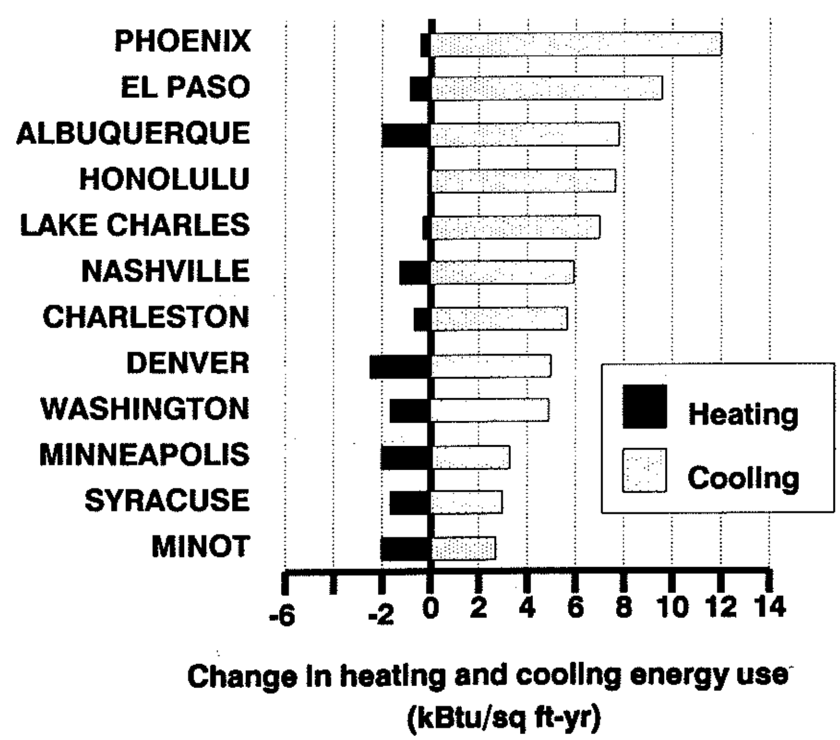

Figure 2. Cooling energy load savings (positive values) and heating energy penalty (negative values) for a change of 0.5 in roof reflectance for several locations. These values are for a roof insulation R-value of 4 hr-ft2-°F/Btu.

ENERGY SAVINGS ESTIMATES FOR HIGHER ROOF SOLAR REFLECTANCE
WORKSHEET

SITE INFORMATION

Building Type: Ia - Office   Cooling Degree Days 1316

Location: Albuquerque   Heating Degree Days 4291

Roof Insulation R-value (hr-ft^2-^{o}F/Btu): 4   Solar Radiation 1828

COST OF ENERGY FOR HEATING AND COOLING

(A) COOLING SYSTEM COP	(B) HEATING SYSTEM EFFICIENCY (%)	(C) COOLING FUEL COST ($/10^6 Btu)	(D) HEATING FUEL COST ($/10^6 Btu)	(E) COOLING ENERGY COST ($/10^6 Btu) [C / A]	(F) HEATING ENERGY COST ($/10^6 Btu) [(D / B) x 100]
1.7	75	31.9 (elec.)	4.7 (gas)	18.8	6.27

For calculation of energy costs: electricity – $/10^6 Btu = ¢/kWh x 2.93
natural gas – $/10^6 Btu = ($/therm or $/CCF) x 10   #2 fuel oil – $/10^6 Btu = $/gal x 7.15

CALCULATION OF ESTIMATED ENERGY SAVINGS

(1) SOLAR RADIATION (Btu/ft^2/day)	(2) ROOF AREA (ft^2)	(3) CHANGE IN REFLEC-TANCE	(4) COOLING ENERGY FACTOR	(5) HEATING ENERGY FACTOR	(6) DECREASE IN COOLING ENERGY (10^{6}Btu/yr) (1 x 2 x 3 x 4) / 10^6	(7) INCREASE IN HEATING ENERGY (10^{6}Btu/yr) (1 x 2 x 3 x 5) / 10^6
1828	5,000	0.5	8.3	2.4	37.9	11.0

ANNUAL COST SAVINGS ESTIMATE

(8) COOLING COST REDUCTION ($/YR) 6 x E	(9) HEATING COST INCREASE ($/YR) 7 x F		(10) NET COST SAVINGS ($/YR) 8 – 9
712	69	=	643

Figure 3. Sample worksheet with values entered for the example discussed in the paper