Economic comparison of cool and grey roofs of a small office building in the USA

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Abstract. EnergyPlus V9.0 simulations of a typical small office building prototype in five USA cities (Albuquerque, Atlanta, Buffalo, San Diego, Rochester) indicate that adding a cool roof (albedo 0.6) for an aged grey roof (albedo 0.2) would reduce the annual energy and annual energy cost in all hot dry or humid cities (Albuquerque, Atlanta, San Diego) and in severe cold or mixed humid cities (Buffalo, Rochester). The CO2, SO2, and NOX savings are positive in all selected cities. This work considers the economics of using cool roofs of an office building in the USA by performing a 20-year life-cycle cost analysis that compares each type of roof to a grey roof. The 20-year net present values (NPVs) of annual conditioning (heating + cooling) energy cost savings were calculated. The life cycle cost savings (NPV of annual streams – initial cost premium) of cool roofs have both positive and negative values. The NPV with the cool roofs is from -17.3 USD/m2 in Rochester to 6.5 USD/m2 in San Diego. Among the five cities in the USA, Albuquerque, Atlanta, and San Diego were able to apply the cool roofs since they all have positive NPV, while Buffalo and Rochester were unsuitable to apply the cool roofs methods because of the negative NPV. Owners concerned with urban heat island mitigation and slowing climate change may prefer cool roofs

1 Introduction

1.1 Background

The USA became the world's second-largest energy consumer in 2009 with 2,170 million tons of crude oil, coal, natural gas, nuclear power, and renewable sources (China Said to Pass U.S. As World's Biggest Energy Consumer, 2010). In addition, buildings consume in the USA about 38% of total energy use and contribute to 40% of CO2 emissions in the USA (2022). More CO2 emissions facilitate summer urban heat islands and contribute to more energy consumption, heat-related deaths, peak electricity use and other ecologically adverse impacts.

Facing problems of energy sources security, global warming, and ecological pollution, the USA has taken a series of measures to decline energy consumption. As a part of the building envelope which is an important element for building energy efficiency, the roof has a great influence on energy saving for a multi-story building. An alternative effective way to reduce solar heat gain and energy consumption in buildings is to increase the surface reflectance of buildings like the cool roof. Cool roofs can increase the reflectivity of the exterior surface of the buildings to reflect more solar radiation than bare roofs, reducing the surface temperature and ceiling temperature, thereby reducing the cooling energy use. What's more, it can help to reduce building energy consumption and ensure sustainable development of the environment [1].

1.2 Background

White is the most general colour for "cool roofs". A white roof can reflect 55-80% of incident sunlight making its roof surface cool on a clear summer day [2]. This decreases heat transfer through the roof and makes the space below the roof more comfortable in unconditioned buildings. An air-conditioned non-residential building applying the cool paint with a solar reflectivity of 0.73 can decrease cooling energy use by 19% on average in Trapani [3].

On the other hand, when the solar reflectance of roof surfaces increases, the earth's surface would reduce the amount of heat absorbed and transferred into the atmosphere, which neutralizes global warming. Studies estimate that approximately 16,000t CO2eq could be offset in 30 years with the installation of about 115,000m2 of high-reflective surfaces [4].

Compared with grey roofs which increase the urban heat island effect, cool roofs provide social benefits to make cities cooler. Whereas comparisons between these two roofs are rare. There have been some published case studies to compare cool roofs to grey roofs in the USA (Cool Roofs in Washington, D.C.at 2009; United States Department of Energy Headquarters White Roof). However, we could not find a comprehensive comparison of cool roofs in the different climatic regions of the USA.

This paper presents a 20-year life-cycle cost analysis (LCCA) for cool and grey roofs by simulation in five cities in the USA. We seek to present an economic

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evaluation of cool roofs in searching for which climates zone are better off using cool roofs.

2 Methodology

This paper pays attention to the annual conditioning (heating + cooling) energy savings gainable by decreasing roof solar absorbed and increasing heat loss by evaporation. It simulates energy savings and emission reductions in five cities which are in various USA climates by increasing the albedo of roofs or evaporation and insulation of roofs on code-compliant prototypes of small office buildings. Then, it processes economic analysis including net present values for two roofs by 20-year LCCA.

2.1. Roof simulations

2.1.1 Overview of simulations in the current study

The annual heating and cooling energy use of a prototype small office building were simulated with an aged white roof (albedo 0.6) for an aged grey roof (albedo 0.2) in five representative USA climates. Heating and cooling energy use were calculated by subtracting heating and cooling energy use with high roof albedo. Site energy savings were then used to estimate site energy savings, source energy savings, energy cost savings, and emission reductions.

2.1.2 Prototype design

Figure 1 details prototypes of the top floor of an office building. Table 1 shows the building envelope characteristics, ventilation and infiltration rates, internal energy use, operating schedules, and cooling and heating set points compliant with prescriptive requirements or recommended design values in current USA building energy efficiency standards.

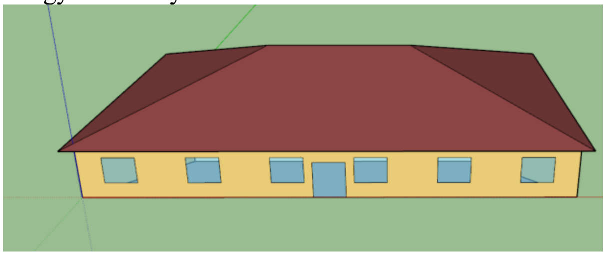

Fig. 1. View of the model and the case room

Table 1. Characteristics of the simulated office building prototypes.

Layout	(Office room, corridor)
Total floor area (m2)	510.9
Roof area (m2)	101.9
Story height (m)	3.0
Internal heat (w/person)	120
lights (W/m2)	10.8
Electric equipment (W/m2)	6.8
Infiltration (ac/h)	0.1
U-value of roofs (W/m2k)	2.5
U-value of walls (W/m2k)	0.3
U-value of floor (W/m2k)	0.2
Thermostat Setpoint(°C)	23.8: Cooling 21.1: Heating
Thermostat Setback(°C)	29.4: Cooling 15.5: Heating

2.1.2 Modelling heating and cooling energy use

The EnergyPlus building energy model (EnergyPlus V9.0) is used in this study to build a model, and simulate annual heating and cooling site energy use (heat energy per unit conditioned roof area). The prototype was modelled with an aged white roof (albedo 0.6) for an aged grey roof (albedo 0.2). Simulations were performed in five USA cities spanning five climate zones: Marine (Albuquerque), Cold/ Very Cold (Rochester), Mixed Humid (Buffalo), Hot humid (Atlanta), and Hot dry(San Diego) (Figure 2).

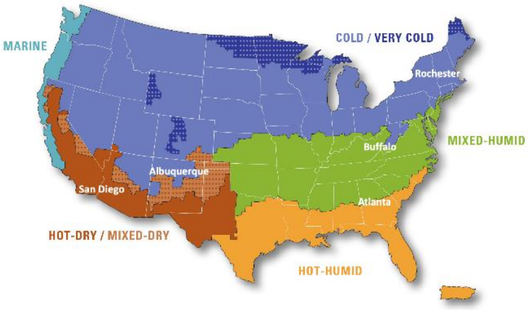

Fig. 2. Map of USA climates zones and cities

2.2 Life-cycle cost analysis (LCCA)

LCCA was adopted to determine the net savings for cool roofs and grey roofs over a 20-year life. Some parameters account for the LCCA, including roof installation, energy-related benefits (cooling/heating costs, A/C downsizing), avoided power plant emissions (CO2, NOx, and SO2), and equivalent CO2 offset by global cooling.

2.2.1 Roof installation costs

For architectural reconstruction, the cool roof was added upon the grey roof. So compared with the cool roof, the installation, replacement and maintenance costs for the grey roof were zero. Due to the wide range of cool roof costs, the LCCA only includes the medium expensive category. The service life for cool roofs was 20 years [5]. There is no need to consider the main difference of power washing to maintain high solar reflectance for cool roofs. We assume the grade of waterproofing for the grey roof was A. The LCCA does not include the added cost of waterproofing upgrading.

According to the Economic comparison of cool, and grey roofs in the USA, the installation fee is 22 USD/m2[5]. Combining the installation fee per square meter with the total cool roof area of 101.9 m2, the total installation fee is 2241.8 USD.

2.2.2 Heating and cooling site energy, and source energy cost savings

Heating and cooling site energy savings were computed directly by EnergyPlus simulations. Heating and cooling source energy savings were calculated by multiplying each site energy savings by the appropriate source-to-site ratio (f=3.147 for electricity, 1.05 for natural gas), and then summed to yield source conditioning (heating plus cooling) energy savings. Likewise, heating and cooling energy costs savings (USD per unit conditioned roof area) were computed by multiplying each site energy savings by the appropriate energy price (Table 2) (Electricity Rates & Prices per kWh 2022) and then summed to yield conditioning energy cost savings.

Table 2. U.S electricity price + natural gas price for commercial buildings (Electricity Rates & Prices per kWh 2022)

Electricity price ($/kWh)	Natural gas price ($/kWh)
0.1773	0.032

2.2.3 Power plant emission savings

Finally, reductions in CO2, NOx, and SO2 emissions from heating and cooling energy savings were calculated by multiplying heating and cooling site energy savings by the appropriate energy transmission factor (0.9 for electricity) and pollutant emission factor [6], and then summed to yield emission savings for each pollutant. Mercury emission reductions are not presented because USA-specific electricity and coal mercury emission factors could not be identified.

Table 3. Electricity and natural gas emission factors

	CO2 (kg/kWh)	NOx (g/kWh)	SO2 (g/kWh)
Electricity	0.429	0.65	2.7
Natural gas	0.3292	0	0

2.2.4 Power plant emission savings

To calculate the net present value (NPV) of life cycle energy cost savings, we assume that the roof yield constant annual energy cost savings over its N year service life, C0 means the initial cost premium, Ci means the cash flow in the i year. Then given a real (inflation-adjusted) annual rate of return r to 3%, the net present value (NPV) is

$$NPV = \sum_{i=1}^{N} C_i(1+R)^{-i} - C_0 = C_i[1-(1+r)^{-N}]/r - C_0 \quad (1)$$

3 RESULTS AND DISCUSSION

3.1 Simulations

3.1.1 Site and source energy savings

Figure 3 shows the annual site and source energy savings per unit conditioned roof area in a cool roof for the simulated small office. Raising the cool roof albedo to 0.60 (aged cool roof) from 0.20 (aged grey roof) decreases the annual site electricity use by 5.4 kWh/m2 (Buffalo) to 10.8 kWh/m2 (San Diego), and annual source electricity use by 6.8-34.2 kWh/m2 (where Rochester < Buffalo < Atlanta < Albuquerque < San Diego), respectively.

Relative to the natural gas energy type, the electricity energy type has more site energy saving and source energy saving. It has 9.7 kWh/m2 electricity type (Albuquerque) in site energy in 30.7 kWh/ m2 in source energy. While it only has -0.8 kWh/ m2 (Albuquerque) natural gas energy type in site energy saving and -0.9 kWh/m2 (Albuquerque) natural gas energy type in source energy saving. It was the same trend in other 4 cities, like Rochester, Buffalo, Atlanta, San Diego. However, the site energy savings in Rochester and Buffalo were lower than in other cities. It is because they have long winter days, they might require much more energy in winter by using more electricity and natural gas after having cool roofs. Therefore, the total site and source energy savings are smaller in Rochester and Buffalo compared to other temperate climate cities like Atlanta, Albuquerque, San Diego.

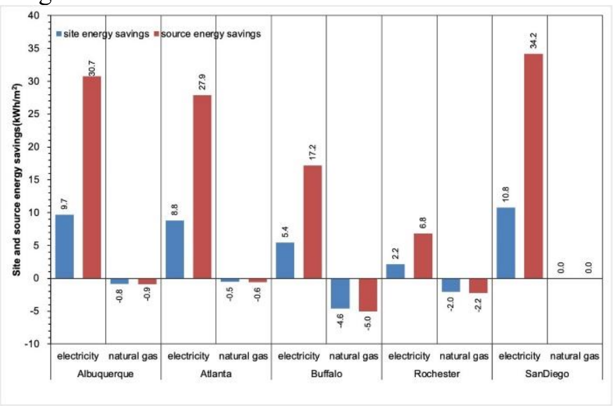

Fig. 3. Annual site and source energy savings per unit conditioned roof area in a cool roof for the small office prototype

3.1.2 Emission savings

CO2 emission savings ranged from 0.4 kg/m2 (Rochester) to 5.1 kg/m2 (San Diego) in the cool roof; CO2 savings in the cool roof were all positive in various climate zone. NOx emission savings ranged from 1.6 g/m2 (Rochester) to 7.8g/m2 (San Diego) in the cool roof. Finally, SO2 emission savings ranged from 6.5 g/m2 (Rochester) to 32.4 g/m2 (San Diego) in the cool roof (Figure 4). It should be noted that while CO2 emission factors are independent of combustion system type and boiler firing configuration [7], the NOx and SO2 emission factors used here are for spreader stokers characterized by the US EPA [8], and may or may not represent building furnaces in the USA.

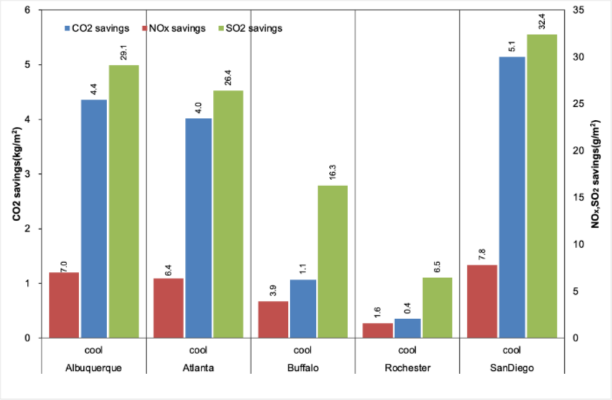

Fig. 4. Annual site and source energy savings per unit conditioned roof area in a cool roof for the small office prototype

3.2 Economic comparison

3.2.1 Energy cost savings

Energy cost savings in cool roofs ranged from 0.3 USD/m2 (Rochester) to 1.9 USD /m2 (San Diego). The biggest energy cost saving of is using cool roofs is San Diego, following Albuquerque, Atlanta, Buffalo, Rochester. The medium data in energy cost saving is 1.5 USD/m2 in Atlanta. In cities that are cold or mixed humid (Buffalo and Rochester), the energy cost saving is relatively smaller than other cities which are 0.3 USD/m2 and 0.8 USD/m2 respectively. (Figure 5)

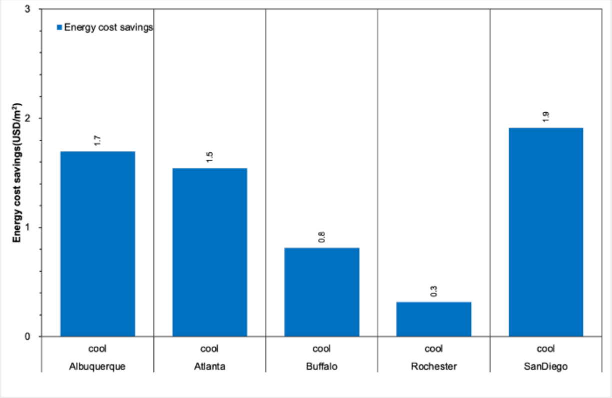

Fig. 5. Energy CO2 price chart in the cool roof for the office prototype

3.2.2 Energy cost savings

Compare to grey roofs, 20-year NPV savings in cool roofs ranged from -17.3 USD/m2 (Rochester) to 6.5 USD /m2 (San Diego) (Figure 6). It can be observed that the NPV in Buffalo and Rochester are negative, which means that cool roofs were not economic in either two place. These two cities are cold or mixed humid cities. Therefore, affected by the climate, the long winter time, the cold roofs have more part of increased energy consumption in winter and less part of energy saving in summer. Therefore, in general, the energy savings in these two cities, Buffalo and Rochester, are smaller than the other cities. Since the total energy savings are reduced, their annual economic benefits are also reduced. With the high initial investment, these two cities do not recover their costs and thus have negative economic benefits.

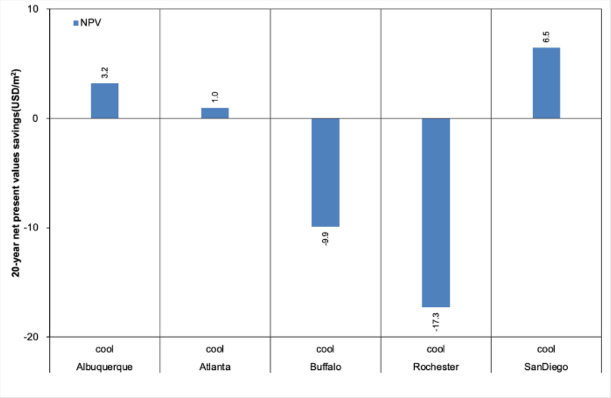

Fig. 6. Net present values (NPV) savings for cool roofs for the office prototype

3.3 Discussion

3.3.1 Simulation discussion

Office site and source energy savings in cool roofs tend to increase as one moves from the coldest cities to the warmest cities (Rochester, Buffalo, Albuquerque, Atlanta, San Diego) (Figure 2) because of the different climate zones. From Figure 3, we can see that the electricity energy type and natural gas energy type in Rochester both were the lowest data among the five places. It shows it has the smallest site energy saving and source energy saving. While other cities (Albuquerque, Atlanta, Buffalo, San Diego) seem to follow the climate zone change, they also increase as one migrates from the coldest cities to the warm/ humid ones.

According to the site energy savings data, although Rochester has almost no site energy savings in its small office building, it still has a positive total energy saving overall (see Figure 3).

3.3.2 Life-cycle analysis discussion

The energy cost savings in cool roofs tend to increase as one moves from the coldest cities to the warmest cities (Figure 4), like from Rochester which is in a cold area to San Diego in a hot-dry area.

Cool roofs have also grown more popular in recent years, the LCCA based on the simulation at present shows both NPV in cool roofs have both positive and negative (Figure 6). When annualized over 20 years, however, these premiums for cool roofs are just ranged from 0.3 USD/m2.year to 1.9 USD/m2.year. This annualized cost difference should not deter building owners in warm cities who are relatively unconstrained by budget to select white roofs to capture their positive environmental qualities of more CO2, NOx, SO2 savings, and heat island mitigation potential.

4 CONCLUSION

EnergyPlus simulations of standard-compliant USA small working office prototypes in five USA cities (Albuquerque, Atlanta, Buffalo, San Diego, Rochester) indicate that substituting a cool roof (albedo 0.6) for an aged grey roof yields positive annual site energy savings, source energy savings, CO2 savings, NOx savings, and SO2 savings in all hot dry or humid cities (Albuquerque, Atlanta, San Diego) and cold zone cities (Rochester) In these four cities, a cool roof on an office building yields annual savings per unit conditioned roof area of -2.2 – 34.2kWh/m2 source energy, 0.4 – 5.1kg/m2 CO2, 1.6 – 7.8g/m2 NOx, and 6.5 – 32.4g/m2 SO2.

LCCA was intended to address the one principal types of environmentally friendly roofing strategies which is white. Among these, summer rainfall patterns, climate, energy prices, and stormwater management fees and policies may greatly influence the results of the comparison. Cool roofs feature both positive and negative life cycle cost savings in NPV. The available cool roofs range in NPV is from -17.3 USD/ m2 in Rochester to 6.5 USD/m2 in San Diego. Albuquerque, Atlanta, and San Diego were allowed to use cool roofs among the five US cities since they all have positive net present values, while Buffalo and Rochester were not able to use cool roofs because they have no economic effects. It is difficult to therefore present a simple conclusion for environmentally friendly roofing, but it has become common for people not to opt for dark roofs that increase building energy costs, summer urban heat islands, and global warming.

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