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Cool Roof Use in Commercial Buildings in the United States: An Energy Cost Analysis

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ABSTRACT

Solar radiation absorption and reflection on roof surfaces affects heating and cooling energy demand. Prior studies of energy costs associated with the long-term trend toward using highly reflective roof membranes, (i.e., "cool roofs") are reviewed and shown to have conflicting results in terms of the impact on heating costs. Also, the guidance for membrane reflectivity selection for building designers in terms of climate zone and/or heating and cooling degree days has not been clear. In this paper, both 2015 energy costs and insulation codes by state have been used to model the impact of cool roofs on building energy demand. Assuming natural gas as a heating energy source and electric air-conditioning, then the modeled cool roofs are shown to provide a net cost savings across all cities studied, even when long-term membrane reflectivity values are considered. When electric demand charges are factored in, there is little correlation between the magnitude of savings and location climate.

INTRODUCTION

Reflective roof membranes, otherwise known as *cool roofs*, account for greater than 50% of roof surfaces installed onto industrial and low-slope commercial buildings each year. Such reflective roofs have the potential for decreasing cooling energy consumption by lowering roof temperatures (Freund et al. 2006; Ennis and Desjarlais 2009; Gaffin et al. 2010; Graveline 2013). The reduced heat flux can result in both lowered total energy use and peak demand—the latter associated with electric demand charges (Hoff 2015).

While cool roof effects during summer seasons appear to be well established, there are potential trade-offs during the winter months because of reduced heat flux into the building. Potentially, summer cooling energy savings need to be balanced against winter heating penalties. Surprisingly, there does not seem to be a consensus amongst roofing material manufacturers, building design professionals, or other industry professionals as to whether cool roofs provide savings across the United States or only in certain regions (Ibrahim 2009, Ibrahim 2013, Graveline 2013). These analyses are frequently used to drive building codes and associated material choices. Notably, the Denver City Council recently accepted many of the International Code Council's (ICC's) 2015 model codes but rejected those calling for the use of highly reflective roof materials (Hart 2016).

The aim of this paper is to examine the winter versus summer energy costs associated with cool roofs across a range of cities in the United States using modeling tools. Recent energy cost data, specific to each region has been used along with recent International Energy Conservation Code (IECC) roof insulation requirements. Previous studies are reviewed and the modeling methodology used in this paper, with its prior validation, is described.

PRIOR STUDIES

The role of thermal insulation to control heat flux in and out of buildings has been understood, at least intuitively, for millennia. For example, white reflective building coatings have been employed in Mediterranean and equatorial cultures to reduce summer heat loads for hundreds, possibly thousands, of years. Previous studies based on both model analyses and field surveys are discussed in the following subsections.

Model-Based Analyses

Formal studies on roof reflectance and building energy use have consistently shown that higher reflectance membranes result in lowered cooling energy use for southern climates (Akbari 1998,

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Akbari et al. 1998). Also, data derived from heat flux data through roof systems were found to closely match that measured in buildings, and the reduced heat load due to higher reflectance roof coverings found to lower cooling costs (Akridge 1998; Parker et al. 1998). However, these studies focused on southern locations where, by any measure, cooling costs far outweigh heating costs.

An analysis of energy costs associated with membrane reflectance as well as various insulation level choices was done for West Virginia locations using the Department of Energy's cool roofing calculator, CoolCalc (Matter 2008). This analysis, which has been widely promulgated, was claimed to show that highly reflective membranes actually increase energy costs. The study suggests that cool roof decisions should be based on a comparison of heating degree days (HDD) versus cooling degree days (CDD). If HDD are larger than CDD, the study suggests that cool roofs do not provide savings. Unfortunately, information about the energy type and cost assumptions used in Matter's analysis were not disclosed.

HDDs and CDDs are a measure of how much (in degrees) and for how long (in days) average outside air temperature differs from a specific base temperature, typically 65°F (18°C). The proposal that roof reflectivity decisions should be based on an HDD versus CDD basis (i.e., that cool roofs provide a benefit only if cooling days dominate) was also proposed by Ibrahim (2009). In this paper, it was disclosed that the analysis used electricity as the energy source for heating.

A detailed analysis of cool-roof-based energy savings for nine major U.S. cities suggested that cities with very large CDDs would benefit from cool roofs while those with high HDDs would benefit from darker, more absorptive roofs (Mellott et al. 2013). This result was obtained using a beta version of the Oak Ridge National Laboratory's (ORNL's) Roof Savings Calculator, which used a whole-building approach. However, a comparison of the data using CoolCalc shifted the results to suggest that more cities would benefit from cool roofs. The Roof Savings Calculator remains as a beta version on the ORNL site.

Using CoolCalc, an examination of the benefits and tradeoffs of insulation levels and reflectance showed that energy cost savings were achieved with cool roofs in both southern and northern cities (Xing and Taylor 2009). In this study, carried out using regional energy costs, the northernmost city, Chicago, had savings, albeit at a small level. Similarly, increasing insulation levels reduced the magnitude of energy savings, but did not change a savings to a cost.

Hosseini and Akbari (2015) modeled the behavior of a range of buildings in four cold-climate cities in North America: Anchorage, AK; Milwaukee, WI; Montreal, QC; and Toronto, ON. They found net annual energy cost savings for cool roof use for all four cities.

Modeling results must always be validated with experimental or real world data. The following subsection is a summary of available field surveys.

Field Surveys

Konopacki and Akbari (2001) studied rooftop temperatures and energy costs of a retail store in Austin, TX, before and after switching a black membrane to a white membrane. The average summertime roof surface temperature decreased from 168°F to 126°F (75.5°C to 52.2°C) and significant overall and peak energy costs savings were achieved. Because the membrane installation costs were nearly identical, the payback was essentially instantaneous.

Fenner et al. (2014) described the experience of a major national retailer after instituting cool roof use. Energy cost savings associated with cool roofs were experienced across the entire national store portfolio. It was noted that even in northern climates overall cooling costs exceeded heating costs in all of the retail outlets. In the few instances of using dark roofs in northern areas within the portfolio, no reduction in heating energy was noted.

Fischer (2013) reported heat flux measurements and energy costs associated with a multiwing correctional facility in New York. Building sections roofed with dark colored membrane showed significantly more summer heat flux into the building as compared to sections roofed with a cool roof, all having the same insulation level. During the winter months, the dark roof showed slightly less heat loss versus the reflective membrane. However, an energy cost analysis was not truly possible because only the cool roof section had air-conditioning and the absorptive roof section did not.

Gaffin et al. (2012) evaluated the multi-year albedo and surface temperatures of a range of reflective roof surfaces within New York City. The results showed that dark roof surfaces were notably warmer during summer months and that temperatures were almost equivalent during winter months. The authors noted that while the reflective roofs generally maintained EPA ENERGY STAR® Reflective Roof standards over a three year time frame, some maintenance was required after storm events that deposited dirt and debris on the surfaces.

Field studies of the impact of reflective roofs on building energy costs appear to be limited in number. It could be that side by side comparisons are difficult, given the variability of building designs. Also, when converting a roof from one type to another the associated energy costs are temporal and other parts of the roof system, such as insulation quantity, can be changed at the same time. For these reasons, models remain as a primary tool to examine reflectivity impacts on energy costs. The following discussion examines common modeling tools and their validation.

HEAT FLUX MODELS

In the United States, models were initially used to quantify energy flux in and out of the building envelope. PROPOR (Properties, Oak Ridge) was an early example and was used for parameter estimation of thermal conductivity and heat capacity of building components using temperatures and heat fluxes as inputs (Courville and Beck 1987). The STAR (Simplified Transient Analysis of Roofs) model, developed by Wilkes (1989), simulates heat flow in multilayer roof systems and includes the effects of solar radiation, infrared radiation, and outdoor temperature.

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CoolCalc

Petrie et al. (2001, 2004) used the STAR model as the basis of the energy calculator tool known as CoolCalc, published by ORNL. The tool was developed to provide estimated energy cost differences associated with changing reflectivity and emissivity properties for a roofing membranes and thermal insulation values. Subsequently, a modified version, CoolCalcPeak, was published that calculated savings when demand charges were factored in. Demand charges are a cost per kilowatt at the highest level of demand during a billing period and are added to the total kilowatt per hour usage level in that period. The tool also enables the savings associated with increasing insulation levels to be calculated. The tools incorporate climate data for 263 U.S. cities.

CoolCalc and CoolCalcPeak do not assume building geometry. They simply calculate energy loads on a building based on roof design (reflectance, emissivity, and insulation values) and local climate factors. Those energy loads might be a large percentage of the total, for a wide, low building, or a small percentage for a tall, narrow building. These calculators estimate energy loads based on the roof alone.

Validation of CoolCalc

Desjarlais et al. (2008) used STAR, the underlying model, to calculate the energy loads of a range of roofs and then compare them to test a roof's measured values. Their data was shown for a range of roofs, including ballasted systems, relative to a white TPO roof. In general, the modeled data agrees well with the measured heat flows. However, in the case of EPDM, they found the measured heat flux to be significantly lower than was predicted. Since EPDM is frequently used as the "comparison membrane" in cool roof calculations, this suggests that CoolCalc might overestimate savings. The error could be as large as around 20%, based on data shown.

Freund et al. (2006) simulated the effect of roof reflectance on energy costs in Minneapolis, MN, and Denver, CO. This study is notable in that it did not use CoolCalc or any other STAR variant, but used TRNSYS, a transient systems simulation program developed by the University of Wisconsin (Klein et al. 2017). The work was based on a hypothetical large, single-story, retail store (i.e., "big box"), and factored in door and window areas, wall insulation values, internal energy gains (including people), and detailed local weather factors. The latter included snow load on the building roof. The conclusion was that the building would experience energy savings in both Denver, CO, and Minneapolis, MN, with a white roof as compared to a dark roof. The savings were reduced with more insulation, but there was no evidence of a heating penalty caused by white roofing. This study therefore suggests that CoolCalc, which shows a similar result, is indeed valid.

METHODS / ANALYSIS INPUTS

Utility Costs

According to the Department of Energy Buildings Energy Data Book (DOE 2011), electricity is used to supply less than 20% of space heating energy demand for commercial buildings. Therefore, natural gas was the assumed heat source, with costs based on the annual average by state for commercial customers using 2015 U.S. Energy Information Administration (EIA) data. Electric costs were based on EIA commercial customer data by state for May 2015—the latest data available.

Demand charges were obtained per utility for each city being studied from a Utility Rate Database for which rates are checked and updated annually by the National Renewable Energy Laboratory (NREL) in partnership with Illinois State University's Institute for Regulatory Policy Studies. In cases where multitiered demand charges were cited, they were averaged across the applicable months to provide the single input required by CoolCalcPeak.

Although this study is necessarily limited to the use of the most recent published energy cost information, projections to 2040 do not suggest large changes. The Annual Energy Outlook for 2017 from the U.S. Energy Information Administration projects gas costs rising from $8 to $12 per thousand cubic feet ($28.25 to $42.38 per hundred cubic meter) between 2016 and 2040. Similarly, electric costs were projected to increase from $0.105 to $0.115 per kWh across the same period (EIA 2017).

Roof System

The CoolCalc calculators compare energy costs relative to a nominally nonreflective roof membrane. Two scenarios were used: an initial solar reflectance of 76 and emittance 90 and a three year aged reflectance of 68 and emittance 83, these representing long term roof performance. This would be typical of a thermoplastic polyolefin membrane (TPO).

An insulation R-value was selected according to the 2015 International Energy Code per state (ICC 2014). An exception was made for Fargo, ND, where the Code is R-35 (RSI 6.16). However, CoolCalc only allows a maximum of R-32 (RSI 5.64), because it has not been updated for R-values any higher. The maximum value of R-32 (RSI 5.64) was therefore used for Fargo, ND.

Heating and Cooling Efficiencies

Building air-conditioning coefficient of performance (COP) was set as 2.0 and the natural gas heating efficiency was set as 0.7 (i.e., both at mid range). These values are recommended within the CoolCalc model as being typical for existing buildings. Re-roofing accounts for approximately 80% of commercial roof installations (National Contractor 2016). Therefore, roofing reflectivity comparisons based on average heating and cooling efficiencies are appropriate.

Climate Data

The CoolCalc calculators report the HDD and CDD data on which the calculations are based. Energy savings were scaled by the ratio between those historical values and data reported specifically for 2015 by AccuWeather. A total of 18 U.S. cities were included in the analysis, selected on the basis of size and availability of all the required input data, as shown in Table 1.

Table 1. Location, Climate, and Energy Cost Data for the Cities Used in the Analysis

City	Climate Zone[1]	Heating Degree Days 2015[2]	Cooling Degree Days 2015[2]	Δ Degree Days	IECC 2015 R-Value (RSI)	Electric Cost 2015[3], \$/kWh	Demand Charge, \$[4]	Months Demand Charges Apply	Gas Cost Commercial 2015[3], \$/1,000 ft^3 (\$/100m^3)	Gas Cost Commercial 2015, \$/Therm (\$/kWh)
Miami, FL	1A	28	7115	–7087	25 (4.4)	0.0955	7.4	12	10.74 (37.93)	1.074 (0.0367)
Houston, TX	2A	1231	4919	–3688	25 (4.4)	0.0786	5.477	12	7.25 (25.60)	0.725 (0.0247)
Charlotte, NC	3A	3436	3020	416	25 (4.4)	0.0855	4.91	12	7.99 (28.22)	0.799 (0.0273)
Fort Worth, TX	3A	2361	4408	–2047	25 (4.4)	0.0786	9.965	12	7.25 (25.60)	0.725 (0.0247)
Fresno, CA	3B	1639	3631	–1992	25 (4.4)	0.1487	3.49	12	7.98 (28.18)	0.798 (0.0272)
Las Vegas, NV	3B	1196	5287	–4091	25 (4.4)	0.0947	15.01	5	8.66 (30.58)	0.866 (0.0296)
Kansas City, MO	4A	5158	2586	2572	30 (5.3)	0.0935	3.41	5	9.10 (32.14)	0.91 (0.0311)
Nashville, TN	4A	4081	2867	1214	30 (5.3)	0.1015	12.76	12	8.46 (29.88)	0.846 (0.0289)
Newark, NJ	4A	6513	2340	4173	30 (5.3)	0.1274	9.2736	4	8.52 (30.09)	0.852 (0.0291)
Albany, NY	5A	9116	1547	7569	30 (5.3)	0.1448	3.49	12	6.89 (24.33)	0.689 (0.0235)
Boston, MA	5A	7925	1557	6368	30 (5.3)	0.1486	8.71	12	11.88 (41.95)	1.188 (0.0405)
Boulder, CO	5B	3928	1317	2611	30 (5.3)	0.0955	3.53	12	8.30 (29.31)	0.83 (0.0283)
Chicago, IL	5A	8524	1345	7179	30 (5.3)	0.0892	3.49	12	7.26 (25.64)	0.726 (0.0248)
Columbus, OH	5A	7228	1772	5456	30 (5.3)	0.0983	—	—	6.62 (23.38)	0.662 (0.0226)
Seattle, WA	5C	3878	997	2881	30 (5.3)	0.0798	3.7	12	9.14 (32.28)	0.914 (0.0312)
Minneapolis, MN	6A	9317	1432	7885	30 (5.3)	0.0963	9.49	12	7.30 (25.78)	0.73 (0.0249)
Portland, ME	6A	9597	1016	8581	30 (5.3)	0.1278	7.055	8	14.40 (50.85)	1.44 (0.0491)
Fargo, ND	7A	6397	1217	5180	35 (6.2)	0.0876	13.49	12	6.70 (23.66)	0.67 (0.0229)

1. ASHRAE (2013).
2. EnergyCAP (2016)
3. EIA (2016a)
4. Utility Rate Database (EIA 2016c)

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RESULTS AND DISCUSSION

The CoolCalc tools provide energy savings data on a floor area; this was scaled to a 125,000 ft^2(11,613 m^2) building, which is representative of a typical big box retail store.

The annual cost savings, calculated without peak demand charges, as a function of climate zone are shown in Figure 1.

The data suggest that energy savings are obtained climate zones 1 through 7, so long as air-conditioning is used. It is worth noting that the northernmost city included was Fargo, ND. There is a significant spread of data within some of the climate zones, which could not be correlated with known factors such as climate zone sub-type (e.g., Zone 3A versus Zone 3B). Therefore, the savings were also compared to the (HDD – CDD) values, as shown in Figure 2.

In cases where HDD – CDD is positive, heating dominates, and when they are negative, cooling dominates. The data strongly suggest that the energy cost associated with mitigating heat flux into a building during summer months (i.e., via air conditioning) is always greater than the cost of

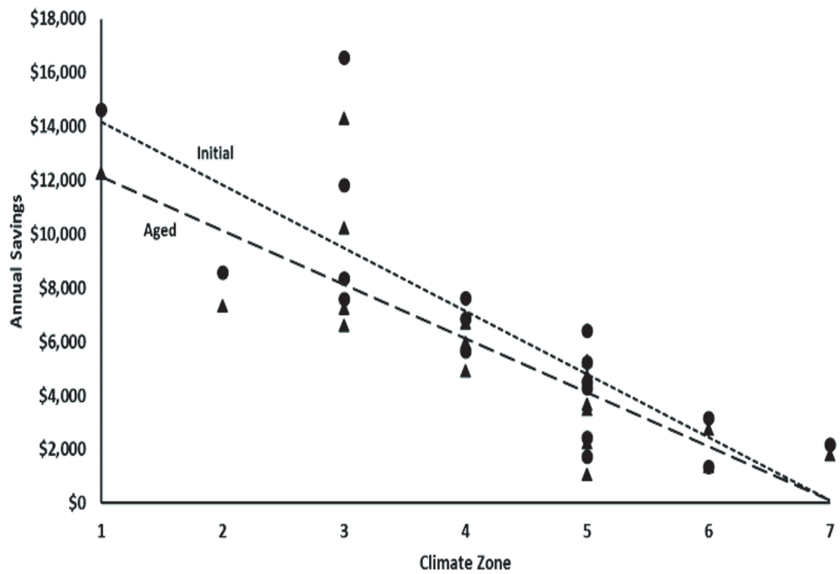

Figure 1 *Annualized costs savings obtained for 18 cities as a function of climate zone based on a 125,000 ft^2 (11,613 m^2) roof with the circles indicating the initial reflectance and emittance values and the triangles indicating aged reflectance and emittance values.*

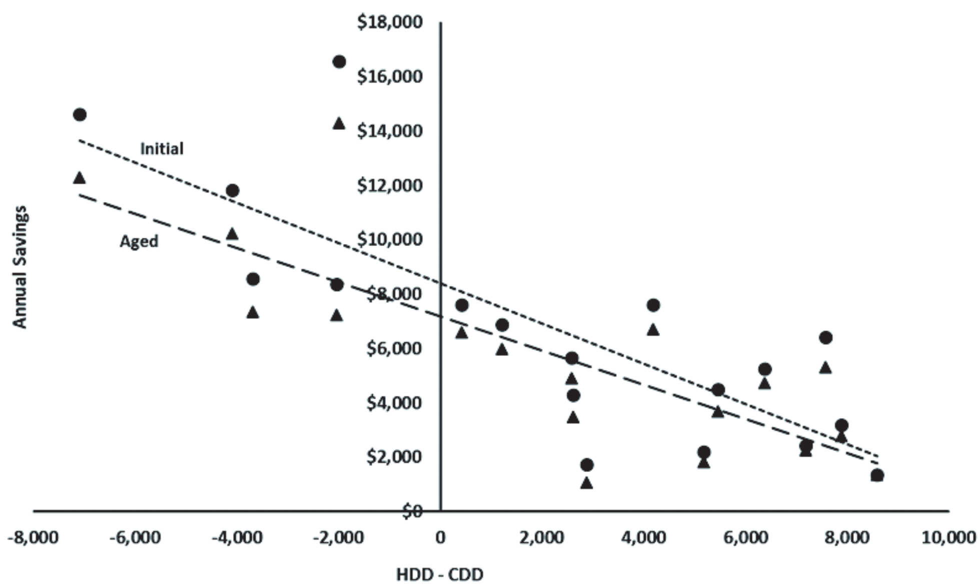

Figure 2 *Energy savings for 18 cities as a function of HDD – CDD values with the circles indicating the initial reflectance and emittance values and the triangles indicating aged reflectance and emittance values.*

replacing the heat lost through the roof system during winter months. If absorptive roofs are selected whenever HDD is larger than CDD, then the savings identified across 13 cities in this analysis would be lost. This finding is significantly different to that of Mellott et al. (2013), who used a different calculator than the one used in this paper. They did note a difference between results when comparing their data with that from CoolCalc. This suggests that work remains to be done to validate the various models and calculators that are in use within the industry.

When demand charges are included in the analysis, the savings versus HDD – CDD increase significantly as shown in Figure 3. However, the relationship between HDD – CDD and savings was very weak and a linear correlation was essentially meaningless.

The inclusion of demand charges in the analysis appears to remove any climate zone considerations into energy savings achieved with cool roofs. This strongly suggests that if a cool roof is being considered for energy cost savings, an analysis should be done regardless of geographic location.

Effect of Membrane Aging

The data discussed so far has shown both the savings associated with as supplied membrane (i.e., new) and aged membrane. Comparing the savings obtained at the three-year point as a percentage of original is shown as a function of HDD – CDD in Figure 4.

The average savings across all cities was 85.4%. The three-year-old reflectance and emittance values represent a long-term expectation of performance. This suggests that, regardless of location and energy costs, the aged membrane reflectivity will result in savings around 85.4% as compared to the original installation.

CONCLUSION

For every examined city, spanning climate zones 1 through 7, modeling predicts energy savings will be achieved by converting from a dark, absorptive roof membrane to a highly reflective cool roof. When calculated using three-year-old reflectance values (which assume some dirt buildup on the membrane), the savings were at 85% of the original across all locations and associated energy costs. The work strongly suggests that, regardless of location and local climate, cool roofing will result in building space heating and cooling energy savings providing that buildings are heated with natural gas and cooled by electric air conditioning.

Previously published correlations of energy savings with HDDs and CDDs, for example those by Ibrahim (2009) and Mellot et al. (2013), have not been validated. In fact, once demand charges are factored in, there appears to be little correlation between energy savings and local climate. This suggests that a building designer should model energy costs versus roof reflectivity on a case-by-case basis but can always expect some level of savings.

This study used 2015 energy cost data, the latest year for which such data are available on a state-by-state basis. The potential impact of long-term energy cost trends was beyond the scope of this work. However, it was noted that projections

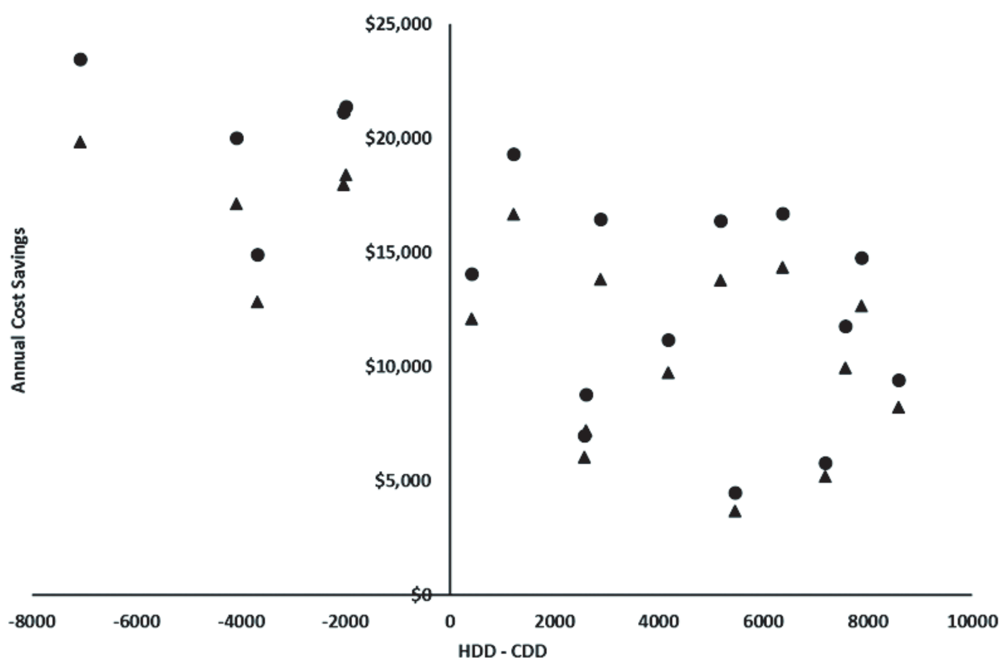

Figure 3 *Energy savings, including demand charges for 18 cities as a function of (HDD - CDD) values with the circles indicating the initial reflectance and emittance values and the triangles indicating aged reflectance and emittance values.*

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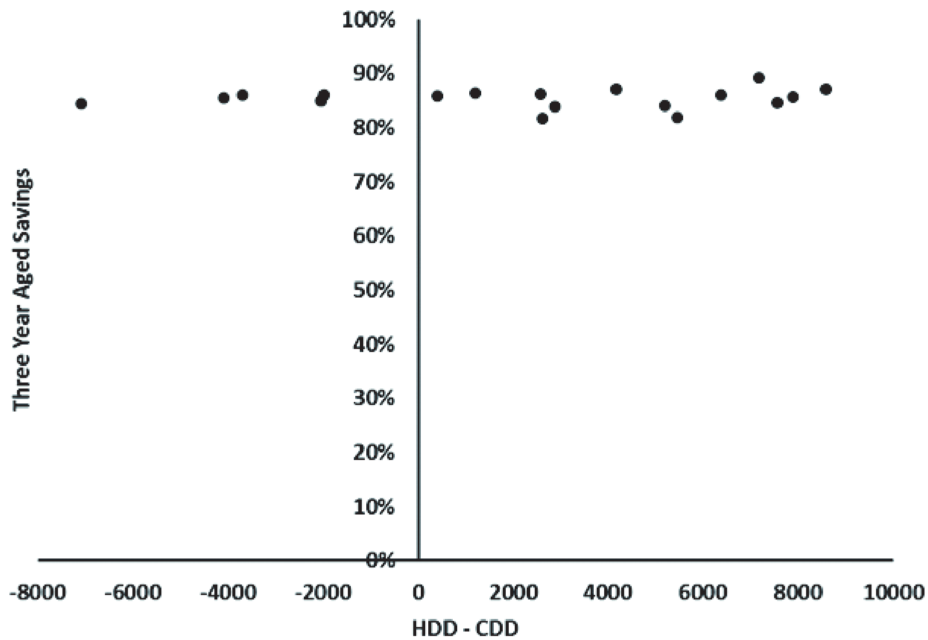

Figure 4 *Relative percentage of savings obtained at the three-year point versus the original as a function of HDD – CDD.*

to 2040 suggest modest increases for both electric and gas costs. Such an eventuality would result in the broad conclusions reached in this paper remaining valid. Future work could consider presenting data in terms of energy units saved to avoid being locked into a specific temporal cost model.

The calculated energy savings achieved with cool roofs can be regarded as being conservative because the latest high levels of insulation are assumed.

When aged reflectance and emittance values for cool roofs are factored in, energy savings remain at 85% of the initial installed values. This would suggest that energy cost savings achieved with cool roofs will remain, albeit slightly reduced, throughout the life expectancy of the roof.

Definitive validation of the data provided here would require side-by-side comparison of energy costs for buildings that only varied by roof reflectance. However, the work of Fenner et al. (2014) is indicative of the value of converting absorptive roofing to highly reflective materials. Also, in comparing the results here with those of previous studies, it is clear there is a need to understand differences between the various models and calculators in use within the industry.

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