The Joint Influence of Albedo and Insulation on Roof Performance: A Modeling Study

P. Ramamurthy^{1,2}, T. Sun^{2,3}, K. Rule⁴ and E. Bou-Zeid^{2*}

1-Department of Mechanical Engineering, City College of New York, New York, NY 10021.

2-Department of Civil and Environmental Engineering, Princeton University, Princeton NJ 08544.

3- State Key Laboratory of Hydro-Science and Engineering, Department of Hydraulic Engineering,
Tsinghua University, Beijing 100084, China

4-Princeton Plasma Physics Laboratory, Princeton NJ 08540.

*Corresponding Author: Princeton University Department of Civil & Environmental Engineering E414,
EQquad Princeton, NJ 08544 USA Tel: +1-609-258-5429 email: ebouzeid@princeton.edu

Abstract

The advanced Princeton Roof Model (PROM) is evaluated and then applied to quantify the heat transferred through various modular roof structures over an entire year. The goal is to identify an optimal combination of roof reflectivity and insulation thickness that will reduce energy consumption and minimize cost. Meteorological data gathered over the Northeastern United States (Princeton, NJ) is used to force PROM. Our results reveal that for new constructions or for retrofits in the region, an R8.4 (around 46 cm thick roof insulation) white roof (assumed albedo = 0.6 or greater) would significantly reduce the combined heating and cooling load attributable to the roofs. The wintertime penalty of white roofs is also shown to be insignificant compared to their summertime benefits. The findings are pertinent to many other densely populated areas with comparable climates where, despite a much higher number of heating versus cooling degree-days, white roofs are overall advantageous. A cost optimization analysis found that doubling, tripling and quadrupling the insulation thickness from the baseline case of 5.08 cm (2 in), at an albedo of 0.45, requires 13, 17 and 19 years, respectively, to recover the additional cost incurred.

Keywords

Cool Roof, Roof energy savings, Roof Albedo, Roof Heat Flux, Roof Insulation, Princeton Roof Model

1 Introduction

This modeling study is focused on understanding the role played by roof albedo and insulation in modulating the heat transfer through roofs, and on quantifying the resulting impact on building energy consumption. The overall goal is to provide guidance on roof design that would help reduce the large environmental footprint of building air conditioning: in the US, about 20% of primary energy is consumed in heating and cooling of buildings; this (heating and cooling of US buildings only) is equivalent to about 3.5% of the worldwide consumption of primary energy [1].

One of our unambiguous conclusions from an associated experimental study [2] was that white roofs were highly effective in reducing the cooling loads during the summer months, while insulation thickness (R-value) was the main determinant of roof energy efficiency during winter periods. But the observational study was not well suited for exploring the optimum (in term of financial cost) combination of albedo and R-value for a given geographical location. Our further investigations detailed in this article will use the Princeton Roof Model (PROM), which is a component of the broader Princeton Urban Canopy Model (PUCM, [3]) and which can capture the vertical heterogeneity of complex modern roofing structures, to address this fundamental question. The model will be applied to simulate the transfer of heat in/out of multiple modular roofs of varying membrane reflectivity and thickness, continuously for an entire year, using

hydrometeorological forcing data collected in Princeton, NJ, in the US Northeast. The aim is to identify the optimal combination of albedo and insulation that would minimize total cost (material and operating energy costs) for roofs in the region, but the research methodologies used here (though clearly not the conclusions) can obviously be applied to any other site anywhere in the world. The observational part of the study [2], as well as previous research in the same region [4], suggest that the albedo expected to yield the highest energy efficiency would be a high one, corresponding to a white roof. The simulations we conduct here will aid in corroborating these conclusions, and the expansion of the parameter space (albedo and insulation) will allow us to explore/identify the optimal roof design.

Research in the last two decades has highlighted the importance of roofs as a possible tool to mitigate urban heat islands and improve energy sustainability [5-7]. A number of numerical studies have been conducted to assess and quantify the effectiveness of green roofs and white roofs in moderating the urban microclimate and improving energy efficiency of building structures. Akbari et al. [8] used DOE 2 to simulate energy consumption for typical buildings at 11 Metropolitan areas and quantified the corresponding energy savings. The DOE 2 model has been extensively used in the literature to study the effectiveness of highly reflective roofs [9]. Sailor et al. [10] further improved the DOE 2 model by adding a green roof module. DOE 2 is primarily used as a numerical engine for several building energy simulation programs like eQUEST [11] and EnergyPlus [12]. Other notable models include the DeST, predominantly used in China and Energy Express developed by CSIRO, Australia [11,13]. In addition to the stand-alone building energy simulations models, urban canopy models (UCM) have also been

used to study the energetic interactions between the building envelope and the environment [14]. UCMs represent the street canyon as an infinite rectangular cavity bordered by two buildings (usually of equal height in the single layer representation; an infinite regular array of cubes can also be represented with minor modifications to the model)[15]. These models are widely used by urban climatologists as they can be readily coupled to mesoscale climate models. In this study we use the Princeton Roof Model (PROM) to simulate the energy transfer through the roof between the building interior and the exterior. PROM is part of the broader Princeton Urban Canopy Model and is explained in detail in the succeeding section.

2 Methods

2.1 Princeton Roof Model

A schematic of PROM is shown in figure 1. A primary advantage in using PROM is its ability to account for the various distinct layers in a roof. Many current models consider roofs to be vertically homogenous, and assume steady state conditions when solving for the heat flux [16]. These assumptions might be acceptable for simple, relatively thin older roof designs. However, for the modern multilayer roofs, accounting for the various vertical layers, and for the transient dynamics of the heat flux (since the conduction time scale through these roofs can be ~ 24 hours), becomes important. In contrast to these models, PROM accounts for the thermal dynamics in individual roofing elements/layers to compute the heat transferred between them. PROM is equipped with a multilayer, spatially-analytical and temporally numerical, conductive heat transfer scheme based on the Green's function solution of the one dimensional heat equation in each layer.

Individual layers of the roofing structure are assigned their distinct physical and thermal properties. Additionally, this analytical scheme obviates the need to spatially discretize the domain, which reduces numerical errors [17]. While this approach is comparable to the relaxed conduction heat transfer equations used in the advanced module of DOE2.1 [18], PROM can be applied to any roofing configuration without the need to compute pre-configured roof parameters, as required in DOE2.1. In addition, the time steps in PROM are variable compared to the fixed 1-hr period for DOE2.1 (those fixed time steps are linked to the pre-configured parameters DOE2.1 needs). PROM can also be used to model energy exchanges over vegetated roofs. The implementation and validation of PROM over green roofs is detailed by Sun *et al.* [19, 20]; these references also provide full further details about the approach used in PROM for solving the heat equation.

Figure 1 Schematic of Princeton ROof Model (PROM) – Princeton Urban Canyon Model (PUCM) framework. In the schematic of PROM on the left, heat fluxes are denoted with red arrows, along with notations: H for sensible heat flux, LE for latent heat flux, G for heat flux through roof. Figure reproduced from Sun *et al.* [19].

PROM is one component of the broader Princeton Urban Canyon Model (PUCM), which employs the widely-adopted single layer framework [21] to represent energy exchanges

over an urban area (though the other aspects of PUCM are irrelevant here). This integration effectively couples the roof structure to the shifting meteorological conditions of the surrounding environment. As such, validations of PUCM [3], [22], [15], and [23] also imply that the convective turbulent heat transfer parameterizations of PROM are reasonably accurate; however, further evaluations are conducted through this study to ensure the model is able to capture the heat transfer dynamics of the roofs under investigation.

In the succeeding sections of this article, the integrated, multilayer, spatially-analytical scheme implemented in PROM framework will be evaluated over different roofing structures. The model will then be used to simulate energy exchanges over a suite of roofs with gradually varying albedo and roof thickness, forced by atmospheric data obtained over the validation site in Princeton, NJ. The results from this simulation will then be used to identify the optimal combination of surface reflectivity and insulation thickness to minimize heating and cooling costs over a whole year.

2.2 Model Evaluation

Before using PROM to identify the optimal albedo and roof thickness, the model is validated using the extensive and unique heat flux measurements collected at the Princeton Plasma Physics Lab (PPPL) rooftops located in Princeton, New Jersey (N 40.3489° W 74.6029°). According to the Koppen index [24], the region experiences a continental humid climate. Heat flux and temperature measurements were made at five different rooftops, each with varying albedo, roof thickness and insulation materials. Figure 2 shows the plan view of the installation site. We will denote the roofs as ADMw-

R8.4, THYb-R3.6, LSBb-R4.2, LSBw-R4.2, EGRb-R6.3, where the first three upper case letters indicate the building, the 4th lower case letter indicate whether the roof is white (w) or black (b) and the two digits after the R indicate the R value (insulation) of the roof. The SI unit of R is $\text{m}^2 \text{K W}^{-1}$, and the equivalent US unit is $\text{hr ft}^2 \text{ }^\circ\text{F BTU}^{-1}$. At each of the five roofs, the heat fluxes were monitored beneath the Ethylene Propylene Diene Monomer (EPDM) membrane and at the bottom of the final insulation layer, i.e at the interface between the insulation foam and roof frame. The complete details of the measurements and schematics of the installed sensors are provided in Ramamurthy et. al. [2].

Apart from quantifying the thermal state of the roof, the measurements also included ambient weather conditions. The incoming and outgoing shortwave radiation were measured by Davis shortband radiometer (model 6450, accuracy $\pm 90 \text{ W m}^{-2}$, resolution 1 W m^{-2}). The surface temperature over different membranes was measured by ZyTemp infrared gun (TN0am, accuracy $0.6 \text{ }^\circ\text{C}$ for most of our measurement range, resolution $0.0625 \text{ }^\circ\text{C}$). The Vaisala WXT520 was employed to monitor the ambient atmospheric pressure (accuracy $\pm 1 \text{ hPA}$), relative humidity (accuracy $\pm 3\%$), wind speed (accuracy $\pm 3\%$ at 10 m s^{-1}), temperature (accuracy $\pm 0.3^\circ\text{C}$), and precipitation (accuracy $\pm 5\%$ of measurement). The weather data were logged using a GPRS-based Sensorscope mobile weather network [25].

Figure 2: Map illustrating the buildings and roof installation at the PPPL test site. The weather stations (red markers) were placed in close proximity to the heat flux sensors and thermocouples installed inside the roof layers. Figure reproduced from Ramamurthy et al. [2].

While all roof structures used Polyisocyanurate (PolyIso) foam as the primary insulation material, over the LSBb-R4.2, LSBw-R4.2 and EGRb-R6.3 roofs, a gypsum based fiberglass and plywood were also used as the topmost insulation layer, directly beneath the membrane. All five test roofs were shielded with an EPDM membrane; however, the membrane albedo varied between the rooftops quite considerably. These albedos were independently measured using a combination of downward and upward facing shortband radiometers. The different roofs also varied in age; the LSBw-R4.2 and LSBb-R4.2 were newly installed before the experiment (in the summer of 2012), the ADMw-R8.4 and

THYb-R3.7 were installed in 2005 and 2002 respectively. The EGRb-R6.3 roof was installed in 2009.

The measurement accuracy of the thermal state of the roof structures and of the ambient weather conditions are adequate for the analyses conducted here; however, the largest uncertainty in the inputs provided to PROM is in the imposed thermal properties (thermal conductivity and volumetric heat capacity) of the membranes and the insulation materials. While most manufacturers do disclose the lab-tested values, these numbers vary depending on the batches and installation technique; more importantly, they vary considerably with ageing and weathering of the roof. The PolyIso foams, whose cell structures are initially filled with an inert gas that over time gets replaced by air, start experiencing an increase in thermal conductivity [26, 27]. While these changes are hard to estimate and beyond the scope of this experiment, we modeled them by starting with the common values used in the literature and then calibrating them over successive validation runs to match observations. In addition, white membranes are known to start absorbing more radiation due to dirt accumulation over time [28, 29], which reduces their albedo. To capture this variation, the actual albedo was measured and used here. Table 1 lists the thermal conductivity and the volumetric heat capacity of all the roofing members as determined through this calibration and used to parameterize the model. The calibration might be biased since it inherently lumps all experimental or modeling errors and determines values for these properties that partially offset these errors, but the validation we show next is able to replicate observed fluxes reasonably well. Therefore, and despite the possibility of some local error cancelations, PROM will be able to

simulate the heat transfer dynamics in roofs with sufficient accuracy to allow us to confidently interpret and build upon its output.

Table 1: Heat capacity, thermal conductivity and albedo values used to validate the PROM for various roofs

Roof Structure	Volumetric Heat Capacity ($\text{JK}^{-1}\text{m}^{-3}$)	Thermal Conductivity ($\text{Wm}^{-1}\text{K}^{-1}$)	Albedo
EGRb-R6.3 [EPDM, Plywood, PolyIso]	$10^6 \times [1.74, 0.9, 0.04]$	[0.5, 0.1, 0.035]	0.06
THYb-R3.7 [EPDM, PolyIso]	$10^6 \times [1.74, 0.07]$	[0.3, 0.009]	0.1
ADMw-R8.4 [EPDM, PolyIso]	$10^6 \times [1.74, 0.16]$	[0.3, 0.015]	0.35
LSBb-R4.2 [EPDM, Densdeck, PolyIso]	$10^6 \times [1.74, 0.57, 0.1]$	[0.4, 0.3, 0.02]	0.07
LSBw-R4.2 [EPDM, Densdeck, PolyIso]	$10^6 \times [1.74, 0.57, 0.1]$	[0.27, 0.3, 0.02]	0.65

The model was validated for a 3-day period in September 2012 (shown in figure 3 and 4). The forcing data required to run the model was obtained from the meteorological observations over PPPL presented above. Figure 3 compares the model runs indicated by continuous curves to observed heat flux plate data indicated by markers. Overall, given the heterogeneity in albedo, insulation thickness, and construction materials properties, as well as the uncertainty and variability in the hydrometeorological forcing and the fact that partial roof shading is not accounted for in the solar radiation inputs which are taken from an unshaded measurement site, the model performs remarkably well in capturing the heat entering and leaving the top and bottom of the roof interfaces. The model is especially successful in capturing the bottom heat fluxes, at all the sites, indicating that part of the errors near the top are due to the hydrometeorological variability that are not fully

captured in the inputs to the model. PROM is also able to replicate the diurnal variation of fluxes very well. In fact the model only misses the intermittent sharp peaks during the midday period, which could be directly attributed to the averaged input forcing data used to run the model. The model was forced with 30 minute averaged dataset, and it outputted data at 5-minute intervals, which were then averaged over 30 minutes (the actual time step of the model was 5-minute).

Table 2 provides the Root Mean Square Error (RMSE), Mean Bias Error (MBE), and the corresponding Percentage RMSE and Percentage Bias (PBIAS) between the observed and modeled data for all five rooftops. In addition, the table also lists Nash-Sutcliffe Efficiency (NSE) of the model. The equations used to calculate these error parameters are:

$$MBE = \frac{1}{N} \sum_{i=1}^n (O_i - M_i) , \quad (1)$$

$$PBIAS = \frac{\sum_{i=1}^n (O_i - M_i)}{\sum_{i=1}^n O_i} , \quad (2)$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^n (O_i - M_i)^2} , \quad (3)$$

$$PRMSE = \frac{RMSE}{\frac{1}{N} \sum_{i=1}^n O_i} , \quad (4)$$

$$NSE = \frac{\sum_{i=1}^n (O_i - \bar{O})^2 - \sum_{i=1}^n (M_i - O_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2} . \quad (5)$$

In the above set of equations, O_i and M_i respectively represent the observed and modeled values; $\bar{O}$ is the mean of the observed values; and N is the number of samples.

Figure 3: Comparing observed heat flux plate measurements made at the top and bottom of various roofs to modeled values (30 minute averages). The left column, 1a, 2a, 3a, 4a and 5a represent heat fluxes at the interface of EPDM membrane and the insulation layer at the top of the roof structure and the right column, 1b, 2b, 3b, 4b and 5b, represent the heat fluxes leaving/entering the bottom of the roof structure.

Table 2: Mean Bias Error, Percentage Bias, Root Mean Square Error, Percentage Root Mean Square Error, and Nash-Sutcliffe Efficiency for PROM-modeled heat flux. The shaded cells display the error parameters for the heat flux at the top of the insulation, underneath the membrane, while the un-shaded cells represent errors compared to the bottom heat flux plate measurements.

	MBE (W m⁻²)	PBIAS (%)	RMSE (W m⁻²)	PRMSE (%)	NSE
ADMw-R8.4	3.52	48	6.65	71.3	0.49
	0.08	6.7	0.42	30.73	0.87
EGRb-R6.3	1.92	11	17.92	74.01	0.38
	-0.014	0.4	1.53	36.6	0.86
LSBb-R4.2	-0.74	3.8	13.67	53.78	0.71
	-0.33	6.18	1.42	23.15	0.94
LSBw-R4.2	0.59	4.7	7.88	51.95	0.72
	0.059	2.07	0.86	25.21	0.87
THYb-R3.7	1.97	15.82	11.96	67.55	0.54
	-1.18	21.5	2.38	37.17	0.86

The average PBIAS for the top heat flux, underneath the membrane is 17%, compared to 7% for the bottom heat flux. The corresponding NSE index, which indicates the strength of the model to predict observed values, improves from a modest 0.56 for the modeled top to 0.88 for bottom heat fluxes. As explained above, the higher error values at the top of the roof, underneath the membrane, are potentially due to the low sampling rate of the forcing data. However, the errors observed at the bottom of the roof are on the order of the accuracy of the measurements of the heat flux plates. In addition, bias errors, which are much lower than RMS errors here, are more representative of the model's performance when time-averaged or time-integrated heat fluxes are considered, which will be the case for this study where we focus on yearly heating and cooling loads.

In addition to heat flux validations at the top and the bottom of the roof layer, figure 4 compares the external roof surface temperature simulated by the model to its observed values. Similar to heat fluxes, the model performs well in simulating the diurnal variation of roof temperatures. In particular, the model captures the peak temperature values during the midday period and the nightly lows well. The anomalies are a result of minor differences in accurately defining the thermal properties of the membrane and shading caused by buildings adjacent to the roof. The MBE, RSMSE and NSE values for ENGb and LSBw are [0.62 K, 3.26 K and 0.96] and [3.73 K, 7.30 K and 0.83], respectively. These comparisons demonstrate that PROM is a robust and reliable tool for modeling heat fluxes through the roofs for the purposes of this study.

Figure 4: Comparing observed surface temperature measurements made at ENGb (a) and LSBw (b) to PUCM simulations.

3 Model setup

The primary objective of this study is to provide guidance on the optimal combination of roof insulation thickness and roof surface albedo in terms of costs incurred; minimizing

the cost is also expected to yield significant energy savings but this has to be confirmed through the analyses. To that end, a modular conventional roof structure consisting of three layers, an EPDM membrane at the top, PolyIso foam insulation in the middle, and a concrete deck at the bottom, was simulated. Based on the calibrated values in table 1, EPDM, PolyIso and the concrete deck were assigned thermal conductivities of 0.3, 0.023 and $1.16 \text{ W K}^{-1} \text{ m}^{-1}$, respectively, while their volumetric heat capacities were set to 1.74, 0.07 and $0.4 \text{ MJ K}^{-1} \text{ m}^{-3}$, respectively. For different simulations, the albedo of the rooftops was varied from 0.05 to 0.75, in steps of 0.15, and the insulation foam thickness was varied from 0 to 23.876 cm, (0.0025, 3.5763, 5.6083, 9.2659, 14.1427, 19.0195, 23.876). In terms of R-value, this is equivalent to varying the roof insulation from R0.17 to R10.5 (the US equivalent is from R1 to R60 (R1, R10, R15, R24, R36, R48 and R60)). The thermal properties of all the materials were fixed and remained unchanged between simulations. Other model parameters are listed in table 3.

Table 3: Physical and aerodynamic properties used in PROM

Properties	Values
Thermal roughness length for roof surface	0.001 m
Momentum roughness length for roof surface	0.01 m
Roof surface albedo	[0.05 0.15 0.30 0.45 0.60 0.75]
Roof surface emissivity	[0.92]
Roof volumetric heat capacity [EPDM, PolyIso, Deck]	$[1.74, 0.07, 0.42] \times 10^6 \text{ JK}^{-1} \text{ m}^{-3}$
Roof thermal conductivity [EPDM, PolyIso, Deck]	$[0.3, 0.023, 1.16] \text{ WK}^{-1} \text{ m}^{-1}$
Roof thickness [EPDM, Deck]	[0.0028, 0.254] m
PolyIso Variable Thickness	[0.0025, 3.5763, 5.6083, 9.2659, 14.1427, 19.0195, 23.876] cm
Internal constant building temperature	23 °C

Input meteorological data for the model were obtained from an eddy covariance flux tower located on the campus of Princeton University, Princeton, NJ, which is about 4 km from the experimental roofs. The incoming longwave and shortwave radiation were observed using a HuskeFlux 4-component radiometer, NR01 (accuracy: $\pm 10\%$ for daily totals). A Campbell Scientific CSAT3 sonic anemometer was used to measure the wind speed (accuracy (offset error): less than $\pm 0.08 \text{ m s}^{-1}$ for the horizontal wind components and less than $\pm 0.04 \text{ m s}^{-1}$ for the vertical wind component) and a Vaisala HMP45C was used to observe air temperature and specific humidity (accuracy for RH: $\pm 3\%$ and for temperature $\pm 0.5^\circ\text{C}$). A LICOR 7500 (accuracy: $\pm 1.5\%$) was used to measure atmospheric pressure. The simulations were forced using data gathered between May 1st, 2010 and 30th April 2011. The averaged monthly variation in temperature for the 12-month period is shown in figure 5. While May through September represented the warmer period or the cooling period, November through March was the heating period during the colder months. The average temperatures during the summer months (June-August) were around 30°C , daily peaks close to 38°C were not uncommon. January was the coldest month with average daily temperatures close to 0°C . Overall, the cooling and heating degree days for this one year period were 1397 and 5086, respectively.

4 One year run

Multiple runs over the same one-year period were completed with the data gathered from Princeton and for the various combinations of albedo and roof thicknesses discussed above. Figure 6 shows the variation of the heat transfer through the roof for various albedo values for warmer (May-September, heat gain) and colder (October-March, heat

loss) months; April is omitted since it is a mild month with relatively low gains or losses. The x-axis represents the insulation thickness in cm (the equivalent R-values are shown just inside the axis box), and the y-axis represents the average heat lost/gained per unit area per day. In the figure, the heat lost through the roof structures is taken as negative and shown on the negative axis, while the heat gained during the warmer months is positive. The average heat entering/leaving the roof structure per unit area per day J_0 ($\text{J m}^{-2} \text{ day}^{-1}$) was calculated following:

$$J_0 = \frac{1}{N_d} \int_{t_1}^{t_2} Q dt, \quad (6)$$

where, Q indicates the heat flux between the roof deck and the interior of the building (W m^{-2}); N_d represents the total number of days; and t_1 and t_2 are the start and end time periods (s).

Figure 5: Boxplot showing monthly variation in ambient temperatures for the one year run, recorded at Princeton, NJ. The top edge of the box represents the 75th percentile and the bottom edge represents the 25th percentile. The top and bottom whiskers represent the 95th and the 5th percentile. The horizontal black line shows the median and the circle indicates the mean. The plus symbols represent data points that are removed from the mean by more than $\pm$ one-and-a-half times the interquartile range.

Figure 6: Thermal energy (J_0) gained/lost as a function of insulation thickness from the one-year simulations using PROM. The curves represent different albedos α . Warmer months include May to September, while the colder months extend from October to March.

Analyzing the summer months, it is clear that for very low insulation thickness, the differences between various albedo values are quite significant. When insulation thickness is less than 4 cm, a roof with an $\alpha = 0.05$ gains $718 \text{ KJ m}^{-2} \text{ day}^{-1}$ compared to a highly reflective roof ($\alpha = 0.75$), which only gains $212 \text{ KJ m}^{-2} \text{ day}^{-1}$. While the heat gained is reduced as insulation thickness increases, even for a moderately insulated R6.3 roof, the heat gains from the lowest albedo roof are nearly four times higher than from the highest albedo roof: the highly reflective R6.3 roof gains $54 \text{ KJ m}^{-2} \text{ day}^{-1}$ compared to a black ($\alpha = 0.05$) roof that admits $190 \text{ KJ m}^{-2} \text{ day}^{-1}$. When the insulation thickness exceeds 18 cm, the heat gained for all albedo values remains almost constant, indicating that additional insulation is not needed. The family of curves shows that, for warmer months, albedo plays a dominant role in reducing the energy gained through the roofs. In fact, increasing the albedo of a very low insulation roof ($<R10$) from $\alpha = 0.05$ to $\alpha = 0.75$

is roughly equivalent to adding 14 cm of insulation thickness (see more on this concept of expressing the increase in albedo as an equivalent increase in R-value in Gaffin et al. [4]). In stark contrast, during the colder months, the differences in albedo values do not affect the heat loss in a significant manner. For a roof with less than 4 cm of insulation (lesser than R10), the difference in heat lost between $\alpha = 0.05$ and $\alpha = 0.75$ is roughly 125 KJ $\text{m}^{-2} \text{ day}^{-1}$, and for a roof with insulation thickness higher than 24 cm the difference is reduced to 50 KJ $\text{m}^{-2} \text{ day}^{-1}$. However, insulation thickness plays a dominant role in controlling the heat loss through the roof structures. A roof with $\alpha = 0.30$ loses nearly 600 KJ $\text{m}^{-2} \text{ day}^{-1}$ at R10 compared to 175 KJ $\text{m}^{-2} \text{ day}^{-1}$ at R6.3. Similar to warmer months, this difference is significantly reduced for insulation thickness greater than 18 cm (R8.4). As we also point out in the associated experimental study [2], this discrepancy between summer time benefits and winter time penalties of cool roofs, despite the fact that the northeastern US has about 5 times more heating degree days than cooling degree days, is related to the negligible impact of albedo during peak heating periods (which occur during nighttime and in the winter when the insolation periods are short), as opposed to its prominent role during peak cooling periods (occurring in the afternoon and in the summer when the insolation periods are long).

The model results suggest that for newer constructions, a high albedo ($\alpha > 0.7$, although this value might be difficult to maintain for roofs as they age in practice) – R8.4 roof is a practical solution for significantly reducing energy losses/gains during winter and summer months at the NYC Metropolitan region. Beyond an R8.4 roof insulation, the reductions in energy consumption become incremental. Another point to underline is that since it is difficult to maintain high reflectivity over an extended period of time, a thick

insulation layer would reduce the need to constantly maintain high membrane reflectivity. Rain, dust and air pollution are known to reduce the solar reflectance of white roofs [29]; the decline in solar reflectance, particularly in the first year of operation, could be considerable. Bretz et al. [28] found that some white roofs lost nearly 70% of their reflectivity within a year, resulting in an estimated 20% reduction in energy savings for succeeding years compared to the savings in the first year. The staining causing albedo reduction, while not permanent, would require considerable effort to remove and regain the original reflectivity. Bretz et al. [28] tested 40 samples of weathered and unweathered roofs obtained from various regions in US and Canada and suggested periodic power washing to maintain the membrane reflectivity. At the PPPL site, over the ADMw-R8.4 roof, an area of $1\text{m} \times 1\text{m}$ was cleaned thoroughly and the subsequent change in albedo was observed. Figure 7 depicts the daily variation in the albedo measured during peak solar radiation from May 1, 2012 to October 1, 2012. In the five-month period, the roof albedo dropped dramatically from ≈ 0.65 , post cleaning, to ≈ 0.35 . In fact, during a 15-day period, beginning June 2012, the albedo suddenly dropped by more than 25% before stabilizing at around 0.35 after the beginning of August 2012.

Figure 7: Variation in peak time albedo over the reflective ADMw-R8.4 roof at the PPPL test site in Princeton, NJ, after cleaning.

White roofs, on the other hand could be advantageously used to moderate the urban microclimate. Urban areas, in general experience higher temperatures compared to the surrounding rural environment though what is now a very well documented anthropogenic climate modification known as the Urban Heat Island (UHI) effect [30], [31]. Apart from increased anthropogenic heat releases, the thermal and radiative properties of the built environment sustain this higher energy state [32]. This phenomenon has a direct impact on human health [33], as it abets and augments the impact of heat waves in urban areas and also increases cooling loads on air conditioning systems [34] by raising the ambient air temperature. White/Cool roofs can be effectively used to reduce the impact of UHI by reflecting most of the incoming shortwave radiation back in to the atmosphere. This will remain a significant advantage of such roofs even if higher insulation reduces the direct impact of albedo on heat transfer in/out of the building.

To illustrate this microclimatic influence of white roofs, figure 8 shows the influence of albedo and roof insulation on the simulated convective sensible heat flux from the roof to the atmosphere for the warmer months. Unlike the ground/roof flux seen in figure 6, sensible heat flux is entirely dependent on albedo. Insulation thickness does not play a role in determining the magnitude of sensible heat and the figure clearly shows that as insulation thickness increases, the sensible heat remains almost constant for all albedos. Importantly, as albedo values increase, sensible heat flux falls down rapidly. The magnitude of sensible heat flux released to the atmosphere decreases to nearly $2 \text{ MJ m}^{-2} \text{ day}^{-1}$ from $12 \text{ MJ m}^{-2} \text{ day}^{-1}$ as the albedo values decrease from 0.75 to 0.05. Even a more modest increase in albedo, from 0.05 to 0.45 reduces the sensible heat values by half. Sensible heat flux is directly responsible for maintaining high near-surface air temperatures in urban areas relative to the surrounding rural areas, thus producing the urban heat island effect. As such, variations in this flux, if cool roofs are widely adopted in a given city, will result in indirect improvement in building energy consumption by reducing the summertime outdoor temperatures [35]. These indirect impacts are not quantified in this study since they depend on the fraction of cool roofs adopted at the city-scale.

Recent work has highlighted the costs and benefits of using white roofs compared to black and green roofs [36]. Akbari et al. [8] found that nationwide implementation of high albedo roofs can lead to \$1 billion in annual energy savings and decrease the urban air temperature by at least 0.5°C . This has led to campaigns such as the Global Cool Cities alliance [37] and the NYC Cool Roof initiative [38], that are dedicated to increasing the solar reflectance of urban roofs.

Figure 8: Modeled sensible heat flux released during warmer months (May to September) as a function of insulation thickness from the one-year simulations using PROM. The curves represent different albedos α .

While a high albedo ($\alpha = 0.7$) and R8.4 might be the perfect combination for newer roof structures, for older roof structures (based on bitumen or asphalt shingles) that are commonly found in the northeastern United States, a white paint coat during summer months would be highly beneficial. Roofs constructed around the mid-twentieth century have very low insulation in general; they are mostly coated with tar and covered by a layer of gravel. These remain the most commonly-found roof structures in the northeastern United States, which in general has an older housing stock [39]. Apart from their lack of proper insulation layer, the gravel and tar increase the radiative absorptivity of the roof structure. This combination makes them highly ineffective in preventing building heat gains, as well as excessive heating of the lower atmosphere during warmer months. Wide adoption of white roofs will thus result in reductions in urban air temperatures [35] that will feed back to further reduce building energy consumption.

5 Cost Optimization Analysis

The costs incurred for various roof combinations were calculated along with the energy lost/gained. To compute the costs, a chilled water cooler and a natural gas furnace were assumed to cool and heat the space during the summer and winter periods. These two modes are the most widely adopted means of air conditioning in US commercial buildings [40]. The heat entering and leaving the building through the roof was obtained from the PROM's yearlong simulation outputs. For the chilled water system, a COP (coefficient of performance) of 3 was assumed. COP of a heat pump is defined as the ratio of heat supplied or removed to work done. Hence, a COP of 3 indicates that 3 units of heat are removed for every 1 unit of energy consumed. For winter heating, a conservative 60% efficiency was assumed, which equates to burning 29.307 kWh (1 therm) of natural gas to produce 63 MJ of energy.

The costs of electricity and natural gas were assumed to be \$0.201 per kWh and \$1.124 per 29.307 kWh (1 therm), respectively [41]. The values indicated above represent the average 2012 prices for electricity and natural gas in the New York Metropolitan region (Princeton, NJ is located on the fringes of NYC Metropolitan area).

Figure 9 shows the savings in energy cost for a moderately reflective (0.45 albedo) roof as a function of PolyIso foam insulation thickness (this does not yet account for costs). A conservative albedo value of 0.45 was picked based on our experimental evidence that showed it was highly unlikely to maintain much higher reflectivity of white roofs for extended periods. The relationship shown in figure 9 was computed by adding the summer and winter savings for each step increase in insulation thickness. This way, the winter penalty for high albedo roofs was subtracted from the summer savings. The net

sum was calculated for multiple insulation thicknesses and a power law fit was then introduced to capture the trend (this fit will be used in the remainder of this section for the studied roof, but is not intended as a generalizable result for other roofs). Figure 9 shows that increasing the insulation thickness from none (only concrete deck) to 5.08 cm (2 in) will result in energy savings close to $\$12 \text{ m}^{-2}$, and increasing from 5.08 cm to 10.16 cm (4 in) would further lower the cost by $\$0.83 \text{ m}^{-2}$ over a year.

Figure 9: Energy costs saved in terms of PolyIso insulation foam thickness (not including costs incurred in insulating the roof). The dotted line indicates the baseline thickness, 4.508 cm (2 in). The circles indicate the simulated values from the model and the line represents the power law fit. The zero foam thickness simulation corresponds to a bare roof with a concrete deck (0.254 m thickness), as per table 1.

The analysis above does not yet account for the costs of adding the insulation. Assuming a baseline thickness of 5.08 cm (PolyIso roof insulation is readily available in prefabricated 5.08 cm thick (2 in) slabs, which is commonly used by commercial roof installers) and fixing the price of one PolyIso foam slab to $\$7.5 \text{ m}^{-2}$ (this price is based on our inquiry to multiple commercial installers in the Northeastern US), the cost recovery

time for the investment in upgrading the insulation can be calculated using the following equation [36]:

$$NS_{xy} = \sum_{t=0}^N \frac{S_{xy}(1+e)^t}{(1+d)^t} - \sum_{t=0}^N \frac{C_{xy}(1+e)^t}{(1+d)^t}. \quad (7)$$

In equation 7, S_{xy} and C_{xy} represent respectively the total savings (as in figure 9) and costs incurred by adding an additional layer of insulation foam over the baseline of 2 in. S_{xy} is calculated from the power fit relationship computed above. For this analysis, maintenance cost is omitted, as it would remain about constant, irrespective of additional insulation layers. C_{xy} thus only includes material cost, which is just the initial cost at $t = 0$. In the equation, e is the annual fuel price escalation rate. The average fuel price escalation rates for natural gas and electricity for the northeastern US are expected to be -1.0% , 0.85% , 0.4% and 0.6% for the periods 2012-2017, 2017-2022, 2022-2027 and 2027-2032, respectively [42]. The intergenerational real discount rate d , which accounts for future costs and benefits is set at 3.0% [43]. In the equation, N represents the year number and NS_{xy} is the present value of the net savings. A negative NS_{xy} implies net losses and a positive one implies net savings.

Based on equation 7, the break even time to recover the material cost for doubling, tripling and quadrupling the insulation thickness from the baseline case, i.e. when $NS_{xy} = 0$, is found to be 13, 17 and 19 years respectively. At the end of the life cycle (20 years), the net savings for all three cases is $\$3.7 \text{ m}^{-2}$, $\$2.5 \text{ m}^{-2}$ and $\$0.35 \text{ m}^{-2}$. This indicates that a 4-inch insulation maximizes the savings over a 20-year expected life of the roof. While these numbers are encouraging, many commercial establishments would find the 13-19 year recovery period too high, despite the fact that the average life span of a roof structure is around 20 years. Furthermore, the cost of borrowing money to

undertake such renovations was not fully accounted for since the intergenerational real discount rate d would likely be lower than the borrowing costs of these commercial establishments. However, only direct energy savings are accounted in this analysis since they have immediate and noticeable benefits to the consumer. Adding additional layers of insulation also has a myriad other socio-economic benefits: health benefits due to lower NO_x and SO_x emissions from power plants, reduced CO₂ emission and the associated impacts related to advancing climate change mitigation strategies, etc. Hence, since our computations indicate that there is a net socio-economic benefit associated with such roof upgrades, tax incentives or rebate plans could be developed to reduce the cost recovery period to 10 years, thus encouraging the businesses to undertake the upgrade and allowing for the various socio-economic benefits to be actualized.

6 Conclusion

The analysis detailed in this paper focused on identifying the optimal combination of roof insulation and roof reflectivity. The yearlong simulations using the Princeton ROof Model (PROM), forced by meteorological data for the NYC Metropolitan region, show that for newer constructions, an R8.4 roof with a highly reflective membrane ($\alpha > 0.7$) would be ideal in reducing the heat gained/lost, when the warmer and colder months are aggregated. Since maintaining roof reflectivity remains a challenge, the highly insulated R8.4 roof would considerably decrease the energy exchanges between the building roof and the surrounding environment and would eliminate the need to frequently clean the roofs to maintain high reflectivity. However, even with higher insulations, cool roofs are still advantageous, particularly for mitigating the urban heat island effect. Higher albedo

roofs resulted in significant reductions in the sensible heat transferred from the roofs to the atmosphere in our simulations.

The results illustrate that for older buildings that suffer from lack of proper insulation, increasing the albedo would help cut energy costs during the warmer months. This study also found that the energy and cost benefits of using white roofs clearly outweigh the wintertime penalty. The physical reason for this discrepancy between summer time benefits and winter time penalties of cool roofs, despite the fact that the northeastern US has about 5 times more heating degree days than cooling degree days, is related to the negligible impact of albedo during peak heating periods (which occur during nighttime and in the winter when the insolation periods are short), as opposed to its prominent role during peak cooling periods (occurring in the afternoon and in the summer when the insolation periods are long). Despite using meteorological data to force the model from the Northeastern United States, our results are pertinent to many other densely populated areas with comparable climates (e.g. northern Europe, China, Japan) where, despite a much higher number of heating versus cooling degree-days, our findings indicate that white roofs would be overall advantageous due to the asymmetry in the role and impact of albedo between the summer and winter time.

The model runs have also highlighted the importance of insulation thickness in reducing building energy consumption. Roughly, doubling the insulation thickness halves the heat lost during the colder months, which is the result to be expected from steady state heat transfer through the roof. Our analyses also indicate that additional layers of insulation foam help in offsetting the loss of reflectivity suffered by white roofs. However, the cost optimization analysis showed that the time to recover the additional cost incurred by

adding extra layers of insulation is moderately high by current pricing standards. Commercial roofs have a lifespan of around 20 years, private enterprises might be dissuaded by the relatively high recovery periods of 13, 17 and 19 years for doubling, tripling and quadrupling the thickness from the baseline case (5.08 cm). These results apply only to the Northeastern United States, but the methodology we describe and use to generate them can be easily applied to other regions to obtain the corresponding cost recovery periods.

In order to encourage commercial establishments to move towards green buildings and energy sustainability, policy makers can incentivize adding insulation layers either by subsidizing the cost of additional insulation layers, or through tax benefits. Currently many city and state administrations in the U.S. subsidize the cost of green roofs or offer tax credits. For example, in New York City and Philadelphia, consumers can receive up to \$100,000 in tax credits for converting more than half of their conventional roof to green roof [44, 45]. The Portland city administration offers zoning incentives for green roof installations [46]. In Arizona, green energy standards are mandatory for state and state-funded buildings [47]. In a similar fashion, policy makers in other cities and states should strongly consider incentivizing the addition of layers of roof insulation, as well as measures that increase the albedo

Overall, this study has unraveled the interacting roles played by roof reflectivity and insulation thickness in modulating the heat gained/lost through heterogeneous roof structures. Our results clearly demonstrate that high albedo roofs with thicker insulation can cost-effectively reduce energy consumption for heating and cooling in buildings. Furthermore, we reiterate that cool roofs will help moderate extreme heat in cities, as

well as provide urban planners and policy makers with an affordable but effective mode to advance towards urban energy sustainability.

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