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Direct and indirect effects of high-albedo roofs on energy consumption and thermal comfort of residential buildings

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A R T I C L E I N F O

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A B S T R A C T

Over the past three decades, high-albedo roofing has been promoted as a strategy to mitigate the urban heat island effect and reduce cooling energy demand and costs. In addition, high-albedo roofs can increase thermal comfort in non-conditioned buildings. Energy saving and thermal comfort benefits from these roofs have two components: 1- Direct benefits to individual buildings by reducing absorbed shortwave radiation through the roof, and 2- Neighborhood-scale indirect benefit resulting from reduced ambient air temperatures, particularly when high-albedo surfaces are deployed on a large scale. This study is an effort to quantify the relative importance of these direct and indirect benefits and identify how they are affected by building and climate characteristics. We used whole-building energy simulations of a set of archetypical single family residential buildings in three locations with distinct characteristics within the Los Angeles area (one coastal, and two inland). Our simulations show that benefits from the indirect effect can be the same order of magnitude as the direct effects. More importantly, these benefits depend on the climate and building characteristics. The highest energy and thermal comfort benefits were observed in a low-performance building (defined by airtightness and ceiling insulation level) in Long Beach, where simulations indicated an energy savings of 41% and thermal comfort improvement of 23% due to a combination of direct and indirect effects.

1. Introduction

Many urbanized areas around the world are dealing with challenges posed by the urban heat island (UHI) effect. Warmer urban climates are a result of dark surfaces, anthropogenic heat, high heat storage capacity of urban elements, lack of green spaces, reduced infrared emittance to the sky due to trapping of radiation by urban morphology, and low circulation of air in dense urban environments [15]. The increased cooling energy demand of buildings is a major challenge caused by UHIs since it contributes to a feed-back loop, further intensifying the UHI. Not only do increased ambient air temperatures increase the heat gain through building envelopes, but they also reduce the overall efficiency of air conditioners [23]. Perhaps more importantly, air conditioner use results in waste heat emission into the urban environment, further exacerbating the UHI effect. Accordingly, as reported by Santamouris [22], on average, urban buildings consume 13% more air conditioning energy than comparable non-urban buildings. Kolokotroni et al. [10] also consider future scenarios and report that for office buildings in London, the urban to reference (rural) building cooling energy consumption ratio will increase from 1.08 in 2000 to 1.15 in 2050. High-albedo urban surfaces (e.g., roofs, or pavements), also known as cool surfaces are effective strategies to counterbalance the heat island impacts. By reducing the absorbed solar energy, these surfaces provide a cooling effect. This cooling of the urban environment indirectly benefits indoor thermal comfort and energy consumption of buildings [3]. Santamouris [21] performed a broad meta-analysis of the literature on the UHI mitigation benefits of high-albedo and green (vegetated) roofs. His work suggests that in sunny climates (e.g., southwest U.S.), high-albedo roofs are a highly effective strategy to mitigate the UHI and outperform green roofs in this regard. He also used regression analysis of data from previous studies and reported a 0.3 °C decrease in summertime average ambient temperature in urban areas per 0.1 increase of average albedo of urban surfaces. In another study, Scherba et al. [24] compared white, green, and PV-shaded roofs in five major U.S. cities and reported that white roofs have the lowest daily sensible heat flux rate to the urban environment. They report that white roofs can reduce this metric by up to 80%, as compared to a 60% reduction associated with the second best option (green roofs).

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While the observed cooling effect from implementation of high-albedo roofs can indirectly benefit the thermal comfort and energy consumption of buildings, the literature has mostly focused on its direct benefits to buildings. Depending upon the climate and building characteristics, heat gain through the roof can be a significant contributor to the cooling energy demand of buildings [4,26]. Moreover, in the case of free-running buildings (no Air Conditioning), this heat gain has detrimental impacts on thermal comfort and reducing it can significantly improve buildings' passive performance—especially, in sunny climates. For example, the two-year data measurement campaign of Akbari et al. [1] in two buildings in Sacramento, CA showed seasonal energy savings and peak load reductions of 2.2 kWh/d and 0.6 kW in a house and 3.1 kWh/d and 0.6 kW in a school building. In another study for the same climate, Rosenfeld et al. [19] report a 20–40% cooling energy savings potential for a single-family detached building. Synnefa et al. [27] used whole-building simulations of buildings in 27 cities around the world and reported cooling energy savings and peak demand reductions of 18–93% and 11–27%, respectively. Moreover, in non-conditioned buildings in the considered cities, they observed 9–100% decrease in the number of uncomfortable hours. In addition to these studies, some papers consider the aggregate effect of these savings on total energy consumption within a region. For example, Boixo et al. [5] report that high-scale implementation of cool roofs in Andalusia, Spain can save up to 295,000 kWh of energy annually. This corresponds to 59 million euros in energy costs and 135,000 metric tons of emitted CO_2. Finally, most studies that compare the economic profitability of cool roofs to other roofing strategies, e.g., the work done by Sproul et al. [25], report that cool roofs are the most cost-effective energy saving strategy when it comes to rooftops. All mentioned studies are limited to the direct benefits of cool roofs. Among the few papers that investigate the indirect benefits, there is the notable study by Akbari and Konopacki [2] on 3 building types (office, residential, retail) with different vintages in 240 locations. Their work resulted in tables that included direct savings from implementation of cool roofs on each building as well as the indirect savings from UHI mitigation strategies (shade trees, and high-albedo surfaces).

The present study addresses the research gap in understanding direct and indirect benefits to energy consumption and thermal comfort by focusing on their dependency on building and urban climate characteristics. In addition, given the lack of studies looking at the impact of building characteristics on the effectiveness of high-albedo roofs, we sought to identify envelope properties and climate types that would result in significant benefits from implementation of high-albedo roofs. In order to do this, we used whole-building simulations of archetypical low-, moderate-, and high-performance residential buildings in three locations with distinct geographical characteristics and urban morphologies within Los Angeles, CA. In addition, we conducted a sensitivity analysis to identify envelope properties that are key determinants of high-albedo roof effectiveness in single-family residential buildings. Based on our simulation results, we compared all cases and discussed building/climate characteristics that are determinant of high-albedo roof effectiveness.

2. Methods

The analysis in this study is based on validated whole-building energy simulations supplemented with national and regional data sources to inform the input to the models. First, we conducted a sensitivity analysis to study how different building characteristics impact the effectiveness of high-albedo roofs. Then, based on the result from the sensitivity analysis, we defined three archetype buildings using variables that we found to be the main determinants of high-albedo roof effectiveness. These archetypes where then used in the main simulations under three different scenarios. In the first scenario, we simulated the effects of roof albedo change under version 3 of the Typical Meteorological Year (TMY3) weather data. This gave us the direct benefits of high-albedo roofs to different buildings. Then, we ran the same simulations using modified weather files that reflect urban cooling due to large-scale implementation of cool surfaces. Hence, this case includes direct benefits of installing high-albedo roofs on a building combined with indirect benefits of neighborhood scale implementation of cool surfaces. Finally, to isolate the indirect benefits, we simulated buildings with typical low-albedo roofs under the modified weather files. This scenario highlights the effects from large-scale adaptation of cool urban surfaces to buildings without high-albedo roofs. In all scenarios, buildings were simulated with and without AC. In buildings with AC, in each simulation, the cooling system electricity consumption (kWh) over the whole period was exported. We used this information to calculate the costs based on a simplified billing system (with a constant rate of 0.2 $/kWh representing local residential energy prices in 2017). In free-running buildings (i.e., those without AC), we outputted the number of uncomfortable hours as a metric to assess thermal comfort. This was calculated using the ASHRAE 55 adaptive method, which considers the fact that an occupants' thermal comfort threshold is a function of the outdoor weather conditions. This method is based on the fact that occupants would adapt to heat over time. Therefore, their preferred indoor temperature is a function of the outdoor temperature they have been exposed to over the last month. To account for this, the adaptive method modifies the indoor thermal comfort threshold based on the monthly running average of outdoor temperature. In all runs, the simulated period was May to August and the timestep was set to 15 min.

2.1. EnergyPlus

Decades of research dedicated to developing and validating whole-building energy models has resulted in various tools currently available to engineers and researchers. These physics-based models dynamically solve mass and energy balance equations for all zones within a building while considering the interactions with the outdoor environment (e.g., radiation exchange, heat transfer through envelopes) and heat sources inside zones (e.g., people, electric equipment). Most modern whole-building energy simulation tools have proven to be capable of accurately simulating the thermal conditions inside buildings, as well as heating and cooling loads. Developed by the U.S. Department of Energy (DOE), EnergyPlus is a validated tool widely used by researchers in this field [6]. In particular, it is a simulation tool mostly chosen by researchers for studies with similar scope and building type as this our work [16,31]. Therefore, we chose it as the simulation tool for this study.

2.2. Climate data and study regions

In this study, two sets of weather data were required for each location. First, we needed to simulate buildings under typical conditions. In addition, we needed a separate set of weather data that reflects urban cooling effects from large-scale implementation of cool surfaces. Therefore, we used the original and a modified version of TMY3 data for the two scenarios. TMY3 data is a climatically representative dataset for a given location, created from a 30-year climate record using the Sandia method [28]. The method identifies the most representative January from the data record, then repeats this process for each subsequent month of the year, concatenating the representative months from across the 30-year climate record, using linear curve-fitting (for the first and last 6 h of each month) to stitch the individual months together.

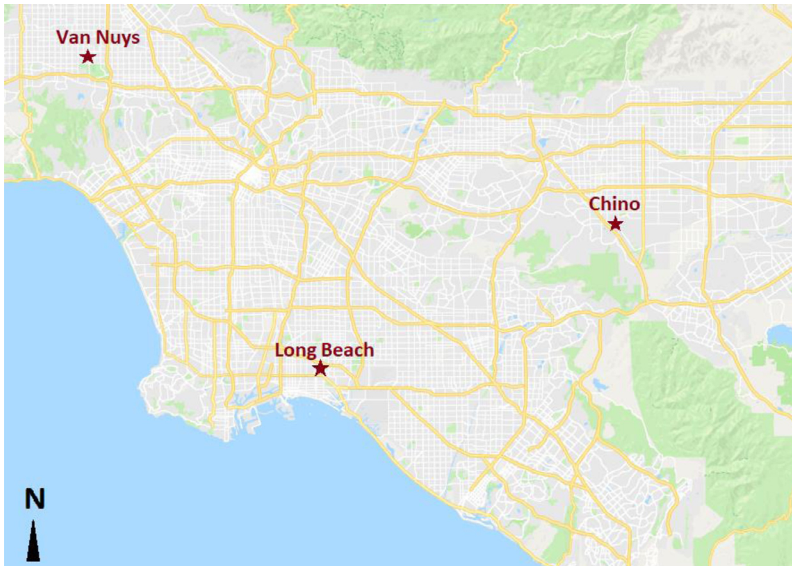


Fig. 1. The location of three airport stations within the L.A. basin. While Long Beach and Van Nuys had airport stations with available TMY3 data, data for Pomona was extracted from Chino airport which is the closest station with TMY3 data. Map data © 2018 Google, INEGI.

Table 1
Summary climate characteristics of the three locations. All data from May to Aug.

Weather station	Cooling degree - days (°C –day)	Minimum temperature (°C)	Mean temperature (°C)	Maximum temperature (°C)
Van Nuys	666	11	21.8	39
Chino	670	10[1]	21.4	39
Long Beach	406	10.6	20.1	35

[1] The outlier data point of 6 °C was removed.

Using the California poverty data from CalEnviroScreen 2.0 [8] and tree cover data from LAR-IAC [11], we identified 3 regions in the Los Angeles metro area that have high levels of poverty and low vegetation cover. In general, the population in such locations are considered to be more vulnerable to heat due to limited financial and social resources [9]. In addition, limited financial resources means that they could benefit more from saving in utility bills. Pomona is in the eastern inland reaches of Los Angeles County with very warm conditions during the summer. Van Nuys is located in the San Fernando Valley. This valley is isolated from direct airflow from the ocean even though the distance to the Pacific Ocean is relatively small. There is a small bottleneck for air flow into and out of the valley between the Hollywood Hills and the Verdugo Mountains. Due to the physical geography of the valley, the San Fernando Valley becomes hot very quickly under synoptically benign conditions and air quality can quickly deteriorate with the large volume of pollution within the valley that cannot escape under these conditions. This is in some contrast to the San Bernardino Valley where Pomona is located. The San Bernardino Valley is further inland; however, there is better airflow through this valley due to a wider gap between the Chino Hills, the San Jose Hills, and the Angeles National Forest. This flow changes the physical processes by which Pomona experiences extreme heat and poor air quality compared to those processes in action in the San Fernando Valley and Van Nuys. Finally, Long Beach is on the Pacific Ocean coast in SW LA County and gives us another type of microclimate (i.e., lower mean and maximum temperatures) that helps capture land cover and baseline climate variations within the area. Fig. 1 shows the location of three airport stations within the L.A. basin. In addition, summary climate characteristics are provided in Table 1.

To analyze the effect of high-albedo roofing and paving across the LA basin on energy usage and indoor thermal comfort for a single house, we adjusted the outdoor temperature from the TMY3 data to account for the cooling associated with these mitigation strategies. To do so, we assumed that the effect of these strategies on lowering outdoor temperature may be unevenly distributed across the day. As a sensitivity test, we ran whole-building energy models using several diurnal temperature perturbation profiles (uniform, single modal, and bimodal) for a nominal 1 °C cooling effect, while controlling for the total degree-hours of reduction (area below the curve) over a 24-hr period. We found no significant difference between the tested profiles (shown in Fig. 2). Hence, to mimic temporal profiles of mitigation-induced cooling most commonly reported in the literature [14,30], we selected a bimodal sinusoidal profile. In addition, since cloud cover is a key determinant of the temperature reduction profile, we scanned all weather data to identify days with considerable cloud cover. Notably, in all three locations, less than 8% of days had considerable cloud cover. Thus, ignoring the errors caused by assuming a single temperature profile for all days is justified. It is important to note that magnitude of the urban cooling (1 °C daily maximum) used in this study is arbitrary. Based on the previously-mentioned study by Santamouris [21], our selected scenario is a conservative estimate of the effect of city-wide cool surface implementation. Hence, a more aggressive urban cooling scenario would result in higher indirect benefits than those reported in this study.

2.3. Archetype building

In this study, we focused on single-family residential buildings with wood-frame construction. This is the dominant type of residential building in the U.S., and in particular, within the Los Angeles metro area [7]. All modeled buildings were based on a typical size and geometry for this region, as shown in Fig. 3.

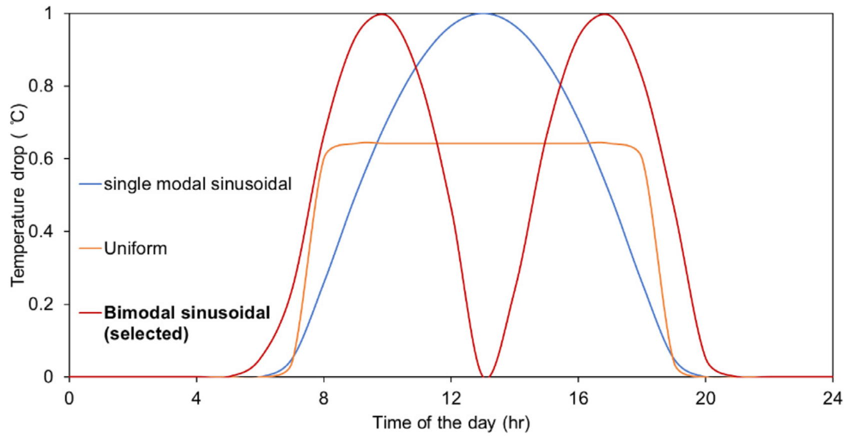


Fig. 2. Different temperature reduction profiles considered for the effect of high-albedo surfaces on urban climates.

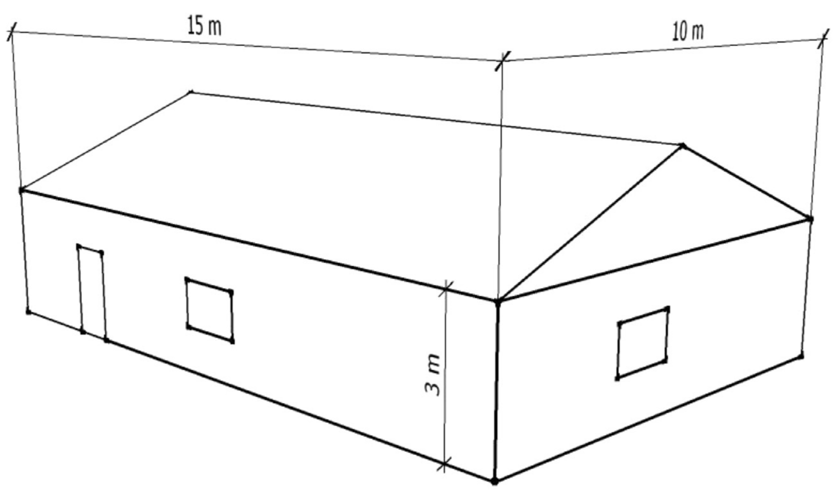


Fig. 3. The geometry of the modelled archetype buildings. Here, the building orientation and window sizes are not shown as they are variables in the sensitivity analysis.

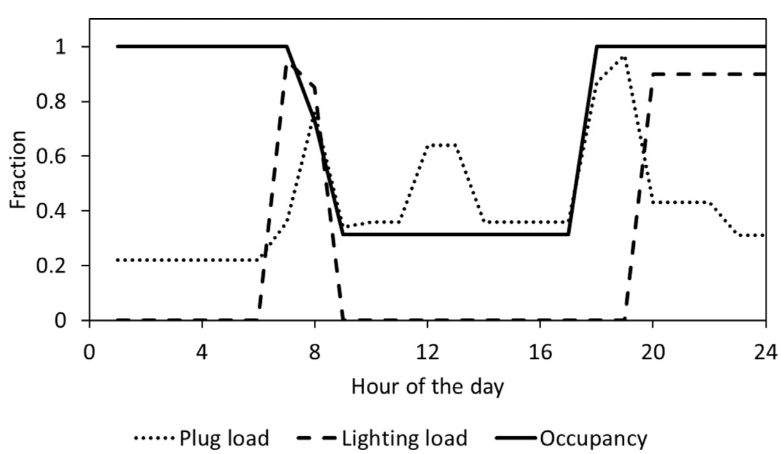


Fig. 4. Daily occupancy, plug, and lighting schedules.

Each simulated building was assumed to have four residents. For buildings with air conditioning, the cooling set point temperature was fixed at 24 °C. The activity level (human metabolic rate) was set as the default value for residential buildings (117 W/person). Plug power density and lighting power density were set as 1.07 and 2.15 W m^{-2}, respectively (see Fig. 4 for profiles of schedules). All internal load input values were obtained from the Residential Prototype Building Models provided by the Office of Building Technology of the U.S. Department of Energy (www.energycodes.gov).

Table 2
List of variables considered for sensitivity analysis.

Variable	Range / Types
Ceiling Insulation R-Value ($m^2.K.W^{-1}$)	4.1–7.5
Wall Insulation R-Value ($m^2.K.W^{-1}$)	1–3
Glazing U-Value ($W.m^{-2}.K^{-1}$)	1.9–4.9
Solar heat gain coefficient (SHGC)	0.4–0.6
Air exchange rate (1/hr)	0.3–1.2
Orientation (degrees from N axis)	0 (S-N)–90 (E-W)
Window to wall ratio (WWR) on all sides (%)	0.15–0.3

Table 3
Archetypes defined based on the result of sensitivity analysis.

Archetype	AER (1/hr)	Ceil. insulation *R*-Value
High performance	0.5	7.5
Moderate performance	1	4.1
Low performance	1.5	1.8

3. Sensitivity analysis

We conducted a sensitivity analysis for building characteristics that could potentially be determinants of high-albedo roof effectiveness for improving thermal comfort or energy efficiency (listed in Table 2). For envelope properties, the range of each variable was determined based on values from different versions (2003–2012) of the International Energy Conservation Code (IECC) obtained from www.iccsafe.org. Variables that remained constant (or were not addressed) in the last 4 versions of the IECC code, e.g., floor R-value or AC efficiency, are excluded from the sensitivity analysis and were set based on the 2006 code. In addition, although ventilating the attic could potentially have a large impact on the effectiveness of high-albedo roofs, we consider it an active strategy that is not inherent to the building design. Hence, while acknowledging that a highly ventilated attic could potentially render high-albedo roofing of little additional value, we did not include attic ventilation in our sensitivity analysis. For infiltration rate, the range reported by Yamamoto et al. [29] was used. We conducted all simulations using the unmodified TMY3 data. Hence, the sensitivity analysis is based only on the direct benefits of high-albedo roofs.

After generating the models, we set up a run procedure in which, for each variable, the lower and higher limits were simulated using all possible combinations of the remaining variables. Therefore, 128 simulations were run for each building (64 for energy and 64 for thermal comfort). This was done for all three locations. Therefore, a total of 384 (128×3) simulations were run. Then, we repeated all simulations while changing the roof albedo from 0.2 to 0.5. We obtained these values from the work of Prado and Ferreira [17]. While the albedo of 0.2 represents a typical roof with a dark surface (default value in EnergyPlus), the albedo of 0.5 represents a roof top with a bright color after weatherization (deterioration of albedo during the first years) and is a conservative estimate of the albedo of high-albedo sloped roofs.

This enabled us to calculate energy savings or thermal comfort improvements (defined as the reduction in the number of uncomfortable hours) of high-albedo roofs for all runs. Consecutively, for both ends of each variable in our sensitivity analysis, we calculated the average energy saving / thermal comfort improvement that reflect all possible scenarios with respect to the other remaining variables. Accordingly, for each variable, the larger the difference between average energy saving/ thermal comfort improvement of lower and higher ends of its range, the more influential that variable would be on the effectiveness of high-albedo roof on energy saving / thermal comfort improvement. The advantage of the applied method is that it helps to ensure we are capturing the interactions between these variables. Figs. 5 and 6 show the results from this analysis for thermal comfort and cooling energy consumption.

As suggested by the results, ceiling insulation level is the key variable in determining the benefits from high-albedo roof implementation. This can be justified by the fact that the ceiling insulation is the only thermal barrier between the interior space and the attic, which is in direct contact with the roof. Therefore, the more thermally-resistant the ceiling layer, the more thermally isolated the living space from the attic, and hence the less impact from rooftop albedo modification. In addition to ceiling insulation, air exchange rate (AER) has non-trivial effects on thermal comfort, especially in the case of Long Beach, for which the ambient environment is typically closer to the thermal comfort threshold (refer to Table 1). Hence, the disturbance caused to the system by the albedo change in Long Beach could cause a higher increase in the number of comfortable hours if there is a higher air exchange rate with outdoors. Based on these findings, in a shell-dominated single family detached residential building in these climates, the ceiling insulation *R*-value and the AER are the primary determinants of the effectiveness of high-albedo roofs in reducing cooling energy demand or improving thermal comfort. Hence, for the rest of the analysis, the archetypes will be defined solely based on these two variables. Table 3 shows ceiling *R*-value and AER for the three archetypes that represent low, moderate, and high-performance buildings. While for the high and moderate performance buildings, ceiling *R*-value is from IECC 2012 and 2006, the low performance building represents a building not complying to any IECC version. AER values for all archetypes were selected based on the range reported by Yamamoto et al. [29]. All other variables were set based on the IECC 2006 model building with a south facing orientation.

As a final step in the sensitivity analysis, we investigated the potential impacts that window operation behavior might have on thermal comfort results for the non-conditioned buildings. Hence, we simulated all three buildings in all locations (a total of 9 cases), exporting thermal comfort metrics for the base case and for the case of roof albedo increase under two scenarios: 1- occupants do not have any window operation strategy (windows are closed all the time) 2- occupants would open windows when the outdoor temperature is at least 2 °C cooler than indoors (only between 6 AM and 10 PM). As Fig. 7 shows, while in some cases, the baseline values are highly-dependent on window operation strategy, in general, the impacts from high-albedo roofs are less sensitive to the window operation strategy. Therefore, we did not include window operation strategy in our analysis. In our final simulations of buildings without AC, we assumed the occupants do not actively open windows. Nevertheless, as Fig. 7 suggests, we expect the effects from this assumption on our final results for the improvement potential to be insignificant.

4. Results and discussion

In the final simulations, we used the defined archetypes to run EnergyPlus models in all three locations. First, in order to verify that our archetypes accurately represent the target building stock, we compared simulated total monthly electricity demands of all archetypes with the average monthly electricity consumption of residential buildings in each location reported by the utility company serving the area. Since the utility data was from 2016, we ran the simulations using actual weather data recorded at each airport station in summer 2016. As Fig. 8 shows, considering the California Climate Zone Averages (CCZ Avg.), our archetypes provide an acceptable representation of the existing building stock. Here, H.P.,

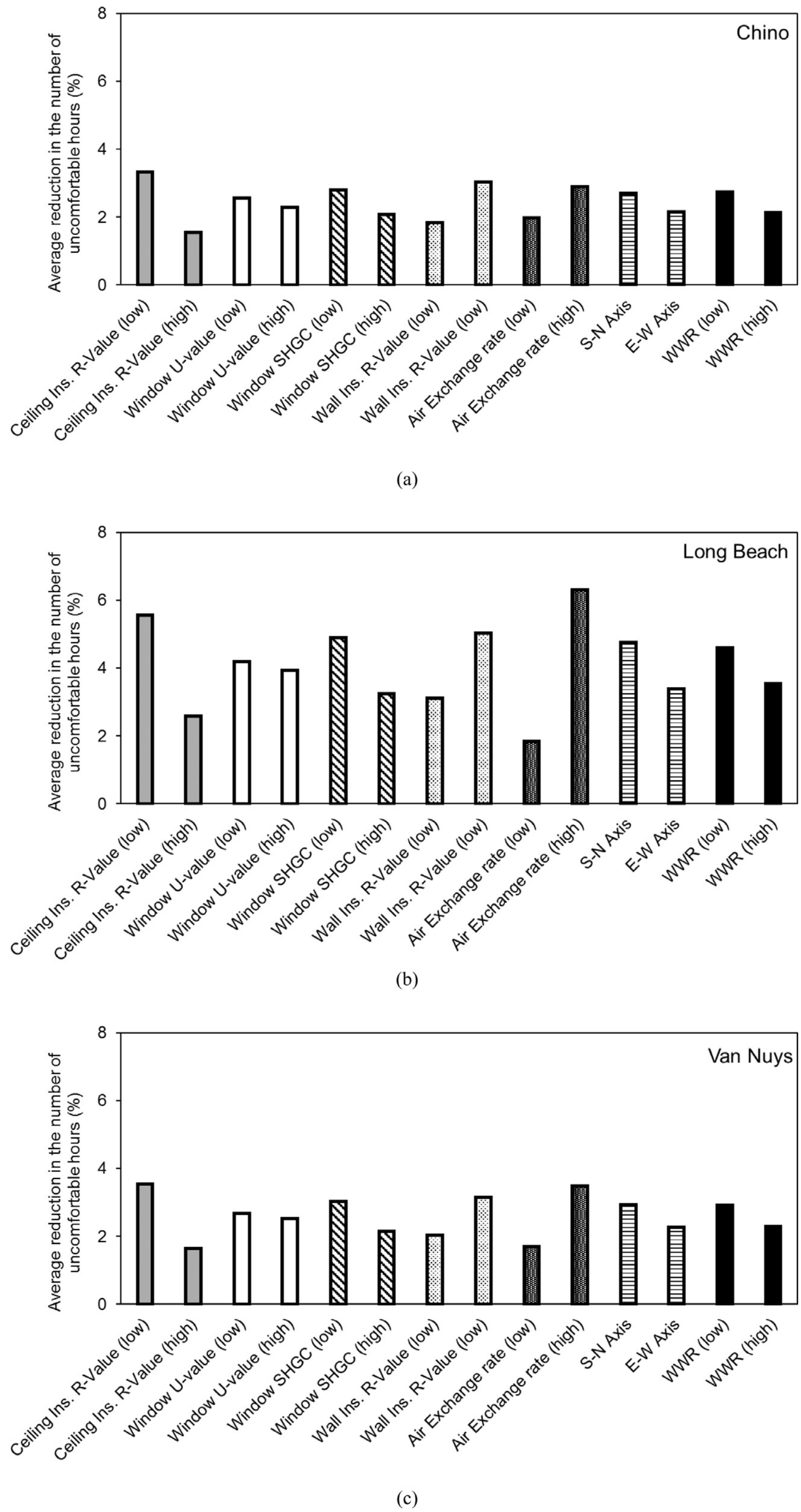
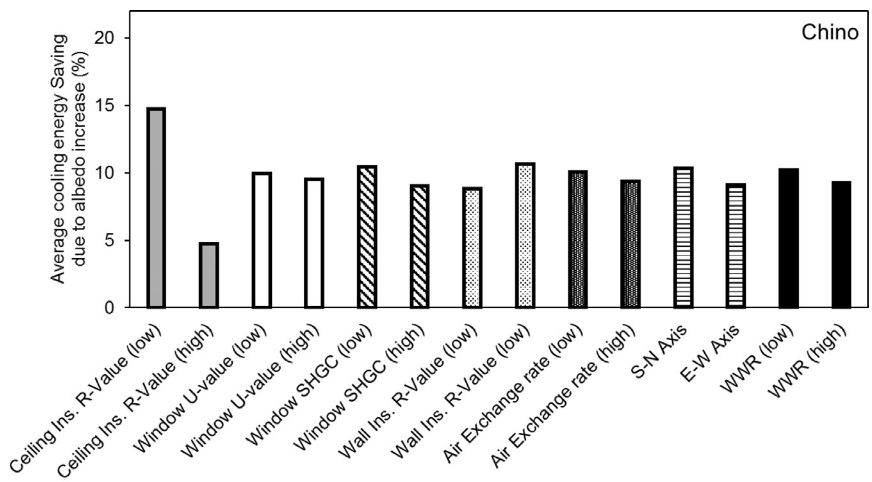


Fig. 5. Sensitivity of thermal comfort improvement (in buildings without AC) to albedo-increase to different variables in (a) Chino (b) Long beach (c) Van Nuys. Here, "low" and "high" refer to the low and high ends of the considered range (reported in Table 2) for each variable. The two bars for each variable show the possible range of benefits for each variable. Hence, the higher the difference between the two bars, the more important that variable in determining the benefits of high-albedo roofs.



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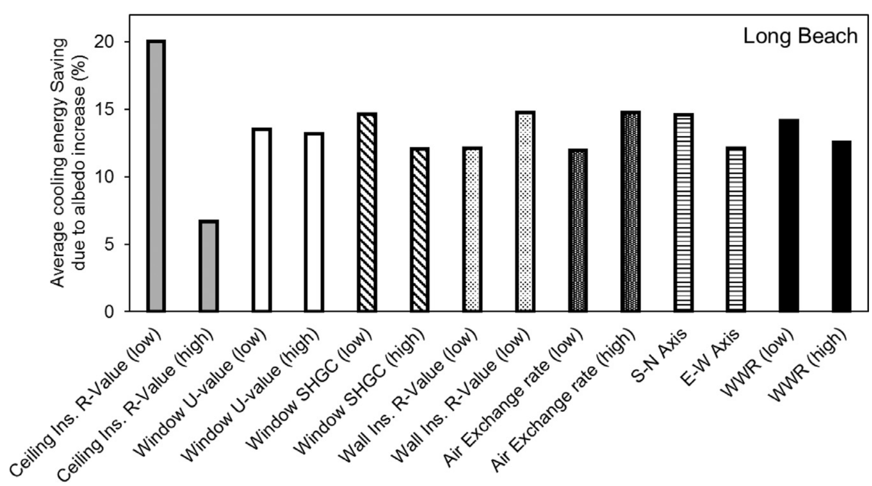

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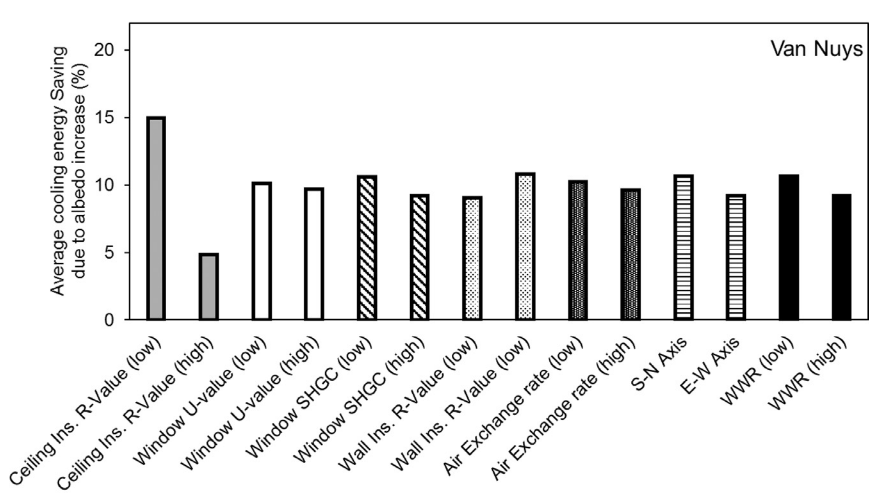
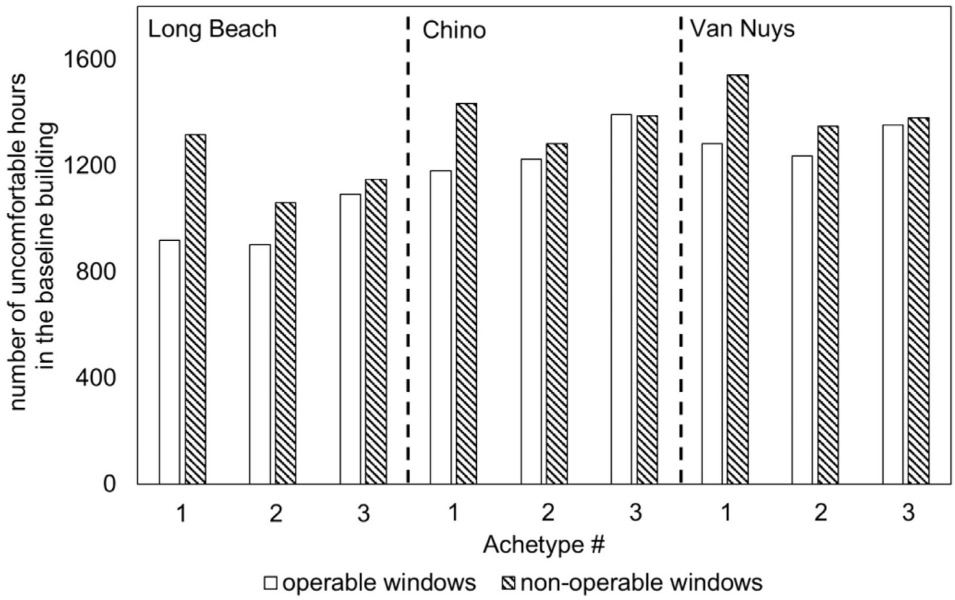
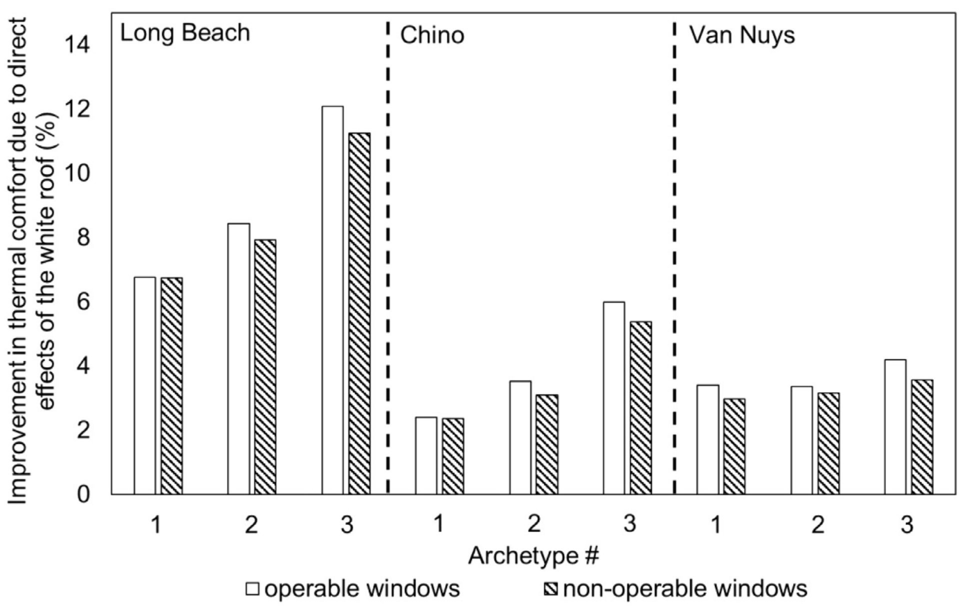


(C)

Fig. 6. Sensitivity of cooling energy savings (in buildings with AC) to albedo-increase to different variables in (a) Chino (b) Long beach (c) Van Nuys. Here, "low" and "high" refer to the low and high ends of the considered range (reported in Table 2) for each variable. The two bars for each variable show the possible range of benefits for each variable. Hence, the higher the difference between the two bars, the more important that variable in determining the benefits of high-albedo roofs.



(a)



(b)

Fig. 7. The effects of window operation strategy on: (a) thermal comfort in baseline buildings (b) the effectiveness of high-albedo roof in reducing the number of uncomfortable hours. Here, archetypes 1, 2, and 3 refer to high, moderate, and low-performance buildings, respectively.

M.P., and L.P., stand for High, Medium, and Low Performance buildings.

After verifying that the archetypes represent the building stock well, we proceeded with the final simulations in which we used original and modified (urban cooling scenario) versions of TMY3 data. For direct and combined (direct + indirect) benefits, we increased the roof albedo from a baseline value of 0.2 to a retrofitted value of 0.5 and simulated the buildings under original and modified TMY3 weather data. For the indirect scenario, we simulated buildings with an unmodified roof albedo of 0.2 under the modified TMY3 data. Thermal comfort (reported as the number of uncomfortable hours based on ASHRAE 55 standard) and cooling energy demand (reported as the electricity cost of cooling system over the summer) were exported for further analysis.

4.1. Effects on cooling energy demand

Fig. 9 shows the direct and indirect impacts of increasing the roof albedo on cooling energy costs for low (L.P.), moderate (M.P.), and high (H.P.) performance buildings. In these plots, bars with dashed outlines represent the baseline values and the bars with solid colors show the reduced values to due higher albedo. In addition, Δ refers to the cooling energy cost saving over the summer in U.S. dollars (and in percentages of saving).

These simulations highlight the impact of building characteristics (namely, insulation level and air-tightness) as well as the climate on the effectiveness of high-albedo roofs. First, in all three locations, the direct benefits of high-albedo roofs in low-performance buildings is more than two times higher than the high performance buildings. Second, indirect energy savings, while

Table 4
Energy and thermal comfort benefits of high-albedo roofs in low-performance buildings.

Location	Cooling system electricity cost over the summer ($)				Number of uncomfortable hours over the summer			
	Base-line	Direct reduction	Indirect reduction	Combined reduction	Base-line	Direct reduction	Indirect reduction	Combined reduction
Long-Beach	118	33	16	47	1148	138	82	226
Chino	235	36	19	54	1388	53	47	105
Van Nuys	234	38	18	55	1380	58	45	105

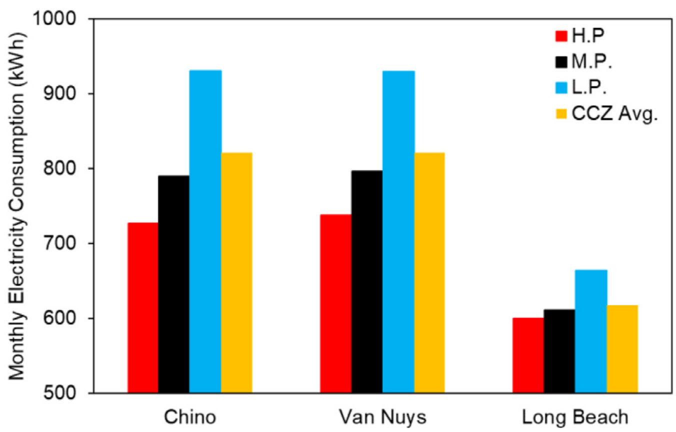


Fig. 8. Validating the archetypes' representativeness of the actual building stock by comparing the simulated energy consumption to average household energy demand in each area. Results are for low (L.P.), medium (M.P.), and high (H.P.) performance buildings, as well as for the corresponding California Climate Zone averages (CCZ Avg.).

lower, are the same order of magnitude as the direct savings in all cases. However, it should be noted that the numbers reported here are per 1 °C of ambient air cooling. Hence, effects from a more aggressive urban cooling scenario could easily surpass the direct benefits from roof albedo increase. Third, irrespective of the baseline values, the direct and indirect energy savings are very similar in all climates. This can be explained by the fact that these locations have approximately the same latitude; thus, considering the low fraction of cloudy days in the TMY3 data, they all receive roughly the same amount of solar radiation. Hence, introducing similar albedo increase to the system would result in almost the same amount of avoided heat gain for similar buildings in all three climates. With respect to indirect effects, the observed similarity between the climates are due to the same temperature reduction profile that we assumed for all three locations. However, when considering the relative savings, since baseline values in Long Beach were significantly lower, the percent saving in energy costs (for direct and indirect effects) is much higher than the other locations. Finally, expectedly, the results suggest that combined effects present a scenario with maximum energy saving. For low-performance buildings, the calculated reduction in summertime cooling electricity cost ranges from 23% in Van Nuys and Chino to 40% in Long Beach. Notably, in all cases, the combined benefits (direct + indirect) are roughly equal to the sum of the isolated direct and indirect benefits. Therefore, combined benefits can be approximated by simply adding the two components.

4.2. Effects on indoor thermal comfort

Fig. 10 shows the direct and indirect impacts of increasing the roof albedo on summertime thermal comfort inside unconditioned buildings. In these plots, bars with dashed outlines represent the number of uncomfortable hours in the baseline building and the bars with solid colors show the reduced values to due higher albedo. Here, Δ refers to the reduction in the number of uncomfortable hours over the summer.

As seen in the figure, depending upon the location and building type, the reduction in the number of uncomfortable hours during the summer due to implementation of high-albedo roofing could be between 50 and 155 h. Also, similar to the energy savings results, the low-performance building is associated with a larger thermal comfort benefit than the other buildings. In addition, direct benefits of albedo increase to thermal comfort are higher in Long Beach, which has the coolest climate among the selected regions (an average reduction of 94 h compared to 41 and 45 h in the other locations). As mentioned earlier, this is due to the fact that in Long Beach, the outdoor conditions are relatively closer to the thermal comfort threshold (based on ASHRAE-55 method). Hence, in this location, increasing the roof albedo can have more substantial effects on the number of uncomfortable hours. Moreover, in contrast to energy demand, direct and indirect benefits to thermal comfort have generally the same magnitude (across all locations and in different buildings types). In other words, when considering the thermal comfort inside a non-conditioned building, large-scale implementation of high-albedo roofs in the area could potentially lead to the same result as increasing the roof albedo of that single building.

Another notable trend observed in the results is that baseline M.P. buildings have fewer uncomfortable hours than the H.P. ones. Several other studies on summertime thermal comfort in non-conditioned buildings have reported similar findings [12,13,18]. In the absence of ventilation (especially, nighttime ventilation such as leaving the windows open during the night), buildings that are more insulated and airtight could potentially overheat more than average buildings. Since in our model, occupants would not open windows at night (a realistic assumption, especially in high crime or noisy neighborhoods), benefits from nighttime ventilation are minimal. Therefore, there is an optimum infiltration rate that can provide more comfort. In this case, M.P. buildings are closer to that optimum than the other two archetypes.

Finally, when considering the combined (direct and indirect) effects, the improvement in thermal comfort in non-conditioned buildings could be significant. The average reduction in the number of uncomfortable hours (across different building types) is 226 in Long Beach, and 105 in Chino and in Van Nuys. In addition, for thermal comfort, the sum of isolated direct and indirect benefits is not as close to the combined benefits as it was for cooling energy. In other words, the approximate additivity of the cooling energy benefits cannot be applied to obtain the reduction in the number of uncomfortable hours in non-conditioned buildings.

4.3. Improvement potential in low-performance buildings

Based on the simulation results, the less energy efficient and thermally comfortable the building (the low-performance building), the more the potential for improvement. So, there is value in exploring the low-performance building in more depth. Table 4 lists both performance metric and the associated improvement due the high-albedo roofs for low-performance buildings in

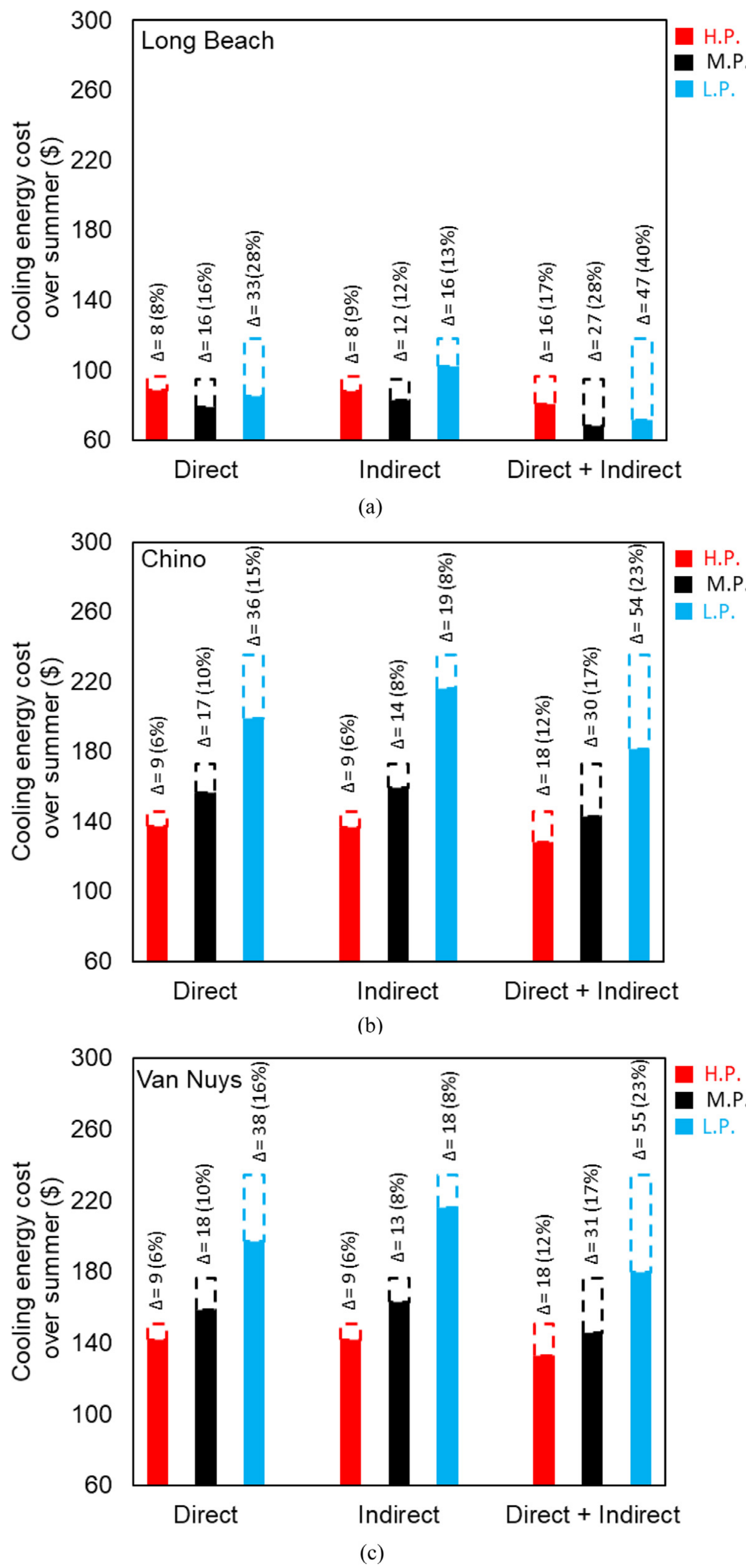


Fig. 9. The direct, indirect (per 1 °C of ambient air cooling), and combined benefits of increasing the roof albedo on summertime cooling energy costs in conditioned low (L.P.), moderate (M.P.), and high (H.P.) performance buildings in (a) Long Beach (b) Chino (c) Van Nuys.

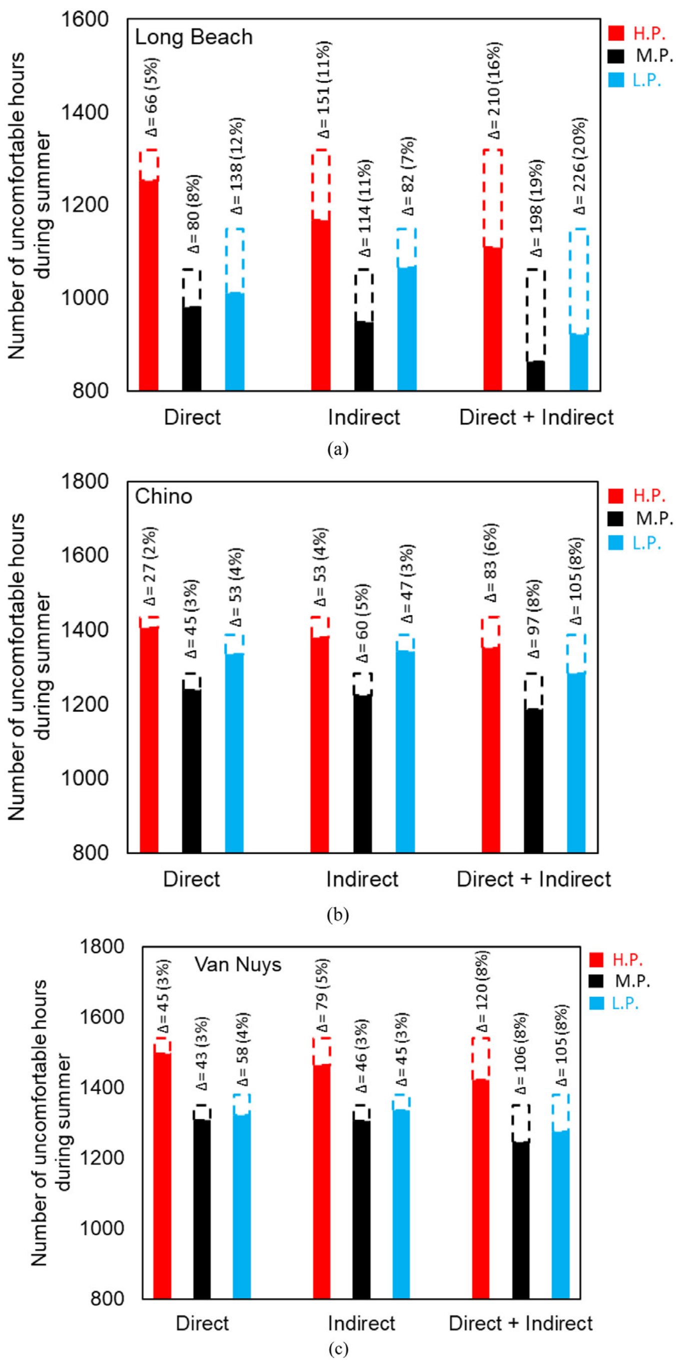


Fig. 10. The direct, indirect (per 1 °C of ambient air cooling), and combined benefits of increasing the roof albedo on summertime thermal comfort in unconditioned low (L.P.), moderate (M.P.), and high (H.P.) performance buildings in (a) Long Beach (b) Chino (c) Van Nuys.

all locations. In addition, Fig. 11 shows the percentages of improvement for both thermal comfort and energy efficiency.

In general, increasing the roof albedo of buildings within an urban environment can reduce cooling energy costs of low-performance buildings by 24–41%. Given the relatively low incremental cost of high-albedo roofs [19], we find this strategy to be promising both for improving energy efficiency and thermal comfort. More importantly, our study shows that in the climates we modeled, the indirect cost benefits from urban cooling to residents of low-performance building with low-albedo roofs can be around 10%. It is noteworthy that a less conservative assumption with respect to the magnitude of urban cooling can potentially lead to more savings.

In non-conditioned buildings, the modeled reduction in the number of uncomfortable hours from the combined benefits ranges from 105 in Chino and Van Nuys to 226 in Long Beach. The important point here is that this strategy has more noticeable benefits in climates that are more moderate. When averaged over the entire modeled period, the 226 h of reduction in Long Beach corresponds to an average of 2.4 more comfortable hours per day in these residences. Nevertheless, in warmer climates, since the hot ambient air is the main contributor to thermal discomfort inside buildings, increasing the roof albedo (which reduces the heat gain through short wave radiation) is relatively less effective in providing more comfortable hours. Although, considering the relatively low-cost [25]), even in these climates, large-scale increase in the roof albedo of buildings in low-income neighborhoods can be considered as an effective strategy to relatively reduce heat exposure of more vulnerable groups. In addition, it could lead to less tendency (or need) to purchase and install AC.

5. Conclusion

In this study, we used whole-building energy simulations to estimate direct and indirect benefits of high-albedo roofs on single-family detached residential buildings in three locations within the Los Angeles area in Southern California. An important finding of this study is that in shell-dominated buildings, air-tightness and ceiling insulation levels are the main determinants of the effectiveness of high-albedo roofs. Moreover, across all climates, the low-performance buildings had the highest potential for energy use reduction (in conditioned buildings) and thermal comfort improvement (in non-conditioned buildings). This is significant as the population most at risk during extreme heat events (the poor) are also most likely to reside in lower performance buildings [20]. In addition, buildings in Long Beach, which is closer to the coast and has a cooler climate (closer to the thermal comfort threshold), would see more thermal comfort benefits than buildings in the two other locations that are further inland (Chino and Van Nuys). Furthermore, the indirect benefits from the ambient cooling caused by large-scale implementation of cool urban surfaces are similar in magnitude to the direct benefits from implementing a high-albedo roof on a single building. The two inland locations, although geographically different, showed very similar results, suggesting that the dependencies observed here are mostly determined by distance from the coast.

When the combined effects (direct and indirect) are considered, our simulations show that, depending on the climate, large-scale implementation of high-albedo roofs over an area could result in a 24–41% savings in cooling energy costs for low-performance buildings. In non-conditioned buildings, albedo increase can reduce the number of uncomfortable hours during the summer by up to 20%. Notably, in the case of cooling energy savings, we noticed a linearity in the results showing that the combined benefits can be approximated by simply summing the direct and indirect benefits. However, this linearity was not observed with respect to thermal comfort benefits.

From a policy standpoint, this work has two key findings. First, the fact that the magnitude of the direct and indirect benefits of high-albedo roofing are similar highlights the potential benefit from large-scale implementation of high-albedo roofs. In addition, considering the ranges observed, these findings highlight the importance of prioritizing buildings and areas that would benefit the most from high-albedo roof adoption. According to our findings, low-performance buildings in cooler parts of the urban area show the highest potential for improvement and should be prioritized.

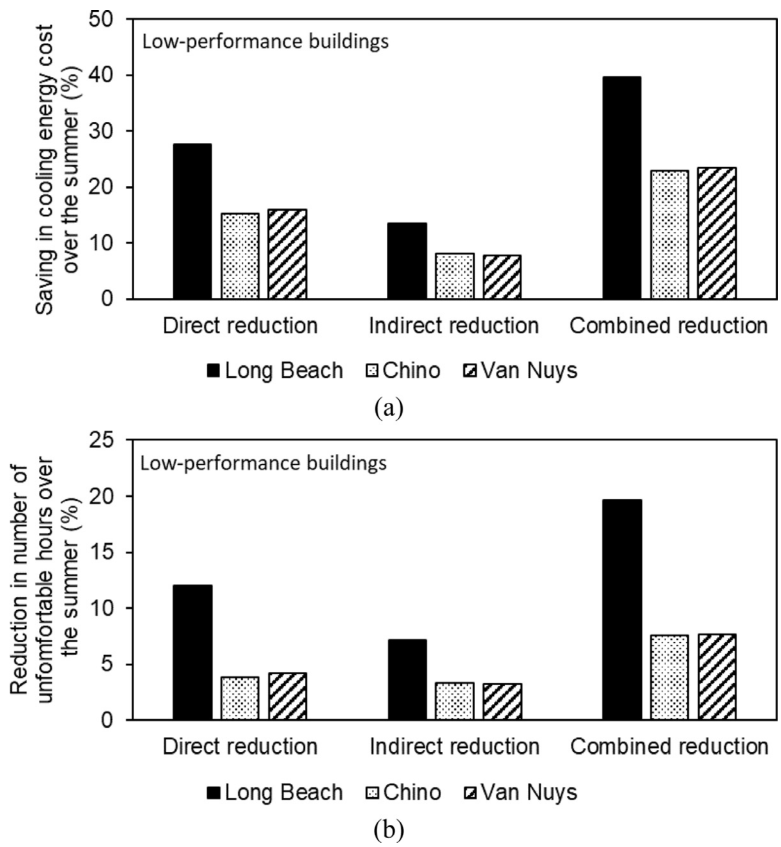


Fig. 11. The direct, indirect (per 1 °C of ambient air cooling), and combined benefits of increasing the roof albedo on (a) cooling energy cost, and (b) thermal comfort.

Conflict of interest statement

The following conflict of interest statement applies for all authors: No conflicts of interest exist.

Declarations of interest

None.

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