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Seasonal Load-Path Accountability for Residential High-Albedo Heat Adaptation

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Abstract

Where high-albedo roofs and pavements reduce the amount of heat absorption through solar rays, the annual residential-energy implications will depend on whether the home appliances used are electric-powered cooling, gas space heating or heat pumps. The key issue here is how the 15–30% neighborhood high-albedo application should be interpreted, where air-temperature reliability is strongest under specific conditions and the same housing stock has both cooling and heating technology overlap. Seasonal Reversal–Technology Allocation Sizing (SRTAS) analysis is employed using the following numerical examples: temperatures for Los Angeles and Seattle in terms of validation quantities; Pacoima treated-area high-albedo impact; demand for cooling reduced by albedo and cool roofs; and a 89-home Los Angeles County residential-equipment inventory data set. The residential equipment data set involves 58 homes using electric cooling, 53 using gas heating, 40 using electric cooling and gas heating, and 6 using heat-pump cooling and heating. Los Angeles offers 25.7% contraction in near-surface air-temperature MAE at all hours and 32.4% in the highest built-volume cells. On the other hand, Seattle offers modest contraction in all hours, although it achieves 30.3% contraction in MAE during the hottest hour, thus creating a hot-tail concentration of 4.04. The 15–30% albedo range offers approximately 0.0107 °C cooling per treated-area percentage point while the 30% albedo plus cool-roof case results in an 11% reduction in the increase in cooling demand, hence avoiding 57.9% of the warming-induced increment. It changes the claim that technology allocation: gas-heating exposure 0.923 relative to electric-cooling exposure; non-heat-pump reversal pressure 0.815 and heat-pump exposure 0.108. The research data confirm heat adaptation and cooling demand reduction, but not any unconditional annual energy savings statement, unless cool roof envelope advantages and heat pump conversion are mentioned in the same context in one claim.

Keywords: high-albedo surfaces; cool pavements; cool roofs; urban heat adaptation; residential energy demand; heat pumps; seasonal heating penalty; temperature validation

1. Introduction

Residential heat adaptation is now part of urban climatology, building energy, and technology. Streets, roofs, walls, and paved surfaces collect shortwave radiation and emit thermal energy during the daytime, and high construction density, vegetation absence, and limited air circulation are enough to retain the heat next to houses when regional temperatures decline in the evening [1]. These phenomena explain why urban temperatures are not just a shift in

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background conditions, but a spatial distribution field depending on land cover, built volume, surface reflectance, and turbulent heat transfer [2, 3]. In residential areas, this spatial distribution affects outdoor temperature, indoor cooling needs, electricity consumption peaks, and daily operation of air conditioners and heating systems. Thus, the same intervention can be assessed by several communities of practice: the former looks for heat exposure reduction, the latter two are interested in energy consumption change.

Reflective coatings and materials are a tempting tool for heat adaptation because it involves a clear physics. Higher reflectivity of roofs or roads reduces energy collection and thus keeps surface and possibly nearby air temperatures lower [5–7]. Experimental and model studies confirm that reflective surfaces help with urban heat reduction, but the efficiency of the process depends on treated area, urban structure, time of day, cloudiness, adjacent surfaces, and a difference between surface and air temperatures [8]. Recently published studies focusing on roof and pavement reflectivity added an important caveat: reflectance is an energy balance intervention which is effective in certain local conditions, not a universal energy-saving measure [9]. Reflectance increasing which reduces the load in hot days may have opposite effects during cold days [10, 11].

The annual energy issue is especially relevant for residential buildings using mixed equipment types. Electricity-driven air conditioning creates a direct link between lower outdoor temperatures and reduced cooling electricity consumption [12]. Fuel-driven heaters make a pathway in which cooler environment increases the fuel demand. Heat pumps combine both heating and cooling functions in one electrified device, but its usefulness depends on coefficient of performance, power grid state, control mechanisms, and indoor comfort preferences [13]. This information is important because climate change is expected to increase cooling dependence and reduce some heating demand, and urban temperature and humidity will affect total annual energy and cooling load [14]. Thus, the intervention that is great for heat exposure reduction may turn out to be a conditional annual energy-saving measure.

The research question is specific: what is the extent of energy savings in residential neighborhoods receiving 15%- or 30%-reflective treatment? The question is narrower than general assessment of cool surfaces because it is not about proving that albedo reduces heat in each city, comparing cool roofs and vegetation, or building a building-energy simulation. It is about how validation, albedo response, cooling load change, and equipment composition should be connected in order to preserve the load-path logic.

Four groups of numerical values are needed for the calculation. The first one contains temperature-validation data for Los Angeles and Seattle, including land surface temperature quantities and near-surface air temperature contractions. The second group is a Pacoima-type albedo response, when 15% and 30% treated areas result in 0.16 °C and 0.32 °C of cooling, correspondingly. The third group is residential cooling demand change, with projected 19% increase driven by warming falling down to 8% under 30%-albedo-plus-cool roof conditions. The fourth group is an 89-household equipment record, with electric cooling, gas heating, cooling-gas overlap, and heat pump equipment. Connecting these four quantities results in a specific answer compared to traditional heat island discussion: the albedo action is highly efficient in terms of seasonal adaptation, but its residential energy benefits depend on the presence and share of gas heaters and heat pumps.

The SRTAS calculation uses only the quantities mentioned above. No separate climatic forcing, building simulation, adoption pathway, or material performance assumptions are used. The calculation distinguishes three claims which are usually confused: validated cooling, avoided cooling demand increase, and whole-year residential energy benefits. The conclusion identifies the conditions under which each of these claims is valid.

Another reason why this formulation is narrower is that high-albedo policy language can contain incompatible units. Small air temperature change, large surface temperature change, cooling demand percentage, and annual utility bill statement can be used in the same discussion even though each of them belongs to a different physical or institutional domain. Decision-making on the residential level requires keeping these units apart until connections between them become clear. Thus, each major number in the calculation is a load path statement: validation says where outdoor air temperature estimation can be trusted; albedo dose shows how much cooling can be allocated to the treated area; cooling demand change indicates avoided increase of the summer demand; and equipment composition shows whether the same houses require heating.

This approach differs from research which focuses on design of reflective material, identification of urban heat spots, and comparison of greening and other adaptation methods. The subject of investigation is not the reflective coating and not urban heat index. It is credibility of the residential annual energy statement based on neighborhood cooling intervention. This approach is valuable for municipal programs because heat adaptation intervention can be justified by public health and cooling demand reasons even if it is too early to talk about whole-year energy savings.

2. Literature Background

There has been a significant evolution in the study of urban heat, from basic urban/rural comparison to a richer description of spatial and temporal variability and vulnerability. Remote sensing, urban canopy model, mobile transect, neighborhood observation, and machine learning techniques now allow one to measure thermal variability at finer scales, yet they do not measure the same physical quantity [16]. The response of land-surface temperature to material, exposure, and radiative properties is strong, while near-surface air temperature is much more relevant to outdoor exposure and building energy input [17, 18]. This contrast justifies the use of the reliability gate in this work. An intervention to decrease outdoor air temperature should not be evaluated simply by its impact on land-surface-temperature error value, but also by the improvement in air-temperature prediction under the condition of interest [19].

The public-health literature highlights the importance of the above reliability issue. Heat exposure raises mortality and morbidity risk; climate change expands the number of people who experience hazardous heat exposure [20, 21]. Evaluations of cool roofs and reflective surfaces have considered the benefit from reduced temperature as well as avoided heat-related mortality [22]. In London, Simpson et al. found that adoption of the cool roof in the summer 2018 would reduce mean near-surface air temperature and potentially avoid more heat-related mortality cases compared to rooftop photovoltaic installation in that particular heat period [23]. Similarly, Macintyre and Heaviside have found connection between temperature reduction and heat-related mortality benefits for European heat waves [24]. It demonstrates that despite being dependent on building energy conditionality, an intervention is valuable due to heat-exposure reduction.

The literature on albedo effect explains the importance of treated area. Roofs coating, reflective strip on road, and large cool-surface district-scale program are not equally effective [25, 26]. The cooling response depends on geometry, sky view factor, shading, thermal admittance, surface soiling, and absorption of reflected radiation by surrounding walls and pavements [27]. Measurement data from neighborhood cool-pavement project in Los Angeles and detailed observations in Pacoima confirm that cool pavements indeed decrease heat exposure locally, but the cooling response depends on time and place [28]. The SRTAS calculation of treated area uses 15–30% interval as a local sizing equation, not universal law [8].

Building energy literature gives an explanation for the non-intuitive seasonal nature of annual energy consumption change [29]. Higher temperature of an urban area increases cooling needs and decreases heating needs, humidity modifies latent cooling; annual difference might be quite small even when cooling and heating components are moving sharply in opposite direction [30, 31]. In the same way, the cool-envelop literature explains why higher albedo reduces heat gain during cooling period but increases heating demands during cold period [32]. The problem of opposite seasonal signs of temperature effect is solved in radiative roof research by looking for materials which would cool during hot period and decrease undesired cooling during cold period [33]. Adaptive materials are not mentioned; the above literature proves the necessity to state seasonal sign of high-albedo intervention.

Heat pumps represent another technological connection between summer and winter sides of the problem. In a typical house which is heated by gas and air-conditioned, albedo-driven cooling would reduce summer electricity consumption but increase winter gas consumption. With heat pump system in a house both cooling and heating are served by electricity, thus annual energy consumption changes will depend on heat pump efficiency and balance of summer/winter loads. Reviews of heat pumps in domestic buildings and smart grid integration highlight that the value of heat pumps depends on building envelope, climate, controls and system operation, not on mere presence of heat pump [34]. For this reason, heat pumps are not assumed to be some sort of magical corrective element. Their count and share act as necessary conditions for stronger annual-energy compatibility.

The large-scale albedo modification literature suggests an important principle that one should be careful assuming that local reflectance changes will produce only local benefits. Cheng and McColl find that land radiative management creates unexpected warming around modified area due to atmospheric circulation responses in idealized experiments [37]. This finding is not numerically applied in the current calculation, but it is an additional support for the principle that reflective interventions should be described at scale and under condition supported by evidence. In the present calculation the supported scale is residential high-albedo treatment based on Los Angeles/Seattle validation behavior, Pacoima treated-area response, cooling-demand data, and technology record from 89 homes.

The literature shows a specific gap. Cool-surface analysis often measures or simulates thermal reduction, building-energy analysis often translates weather into heating and cooling load. Much less frequently there are analyses that reveal residential load at the same time with outdoor-temperature evidence. The lack of joint reading might lead to two types of overstatement: one is to treat summer cooling result as a year-round saving in a gas-heated stock; the other is to discard high albedo intervention due to heating penalty, although intervention might still provide a lot of summer cooling benefits. The SRTAS calculation is used to avoid both mistakes.

Finally, any residential intervention should be transparent for non-specialist audience. Urban climate models and building simulation can be very rigorous but difficult to audit in terms of the choice of target surface fraction by a local program. The calculation uses simple ratios and slopes in order for each claim to be testable against specific numerical data: percent error contraction, degrees Celsius per treated area point, percentage-point cooling-demand avoidance, and counts of homes. Interpretive paragraphs after figures and tables prevent the equations from carrying the argument by themselves.

3. Numerical data and study design

All numerical data used in this analysis are those found in Table 1, which are drawn from the high-resolution urban microclimate and residential-energy study by Buster et al. [38]. This numerical configuration answers a smaller question of annual-energy accountability, specifically whether a high-albedo cooling response is an energy-saving story for the year once the heating seasonal pathway and the heat pump fraction are clearly defined.

The four-register arrangement in Figure 1 precludes the analysis from becoming just a simple cooling calculation. Temperature dependability dictates which outdoor air temperature response is most credible. Albedo of the treated area provides the local cooling dose. Cooling demand accounting converts that cooling dose along with the cool roof envelope portion into an avoided increment. The residential load-path information then determines whether the avoided cooling increment is a full-year residential-energy saving or just seasonal cooling savings.

These numbers have been chosen on purpose to be heterogeneous, consisting of validation errors, treated area percentages, air temperature response, cooling-demand percentages, and the number of home technologies. Such heterogeneity is required since the research question is not purely about temperature; it is more about whether the thermal response can make possible an annual residential energy claim based on outdoor cooling that would require a connection between outdoor cooling, demand reduction and the technologies that are present in the home.

Los Angeles and Seattle validation values serve different purposes. Los Angeles is valuable due to the fact that albedo and residential energy amounts are defined within the Southern California context. Seattle was kept in place due to the fact that it has a difference in hot hour and all-hour reliability, making it useful in determining whether the calculation takes into account heat tail support despite limited all-hour improvement. Such comparison of two cities allows for improving interpretation without introducing another input or making any changes to the calculation.

The number of home equipment record serves as the basis of the calculation as it provides it with the actual residential technology portfolio, rather than cooling-load response. The counts are sufficiently small to fit the mosaic but still high enough to allow us to see the trends in the data: cooling and gas heating are common, there is significant intersection between them and there are few heat pumps. This creates an interpretative challenge. It is possible to have a strong high-albedo cooling effect in conjunction with weak whole-year energy confidence when gas-heated homes dominate the heating technology side of the stock.

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The figures serve as evidence summary, not a decorative one. The first figure serves as a compacted view of four numerical registers, while the rest of the figures split them up in terms of residential mosaic, reliability profile, albedo dose, cooling-demand partition, technology ratios, seasonal signs, and planning claim plate.

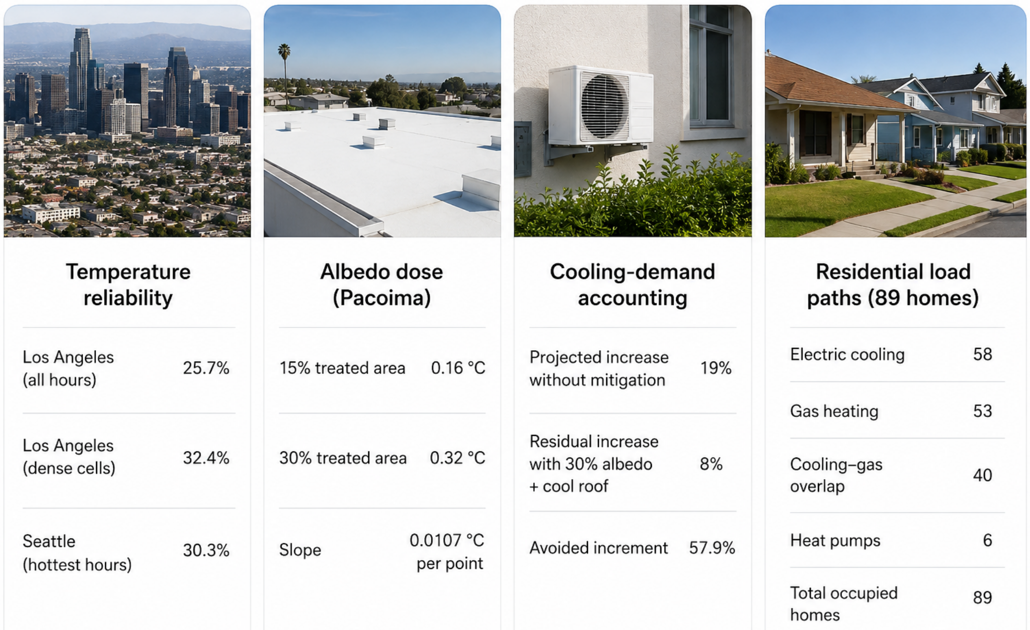

Figure 1. Numerical inputs.

Table 1. Numerical record.

Register	Values used	Role in the calculation
Temperature validation	Los Angeles and Seattle LST and near-surface air-temperature error values	Identifies condition-specific reliability for ordinary, dense-built, and hottest-hour settings
Albedo response	15% treated area = 0.16 °C; 30% treated area = 0.32 °C; annual response = 0.15 °C ± 0.13 °C; summer-afternoon response = 0.18 °C ± 0.09 °C	Provides a local treated-area cooling slope and response-stability check
Cooling-demand change	Warming-driven cooling-demand increase = 19%; residual increase under 30% albedo plus cool roofs = 8%	Measures the avoided portion of warming-driven cooling-demand growth
Residential equipment	89 occupied homes; 58 electric-cooling homes; 53 gas-heating homes; 40 cooling–gas homes; 6 heat-pump homes	Allocates the energy interpretation across summer cooling, winter gas reversal, and electrified dual-service technology

4. Methodology

The SRTAS methodology converts air temperature validation into reliability weight, converts the albedo effect into slope for the treated area, quantifies the avoided cooling demand increase, and apportions the value along residential equipment pathways. Each step involves quantities that appear in Table 1. None of the following items: weather year, material property, building type, household behavior factor, or heat pump adoption pathway is used.

Air temperature reliability is described through error reduction. For city or condition i, the RMSE and MAE reductions are defined as

$$\rho_i^{\mathrm{RMSE}} = 100\frac{\mathrm{RMSE}_{0,i} - \mathrm{RMSE}_{1,i}}{\mathrm{RMSE}_{0,i}}, \tag{1}$$

$$\rho_i^{\mathrm{MAE}} = 100\frac{\mathrm{MAE}_{0,i} - \mathrm{MAE}_{1,i}}{\mathrm{MAE}_{0,i}}. \tag{2}$$

The subscript 0 denotes the comparison condition and the subscript 1 denotes the higher-fidelity temperature estimate. These contractions are not used as abstract model-quality labels. They determine how strongly a temperature response can be relied upon for the specific condition being interpreted, such as dense built-volume cells or hottest-hour observations.

A hot-tail concentration value compares a condition-specific MAE contraction with the all-hour MAE contraction in the same city:

$$\mathcal{T}_i = \frac{\rho_{i,\text{condition}}^{\text{MAE}}}{\rho_{i,\text{all}}^{\text{MAE}}}. \tag{3}$$

A value above 1 indicates that reliability is concentrated in the heat-relevant subset rather than distributed evenly across all hours. This is important for Seattle, where all-hour improvement is limited but hottest-hour improvement is strong.

The treated-area albedo slope is calculated over the observed 15–30% interval:

$$\gamma_\alpha = \frac{\Delta T_{30} - \Delta T_{15}}{30 - 15}. \tag{4}$$

With $\Delta T_{15} = 0.16\,^\circ\text{C}$ and $\Delta T_{30} = 0.32\,^\circ\text{C}$, the local slope is approximately 0.0107 °C per treated-area percentage point. This value is used only inside the 15–30% interval. It should not be read as a transferable material constant.

Reliability-weighted albedo leverage is then defined as

$$\mathcal{L}_i = \gamma_\alpha \left(\frac{\rho_i^{\text{MAE}}}{100} \right). \tag{5}$$

The value is expressed in °C per treated-area percentage point after weighting by condition-specific air-temperature reliability. Its purpose is interpretive: it identifies whether the same albedo dose has stronger evidence support in Los Angeles dense built-volume cells or in Seattle hottest hours.

Cooling-demand avoidance is calculated as

$$\Omega_C = 100 \frac{\Delta C_{\text{warm}} - \Delta C_{\text{adapt}}}{\Delta C_{\text{warm}}}, \tag{6}$$

where ΔC_{warm} is the projected cooling-demand increase under warming and ΔC_{adapt} is the residual increase under the albedo plus cool-roof condition. With 19% and 8%, respectively, the calculation yields 57.9% avoided cooling-demand growth. The value is a cooling-demand result, not a complete annual-energy result.

Residential technology exposure is calculated with the shares of homes having electric cooling, gas heating, both electric cooling and gas heating, and heat-pump service:

$$R_G = \frac{w_G}{w_C}, \qquad R_{CG} = \frac{w_{CG}}{w_C}, \qquad R_{HP} = \frac{w_{HP}}{w_C}. \tag{7}$$

Here w_C, w_G, w_{CG}, and w_{HP} denote the corresponding shares of the 89 occupied homes. These ratios do not predict fuel use directly. They state how much of the housing stock can carry the seasonal signs of the albedo intervention.

The non-heat-pump reversal pressure is

$$\Psi_N = \frac{w_G - w_{HP}}{w_C}. \tag{8}$$

This value compares the gas-heated share not already represented by heat pumps against the electric-cooling share. A high value means that the summer cooling pathway is accompanied by a large winter gas pathway.

Heat-pump parity distance is calculated in count and share terms:

$$\Delta_{HP}^{N} = n_{CG} - n_{HP}, \tag{9}$$

$$\Delta_{HP}^{w} = w_{CG} - w_{HP}. \tag{10}$$

The count value represents the number of heat-pump homes that would have to have heat-pump service in order to achieve equality with the 40-home cooling-gas overlap group. The share value represents the same distance expressed in percentage points of the occupied stock. Neither set of equations defines a target retrofit rate. Instead, they express the distance from the present-day electrified dual service pathway to the present cooling-gas overlap pathway.

Sign conventions are explicit. Cooling demand avoidance receives a positive summer sign because there is less electricity required for air conditioning. Gas heating exposure receives a negative winter sign because colder outside temperatures can cause increased heating fuel demand. Heat pump exposure receives an annual sign which is conditional in nature since the technology serves heating and cooling needs simultaneously, though its annual value may depend on seasonal load balance and heat pump performance. The equations maintain the signs until the discussion stage and do not collapse them into a single score.

The final benefit from this calculation method is the point at which the claim made by the equations should be narrowed down. When the cooling demand value is high but heat pump exposure is low, the claim should be limited to heat adaptation and cooling demand relief. When the heat pump exposure is high or the gas heating exposure is low, the same albedo and cool roof values can provide support for a whole-year energy claim.

5. Results and Discussion

5.1. Load-path composition for the residential sector

The residential sector record immediately affects how the energy value of the high-albedo option must be interpreted. Electric air conditioning systems are installed in 58 out of 89 occupied houses, which represents 65% of the total stock. Gas-fired heating systems are present in 53 homes, representing 60%. The size of the overlap group is significant: 40 homes, or 45%, use both electric air conditioning and gas-fired heating. Six houses, 7%, use heat pump systems for cooling and heating.

The mosaic in Figure 2 includes all possible combinations of systems rather than being purely categorical. It is perfectly possible for one house to belong to both electric-cooling and gas-heating pathways. This overlap is the main reason why it is not possible to draw conclusions about annual energy consumption based on summer cooling demand alone. The most important group in terms of interpretation is the 40-house overlap group.

Table 2 demonstrates why the claim must be qualified. The 65% electric-cooling share creates a summer pathway for the high-albedo surfaces. The 60% gas-heating share provides a winter pathway to the same cooling effect but with the opposite energy sign. The figure of $R_G = 0.923$ implies that there is a significant similarity between gas-heating and electric-cooling exposure. The overlap ratio of $R_{CG} = 0.692$ implies something important too, namely that the cooling and heating signs belong to the same residential population.

Heat-pump exposure is too insignificant to cover the whole stock. Given $R_{HP} = 0.108$, it can be said that there is only one home with heat pump service for every nine to ten homes with electric cooling. The parity distance of 34 homes offers a concrete measure of the technology gap. In order for the heat-pump service to reach 40 homes, it will have to increase from 6 to 40. This is no justification for waiting with reflective surfaces until all heating is electrified. This is the message that stands behind the idea of reflective surfaces being treated as heat adaptation and cooling-demand relief unless heat-pump service and roof-envelope effects are considered in annual energy use.

The ratio pattern also has some equity considerations, although household income and tenure are not covered by the figures. If the gas-heated and air-conditioned homes are prevalent in the area, there are cooling and heating expenses in both summer and winter. In such a case, a public statement that focuses on cooling savings might downplay the winter aspect of the intervention. This is another reason why the technology table must accompany any claim about outdoor heat reduction.

The small count of heat pumps cannot be seen as a drawback of the calculations. It is one of the most important results. Ignoring the 6-home heat-pump count would overestimate annual energy use. Ignoring the 40-home overlap would underestimate the connection between the cooling beneficiaries and the winter reversal. The load-path composition is thus the key to the residential interpretation of the analysis.

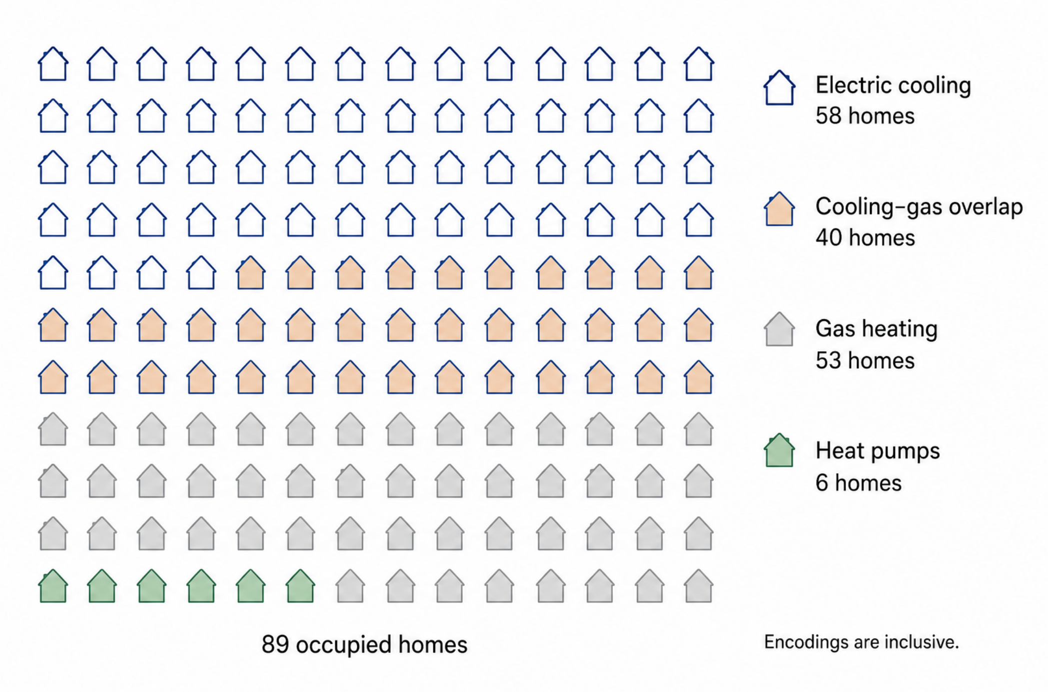

Figure 2. Residential load paths.

Table 2. Load-path allocation.

Quantity	Count	Share or ratio	Interpretation
Electric cooling	58	65%	Main summer electricity pathway
Gas heating	53	60%	Main winter reversal pathway
Electric cooling plus gas heating	40	45%	Same homes can carry both seasonal signs
Heat-pump cooling plus heating	6	7%	Electrified dual-service pathway remains small
Gas-heating exposure, R_G	–	0.923	Gas exposure nearly matches cooling exposure
Cooling–gas overlap, R_{CG}	–	0.692	Most cooling exposure is winter-sensitive
Heat-pump exposure, R_{HP}	–	0.108	Heat-pump pathway is minor in the stock
Non-heat-pump reversal pressure, Ψ_N	–	0.815	Gas-sensitive load remains large relative to cooling exposure
Heat-pump parity distance, Δ_{HP}^{N}	34	38 percentage points	Heat-pump homes needed to match the overlap count

5.2. Reliability of temperature under different conditions

Land surface temperature measures are the first step towards establishing reliability. In the case of Los Angeles, the RMSE is 2.61 °C, and the MAE is 1.95 °C for all data. In the case of Seattle, the RMSE is 3.80 °C, and the MAE is 2.68 °C. For dense built volume values in Los Angeles, the RMSE is 2.49 °C, MAE is 1.86 °C, and bias share is 3.2%. Seattle dense built volume LST values have higher RMSE of 3.85 °C, MAE of 2.74 °C, and bias share of 11.3%. Hottest observation subsets differ in behavior in that the bias share in Los Angeles is 47.2%, while in Seattle it is 25.9%.

The LST results in Table 3 warn about the over-simplification of city ranking. Los Angeles is superior in terms of all-data and dense-built LST. However, the share of LST hottest observation bias is high there. Seattle has worse agreement in all-data and dense-built LST, while its RMSE and MAE of hottest observation are smaller than in all-data case. The interpretation is that LST agreement is valuable but insufficient for energy claim. Reliability of near-surface air-temperature is still necessary, because it is people and cooling systems, which react to the outdoor air temperature, not skin temperature only.

Table 3. LST reliability values.

City	Condition	RMSE	MAE	MBE	Bias share
Los Angeles	All data	2.61	1.95	-0.17	8.7%
Los Angeles	Daytime	2.92	2.18	-0.01	0.5%
Los Angeles	Top built volume	2.49	1.86	0.06	3.2%
Los Angeles	Hottest observations	2.66	1.97	-0.93	47.2%
Seattle	All data	3.80	2.68	0.31	11.6%
Seattle	Daytime	3.67	2.60	0.48	18.5%
Seattle	Top built volume	3.85	2.74	0.31	11.3%
Seattle	Hottest observations	2.70	2.01	-0.52	25.9%

The reliability of near-surface air-temperature gives the key gate for the high-albedo calculation. Los Angeles demonstrates a good improvement in terms of the major conditions: 25.7% MAE contraction for all-hour condition, 20.0% for spatial holdout, 32.4% for top built-volume condition, and 19.9% for hottest hour. Seattle has poorer improvements in all-hour and dense-built subsets, but its hottest-hour subset performs much better: 22.5% RMSE contraction, 30.3% MAE contraction, and 66.8% absolute-bias contraction.

Figure 3 illustrates the difference in reliability profiles between two cities and explains the conditional nature of the reliability gate. Los Angeles is best at the dense built-volume subset condition. This result agrees well with spatially concentrated heat-adaptation efforts. Seattle demonstrates highest improvements in hottest hour subset. This result corresponds well with heat tail exposure and demand stresses. The comparison does not say that one city is better than another. It says that defensible use of albedo response depends on the validation of relevant temperature condition.

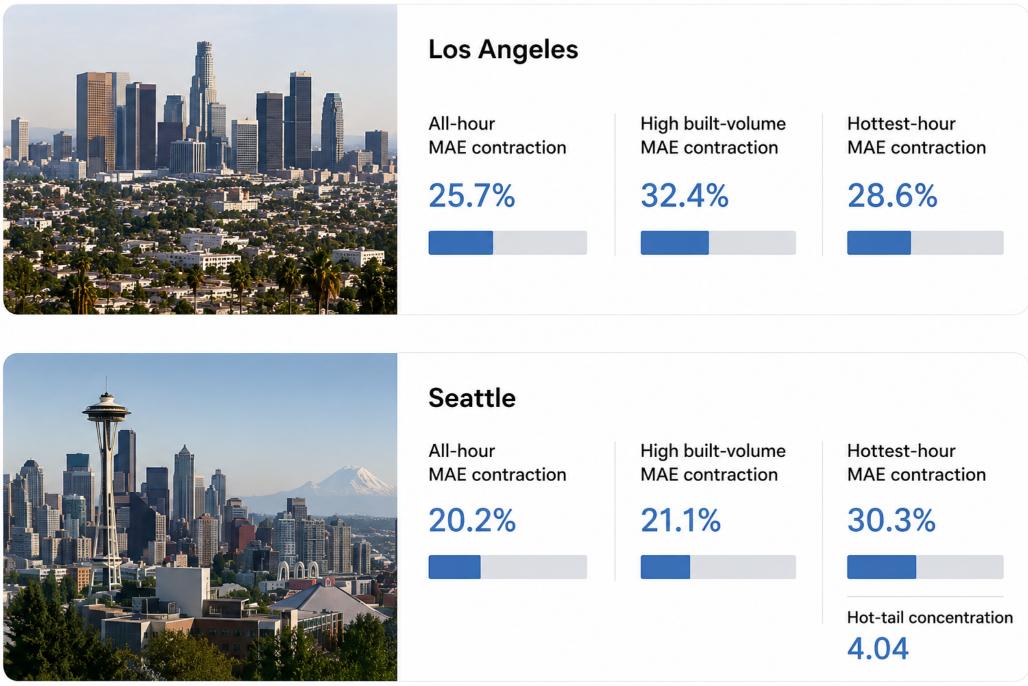

Figure 3. Air-temperature reliability.

These values give more context to the planning interpretation. The leverage of Los Angeles dense built-volume treatment is 0.00347, the highest value in the Table 4. Seattle's leverage of its hottest hour albedo treatment is 0.00324, just behind the Los Angeles dense built-volume treatment leverage even though Seattle's all-hour results are poor. The value of 4.04 shows that Seattle's most compelling evidence comes from its most heat-stress-relevant condition. Any plan using only Seattle's all-hour albedo would miss the former strength while a plan based only on Los Angeles' all-hour albedo would overlook the latter.

Table 4. Air-temperature sizing values.

City	Condition	RMSE contraction	MAE contraction	$\mathcal{T}_i$	$\mathcal{L}_i$
Los Angeles	All hours	23.9%	25.7%	1.00	0.00275
Los Angeles	Spatial holdout	16.9%	20.0%	0.78	0.00214
Los Angeles	Top built volume	30.9%	32.4%	1.26	0.00347
Los Angeles	Hottest hours	19.7%	19.9%	0.77	0.00213
Seattle	All hours	7.7%	7.5%	1.00	0.00080
Seattle	Spatial holdout	4.0%	3.8%	0.51	0.00041
Seattle	Top built volume	7.1%	5.3%	0.71	0.00057
Seattle	Hottest hours	22.5%	30.3%	4.04	0.00324

$\mathcal{L}_i$ is expressed in °C per treated-area percentage point after weighting by MAE contraction.

The leverage plot in Figure 4 contrasts the fixed albedo yield of 0.0107 °C per percentage point increase to condition-specific MAE reduction. It explains why some albedo treatments carry much greater evidentiary weight than others even though they represent the same absolute albedo change. Dense built volume cells in Los Angeles are compelling because the model improves in places where dense built form exists. Hottest hours in Seattle are compelling because the model improves where heat stress is at its peak. The takeaway is that any treated area target will need to be supplemented by the validation condition that makes it justified.

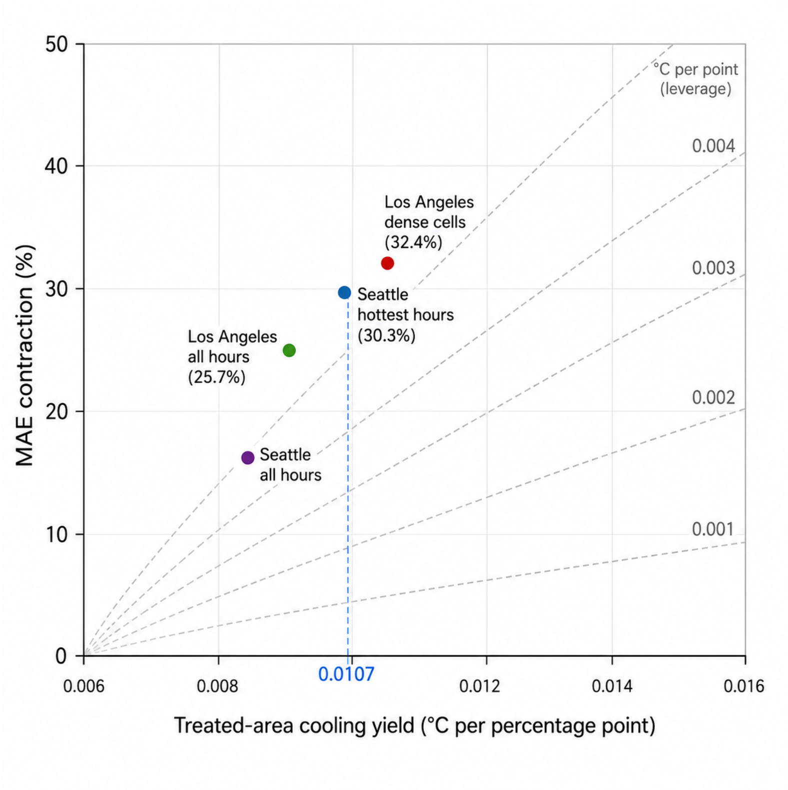

Figure 4. Reliability-weighted leverage.

The comparison between Los Angeles and Seattle is particularly instructive because it does not fall into one hierarchy of cities. Los Angeles provides a spatial perspective: dense built-volume areas are those that provide the strongest validation support for reflective treatment. Seattle provides a temporal perspective: hottest hours are when the temperature improvement gains planning salience. These are two forms of evidence. A heat wave program might care about the Seattle evidence while a district-level resurfacing program cares about the Los Angeles evidence. The calculation clarifies the interpretation without changing the raw data.

The LST and air-temperature results also highlight the necessity of visual interpretation. Values of land-surface-temperature describe the surface agreement, but the air-temperature contraction values convey energy and exposure. Without showing both values, the reader would have no way to know if the albedo effect in question is a reliable predictor of the air temperature layer felt by residents and air conditioning units.

5.3. Albedo dose and cooling-demand reduction

The 15–30% albedo values show a simple local relation. A 15% treated-area condition produces 0.16 °C cooling, and a 30% condition produces 0.32 °C cooling. Both values imply approximately 0.0107 °C per treated-area percentage point. The annual Pacoima-type response is 0.15 °C ± 0.13 °C, while the summer-afternoon response is 0.18 °C ± 0.09 °C. The corresponding coefficients of variation are 0.87 and 0.50.

The values in Table 5 distinguish outdoor cooling from demand reduction. The outdoor air-temperature difference is small in absolute terms, but it takes on significance with respect to cool roofs. Avoiding the warming-induced 19% increase in cooling-demand from 8% reduces the demand increase by 11 percentage points or 57.9%. This provides support for a robust cooling-demand conclusion, but not a residential-energy conclusion for the entire year.

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Table 5. Albedo and cooling-demand values.

Quantity	Input value	Derived value	Interpretation
15% treated area	0.16 °C cooling	0.0107 °C/point	Local treated-area response
30% treated area	0.32 °C cooling	0.0107 °C/point	Same interval slope
Annual albedo response	0.15 °C ± 0.13 °C	$CV_T = 0.87$	High relative variability
Summer-afternoon response	0.18 °C ± 0.09 °C	$CV_T = 0.50$	More stable hot-period response
Warming cooling-demand increase	19%	–	Demand pressure without albedo and cool roofs
30% albedo plus cool roofs	8% residual increase	$\Omega_C = 57.9\%$	More than half of the increment avoided

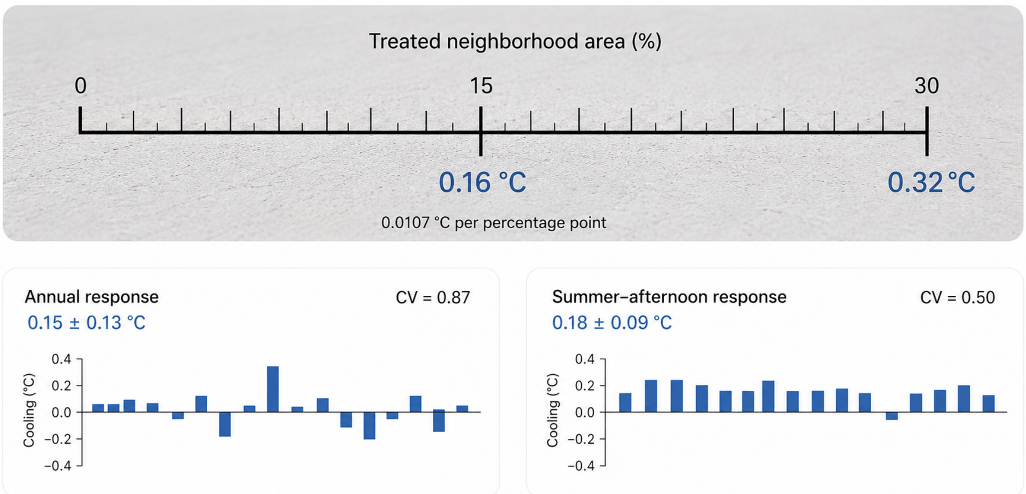

Figure 5. Albedo dose.

The dose ruler in Figure 5 should be considered as a Pacoima-specific interval relation and not a general rule of thumb for any neighborhood. The response has a coefficient of variation of 0.87. This means that the standard deviation is very close to the mean. The summer afternoon response has a much lower coefficient of variation of 0.50. This suggests that the annual response has a seasonal component because the albedo intervention is the most consistent with respect to hot period heat relief, but not the rest of the year.

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This kind of partition makes the avoided increment clear. In the context of 19 percentage points of warming-induced cooling-demand increase, 11 points are avoided and 8 points persist. This mode of presentation is valuable because the 57.9% figure would otherwise sound greater than the increment. The residential cooling-demand finding is significant, but it is based on the combination of 30% albedo and cool roofs and does not take into account winter gas heating.

Another implication arises from the relationship between Figures 5 and 6. The outdoor cooling response is measured in tenths of a degree Celsius, while the cooling-demand increment is measured in percentage points. The reason the demand finding is more significant is that the roof-envelope interaction gives direct access to the building heat gain, while neighborhood cooling gives indirect access through outdoor air temperature. This is why the pavement albedo intervention and cool roof-albedo intervention should not be considered equivalent residential-energy interventions. They have different physical contact with the building.

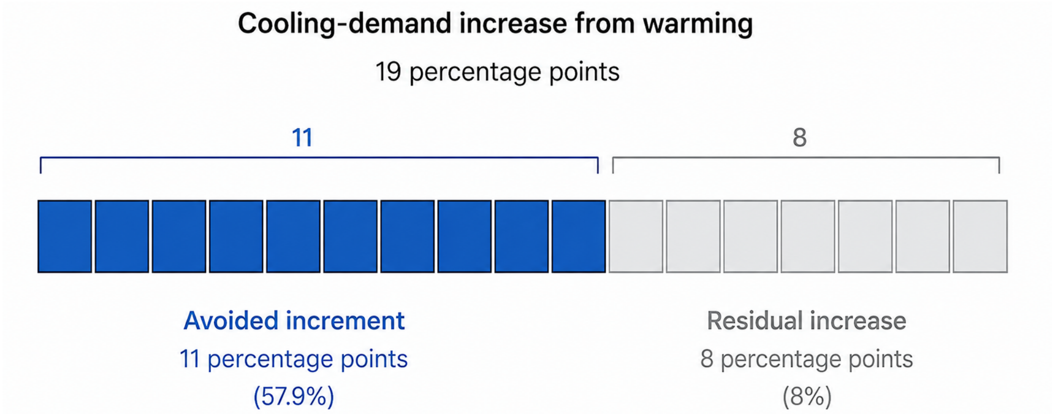

Figure 6. Cooling-demand partition.

The coefficient of variation values provide additional information. The annual response variability is high because the year contains periods where the albedo effect is less related to cooling need. Summer afternoon response variability is lower because the intervention, solar forcing, and cooling need are better aligned. Therefore, the wording of the finding should be cautious. The albedo interval can be relied upon to quantify hot period heat relief, while the annual energy result is mediated by technology and seasonality.

The avoided 11 percentage points of cooling-demand growth can now be interpreted more accurately. It is not a statement that each home will save 11 percentage points of energy. The avoided value refers to the increment in the cooling-demand that results from warming under the conditions of 30% albedo and cool roof. This interpretation precludes overstating the result and necessitates the subsequent technology ratio values.

5.4. Seasonal energy analysis

Compatibility with technology is the combination of the cooling demand effect and the residential technology history. The important factors are avoidance of cooling demand effect, exposure to gas heating effect, cooling-demand-gas heating effect, exposure to heat pump effect, reverse effect on non-heat pump technologies, and heat pump effect equality effect.

It follows from the values in Table 6 that both the 30%-albedo plus cool-roof and the winter gas-reversal statements are valid. First, the former combination avoids 57.9% of the predicted cooling-demand increment. Second, the latter situation shows that the housing stock is highly exposed to the gas-reversal risk. The ratio $R_G = 0.923$ implies almost equal heating-exposure and cooling-exposure shares. The value $\Psi_N = 0.815$ indicates that despite subtraction of the heat-pump share, the gas-sensitive share is relatively large as compared to the cooling pathway.

As illustrated by Figure 7, there is an imbalance between the technology amounts. Cooling-demand avoidance is high, gas-heating exposure is high, and heat-pump exposure is low. This situation explains the obtained result. A reflective community plan can be a good cooling-demand strategy as well as a conditional annual-energy strategy.

Table 6. Technology compatibility values.

Quantity	Formula basis	Value	Energy meaning
Cooling-demand avoidance, Ω_C	19% to 8%	57.9%	Strong reduction in warming-driven cooling growth
Gas-heating exposure, R_G	53/58	0.923	Winter gas pathway nearly equals cooling pathway
Cooling–gas overlap, R_{CG}	40/58	0.692	Large share of cooling homes also heat with gas
Heat-pump exposure, R_{HP}	6/58	0.108	Electrified dual-service pathway remains small
Non-heat-pump reversal pressure, Ψ_N	(53–6)/58	0.815	Gas-sensitive exposure remains high after heat-pump homes are removed
Heat-pump parity distance	40–6	34 homes	Heat-pump count is far below cooling–gas overlap

What is needed here is not another temperature computation but the small amount of the dual-service pathway.

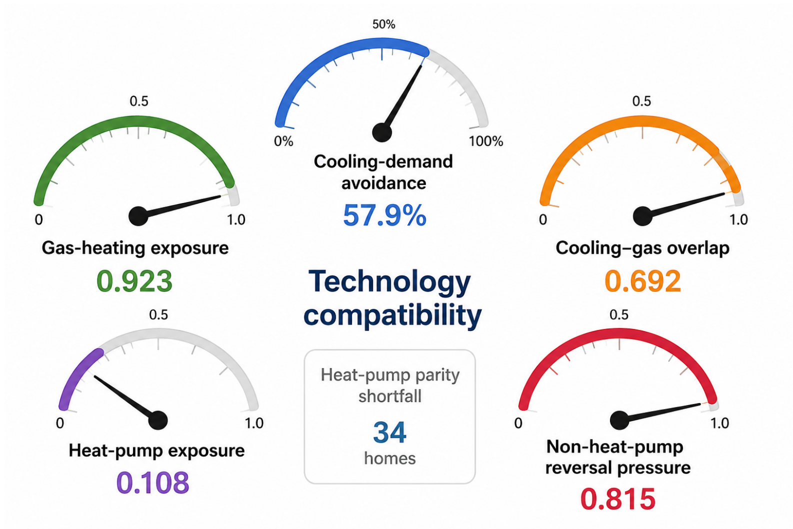

Figure 7. Technology ratios.

The seasonal sign tablet in Figure 8 transforms the above technology ratios into their interpretation. Summer cooling has a positive sign since the avoided cooling increment is 57.9%. Winter gas reversal has the opposite sign due to gas-heating exposure 0.923 and non-heat-pump reversal pressure 0.815. Heat-pump alignment is still weak due to heat-pump exposure 0.108 and the parity distance 34 homes. The annual result is, thus, not the summation of one cooling number. It is the balance of these pathways.

The results clarify the special role of cool roofs. Reflective pavements can provide outdoor cooling and help with the heat relief at the neighborhood level. Cool roofs, however, influence the heat flux through the building envelope directly. That direct interaction can partially explain why the 30%-albedo plus cool-roof combination avoids a significant portion of the cooling-demand increment. Nevertheless, the same roof reflectance decreases winter solar gain. There are plenty of works on cool envelopes which stress this seasonal trade-off, particularly in cases of relevant heating demand [35, 36]. The current record turns this general statement into the stock-specific one.

Finally, it becomes clear that high-albedo treatment should not be given an annual-energy label without a technology explanation. In the current record, the high cooling share provides summer electricity relief, the gas-heating share limits whole-year certainty, and the heat-pump share shows how many dwellings are already compatible with the annual-energy interpretation. It is a special result which differs from those obtained in the studies on the material surfaces, urban greening, pedestrian comfort, or coating durability. This finding is a residential load-path solution to a thermal adaptation problem.

It also clarifies why there is no need for another computational layer. One can create a more complex building-energy model that estimates the amount of fuels and electricity but still will face the stock-composition problem. The calculation is stopped at the point where the available values are strong: cooling-demand avoidance is quantified, and annual-energy caution is quantified by means of gas and heat-pump exposures. Addition of uncertain assumptions regarding heating loads or retrofit penetration rate makes the result unclear.

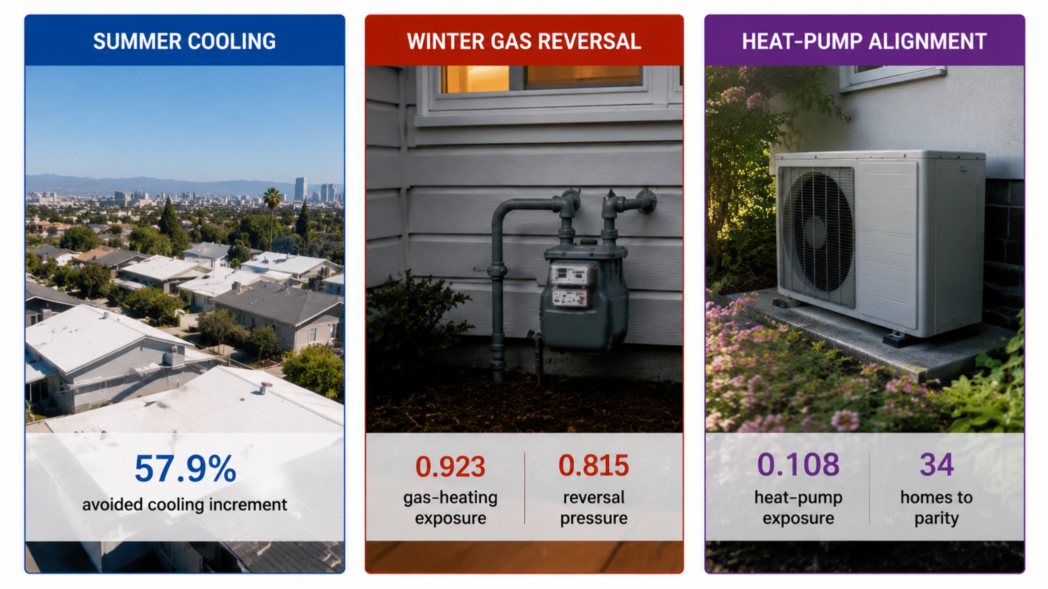

Figure 8. Seasonal signs.

From the practical perspective, the findings lead to the two-part planning language. The first part can be definitive: reflective treatment plus cool roofs reduces the heat exposure and avoids more than half of the warming-driven cooling-demand increment in the given condition. The second part, however, should be conditional: whole-year residential energy relief requires reduction of the gas-heating pathway or expansion of the heat-pump pathway sufficient to serve both heating and cooling. The two-part formulation is the main difference between the heat-adaptation statement and the annual-energy statement.

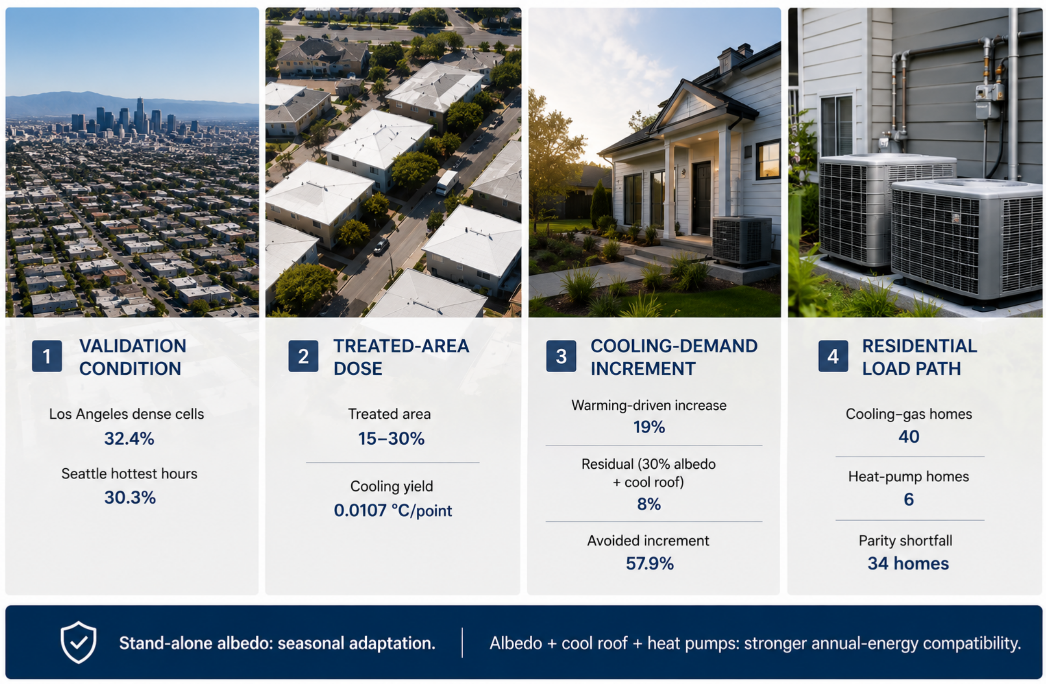

Figure 9. Planning claim plate.

The planning plate in Figure 9 illustrates the evidentiary requirements before making an annual-energy statement. Such a statement should contain the validation condition, treated-area dose, cooling-demand change, and residential technology composition. In the current case, such quantities are Los Angeles dense-cell MAE contraction of 32.4% or Seattle hottest-hour MAE contraction of 30.3%, 15–30%-interval treated area with 0.0107 °C per percentage

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point, 19%-to-8% cooling-demand change, and 40 cooling–gas homes against 6 heat-pump homes. Mentioning of all these numbers prevents the seasonal heat-adaptation result from being overstatement of the unconditional annual energy relief.

The planning plate also examines the evidentiary hierarchy. Every preceding figure and table contains one element of the final claim: the numerical record shows what values enter the calculation; the residential mosaic and load-path table show who carries the seasonal signs; the reliability tables show where the outdoor-air evidence is strong; the albedo and cooling-demand displays show the summer effect; and the technology displays show the annual claim reason. Therefore, the entire discussion is the single chain of evidence leading to the restricted answer to the research question.

6. Conclusions

This research question was whether a 15–30% high-albedo residential treatment could be understood with both temperature reliability and household load paths in mind. The answer is specific: the treatment backs a heat-adaptation and cooling-demand claim, but it does not back an unconditional annual residential-energy-saving claim unless the heating pathway is specified.

Temperature data reveal which conditions justify the cooling claim the most. Los Angeles has 25.7% all-hour near-surface air-temperature MAE contraction and 32.4% contraction in highest built-volume cells. Seattle has just 7.5% all-hour MAE contraction, yet its hottest-hour MAE contraction is 30.3%, resulting in a hot-tail concentration of 4.04. Leverage values for reliability-adjusted temperatures prove that Los Angeles dense cells and Seattle hottest hours are the most favorable conditions for application of the albedo dose in the treated area. This is the answer to the reliability portion of the research question: the same 15–30% albedo treatment gains more confidence when it is linked to the condition in which air-temperature improvement is the greatest.

The treated-area and cooling-demand estimates answer the cooling portion of the research question. The 15–30% interval yields about 0.0107 °C cooling per treated-area percentage point. Cooling demand increment from 19% is cut down to 8%, and thus 57.9% of the increment is avoided, with 30% albedo plus cool-roof condition. This is a significant residential cooling-demand result, particularly since cool roofs provide not only the neighborhood pathway, but the envelope pathway as well.

The equipment record answers the annual-energy portion of the research question. Electric cooling is available in 65% of the occupied stock, while gas heating is available in 60%, and in 45% of homes both electric cooling and gas heating are available. Heat pump cooling and heating occur in only 7% of homes. Gas-heating exposure relative to electric cooling is 0.923, non-heat-pump reversal pressure is 0.815, and the heat-pump parity distance is 34 homes. It means that the summer cooling advantage remains associated with the winter gas-heating pathway.

Therefore, the conclusion is not an endorsement or criticism of reflective surfaces. In the residential case studied, reflective surfaces and cool roofs are justified for valid heat relief and cooling-demand decrease. Their annual energy advantage becomes the greatest when the same planning statement mentions heat pump transition or another reduction of gas-heating exposure. High-albedo programs can be planned now for heat adaptation, but they must be characterized as annual residential energy advantage only after the equipment mix in the stock becomes specified.

The practical answer to the research question is a chain of allowable claims. First of all, high-albedo treatment has a valid heat-adaptation advantage in the conditions where air-temperature reliability is the greatest. Secondly, 30% albedo plus cool roofs significantly reduce the projected cooling-demand increment. Thirdly, the full annual residential energy advantage is not backed by the current equipment record, as gas heating is still almost as common as electric cooling and heat pumps are still uncommon. Thus, the last and precise conclusion is the following: the intervention is thermally advantageous, seasonally useful, and annually conditional.

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References

[1] Masson, V. (2006). Urban surface modeling and the meso-scale impact of cities. Theoretical and applied climatology, 84(1), 35-45.

[2] Oleson, K. W., Bonan, G. B., Feddema, J., Vertenstein, M., & Grimmond, C. S. B. (2008). An urban parameterization for a global climate model. Part I: Formulation and evaluation for two cities. Journal of Applied Meteorology and Climatology, 47(4), 1038-1060.

[3] Chakraborty, T., & Lee, X. (2019). A simplified urban-extent algorithm to characterize surface urban heat islands on a global scale and examine vegetation control on their spatiotemporal variability. International Journal of Applied Earth Observation and Geoinformation, 74, 269-280.

[4] Zhao, L., Oleson, K., Bou-Zeid, E., Krayenhoff, E. S., Bray, A., Zhu, Q., ... & Oppenheimer, M. (2021). Global multi-model projections of local urban climates. Nature Climate Change, 11(2), 152-157.

[5] Taha, H. (2015). Meteorological, air-quality, and emission-equivalence impacts of urban heat island control in California. Sustainable Cities and Society, 19, 207-221.

[6] Millstein, D., & Levinson, R. (2018). Preparatory meteorological modeling and theoretical analysis for a neighborhood-scale cool roof demonstration. Urban climate, 24, 616-632.

[7] Mohegh, A., Rosado, P., Jin, L., Millstein, D., Levinson, R., & Ban-Weiss, G. (2017). Modeling the climate impacts of deploying solar reflective cool pavements in California cities. Journal of Geophysical Research: Atmospheres, 122(13), 6798-6817.

[8] Taha, H. (2024). Micrometeorological effects and thermal-environmental benefits of cool pavements: findings from a detailed observational field study in Pacoima, California. Environmental Research Communications, 6(3), 035016.

[9] Garshasbi, S., Feng, J., Paolini, R., Duverge, J. J., Bartesaghi-Koc, C., Arasteh, S., ... & Santamouris, M. (2023). On the energy impact of cool roofs in Australia. Energy and Buildings, 278, 112577.

[10] Ziaeemehr, B., Jandaghian, Z., Ge, H., Lacasse, M., & Moore, T. (2023). Increasing solar reflectivity of building envelope materials to mitigate urban heat islands: State-of-the-art review. Buildings, 13(11), 2868.

[11] Amani, M. J., Tanzadeh, R., Moghadas Nejad, F., Kabiri Nasrabad, M. M., Chalabii, J., & Movahedi Rad, M. (2025). Urban sustainability through pavement technologies: reducing Urban Heat islands with cool pavements. Buildings, 15(3), 504.

[12] Fischer, D., & Madani, H. (2017). On heat pumps in smart grids: A review. Renewable and Sustainable Energy Reviews, 70, 342-357.

[13] Zhou, E., & Mai, T. (2021). Electrification futures study: operational analysis of US power systems with increased electrification and demand-side flexibility (No. NREL/TP–6A20-79094). National Renewable Energy Laboratory (NREL), Golden, CO (United States).

[14] Davis, L. W., & Gertler, P. J. (2015). Contribution of air conditioning adoption to future energy use under global warming. Proceedings of the National Academy of Sciences, 112(19), 5962-5967.

[15] Colelli, F. P., Wing, I. S., & Cian, E. D. (2023). Air-conditioning adoption and electricity demand highlight climate change mitigation–adaptation tradeoffs. Scientific reports, 13(1), 4413.

[16] Good, E. J. (2016). An in situ-based analysis of the relationship between land surface “skin” and screen-level air temperatures. Journal of Geophysical Research: Atmospheres, 121(15), 8801-8819.

[17] Hulley, G., Shivers, S., Wetherley, E., & Cudd, R. (2019). New ECOSTRESS and MODIS land surface temperature data reveal fine-scale heat vulnerability in cities: A case study for Los Angeles County, California. Remote Sensing, 11(18), 2136.

[18] Shandas, V., Voelkel, J., Williams, J., & Hoffman, J. (2019). Integrating satellite and ground measurements for predicting locations of extreme urban heat. Climate, 7(1), 5.

[19] Li, P., & Sharma, A. (2024). Hyper-local temperature prediction using detailed urban climate informatics. Journal of Advances in Modeling Earth Systems, 16(3), e2023MS003943.

[20] Mora, C., Dousset, B., Caldwell, I. R., Powell, F. E., Geronimo, R. C., Bielecki, C. R., ... & Trauernicht, C. (2017). Global risk of deadly heat. Nature climate change, 7(7), 501-506.

[21] Heaviside, C., Macintyre, H., & Vardoulakis, S. (2017). The urban heat island: implications for health in a changing environment. Current environmental health reports, 4(3), 296-305.

[22] Jones, B., O'Neill, B. C., McDaniel, L., McGinnis, S., Mearns, L. O., & Tebaldi, C. (2015). Future population exposure to US heat extremes. Nature Climate Change, 5(7), 652-655.

[23] Simpson, C. H., Brousse, O., Taylor, T., Grellier, J., Taylor, J., Fleming, L. E., ... & Heaviside, C. (2024). Modeled temperature, mortality impact and external benefits of cool roofs and rooftop photovoltaics in London. Nature Cities, 1(11), 751-759.

[24] Macintyre, H. L., & Heaviside, C. (2019). Potential benefits of cool roofs in reducing heat-related mortality during heatwaves in a European city. Environment international, 127, 430-441.

[25] Taleghani, M., Crank, P. J., Mohegh, A., Sailor, D. J., & Ban-Weiss, G. A. (2019). The impact of heat mitigation strategies on the energy balance of a neighborhood in Los Angeles. Solar Energy, 177, 604-611.

[26] Middel, A., Turner, V. K., Schneider, F. A., Zhang, Y., & Stiller, M. (2020). Solar reflective pavements—A policy panacea to heat mitigation?. Environmental Research Letters, 15(6), 064016.

[27] Rawat, M., & Singh, R. N. (2022). A study on the comparative review of cool roof thermal performance in various regions. Energy and Built Environment, 3(3), 327-347.

[28] Ko, J., Schlaerth, H., Bruce, A., Sanders, K., & Ban-Weiss, G. (2022). Measuring the impacts of a real-world neighborhood-scale cool pavement deployment on albedo and temperatures in Los Angeles. Environmental Research Letters, 17(4), 044027.

[29] Auffhammer, M., Baylis, P., & Hausman, C. H. (2017). Climate change is projected to have severe impacts on the frequency and intensity of peak electricity demand across the United States. Proceedings of the National Academy of Sciences, 114(8), 1886-1891.

[30] Berardi, U., & Jafarpur, P. (2020). Assessing the impact of climate change on building heating and cooling energy demand in Canada. Renewable and Sustainable Energy Reviews, 121, 109681.

[31] Yang, X., Yao, L., & Peng, L. L. (2024). Impacts of urban air temperature and humidity on building cooling and heating energy demand in 15 cities of eastern China. Energy, 288, 129887.

[32] Hosseini, M., & Akbari, H. (2016). Effect of cool roofs on commercial buildings energy use in cold climates. Energy and Buildings, 114, 143-155.

[33] Zhang, K., Zhao, L., Oleson, K., Li, X. C., & Lee, X. (2025). Enhancing Urban Thermal Environment and Energy Sustainability With Temperature-Adaptive Radiative Roofs. Earth's Future, 13(1), e2024EF005246.

[34] Staffell, I., Brett, D., Brandon, N., & Hawkes, A. (2012). A review of domestic heat pumps. Energy & Environmental Science, 5(11), 9291-9306.

[35] Feng, J., Saliari, M., Gao, K., & Santamouris, M. (2022). On the cooling energy conservation potential of super cool roofs. Energy and Buildings, 264, 112076.

[36] Bamdad, K. (2023). Cool roofs: A climate change mitigation and adaptation strategy for residential buildings. Building and Environment, 236, 110271.

[37] Cheng, Y., & McColl, K. A. (2024). Unexpected warming from land radiative management. Geophysical Research Letters, 51(22), e2024GL112433.

[38] Buster, G., Cox, J., Benton, B. N., & King, R. N. (2024). Tackling extreme urban heat: a machine learning approach to assess the impacts of climate change and the efficacy of climate adaptation strategies in urban microclimates. arXiv preprint arXiv:2411.05952.