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Cooling Degree Day Trends and Their Implications for Climate Responsive Housing Design in Selected Cities

A comparative critical synthesis of London, New York City, Athens, New Delhi, and Singapore

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Abstract

Increasing cooling degree days provide a useful warning that housing will face changing thermal demands, yet their design significance depends on the climate metric, the dwelling, and the household. This article develops a comparative critical synthesis of literature published before 1 December 2023 for London, New York City, Athens, New Delhi, and Singapore. It distinguishes observed degree-day trends, climate projections, monitored indoor conditions, and design inferences rather than treating these as interchangeable evidence. The analysis finds that cooling pressure cannot be translated directly into residential electricity demand or a uniform specification for housing. Common temperature thresholds improve climatic comparability but obscure differences in balance temperatures, humidity, solar exposure, ventilation, and adaptive opportunities. Similarly, annual totals conceal extreme episodes and night-time conditions that determine whether dwellings can discharge accumulated heat. The article proposes a four-stage interpretation linking climate exposure, building heat balance, available household responses, and performance verification. Applied comparatively, this framework supports seasonal flexibility in London and New York City, heat rejection and protection when nocturnal cooling is insufficient in Athens, seasonally differentiated strategies in New Delhi, and humidity-aware air movement and efficient cooling in Singapore. These priorities remain conditional on dwelling type, urban context, and affordability. The principal contribution is a testable design framework that uses cooling degree days for screening while requiring hourly thermal, moisture, and access assessments for consequential decisions. Climate-responsive housing should reduce unwanted heat gains, preserve viable passive operation, and provide efficient cooling where necessary, with performance judged by occupied conditions and resilience as well as annual energy consumption.

Keywords: cooling degree days; residential overheating; passive cooling; adaptive comfort; urban climate; climate adaptation

Introduction

Housing designed around historical weather can become progressively less suited to the conditions experienced during its service life. The Intergovernmental Panel on Climate Change (IPCC, 2021) establishes the physical basis for expecting further changes in heat exposure as global warming continues. That broad finding does not determine the overheating risk of a particular flat, because indoor conditions emerge from construction, solar exposure, occupancy, ventilation, and access to cooling. The architectural problem is therefore one of translation: a credible climatic signal must become an appropriate decision about a specific dwelling. Cooling degree days offer an accessible starting point for that translation, but their simplicity also encourages conclusions that exceed what they measure. This article examines how the metric can support design while identifying where additional evidence is indispensable.

The importance of that translation extends beyond the size of an air-conditioning system. The International Energy Agency (IEA, 2018) identifies space cooling as a substantial and growing component of electricity use and emphasizes the consequences of inefficient equipment and coincident peak demand. Nevertheless, reducing recorded electricity consumption is not an adequate objective when a household uses little cooling because it cannot afford enough thermal protection. A dwelling may look efficient in utility data while remaining persistently uncomfortable. Conversely, higher electricity consumption may reflect improved access to an essential service. The relevant design objective is consequently to provide acceptable occupied conditions with lower resource demand, while retaining a margin of protection when equipment, electricity, or occupant action is unavailable. Degree-day analysis becomes valuable when it contributes to that service-oriented objective.

The title's reference to trends requires an explicit distinction between climatic change and its consequences. An observed upward trend in cooling degree days indicates increasing accumulated temperature exceedance above a specified base. It does not, by itself, identify the share caused by regional warming, urban development, station relocation, or changes in measurement practice. Nor does it establish an equivalent percentage increase in household cooling energy. A climate-model projection describes a conditional future under stated assumptions, whereas a monitored overheating episode describes actual conditions in a particular sample. These forms of evidence answer related but different questions. The paper connects them through physical mechanisms and clearly bounded interpretation, preserving the distinction between a published result and an inference developed here.

London, New York City, Athens, New Delhi, and Singapore provide a useful set of contrasting design problems. They allow comparison between climates with substantial winter requirements, Mediterranean summer heat, strong monsoonal seasonality, and persistently warm humid conditions. Their selection does not imply that five cities represent the world's housing stock, or that climatic contrasts outweigh differences within each city. A shaded ground-floor home and an exposed upper-floor flat can face very different conditions in the same weather. The cities are therefore treated as analytical cases rather than statistical samples. Their purpose is to test whether a proposed design principle survives changes in seasonality, moisture, urban form, and occupant resources, and to identify the information needed before that principle becomes a local specification.

The central argument is that the usefulness of cooling degree days increases when their role is carefully limited. Their aggregation makes them suitable for identifying changing seasonal exposure, comparing climatic scenarios under a consistent definition, and informing preliminary assessments. Their aggregation simultaneously removes much of the timing and physical detail needed to predict residential performance. This is not a reason to abandon the metric; it is a reason to place it within a sequence of increasingly specific analyses. A common climatic indicator should lead to questions about buildings and households, rather than prematurely close those questions. The article develops that sequence and uses the five cities to show how a shared warming concern can produce distinct design priorities.

Three questions organize the inquiry. First, what does the eligible literature establish about the

direction, geographical variation, and interpretation of cooling degree-day change? Second, which building and household conditions prevent a direct conversion of that change into cooling demand or indoor comfort? Third, how can those conditions be translated into design choices that remain useful across uncertain future climates? These questions are deliberately broader than a comparison of annual totals, but they do not authorize unsupported claims about local performance. The contribution is a structured synthesis and a set of testable propositions, not a new meteorological dataset, a calibrated building simulation, or a claim to have demonstrated an optimal design for every city.

Review scope and analytical method

The article uses a critical integrative review rather than a systematic review or statistical meta-analysis. Sources were identified through targeted web searches of scholarly titles, publisher pages, institutional repositories, and official publications, followed by checking bibliographic records and tracing relevant studies. Search concepts combined cooling degree days, cooling demand, climate change, overheating, residential monitoring, thermal comfort, and passive cooling with the five city names. This strategy can assemble complementary physical and empirical evidence, but it cannot establish exhaustive coverage of every database or language. No database-wide retrieval count, screening flow, or pooled effect estimate is claimed. The findings should be assessed as a transparent argument grounded in identifiable sources, with the limits of that source selection retained throughout.

Eligibility was restricted to literature published before 1 December 2023. Publication timing is interpreted by the availability of the original work, including eligible online publication, rather than a search engine's crawl date or a later repository upload. This rule preserves the requested historical boundary, although it means that subsequent developments cannot be used to strengthen the argument. Peer-reviewed empirical and modelling studies provide the main technical foundation; dated institutional assessments supply broader context where appropriate. A bibliographic record was not treated as proof of every claim made about a paper. Where only an abstract or limited accessible text supported a finding, the discussion remains within that evidence and avoids details that would require unavailable methods or supplementary material.

Four evidence classes guide the synthesis. Direct climatic evidence includes degree-day series or projections, with calculation details and geographical scale recorded where accessible. Building evidence includes monitored indoor conditions and thermal simulations. Comfort evidence addresses occupants' responses and the conditions under which adaptation is possible. Institutional evidence establishes wider energy or climate context. These classes strengthen one another when their relationships are explicit, but combining them does not remove their individual limitations. For example, indoor monitoring can demonstrate that outdoor temperature inadequately represents a dwelling's exposure; it cannot reconstruct a missing multi-decadal cooling degree-day trend. The review accordingly uses building and comfort studies to interpret climatic signals, without relabelling their findings as direct climate-trend measurements.

The comparison records, where available, the source's time period, spatial unit, temperature threshold, observational or modelled status, and relationship to housing. These attributes are essential because similarly named indicators can represent different quantities. A country average weighted by land area, a population-weighted regional series, and an airport station record may all be valid, yet they answer different questions. The article therefore does not calculate a five-city league table by combining incompatible published numbers. Instead, it compares mechanisms and conditional priorities, drawing numerical findings only from their original analytical scale. This approach sacrifices an apparently simple ranking in exchange for conclusions that remain interpretable and can guide a future harmonized empirical study.

Each substantive argument follows a dialectical structure. A claim is advanced, a meaningful limitation or competing consideration is examined, and a qualified implication follows. The purpose is to make the reasoning contestable, rather than manufacture disagreement where the underlying physics is well established. For example, shading reduces solar gains, but its

usefulness depends on orientation, season, daylight, and practical operation; the synthesis is therefore a specification that responds to those conditions. The same structure governs the evaluation of degree days themselves. This paragraph-level method does not substitute for evidence and does not imply that every opposing consideration has equal evidential weight. It helps identify the circumstances under which a conclusion can reasonably travel from one context to another.

Understanding the degree day signal

For a fixed base temperature b and daily mean outdoor temperature $T_{mean,d}$, annual cooling degree days can be written as $CDD_b = \Sigma d \max(T_{mean,d} - b, 0)$. The units are temperature differences multiplied by days, conventionally °C·days when Celsius temperatures are used. The expression gives a transparent measure of accumulated warmth above a threshold, but the threshold is a modelling choice rather than a universal boundary between comfort and discomfort. A reference value can support comparison across climates while remaining different from the balance temperature of a real dwelling. Every reported CDD value should therefore carry its base temperature, time aggregation, and spatial definition. Without those qualifications, an apparently precise number may have little reproducible meaning.

The importance of threshold choice follows directly from the equation. Consider a deliberately hypothetical sequence with daily mean temperatures of 20, 24, and 28°C. At an 18°C base, the total is 18°C·days; at a 24°C base, it is 4°C·days. These are arithmetic illustrations, not observations from any selected city. Neither result is incorrect, but they describe exceedance relative to different reference conditions. Comparing one city's value at the lower base with another city's value at the higher base would confound climate with definition. A sound comparative analysis should first standardize the climatic reference, then separately test thresholds relevant to actual buildings and operating practices. Treating those two tasks as distinct preserves both comparability and design relevance.

Annual CDD can also be decomposed into the number of days above the base and their average positive exceedance: $CDD_b = N_b \times E_{mean,b}$, provided N_b is nonzero. This identity distinguishes the extension of the cooling season from greater intensity on already warm days. A larger annual total could arise through either pathway or both, so a single annual trend cannot determine which operating change a dwelling will experience. Additional shoulder-season exceedances may increase the value of flexible ventilation controls, whereas more intense summer episodes may challenge heat rejection and equipment capacity. The decomposition does not replace hourly analysis, but it provides a useful first diagnostic and prevents a rise in cumulative exposure from being interpreted automatically as an equal rise in peak conditions.

Daily averaging introduces a further limitation that can be demonstrated without empirical assumptions. Suppose one day contains twelve hours at 30°C and twelve at 18°C, and the base is 24°C. The daily mean equals the base, so the daily-mean method yields zero CDD. Hourly positive exceedances total 72°C·hours, equivalent to 3°C·days after division by twenty-four. These hypothetical calculations show why averaging before applying the threshold loses information about warm hours. They do not imply that the dwelling requires a specific quantity of cooling energy, because storage, solar gains, and occupancy remain unspecified. For design, hourly degree hours can improve temporal resolution, while dynamic simulation is still required to determine the building's actual response.

Absolute and relative changes convey different information. In an illustrative example, an increase from 50 to 100°C·days is 100%, while an increase from 2,000 to 2,100°C·days is 5%. The second climate nevertheless experiences the larger absolute increment and a much larger total burden. These invented values serve only to explain the mathematics and are not city estimates. A large percentage rise in a previously cool climate can identify a rapid transition in expected housing practice; a smaller percentage rise in an already warm climate can add substantial recurring demand. Both measures should therefore be reported together, and neither should be interpreted as a direct ranking of human vulnerability or adaptation urgency.

The nonlinearity of threshold crossing explains why similar warming can affect CDD differently across climates. Adding a small temperature increment to a day already above the base increases its contribution immediately. Adding the same increment to a sufficiently cool day leaves its contribution at zero. Days close to the threshold can enter the total for the first time. This mathematical structure helps explain why the shape of a city's temperature distribution matters alongside its average warming. It does not identify the future distribution by itself, because changing variability and seasonal patterns also matter. A useful interpretation of trend evidence consequently asks whether warming intensifies an established cooling season, extends that season, or changes the frequency of exceptional events.

Cooling degree days should also be distinguished from a dwelling's cooling load. Outdoor dry-bulb temperature affects conductive and ventilation heat exchange, but solar radiation, internal gains, thermal storage, and moisture loads follow additional pathways. Two apartments exposed to the same CDD can therefore require different interventions because their orientation, roof exposure, glazing, or occupancy differs. Conversely, similar energy bills may conceal different comfort outcomes if residents operate cooling for different durations. The climatic metric becomes more informative when paired with a building model or calibrated observations, but that pairing must not be mistaken for a universal conversion factor. Design conclusions should state which physical pathways are represented and which remain outside the analysis.

Humidity is particularly important when comparing seasonally warm cities with persistently humid ones. A dry-bulb degree-day total does not quantify the energy required to remove moisture, nor does it describe the full comfort effect of air movement or radiant temperature. Adding humidity to an assessment does not make temperature irrelevant; it identifies why the same sensible-temperature indicator can correspond to different operating requirements. In Singapore, and during humid periods in New Delhi or New York City, ventilation may provide air movement while introducing moisture that mechanical systems must later remove. The appropriate synthesis is to retain CDD as a clearly defined sensible-climate indicator and assess latent loads and occupied comfort separately, rather than imply that a single temperature threshold captures them all.

The temporal sequence of heat exposure also determines whether a passive strategy can recover between events. Equal annual CDD totals can be distributed across isolated warm days or concentrated into a prolonged episode with warm nights. A thermally massive dwelling may perform well in the former sequence if stored heat can be released, yet progressively accumulate heat in the latter. Annual totals therefore cannot establish passive survivability during a heatwave, even when they characterize seasonal exposure accurately. Design evaluation should include representative annual weather and adverse consecutive-day sequences, with explicit treatment of night-time conditions. This preserves the screening value of degree days while assigning questions about recovery and persistence to evidence capable of answering them.

Published evidence on changing cooling exposure

The literature supports a substantial shift toward greater climatic pressure for cooling, although the apparent size of that shift depends on whose exposure is measured. Kennard et al. (2022) analysed 1981-2018 ERA5-Land temperatures and population distributions. At a 22°C base, their estimated global increase was 2.96 ± 0.79°C·days per year when weighted by land area and 6.00 ± 0.96°C·days per year when weighted by population, with the reported uncertainty representing 95% confidence intervals. These quantities describe different distributions of exposure; neither measures the electricity used by an average household. Population weighting also incorporates demographic change, so its greater slope cannot be attributed entirely to faster local warming. The substantive implication is that housing research needs to connect changing weather to the location of people and dwellings. A regional climate map can identify a physical trend while understating the exposure relevant to residential investment when population is growing disproportionately in warm places.

Projected changes strengthen the case for adaptation while requiring a separate vocabulary

from historical trends. Miranda et al. (2023) compared global warming levels of 1.5°C and 2°C using an 18°C cooling base and subdaily climate simulations. Their results distinguish large absolute increases in already warm regions from large percentage increases in countries with comparatively little existing cooling exposure, including the United Kingdom. These are conditional differences between climate states, rather than a measured annual increase in London or a forecast tied to one particular calendar year. Treating them as a city time series would confuse both scale and temporal interpretation. Used correctly, they reveal two distinct adaptation problems: extending capacity in places with persistent cooling needs and preparing buildings in places where cooling has historically been intermittent. The latter problem can be serious even when the additional annual degree-day total remains modest.

European evidence illustrates why convergent direction does not make numerical estimates interchangeable. Spinoni et al. (2015) found increasing cooling degree-days in the Mediterranean, particularly during the later part of their reconstructed historical record. Spinoni et al. (2018) subsequently projected increases concentrated in the Mediterranean and Balkans under two emissions pathways. However, the projection study used a 22°C base, a method incorporating daily minima and maxima, and an April-September cooling season. An annual daily-mean CDD18 series would include a different set of temperature exceedances. Athens and London can therefore be discussed within a common regional warming context, but their values cannot be ranked against other studies without recalculation. The useful comparison concerns the direction and conditions of change, followed by a transparent statement of the calculation required before numerical differences can support design decisions.

New York City provides direct evidence of the value and limitations of degree-day monitoring. Blake et al. (2019) report LaGuardia cooling degree-days using the United States convention of a 65°F base, with substantial variation among completed years in their 2007-2017 table. The final year is incomplete, and the short series should not be represented as a newly established long-term climatic slope. Furthermore, Fahrenheit degree-days require conversion before comparison with Celsius degree-days, and an airport record cannot represent every neighbourhood microclimate. The record is nevertheless useful for showing how annual weather varies around a reference period and for motivating continued monitoring. Together with the broader assessment of temperature and humidity extremes by González et al. (2019), it supports a design interpretation in which seasonal energy demand and dangerous heat episodes are related but separately evaluated outcomes.

Athens demonstrates how hourly heat evidence can deepen, without replacing, degree-day analysis. Livada et al. (2007) examined summer temperatures at the National Observatory of Athens, distinguishing the observed hourly period of 1977-2004 from earlier information based on daily maxima. They found higher hot-hour and degree-hour values in 1990-2004 than in 1977-1989, together with a longer daily interval of high temperatures. Their threshold was 30°C, making the result distinct from a conventional annual CDD18 total, and their vegetated hilltop station did not capture the whole urban thermal environment. These limitations sharpen the architectural relevance of the study: the persistence and timing of heat determine whether a dwelling can release stored energy overnight. For Athens, a rising cooling burden should consequently be interpreted through both cumulative exposure and the remaining opportunities for passive heat rejection.

Delhi has stronger direct city-oriented degree-day evidence than can be inferred from country averages alone. Ukey and Rai (2021) studied eight major Indian cities, including Delhi, using historical weather for 1969-2017 and projections for 2018-2100. They report upward historical and projected cooling degree-day tendencies and generally declining heating degree-days. However, the percentage ranges in their abstract span several cities and emissions scenarios; assigning the upper or lower value to Delhi would create an unsupported local finding. The base-temperature calculation was not independently verified from the accessible abstract, so these findings are not used for a numerical cross-city comparison. The defensible

conclusion is that Delhi belongs within a documented multi-city transition toward greater cooling pressure, while the exact size of its change must be extracted from its own series and assumptions. Housing implications should therefore address the seasonal structure of Delhi's climate, especially the shift between dry heat and monsoon humidity, rather than applying a single percentage increase indiscriminately to every dwelling type.

Singapore illustrates the distinction between evidence of warming and a calculated CDD trend. The Meteorological Service Singapore (2023) reports warming of approximately 0.24°C per decade at the climate station over 1984-2022 and describes spatial differences associated with urban development and coastal influences. Those observations substantiate increasing thermal pressure but do not themselves provide a harmonized annual degree-day slope. Multiplying an annual-mean trend by the number of days would only be valid under restrictive threshold conditions that should be tested against daily temperatures. Moreover, neither that operation nor a conventional CDD series would quantify the latent load associated with humid air. Singapore therefore contributes an important boundary case to the comparison: frequent exceedance of a cooling base makes the cumulative sensible-temperature signal useful, while persistent humidity and limited nocturnal relief constrain how far that signal can guide naturally ventilated housing design.

Base temperature should be treated as a modelling choice whose purpose must be declared. A fixed base makes climate comparisons reproducible, and it allows users to separate changes in weather from changes in assumptions. Bhatnagar et al. (2018), however, showed substantial variation in simulated cooling balance points across Indian cities and reference building types, even while recommending an aggregate base for Indian applications. A building's balance point incorporates internal gains, envelope characteristics, and operating conditions; it is not simply the temperature every occupant prefers. A defensible study should therefore use one declared reference base for comparative climatic description and additional bases for sensitivity analysis. When moving to a particular housing design, it should calibrate or simulate that building's response. Standardization and contextualization serve different stages of the analysis, and neither can substitute for the other.

Finally, rising climatic cooling pressure should not be equated with an inevitable or uniformly desirable rise in electricity consumption. Yaduvanshi et al. (2022) distinguish cooling hazard from population exposure and alternative vulnerability measures in urbanized India, showing that the resulting risk assessment depends on socioeconomic and energy-system assumptions. A household can experience severe unmet cooling needs while using little electricity; another can consume considerable energy while maintaining a narrowly controlled indoor temperature. Consumption alone therefore confounds climate, access, behaviour, and equipment efficiency. The comparative synthesis should keep four outcomes separate: outdoor heat exposure, indoor thermal conditions, cooling service delivered, and energy consumed. This separation provides a clearer basis for housing policy because an intervention may improve safety, reduce energy intensity, or expand access without moving every indicator in the same direction. It also avoids interpreting low consumption caused by deprivation as evidence of successful adaptation.

Table 1. Why the climatic evidence cannot be pooled into a five city ranking

Source and scope	Period or scenario	Indicator	Interpretation limit
Kennard et al. (2022) Global	1981-2018	CDD at multiple bases; area and population weights	Weighted exposure differs from a city series.
Miranda et al. (2023) Global	1.5°C versus 2°C global warming	Annual CDD18 from subdaily simulations	Scenario difference; no observed annual city slope.
Spinoni et al. (2018) Europe	1981-2100	CDD22; April-September; daily minima and maxima	Seasonal totals differ from annual daily-mean CDD18.
Blake et al. (2019) LaGuardia	2007-2017 table	65°F base; Fahrenheit degree-days	Short record; final year incomplete.
Livada et al. (2007) Athens station	1977-2004 hourly record	Summer hours and degree-hours above 30°C	Hourly heat indicator; not CDD18.
Ukey and Rai (2021) Eight Indian cities	1969-2017 history; 2018-2100 projections	Historical and projected HDD and CDD	Base not independently checked in accessible abstract; ranges not Delhi-specific.
Meteorological Service Singapore (2023)	1984-2022	Observed mean-temperature trend	Warming evidence; not a calculated CDD trend.

Note. CDD18 and CDD22 denote bases of 18°C and 22°C. HDD denotes heating degree days. The table records study distinctions; it is not a new dataset or meta-analysis.

Contrasting city pathways from cooling degree days to housing performance

London and the transition from winter protection to seasonal flexibility

London demonstrates why a historically modest cooling requirement does not justify treating summer performance as a secondary housing concern. Pathan et al. (2017) monitored 122 dwellings during the summers of 2009 and 2010 and identified overheating under both fixed and adaptive assessment approaches. This is direct evidence that outdoor climate can combine with building characteristics and operation to produce excessive indoor temperatures before mechanical cooling becomes a dominant household service. Nevertheless, the sample was recruited through a university network, and two monitored summers cannot establish either a citywide prevalence or a long-term CDD trend. The defensible conclusion is narrower and more useful: buildings in a predominantly heating-oriented housing system can already need deliberate summer protection, so a rising CDD trajectory should trigger checks of existing design assumptions rather than merely a larger allowance for future air-conditioning electricity. The relevant question is whether a dwelling can prevent and release heat while continuing to provide winter protection.

Ventilation appears an economical response because it can remove heat without a refrigeration cycle, but its availability is conditional. In selected Central London social housing, Mavrogianni et al. (2015) combined monitoring with thermal and airflow modelling to examine overheating and pollutant exposure. Their analysis supports shading and carefully timed ventilation while showing that outdoor heat and pollution constrain their effectiveness. The findings cannot be generalized into one ventilation schedule for every London dwelling: orientation, floor level, noise, opening restrictions, and residents' capacity to operate controls differ. They instead support a design test in which the assumed cooling opening is assessed as an actual usable component. A window that is theoretically sufficient in a simulation may provide little protection if its permitted opening is small or residents cannot safely operate it at night. CDD screening should consequently lead to room-specific assessment of

solar gains and usable heat-removal paths, with special attention to sleeping spaces and occupants who remain at home.

For this comparison, London's design pathway is proposed as seasonal flexibility: prevent unnecessary solar gains in warm periods, preserve the ability to admit useful winter gains, and provide controlled heat release when outdoor conditions permit. This approach avoids inferring that a warmer future eliminates the value of insulation or airtightness. Those properties describe heat transfer and leakage, whereas overheating depends on the complete heat balance and control regime. The practical synthesis is to evaluate retrofit packages together. Window replacement, insulation, shading, ventilation provision, and any cooling system should be assessed in the same model, using both ordinary and extreme weather. An intervention should not be called climate responsive solely because it reduces annual heating consumption. Its justification should also show how bedrooms cool after a hot day, how the dwelling behaves during several hot nights, and how residents can operate the proposed controls. These are proposed evaluation requirements, not outcomes measured in the cited London studies.

New York City and the difference between cooling ownership and protection

New York City illustrates a different problem: the existence of mechanical cooling does not make the outdoor-to-indoor relationship predictable. Quinn et al. (2014) measured indoor temperature and humidity in 285 low- and middle-income homes and found substantial variation among dwellings exposed to similar outdoor conditions. They then used fitted relationships to simulate extreme heat episodes. These two stages must remain distinct; the modelled extreme conditions are not additional monitoring observations. The evidence nevertheless challenges any direct conversion from a city's CDD total to household thermal safety. An outdoor index describes a shared climatic burden, while housing determines how that burden is received and retained. A sound design assessment should therefore use CDD to establish the direction of climatic pressure and use indoor models or measurements to examine the distribution of consequences. The most informative outcome is not simply the predicted average household cooling bill, but the set of dwelling types in which excessive indoor heat can persist.

Roof exposure and the operation of cooling equipment warrant particular attention in multifamily housing. Quinn et al. (2017) monitored 36 New York apartments over two summers and found that top-floor apartments were hotter during heat-advisory periods; elevated indoor heat index also persisted in some homes after the outdoor event had ended. Their equipment comparisons indicate variation in achieved indoor conditions, but a small convenience sample cannot establish a universal causal ranking of air-conditioning systems. The stronger inference is that ownership alone is an inadequate measure of protection. Capacity, room coverage, maintenance, affordability, and envelope loads must be considered together. For design, this shifts attention toward exposed roofs and bedrooms, where a common city weather file can conceal different thermal burdens. For assessment, it supports reporting post-event recovery as well as peak exposure. A dwelling that remains hot into the following night may impose a greater cumulative burden than a short outdoor threshold exceedance suggests.

The proposed New York pathway combines reduction of heat gains with dependable delivery of an affordable cooling service. Additional equipment capacity might meet a simulated peak, but it can also leave the household dependent on uninterrupted power and sufficient money to operate it. Conversely, an envelope-only strategy may not deliver acceptable conditions during a prolonged humid event. A useful synthesis is to compare packages against normal operation, restricted operation, and an interruption scenario. This does not assume that passive measures can maintain safety indefinitely without cooling. It asks how much they reduce the rate and extent of indoor deterioration and whether essential rooms receive protection first. The resulting specification would address shading and roof performance alongside equipment commissioning, accessible controls, and the room-by-room distribution of cooling. In this framework, a higher CDD total is a reason to strengthen the reliability of the entire housing service, rather than an isolated instruction to increase installed electrical capacity.

Athens and the limits of nighttime recovery

Athens provides particularly clear evidence that prolonged heat can overwhelm low-income housing even where warm summers are familiar. Sakka et al. (2012) examined fifty non-air-conditioned low-income houses during the exceptionally hot summer of 2007 and recorded indoor temperatures reaching 40°C. The importance of this result lies partly in the persistence of exposure across extended heatwaves, not only in the highest recorded temperature. Yet the sample and the exceptional season should not be used to describe the average Athens home or to infer an annual CDD trend. They identify a consequential failure mode: dwellings can progressively lose their capacity to recover between hot days. A climate-responsive interpretation therefore couples annual cooling accumulation with the duration of hot spells and the availability of nighttime heat removal. This strengthens the case for testing sequences of weather rather than isolated design temperatures, especially for households whose economic circumstances restrict mechanical cooling.

Urban form also changes whether the outdoor environment can serve as a heat sink. Santamouris et al. (2001) combined observations from urban and suburban stations in Athens with canyon measurements and building simulations, demonstrating how urban temperatures and sheltered airflow affect energy requirements and ventilation potential. Their widely cited load multipliers were obtained for a representative office building; they are not measured residential increases and should not be transferred to housing. The appropriate lesson is methodological. Even a correctly calculated regional CDD series may omit the temperature and wind conditions at a particular dwelling's openings. A design that relies on nocturnal flushing should therefore test local air temperatures, pressure differences, and actual opening arrangements. Thermal mass can moderate short fluctuations, but its useful storage must be regenerated; where the outside air stays warm, stored heat may continue to affect occupants. The synthesis is to specify mass together with a credible heat-rejection process.

The proposed Athens pathway gives priority to preventing heat absorption and protecting the conditions needed for recovery. External shading, appropriate roof treatment, and selective ventilation offer a coherent starting package, but their effectiveness must be evaluated within the actual apartment and street configuration. A roof intervention, for example, has a different direct effect on a top-floor dwelling from that on an intermediate apartment. Nor can physical efficiency alone determine whether a household can afford an adequate cooling service. The practical synthesis is to make vulnerability part of project selection: interventions should be assessed by reductions in occupied indoor exposure, with investment directed toward dwellings where high climatic burden coincides with weak fabric and restricted cooling access. Annual energy savings remain relevant, but they should be reported alongside the time spent under excessive indoor conditions. Such paired reporting prevents low electricity consumption caused by unaffordable cooling from being misclassified as evidence of successful climatic adaptation.

New Delhi and the need to distinguish seasons and settlements

New Delhi is considered here through research from the wider Delhi urban region, because available studies do not all use the administrative boundary of New Delhi. Yadav and Sharma (2018) used mobile measurements to investigate spatial and temporal variation in intra-city air temperatures during monsoon and winter conditions. The measured differences show why a single off-site station cannot automatically stand for all neighbourhoods. However, this short campaign cannot establish a long-term trend, and its winter urban heat-island maximum is not a valid increment to add to every summer day. The synthesis is to retain the study's spatial lesson while declining its misuse as a universal correction factor. A defensible housing analysis needs seasonal weather sequences and a clearly stated site representation. The same annual CDD can combine dry hot conditions, humid periods, and different nighttime temperatures, each of which changes the suitability of ventilation and cooling strategies.

Household evidence further shows why the meaning of climatic demand depends on the housing that receives it. Tasgaonkar et al. (2022) published indoor and outdoor heat measurements from low-income locations across South Asia,

including Delhi, with information about roof and wall materials and ventilation practices. Their urban sampling deliberately included homes without electric air conditioning. This provides valuable material for assessing heat exposure where metered cooling demand would understate unmet need. Nevertheless, the publication is a data descriptor, and its sample does not represent all Delhi households or by itself establish the effect of a particular retrofit. The justified conclusion is that design evaluation should include unconditioned operation and the constraints present in low-income homes. It should also use measurements of the indoor environment to check assumptions about the protective value of basic construction. Outdoor CDD identifies the climatic pressure; indoor monitoring helps determine whether limited electricity consumption reflects successful passive protection or exposure that households lack resources to avoid.

The proposed Delhi pathway is a seasonally operated building package whose components remain usable under restricted household resources. Strong control of roof and window gains can reduce the burden before cooling is supplied, while fans, ventilation, evaporative devices, and refrigeration need different operating conditions. It would be misleading to prescribe one device for the entire year from a dry-bulb CDD total alone. For instance, the cooling opportunity associated with evaporation depends on atmospheric moisture, and outdoor-air ventilation can import heat when the exterior is hotter than the interior. The synthesis is an operating sequence supported by the building itself: adequate shade, manageable openings, room layouts that permit intended airflow, and clear criteria for changing modes. Design assumptions should also be tested against constraints such as shared rooms and limited control over external alterations. This proposed method asks whether an intervention delivers its benefit in the actual settlement and tenure context, rather than merely under an idealized equipment schedule.

Singapore and the distinction between air temperature and thermal acceptability

Singapore demonstrates why a persistent dry-bulb cooling burden does not imply that every occupied hour requires the same refrigerated indoor setpoint. Wong et al. (2002) investigated naturally ventilated public housing and found that reported thermal acceptability did not correspond mechanically to thermal sensation categories; residents used available controls, including windows and fans, to modify their experience. This supports taking adaptive opportunities seriously. It does not establish unlimited tolerance of heat or make a comfort survey equivalent to a health-protection threshold. Nor should findings from the original survey be treated as a current census of behaviour. The synthesis is to distinguish climate exposure, perceived comfort, and physiological risk while recognizing that building design influences all three. A residence that permits useful air movement and shading may meet some comfort needs with less refrigeration, but its performance must still be assessed under low-wind, high-humidity, and extreme-heat conditions.

Local urban climate complicates this opportunity because natural cooling depends on the air available at the dwelling. Chow and Roth (2006) analysed a year of canopy-level temperatures at different Singapore land uses and a rural reference, documenting differences in the timing and magnitude of urban warming. Their results show that nighttime conditions and site characteristics matter, but an episodic maximum urban-rural difference cannot be added uniformly to a climate projection. The useful inference is that urban context belongs inside the performance assessment. Ventilation estimated from an exposed meteorological station can overstate the cooling available between closely spaced buildings, and the outdoor temperature alone does not describe the effect of air movement on occupants. CDD should therefore be accompanied by humidity and wind information before design choices are made. This preserves the simplicity of degree days for climate screening while preventing them from carrying explanatory responsibilities they cannot meet.

The proposed Singapore pathway protects opportunities for low-energy comfort while making moisture control and mechanical fallback explicit. Shading and air movement can be incorporated into dwelling form, but opening windows during refrigerated operation can add a moisture burden that the cooling system must remove. A mixed-mode strategy therefore requires

understandable control transitions, a suitable enclosure when cooling is operating, and dependable ventilation under either mode. The synthesis is flexibility with a defined operational logic, rather than a nominal designation of the building as naturally ventilated or air-conditioned. Performance should be assessed for the hours in which each mode is available and appropriate, including sleeping conditions and periods when outdoor air is unsuitable. CDD can describe the persistent thermal context, but hourly analysis must resolve whether the proposed package manages temperature, moisture, airflow, and energy use together. These are design propositions derived from the comparison, not measured savings claimed for a specific Singapore retrofit.

What the comparison establishes

The five cases reveal different ways in which a warming climate becomes a housing problem: seasonal control in London, unequal delivered cooling in New York, prolonged recovery failure in Athens, seasonal and settlement variation in Delhi, and the coordination of air movement with moisture management in Singapore. These distinctions should not be mistaken for exclusive categories; each mechanism can occur in more than one city. Nor does this purposive set support a statistical ranking of global urban vulnerability. Its value is analytical: it identifies why comparable CDD changes can require different design responses, and why different climatic totals can coexist with similar forms of household exposure. The resulting framework treats city climate as an initial condition and the dwelling, its operation, and access to services as the mechanisms that determine outcomes. That relationship provides a more defensible basis for climate-responsive design than applying one envelope prescription or one proportional energy multiplier to every increase in cooling degree days.

Table 2. Proposed housing priorities and the conditions that must be tested

City	Priority from the synthesis	Candidate design response	Required performance check
London	Seasonal flexibility	Solar control, winter-efficient fabric, usable heat release	Summer bedrooms; winter trade-offs; restricted window use.
New York City	Reliable delivered cooling	Roof and solar-gain reduction; efficient room-level cooling	Affordability, room coverage, post-event recovery, interruption.
Athens	Heat rejection during prolonged events	Shading, suitable roof treatment, mass with a discharge route	Hot-night sequences, local airflow, cooling access.
New Delhi	Seasonal and settlement differences	Roof and solar protection; controls for dry and humid periods	Indoor exposure in unconditioned homes; moisture; maintenance.
Singapore	Air movement with moisture control	Shading, feasible airflow, fans, coordinated mixed-mode cooling	Low-wind and humid periods; sleep conditions; mode transitions.

Note. These are proposed priorities derived from the comparative argument. They are neither exclusive city categories nor measured intervention savings. Each package requires dwelling-specific assessment.

Translating cooling exposure into housing decisions

A rise in cooling degree-days provides a reason to reconsider housing performance, but it does not identify which building component should change. A dwelling's response depends on the paths through which heat enters, accumulates, and leaves, as well as the opportunities residents have to modify those paths. The adaptive comfort research of de Dear and Brager (1998) establishes that acceptable conditions also depend on environmental experience and opportunities for adjustment. A design framework therefore needs two linked descriptions: the changing outdoor

exposure and the dwelling's capacity to mediate that exposure. The practical objective is to identify where the climate signal encounters an architectural or social constraint, then choose an intervention directed at that constraint. A large CDD increase alone cannot supply that diagnosis.

The first design priority is to prevent avoidable heat gains, because heat excluded from a dwelling creates no subsequent cooling requirement. Nevertheless, the relative value of a measure depends on orientation, construction, occupancy, and competing winter needs. Porritt et al. (2012) demonstrated through UK dwelling simulations that combinations of interventions could reduce overheating and space-heating energy, while their rankings varied with the modelled cases. This supports evaluating packages rather than prescribing a universal list of individually beneficial products. For example, a shading intervention should be examined together with glazing, ventilation, and room use. The relevant comparison is between complete alternatives meeting the same service requirements, including comfort and daylight, rather than between isolated components whose effects may overlap.

Solar control requires a distinction between reducing unwanted summer exposure and suppressing useful environmental resources throughout the year. External shading intercepts solar radiation before it passes through glazing, making its timing and geometry central design variables. However, a permanently deep obstruction can also reduce daylight, views, or useful winter gains, particularly in London and New York. The proposed synthesis is to specify shading from the room's exposure and seasonal requirements, then test its operation under plausible resident behaviour. Adjustable devices offer flexibility, but their benefits depend on access, durability, and understandable controls. Fixed protection may provide greater reliability where maintenance or operation is difficult. Neither form is intrinsically preferable without a clear account of how the dwelling is occupied.

Insulation should be judged by the heat flows it changes, rather than classified as either a cooling remedy or an overheating cause. Mavrogianni et al. (2012) found different summer-temperature effects for different modelled retrofit components in London housing. That result challenges a simple inference from increasing CDD to either abandoning winter efficiency or maximizing insulation without further evaluation. A well-insulated envelope can restrict external heat entry while also slowing the release of internal and solar gains. Its net contribution therefore depends on solar control, ventilation, exposed thermal capacity, and operating conditions. For climates with both heating and cooling needs, the appropriate synthesis is a whole-year envelope strategy with explicit summer heat-release provisions, rather than a seasonal argument that treats the other season as negligible.

Ventilation is an operating system as well as an architectural provision. A sufficiently large opening can enable heat removal under favourable conditions, but its presence does not establish that residents will use it at the modelled time. Mavrogianni et al. (2014) showed that assumptions about window and shading operation can change simulated overheating rankings. The design implication is to examine realistic constraints before crediting ventilation as a dependable adaptation. Windows may be kept closed because of noise, pollution, security, insects, rain, or privacy; some occupants cannot reach or operate them. Secure openings, manageable controls, and mechanically assisted alternatives should consequently be assessed as part of the same package. Sensitivity analysis should include constrained-operation cases so that claimed performance does not depend on ideal behaviour.

Thermal mass becomes useful for cooling when stored heat can subsequently be released. It can reduce the rate of daytime temperature rise, yet repeated warm nights can leave the structure carrying heat into the next occupied period. Artmann et al. (2007) identified substantial variation in European climatic potential for night ventilation and showed why periods of warm nights matter despite favourable seasonal conditions. Their climate-only assessment does not establish performance for any particular apartment, but it clarifies the missing variable in a CDD-only design method. Designers should assess the timing and magnitude of available heat rejection alongside daytime accumulation. Exposed mass and night ventilation should be evaluated together, with attention to bedroom

conditions, rather than assuming that heavier construction automatically improves summer comfort.

Future warming also changes the reliability of a strategy that currently works. Increasing seasonal cooling exposure can coincide with a reduction in nighttime temperature differences, so both the load and the opportunity to remove it may deteriorate. Artmann et al. (2008) examined this problem through projected European night-cooling potential. It would be excessive to interpret that research as proving the eventual failure of all natural ventilation, but it does argue against assessing adaptations using one historical weather file. A defensible housing brief should test ordinary warm seasons and extended hot episodes under several plausible future conditions. Where passive performance becomes insufficient, the design should preserve the option to add low-energy assistance without requiring major reconstruction of the envelope or occupied rooms.

Reflective roofs offer another means of reducing heat entry, particularly where roof exposure strongly affects occupied spaces. Synnefa et al. (2007) modelled improvements in cooling and comfort from cool coatings under different climatic and roof conditions. Their results also imply that expected benefits cannot be separated from initial reflectance, insulation, heating demand, and building configuration. The same roof treatment should therefore not receive identical credit in a detached house, a top-floor apartment, and a lower-floor dwelling. This article proposes evaluating roof interventions at the level of the affected households while accounting for building-wide costs and maintenance. In mixed climates, annual performance matters; in every climate, the specified reflective performance should remain meaningful after realistic weathering rather than only at installation.

Air movement can improve comfort without reducing room air temperature to a conventional cooling setpoint. In a Singapore office field study, Lipczynska et al. (2018) found that ceiling fans supported comfortable conditions at warmer room temperatures. However, the study involved office occupants, and its findings cannot be treated as proof of adequate sleep conditions or physiological safety for all household members. The appropriate inference is that fans deserve explicit evaluation as part of a residential cooling strategy, with resident control and suitable placement. Their inclusion can change the conditions under which mechanical refrigeration is needed, but it does not eliminate the need to examine humidity, radiant exposure, individual vulnerability, or exceptionally hot periods. Housing specifications should therefore describe supported operating modes, not promise a universally sufficient appliance.

Residential comfort criteria should reflect the population and mode of operation under consideration. Rawal et al. (2022) developed the India Model for Adaptive Comfort-Residential from field studies across five Indian climate zones, providing a more relevant foundation for Indian dwellings than uncritical transfer of office-derived assumptions. The countervailing concern is that an observed range of acceptable temperatures is easily misrepresented as a fixed permissible range for everyone. Such models describe population responses within particular environmental and behavioural contexts; they do not remove individual differences or establish clinical safety thresholds. For New Delhi, the proposed synthesis is to use residential adaptive criteria where their applicability is satisfied, report the conditions of application, and retain separate assessments for vulnerable occupants, sleeping periods, and extreme heat.

Evidence of adaptation should guide the provision of choices rather than justify the removal of services. Gou et al. (2018) observed behavioural adjustments associated with acceptance of warm conditions in naturally ventilated Singapore dormitories. A student sample can illuminate the role of fans, openings, and clothing, but it cannot represent residents with restricted mobility, different routines, or fewer opportunities to modify their environment. The design principle drawn here is therefore opportunity-based: provide usable controls and several feasible responses to heat. A home that achieves acceptable average survey responses while making its hottest room unavoidable for a vulnerable person has unresolved performance problems. Distribution across rooms and household members should remain visible even when an aggregate adaptive-comfort criterion is met.

Performance during an electricity interruption should be examined separately from normal annual energy consumption. Baniassadi et al. (2018) simulated high-rise residential buildings during coincident heat waves and power outages, finding climate-dependent relationships between evolving energy codes and heat resilience. Their results resist a general claim that the most energy-efficient dwelling must also be the safest during service loss. The design implication is to evaluate both operating states explicitly. A proposed assessment can track indoor temperature trajectories, the duration of excessive exposure, and the availability of a usable cooler room under stated outage assumptions. These measures should not be labelled universal survival limits. They are decision tools for identifying dependence on continuous cooling and for comparing ways to reduce that dependence.

Cooling affordability is an architectural performance issue when it determines whether the designed service is available in practice. Madrigano et al. (2018) documented disparities in cooling access and protective behaviour in a New York City survey. However, a correlation between income and cooling access does not identify a single intervention sufficient to remove the disparity. The resulting design and policy task spans capital costs, electricity bills, tenancy conditions, maintenance responsibility, and access to assistance. This article therefore proposes reporting both modelled energy use and the assumptions under which households can operate cooling. A nominally efficient home may still impose an unaffordable bill, while an inexpensive retrofit may be inaccessible to a tenant who cannot alter the building. Technical merit and implementability need separate, visible assessments.

A framework for climate responsive housing decisions

The comparison supports a four-stage framework connecting climate exposure, building response, available household responses, and verified performance. Its advantage is that each stage answers a different question and makes the transition to the next stage explicit. Its cost is greater analytical effort than a single degree-day calculation. The framework should therefore be applied proportionately: preliminary screening can identify where deeper assessment is justified, while decisions with long service lives or serious exposure consequences need more detailed analysis. This is a proposal developed from the review, not an empirically validated new index. Its value can be tested by asking whether it changes design choices, reveals otherwise hidden failure conditions, and improves the correspondence between predicted and occupied performance.

At the first stage, the designer establishes the climatic signal using an identified base temperature, historical period, and geographical representation. Absolute change, relative change, seasonal distribution, and uncertainty should be recorded together. This creates a reproducible account of external exposure, but it leaves unanswered how solar radiation, humidity, or urban sheltering affects the site. The transition to the second stage should therefore depend on an explicit information check: is the available weather adequate to examine the proposed cooling mechanism? If a design relies heavily on night ventilation, an annual CDD series alone fails that check. The design brief must then obtain or conservatively bound hourly night-time temperature and airflow conditions before assigning performance credit to the strategy.

The second stage identifies the dwelling's dominant heat and moisture pathways. Candidate packages can then target the sources and timing of unwanted gains, the opportunity for heat release, and the residual need for conditioning. Yet a simulated improvement is conditional on assumptions about occupancy, openings, maintenance, and equipment operation. The third stage consequently tests whether those assumptions describe actions residents can actually take. A high-performance window that residents cannot open safely and an efficient cooling unit that they cannot afford to run are both incomplete solutions. The combined requirement is a physically effective package with a credible operating arrangement, assessed for the rooms and household members whose circumstances are least well represented by an average operating schedule.

The fourth stage verifies outcomes against the original service requirements. Annual heating and cooling use remain relevant, but should be

accompanied by occupied overheating hours and degree-hours above a declared applicable criterion, peak indoor operative temperature, night-time bedroom exposure, peak electrical demand, and recovery time. Operative temperature accounts for both air and mean radiant temperature; air temperature alone may miss discomfort associated with warm surrounding surfaces. Moisture performance and response to an explicitly defined service interruption also require assessment where relevant. These outcomes can conflict, so the framework should reveal trade-offs rather than hide them inside an unexplained aggregate score. A package that lowers annual energy while worsening bedroom exposure during a heatwave should be identified as such. Verification should also include whether controls work and responsibilities for maintenance are understood. Where monitoring diverges from prediction, the result becomes evidence for revising the specification or operating arrangement, rather than grounds for assuming that residents have used an otherwise perfect design incorrectly.

A protocol for a future harmonized city analysis

A direct comparison of the five cities would require an additional empirical study, for which the present review provides a protocol rather than results. The starting point should be a common historical period, a documented daily or hourly temperature product, and an explicit rule for spatial representation. City-centre stations, airports, and gridded datasets differ in exposure and coverage, so selecting whichever series is easiest to obtain can produce a misleading comparison. A defensible design would compare the principal dataset against local observations and state how urban and suburban conditions are represented. If a sufficiently consistent common period cannot be assembled, that gap should be reported rather than filled with an undocumented adjustment or a synthetic trend presented as measurement.

Data preparation should identify missing observations, changes in instruments or station location, inconsistent time conventions, and differences between hourly averages and averages of daily extrema. Such checks can improve comparability, but an elaborate cleaning procedure cannot guarantee that every series represents the same urban environment. The study should retain an auditable record of exclusions and corrections and examine sensitivity to alternative stations or grids. Annual totals based on incomplete warm-season coverage require special caution because missing hot days can bias the result downward. The synthesis is a reproducible data pipeline accompanied by a statement of residual representativeness limits, rather than a claim that a single cleaned series perfectly describes the climate of an entire city.

A future trend assessment could combine an estimated slope with a rank-based test of monotonic change. Mann (1945) provides the foundational nonparametric trend test, while Sen (1968) develops a slope estimator based on pairwise slopes. These methods are useful when annual degree-day totals depart from convenient distributional assumptions, but their use does not automatically resolve serial dependence, structural breaks, or sensitivity to the chosen period. Effect sizes, uncertainty, and data diagnostics should therefore accompany significance statements. Reporting change in °C·days per decade alongside baseline totals and percentage change would make the result more interpretable. No such test has been conducted for this article, and no statistical significance is asserted for an unanalysed city series.

Projection analysis should maintain a clear separation between alternative emissions pathways, model uncertainty, and internal variability. Belcher et al. (2005) demonstrate how present weather sequences can be transformed using climate-model information to create future design weather. Such methods can connect climate science to building analysis, but reliance on an existing sequence may inadequately explore changes in extremes or the joint behaviour of weather variables. A housing study should therefore compare more than one future weather realization and inspect whether temperature, humidity, radiation, and wind remain physically coherent. The outcome should be a range of conditional performance results over the dwelling's relevant service life, not a single future year portrayed as a precise forecast.

Finally, the climate analysis should be linked to representative dwelling archetypes and verified against occupied conditions. Archetypes allow a manageable comparison of construction, floor level, glazing, and operating modes, yet an average archetype can erase the households at greatest risk. The model set should therefore include plausible adverse combinations, such as exposed upper floors, restricted window opening, or limited cooling operation. Calibration against monitored temperatures and energy use can improve confidence, but it should not conceal uncertainty in occupant behaviour. The appropriate product is a comparison that identifies which design conclusions remain stable across assumptions and which depend on conditions that must be checked locally before implementation.

Testable propositions and implementation priorities

The first proposition is that CDD change alone will explain less variation in occupied overheating across dwelling types than a model that also represents solar gains, heat storage, ventilation constraints, and cooling operation. The physical reasoning is strong, but the additional variables could appear useful merely because a more complex model fits its training data better. A meaningful test would compare out-of-sample predictions for monitored homes, including dwellings and seasons not used in calibration. The proposition would receive support only if the added information improves predictive performance and remains interpretable. This makes the article's critique of a single-index approach empirically contestable and directs future research toward identifying which additional observations are worth collecting under limited project budgets.

The second proposition concerns climate adaptation packages. Interventions that combine gain reduction with feasible heat release and efficient residual cooling should remain useful across more weather and operating conditions than packages dependent on one idealized mechanism. However, additional components can introduce costs, maintenance burdens, and control conflicts. The proposition should therefore be tested through package comparisons under equal service requirements, including plausible failure or non-use of adjustable elements. The relevant outcome is not the number of technologies installed. It is the stability of acceptable performance when weather, occupancy, or operation differs from the assumed case. A simple, durable package could outperform a technically elaborate package if the latter requires operating conditions that households cannot reliably maintain.

The third proposition is that incorporating affordability and operating restrictions will change which housing interventions appear most effective. A comparison based on unlimited cooling can favour equipment improvements, while a comparison representing limited use may reveal greater benefit from reducing exposure before refrigeration is required. This expectation should not be treated as a universal result, because capital costs, tariffs, climate, and household needs vary. A suitable test would compare both delivered comfort and household expenditure under documented operating constraints, alongside an unconstrained service case. The result would distinguish technical energy efficiency from effective access to cooling and would help explain why the same nominal intervention can succeed for one group of residents while providing little practical protection for another.

Implementation should begin with decisions that are difficult to reverse, including orientation, window exposure, ventilation paths, roof construction, and the space needed for future equipment. Their long service lives make anticipatory assessment valuable, but excessive overdesign can increase cost or impair winter and daylight performance. The practical synthesis is to preserve useful options while testing immediate requirements: provide shading opportunities, accessible maintenance routes, and credible transitions between operating modes without assuming that every dwelling needs the same system from the outset. Retrofit projects require a different sequencing logic because constraints already exist. There, the first intervention should address the dominant verified source of exposure and remain compatible with later improvements, rather than create an isolated saving that makes subsequent adaptation harder.

Limitations and research priorities

The main limitation is the absence of a harmonized five-city meteorological and building dataset. The review demonstrates why published indicators require careful interpretation, but cannot supply comparable city slopes, rank the cities by vulnerability, or quantify energy savings from the proposed design pathways. Differences in source periods and methods remain substantive even when their directional conclusions converge. A future study should therefore implement the shared-data protocol described above and publish its weather inputs, calculation choices, archetype definitions, and sensitivity tests. Until then, the strongest conclusions concern the relationships that must be assessed and the errors that should be avoided, rather than the numerical size of a particular city's required adaptation investment.

Evidence coverage also limits the transfer of findings among housing populations. Several monitoring studies use convenience samples, selected low-income groups, or particular building types; simulations depend on model structure and assumed operation. These studies can reveal real mechanisms and important vulnerabilities without establishing their prevalence across an entire city. The appropriate next step is targeted replication across underrepresented dwellings and residents, together with research that connects indoor exposure to actual access to cooling. The present synthesis does not set medical heat-safety thresholds, and comfort acceptance should not be read as evidence of harmless exposure. Its performance framework needs locally appropriate comfort, health, and building criteria before it can become a project specification.

Finally, the literature cutoff deliberately excludes work first published on or after 1 December 2023. That boundary permits a historically consistent synthesis but prevents the article from claiming to describe the latest climate record, equipment market, or regulatory position. The review is also limited by targeted searching and the accessible portions of some publications, so it should not be presented as an exhaustive account of all relevant research. These constraints do not invalidate the comparative argument; they define what it can support. The proposed framework and research questions should be treated as a basis for further testing, with future evidence able to revise the relative importance of particular measures while retaining transparent distinctions between climate, building response, and delivered housing services.

Conclusion

Cooling degree-day trends provide a useful indication of changing accumulated outdoor warmth, and the reviewed literature supports growing cooling pressure across several relevant geographical scales. The evidence does not support a single numerical ranking of London, New York City, Athens, New Delhi, and Singapore using the heterogeneous measures assembled here. Thresholds, seasonal definitions, units, periods, and spatial coverage materially affect interpretation. The defensible conclusion is therefore conditional: degree days can initiate a housing assessment and organize comparisons under consistent assumptions, while indoor performance and design choices require additional evidence about heat gains, moisture, ventilation, operation, and household resources.

The city comparison identifies distinct priorities without reducing each city to a single prescription. Seasonal flexibility is central to the London case; reliable and affordable delivered cooling to New York; heat rejection and recovery during prolonged events to Athens; seasonal and settlement differentiation to New Delhi; and coordination of airflow, shading, moisture control, and mechanical support to Singapore. These priorities overlap and must be tested within particular dwellings. The proposed four-stage framework provides that connection by moving from the climatic signal to building response, feasible household action, and verified occupied outcomes. Its contribution is a disciplined route from evidence to design that can be challenged, measured, and improved as housing adapts to a changing climate.

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