Building For Heat

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Preface

Building For Heat examines how vernacular buildings and settlements moderate heat, and how their environmental principles can inform contemporary design in arid regions. It brings together climate, building physics, patterns of occupation, and the institutions that shape access to cooling.

The central argument is that vernacular cooling should be understood through its mechanisms and conditions of use. Shade, thermal mass, ventilation, evaporation, and adaptive occupation can provide substantial benefits, but their performance depends on climate, maintenance, water, air quality, and the needs of occupants. Architectural form alone does not establish comfort or resilience.

The five chapters move from reading climatic exposure to understanding cooling mechanisms, evaluating performance, examining the transition toward mechanical cooling, and translating evidence into design and policy. The Vernacular Cooling Performance Framework and Passive Cooling Gap Index are presented as proposed tools for organizing questions and evidence. The review protocols and assessment methods require application and local validation; they are not reported as completed comparative experiments.

The book is intended for architects, architectural engineers, researchers, students, and practitioners concerned with heat and the built environment. Its purpose is to support careful adaptation of inherited knowledge while recognizing the limits of passive cooling and the need for reliable protection during extreme heat.

Abbreviations and notation

AC	Air conditioning
ACH	Air changes per hour
CFD	Computational fluid dynamics
CMIP6	Coupled Model Intercomparison Project Phase 6
COP	Coefficient of performance
ENVI-met	Three-dimensional microclimate modelling software
HVAC	Heating, ventilation, and air conditioning
LCZ	Local Climate Zone
LST	Land-surface temperature
PCGI	Passive Cooling Gap Index
PET	Potential evapotranspiration; or physiological equivalent temperature, depending on context
PMV	Predicted mean vote
POE	Post-occupancy evaluation
PPD	Predicted percentage dissatisfied
PV	Photovoltaic
SET	Standard effective temperature
SSP	Shared Socioeconomic Pathway
TMY	Typical meteorological year
UTCI	Universal Thermal Climate Index
VCPF	Vernacular Cooling Performance Framework

About the authors

Dr. Ayesha Mehmood Malik

Dr. Ayesha Mehmood Malik is an accomplished academic, researcher, and architectural professional with over 20 years of experience in teaching, research, academic leadership, and professional practice in architecture and the built environment. She holds a Ph.D. in Architecture and is currently serving as Head of the School of Architecture at the University of Lahore. She is the Editor-in-Chief of Journal of Architecture and Built Environment Research. Dr. Malik is also an Advisory Board Member for several national and international journals, including Research Mosaic, and serves as a Member of the Syndicate, contributing to institutional governance and academic policymaking.

Her research expertise includes Architectural Conservation and Heritage, Energy Efficiency and Sustainable Design, Interior and Landscape Architecture, and Research Methodology. She has authored more than 50 peer-reviewed publications, contributed to international book chapters, and presented extensively at national and international platforms. Dr. Malik is frequently invited as a plenary speaker, guest lecturer, and expert trainer, including her role as an External International Trainer for the Aga Khan Development Network (AKDN) and University of Central Asia, Kyrgyzstan.

Her contributions have been recognized through Best University Teacher distinctions, multiple HEC research grants, and publication-based research awards. Through sustained academic leadership and research mentorship, Dr. Malik continues to advance sustainable and resilient built environments, bridging academia, practice, and policy.

About the authors

Dr. Nijah Akram

Dr. Nijah Akram is an architectural engineering scholar and academic leader with over 16 years of experience in higher education, research, and professional practice. She holds a Ph.D. in Architectural Engineering from the University of Engineering and Technology (UET) Lahore and currently serves as the Head of the Department of Architectural Engineering Technology at Punjab Tianjin University of Technology, Lahore.

Her research focuses on climate-responsive architecture, vernacular and passive environmental design, building performance optimization, adaptive reuse, sustainable construction, daylight-responsive systems, energy-efficient buildings, and evidence-based healthcare environments. Her work integrates building performance simulation, post-occupancy evaluation, and environmental analysis to develop practical, low-carbon, and climate-resilient design solutions.

Dr. Akram is the first author of the scholarly monograph Biophilia by the Numbers: A Systematic Review of Post-Occupancy Evaluations in Healthcare Spaces (2026) and the author of Retrofit Reality: A Longitudinal Meta-Analysis of Energy Performance Gaps in Adaptive Reuse. These works reflect her commitment to advancing evidence-based design, sustainable retrofit strategies, and high-performance buildings.

She has authored more than 40 peer-reviewed publications, contributed to international books, and presented her research at national and international conferences. She also serves as a reviewer for leading Q1 and Q2 indexed international journals in architecture, architectural engineering, sustainability, energy, and the built environment. Her academic excellence has been recognized through institutional awards and Best Teacher distinctions. In addition, she has contributed to curriculum development and academic quality assurance as a Member of the Academic Council, the National Curriculum Review Committee, and Boards of Studies at multiple universities.

Through her research, teaching, and academic leadership, Dr. Akram continues to advance sustainable, energy-efficient, and climate-adaptive architectural engineering for resilient built environments.

About the authors

Dr. Fatima Tuz Zahra

Dr. Fatima Tuz Zahra is an Architectural Engineer, educator, and researcher with more than 12 years of experience in architecture, construction, and higher education. Her research expertise encompasses climate-resilient housing, climate-responsive design, sustainable architecture, vernacular building systems, and resilience in the built environment. She completed her PhD in Architecture, focusing on the development of resilient housing strategies through post-occupancy evaluation and sustainability assessment. Her work explores how traditional architectural knowledge, passive environmental design, and vernacular cooling strategies can inform contemporary climate-adaptive solutions for arid and rapidly urbanizing regions. She is committed to advancing research that integrates sustainability, resilience, and local design wisdom to address the challenges of climate change in the built environment.

CHAPTER 01

Reading Heat

Climate, Aridity, and the Logic of Vernacular Adaptation

1.1 Arid Heat as a Design Condition

1. Aridity Is Not the Same as Heat

Vernacular systems of cooling were developed for those regions that have had unique combinations of heat, scarce water, solar radiation, atmospheric dryness, temperature variability with seasons, and low mechanical power. Although "arid climate" has been used to describe what appears to be a particular type of thermal environment (heat), aridity and heat represent two distinct types of environmental characteristics. Aridity refers to the relationship between the amount of water available from the atmosphere and the potential evaporation rate of the local climate. Heat describes the thermal environment of an area's landscape, building, and inhabitants. An area can be arid while experiencing cold winters or cool annual conditions; conversely, a persistently hot region may remain humid.

A widely used climatological expression of aridity is the ratio of annual precipitation to potential evapotranspiration:

$$\left[AI = \frac{P}{PET}\right]$$

where (P) is precipitation and (PET) is potential evapotranspiration. Potential evapotranspiration estimates the amount of water that could be transferred from land and vegetation to the atmosphere if sufficient water were available. Where precipitation is substantially lower than atmospheric evaporative demand, the aridity index is low and climatic water deficit is high. This relationship is more informative than precipitation alone because the same annual rainfall can produce different environmental conditions under different temperatures, radiation loads, wind regimes, and seasonal distributions.

Köppen–Geiger classifications and aridity-index frameworks address related but distinct questions. Köppen–Geiger distinguishes hot and cold deserts and semi-arid climates using temperature and precipitation. The aridity index describes the balance between precipitation and potential evapotranspiration. Climate classifications support regional comparison, while hourly temperature, humidity, radiation, and wind data are needed for building design. Climatic clustering can provide more specific design guidance than a global classification alone (Roshan, Farrokhzad, and Attia, 2019).

Buildings respond to hourly combinations of solar radiation, moisture, wind, nighttime relief, and temperature. A cold desert may require winter heating and protection from freezing. An arid high-altitude city may combine intense solar radiation with cool nights. A coastal desert can have little rainfall but high humidity, limited nighttime relief, and reduced potential for evaporative cooling. A semi-arid city with monsoonal influences requires seasonal responses to dry heat, dust, humidity, and rainfall.

Hot-arid climates are generally characterized by strong solar exposure, low humidity, limited rainfall, and potentially large differences between daytime and nighttime temperature. These conditions can support thermal-mass strategies, shaded courtyards, evaporative cooling, and nocturnal ventilation where nights become sufficiently cool. Yet even within this category, urban form, altitude, wind, dust, and groundwater availability alter the design response.

Semi-arid climates generally receive more precipitation or experience lower evaporative imbalance than deserts. Vegetation, seasonal humidity, and cloud cover may be more significant. Such climates frequently contain mixed cooling requirements: shading and thermal mass may be effective during dry periods, while ventilation and moisture control become more important during humid or rainy seasons. Treating the semi-arid city as a weaker version of the desert city ignores this seasonal transition.

Coastal-arid climates present a different problem. Rainfall remains limited, but proximity to the sea can increase humidity and reduce the day–night temperature swing. Evaporation from human skin and water-based cooling systems becomes less effective as wet-bulb temperature rises. Heavy thermal mass may also be less useful if the building cannot release stored heat during warm nights. Ventilation becomes more important, but its value depends on wind availability and whether outdoor air actually offers lower heat stress.

High-altitude arid climates combine atmospheric dryness with elevation. Strong solar radiation can produce high daytime surface temperatures, but thin air, radiative cooling, and elevation may generate cool evenings or cold winters. Buildings must therefore moderate daytime solar gain without eliminating beneficial passive heating during cooler periods. The appropriate design may require seasonal control rather than permanent exclusion of solar radiation.

Cold deserts demonstrate most clearly why aridity cannot be equated with heat. They may possess low precipitation, sparse vegetation, dust, strong winds, and large temperature swings, yet their dominant annual building problem may include heating, freezing, and wind protection. Summer overheating may still occur because of intense radiation and poorly shaded construction, but the envelope cannot be designed solely as a cooling device.

The Indian distinction among hot-dry, composite, and cold climates illustrates the value of regional classifications. Composite climates move between hot-dry and warm-humid conditions and therefore require strategies capable of changing seasonally. The literature emphasizes that differences in diurnal range between hot-dry and humid conditions demand fundamentally different envelope responses. Arid-region design must therefore begin not with the category "hot climate," but with the form of climatic exposure experienced at a site.

2. The Building-Relevant Components of Heat

Annual average temperature is a bad way to base your building's design on, as it takes the timing, intensity, duration and the actual make-up of heat in the form of just a single number. For example two cities could be almost identical for their annual averages yet have completely different summer highs, winter lows, nighttime lows, humidity levels, radiation levels, wind speed and seasonal rainfall. Additionally the mean hides where the heat comes from. Is it a short lived heat spike during the afternoons? Is it multiple days worth of continued heat? Are you experiencing hot humid nights? Or are you feeling hot due to high levels of radiation when the outside ambient air temperature is relatively mild?

The dry bulb temperature is the most common measurement of air temperature. The dry bulb is used to determine how much sensible heat will transfer and ultimately how much energy will be needed to cool a space. However, this type of measurement does not show what is going on with all aspects of the thermal environment. For example, someone who is in shade and someone who is directly exposed to the sun may both have the same dry bulb temperature but still feel dramatically different in terms of their body heat load.

Mean radiant temperature represents the combined radiant influence of surrounding surfaces and solar exposure. In arid settings, radiation is often as important as air temperature because cloudless skies, intense sun, exposed roofs, and heated ground surfaces raise radiant load. A shaded street can therefore be substantially more tolerable than an unshaded open space even where weather-station air temperature is unchanged. Within buildings, roof and wall temperatures influence occupant comfort through long-wave radiation.

Solar gain is the heat entering through roofs, walls, windows, openings, and exposed internal surfaces. Its effect depends on solar angle, orientation, shading, surface colour, glazing, thermal resistance, and thermal mass. The timing of gain matters. East-facing openings receive lower-angle morning sun, while west-facing surfaces are exposed during already hot afternoons. Roofs receive intense solar load for long periods and can remain warm into the evening.

Humidity determines the capacity of air to accept additional moisture. Under dry conditions, sweat evaporation and evaporative cooling can remove heat effectively. As humidity rises, the same dry-bulb temperature produces greater physiological strain because evaporation becomes restricted. Coastal deserts and monsoon-influenced drylands can therefore be more difficult to cool than inland deserts with higher daytime temperature but lower wet-bulb temperatures.

Humidity also changes architectural strategy. Water features, wetted surfaces, porous jars, fountains, and evaporative towers can cool dry air, but their performance declines as wet-bulb temperature increases. The practical limit depends on comfort expectations, air movement, water quality, and system design, but the principle remains: low humidity creates evaporative opportunity; high humidity restricts it.

Wind determines the potential for convective and evaporative cooling. Air movement increases heat exchange from skin and can flush stored heat from buildings. However, wind is not automatically beneficial. Hot winds can increase heat gain. Dust-laden winds can reduce the acceptability of open windows, contaminate interiors, damage equipment, and create respiratory risk. Wind direction, speed, daily timing, and cleanliness are therefore more relevant than annual wind averages.

Nighttime cooling potential is one of the most important variables in many arid climates. A building that stores heat during the day can release it at night only if outdoor air and sky conditions provide a sufficiently cool sink. Night ventilation, roof exposure, courtyards, and radiative cooling all depend on this relief. Where nights remain hot, thermal mass can become a liability because stored heat cannot be removed before the next day.

Diurnal temperature range expresses the difference between daytime and nighttime temperatures. Large ranges can make thermal storage and night purging highly effective. Small ranges reduce this potential. The literature identifies diurnal range as a particularly important determinant of passive cooling in drylands and notes that night ventilation is most effective in high-diurnal climates such as Yazd, but less effective in coastal or dusty conditions.

Dust must be treated as a climatic design variable rather than a secondary maintenance concern. Dust storms and suspended particles affect natural ventilation, filtration, daylight, surface reflectance, machinery, water systems, and occupant behaviour. A theoretical night-ventilation opportunity may not be usable when outdoor air carries high particulate concentrations. Vernacular screens, protected courtyards, indirect openings, transitional spaces, and controlled inlet paths can be understood partly as responses to the need for air movement without unrestricted exposure.

Seasonal extremes complete the heat profile. The design problem is not only the average summer day but the hottest sequence of days, the warmest nights, the humid season, winter cold, dust episodes, and unusual rainfall. A building optimized for peak dry heat may perform poorly during a humid monsoon period. A permanently open structure may become uncomfortable during cold desert winters. Climatic exposure must therefore be represented as a temporal pattern, not a single thermal average.

3. Heat Metrics at Regional, Neighbourhood, Building, and Occupant Scales

No single heat metric is appropriate for every scale of architectural analysis. Regional comparison, urban design, building performance, and occupant comfort describe different processes and therefore require different indicators.

Cooling degree-hours estimate the accumulated amount by which hourly outdoor temperature exceeds a selected base temperature. They improve upon annual means and cooling degree-days by preserving sub-daily variation. At regional scale, cooling degree-hours can compare the intensity and duration of sensible cooling demand. At building scale, they can support preliminary load analysis when an appropriate base temperature is chosen.

Their limitation is that they remain temperature-based. They do not directly include humidity, solar gain, radiant temperature, wind, building form, or adaptive behaviour. A coastal city and an inland desert city can record similar cooling degree-hours while offering very different ventilation and evaporative-cooling potential. Degree-hours are therefore best interpreted as one measure of thermal pressure, not as a complete design prescription.

Operative temperature is more appropriate for indoor building and occupant scales because it combines the influence of air temperature and mean radiant temperature. It is a heat-transfer-weighted average of the two; at low air speed and with a modest difference between them, a simple average is often adequate. Operative temperature helps explain why a room with hot walls and roof can feel uncomfortable even when measured air temperature appears acceptable. It is particularly important in high-radiation environments and buildings using thermal mass.

Wet-bulb temperature is relevant at regional, neighbourhood, building, and occupant scales. At regional scale, it indicates the combined temperature–moisture condition and the broad potential for evaporative cooling. At building scale, it establishes a thermodynamic lower limit for direct evaporation. At occupant scale, high wet-bulb conditions indicate reduced capacity for sweat evaporation and greater physiological strain.

The Universal Thermal Climate Index (UTCI) and Physiological Equivalent Temperature (PET) are commonly used to assess outdoor thermal conditions at neighbourhood and public-space scales. They combine air temperature, humidity, wind, and radiation under specified assumptions. Standard Effective Temperature (SET) is also used in comfort analysis, particularly for indoor conditions and elevated air speed; it should not be treated as an interchangeable outdoor index.

These indices must nevertheless be applied carefully. They depend on assumptions concerning clothing, activity, exposure, and physiology. They may not fully represent local acclimatization, cultural clothing, age, health, or behavioural adaptation. They should therefore complement rather than replace direct microclimate measurement and local comfort research.

Adaptive comfort limits are most appropriate at building and occupant scales, particularly in naturally ventilated buildings where occupants can open windows, change clothing, use fans, alter activity, or move within the building. Adaptive models recognize that acceptable indoor temperatures vary with recent outdoor conditions and occupant expectations. They are more relevant to vernacular and mixed-mode buildings than fixed temperature set points derived from sealed, mechanically conditioned environments.

Adaptive models also have limits. Comfort expectations differ according to climate, income, cultural practice, building control, age, and access to alternatives. Carlucci et al. (2018) identify uncertainties in applying adaptive models across climates and operating modes. A model must be used within its stated applicability limits.

The frequency of hot nights is essential at regional, neighbourhood, building, and occupant scales. It can be measured as the number or proportion of nights exceeding a locally meaningful minimum-temperature threshold. Hot nights indicate whether occupants and buildings receive relief after daytime exposure. They affect sleep, heat recovery, the effectiveness of night ventilation, and the capacity of thermal mass to discharge stored energy.

At regional scale, hot-night frequency indicates changing climate risk. At neighbourhood scale, it reveals urban heat-island amplification. At building scale, it tests whether night-purge strategies remain viable. At occupant scale, it captures the duration of exposure across the full twenty-four-hour cycle. Increasing hot nights can undermine vernacular systems that historically depend on cool nocturnal air even where daytime maxima changes less dramatically.

A multi-scale assessment should therefore use degree-hours and hot-night frequency for broad exposure, outdoor thermal indices for neighbourhoods, operative temperature for interiors, wet-bulb temperature for moisture and evaporative potential, and adaptive comfort limits for occupied naturally ventilated spaces. Metrics should be combined according to the process under investigation rather than merged automatically into one index.

4. A Comparative Typology of Arid-Region Cities

The following typology applies the literature's climatic distinctions to representative cities. It is a qualitative comparison, not a ranking based on harmonized hourly observations. Final design analysis would require local station records, recent typical meteorological years, urban measurements, and site-specific assessment.

Table 1.1 Climatic exposures and design implications across arid-region cities

Representative city	Regional setting	Dominant exposure configuration	Main design implication
Cairo, Egypt	North Africa	Hot desert, strong solar load, dust, warm summer nights, dense urban heat storage	Deep shading, solar control, protected ventilation, reduced urban heat storage
Riyadh, Saudi Arabia	Arabian Peninsula	Extremely hot inland desert, low humidity, intense radiation, potentially large diurnal range	Compact shading, thermal mass with controlled night purging, evaporative potential where water permits
Muscat, Oman	Coastal Arabian Peninsula	Coastal arid, high humidity, small nocturnal relief, high wet-bulb stress	Strong air movement, shading, low solar gain, limited reliance on direct evaporation or heavy mass
Yazd, Iran	Iranian plateau	Hot-arid plateau, large diurnal range, low humidity, strong radiation	Thermal mass, courtyards, wind capture, evaporative cooling, night ventilation
Jaisalmer, India	South Asia	Hot-dry desert with intense solar exposure, dust, seasonal variation	Compact form, shaded openings, massive walls, controlled ventilation and seasonal adaptability
Leh, India	High-altitude South Asia	Cold high-altitude desert, intense solar radiation, cold nights and winters	Solar admission with control, insulation, thermal storage, protection from wind and nighttime heat loss
Phoenix, United States	Southwest North America	Hot desert, very high cooling demand, urban heat-island effects, increasingly hot nights	Solar exclusion, cool roofs, shaded urban form, efficient night ventilation where still viable

Representative city	Regional setting	Dominant exposure configuration	Main design implication
Arequipa, Peru	Andean drylands	High-altitude arid, strong solar radiation, moderate air temperature, cool nights	Radiant protection, controlled solar heating, thermal storage, strong day–night adaptation
Windhoek, Namibia	Southern Africa	Semi-arid highland, seasonal rainfall, dry heat, cool nights and winter variability	Mixed-mode design, shading, thermal mass, night cooling and seasonal solar control
Alice Springs, Australia	Interior Australia	Hot desert, high radiation, large seasonal and diurnal variation	Thermal mass, roof protection, deep shade, night purging and winter solar access

The typology demonstrates that arid-region cities do not form one architectural category. Riyadh and Muscat are both located on the Arabian Peninsula and both experience low rainfall, but their moisture and nocturnal regimes differ substantially. Riyadh's dry inland conditions can increase the potential value of evaporative cooling and nighttime heat release. Muscat's coastal humidity reduces evaporative effectiveness and can keep nighttime heat stress high, increasing the importance of continuous air movement and low thermal storage.

Yazd and Arequipa both benefit from cool-night potential, but altitude, seasonal temperature, solar intensity, and cultural water systems produce different design opportunities. Leh is arid but cannot be classified mainly as a cooling climate because cold nights and winters are central to building performance. Windhoek's semi-arid highland conditions require seasonal flexibility rather than permanent heat exclusion.

The literature's discussion of Riyadh, Tehran, Yazd, and Tabas similarly illustrates that arid environments range from ultra-dry deserts with large diurnal swings to semi-arid and high-altitude settings with different humidity, wind, and nighttime conditions. A comparative typology must therefore classify cities according to combinations of exposure variables, not simply latitude, rainfall, or annual temperature.

5. Vernacular Cooling as a Response to Climatic Combinations

The vernacular cooling strategies of people in all climates have evolved based on their history of weather patterns rather than simply being a general response to high temperatures. All these traditional passive systems (walls that are thick, internal courtyards, wind towers, very narrow streets, arcades for shading, roof spaces or balconies, thermal storage through the ground, wetted surfaces for evaporation, screens over windows, moving inside houses during certain seasons) work in response to a particular combination of temperature, humidity, solar radiation and wind speed. For example, thick walls are best at delaying daytime heat gain until evening time when cooler air is available to dissipate this stored heat. The use of thermal mass will only be effective if there is a substantial daily temperature swing and cold evenings allowing for good natural ventilation to carry off the stored heat. On the other hand, thick walls and large amounts of thermal mass would make a coastal city's arid zone hotter and more uncomfortable on warmer humid nights. Thermal mass has been shown to be a solution to a specific type of temperature swing rather than a generic desert/climate solution.

Courtyards are similarly multifunctional. They provide shade, reduce exposure to hot winds and dust, create controlled air volumes, support nocturnal radiative cooling, and organize access to vegetation or water. Their performance depends on proportion, orientation, opening pattern, surface properties, and nighttime operation. A courtyard can become a heat trap when solar exposure is excessive or ventilation is weak.

Wind towers and high-level ventilation devices respond to the spatial distribution of wind and temperature rather than to heat alone. They may capture cooler air, exhaust warm air, or draw air across water and shaded surfaces. Their success depends on reliable wind, pressure differences, air cleanliness, and the thermal condition of the incoming air.

Evaporative systems respond specifically to low wet-bulb temperature and available water. They are highly compatible with hot-dry air but far less effective in humid coastal settings. Water scarcity also imposes ecological and social limits. A historically viable water-based system may become unsustainable under contemporary groundwater depletion, population growth, or water-quality constraints.

Lightweight, highly ventilated structures are more appropriate where thermal storage is undesirable and air movement remains the primary cooling mechanism. Heavy, compact, and shaded construction is more appropriate where daytime heat must be delayed until cooler nights. Composite climates require adjustable openings, seasonal shading, rain protection, and combinations of mass and ventilation rather than one permanent strategy.

Urban form also responds to climatic combinations. Narrow streets and attached buildings reduce direct solar exposure and external surface area.

Compactness can protect against hot dry winds and dust. Yet excessive density can restrict nighttime ventilation and intensify heat storage where urban surfaces remain warm. Climate change and urbanization are increasingly reducing the nocturnal cooling on which many historical systems depended. The reviewed research notes that urban heat islands elevate cooling demand and may diminish diurnal range and nighttime relief.

Vernacular strategies should therefore be interpreted as historically situated systems of environmental regulation. Their performance depended on local materials, water, household practices, occupancy schedules, clothing, social organization, and tolerance of temperature variation. Extracting one visible feature and reproducing it in another climate can fail when the original combination of conditions is absent.

1.2 Vernacular Architecture as Environmental Knowledge - Without Romanticization

1. Distinguishing Vernacular, Traditional, Indigenous, Popular, and Regional Architecture

Vernacular architecture is often treated as a convenient umbrella for buildings described as traditional, indigenous, rural, anonymous, local, or non-professional. These terms overlap, but they do not describe the same relationship among authorship, knowledge, materials, labour, custom, and institutional control. Using them interchangeably can obscure who produced a building, how knowledge was transmitted, which authority regulated construction, and whether the form remains part of a living practice or survives mainly as heritage.

The modern scholarly category of vernacular architecture emerged partly through Bernard Rudofsky's presentation of what he called non-pedigreed architecture. His work brought wide attention to buildings outside professional architectural canons, but its visual and aesthetic emphasis also detached many structures from the social systems that produced them. Rapoport shifted attention from form alone toward the cultural rules underlying dwellings, arguing that climate, landscape, and materials do not determine buildings independently of social convention. Oliver expanded the category by relating buildings of the people to environmental context, available resources, customary construction, and community participation. Vellinga later challenged the implication that vernacular architecture belongs to a completed past, proposing instead that vernacular traditions consciously and creatively adapt inherited experience to present circumstances.

Within this debate, **vernacular architecture** can be defined as built form produced substantially through locally embedded knowledge, customary practice, repeated adaptation, and direct relationships among users, builders, materials, and place. Professional architects may be absent, but absence of a named designer is not the defining feature. Many vernacular environments involved specialized craftspeople, master builders, guilds, patrons, religious authorities, landowners, and local regulations. Vernacular authorship is therefore distributed rather than nonexistent.

Traditional architecture refers more specifically to construction associated with inherited forms, practices, and meanings transmitted across generations. A building can be traditional without being vernacular if its form is reproduced through centralized institutions, professional design, standardized heritage regulations, or elite patronage. Conversely, a vernacular building may incorporate new materials, technologies, or spatial arrangements and therefore depart from an older tradition. Tradition concerns continuity and reference to the past, while vernacularity concerns the social organization of knowledge and production.

Indigenous architecture should be reserved for buildings, landscapes, and construction knowledge connected to Indigenous peoples whose political, territorial, and cultural identities precede or resist dominant state and colonial formations. Indigenous architecture is not merely architecture that is old, rural, natural, or locally made. The term entails relationships to land, collective identity, sovereignty, ecological knowledge, ritual, and historical dispossession. Treating all vernacular architecture as indigenous erases the political specificity of Indigenous communities and can enable the appropriation of knowledge without recognition of rights.

Popular architecture generally refers to ordinary building practices shaped by mass culture, informal markets, self-construction, standardized products, aspirations, and everyday adaptation. It may include concrete-block houses, incremental urban dwellings, commercial shopfronts, migrant-built neighbourhoods, and hybrid constructions combining local custom with industrial materials. Popular architecture is often contemporary and may be strongly influenced by television, social media, developers, remittances, or municipal regulation. It is not necessarily rooted in long-established craft traditions, although it can incorporate them.

Regional architecture refers to built forms associated with a geographic area. The category can include vernacular, professional, monumental, industrial, and state-designed buildings. Regional similarity may result from climate and materials, but also from planning law, political history, construction industries, religious institutions, or architectural movements. A professionally designed building can be regional without being vernacular, just as a vernacular practice can cross administrative regions through migration or trade.

These distinctions reveal different systems of authority. Vernacular construction may be regulated through custom and community knowledge. Traditional construction may be preserved by heritage institutions. Indigenous building may be governed by collective rights and cultural protocols. Popular building may emerge through informal markets and household improvisation. Regional architecture may be promoted through state identity, tourism, or professional discourse. None of these categories should be treated as pure or mutually exclusive. A contemporary house can be popular, regionally recognizable, partially vernacular, and constructed through transformed traditional knowledge.

2. Vernacular Buildings as Evolving Socio-Technical Systems

A vernacular building should not be understood as an anonymous object that passively embodies climate wisdom. It is better understood as part of a socio-technical system connecting environmental knowledge, material supply, labour organization, social hierarchy, household practice, maintenance, and neighbourhood cooperation. Its performance emerged through interactions among physical components and human routines rather than through form alone.

The physical system includes walls, roofs, floors, openings, courtyards, screens, shaded passages, water structures, storage areas, vegetation, and connections to neighbouring buildings. The social system includes households, builders, craft specialists, water managers, traders, neighbours, employers, servants, tenants, and local authorities. Thermal conditions depended on how these groups constructed, operated, repaired, and occupied the environment.

Construction sequences carried environmental knowledge. Builders knew when earth mixtures should be prepared, how long materials needed to dry, which walls required greater thickness, how timber should be positioned, where openings could admit air without excessive sun, and how roofs should be layered against heat or rain. Such knowledge was often procedural rather than written. It existed in the order of tasks, the judgement of moisture and texture, the selection of seasonal labour, and the capacity to identify failure during construction.

Craft guilds and occupational networks were also important in preserving and regulating the construction knowledge. Master builders used apprenticeships to pass on proportions, joinery techniques, plastering methods, vaulting techniques, water control and repair methods to their successors. However, this knowledge was not always shared equally amongst all members of a community. Rather than being an open resource, specialized knowledge may have been protected through occupational authority or patronage. Additionally, it may have been divided along caste lines, class lines, ethnic lines, and gender lines. Therefore, while vernacular construction can be described as communal, we should not forget that there is often a hierarchy of skill and specialization within these Communities.

Similarly, material knowledge was dynamic. Although many local building materials were available because they were locally produced, availability alone did not explain their use. Each community developed its own methodologies for extracting, processing, combining, transporting protecting and renewing them. The stabilizing or layering of Earth depended upon soil conditions and exposure. Similarly, timber selection was based on species, span, insect activity, moisture content, trade routes and other factors. Lime, gypsum, stone brick reeds fibers and animal products entered complex supply chains. What are commonly identified as local materials may have actually traveled throughout regional markets; further, access to land and water may have limited who had controlled access to these materials.

The reviewed literature connects vernacular form to environmental context and available resources but also warns against reducing it to physical determinants. Similar climates can produce different buildings, and similar methods can appear in different climates because social, cultural, economic, religious, technological, and political forces influence form. A socio-technical interpretation therefore asks not only what a wall does thermally, but why a particular community adopted, maintained, or abandoned it.

Vernacular systems evolved through modification rather than perfect repetition. Households added rooms, enclosed courtyards, replaced roofs, introduced glass, connected electricity, changed cooking areas, and altered openings. Population growth, inheritance, migration, new occupations, security concerns, land subdivision, and changing concepts of privacy transformed buildings. What appears today as a stable type may be one moment in a long sequence of adaptation.

This evolutionary quality is central to Vellinga's concept of vernacular traditions. Tradition is not the mechanical reproduction of an original form but the selective adaptation of past experience to present needs. Hybridization with industrial materials or modern services does not automatically destroy vernacular knowledge. It can represent an attempt to resolve new pressures. The analytical task is to determine which relationships are preserved, which are altered, and whether the resulting system performs better or worse environmentally and socially.

3. Environmental Knowledge in Use, Maintenance, and Collective Practice

Climatic knowledge was embedded not only in building construction but in how space was occupied over the day and year. Vernacular thermal regulation often depends on seasonal and daily migration within buildings. Occupants moved between shaded courtyards, roof terraces, lower rooms, upper rooms, semi-open galleries, basements, and outdoor sleeping areas according to sun, wind, humidity, and time.

A room was therefore not expected to maintain a standardized temperature throughout the year. Different spaces offer different microclimates. Thick lower rooms could provide daytime refuge during dry heat. Roofs and courtyards could support sleeping when nights were cool. Winter rooms might admit sun while summer rooms remained shaded. This spatial diversity allowed comfort to be achieved partly through movement rather than through mechanical control of the entire building.

Household routines were equally important. Windows, shutters, screens, doors, roof openings, fabrics, mats, and water surfaces had to be operated at suitable times. Night ventilation required openings to be created after outdoor temperature fell and closed before daytime heat returned. Courtyard vegetation required watering and maintenance. Dust events might require openings to be sealed even when ventilation was thermally desirable. Cooking, bathing, cleaning, and sleeping schedules influenced internal heat and moisture.

Water management frequently formed part of the cooling system. Wells, cisterns, channels, fountains, porous vessels, irrigated courtyards, and planted spaces could reduce temperature or support evaporative processes. Their operation depended on water rights, maintenance, labour, cleanliness, and seasonal availability. The thermal principle cannot be separated from the infrastructure governing access to water.

Repair practices were also performance practices. Earthen surfaces require renewed plaster. Roofs needed inspection after rain. Timber needed protection from insects and moisture. Water channels require cleaning. Screens, doors, and shading devices needed replacement. A vernacular building photographed at one moment may appear inherently durable, but its survival may represent repeated inputs of labour and material.

Maintenance cycles allowed buildings to be adjusted. Cracks, water paths, failed plaster, overheated rooms, and blocked ventilation revealed how construction responded to use. Repair was therefore a form of distributed environmental monitoring. The knowledge generated through failure could be transmitted to builders and households and incorporated into later construction.

Neighbourhood cooperation extended this system beyond the individual dwelling. Attached buildings reduced exposed surfaces. Narrow streets depended on coordinated plot patterns. Shared walls, drainage, water systems, shaded routes, and public spaces required collective rules. One household's alteration could affect another's ventilation, privacy, drainage, or solar access. Vernacular environmental performance was therefore partly a property of settlement morphology and social coordination.

This interpretation challenges the phrase "architecture without architects" when it is taken to mean architecture without expertise or governance. Vernacular environments may have lacked modern professional authorship, but they did not lack designers, technicians, rules, or institutions. Knowledge was distributed among craftspeople, households, communities, and authorities.

It also explains why transferring a visible element often fails. A windcatcher removed from its settlement geometry, room connections, maintenance practices, dust management, and occupancy routines is no longer the same socio-technical device. A courtyard inserted into a sealed commercial building may function as an atrium dominated by solar gain rather than as a night-cooled domestic microclimate. Environmental knowledge resides in relationships among form, operation, and social organization.

4. Separating Physical Principles from Cultural Appearance

A critical study of vernacular performance must distinguish the physical principle of a strategy from its cultural appearance. Historical survival, visual distinctiveness, and symbolic importance do not demonstrate thermal effectiveness. A windcatcher is not effective because it is old, and a courtyard is not cooling because it resembles a celebrated precedent.

The physical performance of a windcatcher depends on height, inlet direction, cross-sectional area, internal partitions, pressure differences, surrounding obstructions, wind frequency, outlet paths, room volume, air temperature, dust, and occupant control. Some devices capture wind; others assist exhaust through buoyancy or negative pressure. Some direct air over water or into subterranean spaces. Their cultural classification under one architectural name can conceal different physical operations.

Courtyards are similarly variable. Geometry determines solar exposure, sky view, shading duration, and airflow. Surface materials affect heat storage. Vegetation and water alter humidity and radiation. Openings determine whether cooled air enters rooms. A deep courtyard in a dry high-diurnal climate does not behave like a broad glazed atrium in a humid city. Courtyards can reduce heat, but they can also store solar energy, obstruct airflow, or produce uncomfortable humidity.

Massive walls operate through thermal resistance, heat capacity, surface properties, and time lag. They perform well where delayed heat flow can be released during cooler periods. Where nights remain hot, mass can retain unwanted heat. Small openings reduce solar gain but may also limit daylight and ventilation. Compact urban form reduces exposed area and shading demand but can weaken airflow and increase urban heat storage.

The reviewed literature explicitly warns that architectural discourse often conflates formal resemblance with actual performance. Appreciation may rest on craftsmanship, heritage, or appearance, while present-day legal requirements, construction systems, comfort expectations, and occupancy differ substantially from the conditions under which the original building operated.

Performance assessment should therefore proceed in stages. The first stage identifies the proposed physical mechanism: shading, conductive delay, convective exchange, evaporation, radiative cooling, reduced infiltration, or spatial migration. The second stage identifies the conditions required for the mechanism to function. The third examines whether those conditions occur at the site and during the relevant hours. The fourth measures or simulates the actual effect. The fifth evaluates whether occupants can and do operate the system.

A strategy can be physically effective but socially impractical. Night ventilation may reduce temperature but conflict with noise, security, insects, pollution, privacy, or sleep. Roof sleeping may provide comfort but be inaccessible to older or disabled occupants. Evaporative cooling may work thermodynamically but consume scarce water. Narrow shaded streets may improve outdoor comfort while limiting emergency access or daylight.

Environmental performance must also be separated from broader sustainability. A building may have low embodied energy but poor sanitation. It may require little operational energy but demand intensive maintenance labour. It may provide acceptable summer comfort but severe winter discomfort. It may perform well for a small household but poorly under contemporary crowding. Sustainability is a multidimensional judgement, not a quality automatically conferred by vernacular origin.

5. Historical Limits, Inequalities, and Exclusions

Vernacular environments were produced within unequal societies. Their cooling systems could distribute comfort, labour, space, water, and risk unevenly. Romantic accounts often describe the house or settlement as though every resident benefited equally, but access to the coolest rooms, shaded courtyards, gardens, water, and roof spaces could be structured by class, ownership, gender, age, status, and occupation.

Large houses could provide multiple seasonal rooms, thick construction, internal courtyards, servants, water storage, and maintained gardens. Poorer households might occupy smaller spaces, share rooms, live near workshops or animals, and possess fewer opportunities for spatial migration. Settlement-level cooling strategies therefore cannot be evaluated without considering who controlled land, building depth, water, and labour.

Gendered spatial restrictions could shape access and exposure. Courtyards and screened spaces may have enabled privacy and domestic life, but they could also reflect restrictions on women's movement. The same enclosure can be interpreted as climatic protection, social security, gendered segregation, or all three simultaneously. Functional explanation must not turn social constraint into an environmental virtue.

Labour inputs were often substantial. Construction, plaster renewal, roof maintenance, water carrying, cleaning, textile adjustment, cooking relocation, and operation of openings required time and skill. Much of this labour may have been performed by women, servants, enslaved people, low-status workers, tenants, or specialized occupational groups. A system that appears energy efficient in mechanical terms may have depended on labour-intensive routines whose social cost was unevenly recognized.

Water-based cooling raises further questions. Fountains, planted courtyards, channels, and evaporative devices may represent sophisticated environmental adaptation, but they presuppose access to water. In water-scarce societies, such access could be governed through property, status, political authority, or collective allocation. Contemporary reproduction of these systems must consider water stress and competing household, ecological, and agricultural needs.

Historic sanitation standards also differed from present expectations. Dense settlement, shared water, animals, waste disposal, smoke, indoor combustion, and limited drainage could produce health risks. Openings designed for climate may admit dust, insects, or disease vectors. Heritage value and thermal performance do not remove these public-health considerations.

Fire and seismic risk were similarly uneven. Timber, thatch, narrow lanes, heavy unreinforced masonry, and poorly connected walls can perform effectively under certain climatic conditions while increasing vulnerability to fire or earthquakes. Contemporary adaptation must retain useful environmental principles without reproducing structural hazards.

Occupancy density has changed. A courtyard house built for an extended household with distributed activities may now be subdivided among several families or converted to commercial use. Conversely, a form developed for dense occupation may be reproduced as a large luxury residence. Performance measured under one occupancy pattern cannot be assumed under another.

The reviewed literature calls for greater attention to gender, labour, affordability, gentrification, and the social effects of rehabilitation. It warns that preserving or replicating vernacular appearance can produce expensive environments serving groups different from those who originally created them. Critical interpretation must therefore ask whose comfort was produced, whose labour sustained it, which risks were accepted, and who benefits from contemporary reuse.

1.3 A Comparative Geography of Arid Building Traditions

1. Regions, Variables, and the Nested Scale of Comparison

A comparative geography of heat-responsive architecture must perform two tasks at once. It must identify recurring environmental principles across arid regions, but it must also preserve the particular histories, materials, institutions, and household practices through which those principles became architecture. If comparison is too narrow, each case appears unique and little can be learned across regions. If it is too broad, the courtyard, windcatcher, thick wall, or shaded street becomes a universal type detached from the social and urban systems that made it effective. The appropriate method is therefore relational and nested: regions are compared through common analytical variables, while interpretation moves from region to settlement, block, building, room, and component.

The major regional families considered here are Saharan and Maghrebi settlements; Nile Valley and Red Sea traditions; Arabian and Gulf courtyard houses; Iranian plateau and Central Asian wind-and-earth systems; South Asian desert settlements; Pueblo, adobe, and Mexican traditions; Andean dryland settlements; southern African drylands; and Australian hot-arid adaptations. These are not homogeneous culture areas. Each contains internal differences of altitude, humidity, rainfall, political history, religious practice, land tenure, settlement density, and material supply. Their value lies in structuring comparison rather than defining fixed architectural identities.

Each region should be examined through the same variables: settlement compactness, street orientation, courtyard prevalence, roof form, wall material, opening ratio, shading system, ventilation device, water use, vegetation, seasonal room use, and relation to topography. These variables connect climatic exposure to spatial and material response. Compactness affects mutual shading and exposed surface area. Street orientation shapes solar access and wind penetration. Courtyards alter radiation, airflow, privacy, and domestic organisation. Roofs mediate solar load, rainfall, sleeping practices, and heat loss to the night sky. Wall materials govern thermal resistance, storage, repair, and construction labour. Openings regulate light, air, dust, security, and visibility.

The same device can perform differently at each scale. A windcatcher cannot be understood only as a roof component. Its effectiveness depends on regional wind patterns, urban obstruction, block density, the pressure relationships around the building, internal shafts, room connections, outlet paths, and household operation. A mashrabiya or screened opening depends on street width, orientation, social expectations of privacy, air temperature, and maintenance. A courtyard depends on the surrounding roof line, height-to-width ratio, planting, water, opening schedules, and seasonal room use. The nested method prevents components from being interpreted as autonomous technological inventions.

Comparison must also distinguish convergent evolution from cultural diffusion. Similar thermal problems can generate analogous solutions in places without direct cultural transmission. Thick earth walls occur in geographically separated deserts because earth is widely available and thermal mass can moderate high diurnal variation. Narrow shaded streets recur because reducing solar exposure benefits outdoor movement and limits wall heating. Such recurrence does not prove a shared origin. Conversely, trade, migration, empire, religion, craft mobility, and colonial exchange did transmit forms and techniques across regions. The task is to determine when similarity follows comparable environmental constraints and when historical contact provides a stronger explanation.

The reviewed literature confirms both recurrence and specificity. Courtyards, thermal mass, compact form, small openings, shading, and natural ventilation appear across many arid regions, yet wind towers, elaborate subterranean systems, Iraqi projecting balconies, Moroccan fortified settlements, and Yemeni tower houses remain more locally concentrated. A comparative geography should therefore identify families of response without converting them into a catalogue of universal devices.

2. Saharan, Maghrebi, Nile Valley, Red Sea, and Arabian Traditions

Saharan and Maghrebi settlements frequently demonstrate the close relationship between compact urban morphology and collective thermal protection. Ksour, kasbahs, medinas, oasis settlements, and earthen villages often minimize exposed external surface through attached buildings, thick walls, narrow passages, and shaded transitions. Street networks may be irregular rather than aligned to one climatic orientation, because defence, land division, topography, social hierarchy, and incremental growth influenced their form. Their environmental performance arises partly from depth, enclosure, and mutual shading rather than from isolated building orientation.

Courtyards are common but not uniform. In large houses they can organise several seasonal rooms and provide protected outdoor space, while in modest dwellings they may be small service courts or light wells. Wall materials include rammed earth, mud brick, stone, lime, and combinations of earth with timber or palm elements. Openings toward streets are generally limited, while internal openings may be larger. Roofs are often flat where rainfall permits, supporting storage, work, drying, or nighttime occupation. Shading is created through building overhang, covered lanes, recessed doors, fabric, arcades, and the depth of openings.

Water use differs sharply between oasis settlements, urban houses, and extremely dry villages. Courtyard pools and vegetation are more feasible where wells, channels, or controlled water systems exist. In other settings, cooling relies primarily on shade, mass, ventilation timing, and reduced exposure. The reviewed research explicitly cautions that water-based cooling cannot be assumed throughout arid regions because scarcity restricts its applicability. Vegetation is therefore not a generic feature of the arid courtyard; it reflects access to land, labour, and water.

Nile Valley traditions share the extensive use of earth and masonry but respond to a different hydrological geography. Settlement has historically been organised in relation to river, cultivation, floodplain, desert edge, and prevailing wind. Mud-brick walls, courtyards, roof terraces, shaded loggias, domed or vaulted spaces, and controlled openings appear in different combinations. Flat roofs support domestic activity and nighttime sleeping in some contexts, while vaults and domes reduce reliance on scarce timber and can modify roof heat transfer. Buildings along the Nile cannot be interpreted as simple desert objects because agricultural humidity, river breezes, cultivated shade, and floodplain land pressure modify their exposure.

Red Sea traditions add coastal humidity, maritime trade, coral or stone construction, and strong social links to port economies. Houses in Red Sea settlements may use projecting wooden screens, shaded balconies, taller forms, and openings designed to admit breeze while preserving privacy. Compared with inland desert settlements, the smaller diurnal range and higher humidity can reduce the value of thermal storage and evaporation. Air movement, shaded façades, and porous internal planning become more significant. Yet these houses also reflect imported timber, merchant wealth, craft exchange, and urban status.

Arabian and Gulf courtyard houses span inland plateau, coastal, oasis, and port conditions. In central Arabian settlements, compact mud-brick compounds, limited exterior openings, internal courts, and thick roofs protect against solar exposure and dust. In Gulf towns, coral stone, gypsum, timber, courtyard planning, roof terraces, shaded passageways, and wind towers respond to humidity, maritime breezes, and dense urban form. Wind towers are especially associated with Persian and Gulf traditions, but their presence does not mean that all Gulf housing used them or that all examples operated identically.

Privacy, religion, security, and household structure are central to this regional family. The introverted courtyard simultaneously regulates climate and controls visibility, movement, gendered access, and relations between household and street. The literature identifies privacy as a product of interacting cultural, climatic, and security conditions rather than as a purely religious rule. Thermal analysis must therefore avoid explaining enclosure through climate alone.

3. Iranian Plateau, Central Asian, and South Asian Desert Systems

The Iranian plateau contains some of the most elaborated combinations of urban compactness, courtyards, wind systems, earth construction, water infrastructure, and seasonal room use. Historic cities such as Yazd, Kashan, Semnan, and settlements in Sistan occupy different wind, altitude, humidity, and water regimes despite their broad classification as arid. Their architectural differences demonstrate the inadequacy of treating Iranian hot-arid architecture as one type.

Settlement compactness generally limits solar exposure and protects movement through narrow lanes, covered passages, recessed entrances, and continuous walls. Courtyard houses may include several courts with rooms oriented for different seasons and times of day. Flat or vaulted roofs, thick adobe or brick walls, small external openings, deep internal recesses, and shaded iwans regulate radiation and heat flow. Seasonal room use is particularly important: households may occupy north- or south-facing rooms differently in summer and winter, move to subterranean spaces during peak heat, or use roofs and courtyards at night.

The bādgīr is one component within this larger environmental system. It can capture prevailing winds, exploit pressure differences, support stack exhaust, or direct air toward subterranean rooms and water. Its operation depends on orientation, height, shaft geometry, internal partitions, surrounding buildings, air cleanliness, and outlet conditions. Iranian systems may also include sardābs, pāyābs, howz-khānehs, qanats, and other underground or water-linked spaces. The literature identifies these subterranean elements as a particularly elaborate regional development rather than a universal arid response.

Central Asian settlements share the widespread use of earth, courtyard compounds, flat roofs, thick external walls, and shaded internal spaces, but their stronger continental seasonality changes the design problem. Cities and oasis settlements must often address very hot summers and severe winters. Courtyards can provide summer shade while south-facing rooms and protected walls support winter solar gain. Roof and wall assemblies must balance thermal storage with resistance to winter heat loss. Topography, irrigation, oasis agriculture, and trade routes influence settlement location and vegetation.

English-language architectural scholarship frequently treats major Silk Road monuments more extensively than ordinary housing, neighbourhood change, or low-income settlement. Consequently, the Central Asian family should be included through paired study of historic courtyard districts, ordinary earthen compounds, peri-urban transformation, and contemporary additions rather than inferred only from monumental madrasas or restored heritage quarters.

South Asian desert settlements display another set of convergent and divergent responses. In Rajasthan and adjoining dry regions, compact towns, sandstone or earthen walls, narrow streets, internal courts, roof terraces, deep recesses, jalis, projecting chhajjas, and shaded thresholds reduce radiant exposure. Jodhpur, Jaisalmer, Bikaner, and smaller villages differ in stone supply, wealth, density, water, and social organisation. Baghel, Mehta, and Agrawal (2024) identify both clay and sandstone as locally significant in Jodhpur, demonstrating how material availability shapes the form taken by otherwise comparable thermal principles.

The South Asian desert also includes composite climates in which dry heat is followed by monsoon humidity or seasonal rain. Flat roofs require drainage and maintenance. Openings that remain small during dusty hot periods may need to support ventilation during humid seasons. Courtyards can provide shade but may become less effective when humidity rises and nights remain warm. Social divisions, caste, gender, ownership, and household occupation influence who has access to shaded courts, roof terraces, water, and well-built stone rooms. The architecture is therefore climatic, material, and social at the same time.

4. The Americas, Southern African Drylands, and Australia

Pueblo and adobe traditions of southwest North America demonstrate strong convergence with other high-diurnal drylands through compact settlement, thick earthen walls, limited exterior openings, and the use of thermal mass. Terraced or clustered forms reduce exposed surface and can use topography for protection. Flat roofs support work, storage, circulation, and seasonal occupation. However, Pueblo architecture cannot be reduced to an environmental type. It is connected to Indigenous political identity, ceremonial organisation, land, collective construction, and colonial disruption.

Adobe buildings in the southwest United States and northern Mexico often combine thick walls with courtyards, portals, shaded verandas, timber roof structures, and small or deeply recessed openings. Mexican arid traditions include Indigenous, Spanish colonial, mission, ranch, mining, and popular urban forms. Courtyards can organise domestic life, work, animals, water, and privacy, while street-facing arcades or portals provide public shade. Water channels, acequias, wells, and planted courts matter where water is available, but their presence reflects institutional control as much as climate.

Compared with the highly compact fabrics of some Saharan or Iranian cities, many Mexican and southwest North American settlements are more dispersed. Land tenure, colonial planning grids, agricultural patterns, transport, and later suburbanisation altered settlement compactness. The climatic value of thermal mass and shade may remain, but wider streets and detached buildings increase exposed surface and solar gain. Convergence at the component scale therefore coexists with divergence at block and city scales.

Andean dryland settlements introduce altitude as a major modifier. Strong solar radiation, low humidity, cold nights, seasonal rainfall, and large day–night variation require both heat protection and heat retention. Stone and adobe walls provide mass, but the design cannot permanently exclude solar gain. Courtyards may occur, but they are less universally dominant than in many Islamic urban traditions. Roof form varies with altitude, precipitation, timber availability, and colonial influence. Compact village forms can reduce wind exposure, while terraces and slopes create strong relationships to topography.

Andean cases should therefore be selected through Spanish-language and national sources, archaeological documentation, housing studies, and contemporary settlement research. Iconic precolonial or colonial sites should not stand in for ordinary highland housing or rapidly expanding peripheral neighbourhoods.

Southern African drylands include desert, semi-desert, highland, savanna-margin, and seasonally wet environments. Settlement may be less compact than in North African medinas because land tenure, pastoralism, rainfall, household compounds, and colonial planning produced different spatial relations. Earthen walls, stone, thatch, verandas, detached shaded structures, trees, and outdoor work areas can regulate exposure. In high-diurnal environments, thermal mass and night cooling may be effective, while lightweight shaded structures can be useful where daytime occupation is distributed outdoors.

These regions are particularly important for challenging the assumption that a courtyard must be the central unit of arid adaptation. Household compounds, clusters of detached rooms, shaded workspaces, livestock enclosures, and seasonal movement can produce environmental control through distributed rather than enclosed form. Vegetation may be more significant where seasonal rainfall supports trees, while water storage and access remain critical.

Australian hot-arid adaptations require a distinction between Indigenous environmental knowledge and settler construction. Indigenous responses often involved mobility, seasonal occupation, the selection of shaded landforms, temporary or adaptable shelters, and detailed knowledge of wind, water, vegetation, and thermal variation. These practices cannot be evaluated only through permanent-building typologies. Settler adaptations later included verandas, shaded outdoor rooms, lightweight structures, corrugated materials, thick masonry, and, in some mining settlements, earth-sheltered or underground occupation. Study of this regional family requires Indigenous scholarship, local archives, housing research, and community-controlled knowledge.

5. Convergence, Divergence, and the Importance of Scale

Across these regions, several forms of convergence are evident. Compactness reduces exposed surface and creates mutual shade. Thick earth, stone, and masonry moderate short-term temperature fluctuation. Small or protected openings reduce solar gain. Courtyards and compounds create controlled microclimates. Flat roofs support night use where rainfall and social practice permit. Shaded transitions allow movement between interior and exterior. These recurrences reflect common physical problems but not necessarily common origins.

Settlement compactness, however, varies significantly. Saharan, Maghrebi, Iranian, and some Arabian settlements often form continuous fabrics with narrow streets. Pueblo settlements can also be compact and terraced, but through different social and historical processes. Southern African compounds and Australian Indigenous patterns may be more dispersed. Mexican colonial grids and modern desert cities introduce wider streets and larger plots. The same need for shade can therefore produce urban canyons, arcades, verandas, detached trees, or mobile occupation.

Street orientation is similarly conditional. Some settlements align routes to reduce solar exposure or admit prevailing winds, but incremental growth, defence, topography, property boundaries, and ceremonial routes may dominate. Courtyards recur widely, yet their prevalence, depth, social meaning, and water use vary. Iranian houses may contain multiple seasonal courts; Maghrebi dwellings may use compact internal patios; Mexican houses may combine service and social courts; Pueblo and southern African traditions may organise collective space differently.

Roof form reflects more than heat. Flat roofs are common where rainfall is limited and roof occupation is useful. Vaults and domes can reduce timber demand and modify heat transfer. Pitched or thatched roofs appear where seasonal rain, available vegetation, ventilation, or construction practice favours them. High-altitude Andean and Central Asian settings must address winter conditions, while humid coastal regions may require more ventilation beneath roof structures.

Wall materials demonstrate both convergence and local specificity. Earth is widespread because of availability, workability, repairability, and thermal mass. Stone dominates where geology and craft support it. Coral and imported timber appear in maritime trade centres. Sandstone produces different opening depths and surface behaviour from mud brick. Material selection is therefore environmental, economic, geological, and institutional.

Opening ratios and shading systems respond simultaneously to radiation, airflow, dust, privacy, and security. Small street openings in Maghrebi or Arabian houses cannot be explained by solar control alone. Jalis, mashrabiyas, shutters, deep reveals, colonnades, portals, verandas, and fabric shades each negotiate climate and social visibility differently. Ventilation devices range from ordinary cross-ventilation and night purging to wind towers, subterranean channels, roof vents, and shaded semi-open rooms.

Water and vegetation produce some of the strongest divergence. Where qanats, rivers, irrigation, wells, or oasis systems provide water, planted courtyards and evaporation may be integrated into cooling. Where water is scarce, architecture relies more heavily on shade, mass, timing, and controlled air movement. Vegetation can be domestic, agricultural, sacred, communal, or absent. Its climatic role depends on ownership and maintenance.

Seasonal room use is one of the most important yet least consistently documented variables. Iranian seasonal rooms, South Asian roof sleeping, Nile Valley courtyards, Pueblo roof occupation, Andean solar orientation, and southern African outdoor workspaces demonstrate that comfort often depended on movement rather than whole-building conditioning. Topography also modifies every scale: cliff, slope, valley, oasis, river edge, plateau, and underground setting alter wind, radiation, drainage, defence, and material access.

The nest method therefore changes interpretation. At the regional scale, one identifies climate, material zones, political history, and broad settlement families. At city or village scale, one examines compactness, water, topography, and street systems. At block scale, one studies party walls, shared shade, access, and density. At building scale, one examines courtyard, roof, wall, and seasonal zoning. At room scale, orientation, height, opening, and occupation become visible. At component scale, the windcatcher, screen, wall, or water surface can finally be evaluated. Removing the component from this hierarchy produces architectural pastiche rather than comparative knowledge.

1.4 Methodological Prologue: A Secondary-Data Architecture for Comparative Performance

1. Units of Analysis and Rules of Aggregation

The comparative study of vernacular cooling requires a research design that distinguishes clearly among the spatial, technical, behavioural, and institutional levels at which evidence is produced. Architectural studies often move too quickly from a measured room to a whole building, from a preserved house to an entire settlement tradition, or from satellite surface temperature to human thermal exposure. Such movement creates an ecological fallacy when relationships observed at one level are assumed to hold at another. The following sections propose a research protocol, rather than report a completed global dataset or meta-analysis. The protocol defines eight principal units of analysis: the climate grid cell, settlement, urban block, building, room, cooling component, occupant observation, and policy jurisdiction.

The **climate grid cell** is the basic unit for regional exposure data derived from gridded climate products, reanalysis, or interpolated observations. It may contain hourly or monthly estimates of air temperature, precipitation, humidity, solar radiation, wind, and potential evapotranspiration. A grid cell is useful for climate classification and cross-regional comparison, but it is not equivalent to a settlement microclimate. Its value depends on spatial resolution, topography, station density, and the extent to which urban surfaces are represented. Grid values may be aggregated to a settlement only when the settlement lies within a relatively homogeneous climatic zone or when several cells are area-weighted. They should not be assigned directly to a courtyard, street, or room without local validation.

The **settlement** is the city, town, village, oasis, or dispersed habitation system within which buildings share morphology, infrastructure, topography, water access, and regional exposure. Settlement-level variables include density, street network, vegetation, land-surface temperature, elevation, water systems, and patterns of expansion. The **urban block** is a more precise morphological unit containing attached or detached buildings, courtyards, passages, walls, and shared open space. Block-level analysis is necessary because mutual shading, party walls, street canyons, and wind obstruction cannot be inferred from an individual building alone.

The **building** is the primary architectural unit and includes form, orientation, floor area, volume, envelope, roof, openings, courtyards, services, and use. Yet a building is not thermally uniform. The **room** must therefore be coded separately when orientation, height, adjacency, occupancy, or ventilation differs. A north-facing summer room, underground chamber, roof room, and street-facing shop cannot be averaged without losing the very spatial differentiation through which vernacular cooling operated. Room observations can be aggregated to building level only when the weighting method is explicit, such as weighting by occupied hours, floor area, or number of occupants.

The **cooling component** is an identifiable physical or operational element such as a windcatcher, courtyard, shaded arcade, thick wall, roof vent, water basin, screen, subterranean chamber, or night-ventilation opening. Components should be analysed through their mechanism, dimensions, materials, connection to other spaces, and operating conditions. Their effects cannot be generalized to the building unless the component's spatial reach and operational influence are demonstrated. A measured temperature reduction near a water feature, for example, does not establish equivalent cooling in distant rooms.

The **occupant observation** is the individual or household-level record of thermal sensation, preference, adaptive behaviour, clothing, activity, room use, window operation, fan use, water use, or seasonal movement. Occupant observations cannot be averaged across households without accounting for age, health, gender, activity, tenure, and access to space. The **policy jurisdiction** is the municipality, district, province, state, or national authority governing codes, heritage rules, housing, energy, water, safety, and construction labour. Policy variables apply to the jurisdiction rather than directly to a building unless implementation and enforcement are documented.

Aggregation is permitted only where units are conceptually aligned, temporally comparable, and weighted transparently. Climate exposure may be summarized at settlement level; block geometry may be summarized across a settlement; room temperatures may be summarized at building level; and buildings may be compared within regions. Aggregation is not permitted where it erases meaningful heterogeneity, combines different seasons, merges measured and simulated values as though identical, or attributes jurisdictional policy to buildings without evidence of enforcement. Under this protocol, every observation should retain its original unit, scale, date, and evidence type before any comparative summary is calculated.

2. The Vernacular Cooling Performance Framework

The Vernacular Cooling Performance Framework, or VCPF, is the proposed analytical structure of the book. It has not been empirically validated as a scoring system. It evaluates vernacular cooling through six dimensions: **Exposure, Form, Fabric, Flow, Practice, and Translation**. These dimensions separate external climatic pressure from architectural response, material behaviour, air and moisture movement, human operation, and contemporary feasibility. The framework prevents visible form from being treated as proof of performance and allows cases from different regions to be compared through equivalent analytical questions.

Exposure records the environmental loads acting on the settlement, building, room, and occupant. Core variables include dry-bulb temperature, wet-bulb temperature, humidity, solar radiation, mean radiant conditions, wind, nighttime minimum temperature, diurnal range, hot-night frequency, dust, rainfall seasonality, altitude, and climate extremes. Exposure must be temporally explicit. Annual mean temperature is insufficient because it does not reveal whether the dominant problem is brief daytime heat, continuous humid heat, intense radiation, warm nights, or severe seasonal variation.

Form captures settlement and spatial geometry. It includes settlement compactness, street orientation, block density, building aspect ratio, courtyard proportion, surface-to-volume ratio, roof form, room depth, orientation, floor level, adjacency, and relation to topography. Form determines how solar radiation, shade, wind, and outdoor space are distributed. It should be coded at settlement, block, building, and room scales because the same building geometry can perform differently within a dense shaded fabric and an exposed suburban plot.

Fabric covers material and envelope behaviour. Variables include wall and roof material, thickness, density, heat capacity, conductivity, thermal diffusivity, time lag, decrement factor, surface colour, reflectance, glazing, opening ratio, air tightness, moisture behaviour, and deterioration. Where direct material tests are unavailable, values should be coded as estimated rather than measured. Fabric analysis must also record repair condition because cracked earth plaster, damaged roofing, replaced windows, or added cement render can substantially alter performance.

Flow captures the movement of air, heat, and moisture. It includes wind capture, cross-ventilation, stack effect, night purging, courtyard circulation, infiltration, evaporative cooling, subterranean airflow, water use, and ventilation control. Flow is not simply the presence of an opening or wind device. It requires evidence about pressure paths, inlet and outlet relationships, air velocity, outdoor air quality, humidity, and operating schedules. The framework distinguishes potential airflow from measured or simulated airflow.

Practice records occupancy, behaviour, and social adaptation. It includes room-use schedules, seasonal migration within buildings, window and shutter operation, roof sleeping, clothing, activity, cooking, water use, shading adjustment, maintenance, household size, and access to different spaces. Practice is necessary because many vernacular systems were designed to be operated rather than left static. The methodological literature confirms that occupant behaviour is central to thermal performance but is often simplified in simulations through standardized schedules.

Translation evaluates whether a vernacular principle can be applied responsibly under contemporary conditions. It includes cost, availability of skills, material supply, building codes, seismic and fire safety, sanitation, water demand, accessibility, maintenance, labour requirements, cultural acceptability, land constraints, and scalability. Translation is not a measure of historical authenticity. It asks whether a principle can be adapted without decorative imitation, excessive cost, unsafe construction, or transfer of maintenance burdens to occupants.

The VCPF does not assume that all six dimensions should be combined into one score. Their interaction is more important than their sum. High thermal mass may be beneficial under large diurnal range and effective night ventilation but harmful under hot nights. A courtyard may improve shade but fail if its geometry traps heat. A windcatcher may create airflow but introduce dust. A low-cost material may become unsuitable when labour skills disappear or seismic codes change. Comparative analysis therefore examines conditional relationships among dimensions rather than ranking features independently.

Each VCPF variable receives metadata identifying unit, scale, season, evidence type, measurement standard, uncertainty, and source. Quantitative indicators are retained in their original units before normalization. Categorical variables use controlled codebooks. Narrative observations are linked to explicit themes and evidence grades. This structure allows the framework to accommodate heterogeneous evidence without pretending that every case provides the same depth or certainty.

3. The Data Pipeline

The research pipeline begins with climate classification. Each candidate settlement is assigned Köppen–Geiger class, aridity-index category, elevation, and relevant regional classification. Where hourly data are available, additional climate clusters can be created from temperature, humidity, diurnal range, wind, radiation, and hot-night frequency. Classification is treated as a descriptive starting point rather than a design conclusion. Historical climate periods and recent periods should be retained separately where the evidence permits.

The second stage is geocoding. Settlements, buildings, blocks, and measurement sites are assigned coordinates with a recorded precision level. Heritage records may provide exact coordinates, approximate neighbourhood locations, or only settlement names. Coordinate uncertainty must be preserved. Geocoding allows cases to be linked to climate grids, elevation, land cover, urban growth, and remotely sensed morphology, but no spatial join should imply accuracy beyond the original location record.

The third stage is case identification. Cases are drawn from systematic literature searches, regional databases, heritage inventories, government reports, theses, archives, remote-sensing surveys, and community sources. Search strings should combine regional names, building types, materials, cooling strategies, and performance terms. The review protocol should follow PRISMA-style documentation of databases, dates, keywords, screening decisions, duplicates, exclusions, and final inclusion. The methodological literature shows that PRISMA-aligned screening, structured databases, iterative coding, and inter-coder reliability checks can improve transparency in architectural reviews.

The fourth stage is literature screening. Studies are included when they provide identifiable location, building or settlement description, method, and evidence relevant to at least one VCPF dimension. Studies are excluded when claims cannot be traced to a case, method, or source; when vernacular terminology is used only decoratively; or when performance claims are repeated without identifiable evidence. Screening decisions are logged with reasons. Multiple publications on the same case are linked rather than treated automatically as independent observations.

Stage five is variable coding. Two investigators should independently code the same subset of cases to test the clarity of definitions and measure agreement. If there are disagreements, they should be evaluated based on written rules that have been documented. Any numeric values that have been identified should include both the unit of measurement and all the precision originally present. Controlled vocabulary's categorical description should be utilized when encoding data in a field that contains descriptive text; however, contextual details that were found within the text field should be preserved. Version control should be used for revising the code book instead of making silent changes.

Stage six is remote sensing extraction. Where resolution is sufficient enough, settlement footprints, settlement density, percent building coverage, vegetation, elevation, albedo, street geometry and land-surface temperatures can be extracted. Remote sensing is generally used to study urban morphological characteristics such as settlement morphology, urban expansion, vegetation and the surface energy context. However, remote sensing is not treated as an actual measure of indoor comfort. Satellite-derived land-surface temperature represents radiative surface conditions seen from above and may fail to capture shaded streets, courtyards, subterranean rooms or indoor thermal behavior.

The seventh stage is harmonization of thermal metrics. Air temperature, operative temperature, mean radiant temperature, relative humidity, wet-bulb temperature, PMV, adaptive comfort exceedance, cooling degree-hours, and indoor–outdoor differentials are retained separately. Values measured under different seasons, sensor heights, or occupancy conditions are not directly pooled without adjustment. Raw outdoor climate data should accompany indoor measurements where possible. Monitoring duration, time step, sensor specification, calibration, room location, window state, occupancy, and mechanical-system use are mandatory metadata.

The eighth stage is evidence grading. Each claim is assigned both an evidence type and a quality score. The ninth stage applies comparative statistics, including descriptive distributions, matched comparisons, correlations, multilevel models, cluster analysis, and qualitative comparative analysis where sample structure permits. Statistical models should reflect nesting, such as rooms within buildings and buildings within settlements. The tenth stage uses spatial analysis to examine morphology, climate gradients, urban expansion, and regional concentration of research.

The final stage is sensitivity testing. Results are recalculated under alternative climate sources, case definitions, evidence thresholds, weighting schemes, missing-data treatments, and inclusion rules. Cases with uncertain geocoding, short monitoring periods, or uncalibrated models can be excluded in stricter specifications. The data pipeline is therefore not a single sequence leading to one fixed result, but a reproducible structure through which assumptions can be altered and their consequences inspected.

4. Integrating Heterogeneous Evidence

Vernacular cooling research contains field measurements, calibrated and uncalibrated simulations, laboratory tests, remote-sensing associations, historical descriptions, architectural surveys, occupant interviews, and expert interpretations. These sources answer different questions. A rigorous synthesis must evaluate each on its own terms before combining conclusions. Heterogeneity is not a defect to be eliminated; it is a condition to be made visible.

Measured field studies provide direct evidence of conditions in occupied or test buildings. Their strengths are ecological validity and connection to real materials, weather, operation, and occupancy. Their limitations include short monitoring periods, uncontrolled variables, sensor uncertainty, and limited generalizability. A one-week summer campaign cannot establish annual performance. A field comparison between one vernacular and one modern building may reveal a local contrast but not a universal type effect.

Calibrated simulations use measured climate, material, occupancy, and indoor data to adjust a model until it reproduces observed performance within stated criteria. They are useful for testing counterfactual changes and extending analysis beyond the monitoring period. Their credibility depends on calibration procedure, parameter transparency, model fit, and whether multiple parameter combinations could produce similar results. Calibrated simulation should not be treated as identical to measurement, but it carries stronger inferential weight than an unvalidated model.

Uncalibrated simulations use assumed or literature-derived inputs without testing against the actual building. They are valuable for parametric exploration, comparative geometry, and hypothesis generation. Their findings are conditional on assumptions about material properties, occupancy, infiltration, weather, and controls. The literature shows that simulation studies employ several platforms and often depend on estimated parameters, making transparent reporting essential.

Laboratory tests measure conductivity, density, heat capacity, moisture behaviour, strength, or other material properties under controlled conditions. They provide strong component-level evidence but do not reproduce whole-building interactions, weathering, workmanship, cracks, or occupancy. Laboratory values can inform simulations, but their transfer to historic walls requires attention to composition, moisture, thickness, and deterioration.

Remote-sensing associations relate settlement morphology, vegetation, albedo, or land-surface temperature to heat patterns. They are useful for large-area screening and comparative urban analysis. Their inferential limits are substantial. Association between compact form and lower surface temperature does not prove indoor comfort, and rooftop surface temperature cannot represent shaded pedestrian conditions or subterranean spaces. Remote-sensing evidence therefore remains at settlement or surface scale unless validated locally.

Historical descriptions provide evidence about construction sequence, seasonal use, water management, repair, household routine, and intended function. They are indispensable for interpreting how systems operated before modern monitoring. They cannot, however, quantify temperature reduction unless measurements were recorded. Historical evidence supports claims about practice and institutional organisation more strongly than claims about precise thermal performance.

Expert interpretations identify plausible mechanisms from form, craft knowledge, or engineering reasoning. They are useful where direct data are unavailable, but they remain interpretations. The literature specifically warns that logical explanations of vernacular forms may lack empirical or numerical confirmation. Expert claims should therefore be coded according to their supporting evidence rather than accepted because of disciplinary authority.

The protocol proposes a two-dimensional evidence matrix. The first dimension is evidence type. The second is quality within that type. A well-documented historical study may be high quality for social use but incapable of proving thermal magnitude. A calibrated simulation may be high quality for comparative performance but weak for actual occupant behaviour. Evidence is synthesized through triangulation when different types support the same mechanism. Quantitative pooling should be attempted only when outcomes, units, conditions, and comparison structures are sufficiently similar.

Meta-analysis is therefore selective rather than universal. Indoor–outdoor temperature differences measured during similar seasons may be pooled after standardization, but values from occupied rooms, laboratory chambers, and uncalibrated simulations should not be merged. Where quantitative pooling is inappropriate, structured narrative synthesis compares direction, mechanism, context, and evidence strength. This preserves the field's diversity without creating false equivalence.

5. Bias, Missingness, and Threats to Validity

Survivorship bias arises because the vernacular buildings available for study are rarely a random sample of those historically constructed. Durable, prestigious, maintained, protected, or wealthy buildings are more likely to survive. Failed, uncomfortable, unsafe, or poorly built examples may have been demolished or replaced. The surviving record can therefore exaggerate performance and craftsmanship. A comparative study should address survivorship bias by pairing heritage examples with ordinary housing, altered buildings, archaeological records, remote-sensing evidence, and documentation of demolished or abandoned forms where available.

Publication bias occurs when successful passive strategies, striking temperature reductions, and iconic buildings are more likely to be published than null or negative results. Missing negative results are especially serious because a failed courtyard, overheated earthen house, or ineffective windcatcher may be interpreted as poor maintenance rather than evidence against a generalized claim. The review should record whether studies report null findings, adverse effects, or unsuccessful interventions. Funnel plots or related diagnostics may be used where a sufficiently comparable quantitative sample exists, but their assumptions will be stated.

Measurement validity is threatened by inconsistent sensor placement. Temperature recorded near a floor, roof, external wall, courtyard opening, or occupied zone can differ substantially. Studies should report sensor height, distance from surfaces, shielding, calibration, sampling interval, and room use. When such information is missing, confidence is downgraded. Short monitoring periods are treated as episode-specific evidence. Studies covering only peak summer days cannot support annual claims, while annual simulations based on uncertain inputs do not automatically outweigh shorter but well-documented field measurements.

Occupancy is frequently uncertain. Historic buildings may be empty museums, partially occupied houses, tourist sites, or buildings used differently from their original function. Window operation, internal heat gains, clothing, cooking, sleeping, and room migration affect results. The framework codes occupancy as observed, reported, assumed, standardized, or unknown. Simulations based on standardized schedules are not treated as evidence of actual household behaviour.

Selective heritage documentation creates geographic and social bias. Elite houses, monumental compounds, and restored urban quarters provide detailed plans and material records, while low-income dwellings, informal settlements, women's spaces, service areas, and labour processes remain underdocumented. The case-selection strategy should therefore include ordinary and transformed housing and record whether a case is elite, communal, middle-income, low-income, institutional, or uncertain.

Urban–rural comparability is another concern. Rural buildings may have greater night-sky exposure, vegetation, land, and ventilation, while urban houses face noise, density, pollution, and heat-island effects. A vernacular strategy measured in a village cannot be assigned directly to a dense modern city. Cases should be stratified by settlement type, density, urban growth, and surrounding morphology before comparison.

The ecological fallacy appears whenever settlement-level association is interpreted as a building- or occupant-level effect. Lower neighbourhood land-surface temperature does not prove lower indoor operative temperature. High regional wind speed does not establish usable ventilation within narrow rooms. Conversely, one successful measured building does not establish settlement-wide performance. Multilevel models, nested coding, and scale-specific language should be used to avoid such inference.

Missing data is not assumed to be random. Material properties may be missing more often for deteriorated buildings, occupancy may be missing in heritage studies, and negative results may be absent from publications. The database should record reasons for missingness where possible. Multiple imputation may be used for comparative models only when the missing-data mechanism is defensible and variables contain sufficient information. Otherwise, complete-case and bounded sensitivity analyses should be reported separately.

CHAPTER 02

The Cooling Grammar

How Vernacular Buildings Control Heat

2.1 Compact Settlements, Orientation, and the Production of Shade

1. Compactness as Selective Thermal Protection

Compact settlement is one of the most frequently cited characteristics of heat-responsive architecture in arid regions. Attached buildings, shared walls, narrow streets, covered passages, arcades, recessed entrances, and shaded thresholds can reduce direct solar exposure and decrease the amount of external surface through which buildings exchange heat with the outdoor environment. Yet compactness should not be treated as a universal environmental virtue. Its thermal value depends on what is made compact, how the resulting geometry is oriented, whether air can circulate, how surfaces store heat, and when outdoor spaces are expected to be used.

At building scale, adjacency reduces the number of façades exposed to solar radiation and hot outdoor air. A detached dwelling presents most of its envelope to the external environment, whereas an attached dwelling may expose only its roof, front façade, and limited rear surface. Shared walls have lower heat gain than external walls because they separate spaces with more similar temperatures. This can reduce daily cooling loads and limit extreme interior surface temperatures. The effect is especially valuable where western façades would otherwise receive intense afternoon solar exposure.

Compactness also reduces the surface-to-volume ratio. A building or block with less external surface relative to enclosed volume generally experiences slower heat exchange than a highly articulated or detached form. This principle helps explain the prevalence of cubic volumes, party walls, deep plans, and continuous urban fabric in many historic arid settlements. However, a lower surface-to-volume ratio can also reduce opportunities for ventilation and nighttime heat release. Its value therefore depends on envelopes' properties, internal heat gains, occupancy, and access to cooler air.

At street scale, narrowness permits buildings to shade each other. The amount of direct solar radiation reaching paving, walls, doors, and pedestrians decreases as the street becomes more deeply enclosed. Covered passages intensify this effect by replacing intermittent façade shade with continuous overhead protection. Arcades and colonnades create shaded pedestrian zones while preserving a degree of visual and aerodynamic openness. Recessed entrances reduce direct solar gain at doors and create small transitional spaces between exposed streets and interiors.

Thresholds are particularly important because they mediate thermal movement between public and private space. A shaded entrance, porch, deep reveal, or covered step allows occupants to pause without standing in direct sun. Such elements also protect doors and openings from radiation, reduce glare, and permit limited ventilation with greater privacy. Their thermal contribution may be spatially small, but their social value is substantial because they support waiting, conversation, trade, surveillance, and gradual movement between indoor and outdoor conditions.

The environmental value of compactness is therefore not density in the abstract. High population or building density can coexist with exposed plazas, wide asphalt roads, heat-retaining towers, and weak pedestrian shade. Conversely, relatively low-density compounds can create extensive shade through verandas, trees, walls, and detached roof structures. Compactness becomes thermally beneficial when it reduces radiant exposure, limits unnecessary envelope area, connects shaded routes, and supports the timing of outdoor activity.

Historic compact settlements often reduced solar penetration through irregular street networks, projecting upper floors, shaded alleys, and short lines of sight. Yet these forms also responded to land tenure, security, trade, privacy, and incremental construction. Climate should not be treated as the sole explanation. The thermal question is whether the resulting geometry produces meaningful shade during the hours and seasons when people need it.

The evidence reviewed for this section shows that compact morphology can reduce solar intensity and shorten the period during which horizontal and vertical canyon surfaces receive direct sun. Comparisons in Jeddah and Makkah also suggest that compact organic fabrics may produce lower daytime temperatures than more open grid patterns. These findings support compactness as a heat-protection strategy, but they do not establish that maximum density is always desirable.

A useful distinction must therefore be made among protective compactness, neutral density, and heat-trapping density. Protective compactness provides shade, adjacency, and reduced exposure while retaining ventilation and nighttime heat release. Neutral density increases occupation without substantially changing exposure. Heat-trapping density combines high thermal storage, low airflow, anthropogenic heat, and warm nights. The design objective is not to maximize density but to create compactness whose geometric and material properties correspond to local exposure.

2. Street-Canyon Geometry and the Daily Heat Cycle

The street canyon is the space formed by building façades on opposite sides of a street. Its thermal behaviour is commonly described through height-to-width ratio, sky-view factor, orientation, façade exposure, and surface properties. These variables influence how much solar radiation enters the canyon, how long walls and paving remain shaded, how freely heat is released to the sky, and whether wind can move through the street.

The height-to-width ratio is commonly expressed as:

$$\left[H/W = \frac{\text{average building height}}{\text{street width}}\right]$$

A low ratio describes a shallow, open canyon, while a high ratio describes a narrow, deep one. Deep canyons generally provide more daytime shade because buildings obstruct a larger portion of the sun path. Shallow canyons expose more paving and façade area to direct radiation. The reviewed literature describes canyons below an H/W ratio of one as shallow, those near one as approximately balanced, and those above one as deep. It also reports substantial reductions in pedestrian heat stress where deep building shade is present.

Sky-view factor expresses the fraction of the sky hemisphere visible from a point. It ranges conceptually from zero, where the sky is almost completely obstructed, to one, where it is fully visible. A low sky-view factor usually indicates strong enclosure and daytime shading. A high value indicates openness to direct solar radiation but also greater exposure to the night sky. Height-to-width ratio and sky-view factors are related but not identical because trees, balconies, irregular roof lines, setbacks, and street orientation modify actual sky exposure.

During the day, low sky-view factor can reduce mean radiant temperature by limiting both direct sunlight and exposure to heated surfaces. This is critical because outdoor thermal comfort in hot-arid environments is often governed more by radiant load than by small differences in air temperature. A shaded pedestrian may experience substantially lower thermal stress even when weather-station air temperature remains unchanged.

At night, the same enclosure can become disadvantageous. Deep canyons restrict long-wave radiative exchange with the sky and can slow the release of heat stored in walls and paving. Narrowness may also reduce convective exchange if street orientation and urban obstruction block prevailing winds. A street that performs well at noon may therefore remain warmer after sunset. The daily value of canyon depth depends on whether daytime shade outweighs reduced nocturnal cooling.

Thermal admittance helps explain this trade-off. Surfaces with high admittance can absorb significant heat during the day and release it later. Stone, concrete, asphalt, and dense masonry may keep a shaded canyon relatively stable during short exposure but contribute to nighttime warmth after repeated hot days. Low-admittance surfaces heat rapidly but may also cool more quickly. Settlement geometry and material behaviour must therefore be analysed together.

Orientation modifies the relationship between canyon geometry and solar altitude. A north–south street receives different solar exposure from an east–west street because the sun crosses the sky relative to its façades in a different sequence. In many hot-arid studies, east–west streets perform poorly because the long street axis permits greater solar access and exposes north- or south-facing pedestrian areas according to season and latitude. North–south or diagonal orientations may create longer periods of façade-generated shade, although local solar path and wind must be examined rather than generalized mechanically.

Solar altitude changes throughout the day and year. Deep canyons may exclude high summer sun effectively but admit lower-angle winter radiation only briefly. This is beneficial in cooling-dominated settlements but problematic where winters are cold or where morning solar access is socially valuable. Seasonal design cannot be inferred from summer simulation alone.

Façade exposure also matters. A street may shade its paving while leaving upper façades exposed. Those façades absorb radiation and later exchange long-wave heat with the canyon. Projecting floors, balconies, arcades, shutters, and façade texture can reduce this load. The thermal performance of a street therefore depends not only on whether pedestrians are shaded but, on the temperature, and view of the surfaces surrounding them.

The reviewed literature identifies strong relationships among H/W ratio, sky-view factor, direct solar access, and pedestrian thermal comfort. It also notes that the same deep canyons that improve summer conditions can suppress beneficial winter sun and contribute to nighttime heat retention.
Street-canyon analysis should therefore follow the full twenty-four-hour

cycle. Midday comfort, evening release, night ventilation, and early-morning recovery should be treated as separate outcomes. The objective is not to identify one ideal aspect ratio for every arid city, but to determine the geometric range within which local shade, wind, season, and material behaviour remain balanced.

3. Shade–Wind Trade-offs Across Arid Settlement Types

Shade and wind access are both important, but settlement geometry cannot always maximize them simultaneously. Deep enclosure increases shade while potentially restricting airflow. Openness improves wind penetration but increases solar and radiant exposure. The appropriate balance varies among dense inland deserts, windy plateaus, coastal deserts, dust-prone regions, and low-density rural compounds.

In dense inland deserts, direct solar radiation is often the dominant daytime outdoor burden. Compact blocks, narrow streets, attached buildings, arcades, and covered passages can create continuous shaded movement. Low humidity may make air movement physiologically useful, but the incoming air itself can be very hot during the afternoon. In such conditions, blocking direct solar exposure may be more important than maximizing daytime wind. Ventilation becomes more valuable during evening and night when outdoor temperature falls.

The design challenge in dense inland settlements is to preserve nocturnal release. This can be supported through street alignments that connect to prevailing evening winds, periodic openings in the urban fabric, courtyards, roof-level ventilation, and variation in canyon depth. High buildings combined with moderately wide streets may preserve a useful aspect ratio while allowing more air movement than extremely narrow alleys. Urban form should create a network of shaded routes rather than one uniformly enclosed fabric.

Windy plateaus present a different balance. Strong prevailing winds and cool nights can make ventilation a central environmental resource. Street and courtyard orientation may need to capture or moderate these winds. Excessive compactness can suppress a valuable cooling mechanism, while full exposure can create discomfort, dust, or winter heat loss. Permeable block structures, controlled openings, windbreaks, and semi-enclosed spaces may be preferable to complete enclosure.

At high altitude, wind can also coincide with intense solar radiation and large diurnal range. A settlement may require shade during the day, wind protection during cold periods, and ventilation during warm evenings. Fixed geometric rules are therefore less useful than seasonal and directional control.

Streets need not be uniformly aligned to the prevailing wind; some routes may admit air while others create sheltered pedestrian zones.

Coastal deserts often have higher humidity and smaller day–night temperature ranges. Air movement is essential because evaporation from the skin becomes more difficult and thermal mass may not discharge fully at night. Extremely deep canyons can obstruct sea breezes and create stagnant humid conditions. Settlement form may therefore prioritize wind corridors, porous blocks, elevated openings, and shaded but ventilated arcades. The ideal configuration offers protection from direct sun without sealing the public realm.

The reviewed literature notes that street orientation should consider prevailing wind as well as solar exposure and that findings vary across climates. Orientations favourable in dry inland settings may not perform equally well in warm-humid environments. The implication is that orientation should be evaluated against both sun path and seasonal wind roses.

Dust-prone regions complicate the assumption that more wind is always beneficial. Strong air movement can carry sand and fine particles into streets, homes, shops, and respiratory systems. Deep streets and compact walls may protect against dust even when they reduce ventilation. Covered passages, recessed entrances, filtered openings, vegetation barriers, and indirect airflow routes can provide limited exchange without unrestricted exposure.

The timing of dust matters. A settlement may be ventilated during calm nights and sealed during daytime dust events. Adaptive operation can therefore compensate for geometric limitations. Design should include controllable rather than permanently open pathways.

Low-density rural compounds operate at another scale. Detached rooms, courtyards, livestock areas, verandas, trees, and shade structures may be dispersed across larger plots. Mutual building shade is limited, but outdoor use can shift between spaces according to sun and wind. Trees, walls, roofed work areas, and topography may provide more important protection than urban canyon depth.

In such compounds, wind access can be high, but exposed ground and roofs receive intense solar radiation. Shaded outdoor rooms, planted areas, deep verandas, and detached canopies can create local comfort without reproducing urban compactness. The settlement strategy is distributed rather than continuous: thermal protection is provided through a network of microclimates rather than a uniformly shaded street system.

A practical trade-off framework should evaluate five questions. First, when is shade most necessary? Second, when and from which direction is wind beneficial? Third, when is wind hot, dusty, humid, or cold? Fourth, how much nighttime cooling is required? Fifth, which public routes and household activities need protection? These questions prevent settlement geometry from being reduced to a single density target.

4. Surface Reflectance, Thermal Storage, and Public Shade

Surface materials influence heat through absorption, reflection, storage, conduction, and re-radiation. High-albedo roofs and paving can reduce surface temperature by reflecting a larger share of incoming solar energy, but they can also increase glare and shortwave radiation received by pedestrians and nearby façades. Low-albedo materials absorb more radiation and may release it later. Material selection must therefore be evaluated through both surface temperature and human radiant exposure.

Paving is especially important because pedestrians are close to it and because it occupies a large fraction of open urban space. Asphalt and dark stone can reach very high daytime temperatures and store heat into the evening. Lighter paving can remain cooler at the surface, but reflected radiation may increase mean radiant temperature for people standing or walking nearby. The most reflective surface is not necessarily the most comfortable one.

The evidence reviewed here illustrates this tension. Simulations have shown large reductions in peak surface temperature when pavement albedo is increased, especially in shallow canyons. Yet increased albedo can also raise reflected shortwave radiation and pedestrian thermal stress. Some studies suggest that reflective paving may work better when combined with deeper canyons or lower-reflectance walls, indicating that ground and façade materials must be designed as a system.

Colour should therefore not be used as a simple proxy for thermal performance. A white surface may have high solar reflectance when new, but dust, staining, ageing, and maintenance can alter its properties. Roughness and material composition also affect how radiation is scattered. Highly reflective glazed tiles, polished stone, and metallic finishes can produce severe glare even where surface temperature is reduced.

Maintenance is central. Cool coatings require cleaning and renewal. Light paving may darken under traffic. Vegetation can shade surfaces but requires water, pruning, and soil. Fabric awnings require repair. The thermal performance of the public realm depends on whether local institutions and households can maintain these interventions.

Thermal storage also affects the timing of outdoor use. A shaded stone plaza may remain tolerable during the day if it has not absorbed much direct radiation, but an exposed plaza can release stored heat after sunset. Asphalt roads, concrete parking areas, and masonry walls can keep evening radiant temperatures high even as air temperature begins to fall. This delays the hour at which outdoor social activity becomes comfortable.

Historic arid settlements often concentrate outdoor activity in shaded streets, courtyards, markets, thresholds, and evening spaces. The distribution of shade was therefore more important than the average albedo of the settlement. A city can have relatively reflective surfaces but remain hostile to pedestrians if shade is absent along routes to work, water, transport, school, or markets.

Public shade must be analysed as an issue of access. Arcades, trees, awnings, overhangs, and covered passages should form connected networks. A single shaded monument or commercial courtyard does not establish equitable thermal protection. The location, duration, and ownership of shade determine who can use it. Workers, vendors, children, older people, and public-transport users may depend on outdoor space during the hottest hours, while wealthier residents can retreat to conditioned interiors.

Covered circulation can provide targeted relief without requiring the entire street to be narrow. Arcades, recessed ground floors, balconies, and overhead fabrics can reduce pedestrian exposure while leaving the upper canyon more open to air movement. The reviewed research reports measurable reductions in pedestrian heat stress under arcades and shows that their proportions and relationship to canyon geometry influence performance.

An effective surface strategy therefore follows a hierarchy. Direct shade should be prioritized where people are present. Reflectance should be adjusted to reduce storage without creating excessive glare or reflected radiant load. Thermal mass should be shaded where possible. Nighttime heat release should be considered alongside daytime surface temperature. Materials should be selected with realistic maintenance and water requirements.

5. Measurable Urban-Form Variables

The evidence on settlement geometry can be translated into measurable variables suitable for GIS, remote sensing, and comparative urban analysis. These variables should represent both geometric form and environmental consequence. They should also preserve scale, because settlement averages can conceal substantial differences among neighbourhoods, blocks, and streets.

Block size can be measured through area, perimeter, length, and compactness. Small blocks may increase route choice and permeability but also expose more intersections and street surface. Large blocks may reduce external street area but create long walking distances and limit ventilation paths. Block size should be analysed together with internal courtyards, plot subdivision, and building coverage.

Built fraction is the proportion of land covered by building footprints. It can be calculated at parcel, block, neighbourhood, or grid-cell scale. A high built fraction often corresponds to lower open-sky exposure, but it does not reveal building height, courtyards, or street width. Floor-space index, ground-space index, and open-space ratio can provide a fuller description where height data are available.

Building adjacency can be represented by the proportion of building perimeter shared with neighbouring structures, number of attached sides, or average gap between buildings. Adjacency is a more direct measure of envelope protection than density alone. It can also help identify continuous fabrics, row housing, compounds, and detached development.

Street orientation can be calculated as the azimuth of street segments. Orientation distributions may be summarized through dominant direction, angular dispersion, or orientation entropy. Street orientation should then be compared with solar path and seasonal wind direction. A geometric orientation has no inherent thermal meaning until it is linked to local latitude, time, and climate.

Canyon ratio requires street width and building height. Width can be derived from road edges, building setbacks, or distance between opposite façades. Height may come from LiDAR, photogrammetry, stereo imagery, local building records, or estimated floor counts. H/W should be calculated along segments rather than assigned as one value to an entire neighbourhood.

Sky-view factor can be derived from hemispherical photography, three-dimensional city models, LiDAR, or rasterized building and vegetation surfaces. It can also be estimated from canyon geometry, although such estimates simplify irregular roof lines and trees. Separate daytime and nighttime interpretations are necessary because low sky-view factor provides shade while limiting nocturnal radiative cooling.

Tree cover can be measured through canopy area, normalized vegetation indices, local inventories, or high-resolution imagery. Canopy should be distinguished from low vegetation because overhead shade has a direct effect on pedestrian radiation. Tree-cover measures should also record species, canopy density, irrigation, and seasonal leaf conditions where possible.

Surface reflectance can be estimated from multispectral imagery or material surveys. Paving, roof, and façade reflectance should be separated because they affect pedestrians differently. Thermal admittance and heat capacity cannot be inferred reliably from colour alone and usually require material information.

Daytime and nighttime land-surface temperature can be extracted from thermal satellite data where spatial and temporal resolution permit. Daytime LST can identify highly exposed surfaces, while nighttime LST provides information on heat retention. However, LST is a surface-energy indicator rather than a direct measure of air temperature, mean radiant temperature, or indoor comfort.

The reviewed research identifies emerging workflows that combine elevation data, aerial imagery, sidewalk polygons, remote sensing, and street-network analysis to model shade and urban heat. It also notes that open-source approaches can distinguish building-generated and tree-generated shade. These methods make large-area comparison possible, especially where field data are limited.

Yet reliability remains a major concern. OpenStreetMap footprints may be incomplete or geometrically inaccurate. Street centre lines do not provide actual pedestrian width. Global elevation models may be too coarse to recover individual building heights. Informal settlements and earthen roofs can be difficult to distinguish from surrounding ground. Trees may be absent from volunteered data.

Every derived variable should therefore include data source, date, resolution, completeness, and uncertainty. A sample of reconstructed streets should be validated against field measurements, street-level imagery, cadastral plans, or high-resolution elevation data. Uncertain building heights should be expressed as ranges. Morphological variables should not be presented with greater precision than the underlying data support.

2.2 Courtyards, Transitional Spaces, and the Timing of Occupancy

1. Beyond the Courtyard as an Architectural Symbol

The courtyard is among the most recognizable features of architecture in arid and semi-arid regions. It appears in houses, palaces, religious complexes, educational buildings, caravanserais, and urban compounds across North Africa, the Middle East, Central Asia, South Asia, the Mediterranean, and parts of the Americas. Its visual persistence has encouraged a tendency to treat the courtyard as an intrinsically climatic form: an inward-looking space that automatically provides shade, ventilation, privacy, and cooling. Such an interpretation confuses typological continuity with environmental performance.

A courtyard is not a cooling device. It is an open or partially open volume whose microclimate is determined by its geometry, orientation, surface properties, degree of enclosure, relationship to the sky, connection to rooms, and method of operation. It can reduce solar exposure, collect cool night air, support ventilation, provide shaded outdoor living, and moderate indoor temperatures. It can also trap radiation, restrict air movement, accumulate humidity, transmit noise, or become an overheated void. Its performance cannot be inferred from the presence of an open central space alone.

The same plan form can behave differently in different climates. A deep courtyard in a dry inland city may remain shaded for much of the day and release heat to a cool night sky. A similarly proportioned courtyard in a coastal-arid climate may receive less nocturnal relief because warm humid nights limit heat loss. A shallow courtyard in a high-altitude dryland may admit useful winter sun but create excessive summer radiant exposure. A courtyard surrounded by low-mass construction behaves differently from one enclosed by thick earth or masonry walls. Climate category is therefore only the beginning of analysis.

The courtyard must also be understood as a social system. It can organize domestic circulation, work, cooking, childcare, religious practice, family gatherings, water collection, vegetation, and seasonal movement. Its environmental value may arise partly because it permits occupants to move between rooms and semi-open spaces as conditions change. A courtyard house does not necessarily keep every space within a narrow temperature band. Instead, it may provide a range of thermal conditions from which occupants select according to time, season, activity, gender, age, and household role.

This relationship between environmental and social performance explains why courtyards became durable in many regions. They could provide light and air while limiting external openings, supporting privacy, security, and household autonomy. The internal open space allowed rooms to face inward and created a graded sequence between street, entrance, vestibule, semi-open space, courtyard, and private room. The form therefore addressed climate and social organization simultaneously.

Yet the same social functions can constrain environmental performance. Privacy requirements may reduce the size or frequency of openings. Security grilles may obstruct air movement. Gendered spatial rules may limit who can occupy roof terraces, courtyards, or street-facing rooms. Household crowding can increase internal heat and reduce flexibility. A thermally promising geometry may not perform as intended when social use prevents openings from being operated or when the courtyard is converted to storage, circulation, parking, or service use.

The courtyard should therefore be analysed through the Vernacular Cooling Performance Framework introduced in Section 1.4. Exposure defines solar, thermal, humidity, wind, and nighttime conditions acting on it. Form records its dimensions, orientation, enclosure, and connections. Fabric describes the thermal and radiative properties of surrounding walls, roofs, paving, and shading. Flow captures wind, stack movement, evaporation, and exchange with rooms. Practice records occupation and operation. Translation evaluates whether the courtyard remains viable under contemporary plot, code, maintenance, privacy, and air-quality conditions.

2. Geometry, Enclosure, and Environmental Configuration

Courtyard geometry governs the proportion of the sky and sun visible from within space. The principal variables are plan aspect ratio, height-to-width ratio, enclosure height, orientation, opening distribution, and the relationship between courtyard area and surrounding building volume. These variables should be analysed together because a proportion that improves one process may weaken another.

The height-to-width ratio determines the depth of enclosure. A courtyard with high surrounding walls relative to its width receives less direct solar radiation and generally provides longer periods of shade. A shallow courtyard remains more exposed to the sky and sun. Research on this subject consistently associates deeper courtyards with reduced summer radiation in hot-dry conditions, although the optimum proportion varies with latitude, orientation, desired winter sun, and ventilation.

Plan shape also changes performance. A square courtyard distributes relatively evenly, while a rectangular courtyard creates different solar and wind conditions along its long and short axes. A rectangular plan may support stronger directional airflow when aligned with prevailing winds or connected to openings, but it may also expose a larger wall area to low-angle morning or afternoon sun. A square form may reduce total solar penetration in some conditions while providing less directional variation. There is therefore no universally optimal courtyard plan.

Orientation determines when each façade and part of the courtyard floor receive sunlight. In hot-dry environments, orientation is often chosen to maximize summer shade while retaining controlled winter solar access. The long axis may be aligned approximately north–south or northeast–southwest, but the value of any orientation depends on latitude, enclosure, surrounding obstruction, and seasonal use. Orientation can have a strong effect on courtyard shade while producing a smaller change in indoor air temperature where massive walls delay heat transfer.

Enclosure can be complete, partial, or porous. A fully enclosed courtyard protects against external solar exposure, dust, noise, and hot winds, but it may restrict cross-ventilation. A three-sided or U-shaped court allows stronger wind entry but is more exposed to external heat and visual intrusion. Studies of courtyard performance show apparently conflicting results: open-sided courtyards can achieve higher air velocity and lower temperature under some conditions, while fully enclosed forms may maintain a larger temperature difference from the outdoor environment. These findings are not contradictory when the competing functions of ventilation and protection are separated.

Opening distribution determines whether the courtyard is connected thermally to adjacent rooms. Large, aligned openings can allow cross-ventilation and pressure-driven exchange. High openings may support buoyancy exhaust. Low openings can admit dense cool air if outdoor or courtyard air is cooler. If all windows remain closed, the courtyard may provide shade and reduced external exposure but contribute little to room ventilation. Experimental work on courtyard ventilation found that courtyard cooling became significant when windows were opened, while closed windows produced much weaker effects.

Shading schedule is as important as permanent geometry. Fixed overhangs, fabric covers, pergolas, vegetation, screens, and arcades can reduce direct radiation during selected periods. A courtyard covered during the hottest hours and opened to the night sky after sunset may combine daytime protection with nocturnal heat release. Permanent covering can prevent radiative cooling and reduce daylight, whereas an uncovered courtyard may become overexposed during midday. Adjustable shading preserves more climatic flexibility.

Surface materials determine whether incoming heat is reflected, absorbed, stored, or re-radiated. Massive earth, brick, stone, or concrete walls can damp short-term temperature fluctuations but may release heat into the courtyard after sunset. Light-coloured surfaces can reduce absorption but may increase reflected radiation and glare. Dark surfaces absorb more solar energy and may become radiant heat sources. Paving is especially important because it can receive direct sun and remain warm after air temperature declines.

Vegetation modifies shade, radiant exposure, humidity, and airflow. Trees and vines can shade courtyard surfaces more effectively than high-albedo paving because they intercept radiation before it reaches people and materials. Yet vegetation requires soil, water, pruning, and sufficient light. Dense planting may restrict air movement or increase humidity in already humid climates. The environmental benefit depends on species, canopy, season, irrigation, and placement.

Water can provide evaporative cooling where wet-bulb temperature is low and air movement is sufficient. Pools, channels, fountains, and wetted surfaces may cool air passing over them and reduce nearby surface temperature. Their effectiveness declines with high humidity, stagnant air, or poor maintenance. Water use must also be evaluated against scarcity, sanitation, mosquito risk, and household labour. A historic fountain in an elite house cannot be treated as a universally available courtyard strategy.

The courtyard's connection to rooms completes the system. A courtyard may be surrounded by shallow rooms with direct openings, deep rooms connected through semi-open spaces, or corridors that separate the open space from occupied interiors. Airflow and radiant influence weaken with distance and obstruction. Claims about courtyard performance must therefore specify whether measurements were taken in the courtyard centre, at openings, within adjacent rooms, or in remote spaces.

3. The Daily Thermal Cycle

Courtyard performance changes continuously across the twenty-four-hour cycle. Its value cannot be established through one afternoon measurement or one daily average. Solar exposure, material temperature, air movement, sky radiation, and occupancy produce a sequence of thermal states.

During a clear dry night, courtyard surfaces can release long-wave radiation toward the sky. If outdoor air temperature falls, dense cool air may accumulate in the lower part of the enclosure. Massive walls and paving also release heat stored during the day. Whether the courtyard becomes a cool-air reservoir depends on the balance between radiative loss and stored heat. A courtyard that received limited daytime sun may cool effectively, while one whose walls and floor were highly exposed may remain warm.

The cool-air-reservoir model is therefore conditional rather than automatic. It is most plausible where the sky is clear, nights are significantly cooler than days, surfaces can view the sky, and warm indoor air is not continuously discharged into the court. The literature describes courtyards as collecting dense cool air at night and moderating conditions during the following morning, but also records instances in which courtyard or indoor temperatures remained above outdoor temperature after sunset because of thermal storage.

In the early morning, the courtyard may provide its most comfortable condition. Surfaces are relatively cool, solar altitude is low, and rooms can be flushed with air accumulated during the night. Household activities such as cleaning, food preparation, work, and social interaction can occur before strong solar exposure begins. Openings may remain open while courtyard air is cooler than the exterior.

As the sun rises, the shading pattern moves across the courtyard floor and walls. Orientation and aspect ratio determine whether the court provides morning shade, afternoon shade, or a sequence of both. High enclosure may preserve a substantial shaded zone even at midday. Occupants can move to the shaded side or occupy an iwan, veranda, or semi-open room protected from direct radiation.

During the hottest period, the courtyard may perform in several ways. A deep shaded court can remain cooler than an exposed roof or street. Massive walls may delay conductive heat flow into adjacent rooms. Vegetation and water may reduce radiant and air temperature locally. If outdoor air is hotter than courtyard air, uncontrolled ventilation can import heat. Openings may therefore need to be reduced or closed while internal and courtyard air remain cooler.

The courtyard can also support stack ventilation. Solar-heated upper air may rise and escape through the opening to the sky, drawing air from rooms or lower openings. Under other pressure conditions, wind above the roof can create suction, or cooler air can descend into the court. Which direction dominates depends on temperature differences, wind, enclosure, and the position of openings. The courtyard is not permanently an inlet or outlet.

During prolonged solar exposure, the courtyard may cease to moderate heat and instead become a radiant reservoir. Paving, walls, and glazing absorb energy and increase mean radiant temperature. Even if the air remains slightly cooler than outside, occupants may experience discomfort because surrounding surfaces are hot. This distinction explains why air-temperature measurements alone are inadequate.

After sunset, the thermal sequence depends on heat storage and ventilation. If surfaces release heat slowly, the courtyard may remain warmer than the outdoor air. Opening all rooms immediately can therefore introduce warm courtyard air rather than cooling. Effective operation may require waiting until courtyard or external air becomes cooler than indoors. Research on ventilation schedules shows that closing openings during the hottest hours and opening them during a defined night and morning period reduced indoor temperature, while opening at unsuitable times increased discomfort.

The daily cycle also changes during heatwaves. Successive hot nights can prevent full discharge of thermal mass. Water temperatures may rise, vegetation may suffer, and the courtyard's early-morning advantage may shrink. The system should therefore be evaluated across ordinary summer days, extreme events, humid periods, and transitional seasons rather than under one representative condition.

4. The Courtyard Within a Sequence of Transitional Spaces

The courtyard rarely functioned alone. Its microclimatic value was reinforced by a sequence of spaces offering different degrees of enclosure, shade, air movement, privacy, and thermal stability. These could include the iwan, riwaq, veranda, loggia, shaded roof, semi-open room, vestibule, corridor, basement, and subterranean chamber.

The **iwan** provides a deep, roofed, open-fronted space facing the courtyard. It reduces direct solar exposure while maintaining visual and aerodynamic connection to the court. Its depth and orientation determine when it is shaded and whether it captures or avoids wind. Different iwans can support different seasons or times of day.

The **riwaq**, arcade, or colonnaded edge creates a continuous shaded band around part or all the courtyards. It protects circulation and adjacent openings from direct radiation. It also forms an intermediate thermal zone between exposed court and enclosed room. The air beneath the arcade may be cooler because surrounding surfaces remain shaded, although limited ventilation can produce stagnation.

A **veranda** or **loggia** performs a similar mediating function. It supports sitting, working, sleeping, and social activity without requiring complete indoor enclosure. In coastal or windy conditions, the semi-open character can provide air movement while reducing sun. In dusty or cold periods, screens or shutters may modify its openness.

The **shaded roof** expands the thermal sequence vertically. Roofs may be used in the evening or night when the sky is open and wind speed is higher. Sleeping on roofs can take advantage of radiative cooling and air movement unavailable at ground level. Yet roof use depends on privacy, safety, dust, noise, mosquitoes, and access.

A **semi-open room** can be enclosed seasonally with screens, curtains, panels, or shutters. This allows one space to change its environmental role. It may function as an extension of the courtyard during summer and as a protected room during cooler periods. Such adaptability is often lost when contemporary construction fixes openings through permanent glazing or air-conditioned separation.

The **vestibule** and bent entrance create a graded transition from street to courtyard. Thermally, they reduce direct exchange between the public exterior and domestic interior. Socially, they protect privacy. They may also reduce dust and solar penetration. The environmental contribution lies in buffering rather than active cooling.

Basements and subterranean rooms provide the most stable thermal refuge. Their connection to the courtyard can permit cooler air exchange, indirect daylight, or access to water systems. During extreme daytime heat, occupants may retreat to these lower spaces. At night or during cooler seasons, they move upward. The house therefore operates as a vertically and horizontally differentiated thermal landscape.

This sequence matters because thermal comfort is not produced only by changing air temperature. It is produced by giving occupants options. A household may move from roof to courtyard, from courtyard to iwan, from iwan to thick-walled room, and from room to basement over the course of a day. The courtyard coordinates these options but does not replace them.

Contemporary designs often isolate the courtyard as a central void while removing this supporting spatial sequence. Rooms may open directly through large, glazed doors, transitional shade may be absent, roofs may be inaccessible, and basements may be used for services or parking. The courtyard remains visible but loses the gradation that supported adaptive occupation.

5. Adaptive Occupancy as Part of the Cooling System

Occupant behaviour should be treated as part of courtyard performance rather than as an external disturbance to architectural analysis. The environmental system includes decisions about where to sit, where to sleep, when to open windows, when to close shutters, when to shade the courtyard, when to use water, and when to retreat to more protected rooms.

Seasonal room use is one of the clearest examples. Rooms with different orientations and wall exposure may be used in summer and winter according to solar access. North-facing or deeply shaded rooms may be preferred during hot periods, while sun-facing rooms provide winter warmth. Courtyard houses can support this movement because several rooms face the same protected internal space while offering different environmental conditions.

Daily movement is equally important. Occupants may use roofs or courtyards at night, carry out morning work in the court, retreat indoors at midday, and return to semi-open spaces in the evening. A thermal survey measuring only one occupied room may therefore misrepresent household comfort. The more relevant unit is the sequence of spaces occupied across time.

Sleeping on roofs or in courtyards takes advantage of nighttime air movement and open-sky radiation. This practice can reduce dependence on mechanical cooling, but it is not universally accessible. Privacy, security, age, disability, insects, noise, and urban pollution may prevent it. Its presence in historical descriptions should not be translated into an assumption of contemporary viability.

Daytime retreat to lower or thicker-walled rooms depends on the availability of spatial depth. Large courtyard houses may include several rooms and subterranean spaces, while smaller houses offer fewer choices. Thermal adaptability can therefore be unequally distributed. Wealthier households may possess more seasonal rooms, water, vegetation, and domestic labour.

Clothing, activity, and expectations affect comfort. Loose clothing, reduced activity during peak heat, and flexible schedules can expand tolerable conditions. These adaptations should not be romanticized where they reflect limited choice or occupational inequality. Workers, caregivers, vendors, and children may be unable to avoid the hottest hours.

Fans can extend the useful range of courtyard and semi-open spaces by increasing air movement at low energy cost. Their effectiveness depends on humidity and air temperature. They can complement natural ventilation, especially when urban obstruction weakens wind. Window control remains central: openings must respond to temperature, wind, dust, noise, privacy, and security.

Household schedules determine internal heat generation. Cooking, washing, gatherings, and equipment use add heat and moisture. Moving cooking to shaded or semi-open spaces can reduce indoor gain but may expose the person cooking to outdoor heat. Environmental performance must therefore be assessed alongside the distribution of domestic labour.

Privacy and gender also affect adaptive use. The courtyard historically permitted family members to occupy outdoor space while remaining visually protected. This could support women's domestic activity and children's play, but it could also reinforce restrictions on movement outside the household. The reviewed literature identifies privacy, gender separation, security, and social gathering as major determinants of courtyard design and use.

Adaptive behaviour should therefore be documented rather than assumed. Monitoring protocols should record window and door states, room occupation, clothing, fan use, shading, water use, and household schedules. Simulations should test several operational scenarios. The courtyard's performance lies partly in the interaction between form and skilled use.

2.3 Wind-Driven Cooling: Windcatchers, Cross-Ventilation, and Subterranean Air Paths

1. A Functional Classification of Vernacular Air-Movement Systems

Vernacular ventilation in arid regions should not be reduced to the windcatcher as a single architectural object. Buildings and settlements employed families of devices that captured higher-level wind, directed air through rooms, accelerated cross-flow, exhausted buoyant air, cooled incoming air through earth or water, and allowed occupants to alter airflow according to season and time. Their shared purpose was not simply to increase ventilation. It was to move air selectively when outdoor conditions offered a useful cooling or air-quality advantage.

The first family consists of **direct wind-capture devices**. The Egyptian and wider Arab *malqaf* is generally a one-directional roof-level inlet oriented toward a prevailing wind. Its elevated opening captures air where wind speed may be higher and where the flow is less obstructed than at street level. The captured air is then directed down a shaft into an occupied room or circulation space. The one-sided form is most appropriate where wind direction is regular and predictable. When wind reverses or approaches from an oblique angle, the same opening may provide little supply or may begin to act as an exhaust.

The Persian *bādgīr*, and the related Gulf *barjeel*, belong to the broader wind-tower family but vary substantially. One-sided towers resemble directional malqafs, while two-sided, four-sided, and multi-faced towers provide openings toward several wind directions. Internal partitions divide the shaft into supply and exhaust channels. One face may receive positive wind pressure while the opposite face experiences suction. The operating direction changes as the wind shifts, allowing the tower to function under more variable wind climates.

A second family consists of **high-level intake and exhaust devices without monumental towers**. Roof monitors, ridge openings, clerestories, high-level vents, roof lanterns, and ventilated parapets can admit wind or discharge warm air. They may operate through pressure differences across a roof or through buoyancy. Their performance is usually more dependent on building geometry and roof pressure zones than that of a tall tower, but they can be integrated more easily into contemporary construction.

A third family consists of **cross-ventilation systems**. These use openings on two or more sides of a building, room, courtyard, or roof space to create a pressure-driven path. Air enters through an opening in a positive-pressure zone and exits through an opening exposed to lower or negative pressure. Cross-ventilation can occur through windows, doors, courtyards, screened galleries, aligned rooms, or roof-level outlets. Its effectiveness depends on the existence of a continuous path. A large inlet without an outlet may increase local air movement near the opening while leaving deeper areas poorly ventilated.

A fourth family comprises **single-sided ventilation systems**. These depend on airflow entering and leaving through the same façade opening or through multiple openings on one wall. Turbulent exchange, wind fluctuations, and buoyancy can move air, but the effective penetration depth is limited. Single-sided ventilation is generally less reliable for deep rooms than cross-ventilation. It remains useful where privacy, security, party walls, or dense urban form prevents openings on opposite façades.

A fifth family includes **stack-driven shafts and solar chimneys**. These systems do not primarily capture wind. They heat or exploit warm air in a vertical shaft so that buoyancy causes it to rise and discharge above the roof. The resulting negative pressure creates replacement air through lower openings. Traditional chimneys, high-level vents, courtyard stacks, and heated roof shafts can perform this function. Contemporary solar chimneys deliberately increase shaft temperature through solar absorption or glazing, making them useful when external wind is weak.

A sixth family links wind towers to **basements, subterranean rooms, earth channels, or high-mass spaces**. Incoming air may pass through a cellar, *sardāb*, underground chamber, or earth-contact duct before reaching occupied rooms. The ground and massive surfaces moderate temperature fluctuations. A wind tower may also draw cooler air from a basement upward or exhaust warm air while replacement air enters through lower, shaded paths. Performance depends on ground temperature, shaft resistance, moisture, hygiene, and the actual direction of pressure-driven flow.

A seventh family combines airflow with **qanats, water channels, wetted surfaces, porous screens, cloths, cooling pads, fountains, or sprays**. Where air passes over water in a dry climate, evaporation converts sensible heat into latent heat and lowers dry-bulb temperature. Qanat-assisted systems can couple subterranean water and cool earth with a wind tower or exhaust shaft. The reviewed literature documents windcatchers using wet cloths, water, cooling pads, sprays, and wet columns, but provides less direct comparative evidence on complete qanat–wind-tower systems.

These families should not be considered mutually exclusive. A multi-faced wind tower may capture wind through one face, exhaust through another, connect to a basement, draw air across water, and rely on buoyancy when wind weakens. A courtyard may act as a distribution chamber during one period and as an exhaust space during another. The correct classification is therefore functional: what supplies air, what drives it, where it travels, how it is modified, and where it leaves.

2. The Physics of Wind Capture, Cross-Flow, and Buoyancy

Air moves through vernacular ventilation systems because of differences in pressure, density, and momentum. Wind-driven flow begins when external wind creates unequal pressure on different building surfaces. The windward face generally experiences positive pressure, while side and leeward surfaces may experience lower or negative pressure. The size of this pressure difference depends on wind speed, wind direction, building shape, roof geometry, surface roughness, and surrounding obstructions.

External wind pressure can be represented conceptually as:

$$\Delta P_w = \frac{1}{2}\rho V^2\left(C_{p,in} - C_{p,out}\right)$$

Where (ρ) is air density, (V) is reference wind speed, and (C_p) represents the pressure coefficient at the inlet or outlet. Pressure coefficients are not fixed properties of an opening. They change with wind angle, surrounding buildings, roof form, and location on the façade.

The resulting airflow through an opening can be approximated by:

$$Q = C_d A \sqrt{\frac{2\Delta P}{\rho}}$$

where (Q) is volumetric airflow, (C_d) is a discharge coefficient, (A) is effective opening area, and (ΔP) is the magnitude of the driving pressure difference. The airflow equation gives a flow magnitude; the pressure sign determines direction. This equation demonstrates why opening size alone cannot determine ventilation. Doubling area may increase flow, but obstruction, screens, bends, partitions, and insufficient outlet area can reduce the effective discharge coefficient or pressure difference.

A windcatcher facing the wind operates as a supply device when its inlet lies in a positive-pressure zone and the building offers a lower-pressure outlet. An opening on the leeward side of the tower may operate as exhaust because suction draws indoor air upward. As wind direction changes, the pressure coefficients on each face also change. A nominal inlet can therefore become an outlet.

Wind-induced pressure can drive greater airflow than buoyancy alone when wind is sufficient; their relative contributions vary with wind speed, temperature difference, and tower geometry (Jomehzadeh et al., 2017). Wind direction is critical: pressure at a directional inlet is greatest when wind approaches approximately perpendicular to it and declines as the approach angle increases. At sufficiently adverse angles, the tower may shift from supply to chimney-like exhaust operation.

Cross-ventilation requires a pressure difference between separate openings. The inlet should face a positive-pressure zone, while the outlet should face a lower-pressure zone. Opening positions affect the airflow path. Two large openings at the same height may create rapid flow across one part of a room but leave upper or lower zones stagnant. A low inlet and high outlet can combine wind pressure with buoyancy and improve removal of warm air.

Single-sided ventilation depends more heavily on turbulence, pulsating wind, and temperature differences. Air can enter through the lower part of an opening and leave through the upper part when indoor air is warmer, or it can exchange through fluctuating eddies. The depth of effective ventilation is limited because supply and exhaust occur through closely related pressure zones. Divided windows, high and low vents, or vertical shafts can improve the separation of inlet and outlet paths.

Stack effect is created by density differences between warmer and cooler air. When indoor or shaft air is warmer than outdoor air, it becomes less dense and rises. The pressure difference increases with vertical height and temperature difference:

$$\Delta P_s \approx \rho g H \left(\frac{T_i - T_o}{T_i}\right)$$

where (g) is gravitational acceleration, (H) is the vertical separation between inlet and outlet, and (T_i) and (T_o) are absolute indoor and outdoor temperatures in kelvin; ϱ is outdoor air density. Here positive stack pressure denotes the upward driving effect when the interior is warmer than outdoors. A taller shaft can increase stack pressure, but additional height also adds friction and does not guarantee a higher room ventilation rate.

Buoyancy is especially important when solar-heated shafts, hot upper rooms, or thermal stratification create a clear vertical temperature gradient. In a solar chimney, the shaft surface is deliberately heated so that warm air rises and draws cooler air through lower openings. During hot nights, however, the flow weakens as outdoor and indoor temperatures converge and can reverse if outdoor air becomes warmer.

Thermal stratification occurs when warm air accumulates above cooler air. High ceilings and shafts can keep the hottest air above the occupied zone, but stratification provides little benefit if the warm layer cannot be exhausted. Disturbance by wind, ceiling fans, occupants, or openings can mix the layers. Whether stratification should be preserved or disrupted depends on the cooling strategy.

Turbulence influences both external pressure and indoor mixing. Real winds fluctuate continuously in speed and direction. Eddies around roof edges and neighbouring buildings can cause intermittent supply and exhaust. Steady-state calculations or simulations simplify these fluctuations and may overstate the regularity of flow.

Performance is often reported through **air-change rate**, calculated as volumetric airflow divided by room volume and expressed in air changes per hour. Air-change rate is useful for comparing ventilation capacity but does not show whether air reaches occupants, removes heat, or produces draught. A high rate can also increase heat gain if incoming air is hotter than indoor air. Airflow quality requires information about distribution, temperature, humidity, and timing.

3. Regional Typologies and the Importance of Configuration

Wind-driven devices should be compared through geometry and operation rather than treated as equivalent regional versions of one object. A malqaf, one-sided bādgīr, four-faced barjeel, roof monitor, solar chimney, and qanat-connected tower may all move air, but they differ in driving force, directional sensitivity, internal resistance, and climatic role.

One-sided towers are well suited to places with reliable prevailing wind. Their opening can be oriented directly toward the useful wind and away from hot, dusty, or undesirable directions. Their simplicity reduces internal resistance, but performance declines rapidly when wind direction changes. A reverse or cross-wind can reduce supply and cause the tower to operate as an exhaust.

Two-sided towers can provide clearer separation between windward supply and leeward exhaust. Internal partitions prevent short-circuiting and carry air toward different parts of the building. Nejat et al. (2016b) report that two-sided forms can outperform one-sided forms under variable wind angles, particularly when wing walls increase the pressure difference.

Four-sided and multi-faced wind towers are less dependent on one wind direction. At least one face may receive useful positive pressure while another experiences suction. This adaptability can be valuable where seasonal or daily wind direction varies. It also introduces complexity. Opposing streams may interfere, internal partitions increase friction, and the active supply face may change frequently.

Tower height influences exposure to roof-level wind but does not have a simple linear relationship with indoor airflow. Greater height can reach faster and cleaner air above the roof boundary layer, increase stack potential, and clear nearby obstructions. It also increases shaft friction and construction cost. The reviewed research notes that higher wind velocity at the top of a taller windcatcher did not always produce greater room ventilation, demonstrating that the full pressure and resistance path matters.

Cross-sectional area determines flow capacity, while internal partitions determine how that capacity is distributed. A larger shaft can move more air but occupies more building area and may be difficult to control. Divergent, convergent, or curved inlets change pressure recovery and resistance. Roof form around the tower also alters the local flow field.

Orientation must be evaluated against a wind rose rather than a single prevailing direction. Seasonal winds may differ from summer cooling winds. Daytime winds may be hot and dusty, while nighttime breezes are cooler.

Urban development can shift the direction or turbulence of wind reaching a tower. A historically correct orientation may no longer correspond to the contemporary wind environment.

Connection to underground or high-mass spaces changes the tower from a direct ventilation device into an air-conditioning sequence. Air moving through a basement can exchange heat with cooler earth and massive surfaces. Air passing over qanat water can be cooled and humidified. A tower connected directly to an upper room provides more immediate wind speed but less thermal moderation.

Evaporative integration produces similar trade-offs. Wet cloths, pads, sprays, and water columns can substantially reduce supply-air temperature in hot-dry conditions. The reviewed research reports large temperature reductions in some studies, although such values depend on initial humidity, water temperature, airflow, measurement location, and system configuration. The same arrangement may perform poorly in coastal humidity and may create maintenance or hygiene problems.

Urban exposure is as important as tower geometry. A wind tower in an open desert settlement, a dense low-rise fabric, and a contemporary district of taller buildings experiences different pressure fields. Historic towers were often designed to project above surrounding roofs. When new construction approaches or exceeds their height, wind speed and pressure may decline, turbulence may increase, and previously clear inlet directions may be blocked.

The literature describes this process in historic settings where urban growth, roof additions, and changing surface roughness have made old towers less effective. It also reports that newly designed devices adapted to current requirements can remain acceptable, suggesting that the principle has not failed but that its environmental context has changed.

Regional typology should therefore record tower height relative to neighbours, number of faces, plan area, partitions, inlet form, orientation, connected spaces, water use, and urban exposure. The local name identifies cultural and historical context; it does not establish performance equivalence.

4. Measured Evidence, Simulations, and the Real Building Gap

Windcatchers are among the most extensively simulated vernacular cooling devices. Computational fluid dynamics allows researchers to visualize pressure, velocity, turbulence, and temperature under controlled conditions. Wind-tunnel testing provides experimental validation at model scale, while field measurements show how systems perform under real weather and occupancy. Each method answers different questions.

CFD is useful for comparing tower forms, wind angles, partitions, wing walls, inlet geometries, and neighbouring obstructions. Researchers can hold one variable constant and test another. The reviewed literature commonly uses steady-state Reynolds-averaged Navier–Stokes models and turbulence models such as standard or RNG k–epsilon. Some studies have compared these approaches with more detailed turbulence modelling and found acceptable agreement for selected applications.

Wind-tunnel experiments provide controlled airflow around physical models. They can validate pressure coefficients and flow patterns predicted by CFD. More realistic experiments place both the tower and building within a modelled atmospheric boundary layer rather than exposing an isolated tower to uniform flow. The reviewed research reports several studies in which CFD and wind-tunnel results showed good agreement.

Field validation is less common but methodologically more important for claims about occupied buildings. Full-scale monitoring captures leakage, changing wind, thermal mass, user control, internal heat, and imperfect construction. The reviewed evidence includes a field comparison in the United Arab Emirates with a relatively small average prediction error for supply temperature and a post-occupancy study reporting measured ventilation rates that varied with wind speed, direction, and indoor–outdoor temperature difference.

Good agreement under selected conditions does not mean that idealized models reproduce all real behaviour. Many CFD studies use steady wind, constant direction, fixed openings, clean inlets, and ideal geometry. Actual buildings experience transient gusts, changing thermal stratification, occupant intervention, door movement, leakage, dust accumulation, and variable internal heat. Steady-state modelling can identify mechanisms but may miss operational instability.

Neighbouring construction is a major source of discrepancy. Buildings alter the atmospheric boundary layer, create wakes, accelerate corner flow, and shift roof pressure zones. A tower simulated in an open domain may perform differently when surrounded by taller or irregular structures. Even a geometrically accurate tower model is incomplete when the urban context is simplified.

Insect screens, privacy screens, filters, grilles, dampers, and acoustic baffles reduce effective opening area and increase pressure loss. A device that produces high airflow through an unobstructed aperture may deliver substantially less air after these elements are added. Fine filtration is especially demanding because pressure drop rises as pores become smaller or as dust accumulates.

Dust affects both indoor air quality and system maintenance. Arid winds may contain sand and fine particles, particularly during daytime or seasonal storms. Roof-level air can sometimes be cleaner than street air, but this is not guaranteed in polluted or dusty cities. Wetted media may remove some particles, yet they also require cleaning and can create mineral or microbial deposits.

Noise can travel through open shafts. Although windcatchers have no mechanical fan noise, they can transmit traffic, aircraft, commercial activity, or neighbouring voices. Privacy similarly influences whether internal outlets remain open, particularly where shafts connect directly to bedrooms or family spaces.

User control is another major uncertainty. Occupants may close openings because of heat, cold, noise, insects, security, or misunderstanding of the system. Automatic controls can improve timing but increase cost and maintenance. Post-occupancy evaluation is therefore necessary to determine whether theoretical airflow is accepted and used.

Evidence should consequently be graded. Full-scale measured studies under documented weather and operating conditions provide the strongest evidence of real performance. Calibrated transient simulations can extend those observations. Wind-tunnel and validated CFD studies provide strong evidence of aerodynamic mechanism. Unvalidated steady-state simulations remain useful for hypotheses but should not be treated as demonstrations of occupied-building comfort.

5. Filtering, Cooling, and Controlling the Air Path

Moving air is beneficial only when its temperature, humidity, cleanliness, speed, and acoustic quality are acceptable. The design task is therefore not merely to maximize airflow but to condition and control the air path.

Filtering can occur at the tower inlet, within the shaft, or at room outlets. Coarse screens can exclude birds, debris, and larger insects with modest pressure loss. Fine insect mesh, particulate filters, and acoustic media create greater resistance. Filter area should therefore be larger than the nominal shaft area, and access for cleaning or replacement must be provided. A filter placed at an inaccessible roof opening is unlikely to remain effective.

Dust separation can also use changes in direction, enlarged settling chambers, washable screens, or wet surfaces. These approaches reduce some particles but add spatial and maintenance requirements. Wet systems must be designed to avoid stagnant water, mould, mosquitoes, and mineral accumulation.

Privacy can be maintained through indirect air paths, offset grilles, high-level outlets, perforated screens, or distribution chambers that prevent direct views. These elements should be incorporated into airflow calculations. A visually secure path with excessive resistance may eliminate the ventilation benefit.

Acoustic control can use lined bends, absorptive chambers, splitters, or indirect paths. Every acoustic treatment adds pressure loss, so passive systems need generous opening area and strong driving pressure. In noisy urban settings, mechanically assisted low-velocity airflow through filtered and acoustically treated paths may be more realistic than fully passive open shafts.

Evaporative cooling should be used only where outdoor wet-bulb temperature leaves sufficient potential for cooling. Wetted cloths, porous ceramics, pads, sprays, and water columns increase humidity while reducing dry-bulb temperature. The process is valuable in hot-dry air but unsuitable when humidity is already high or when water scarcity, quality, and maintenance make it irresponsible.

Heat exchangers and phase-change materials can moderately supply air without adding moisture, but they increase technical complexity. The reviewed research describes contemporary experiments integrating heat pipes, phase-change materials, wet columns, and cooling pads. These systems can reduce supply temperature but may lower airflow or require more maintenance than traditional towers.

Control can be manual, automatic, or mixed. Manual shutters preserve user agency but require knowledge and attention. Automatic dampers can respond to wind direction, outdoor temperature, humidity, particulate concentration, and indoor carbon dioxide. Rotating or multi-faced inlets can follow changing winds. Low-energy fans can overcome filter resistance or weak pressure differences.

The controlled air path should be evaluated as a sequence: external source, capture height, inlet geometry, filtration, thermal modification, shaft, room distribution, occupant zone, and exhaust. Failure at any stage can undermine the system. Clean wind at roof level is of little value if the outlet produces a draught over one bed while leaving the remainder of the room stagnant. A cooled supply is of limited use if no exhaust path exists.

2.4 Thermal Mass, Roofs, Surface Treatments, and Evaporative Landscapes

1. Thermal Mass as a Time-Dependent Heat Strategy

Thermal mass is frequently described as though heavy materials simply keep buildings cool. This is incomplete. Mass does not eliminate heat. It absorbs stores, delays, redistributes, and later releases it. Whether that sequence improves comfort depends on the timing of outdoor heat, the temperature of the night air, the thermal properties and thickness of the envelope, the area of material exposed to indoor air, and the capacity of ventilation to remove the stored energy before the next hot period.

The heat-storage capacity of a material is determined partly by its density and specific heat. Their product, volumetric heat capacity, expresses the amount of energy required to raise a unit volume of material by one degree. Dense earth, stone, brick, and concrete can therefore absorb considerable energy without undergoing the rapid temperature rise characteristic of lightweight materials. Yet heat capacity alone does not determine performance. Conductivity controls the rate at which heat passes through the material, while thermal diffusivity describes how quickly a temperature disturbance propagates through it:

$$\alpha = \frac{k}{\rho c_p}$$

where (α) is thermal diffusivity, (k) is thermal conductivity, (ρ) is density, and (c_p) is specific heat capacity. A material with high heat capacity and relatively low diffusivity can delay the passage of a daytime heat wave through a wall or roof. This delay is commonly described as **time lag**.

Time lag is the interval between the occurrence of peak outdoor surface temperature and the resulting peak temperature at the inner surface. The **decrement factor** expresses how much the amplitude of the outdoor temperature wave is reduced as it passes through the construction. A thick massive wall can therefore shift the indoor heat peak into the evening while reducing its intensity. This is beneficial only when the delayed heat arrives after outdoor conditions have improved or when it can be removed by ventilation.

Wall thickness affects both delay and damping. Increasing thickness generally increases time lag and reduces temperature amplitude, although the relationship is not linear under all material and boundary conditions. Very thick walls can produce long time constants, but they may also remain warm if heat is not discharged. More mass is not automatically better. The material must be connected thermally to the indoor environment and exposed to a sufficiently cool sink.

Surface absorptance determines how much solar radiation is absorbed at the exterior. A dark massive wall can store more solar energy than a light-coloured wall of the same material. External shading and pale finishes can therefore reduce the heat entering the storage cycle. On the interior, furniture, linings, carpets, suspended ceilings, and impermeable finishes can isolate thermal mass from room air and reduce its ability to moderate temperature.

The most important climatic condition is nighttime relief. In a high-diurnal hot-arid climate, outdoor air and the night sky can cool the envelope after sunset. Openings, courtyards, roof vents, fans, and wind towers can then remove heat released from walls and floors. The material begins the following day at a lower temperature and can absorb another cycle of heat. The required temperature difference and duration depend on the building's mass, airflow, internal gains, and comfort target; fixed climatic thresholds should not be transferred between projects (Solgi et al., 2018).

The same mass can become detrimental where nights remain hot. If the exterior temperature does not fall sufficiently, stored heat is re-radiated and convected into occupied spaces during the evening and night. The building may remain cooler than outdoors during the afternoon but warmer during sleeping hours. Small diurnal ranges, humid coastal conditions, urban heat islands, and repeated hot nights reduce the opportunity for discharge.

Ventilation capacity is therefore as important as mass. A thick building can absorb more heat than a limited nighttime airflow can remove. When the time constant of the envelope exceeds the available cooling period, heat accumulates across successive days. Mechanically assisted night purging may restore the strategy where natural wind is inadequate, but it should be controlled using indoor and outdoor temperature, humidity, and air-quality data.

Thermal mass should consequently be evaluated through a complete heat balance: solar absorption, conduction, internal storage, indoor exposure, nocturnal release, and ventilation. Its performance is not a property of material alone. It is a timed relationship among climate, thickness, surface treatment, building operation, and occupant schedule.

2. Comparing Earth, Stone, Brick, Timber–Earth, and Modern Masonry

Material comparison in arid architecture should not be reduced to thermal conductivity. Structural capacity, moisture behaviour, seismic resistance, construction labour, maintenance, embodied carbon, availability, and local knowledge determine whether a material system remains viable. The same material can perform very differently according to density, thickness, reinforcement, workmanship, finish, and exposure.

Adobe and mud brick combine earth with water and sometimes fibres or stabilizers, formed into units and dried without firing. Thick adobe walls can provide substantial heat storage and delayed heat transfer. Their thermal conductivity is not necessarily low enough to qualify as high insulation under modern standards, but thickness and heat capacity can moderate strong daily temperature swings. Their advantages include low processing energy, local availability, repairability, and the possibility of returning material to the earth at the end of use.

Their principal vulnerabilities are water and structural weakness. Raising damp, splash, roof leakage, flood exposure, and poorly detailed openings can erode walls or reduce strength. Protective foundations, roof overhangs, capillary breaks, breathable plasters, and regular maintenance are therefore part of the material system. Cement-rich coatings can trap moisture and accelerate deterioration if they are incompatible with the underlying earth.

Unreinforced adobe is also vulnerable to seismic forces because it has limited tensile strength and can fail at corners, wall junctions, openings, and roof connections. Contemporary translation requires continuous ring beams, controlled opening placement, wall-to-roof ties, vertical or horizontal reinforcement where appropriate, lighter roofs, and engineering standards adapted to local soil and seismicity. Improving safety should not mean replacing earth automatically with high-carbon materials; it requires combining vernacular knowledge with tested structural systems.

Rammed earth is produced by compacting moist soil within formwork. It can create monolithic walls with high thermal capacity and substantial compressive strength when soil selection, compaction, wall proportions, and moisture protection are adequate. Volumetric heat capacity is the product of density and specific heat capacity and should be calculated from verified material properties. A thick rammed-earth wall can provide substantial heat storage while still offering only modest insulation. This distinction is important: thermal mass and insulation are not interchangeable.

Rammed earth generally requires less firing energy than brick or cement production, but embodied carbon rises when large quantities of cement stabilizer, reinforced-concrete foundations, or long-distance transport are introduced. Its contemporary sustainability depends on the actual mixture and supply chain rather than the label “earth.” It also requires trained crews, quality control, formwork, and soil testing. A poorly compacted wall is not equivalent to a well-executed one.

Stone provides durability, compressive strength, and high thermal capacity. In regions where stone is locally available, it can resist weathering and reduce dependence on imported products. Dense stone, however, can conduct heat readily and may remain warm through the night. Thick stone walls perform best when shaded externally and coupled to nocturnal ventilation. Their high weight increases seismic loads, and weak mortar or poor connections can make rubble construction dangerous during earthquakes.

Stone extraction, cutting, and transport can also carry substantial environmental impacts. A local dry-stone or lime-mortared wall differs materially from mechanically quarried stone transported over long distances. Repair requires knowledge of bedding, jointing, and compatible mortar. The embodied-carbon advantage of stone is therefore contextual rather than automatic.

Fired brick offers more standardized dimensions, greater water resistance, and higher compressive capacity than unstabilized mud brick. Thick brick masonry can provide thermal mass, while cavities or composite assemblies can add insulation. Firing, however, consumes energy and may cause deforestation or air pollution where kilns use inefficient fuels. Brick quality varies with clay, temperature, and production control.

Historic fired-brick buildings often used lime or earth mortars that allowed repair and moisture movement. Contemporary cement mortars can create stiffer assemblies and alter seismic behaviour. Fired brick may be suitable where durability and moisture resistance justify its energy cost, but it should not be judged independently of kiln efficiency, fuel source, wall design, and expected service life.

Timber–earth composites include timber frames with earth infill, wattle-and-daub systems, timber-laced masonry, and roofs or walls combining wood, reeds, fibres, and earthen plaster. Timber reduces weight and can improve seismic ductility, while earth provides mass, humidity buffering, fire protection to concealed elements, and repairable finishes. These systems can outperform heavy unreinforced walls during earthquakes when connections are continuous and timber is protected.

Their limitations include insect attack, decay, fire risk, scarcity of suitable timber, and the loss of carpentry skills. In many arid regions timber was historically scarce or imported, so its use was selective. Contemporary systems require responsible forestry, treatment compatible with indoor health, moisture separation, and clear fire detailing. Timber–earth assemblies require case-specific structural and hygrothermal testing; a vernacular origin does not establish superior performance.

Modern concrete and concrete-block masonry provide high compressive strength, standardization, code familiarity, and rapid construction. Concrete also has high heat capacity, but thin reinforced-concrete roofs and walls can transmit and store intense solar heat, especially when uninsulated. Concrete blocks may have lower density than solid concrete, yet their thermal performance depends on cavities, thickness, plaster, and insulation.

The major environmental concern is embodied carbon from cement and steel. Concrete can remain appropriate for foundations, ring beams, seismic frames, or moisture-resistant elements, but using it indiscriminately for the entire envelope may sacrifice local skill, repairability, and thermal adaptability. Hybrid systems can assign concrete to structural and water-critical functions while using earth, brick, insulation, shading, and ventilated layers elsewhere.

A rigorous comparison should therefore use a matrix rather than a simple ranking. Thermal capacity, conductivity, time lag, moisture tolerance, seismic safety, structural span, embodied carbon, local labour, maintenance frequency, and affordability should all be recorded. No material is sustainable merely because it is old or local, and no modern material is environmentally unsuitable in every application. Performance depends on how the material participates in the total building system.

3. Roof Geometry and the Vulnerability of the Upper Envelope

The roof is often the most thermally exposed part of a low-rise arid building. It receives high-angle solar radiation for much of the day, has little mutual shade, and may account for a large proportion of heat gain in single-storey housing. Its geometry, mass, colour, insulation, ventilation, and nighttime exposure therefore have disproportionate effects on indoor comfort.

A **flat roof** is spatially efficient and compatible with dry climates, simple structural spans, water collection, storage, work, and nighttime sleeping. Its main thermal weakness is continuous solar exposure over a horizontal surface. A massive flat roof can delay heat transfer, but if it remains warm into the night it may radiate downward into occupied rooms. Insulation above or within the roof, reflective finishes, shading, and nighttime ventilation are therefore critical.

Flat roofs also function socially. In many arid settlements they support sleeping, food preparation, drying, household work, and seasonal movement. Their environmental evaluation must include surface temperature, parapet shade, privacy, safety, wind, and long-wave radiation to the sky. Roof use may be lost when mechanical equipment, security concerns, neighbouring towers, pollution, or access restrictions make occupation difficult.

Domed and vaulted roofs change solar exposure by presenting curved surfaces at different angles to the sun. At any moment, part of the roof may receive strong radiation while another part receives less. Their greater external area can increase convective and radiative heat exchange, including nighttime long-wave release. Internally, higher ceilings permit thermal stratification, keeping warmer air above the occupied zone if high-level exhaust is available.

Curved roofs are not automatically cooler. Greater surface area can also increase total heat exchange, and uninsulated mass can store considerable energy. Their performance depends on orientation, curvature, thickness, surface colour, ventilation, and indoor height. The reviewed literature reports lower indoor temperatures in some vaulted buildings compared with flat-roofed examples, attributing the difference partly to increased convective and nocturnal radiative dissipation. Such findings should be evaluated against construction and monitoring conditions rather than generalized to all domes or vaults.

A **ventilated roof** separates the solar-exposed outer layer from the ceiling below. Air moving through the cavity removes part of the absorbed heat before it reaches the occupied space. Inlets and outlets must be positioned to support wind or buoyancy flow, and the cavity must remain free of blockage. Ventilation can be combined with reflective surfaces and insulation.

A **double roof** intensifies this principle through a distinct upper shade layer and lower weather or ceiling layer. The outer roof receives direct sun, while the lower roof remains shaded. Lightweight upper layers cool quickly and impose less structural load; heavyweight lower layers may provide thermal storage. The cooling benefit depends on the complete roof assembly, ventilation, climate, and operating conditions. Savings from an integrated passive-design package cannot be attributed to the roof alone.

A **lightweight reflective roof** rejects a large fraction of solar radiation and stores little heat. It can cool rapidly after sunset and is useful where nights remain warm enough to make heavy mass undesirable. Its weaknesses include low acoustic resistance, potential daytime overheating if reflectance deteriorates, wind uplift, condensation, and limited durability. A ceiling, insulation, or ventilated cavity is usually needed to prevent radiant heat from reaching occupants.

Roof reflectance can create a large difference in external surface temperature. The indoor benefit, however, depends on insulation, mass, ventilation, and surface ageing. A dramatic surface-temperature reduction may translate into only a modest change in operative temperature when the roof assembly already has strong insulation.

Roof parapets and openings can influence airflow. Slits, perforations, and shaped edges may create jets or pressure differences that cool roof surfaces and support nighttime occupation. Traditional Omani examples described in the literature use small parapet openings and shaped edges to increase air movement, while open roofs lose long-wave heat to the night sky. These elements should be analysed through actual wind conditions and safety requirements.

Roof selection should therefore respond to climate subtype. High mass with night discharge suits large diurnal ranges. Ventilated and double roofs suit intense solar exposure and can operate under a wider range of nighttime conditions. Lightweight reflective roofs suit rapid rejection where durability and acoustic control are addressed. Hybrid roofs can combine external shade, reflective finish, ventilation, insulation, and internal mass rather than relying on one mechanism.

4. Surface Finishes, Secondary Skins, and the Meaning of Coolness

Surface treatments alter solar absorption, moisture exchange, weather resistance, and the temperature of the envelope. Limewash, whitewash, earthen plaster, reflective coatings, screens, and secondary skins can reduce heat gain, but their value must be evaluated through human comfort and long-term maintenance rather than initial surface temperature alone.

Limewash and whitewash increase visible and solar reflectance and can lower external surface temperature. Lime-based finishes are vapour-permeable and can be compatible with earth, stone, and brick when properly formulated. They can also provide antimicrobial and weathering benefits. Their performance depends on thickness, substrate, curing, and repeated renewal.

Traditional whitewashing was commonly a maintenance cycle rather than a permanent material property. Dust, rain, abrasion, biological growth, and smoke reduce reflectance. A bright surface measured immediately after application may not represent annual performance. Maintenance labour and access to lime or pigments should therefore be included in lifecycle evaluation.

Earthen plaster protects adobe and rammed earth, regulates surface moisture, and can be repaired with local materials. Its solar absorptance depends on soil colour and additives. It may not be highly reflective, but it can reduce cracking, control erosion, and maintain vapour exchange. The thermal contribution is usually secondary to its protective and hygrothermal function.

Cool coatings use pigments or surfaces designed to reflect solar radiation, including parts of the near-infrared spectrum. They can be applied to roofs and walls without changing visible colour as dramatically as whitewash. Their initial laboratory performance may be high, but dust accumulation, ultraviolet exposure, thermal cycling, and surface wear reduce effectiveness. Contemporary projects should therefore measure aged rather than only new reflectance.

Reduced surface temperature does not always produce improved human comfort. A reflective ground or façade can redirect shortwave radiation toward pedestrians, windows, and neighbouring buildings. Glare can make outdoor spaces visually uncomfortable and increase radiant heat at eye and body level. The effect depends on surface angle, texture, canyon geometry, and surrounding shade.

A cool wall can reduce conductive heat gain while still exposing occupants to high outdoor radiation if no shade exists. Conversely, a shaded moderately absorptive wall may provide better pedestrian comfort than an exposed highly reflective one. Direct shade generally reduces both surface heating and shortwave exposure more reliably than reflectance alone.

Screens and secondary skins intercept solar radiation before it reaches the primary envelope. Mashrabiyas, jalis, shutters, lattices, woven mats, perforated panels, arcades, and contemporary ventilated façades can create a shaded cavity and reduce glare. They may also support privacy and filtered ventilation. Their geometry determines the hours of shade and the amount of air movement.

Secondary skins can be fixed or adjustable. Adjustable devices respond more precisely to seasonal sun and occupant needs but require hardware, maintenance, and user knowledge. Fixed screens are simpler but may block winter light, views, or ventilation. Dust can clog perforations and change both optical and aerodynamic performance.

A ventilated façade cavity can remove heat before it reaches the wall. Its effectiveness depends on inlet and outlet design, cavity width, wind, buoyancy, and fire safety. In high-rise or dense construction, cavity barriers and non-combustible materials are necessary. Translation from vernacular screens to contemporary façades must therefore include code, maintenance, and life-safety requirements.

Surface control should be evaluated through at least five outcomes: solar absorption, inner-surface temperature, mean radiant temperature, glare, and durability. A strategy that performs well in only one dimension should not be labelled universally cooling.

5. Evaporative Cooling, Water Infrastructure, and Landscape

Evaporative cooling uses the latent heat required to convert liquid water into vapour. When unsaturated air passes over a wet surface, part of its sensible heat is consumed by evaporation, lowering dry-bulb temperature while increasing humidity. The theoretical limit of direct evaporative cooling approaches the outdoor wet-bulb temperature. The available cooling potential can therefore be expressed approximately as the difference between dry-bulb and wet-bulb temperature.

A large wet-bulb depression indicates strong potential. A small difference indicates that the air is already humid and cannot accept much additional moisture. Evaporative systems are therefore most effective in hot-dry climates and least effective in humid coastal or monsoon periods. The reviewed research confirms this climatic limitation and notes that evaporation alone cannot reliably achieve comfort in hot-humid conditions.

Fountains and salsabils expose water to moving air and increase evaporative surface area. A salsabil directs water across a carved or inclined surface, encouraging thin-film evaporation. Their effect is strongest in shaded, ventilated spaces where cooled air can reach occupants. In still air, water may increase humidity locally without producing significant room-scale cooling.

Wetted pads and mats place a porous wet medium directly in an airflow path. Wind towers and fans can draw hot air through the medium. Their performance can be estimated through saturation efficiency, which measures how closely the outlet temperature approaches wet-bulb temperature. Higher efficiency usually requires greater contact area and controlled airflow but also increases pressure drop.

Porous jars cool stored water through evaporation from their surfaces. Their effect is local and low-volume, making them a low-water strategy for drinking-water cooling rather than whole-building conditioning. Their performance depends on porosity, air movement, humidity, and water quality.

Qanat air paths can combine cool earth, subterranean water, and pressure-driven airflow. Air passing through or above a qanat-related channel may be cooled before entering a building. The system's environmental value depends on groundwater temperature, channel cleanliness, airflow resistance, and the legal and social organization of water. It cannot be separated from the wider hydrological infrastructure that sustains it.

Planted courtyards and oasis vegetation provide shade, evapotranspiration, dust control, and lower surface temperatures. Trees intercept radiation before it reaches walls, paving, and occupants. Vegetation can therefore reduce mean radiant temperature even where its effect on air temperature is modest. The Mzab oasis landscape described in the literature historically operated as an evaporative and shaded microclimatic system.

Shade trees can provide substantial outdoor comfort with water use that varies by species, soil, irrigation method, canopy, and climate. Native or drought-adapted species may require less irrigation after establishment, but no tree is water-free. Selection must consider root damage, pollen, maintenance, seasonal shade, and survival under future heat.

Water consumption should be measured rather than described vaguely. For direct systems, relevant indicators include litres per hour, litres per occupant-hour, litres per square metre cooled, and litres per kilowatt-hour of cooling delivered. For landscapes, annual irrigation demand, source, losses, and potable-water substitution should be recorded. Such systems should therefore not be recommended without a local water budget.

Water quality affects operation. Hard water produces mineral deposits on pads, nozzles, and surfaces. Recycled or grey water may reduce potable demand but requires treatment and separation from aerosol-generating systems. Stagnant water creates odour and vector risks. Mosquito control requires movement, drainage, biological management, or physical exclusion. Legionella and other microbial hazards must be considered in sprayed or recirculating systems.

The ethics of water-intensive cooling depend on scarcity, ownership, and distribution. A private fountain may improve comfort for a small group while consuming water needed for public supply, agriculture, or ecosystems. Historical water systems often reflected unequal access and labour. Contemporary design should therefore prioritize shade, insulation, night ventilation, fans, closed-loop systems, non-potable water, and indirect evaporation before adopting continuous open-water cooling.

Indirect evaporative cooling avoids adding moisture directly to supply air by using evaporation to cool a secondary airstream or heat-exchange surface. It can be more appropriate where humidity control matters. Closed or semi-closed roof ponds and recirculating systems can reduce water loss relative to open fountains, though they still require maintenance and heat rejection. Indirect evaporative systems and contained roof ponds require separate water balances; neither should be assumed to consume less water without accounting for evaporation, leakage, and maintenance.

6. Integrated Heat Rejection and Responsible Translation

Material storage, roof form, surface treatment, airflow, moisture, and landscape should be treated as an integrated heat-management system. No single element is sufficient under extreme arid conditions, and strategies can undermine each other when they are combined without regard to timing.

A massive wall benefits from external shade because less energy enters storage. It benefits further from cool-night ventilation because stored heat can be discharged. A reflective roof reduces the energy reaching the envelope, while a ventilated cavity removes part of what remains. An interior ceiling or insulation layer then limits radiant transfer to occupants. Trees and screens protect walls and outdoor routes, reducing the demand placed on thermal mass and mechanical cooling.

Evaporative systems work best when applied selectively to already shaded or pre-cooled air. Cooling intensely heated air in direct sun requires more water. Passing air through a shaded wind tower, subterranean path, or indirect exchanger before evaporation can reduce demand. Ceiling fans can extend comfort after air temperature has been lowered modestly, avoiding the need to cool the entire space to mechanically conditioned set points.

The reviewed literature emphasizes such combinations. In Ouagadougou, a package of passive measures reduced annual cooling demand and energy use substantially, while examples from Egypt combined air capture, courtyards, evaporation, shading, insulation, and advanced glazing. These results support integration, although the reported percentages remain specific to their models, buildings, climates, and assumptions.

Translation should begin with climate and resource diagnosis. Where diurnal range is large and nights are clean and cool, thermal mass and night purge can be central. Where nights are warm, shading, insulation, reflective roofs, ventilated skins, and fans deserve greater priority. Where humidity is low but water is scarce, indirect or low-water evaporation should be used only after a transparent water assessment. Where dust is severe, surfaces and ventilation paths must be maintainable and filterable.

Safety must be incorporated from the beginning. Earthen and stone walls require seismic detailing and moisture protection. Lightweight roofs require wind resistance and acoustic control. Double skins require fire barriers and maintenance access. Water systems require drainage, hygiene, and vector control. Roof occupation requires parapets, safe access, structural capacity, and privacy.

Local skill is also a performance variable. Earth construction that depends on unavailable craftsmanship may fail despite low-carbon potential. A proprietary cool coating that cannot be renewed locally may lose its benefit within a few years. A qanat-linked system cannot be reproduced responsibly without the hydrological knowledge and community institutions that maintained it. Technology transfer should therefore support training and local supply chains rather than importing isolated forms.

Lifecycle assessment should include construction energy, maintenance materials, labour, water, service life, repairability, and end-of-life recovery. Earth may have low initial embodied carbon but require frequent plastering. Concrete may have high initial emissions but provide essential structural safety in a hybrid system. Reflective coatings may save operational energy but require repeated manufacture and application. The relevant comparison is total performance over time.

The most robust design principle is to reject heat before attempting to store or remove it. Shade roofs, walls, openings, and public spaces. Reduce absorptance where reflection will not increase human radiant exposure. Insulate highly exposed lightweight elements. Use mass only where discharge is possible. Move air only when it is thermally and hygienically useful. Use evaporation only where humidity and water ethics permit it.

The architecture of arid cooling is therefore an architecture of timing and limited resources. Mass delays heat, roofs intercept it, surfaces reject or absorb it, ventilation carries it away, water transforms sensible into latent heat, and vegetation creates shade while consuming moisture. Effective design coordinates these processes so that one strategy does not transfer heat, water demand, maintenance, or risk to another part of the system.

The enduring lesson of vernacular construction is not that thick earth, white roofs, domes, fountains, or trees are inherently sustainable. It is that environmental performance emerges from relationships among material, geometry, climate, labour, water, and use. Contemporary design must preserve that systems intelligence while subjecting every translated strategy to structural, climatic, social, and ethical evaluation.

CHAPTER 03

Does It Still Work?

Measuring Performance Across Buildings, Settlements, and Futures

3.1 Building a Global Vernacular Cooling Evidence Base

1. Defining the Review Universe and Search Strategy

The evidence base for vernacular cooling is distributed across disciplines that use different vocabularies, publication practices, and standards of proof. Architectural history may describe a courtyard, windcatcher, roof, or earthen wall through drawings and historical interpretation. Building science may test the same element through sensors, laboratory measurements, or thermal simulation. Urban climatology may evaluate settlement geometry through land-surface temperature, street-canyon models, or outdoor comfort indices. Heritage studies may document construction and repair without measuring thermal performance. Geography may analyse regional settlement patterns, while energy research may estimate cooling demand under standardized occupancy and weather assumptions. This section develops the proposed review protocol; it does not present a completed search or screened sample. A rigorous review must search across these fields rather than assume that one disciplinary database contains the relevant universe.

The review universe should include peer-reviewed journal articles, conference papers with sufficient methodological detail, books and book chapters presenting primary evidence, doctoral and master's theses, government and heritage reports, technical standards, institutional repositories, and documented post-occupancy studies. The principal disciplinary domains are architecture, architectural history, building physics, energy and buildings, urban climatology, environmental design, heritage conservation, geography, material science, housing studies, and environmental engineering. Archaeological or ethnographic studies should be included when they provide clearly documented evidence concerning construction, operation, repair, seasonal use, water management, or environmental mechanisms.

The temporal range should remain open at the lower boundary because influential measurements and design studies may predate contemporary indexing systems. Database searching should nevertheless record the years covered by each source. Searches should be repeated at defined intervals so that the evidence base can be updated rather than reconstructed from the beginning. Every search iteration should be preserved with its execution date, platform, search string, language, filters, and number of results.

The core English-language search should combine four groups of terms. The first identifies the subject, including "vernacular architecture," "traditional building," "indigenous building," "courtyard house," "windcatcher," "earth building," "adobe," "rammed earth," "passive cooling," and regionally specific device names. The second identifies climate, including "arid," "semi-arid," "hot-dry," "desert," "dryland," "cold desert," and "composite climate." The third identifies performance, including "thermal comfort," "indoor temperature," "operative temperature," "air change," "ventilation," "cooling energy," "heat transfer," "microclimate," and "post-occupancy." The fourth identifies method, including "field measurement," "monitoring," "experiment," "simulation," "CFD," "remote sensing," "laboratory test," and "historical documentation."

Search should be conducted across multidisciplinary and specialist databases, including Scopus, Web of Science, ScienceDirect, Avery Index to Architectural Periodicals, relevant engineering indexes, Google Scholar, and regional academic portals where access permits. Citation chaining should identify earlier sources cited by included studies and later studies that cite them. Repeated architectural claims should be traced backward to determine whether they originate in measured evidence, simulation, interpretation, or unverified statement reproduced across publications.

Multilingual searching is necessary because English-only review reproduces regional and linguistic inequality. Searches should therefore be conducted at minimum in English and Spanish, with French, Arabic, Persian, Portuguese, Turkish, and other regional languages added where feasible through research collaborators, translated keyword lists, regional repositories, and bilingual bibliographies. Machine translation may assist initial screening, but final extraction of technically important passages should be checked by a competent reader or against the original terminology.

Regional repositories and university thesis databases are particularly important because field campaigns, building surveys, and unsuccessful experiments may never reach internationally indexed journals. National libraries, heritage agencies, architecture schools, energy research institutes, municipal archives, and development organizations should therefore be searched separately. Theses should be eligible when they report methods, cases, and results in sufficient detail. Their inclusion should reduce dependence on journal publication while also requiring explicit quality appraisal, since institutional review standards differ.

The review should use a PRISMA-style flow structure to record identification, duplicate removal, screening, eligibility assessment, and final inclusion. The purpose of adopting systematic-review procedures is therefore not to force architectural evidence into a clinical model, but to make search and selection decisions visible, repeatable, and open to audit.

2. Eligibility Criteria and Definition of an Included Case

A study should enter the review only when it satisfies a set of substantive and methodological conditions. First, the case must be located in an arid or semi-arid climate, or in a clearly defined dry seasonal environment relevant to the book's comparative questions. Climate classification should be identifiable through the study, geographic coordinates, recognized climate maps, or linked weather data. Studies using the term "hot climate" without sufficient climatic specification should not automatically qualify.

Second, the building, settlement, urban block, room, or tested construction must be identifiable. An included study should provide a location, building type, settlement name, regional description, plan, photograph, coordinates, or equivalent information allowing the case to be distinguished from a generic design proposition. Abstract discussions of "traditional desert houses" without an identifiable case should be retained only as background literature, not as performance evidence.

Third, the study must identify at least one explicit cooling strategy or operational mechanism. Eligible strategies include settlement compactness, street shading, courtyards, thermal mass, roof forms, windcatchers, cross-ventilation, stack ventilation, evaporative cooling, vegetation, reflective surfaces, subterranean rooms, seasonal occupation, and related combinations. The study must explain what element is being evaluated rather than merely describing a building as climatic, ecological, or sustainable.

Fourth, sufficient geometry, material, or operational information must be available to interpret the claimed mechanism. For a courtyard study, this may include dimensions, height, orientation, openings, materials, or enclosure. For a wall study, thickness, composition, density, conductivity, or construction sequence may be required. For ventilation, opening area, direction, airflow path, wind conditions, or shaft geometry should be reported. Where information is incomplete, the case may be retained with a lower evidence-quality score, but it cannot support highly specific causal claims.

Fifth, the study must provide either a performance outcome or a clearly documented operational mechanism. Performance outcomes may include indoor air temperature, operative temperature, mean radiant temperature, surface temperature, humidity, wet-bulb temperature, air speed, air-change rate, comfort votes, degree-hours, cooling demand, energy use, or temperature damping. A historically documented mechanism may qualify when records or ethnographic evidence show how occupants operated spaces, water, openings, roofs, or seasonal rooms, even when no thermal measurement exists. Such evidence should support claims about use and intended operation, not numerical cooling effectiveness.

Studies should be excluded when they reproduce a claim without identifying its evidential source, use architectural appearance as proof of performance, or report only an idealized design proposal without an analysed case. They should also be excluded from quantitative synthesis when outcome definitions, baselines, or units cannot be reconstructed. Exclusion from quantitative comparison does not necessarily mean exclusion from the review; a study may remain relevant to historical interpretation, regional terminology, or hypothesis formation.

The unit of inclusion should be the **case–study observation**, not simply the publication. One article may report several buildings, rooms, materials, or scenarios. Conversely, several publications may analyse the same building. Each distinct case should receive an identifier, while publications referring to the same physical case should be linked. This prevents one well-documented heritage building from being counted repeatedly as independent evidence.

Baseline definition is mandatory for performance claims. A reduction of 4°C is interpretable only if the comparison is known: outdoor versus indoor temperature, passive case versus conventional case, pre-retrofit versus post-retrofit, or simulation scenario versus baseline model. Percentage energy savings require the original demand, set point, occupancy, system efficiency, and weather conditions. Studies reporting percentage improvement without a reconstructable baseline should be classified as incomplete quantitative evidence.

The reviewed literature emphasizes that air-temperature reductions, U-value improvements, degree-days, air-change rates, and percentage energy savings cannot be equated directly because they represent different physical outcomes and depend on different baselines. Eligibility should therefore establish whether a result is usable, while later harmonization should determine the comparisons for which it is appropriate.

3. Evidence Hierarchy and Quality Appraisal

Evidence hierarchy distinguishes the directness and reliability of performance claims without implying that one method can answer every question. Long-term monitoring is strongest for actual occupied-building behaviour, while laboratory tests may be strongest for a material property. Historical documentation may be indispensable for understanding operation even though it cannot establish an exact temperature reduction.

The highest performance category is long-term monitoring of occupied buildings. These studies measure real buildings across sufficient periods to include daily, seasonal, and operational variability. Strong examples document sensor calibration and placement, outdoor weather, occupancy, window states, mechanical systems, maintenance, and internal gains. A full year is preferable for annual claims, although a complete cooling season may support more limited conclusions. Long-term studies have high ecological validity but remain specific to their climate, building, household, and urban context.

The second category is **short-term field campaigns.** These include monitoring over days or weeks, often during hot periods or heatwaves. They can provide strong evidence of real thermal behaviour under the measured conditions, particularly when paired cases or control spaces are used. Their limitation is temporal representativeness. A campaign during a favourable dry week cannot establish performance during humid periods, hot nights, winter, or unusual occupancy.

The third category is **laboratory and full-scale experimental testing.** Laboratory studies may determine conductivity, heat capacity, moisture response, airflow resistance, surface reflectance, or evaporative performance. Full-scale test cells can compare wall, roof, or cooling systems under controlled exposure. These methods permit strong control of variables, but they may omit furniture, household behaviour, neighbouring buildings, ageing, and construction irregularity.

The fourth category is **calibrated simulation**. A simulation is calibrated when its output is tested against measured data from the same building or a closely matched physical system using a documented procedure. Calibrated models can extend a short campaign across seasons, isolate design variables, and test counterfactuals. Their strength depends on calibration targets, tolerance, parameter transparency, and validation using data not employed during calibration.

The fifth category is **uncalibrated simulation**. These studies use assumed material properties, occupancy schedules, infiltration rates, weather files, or standardized geometries without validation against the actual case. They are valuable for controlled comparison and theoretical exploration, but their numerical outcomes remain conditional. The reviewed literature identifies widespread reliance on tools such as EnergyPlus, DesignBuilder, TRNSYS, Ecotect, SIMEDIF, and Energy2D without field validation and notes that real furniture, internal mass, occupancy, and biological processes may be omitted.

The sixth category is **remote-sensing comparison**. Satellite-derived land-surface temperature, vegetation, albedo, density, and urban morphology can support settlement-scale analysis. These observations are valuable for comparing surface-energy patterns and urban form but cannot be interpreted as direct indoor or pedestrian-level comfort measurements. Remote-sensing associations require validation and careful attention to acquisition time, resolution, surface type, and atmospheric correction.

The seventh category is **historical, archival, oral, or ethnographic documentation**. Such evidence may establish that roof sleeping occurred, that openings were operated at night, that water channels were maintained, or that rooms were occupied seasonally. It supports claims about practice, transmission, and intended function. It does not by itself demonstrate the thermal magnitude of the effect.

The lowest category for performance claims is **descriptive architectural assertion**. This includes statements that a courtyard "creates comfort," thick walls "keep interiors cool," or a windcatcher "provides natural air-conditioning" without measurement, simulation, operational documentation, or traceable evidence. These statements should be recorded because their repetition shapes architectural discourse, but they should not be treated as verified findings.

Within each category, quality should be scored independently. A poorly documented field study may be less reliable than a carefully calibrated model for a particular question. Appraisal domains should include case identification, climatic documentation, measurement or model transparency, baseline validity, occupancy information, duration, uncertainty, reproducibility, and consistency between evidence and conclusion. The hierarchy indicates evidential directness; the quality appraisal evaluates execution.

4. Harmonized Extraction and Outcome Mapping

Every included case should be extracted using a common data schema. The first group records bibliographic and administrative information: publication type, language, year, authors, institution, funding source, declared conflicts of interest, and whether data, code, or model files are available. Funding and conflicts are relevant because commercial products, heritage promotion, development projects, and proprietary simulation tools may influence case selection or reporting.

The second group records location and climate. Fields include country, region, settlement, coordinates, elevation, climate classification, aridity category, urban or rural status, weather source, climate reference period, measurement season, and relevant extreme conditions. Historic buildings studied under contemporary climate should be distinguished from reconstructions of historical climate.

The third group describes the case: building or settlement type, construction date or estimated age, heritage status, preservation condition, ownership, occupancy status, floor area, number of storeys, orientation, surface-to-volume ratio, courtyard dimensions, street geometry, room location, roof form, opening ratio, and relationship to surrounding buildings. A museum, abandoned house, occupied dwelling, test cell, and hypothetical model should be coded separately.

The fourth group covers materials and envelope properties. It includes wall and roof composition, thickness, density, conductivity, heat capacity, insulation, surface finish, reflectance, glazing, moisture condition, deterioration, and whether properties were measured, taken from literature, assumed, or calibrated. This distinction is essential because an estimated earth-wall conductivity does not have the same evidential status as a laboratory-tested sample from the building.

The fifth group records occupancy and operation: number and characteristics of occupants, occupied hours, room use, clothing, activity, window and door states, fan use, shading operation, roof sleeping, seasonal movement, cooking, internal gains, and water use. Occupancy should be coded as observed, logged, reported by occupants, assumed by researchers, standardized, or unknown.

The sixth group records ventilation and mechanical systems. Fields include natural-ventilation type, opening area, airflow path, wind device geometry, measured or simulated air speed, air-change rate, filtration, insect screens, grilles, air-conditioning type, thermostat set point, operating schedule, and whether passive and mechanical systems operated simultaneously.

The seventh group documents measurement design: sensor type, accuracy, calibration, sampling interval, placement, height, distance from walls or windows, number of sensors, outdoor reference location, monitoring duration, missing data, and quality-control procedures. Short campaigns should record exact dates and weather conditions. Sensor placement is critical because a measurement near a roof, massive wall, opening, or courtyard may not represent the occupied zone.

The eighth group identifies the baseline and outcome. Outcomes should be organized into separate families: thermal state, thermal moderation, comfort, airflow, energy, envelope properties, and surface or urban effects. Indoor air temperature should not be merged automatically with operative temperature. Peak reduction should remain distinct from mean reduction. Degree-hours should retain the base and comfort threshold. Air-change rate should not be treated as a temperature benefit without evidence of the supply-air condition. Energy savings should retain units, baseline demand, set point, equipment assumptions, and whether the result is measured or simulated.

A temperature reduction, a U-value improvement, and a percentage cooling-demand reduction are not interchangeable, while adaptive and PMV-based comfort standards may classify the same indoor conditions differently. The extraction database should therefore preserve original outcomes and create harmonized variables only within defensible outcome families.

The final group records uncertainty and interpretation. It includes reported confidence intervals, sensor uncertainty, model error, parameter ranges, missing information, author-stated limitations, reviewer assessment, evidence category, and evidence-quality score. Each conclusion drawn from the resulting review should be traceable to the extracted cases and the type of evidence supporting it.

5. Publication, Language, and Survivorship Bias

Publication bias is likely because studies demonstrating large reductions, successful retrofits, or visually distinctive solutions are more attractive to journals, conferences, heritage institutions, and project sponsors. Null results, failed systems, operational problems, and uncomfortable buildings may remain unpublished. The review should therefore search theses, technical reports, retrofit evaluations, maintenance records, and post-occupancy studies in addition to journals.

Unsuccessful retrofits should be eligible when they meet the same documentation standards as successful ones. Examples may include courtyards converted into heat traps, windcatchers obstructed by neighbouring construction, cool coatings degraded by dust, earth walls damaged by inappropriate render, evaporative systems abandoned because of water or maintenance demands, or night-ventilation strategies rejected because of noise and security. These cases are important because they reveal the boundary conditions under which a physical principle ceases to be useful.

Abandoned devices and non-functioning heritage systems should also be included. Their failure may result from changed urban form, altered wind exposure, sealed openings, mechanical retrofits, loss of craft knowledge, water scarcity, or household transformation. Abandonment should not be interpreted automatically as proof that the original mechanism was ineffective, but neither should the historical presence of a device be treated as proof that it performed well.

Survivorship bias arises because well-built, wealthy, protected, and visually valued buildings are more likely to remain available for study. Poor-quality, structurally unsafe, thermally uncomfortable, or ordinary buildings may have been demolished. The resulting sample can create a circular claim: surviving architecture is assumed to have survived because it was environmentally successful, and its survival is then cited as evidence of performance.

The sample should therefore classify cases as iconic, monumental, elite domestic, ordinary domestic, low-income, rural, informal, reconstructed, abandoned, or uncertain. Analyses should report how much of the evidence comes from each category. Iconic heritage cases should be paired, where possible, with ordinary housing from the same region or climate.

Geographic and language bias should be assessed by mapping included studies by region, climate, language, and evidence type. A region represented mainly by descriptive English-language heritage articles should not be treated as equivalent to one represented by repeated occupied-building monitoring.

Selective outcome reporting should be assessed by comparing methods with published results. A study that measures temperature, humidity, comfort, and energy but reports only the favourable outcome may be at risk of reporting bias. Where protocols, theses, conference papers, and journal articles derive from the same project, their reported outcomes should be compared.

3.2 Indoor Thermal Comfort and Cooling-Energy Performance

1. Defining What Counts as Improved Performance

Claims that vernacular or vernacular-derived buildings “perform better” are meaningful only when the performance outcome, reference condition, measurement period, and building operating mode are specified. A building may reduce afternoon air temperature while remaining uncomfortably warm at night. It may provide acceptable conditions without air conditioning during ordinary summer weather but fail during a heatwave. It may lower annual cooling energy while increasing humidity, reducing daylight, or exposing some rooms to greater heat. Thermal performance must therefore be represented through several distinct outcomes rather than a single claim of climatic suitability.

Peak indoor temperature is the highest indoor air or operative temperature reached during a specified period. It is relevant to acute overheating, equipment sizing, and heat-health risk. A lower peak can indicate that thermal mass, shading, ventilation, or evaporation has moderated extreme conditions. The timing of the peak is equally important. A building that delays maximum temperature from mid-afternoon until midnight may reduce daytime exposure but worsen sleep and nighttime recovery.

The **indoor–outdoor temperature difference** compares indoor conditions with a simultaneous outdoor reference. It can show whether the envelope buffers external heat, but it is easily misused. A room temperature of 34°C should not be described as successful simply because the outdoor midday temperature reaches 42°C. The indoor condition may still be unsafe or far above an appropriate comfort limit. The comparison also depends on where outdoor temperature is measured. A shaded courtyard, exposed roof, official weather station, and street canyon provide different references.

Operative temperature is generally more suitable than air temperature for evaluating occupied interiors because it combines air temperature with mean radiant temperature. In low-air-speed conditions, it can be approximated through a weighted average of the two. Operative temperature is especially important in massive buildings, where walls and roofs may remain significantly cooler or warmer than the surrounding air. The reviewed literature recommends operative temperature as the indoor reference for comfort analysis rather than relying on dry-bulb temperature alone.

Overheating degree-hours measure both the intensity and duration of temperatures above a defined threshold. For each monitored interval, the exceedance above the threshold is multiplied by its duration and then summed. Degree-hours can distinguish a building experiencing a brief high peak from one remaining moderately overheated for many hours. The threshold must be reported because fixed and adaptive comfort models produce different results.

Adaptive comfort compliance is the proportion of occupied time during which operative temperature remains within a selected adaptive comfort band. This outcome is relevant to naturally ventilated buildings where occupants have meaningful opportunities to open windows, use fans, change clothing, adjust activity, or move between spaces. Compliance should be calculated only during occupied hours and within the climatic and operational range for which the chosen model is valid.

Nighttime recovery evaluates whether the building, its thermal mass, and its occupants receive relief after daytime heat. Relevant indicators include nighttime minimum operative temperature, hours below a recovery threshold, bedroom temperature during sleeping periods, cooling rate after sunset, and the fraction of stored heat discharged before morning. This outcome is indispensable in arid buildings that depend on night ventilation or roof sleeping.

Air speed and **air-change rate** describe different aspects of ventilation. Air speed concerns movement at the occupant and can increase convective and evaporative heat loss. Air-change rate measures the volume of outdoor air exchanged relative to room volume. A high air-change rate does not guarantee comfort if incoming air is very hot, humid, dusty, or polluted. Conversely, ceiling fans can improve comfort through elevated air speed without producing large outdoor-air exchange.

Cooling energy should be reported in measured kilowatt-hours, kilowatt-hours per square metre, or another explicit normalized unit. Percentage savings are interpretable only when the baseline system, set point, occupancy, weather, and operating schedule are known. **Peak electricity demand** records the maximum cooling-related electrical load during a defined interval. It matters because passive moderation may reduce grid stress even when annual energy savings are modest.

Finally, **hours of survivable conditions during power failure** measure thermal resilience rather than ordinary comfort. This outcome estimates how long indoor conditions remain below a health-protective threshold after mechanical cooling stops. It should account for temperature, humidity, duration, nighttime recovery, vulnerable occupants, and access to fans or ventilation. A building can fail to maintain comfort yet still prevent life-threatening exposure for substantially longer than a lightweight, highly glazed alternative. Energy efficiency, comfort, and survivability are related but should remain analytically separate.

2. Baselines, Controls, and Credible Comparisons

A credible performance claim requires an explicit counterfactual: what would indoor conditions or cooling demand have been without the vernacular strategy? Four baseline designs are particularly useful. The first is nearby contemporary housing exposed to similar weather. The second is the same building before and after a retrofit. The third is a standardized building archetype. The fourth is a calibrated counterfactual simulation in which the strategy is removed while the remaining building and operating conditions are held constant.

Comparison with **nearby contemporary housing** provides high ecological relevance when buildings experience the same climatic event. The cases should be matched as closely as possible for orientation, floor area, occupancy, internal gains, urban exposure, mechanical systems, and sensor position. Comparing a large, shaded, sparsely occupied heritage house with a small, crowded apartment does not isolate vernacular design. The contrast reflects multiple differences in wealth, use, geometry, and household density.

A **before-and-after retrofit** design controls many building-specific factors because the same structure is observed under two configurations. It is strongest when monitoring covers comparable weather periods or when weather-normalized models are applied. Changes in occupancy, appliances, ventilation behaviour, or mechanical operation must still be documented. A post-retrofit temperature reduction cannot be attributed solely to added shading if occupants also changed air-conditioning schedules.

A **standardized archetype** allows researchers to compare vernacular geometry, fabric, and airflow with a reference building under identical climate and occupancy assumptions. This design is useful for simulations and test cells but sacrifices some ecological validity. The archetype should represent a credible contemporary alternative rather than an intentionally poor baseline. Unsupported assumptions about infiltration, material properties, or thermostat settings can exaggerate the apparent advantage of the vernacular case.

A **calibrated counterfactual simulation** can provide a stronger estimate of causal contribution. The model is first calibrated against measured indoor conditions, energy use, or both. Researchers then remove or alter one component such as the courtyard, thermal mass, roof shading, or night ventilation while preserving the remaining conditions. This procedure does not reproduce a randomized experiment, but it can isolate mechanisms more convincingly than an uncalibrated comparison.

Studies should be rejected as evidence of successful cooling when they compare indoor temperature only with the outdoor midday maximum. Outdoor temperature follows a daily cycle, while heavy buildings delay and damp heat. Comparing an afternoon outdoor peak with an indoor value measured earlier, later, or in a shaded location can create a misleading temperature difference. Valid comparison requires simultaneous observations, a clearly defined outdoor reference, and analysis across the full day.

The same caution applies to claims based on **time lag**. A delayed indoor maximum is not necessarily beneficial if it occurs during sleep. Performance should include peak magnitude, peak timing, nighttime temperature, and the next morning's starting condition. Similarly, a building that remains cooler than outdoors for six hours but warmer for the following twelve hours cannot be represented by the favourable interval alone.

Baseline temperature also matters for energy savings. A naturally ventilated vernacular building may consume no cooling energy because no mechanical system is installed, but this does not prove that it provides conditions equivalent to an air-conditioned comparison building. Energy and comfort should be reported together. Zero cooling energy accompanied by extensive overheating is not equivalent to efficient comfort provision.

Mangeli, Aram, and Abouei (2024) provide an illustrative comparison in which rock-cut dwellings in a semi-arid Mediterranean setting maintained favourable summer comfort indicators without cooling, while modern comparison houses required mechanical energy to maintain comfort. It also notes that modern houses sometimes performed better in winter, demonstrating seasonal asymmetry rather than universal vernacular superiority. Such findings are valuable because they use an explicit comparison and acknowledge trade-offs.

Baseline quality should therefore be graded. Matched occupied-building comparisons and calibrated counterfactuals provide stronger evidence than unmatched examples. Test-cell comparisons provide strong component-level control but weaker household realism. Uncalibrated archetypes support conditional modelling claims. Comparisons with an outdoor maximum alone should not be accepted as evidence of indoor success.

3. Normalizing Climate, Occupancy, Building Use, and Mixed-Mode Operation

Comparisons across vernacular and contemporary buildings require normalization because indoor performance is shaped by more than architecture. Climate severity, monitoring season, solar exposure, household density, floor area, appliances, building use, mechanical operation, and sensor placement can produce differences as large as the strategy under investigation.

Climate normalization should begin with simultaneous outdoor observations and a defined reference period. Temperature outcomes may be adjusted for outdoor mean, maximum, diurnal range, cooling degree-hours, humidity, solar radiation, and hot-night frequency. Adaptive comfort analysis provides one form of normalization by linking acceptable indoor operative temperature to prevailing or running-mean outdoor temperature. Different adaptive standards, however, use different outdoor references and can produce different comfort classifications for the same building.

Monitoring season must be explicit. A two-week dry-season campaign should not support annual claims. Studies covering only mild transition periods may overestimate the fraction of time during which natural ventilation is sufficient. Where annual monitoring is unavailable, results should be classified by weather severity, including ordinary summer, heatwave, humid period, and hot-night conditions. Weather matching or regression-based adjustment can improve comparisons between different years.

Internal gains should be normalized through occupancy, lighting, appliances, cooking, equipment, and hot-water use. A sparsely occupied heritage building may remain cooler partly because it contains fewer heat sources. Reported performance should include occupant density, occupied hours, and internal-load estimates where available. For energy comparisons, cooling energy should be normalized by conditioned floor area and, where useful, occupant-hour.

Building use must also be separated. Residential, educational, office, commercial, religious, and institutional buildings have different schedules, heat gains, clothing expectations, and safety requirements. A passive strategy that performs well in a daytime office may fail in a bedroom because nighttime recovery and sleep are more important. A lecture hall may benefit greatly from ceiling fans but still require high ventilation rates for air quality.

Sensor location can alter reported results. Measurements near a massive wall, high ceiling, courtyard opening, roof, floor, or supply-air jet may not represent conditions in the occupied zone. Studies should report height, shielding, distance from surfaces, room orientation, and whether operative or globe-temperature sensors were used. Where sensor positions differ substantially, values should not be pooled without adjustment.

Mechanical-system operation is particularly important. A building classified as vernacular may contain room air conditioners, ceiling fans, evaporative coolers, or mechanically assisted ventilation. The operating schedule must be logged. Indoor temperatures recorded while air conditioning is active cannot be attributed to passive form. Likewise, a lower cooling load may result from occupants tolerating higher temperatures rather than from envelope performance.

Mixed-mode buildings require time-resolved classification. They should not be labelled simply natural or air-conditioned for an entire season. Each monitored interval should be classified as natural-ventilation mode, fan-assisted mode, passive cooling with closed envelope, mechanical cooling mode, or overlapping operation. Performance can then be evaluated separately by mode.

The comfort model should follow the operating state. Adaptive models are most defensible when occupants control openings and the indoor environment is not being maintained primarily by mechanical refrigeration. PMV-type analysis may be more relevant during tightly controlled air-conditioning periods, although local air movement and acclimatization still matter. Carlucci et al. (2018) note that mixed-mode buildings can behave more like naturally ventilated buildings than fully conditioned ones, while also acknowledging unresolved questions concerning adaptive-model application.

Passive and active systems may interact rather than operate independently. Thermal mass can shift cooling load into evening hours. Night ventilation can pre-cool the structure and reduce the following day's mechanical demand. Air conditioning can prevent night purging if occupants keep windows closed. Condenser heat can warm courtyards. Ceiling fans may permit higher thermostat settings. Mixed-mode analysis should therefore include sequence and control logic, not merely annual totals.

Normalization should be implemented through matched sampling, regression, stratification, or calibrated simulation according to data availability. At minimum, every comparison should report outdoor conditions, season, occupancy, building use, floor area, mechanical operation, and sensor location. Where these data are missing, confidence in quantitative attribution must be reduced.

4. Adaptive Comfort, Vulnerable Occupants, Sleep, and Extreme Heat

Adaptive comfort theory is essential for interpreting free-running vernacular buildings because occupants do not experience temperature independently of climate, expectation, control, and adaptation. Field studies repeatedly show that occupants in naturally ventilated buildings accept a wider range of indoor conditions than occupants in fully air-conditioned environments. Dhaka et al. (2015) and Ye et al. (2006) report seasonally varying comfort temperatures in India and broad accepted operative-temperature ranges in naturally ventilated housing in Shanghai.

Adaptive models translate this evidence into a relationship between acceptable indoor operative temperature and recent outdoor temperature. The ASHRAE approach uses prevailing mean outdoor temperature, while the European approach uses an exponentially weighted running mean. These models are intended for buildings in which occupants can influence their environment, especially through window operation, clothing, activity, and access to air movement.

This framework prevents naturally ventilated buildings from being judged solely against narrow air-conditioned set points. A room at 29°C with shade, low radiant temperature, air movement, and occupant control may be acceptable under conditions in which a sealed room at the same air temperature is not. Elevated air speed is particularly important. Ali, Martinson, and Al-Maiyah (2022) identify air movement as one of the most consistently supported comfort interventions and reports substantial reductions in overheating degree-hours when ceiling fans were introduced in two Nigerian lecture theatres.

Adaptive comfort should not, however, be used to justify exposure without limits. Standard models were developed largely from able-bodied adult populations, often in offices and under sedentary activity. They were not designed primarily around older people, infants, people with cardiovascular or respiratory illness, pregnant occupants, individuals taking heat-sensitive medication, or people with limited mobility.

The assumption of adaptive opportunities may also be false. Occupants cannot open windows safely where outdoor air is polluted, dusty, noisy, or hotter than indoors. They may lack fans during power failure. Older people or children may be unable to move between floors or operate heavy shutters. Renters may have limited control over modifications. A building should not receive adaptive credit for options for its occupants cannot realistically use.

Sleep requires separate evaluation because adaptive behaviours are reduced at night. Occupants cannot continually adjust clothing, move rooms, or monitor windows while asleep. High bedroom temperatures disrupt recovery even when daytime occupants report acceptable conditions. Examples of relevant criteria for performance evaluation are the operative temperature during nighttime; time that indoor conditions exceed sleep related limits (i.e.

hours); wind speeds and humidities inside the bedroom; and the lowest temperature experienced prior to the start of solar gain in the morning. Hot nights affect the ability to physiologically recover and to dissipate stored heat in buildings. Therefore, a building can meet daytime bands for adaptive comfort, yet still pose serious health risks if indoor temperatures do not decrease after consecutive hot days. Thus, daytime satisfaction and nighttime recovery need to be reported as separate values in performance assessments.

There is another constraint added by extreme heat. There appears to be no research on applying currently utilized adaptive comfort standards at very high ambient temperatures. It is exactly these temperatures where vulnerable populations have their highest risk. When evaluating performance outside of this validated range of data for the model, we cannot assume automatic extrapolation. In addition to validated ranges of models, we will use physiological data on heat illness, humidity levels, length of time exposed to heat, and/or local emergency response guidelines.

The concept of thermal survivability offers a complement to adaptive standards. Once there is a loss of electrical power, the goal of maintaining comfort as defined by ASHRAE Standards becomes secondary to providing protection against hazardous heat exposures. A vernacular or passive first approach needs to be evaluated based on how many hours/ days/weeks it takes for the building to drop below a safety threshold. How long does it take for the bedrooms to reach a comfortable sleeping temperature? Is there enough ventilation available to allow for safe ventilation during periods of elevated temperatures? Are there enough small power fans available to run off of backup power systems during extended outages?

Passive survivability should therefore be treated as layered protection rather than a guarantee that active systems are unnecessary.

5. Structured Meta-Synthesis of Strategy Combinations

A conventional meta-analysis requires sufficiently comparable cases, outcomes, baselines, and uncertainty estimates. The evidence summarized for this section does not meet those requirements as a single pool. It combines field surveys, monitored buildings, simulations, comfort databases, energy calculations, and resilience models. Outcomes include PMV, operative temperature, degree-hours, annual energy, air speed, and qualitative comfort. A single pooled temperature or energy effect would create false precision.

A structured meta-synthesis is therefore more appropriate. Studies are grouped by strategy combination, outcome family, baseline strength, climatic setting, and evidence type. Effect direction, consistency, and boundary conditions can then be assessed without merging fundamentally different measurements.

The most consistent pattern concerns **solar control combined with thermal buffering**. Shading, compactness, reduced exposed area, massive walls, earth contact, and controlled openings generally reduce or delay daytime heat gain. Evidence is strongest where measured occupied buildings or calibrated models compare the strategy with nearby contemporary construction or a counterfactual. The benefit is more consistent for peak-temperature moderation than for all-day comfort. Warm nights, insufficient ventilation, and high internal gains can eliminate the advantage.

A second relatively consistent combination is **thermal mass with effective nighttime ventilation**. Mass alone does not guarantee improvement, but mass combined with cool-night purging can reduce daytime peaks and overheating duration. Causal confidence is moderate where before-and-after ventilation schedules, paired buildings, or calibrated simulations isolate the interaction. Association is weaker where traditional massive buildings are simply observed to be cooler than unmatched modern buildings.

A third well-supported combination is **shade with increased air movement**, especially through ceiling fans or controllable natural ventilation. Air movement can increase comfort without reducing air temperature and can permit wider mechanical set points. The measured reductions in overheating degree-hours reported for fan-assisted Nigerian spaces support a real comfort benefit, although the magnitude cannot be transferred directly to residences or other climates.

A fourth pattern is **courtyard or transitional-space systems combined with timed openings and occupant movement**. The courtyard alone has inconsistent effects. Performance improves when geometry provides shade, rooms remain connected to useful airflow, openings are controlled according to the daily cycle, and occupants can move among thermal zones. Evidence is often associative or simulation-based, and causal confidence is lower than for directly tested air-movement or envelope interventions.

A fifth pattern is **passive-first mixed-mode operation**. Shading, mass, ventilation, fans, and adaptive set points can reduce the hours during which refrigeration is required. Energy savings depend strongly on the comfort model and set point, so comparisons must use equivalent comfort criteria and explicit operating assumptions (Attia and Carlucci, 2015).

A Mediterranean hybrid case described in the evidence achieved approximately half the annual energy consumption of the traditional comparison configuration after combining vernacular principles with targeted technological upgrades. This is a useful case-specific result, not a general pooled estimate, because cost, renewables, baseline condition, and climate shaped the outcome.

A sixth pattern concerns **thermal resilience during outages**. Massive, shaded, naturally ventilated buildings tend to warm more slowly than lightweight, highly exposed buildings. Operable windows, reduction of internal loads, fans, and thermal storage can extend survivable conditions. Yet passive systems may not maintain full comfort during prolonged extreme heat. The reviewed research also reports low comfort compliance in naturally ventilated pilot buildings in Burkina Faso, showing that passive construction alone does not assure acceptable conditions in severe climates.

The meta-synthesis therefore supports combinations rather than isolated devices. The most consistent reductions in overheating arise when solar gain is first limited, thermal storage is matched to nighttime discharge, and air movement is available at occupant level. The most consistent energy reductions arise when these measures are combined with widened but safe comfort bands, ceiling fans, controlled natural ventilation, and efficient mechanical backup. Evidence for precise causal magnitudes remains limited because many studies lack matched controls, long-term monitoring, or calibrated counterfactuals.

3.3 Neighborhood Microclimate: Historic Cores, Modern Expansion, and Urban Heat

1. Comparing Historic, Modern, Informal, Industrial, and Peri-Urban Districts

The thermal advantages attributed to vernacular urbanism are often inferred from the appearance of compact historic settlements: narrow streets, attached buildings, shaded courtyards, small plots, and massive construction. At neighbourhood scale, however, these features interact with vegetation, paving, topography, traffic, household income, building condition, and urban expansion. A historic core cannot be compared credibly with a modern district merely by contrasting their average satellite temperatures. The units, weather conditions, surface composition, observation times, and socioeconomic contexts must be made comparable.

Five broad urban conditions are relevant to the analysis. **Historic cores** generally contain compact blocks, attached buildings, high built fractions, narrow streets, low sky-view factors, mixed roof materials, and substantial masonry or earth construction. Their public spaces may be strongly shaded, but vegetation can be limited and nocturnal heat release restricted. **Planned modern districts** commonly contain wider roads, detached or freestanding buildings, larger setbacks, lower building adjacency, and greater exposure of paving and façades. Their openness may increase daytime solar gain but improve wind access and nighttime long-wave exchange.

Informal expansion is more heterogeneous. Some informal districts reproduce compact, attached fabrics with narrow lanes, while others consist of low-density self-built structures on exposed land. Roofing may include corrugated metal, concrete slabs, reused materials, or unfinished masonry. Tree cover, infrastructure, drainage, and public shade are often limited. Informal settlements should not therefore be classified thermally through density alone. A dense informal district with metal roofs and little vegetation can behave differently from a dense historic masonry district.

Industrial zones tend to contain large roof areas, warehouses, paved yards, storage surfaces, machinery, transport activity, and limited tree cover. Their building fraction may be moderate, but roof and ground materials can produce high daytime land-surface temperatures. Waste heat from industrial activity, vehicles, refrigeration, and mechanical equipment may also raise air temperature independently of urban geometry. **Peri-urban settlements** often combine exposed soil, incomplete roads, detached housing, construction sites, agricultural remnants, and rapidly changing land cover. Their thermal condition may shift quickly as bare soil is paved, trees are removed, roofs become concrete, and building density increases.

Comparison across these conditions requires a common spatial unit. Administrative districts are often unsuitable because their sizes and land uses differ. The preferred unit should be a regular grid, a Local Climate Zone polygon, or a matched neighbourhood area containing sufficiently homogeneous urban form. Grid cells in the range of several hundred metres can correspond reasonably well to neighbourhood-scale morphology, although the final resolution must reflect the available satellite, building, and census data.

Each spatial unit should be classified by dominant land cover and structure rather than historical identity alone. A historic district may contain restored monuments, congested commercial streets, vacant buildings, and modern infill. A planned district may include mature trees and shaded apartment courts. The labels “historic” and “modern” remain analytically useful, but they should not substitute for measured morphology.

Climate controls are equally important. Neighbourhoods should be compared under the same satellite overpass, weather event, season, or monitoring period. Elevation, distance from water, prevailing wind exposure, soil moisture, and position within the wider city should be controlled statistically or through matching. A historic core located in a low-lying, congested centre should not be compared directly with a modern district on a cooler elevated plateau without accounting for altitude.

The reviewed literature indicates that elevation can influence intra-urban temperature and that socioeconomic, behavioural, and building differences complicate the relationship between outdoor and indoor heat. These factors are not peripheral. Lower-income districts may have less vegetation, more exposed roofs, higher occupancy, fewer cooling resources, and weaker maintenance, while wealthier districts may contain irrigated landscapes and mechanically cooled interiors that reject waste heat outdoors.

A consistent comparison should therefore record district type, Local Climate Zone, built fraction, building height, roof material, street geometry, vegetation, impervious cover, elevation, anthropogenic heat indicators, and socioeconomic location. Only after these variables are established should historical or vernacular status be tested as an additional explanatory factor. The research question is not whether all historic cores are cooler, but whether particular features associated with historic urbanism continue to produce measurable thermal effects after climate and context are controlled.

2. Land-Surface Temperature Is Not Human Heat Exposure

Satellite-derived land-surface temperature is one of the most widely available tools for comparing urban heat across large areas. Thermal sensors estimate the radiative temperature of surfaces visible from above, including roofs, roads, bare soil, vegetation canopies, and water. These observations are valuable for identifying spatial patterns, tracing urban expansion, and comparing material transitions across neighbourhoods. They are not direct measurements of the air people breathe, the radiation they experience within streets, or the temperature inside buildings.

Land-surface temperature, or LST, describes the radiative condition of the visible surface skin. **Air temperature** describes the thermal state of the atmosphere at a specified height and location. **Mean radiant temperature** represents the combined radiant influence of surfaces and solar exposure on a person. **Human heat exposure** additionally depends on humidity, air speed, clothing, metabolic activity, duration, health, and access to shade. These outcomes are related, but they are not interchangeable.

The distinction is especially important in compact neighbourhoods. Satellite sensors observe warm roofs and upper surfaces more clearly than shaded walls, arcades, streets, and courtyards. A compact district may therefore appear thermally hot from above even while pedestrians move through shaded canyons with lower radiant exposure. Conversely, a light-coloured roof may appear cool in satellite imagery while people at street level experience severe reflected radiation from exposed walls and paving.

Two-dimensional thermal imagery can therefore overstate daytime pedestrian heat in compact fabrics when it primarily records sunlit roofs rather than shaded occupied spaces.

Satellite observations also cannot resolve many thermal extremes relevant to health. Narrow streets, shaded thresholds, bus stops, metal roofs, playground surfaces, and individual courtyards can vary sharply over distances smaller than a satellite pixel. The satellite records an aggregate radiative signal rather than the thermal experience of a person within one microclimate.

The discrepancy between LST and air temperature changes across the day. During strong sunlight, dark roofs and bare soil may become much hotter than the air. At night, surfaces and air can converge more closely, but material storage, wind, and sky exposure still create differences. Satellite overpass timing is therefore crucial. A late-morning image cannot establish evening or nocturnal performance.

Cloud cover and atmospheric correction create further constraints. Thermal imagery is often available only under clear-sky conditions, which may overrepresent weather types. Emissivity assumptions differ across roofs, soil, vegetation, and mixed pixels. Resolution can also change historical comparisons when older sensors provide coarser data than newer ones.

LST remains useful when interpreted at the correct scale. It can identify exposed industrial roofs, hot peri-urban soil, cooler irrigated vegetation, material transitions, and broad daytime or nighttime surface patterns. It can support matched comparisons when neighbourhoods are observed under the same atmospheric conditions. It can also reveal whether redevelopment replaces shaded, permeable, or vegetated land with heat-storing surfaces.

Validation is required before LST is interpreted as pedestrian or indoor exposure. At minimum, satellite observations should be compared with ground-based air-temperature loggers, globe or radiant-temperature measurements, mobile transects, weather stations, or three-dimensional surface models. Pedestrian-comfort analysis should incorporate shade, humidity, and wind through indices such as UTCI, PET, or equivalent measures. Indoor inference requires building information and direct indoor monitoring.

The reviewed research notes that satellite LST may substantially overestimate urban–rural heat-island magnitude relative to air-temperature measures and that the relationship between LST and indoor conditions is mediated by building type, behaviour, neighbourhood, elevation, and socioeconomic status. Satellite evidence should therefore be described as evidence of **surface thermal pattern**, not as proof of comfort, health exposure, or building performance.

A rigorous urban analysis should maintain parallel outcome families: daytime LST, nighttime LST, screen-height air temperature, pedestrian mean radiant temperature, outdoor thermal stress, and indoor operative temperature. Agreement among these outcomes strengthens interpretation. Disagreement is not an error to be concealed; it reveals the mechanisms through which geometry, material, and occupation redistribute heat.

3. Daytime Cooling and Nocturnal Heat Retention

A recurring neighbourhood-scale pattern is a day–night reversal. Compact masonry districts can be cooler by day because streets, walls, and pedestrians receive less direct solar radiation. The same districts can remain warmer at night because their surfaces store heat, ventilation is restricted, and a limited view of the sky reduces long-wave radiative loss.

During the day, attached buildings reduce exposed wall area. Narrow streets and high height-to-width ratios create mutual shade. Lower sky-view factors reduce the duration of direct solar penetration. Massive walls and paving absorb heat without producing immediate increases in air temperature. These mechanisms can make historic cores function as daytime heat sinks relative to exposed suburban or peri-urban districts.

The daytime advantage is often clearest in pedestrian mean radiant temperature rather than air temperature. Shade can dramatically reduce radiant heat even where air-temperature differences between districts are small. A neighbourhood may therefore be warmer in air-temperature terms yet more tolerable for pedestrians during direct sun.

At night, the balance changes. Thick masonry, stone, asphalt, and concrete release heat accumulated during the day. Narrow streets restrict long-wave radiation to the sky. Dense roofs and walls increase the amount of stored energy within the urban canopy. Wind speed may decline because compact form increases aerodynamic roughness and blocks low-level airflow.

The resulting nocturnal heat island is especially important for residential exposure. People return home, attempt to sleep, and lose many of the behavioural options available during the day. A shaded commercial street that performs well at noon may be irrelevant if surrounding bedrooms remain hot until dawn. Daytime and nighttime performance must therefore be reported as separate outcomes.

Historic districts are not guaranteed to follow one pattern. Where streets are extremely shaded and surfaces absorb little heat, nighttime storage may be reduced. Where roofs are reflective or ventilation channels remain open, nocturnal cooling may improve. Conversely, contemporary districts with concrete slabs, asphalt, air-conditioning exhaust, and little vegetation may remain hot both day and night.

The reviewed research characterises hot-desert cities through a "daytime heat sink and nighttime heat island" pattern and notes that new urban districts can be warmer by day than compact historic cores. This should be understood as a common configuration rather than a universal law.

Day–night analysis requires observations at comparable times. Daytime satellite data should be paired with nighttime imagery where possible. Fixed sensors should report hourly trajectories rather than daily means. Useful outcomes include maximum daytime LST, daytime air temperature, peak mean radiant temperature, sunset cooling rate, midnight air temperature, pre-dawn minimum, and the duration of nocturnal heat.

The timing of outdoor use should also be considered. Historic urbanism may protect markets, streets, and thresholds during the afternoon while supporting social activity after sunset. If nocturnal warming delays comfortable evening use, part of the settlement's social adaptation is weakened. Urban heat therefore affects not only temperature but the temporal accessibility of public space.

Vegetation can modify the day–night balance. Tree shade reduces daytime surface heating and therefore the amount of energy released later. Dense canopies can, however, reduce night-sky exposure and restrict airflow. The net result depends on canopy form, irrigation, street width, and climate. The reviewed literature notes that dense tree arrangements may delay daytime heat gain while also limiting overnight cooling in some settings.

Cool roofs likewise have stronger daytime than nighttime effects. Increasing roof reflectance reduces solar absorption and can lower daytime roof and air temperatures but offers little direct benefit after sunset unless reduced daytime storage produces a secondary nocturnal effect. Street and wall reflectance may also increase pedestrian radiant exposure. Interventions should therefore be evaluated against the particular outcome they are intended to improve.

The critical methodological rule is that a lower daytime satellite temperature cannot be generalized into a claim of all-day urban superiority. Historic cores may provide strong midday shade yet weak nighttime recovery. Modern districts may be exposed by day but cool more rapidly after sunset. Neighbourhood evaluation must represent the entire thermal cycle.

4. Explaining Variation Through Urban Form and Local Climate Zones

The thermal behaviour of a neighbourhood emerges from interacting variables rather than from its age or architectural label. The principal explanatory variables are built fraction, street orientation, building height, sky-view factor, surface albedo, vegetation, exposed soil, and anthropogenic heat. Their relative importance changes by time of day, weather, and urban context.

Built fraction measures the proportion of land covered by buildings. A high fraction can increase mutual shade and reduce direct solar access to the ground. It can also increase roof area, material storage, and obstruction of ventilation. Its effect should therefore be modelled separately for daytime and nighttime outcomes.

Street orientation determines the duration and sequence of solar exposure. North–south, east–west, and diagonal streets experience different façade and ground radiation according to latitude and season. Orientation also affects alignment with prevailing winds. A solar-favourable orientation may be aerodynamically unfavourable, and the balance differs between coastal and inland arid cities.

Building height increases the potential for shade but also changes aerodynamic roughness and roof exposure. Height should be analysed together with street width and block spacing. The same average height can describe a compact canyon or isolated towers surrounded by exposed paving.

Sky-view factor represents openness to the sky. Low values usually indicate strong daytime enclosure and reduced solar access, but they also limit nocturnal long-wave loss. The reviewed literature reports that sky-view factor is strongly related to nocturnal urban heat, while its daytime effect depends more heavily on shade, orientation, and solar geometry.

Albedo influences how much solar radiation is reflected rather than absorbed. High roof albedo can reduce roof heat storage and cooling demand. High street or wall albedo may expose pedestrians to reflected radiation.

Albedo should therefore be separated by surface type and evaluated alongside shade and canyon geometry.

Vegetation provides shade, evapotranspiration, lower surface temperature, and reduced heat storage. Tree canopy is usually more relevant to pedestrian exposure than generalized vegetation indices because overhead shade intercepts radiation before it reaches people and paving. In water-stressed cities, vegetation performance depends on irrigation, soil moisture, species, and maintenance.

The reviewed evidence reports a strong negative association between tree cover and daytime LST in Niamey and notes that vegetation can explain a substantial fraction of intra-city temperature variation in some studies. These associations remain context-dependent because irrigated trees in an arid city operate differently from sparse, drought-stressed vegetation.

Exposed soil can be cooler than paving under some nighttime conditions yet extremely hot during direct daytime sun. Its thermal response depends on moisture, colour, compaction, and texture. Peri-urban land should not be assumed to be thermally neutral simply because it is undeveloped.

Anthropogenic heat includes waste heat from air conditioning, traffic, industry, cooking, generators, and other energy use. It can be especially important at night, when solar input has ended but mechanical systems continue rejecting heat. Industrial and commercial districts may therefore remain warm even when their morphology appears relatively open.

Local Climate Zones provide a standardized structure for comparing these combinations. The LCZ framework classifies urban and natural landscapes into categories defined through building height, compactness, surface cover, materials, and human activity. It was designed to improve comparison of urban heat islands across cities by replacing vague labels such as "urban" and "rural" with morphologically interpretable zones.

The reviewed research describes LCZs as areas with relatively uniform surface cover, structure, material, and human activity at neighbourhood scale and reports their usefulness for distinguishing air-temperature and mean-radiant-temperature distributions. Historic cores may correspond to compact low-rise or compact mid-rise classes, while planned suburbs, industrial zones, informal settlements, and peri-urban areas may fall into open, lightweight, large low-rise, or sparsely built classes.

LCZs improve comparability, but they are not sufficient for detailed human-centred analysis. They may represent vegetation, ventilation paths, street orientation, and informal morphology too coarsely. Two neighbourhoods in the same LCZ can differ in tree distribution, socioeconomic conditions, roof material, traffic, and distance from the city centre. The reviewed research cautions that LCZ classifications require local calibration and may be too coarse for street-scale heat exposure.

The preferred method is therefore hierarchical. LCZs provide the first level of standardized classification. Within each zone, finer variables such as canyon ratio, street orientation, roof material, canopy distribution, air-conditioning density, and socioeconomic indicators should be measured. Models can then estimate how much of the daytime and nighttime thermal difference is associated with each factor.

Multilevel or spatial-regression models should account for clustering of neighbourhoods within cities and spatial dependence among adjacent units. Separate models should be estimated for daytime LST, nighttime LST, air temperature, and mean radiant temperature. Variable importance should not be inferred from one outcome alone.

5. Urban Change, Material Transition, and Quasi-Experimental Designs

Urban expansion changes thermal conditions by replacing soil, vegetation, and traditional building systems with new roads, roofs, walls, and mechanical infrastructure. The most informative analysis therefore compares not only different neighbourhoods at one moment, but the same or matched areas over time.

Historic cores may lose thermal advantages through demolition, street widening, roof replacement, courtyard enclosure, traffic growth, tree loss, and air-conditioning exhaust. Modern districts may improve through mature vegetation, cool roofs, shaded walkways, and reduced traffic. Informal settlements may become hotter as metal or earth surfaces are replaced by unshaded concrete and asphalt, but they may also become more shaded as building adjacency increases.

Longitudinal analysis should use consistent satellite products or carefully harmonized sensors. Changes in spatial resolution, overpass time, atmospheric correction, and land-cover classification can create artificial temperature trends. Daytime and nighttime records should be analysed separately, and local weather variation should be controlled through reference stations or matched unaffected neighbourhoods.

A **matched-neighbourhood design** compares a changed area with one or more control areas that had similar baseline morphology, climate, socioeconomic conditions, and temperature trends. For example, a historic block receiving a cool-roof programme could be matched with a similar block without intervention. A district losing tree cover could be matched with one retaining comparable vegetation.

A **difference-in-differences design** estimates whether the temperature change in an intervention area differs from the change in a control area over the same period. Conceptually, the effect is:

$$(\mathrm{Post}I - \mathrm{Pre}I) - (\mathrm{Post}C - \mathrm{Pre}C)$$

where (I) denotes the intervention neighbourhood and (C) the control. The design can be applied to redevelopment, demolition, paving, cool roofs, traffic reduction, tree loss, or block redesign. Its credibility depends on the assumption that treatment and control areas would have followed parallel trends without the intervention.

Parallel-trend testing requires several pre-intervention observations rather than one before-and-after image. Controls should be selected through LCZ class, built fraction, elevation, distance from the centre, vegetation, income, and baseline temperature. Weather anomalies should be removed through city-wide reference temperatures or fixed effects.

Redevelopment studies should distinguish several pathways. Demolition may temporarily increase open soil and solar exposure. New high-rise construction may provide shade but obstruct wind. Street widening may improve ventilation while increasing asphalt area and pedestrian radiation. Paving may reduce dust but increase heat storage. Cool roofs may lower daytime roof temperature without improving street-level comfort. Tree planting may take years to produce mature shade.

Where no formal intervention exists, urban expansion can be analysed through **event studies** or **trajectory analysis**. Newly developed peri-urban cells can be followed from bare land through construction to mature occupation. Changes in built fraction, vegetation, albedo, roof material, and LST can then be linked temporally. Historic districts can be analysed through roof replacement, courtyard infill, and density change derived from historical imagery.

These designs should therefore be understood as the methodological standard proposed for strengthening causal inference, not as a claim that the existing literature has already applied them consistently.

Intervention outcomes should include more than daytime LST. A cool-roof programme should be evaluated through roof temperature, neighbourhood air temperature, indoor temperature, cooling demand, and night-time conditions. Tree programmes should include canopy growth, irrigation, pedestrian radiant temperature, and survival. Traffic interventions should estimate both anthropogenic heat and air-quality change.

The strongest causal evidence will arise where satellite analysis is combined with ground monitoring, building energy data, and clearly timed interventions. Urban change can then be interpreted as a modification of thermal mechanisms rather than a simple association between land cover and temperature.

3.4 Climate-Change Stress Testing: Robustness, Failure Thresholds, and Hybrid Futures

1. A Multi-Model Framework for Future Arid-Region Climates

Vernacular cooling systems evolved through repeated adjustment to historical relationships among daytime heat, cool nights, low humidity, predictable winds, available water, and seasonal household practices. Climate change does not merely raise the average temperature within this established system. It changes the timing, duration, coincidence, and reliability of the environmental conditions on which passive cooling depends. A strategy that performed well under a large day–night temperature range may weaken as nights warm. A wind tower may lose effectiveness if useful winds become less frequent or if hot, dusty air dominates the period when ventilation is needed. An evaporative system may retain substantial psychrometric cooling potential while becoming socially indefensible because drought reduces water availability. Past performance can therefore inform future design, but it cannot guarantee future suitability.

The future-climate assessment should use a multi-model ensemble drawn from CMIP6 global climate models and, where available, dynamically or statistically downscaled regional products. At least two contrasting emissions pathways are required. **SSP2-4.5** represents an intermediate pathway in which emissions and warming are moderated but not eliminated. **SSP5-8.5** represents a high-emissions future with more severe late-century warming. A lower-emissions pathway such as SSP1-2.6 can be retained as an additional sensitivity case, especially where the timing of stabilization affects investment decisions. No single model or pathway should be presented as the forecast. The objective is to identify a range of plausible climates and determine which building decisions remain useful across that range.

Three periods should be compared: a historical or recent baseline, a mid-century period such as **2041–2060**, and a late-century period such as **2081–2100**. Near-term periods can also be included where current retrofit decisions have a twenty- to thirty-year service life. The reviewed literature specifically recommends assessing historical, mid-future, and far-future conditions and warns that a single model and emissions pathway cannot represent the full spread of climate uncertainty.

The city sample should represent different arid climate mechanisms rather than only different national locations. A defensible set would include an inland hot-dry city with a large historical diurnal range, a humid Gulf or lower-Mesopotamian city such as Basrah, a North African desert or semi-arid city, a Central Asian continental desert city, a high-altitude dryland city, and a rapidly expanding North American desert city such as Phoenix. Where available projections are regional rather than city-specific, those regional signals should guide the variables tested, while actual city values should be extracted later from bias-corrected grid cells surrounding the selected urban areas.

For each city, the analysis should calculate changes in annual and seasonal maximum temperature, the intensity and duration of heatwaves, and the frequency of days exceeding locally relevant heat thresholds. Yet daytime maximum temperature alone is inadequate. The number and sequence of **hot nights** are central because many vernacular systems depend on nocturnal recovery. Useful indices include the annual number of nights above fixed minimum-temperature thresholds, the number of consecutive hot nights, the nighttime cooling rate, and the difference between afternoon maximum and pre-dawn minimum.

Regional studies project increasing heat exposure across many arid regions, including more severe and prolonged heatwaves in the Eastern Mediterranean and Middle East (Zittis et al., 2022). These are regional signals rather than uniform city forecasts. Future design testing should therefore include extreme sequences as well as ordinary warm-season conditions, using a stated baseline, time horizon, and emissions pathway.

Humidity should be analysed jointly with temperature. Coastal and Gulf cities may experience dangerous combinations of hot desert air and moisture advection from warming seas. Increasing nighttime humidity reduces evaporative heat loss from the human body and weakens the relief historically provided by outdoor sleeping, roof use, or open courtyards. Relevant variables include relative humidity, specific humidity, dew-point temperature, wet-bulb temperature, and hours of coincident high heat and humidity.

Wind projections should include seasonal wind speed, prevailing direction, calm-hour frequency, and the occurrence of hot or dusty winds. Mean wind speed alone is insufficient because natural ventilation often depends on wind during specific evening and nighttime periods. Changes in low-level jets, sea breezes, monsoon circulations, or urban roughness can alter the number of useful ventilation hours even where annual wind averages change little. The reviewed literature notes that changing wind patterns and weakening low-level flows may deprive some regions of expected ventilative cooling.

Solar exposure requires a similarly careful interpretation. Incoming solar geometry changes little, but clear-sky conditions, cloud cover, atmospheric dust, and enhanced downwelling long-wave radiation modify the surface-energy balance. Future heat in arid regions may be intensified by increased net radiation and reduced evaporative cooling from drying soils. Solar-gain calculations should therefore be combined with projected surface dryness, cloud change, and atmospheric long-wave conditions rather than represented through air temperature alone.

Dust risk should be estimated through drought, soil moisture, wind, bare-land exposure, and regional aerosol projections where available. Wildfire smoke should also be included for arid and semi-arid regions connected to fire-prone landscapes. These hazards affect whether windows, windcatchers, courtyards, and night-purge systems can be used safely.

Drought and water availability complete the climate profile. Indicators should include precipitation change, consecutive dry days, potential evapotranspiration, soil moisture, reservoir or aquifer stress, and municipal water restrictions. The reviewed research projects increasing water stress across the Eastern Mediterranean and Middle East and emphasizes that water scarcity constrains both evaporative cooling and vegetation-based adaptation, even when dry air offers strong evaporative potential.

The result should be a city-by-period ensemble rather than one deterministic future file. Median changes, interquartile ranges, lower and upper ensemble bounds, and high-impact low-likelihood outcomes should all be retained. The building analysis can then ask whether a strategy works in most models, only under optimistic conditions, or fails in a substantial part of the plausible range.

2. Stress-Testing the Major Vernacular Strategy Families

Future testing should begin with the climatic dependency of each strategy. Some measures reduce heat gain regardless of whether nights remain cool. Others rely on environmental conditions that are projected to weaken. The purpose of threshold analysis is not to declare one universal temperature at which a strategy fails, but to identify the point at which its intended mechanism no longer produces a useful or safe outcome.

External shading and solar control are among the most robust strategies. Roof shade, deep overhangs, screened façades, arcades, shutters, reduced east–west glazing, and shaded streets act directly on solar gain. Their relative benefit often increases as solar-driven cooling loads rise. Shading can still fail through poor orientation, insufficient coverage, maintenance loss, or the obstruction of beneficial winter sun, but warming does not remove its basic physical mechanism. The reviewed research identifies external solar protection as effective across warming levels and describes envelope insulation as a leading strategy in hot-desert climates.

Insulation combined with controlled thermal mass is also comparatively robust. Insulation slows heat entry, while interior mass can damp short-term temperature variation. Yet mass should no longer be recommended independently of nighttime discharge. The operational threshold for useful mass is crossed when the building cannot release enough stored heat before the next hot period. This can be identified when the indoor or mass minimum rises on successive nights, when outdoor nighttime temperature remains above indoor temperature for most of the purge period, or when mechanically assisted night ventilation cannot restore the material to a lower starting temperature.

Future thermal mass testing should therefore compare four configurations: mass without insulation, insulated lightweight construction, externally insulated mass, and mass with controlled mechanical purge. The key outputs are not only daytime peak reduction but nighttime operative temperature, cumulative heat storage, and recovery after multi-day heatwaves. A massive building may still delay dangerous peaks during a power outage even when it no longer maintains comfort, so the thresholds for **comfort failure** and **life-safety failure** should remain separate.

Night-purge cooling requires outdoor air cool enough to remove sensible heat from indoor air and exposed building mass. Moisture and air quality must also be acceptable. A lower outdoor enthalpy alone does not establish that warmer incoming air will cool the mass. Useful operation depends on the temperature difference, airflow, duration, stored heat, and fan energy; ventilation should not operate merely because it is nighttime.

Night ventilation loses cooling potential as outdoor nights warm. Fan-assisted purging may improve heat removal when a useful temperature difference remains, but increasing airflow cannot provide a cool sink during persistently hot nights. Future simulations should test window-driven, wind-driven, and fan-assisted purge separately under sequences of hot nights (Sobhy, Brakez, and Benhamou, 2024).

Direct evaporative cooling depends on wet-bulb depression, water availability, and air quality. Its thermodynamic limit is the wet-bulb temperature. The strategy loses practical effectiveness when the achievable supply-air temperature remains above the required comfort or safety threshold, even at a realistic saturation efficiency. It also crosses a social or ecological threshold when water consumption exceeds the building's defensible allocation or depends on scarce potable water during drought restrictions.

Humidity rise may weaken evaporation even in cities historically considered dry, particularly where night moisture increases or coastal air penetrates inland. The reviewed research reports that direct evaporation improved comfortable hours in several Iraqi cities but was least effective in the more humid conditions of Basrah. It also emphasizes that rising water stress may constrain cooling even where psychrometric potential remains. Future assessment must therefore combine wet-bulb performance with litres of water consumed per cooling-hour and with scenario-specific water availability.

Outdoor sleeping and roof occupation depend on nighttime operative temperature, humidity, wind, privacy, security, insects, noise, dust, and smoke. The strategy becomes ineffective when nights no longer provide meaningful thermal relief. It becomes unsafe when high humidity limits bodily heat loss, when dust or smoke makes outdoor air hazardous, or when extreme heat continues through the night. Outdoor sleeping should therefore be treated as an adaptive option rather than as a reliable future cooling strategy.

Courtyard cooling is similarly conditional. Courtyards remain useful as sources of shade, protected circulation, privacy, and spatial organization. Their cool-air-reservoir function weakens when nocturnal radiative loss declines, surrounding walls remain warm, or urban humidity and hot nights prevent recovery. A courtyard crosses its thermal threshold when its predawn temperature remains above that of useful external or adjacent spaces, when its surfaces release more stored heat than the opening can dissipate, or when mechanical condensers discharge waste heat into it.

Courtyard stress tests should vary enclosure ratio, sky-view factor, material storage, vegetation, shading, ventilation, and neighbouring height. The output should identify whether the courtyard functions as daytime shade, nighttime sink, ventilation chimney, or heat reservoir under each future climate. It may retain some functions after losing others.

Windcatchers and natural wind systems depend on wind direction, roof-level exposure, outdoor air quality, and the temperature of supply air. Their threshold is crossed when the expected wind no longer produces sufficient pressure and air-change rate during useful hours, when surrounding development obstructs the device, or when incoming air is hotter, dustier, or more polluted than indoor air. Changing circulation patterns make their future performance uncertain rather than universally obsolete.

The robust strategy family is therefore one that reduces exposure without depending heavily on a disappearing climatic resource: shade, insulation, reduced leakage during hot hours, efficient glazing, shaded roofs, and low internal gains. Conditional strategies night ventilation, evaporation, outdoor sleeping, courtyard air storage, and wind capture should remain in the design toolkit but operate through monitored controls and climate-specific thresholds.

3. Compound Events, Resilience, and Safe Failure

Average-year comfort analysis is insufficient because future risk will be shaped by compound events. A building may perform adequately during a typical hot week yet become dangerous when heat coincides with power failure, smoke, dust, water shortage, or humid nights. Passive design should therefore be evaluated not only by how often it maintains comfort, but by how it fails and how long it preserves survivable conditions.

A **heatwave plus power outage** is the most direct compound threat. Cooling demand rises during the heatwave, increasing stress on electricity generation and distribution. If power fails, buildings designed around continuous mechanical cooling can heat rapidly, particularly when they contain large, glazed areas, poorly shaded roofs, sealed façades, and high internal gains. Even highly efficient or nominally net-zero buildings may overheat if renewable production, storage, or grid supply is unavailable.

Rahif, Kazemi, and Attia (2023) warn that optimized low-energy and nearly zero-energy buildings may still reach dangerous conditions during future heatwaves with cooling-system outages. It also notes that rising cooling demand and reduced photovoltaic performance can occur together, weakening energy resilience. Resilience testing should therefore include at least 24-, 48-, 72-, and multi-day outage scenarios during severe heat sequences.

Safe-failure metrics should include hours before indoor operative temperature crosses a protective threshold, maximum bedroom temperature, nighttime recovery, rate of temperature rise, and conditions for vulnerable occupants. A building that loses normal comfort but remains below dangerous exposure for three days performs differently from one becoming hazardous within several hours.

A **heatwave plus dust storm or wildfire smoke** disables many natural-ventilation strategies. Windows, windcatchers, and courtyards may need to remain closed during the hours when night purge would otherwise occur. Fine particulate matter can enter through insect screens and simple grilles. Smoke can persist overnight even when outdoor temperature is favourable. The building must then rely on filtration, low internal gains, thermal buffering, recirculating fans, and mechanically supplied clean air.

This event reveals the danger of designing natural ventilation without a protected closed mode. The safe building needs two environmental states: an open mode for clean, favourable air and a filtered mode for hazardous outdoor conditions. Mechanical assistance is not a failure of passive design; it is part of resilient hybrid operation.

A **heatwave plus water shortage** directly affects evaporative cooling, irrigated vegetation, fountains, wetted surfaces, and roof ponds. Water restrictions may occur precisely when cooling demand is highest. Open-water systems may also experience higher evaporation, poorer water quality, and increased maintenance. The design should prioritize low-water shade, drought-adapted vegetation, closed-loop or indirect systems, and the use of non-potable water where health rules permit.

Evaporative cooling should be assigned a drought operating hierarchy. At the first level, full operation occurs when water is available and psychrometric benefit is high. At the second, restricted operation is reserved for vulnerable occupants or peak-risk hours. At the third, the system shuts down and the building depends on shade, fans, insulation, and efficient refrigeration. A strategy without a viable dry mode is not resilient in a water-stressed climate.

A **heatwave plus high nighttime humidity** is particularly dangerous because both people and buildings lose their usual recovery period. Humidity reduces evaporative heat loss from the skin. Warm moist air limits the effectiveness of direct evaporative cooling and may make outdoor sleeping or night ventilation ineffective. Massive walls remain warm because air and sky provide less cooling.

This combination should be tested through wet-bulb temperature, indoor enthalpy, nighttime operative temperature, and sleep-period exposure. Ceiling fans remain useful within physiological limits, but their benefit declines as air temperature and humidity approach dangerous combinations.

Dehumidification or efficient mechanical cooling may become necessary even in buildings historically designed for free-running operation.

Compound analysis should include sequences rather than isolated peak days. Three or five consecutive hot nights can produce cumulative heat storage and physiological fatigue even when no single hour appears unprecedented. Bobde, Akinsanola, and Taguela (2025) emphasize that compound daytime and nighttime heat events are projected to intensify and that historically rare events may recur much more frequently.

Resilience must also account for occupants. Older people, infants, people with chronic illness, those living alone, and households unable to relocate require lower risk thresholds and stronger backup. Safe failure means that the building limits the rate and magnitude of overheating, provides at least one protected refuge, supports filtered air and low-power fans, and can connect to emergencies or renewable power.

4. Comparing Three Cooling Futures

The first future is **conventional mechanical cooling**. Buildings are designed primarily around refrigeration, with limited investment in shade, thermal buffering, natural ventilation, or adaptive space. Under normal grid conditions, this pathway can maintain narrow temperature bands and manage humidity. It can also protect vulnerable occupants during extreme heat when equipment and power remain available.

Its weaknesses are high electricity demand, peak grid stress, refrigerant impacts, outdoor waste heat, unequal affordability, and catastrophic dependence on continuous power. As cooling demand rises, households may experience energy poverty even where air-conditioning units are installed. Urban heat can intensify as condensers reject heat into streets and courtyards. Equipment is frequently oversized for ordinary weather yet still vulnerable to exceptional events.

The second future is **passive-only adaptation**. Buildings rely on shade, compactness, thermal mass, natural ventilation, courtyards, vegetation, reflective surfaces, and behavioural adaptation. This pathway minimizes direct cooling energy and can provide valuable thermal moderation. It also preserves habitable conditions during short outages because its basic mechanisms do not depend entirely on the grid.

Its principal weakness is the decline of the climatic resources on which some passive strategies depend. Hot nights weaken mass discharge and night ventilation. Humidity reduces evaporative and physiological cooling. Dust and smoke disable open-air strategies. Water scarcity constrains vegetation and evaporation. Under severe late-century conditions, passive-only buildings may remain cooler than unadapted buildings yet still exceed comfort or safety thresholds.

The reviewed literature reports that passive techniques can substantially reduce the need for air conditioning but are unlikely to replace it completely under intensifying heat. Passive-only design should therefore not be presented as a universal alternative to mechanical cooling, especially for hospitals, care homes, bedrooms, schools, and vulnerable households.

The third future is **passive-first hybrid cooling**. Heat gain is reduced through external shade, insulation, efficient glazing, reflective or ventilated roofs, controlled thermal mass, and low internal loads. Natural ventilation operates only when outdoor temperature, humidity, air quality, and wind are favourable. Ceiling fans increase air speed and permit wider but safe thermostat settings. Efficient heat pumps provide cooling and dehumidification when passive modes are insufficient. Thermal storage, photovoltaics, batteries, and backup power protect critical spaces during outages.

Hybrid design treats natural and mechanical modes as a coordinated sequence. During a cool night, the building purges stored heat. During a dusty but mild night, filtered mechanical ventilation may replace open windows. During a humid heatwave, the envelope remains shaded and closed while efficient refrigeration protects a limited refuge zone. During a power outage, thermal mass, shade, low gains, battery-supported fans, and stored energy slow the transition from comfort to danger.

The reviewed research identifies mixed-mode systems, efficient heat pumps, high ventilation rates when conditions permit, rooftop photovoltaics, storage, and complementary street-tree strategies as the most promising combined response. It also notes that cool roofs and vegetation contribute differently: rooftop systems address building energy, while street trees address outdoor exposure.

The hybrid pathway is not automatically affordable or low-carbon. Poor controls can operate ventilation and air conditioning simultaneously. Oversized systems can increase cost. Batteries and photovoltaics require embodied materials, maintenance, and replacement. Heat pumps may be inaccessible to low-income households. The design objective is therefore **passive load reduction first, efficient active protection second, and renewable resilience third**.

Comparative simulation should evaluate the three futures through annual energy, peak demand, comfort hours, adaptive compliance, extreme-event survival, indoor air quality, water use, carbon emissions, and lifecycle cost. A pathway that minimizes annual energy but fails during a three-day outage should not be ranked above one with slightly higher energy and substantially greater life safety.

5. Adaptation Pathways and Decision Triggers

Future uncertainty makes a single fixed design inappropriate. Adaptation should proceed through pathways: staged actions that remain useful under several futures and can be strengthened when observed conditions approach predefined thresholds. This reduces the risk of premature over-investment while avoiding dangerous delays.

Near-term no-regret measures should address current heat and remain beneficial across emissions pathways. These include external roof and wall shading, improved roof insulation, control of east and west solar gain, efficient glazing where appropriate, airtightness during hot or polluted periods, controllable ventilation, ceiling fans, cool or ventilated roofs, reduction of internal gains, maintenance of existing trees, and preservation of safe nighttime airflow where it remains useful.

No-regret measures should also include basic resilience infrastructure: operable windows that can be secured, filtered ventilation routes, one thermally protected room, backup power connections for fans and medical equipment, reflective emergency roof coatings, and monitoring of indoor temperature and humidity. These interventions reduce present exposure and create a platform for later systems.

Medium-term retrofits become necessary when monitoring shows rising overheating, declining night recovery, or more frequent mechanical operation. Measures may include external insulation, shaded secondary skins, high-efficiency heat pumps, mechanically assisted night purge, demand-controlled filtered ventilation, solar chimneys, phase-change or water-based thermal storage, rooftop photovoltaics, batteries, and zoned cooling that protects occupied rooms rather than conditioning the entire building continuously.

Courtyards and wind systems may require modification rather than abandonment. Adjustable covers can preserve nighttime sky exposure. Screens and filters can protect against dust. Fans can support weak airflow. Mechanical condensers can be relocated away from courtyards. Water-dependent landscapes can shift toward drought-adapted canopy, non-potable irrigation, and shaded hardscape.

Long-term transformation should be triggered when key climatic thresholds are crossed. A night-ventilation threshold is crossed when outdoor air no longer falls below indoor temperature for sufficient hours in most ensemble projections or observed summers. An evaporative threshold is crossed when wet-bulb conditions or water restrictions make the system unable to provide a safe supply temperature. An outdoor-sleeping threshold is crossed when hot, humid, polluted, or unsafe nights become frequent rather than exceptional.

At settlement scale, transformation may include deep shaded transit routes, district cooling, renewable microgrids, cooling centres, reduced traffic heat, tree networks with secure water budgets, reflective and insulated roof programmes, and revised urban blocks that combine shade with nighttime ventilation. At building scale, it may require conversion from free-running to mixed-mode operation, installation of filtered mechanical ventilation, or creation of protected refuge rooms.

Adaptation triggers should be based on observed and projected indicators rather than calendar dates alone. Examples include a specified increase in annual overheating degree-hours, repeated failure of nighttime recovery, cooling-system operation exceeding its intended seasonal share, water restrictions affecting landscape cooling, or outage simulations showing unsafe conditions before emergency support can arrive.

The reviewed literature proposes staged implementation: immediate robust passive measures, design for later efficient cooling, renewable generation with storage, and monitoring-based escalation as climate signals emerge. This approach recognizes that under lower-emissions pathways some extreme investments may not be required, while under high emissions delay could lock households into unsafe buildings.

Pathways should also account for unequal capacity. Wealthier households may retrofit repeatedly, while low-income residents, renters, informal settlements, and public institutions require collective finance, codes, subsidies, and neighbourhood infrastructure. Adaptation flexibility should not become an excuse to transfer responsibility entirely to occupants.

CHAPTER 04

The Cooling Transition

Standardized Construction, Mechanical Dependence, and Thermal Inequality

4.1 From Climate-Responsive Form to Standardized Construction

1. From Climate-Responsive Building Systems to Standardised Urban Production

The evolution of arid region architecture did not simply involve moving away from traditional forms toward modern forms; it involved a move from localized, environmentally organized systems to standardized systems of urban production. Earth, stone, wood, lime, shaded streets, shared walls, roof top terraces, courtyard spaces, arcades, and wind devices were linked as part of an organizational system that included the relationship of land, craft, household organization, climate, water, and the incremental process of repairing structures.

In contrast, reinforced concrete frames (and later hollow block infills), exposed concrete roofing, wide glass surfaces, asphalt streets, single family homes set back from the street line (detached) with elevators, air conditioning and/or refrigeration and large scale typological configurations (high rise or villas) are all elements of a different organizational system which includes the use of industrial materials, formal engineering practices, mass production techniques (rapidly constructed), automobile transportation systems and financial capital combined with a continuous flow of electrical power.

Arctic settlements usually employ a method to minimize the degree of exposure to exterior conditions by employing adjacent building structures and shared walls. Narrowed street widths allow for opposing buildings to provide each other shading. Projections, balconies, screens, arcades and covered passageways protect both people and openings from direct sunlight. The concentration of natural light and ventilation occurs within individual parcels due to courtyard spatial arrangements reducing the necessity for extensive window areas. Walls of considerable thickness moderate temperature variations while flat roof tops support sleeping space, drying areas, storage areas, household work stations and nighttime cooling processes. The environmental functions occurred at multiple scales rather than being located in a singular element of the building.

The separation of many of the above mentioned relations is characteristic of contemporary construction. Reinforced concrete frames allowed for the development of higher towers with longer structural spans providing for unobstructed floor areas beneath, larger windows and quicker reproduction. Hollow concrete or fired clay block infill decreased wall thickness and construction duration. Cement rendering provides a uniform finish surface that can hide disparate craftsmanship. Wide flat reinforced concrete slabs have become popular due to familiarity of their structure for designers, compatibility for vertical extensions and ease of integration with rainwater collection tanks and mechanical equipment. However, exposed flat slab has proven to be a primary source of solar heat gain in low-rise residential housing.

At the urban scale, widened roads, detached houses, parking lots, yards and setbacks created additional areas of exposed ground, roof and facade. Paved asphalt/concrete replaced earth/stone paved ways, landscaped edge treatments and shaded threshold spaces. Wider roads serve as symbols of accessibility and sanitation for emergency vehicles and modern planning but increase pedestrian's exposure to full sun and reduce mutual shading previously provided. Detached house plots provide greater privacy and social status for some households but increases total area of exterior envelope requiring mechanical cooling systems.

The lift allowed household and commercial activity to expand vertically without the physical effort that had constrained traditional building height. Air conditioning reduced the immediate need for operable openings, seasonal room use, roof sleeping, courtyard occupation, and thick walls. Glazed façades and large street-facing windows became feasible because cooling systems were expected to manage solar gain. Buildings were reconceived as mechanically regulated interiors rather than structures that had to remain tolerable through geometry, material storage, airflow, and adaptive occupation.

The reviewed literature describes this wider modernist change as a movement towards universal concrete-and-glass prototypes that treated buildings as climate modifiers instead of climate-responsive forms. It also reports the declining status of low-technology materials, including cases where earthen blocks are no longer produced commercially or recognised in building codes.

The transition was therefore institutional as well as architectural: materials and forms disappeared partly because contemporary systems stopped training, financing, insuring, regulating, and supplying them.

This does not mean that every older building was comfortable or every modern building was thermally unsuitable. Traditional systems could suffer from structural weaknesses, moisture damage, fire risk, poor sanitation, overcrowding, or limited accessibility. Modern systems provided clear advantages in structural span, vertical circulation, standardisation, and rapid housing delivery. The relevant question is how the transition redistributed environmental performance, risk, labour, and energy dependence.

2. Urbanisation, Finance, Regulation, Labour, and Aspiration

Rapid urbanisation placed demands on construction systems that incremental craft production could not always satisfy. Cities needed large numbers of houses, schools, offices, hospitals, roads, and utilities within short periods. Reinforced concrete, standard blocks, steel reinforcement, manufactured windows, and cementitious finishes could be specified, priced, transported, and inspected through formal contracts. These systems were easier to reproduce across many sites than building traditions dependent on local soil selection, timber knowledge, lime preparation, or specialised masonry.

Construction speed became economically decisive. Earth walls often require soil testing, careful moisture control, weather protection, staged drying, and trained labour. Stone construction can be slow and dependent on quarrying and skilled fitting. Lime mortars and plasters cure differently from cement. Concrete frames and block infill, by contrast, fit contractor schedules, subcontracting, mechanised mixing, and standard bills of quantities. The apparent affordability of modern construction therefore reflects the value assigned to time, predictability, and formal contracting as much as the market price of materials.

Mortgage and insurance systems also favour buildings that can be valued through standard classifications. Lenders prefer materials with recognised service lives, legal approvals, and comparable resale markets. Insurers favour structures with codified fire, seismic, moisture, and structural performance. An earthen or hybrid house may have low embodied carbon and good thermal performance yet remain difficult to finance when it falls outside standard valuation categories. The resulting market disadvantage can persist even where the building is technically sound.

Building codes can improve life safety while unintentionally marginalising local materials. Requirements for compressive strength, seismic resistance, fire separation, moisture protection, accessibility, and structural documentation respond to genuine risks. The problem arises when compliance routes are written only for reinforced concrete, fired masonry, steel, or proprietary systems. A material that lacks a standard test procedure, accredited supplier, or recognised engineer may become effectively illegal even when safer modern versions could be developed.

Material standardisation affects design culture. Standard blocks encourage standard wall thickness. Standard concrete frames encourage repeated structural bays. Standard aluminium or UPVC windows encourage larger sealed openings. Standard mechanical systems encourage closed interiors and uniform temperature expectations. Once these supply chains become dominant, alternative materials face higher procurement costs even when their raw resources are locally available.

Labour economics reinforce the transition. Traditional building knowledge was often distributed among masons, carpenters, plasterers, household members, and seasonal workers. Skills were transmitted through apprenticeship and repeated maintenance. As wages, migration, education, and employment patterns changed, fewer workers remained in craft systems. Concrete construction could also be labour-intensive, but its tasks were easier to divide among specialised crews and less dependent on place-specific knowledge.

Maintenance influenced household decisions. Earthen plaster, limewash, timber screens, roofs, and drainage systems require periodic attention. Such maintenance may be affordable where household labour and local skills are available, but expensive where labour is monetised and residents expect low-maintenance surfaces. Cement render, ceramic tiles, aluminium frames, waterproof membranes, and paints became attractive because they appeared permanent, even though they also weather, crack, trap moisture, or require replacement.

Colonial planning contributed to the institutional separation between older urban fabrics and modern expansion. Gridded roads, sanitary clearances, administrative quarters, zoning, and segregated land uses often contrasted with compact, mixed-use settlement. Later national planning systems retained many of these assumptions. Car-oriented development intensified the pattern through wider roads, parking, setbacks, traffic engineering, and detached residential plots.

Aspiration cannot be dismissed as false consciousness. Concrete villas, glazed façades, lifts, air conditioning, imported stone, and large roads became associated with wealth, hygiene, permanence, privacy, technological progress, and global belonging. Local earth or timber could be associated with poverty, rurality, maintenance burdens, or structural insecurity. The literature documents this cultural marginalisation, describing vernacular methods as having been treated as backward even where modern replacements reduced climate responsiveness.

A rigorous explanation must therefore hold several truths together. Modernisation expanded structural capacity, construction speed, sanitation, accessibility, and urban opportunity. It also weakened local environmental feedback by making cooling energy, industrial materials, and motorised access substitutes for shade, adjacency, adaptive use, and craft maintenance. The transition was neither an irrational abandonment of a perfect past nor an uncomplicated advance towards superior buildings.

3. Plot Fragmentation, Vertical Growth, and the Disassembly of Environmental Logic

Plot subdivision changes more than ownership. It changes the dimensions through which shade, air movement, courtyards, shared walls, and household adaptation operate. A large courtyard compound may accommodate several room orientations, a shaded arcade, vegetation, water, storage, roof access, service areas, and seasonal movement. When it is divided among heirs or sold in smaller parcels, the courtyard can become a narrow light well, a rear setback, a corridor, or additional floor area.

Fragmentation reduces the ratio between useful courtyard width and surrounding building height. A court that once received controlled sun and supported ventilation may become too narrow for occupation or too enclosed for airflow. New walls interrupt circulation and cross-ventilation paths. Shared water and maintenance arrangements become difficult. Rooms that originally faced a central open space may be separated from it or converted to street-facing units.

The reviewed literature records the replacement of central courtyards by corridors in contemporary housing and links this transformation to larger mechanically conditioned volumes. It also describes traditional buildings clustered closely enough to produce mutual shade and protected airflow, in contrast to dispersed contemporary development. The loss is therefore not simply the disappearance of an open space, but the weakening of a spatial system that organised circulation, privacy, light, ventilation, and seasonal occupation.

Vertical expansion creates additional contradictions. Adding floors can increase courtyard shade, reduce roof exposure per unit of floor area, and accommodate urban growth without outward expansion. It can also obstruct wind, reduce sky-view factor, increase structural load, create overlooking, and make courtyards permanently dark or stagnant. Historic walls and foundations may be unable to support additional storeys safely, encouraging replacement by reinforced-concrete frames.

Roof use changes when buildings grow taller. A roof that once supported sleeping, food preparation, drying, or evening gathering may become inaccessible, subdivided, overlooked, or occupied by water tanks, lift overruns, satellite equipment, solar panels, and air-conditioning condensers. The roof remains physically present but no longer functions as an adaptive seasonal room.

Shared walls may also disappear even when density increases. Apartment towers surrounded by parking or setback land can contain many households while exposing far more façade and ground area than attached low-rise blocks. Density should therefore be distinguished from adjacency. A high floor-area ratio does not automatically reproduce the thermal protection of continuous party walls and shaded streets.

Road widening disrupts the urban counterpart of the courtyard system. Demolition removes projecting rooms, arcades, trees, walls, market covers, and thresholds. Remaining façades become newly exposed to low-angle sunlight. Wider carriageways increase asphalt, traffic, and crossing distance while reducing shade from opposing buildings. The road may improve vehicle access but reduce the environmental value of the public realm.

Privacy requirements can accelerate the transition. Taller neighbours and wider streets expose houses to more distant views. Residents respond through sealed glazing, curtains, high boundary walls, security screens, or permanent courtyard covers. These adaptations may protect visual privacy while reducing night ventilation and sky exposure.

Traditional decoration can survive after environmental logic disappears. A contemporary villa may display arches, mashrabiya-like panels, domes, wind-tower profiles, decorative earth colours, or a central atrium. If the building is detached, heavily glazed, sealed, unshaded, mechanically cooled, and surrounded by asphalt, its visual language does not restore vernacular performance. A wind-tower form without a pressure path is a roof ornament. A courtyard beneath fixed glazing is an atrium. A screen placed inside solar-control glass may evoke tradition while allowing the outer glazing to absorb heat.

Environmental continuity should therefore be judged through mechanism rather than appearance. The relevant questions are whether the screen stops solar radiation before it reaches the envelope, whether the courtyard supports shade and usable airflow, whether shared walls reduce exposure, whether roof space remains thermally and socially accessible, and whether occupants can move between different thermal zones.

4. Measuring Change Across Cities and Historical Periods

The material and morphological transition can be measured rather than narrated only through selected examples. A longitudinal framework should combine historical maps, aerial photography, declassified satellite imagery, contemporary high-resolution imagery, building footprints, census records, construction statistics, planning documents, and field surveys.

A practical periodisation for the book uses at least three intervals. The first is a pre-industrial or early twentieth-century baseline, representing settlement before mass concrete construction, widespread private cars, and household air conditioning. The second is a mid-century modernisation period, approximately from the 1950s to the 1980s or 1990s depending on the city, when road expansion, concrete construction, formal planning, and new housing typologies accelerated. The third is a recent metropolitan period, from the 1990s or 2000s to the present, characterised by high-rise development, villa expansion, intensified air conditioning, new infrastructure, informal growth, heritage redevelopment, and selective hybrid adaptation.

These dates should not be imposed identically on every settlement. They are comparative analytical periods whose local boundaries must be adjusted to the timing of planning reform, oil revenue, industrialisation, conflict, migration, or infrastructure investment. The essential requirement is that each city be represented by at least three spatially comparable observations.

Jodhpur can represent a South Asian desert city in which compact stone neighbourhoods and narrow lanes coexist with peripheral road-based expansion. Sousse can represent a North African city where a historic compact fabric is contrasted with rapid transitions towards contemporary housing. Abu Dhabi and the wider Gulf context can represent the movement from low-rise shaded or courtyard-based settlement towards villas, towers, wide roads, mechanical cooling, and later experiments such as Masdar City. The selected cases need not be identical; their analytical value lies in exposing different pathways into standardised construction.

For every period, building footprints can be used to calculate built fraction, average block size, street width, building adjacency, courtyard area, plot size, and orientation. Historical cadastral maps can reveal subdivision and consolidation. Aerial imagery can identify roof additions, road widening, courtyard infill, tree loss, and conversion of open ground to paving. Digital elevation models, stereo imagery, LiDAR, or floor-count surveys can estimate changes in height and surface-to-volume ratios.

Material transition is more difficult to observe remotely. Roof colour, texture, and thermal response can provide partial classification, but field validation is necessary. Municipal permit data, cement and brick production statistics, housing censuses, building-age records, and sample surveys can estimate the shift from earth, stone, timber, or fired brick towards concrete frames and hollow blocks. Census data may also identify air-conditioning ownership, housing type, crowding, tenure, and access to water or electricity.

Thermal remote sensing can trace changes in daytime and nighttime land-surface temperature, but regional climate warming must be separated from urban transformation. Each city should therefore include stable reference zones outside the area of urban change, elevation controls, consistent seasons, and weather-normalised temperature anomalies. A difference-in-differences approach can compare the temperature trajectory of redeveloped neighbourhoods with similar areas that retained their earlier form.

Matched analyses can examine specific events: road widening, courtyard-block demolition, tree removal, asphalt paving, concrete-roof replacement, or cool-roof programmes. The pre-change thermal trend should be tested before attributing a post-change difference to redevelopment. Historical images should be registered to a common coordinate system, and uncertainties caused by different spatial resolutions should be documented.

The longitudinal framework described here is therefore a proposed research design rather than a summary of a mature existing evidence base. Its purpose is to convert claims of decline into measurable changes in morphology, material, thermal exposure, and energy dependence.

5. Comparing Old and New Materials Through Multiple Criteria

Material transition is often explained through a contrast between thermally superior local construction and thermally inferior modern construction. This is too simple. Materials should be compared through thermal behaviour, structural capacity, moisture resistance, seismic safety, construction speed, maintenance, embodied carbon, availability, cost, regulation, and local skill.

Earth and adobe can provide high thermal storage, low processing energy, local sourcing, and repairability. They can also suffer from rising damp, erosion, poor foundations, incompatible cement renders, and weak seismic performance when unreinforced. Rammed earth can achieve greater strength and dimensional control, but requires soil assessment, formwork, compaction, and quality assurance. Reinforced earth and engineered earthen systems can address some structural limitations, though code recognition remains uneven.

Stone provides mass, durability, fire resistance, and regional identity. Its performance depends on thickness, density, mortar, external shade, and nighttime discharge. Heavy unreinforced walls create seismic risks, while quarrying and transport can increase environmental impacts. Timber and timber–earth composites reduce structural weight and can improve earthquake behaviour, but depend on forestry, insect control, fire detailing, moisture protection, and carpentry knowledge.

Lime mortars and plasters are compatible with many earth, brick, and stone walls because they permit moisture movement and repair. Cement can offer faster strength and greater water resistance in selected conditions but may create rigid, impermeable layers that damage softer historic materials. Material choice should therefore be based on compatibility rather than on the assumed superiority of either traditional or industrial products.

Reinforced concrete provides high compressive capacity, structural continuity, large spans, vertical extension, and code familiarity. These qualities are particularly valuable in seismic areas and rapidly urbanising cities. Concrete also has high embodied carbon and can produce severe heat gain when roofs and walls are thin, uninsulated, exposed, or poorly shaded. Hollow-block infill may reduce weight and cost but frequently provides inadequate thermal resistance unless cavities, insulation, and external shading are designed deliberately.

The reviewed evidence records better temperature moderation in several earth, stone, and traditional-masonry examples than in concrete or modern-brick comparisons. It also acknowledges poor insulation in some traditional walls and clear structural or durability advantages in modernised systems. This combination of findings supports hybridisation rather than a simple material ranking.

Embodied carbon is similarly contextual. Local earth generally requires less processing than fired brick, cement, steel, or imported insulation. Yet stabilised earth with high cement content may lose much of that advantage. A long-lasting concrete structural frame combined with low-carbon infill, external insulation, and effective shade may outperform a poorly maintained supposedly natural building over its full lifecycle.

Construction statistics should therefore distinguish structural frame, infill, insulation, finish, and roof rather than classifying an entire building by one material. A concrete-frame building with earth blocks and deep external shade differs substantially from a fully concrete, glass-clad, mechanically sealed structure. Likewise, an "earth building" with concrete foundations, cement stabilisation, steel reinforcement, synthetic membranes, and imported finishes is already a hybrid.

4.2 Air-Conditioning Dependence and Energy Lock-In

1. The Expansion of Cooling Demand

Space cooling has become one of the fastest-growing forms of energy service in hot and rapidly warming regions. Its expansion is driven by rising temperatures, urban growth, household income, changing expectations of indoor comfort, increasing ownership of electrical appliances, and the spread of building types that cannot remain habitable without mechanical cooling. The growth of air conditioning is therefore neither a purely technological trend nor a simple consequence of personal preference. It reflects the interaction of climate, architecture, electricity systems, urban development, and inequality.

Cooling degree-days provide one way to describe the climatic pressure behind this expansion. They estimate the accumulated temperature above a selected base temperature over a defined period. Higher cooling degree-days generally imply a longer or more intense cooling season, although actual energy demand also depends on humidity, solar gain, building use, envelope quality, and thermostat settings.

Saudi Arabia illustrates an electricity system already strongly shaped by residential consumption. Domestic users account for roughly half of annual electricity use across sectors, with mechanical cooling forming a dominant share of household demand. In Jeddah, the cited building-performance research indicates that existing residential buildings require air conditioning through much or all of the year under infiltration-sensitive conditions. These findings point to a cooling system that is no longer seasonal in the conventional sense. It is embedded in everyday habitation, household expenditure, grid planning, and building design.

Cooling demand is also important in regions where air-conditioner ownership and electricity access remain limited. Electrification planning must account for air circulation and cooling services as incomes, access, and climate conditions change (Falchetta and Mistry, 2021). These needs affect generation, network capacity, appliance efficiency, and affordability.

Room air conditioners offer an accessible, incremental path to household cooling, but they can also produce fragmented and inefficient systems when units are purchased on upfront price, poorly sized, or operated in leaky rooms. Installed capacity can therefore grow faster than effective or affordable cooling service.

Peak electricity load is more critical than annual consumption alone. Cooling demand concentrates during the hottest hours, when many buildings require mechanical cooling simultaneously. Poorly shaded roofs, exposed glazing, air leakage, and low-performance walls increase this coincidence by allowing outdoor heat to enter rapidly. The electricity system must then maintain generation, transmission, and distribution capacity capable of meeting extreme peaks, even if that capacity is underused during milder periods.

Cooling-related emissions arise through electricity generation, refrigerant leakage, appliance production, and construction systems designed around continuous mechanical cooling. The mechanism is nevertheless clear: where electricity remains carbon-intensive, rising cooling demand increases operational emissions; where cooling equipment uses high-impact refrigerants or is poorly maintained, direct emissions add to the burden. Climate change then raises cooling demand further, creating a reinforcing relationship between warming, electricity use, and emissions.

The transition should be measured through cooling degree-days, ownership and sales, normalized cooling energy, peak demand, appliance efficiency, grid carbon intensity, refrigerants, and unmet need. No single indicator is sufficient.

2. The Cooling Feedback Loop and Built-Environment Lock-In

Mechanical cooling can compensate for heat-amplifying buildings, but that compensation can lock cities into forms that require ever more cooling. The feedback begins when buildings are constructed with exposed concrete roofs, thin or uninsulated walls, large east- and west-facing windows, poor airtightness, limited shade, and high internal gains. These buildings absorb and admit more heat than climate-responsive alternatives. Air conditioning becomes necessary not only during extreme weather but throughout ordinary warm periods.

Envelope quality directly affects system sizing and operating duration. Air leakage allows hot outdoor air to enter while conditioned air escapes. Solar gain through roofs and glazing raises peak loads. Poor insulation increases conductive heat transfer. The cooling system must therefore be larger, operate for longer hours, and cycle more frequently. Felimban, Knaack, and

Konstantinou (2023) link poor envelope quality in Saudi housing to prolonged mechanical cooling and reports that improved windows, wall insulation, roof insulation, airtightness, and equipment replacement can produce substantial reductions in energy use.

Once air conditioning is widely available, developers face less immediate market pressure to improve passive performance. A deep external shade, insulated roof, ventilated façade, smaller west-facing window, or thermally buffered courtyard can be omitted because a mechanical system is expected to correct the resulting indoor conditions. Low electricity tariffs can strengthen this incentive. The capital cost of the envelope is paid during construction, while future electricity bills are paid by occupants or tenants. The developer can therefore reduce initial cost even when the decision increases long-term energy demand.

Outdoor condenser heat adds local feedback. Air conditioners remove heat from indoor spaces and reject it outdoors together with the electrical energy consumed by the compressor and fans. At low building density, this heat may disperse relatively easily. In dense districts, courtyards, narrow service alleys, roof zones, and street canyons can receive concentrated condenser discharge. The outdoor environment becomes warmer precisely where other systems draw ventilation air or where pedestrians and neighbours are exposed.

Electricity generation adds a system-level burden. During peak cooling periods, utilities may rely on less efficient generation, imported fuels, emergency capacity, or load shedding. Transmission and distribution equipment operate under high thermal and electrical stress. Where hydropower or thermal plants are affected by drought and high-water temperature, heat can simultaneously increase demand and reduce supply reliability. The city becomes dependent on uninterrupted electricity now when the grid is under great pressure.

Mechanical cooling also changes urban morphology and household behaviour. Sealed windows reduce natural ventilation and street interaction. Roofs become sites for condensers rather than sleeping or evening use. Courtyards may be covered or filled because their climatic role appears unnecessary. Large glazed towers, deep-plan buildings, and detached villas become feasible. Over time, development standards, real-estate values, mechanical-engineering practice, and user expectations align around continuous cooling.

This is infrastructural lock-in: buildings, electricity systems, finance, regulations, and social practices evolve together in a way that makes reversal difficult. A city built around conditioned interiors and exposed outdoor space cannot reduce cooling demand through appliance replacement alone. Its roads, plots, façades, roofs, and public spaces continue to amplify heat.

The feedback is not unavoidable. Efficient equipment, low-load envelopes, district systems, and solar generation can reduce some burdens. The problem is using mechanical cooling as a substitute for controlling heat gain.

Felimban, Knaack, and Konstantinou (2023) modelled annual energy savings of approximately 25–66 per cent across retrofit scenarios for a residential building in Jeddah. The scenarios included envelope measures and air-conditioning replacement, so the range is not an envelope-only result. Savings also depended on infiltration and thermostat assumptions. The study shows that part of cooling demand can be reduced through building and equipment improvements; it does not establish a universal saving.

Lock-in should therefore be analysed through the relationship between the building load and the cooling service. An efficient appliance installed in a highly exposed building can still consume large amounts of electricity. A high-performance envelope paired with an inefficient unit wastes part of its potential. Durable reduction requires both load reduction and efficient cooling.

3. Air Conditioning as Health, Sleep, and Social Infrastructure

A fair analysis must recognize that air conditioning is a life-protecting technology. Blanket opposition to mechanical cooling would expose many people to dangerous heat, especially as hot nights, humidity, urban heat islands, and heatwaves intensify. The correct policy objective is not to deny cooling, but to provide sufficient, efficient, reliable, and low-emission cooling while reducing the building loads that make it costly.

Heat illness develops when the body cannot dissipate metabolic and environmental heat. Shade, ventilation, hydration, and reduced activity are important, but they do not always maintain safe conditions during extreme temperature and humidity. Older people, infants, pregnant people, outdoor workers returning to hot homes, individuals with cardiovascular or respiratory illness, and people taking heat-sensitive medication may require mechanically cooled refuge.

Sleep is a major cooling service. High nighttime temperatures disrupt sleep quality and reduce physiological recovery from daytime exposure. Naturally ventilated or massive buildings may moderate afternoon peaks yet remain warm at night after successive hot days. Mechanical cooling in bedrooms can therefore provide a health benefit that daytime comfort studies may underestimate.

Healthcare facilities depend on cooling for patients, staff, medicines, equipment, and infection control. Hospitals and clinics require reliable thermal conditions, but the source evidence notes that many facilities in sub-Saharan Africa lack reliable electricity. Cooling policy must consequently link efficient buildings and appliances with backup power, renewable generation, storage, and maintenance rather than assuming that grid connection alone guarantees protection.

Education and productivity are also affected. Hot classrooms reduce concentration and learning. Heat in offices, factories, shops, and homes lowers work capacity and can increase errors or accidents. Cooling access contributes not only to comfort but to welfare, labour productivity, healthcare, food preservation, and the storage of medicines. The reviewed literature explicitly treats cooling as a sustainable-development service rather than a luxury.

Cooling also supports dignity and usable domestic space. A protected room during severe heat can provide rest and refuge for vulnerable household members; treating all air-conditioning use as excessive would burden those with the least adaptive capacity.

At the same time, necessary cooling does not require every space to be maintained at a narrow low temperature continuously. Zonal cooling, ceiling fans, adaptive set points, night setback, shading, and refuge-room strategies can preserve health while reducing demand. The distinction should be between **adequate cooling service** and **unlimited conditioned volume**.

Minimum service standards should include access to a safe indoor space, reliable or backed-up power for critical users, humidity control where necessary, affordable tariffs, efficient equipment, and buildings that slow heat gain during outages.

Air conditioning and passive design should therefore be treated as complementary layers. Passive design reduces ordinary exposure and cooling cost. Fans increase comfort at low energy. Mechanical cooling protects occupants when passive conditions are insufficient. Backup power and thermal storage preserve critical service during outages. This layered approach avoids both mechanical dependence and dangerous anti-cooling austerity.

4. Unequal Cooling Access and Energy Burden

Cooling inequality is not adequately described by the division between households that own air conditioners and those that do not. At least four situations should be distinguished: households with no electrical cooling, households dependent on low-cost inefficient devices, households owning air conditioners but facing intermittent electricity or unaffordable operation, and affluent households with efficient equipment, high-quality envelopes, backup generation, and redundant systems.

The first group experiences direct cooling deprivation. In sub-Saharan Africa, large unmet cooling needs coincide with low electrification, and the Sahel is identified as a region of particularly severe unmet demand. Unmet needs extend to human comfort, health, and other temperature-sensitive services. Mechanical cooling expansion can therefore occur alongside substantial exclusion.

The second group may have fans, second-hand air conditioners, or inexpensive new units with low efficiency. Upfront purchase price dominates the decision because long-term electricity savings are uncertain or unaffordable. Inefficient appliances then increase household bills and grid demand. Standards that remove the least efficient products can help, but only if compliant appliances are affordable and replacement programmes reach low-income users.

The third group owns equipment but cannot rely on it. Grid outages, voltage fluctuation, fuel shortages, and high tariffs limit operating hours. Households may cool only one room, use the unit intermittently, or avoid it until heat becomes extreme. A nominal ownership statistic therefore overstates effective access. Electricity connection similarly overstates service where supply is unreliable.

High energy burden arises when cooling expenditure consumes a large share of household income. Poor envelopes increase this burden because appliances must operate longer. Tenants may pay the electricity bill while landlords control insulation, roof treatment, glazing, and equipment. This split incentive discourages investment even when lifecycle savings are substantial.

Affluent households occupy a different cooling system. They may have multiple air conditioners, whole-house systems, insulated construction, photovoltaic generation, batteries, generators, and access to shaded vehicles or workplaces. They can maintain cooling during outages and avoid public heat exposure. Their greater energy use may contribute disproportionately to peak load and condenser heat, but their health risk is lower.

Cooling inequality is also spatial. Informal settlements, top-floor rooms, exposed roofs, peri-urban districts, and crowded rentals often combine greater heat with weaker power and less control over the building. Appliance subsidies that ignore housing condition can reproduce unequal benefit.

Low incomes can restrict households to cheaper, less efficient cooling devices, and grid connection does not guarantee adequate or reliable energy. It also estimates that planning for cooling needs substantially increases required electrification investment compared with planning for basic household demand alone. Cooling access must therefore be included in generation, network, housing, and social-protection planning from the beginning.

Equitable policy should prioritize heat-vulnerable households, care facilities, schools, and clinics. It should support envelope retrofits, efficient appliances, fans, tariff protection for essential cooling, and reliable power. Cooling centres can provide emergency refuge but should not replace safe housing. Community microgrids or solar-plus-storage may protect critical services, although ownership, maintenance, and battery replacement must be planned.

The most equitable unit of policy is the cooling service delivered, not the number of devices sold. Measures should assess whether people can maintain safe sleep, protect medicines, use schools and clinics, and survive outages without catastrophic bills.

5. Policy Pathways, Rebound Effects, and Split Incentives

Appliance standards are a necessary first line of policy. Minimum energy-performance standards remove inefficient units from the market, while comparative labels help purchasers understand operating cost. Standards should be revised as technology improves and should cover part-load performance, high-ambient operation, standby consumption, and refrigerant impact. Enforcement is essential because nominal standards have little value when informal or second-hand markets remain dominated by inefficient products.

Efficient heat pumps can provide more cooling per unit of electricity and, in reversible systems, efficient heating where winter demand exists. Their benefits are greatest when equipment is correctly sized, installed, maintained, and matched to a low-load envelope. The reviewed research emphasizes that equipment efficiency alone is insufficient where hot air infiltration, exposed roofs, and poor insulation force systems to operate longer.

Passive-building requirements address this upstream load. Codes can require roof and wall performance, solar-control glazing, external shading, airtightness, cool or ventilated roofs, and ceiling-fan provision. Performance-based compliance can allow reinforced earth, insulated mass, hybrid masonry, and other regional systems to compete with conventional construction. Requirements should be climate-specific and should not force sealed buildings where natural ventilation remains useful.

Ceiling fans are among the most affordable demand-reduction measures. They increase air speed and can permit higher cooling set points while maintaining comfort. Fan-ready design should include appropriate ceiling height, wiring, blade clearance, and occupant control. Fans do not replace refrigeration during dangerous hot-humid conditions, but they can reduce compressor use during moderate periods and support resilience on limited backup power.

Demand response can reduce peak load by adjusting thermostat settings, cycling compressors, pre-cooling thermally buffered buildings, or shifting cooling into periods of greater renewable generation. Participation must protect health and avoid penalizing households already using minimal cooling. Automated control should include opt-out provisions for medically vulnerable occupants.

Solar-plus-storage can align daytime generation with cooling demand and protect critical facilities or households during shorter outages, but it does not automatically eliminate evening peaks or multi-day risk.

District cooling can centralize maintenance, use thermal storage, and reduce individual condensers in dense, high-load districts. High capital cost, distribution losses, monopoly risk, and provider lock-in require strong regulation of efficiency, pricing, resilience, and access.

Cool roofs reduce solar heat gain and can lower peak cooling demand, especially in top-floor and low-rise housing. Their effectiveness depends on insulation, dust, maintenance, and roof use. Passive-first mixed-mode design combines such envelope measures with natural ventilation when outdoor air is safe, ceiling fans, and efficient mechanical cooling during severe periods.

Rebound effects can erode policy savings. A household receiving an efficient air conditioner may operate it for more hours, cool additional rooms, or choose a lower thermostat setting. Improved affordability can expand access, which is socially desirable but reduces the expected fall in total electricity use. Rebound should not be treated as policy failure when it represents previously unmet health needs. It should be distinguished from unnecessary overcooling.

Split incentives affect both rental housing and commercial property. Developers or landlords choose the envelope and equipment, while occupants pay electricity bills. Tenants may be prohibited from installing shade or efficient equipment. Policies can address this through minimum rental-efficiency standards, disclosure of expected cooling cost, retrofit finance tied to the property, and incentives shared between owner and tenant.

Low tariffs may improve access while discouraging envelope investment and increasing peak demand. Tariff reform should protect essential cooling while placing higher costs on discretionary consumption, rather than reducing poor households' access to safe temperatures.

4.3 The Passive Cooling Gap: Housing Vulnerability and Unequal Heat Exposure

1. Defining the Passive Cooling Gap Index

Heat exposure is not produced by climate alone. The same outdoor temperature can result in very different indoor conditions depending on roof material, wall construction, building density, vegetation, ventilation, electricity reliability, appliance efficiency, household income, tenure, crowding, age, disability, and the availability of public or healthcare protection. A household living beneath an insulated and shaded roof with reliable electricity faces a different risk from one living beneath exposed metal sheeting, even when both are located in the same neighbourhood. Heat vulnerability must therefore be understood as the interaction of environmental exposure, the physical capacity of buildings to resist heat, access to cooling services, and the capacity of households or communities to adapt.

The **Passive Cooling Gap Index**, or **PCGI**, is proposed here as a composite screening measure for identifying weak thermal protection relative to climatic need. It is a conceptual tool that requires local calibration and validation before operational use. It considers passive design, cooling infrastructure, economic resources, and social capacity together; it does not measure the absence of vernacular features alone.

The index consists of four analytically separate domains:

1. **Climatic exposure**, including the intensity, duration, and timing of heat.
2. **Heat-amplifying built form and materials**, including housing and neighbourhood characteristics that increase indoor or outdoor heat.
3. **Limited access to affordable and reliable cooling**, including electricity, appliances, tariffs, and public cooling infrastructure.
4. **Constrained household or community adaptive capacity**, including poverty, tenure, crowding, age, disability, care responsibilities, employment conditions, mobility, and access to healthcare.

The four-domain structure builds on vulnerability frameworks that distinguish exposure, sensitivity, and adaptive capacity, but it gives greater weight to housing and cooling infrastructure. Existing indices often rely heavily on demographic indicators while treating housing quality through only one or two variables, such as building age or air-conditioner ownership. The review by Li, Toll, and Bentley (2022) shows that housing adequacy, ventilation, roof construction, energy efficiency, dwelling size, overcrowding, homelessness, and tenure remain underrepresented despite their direct influence on indoor heat.

The PCGI should retain separate domain scores before producing any composite score. A neighbourhood may have very high climatic exposure but comparatively strong housing and cooling infrastructure. Another may experience moderately high outdoor temperatures but severe vulnerability because its dwellings amplify heat and electricity is unreliable. Collapsing both places into one undifferentiated risk score would obscure the different interventions required.

The conceptual form of the index can be written as:

$$PCGI_i = w_E E_i + w_B B_i + w_C C_i + w_A A_i$$

where (E_i) is climatic exposure, (B_i) is heat-amplifying built form and materials, (C_i) is limited access to cooling, and (A_i) is constrained adaptive capacity for spatial unit (i). The weights (w) should sum to one, but no single weighting scheme should be treated as universally correct.

Under the proposed scoring system, a high PCGI score would indicate a large gap between heat exposure and available protection. It does not mean that every resident is vulnerable, that the community is incapable, or that one intervention will solve the problem. It should trigger closer investigation, community consultation, building assessment, and targeted resource allocation.

The spatial unit may be a census tract, neighbourhood, settlement, urban grid cell, district, or country. The unit should be small enough to reveal meaningful differences but large enough to protect privacy and maintain data reliability. National profiles can guide funding and policy, while neighbourhood profiles can identify the form of intervention required. Household-level application requires stronger privacy protections and should generally be used for voluntary programme eligibility rather than public mapping.

The PCGI is therefore a **proposed decision-support tool** rather than a validated measure of human vulnerability. Its value lies in making assumptions visible, separating mechanisms, and linking high scores to specific forms of action.

2. Operationalising the Four Domains

The climatic-exposure domain should represent not only daytime heat but the full thermal sequence that determines indoor accumulation and human recovery. Core variables include annual and seasonal cooling degree-days, maximum daily temperature, heatwave duration, hot-night frequency, consecutive hot nights, minimum nighttime temperature, wet-bulb temperature, humidity, and urban heat-island intensity. Where data permit, radiant exposure, drought, dust, and smoke should also be incorporated.

Cooling degree-days indicate accumulated cooling pressure but depend on the chosen base temperature. The base must therefore be reported and tested through sensitivity analysis. Hot-night frequency is particularly important because buildings and occupants require nocturnal recovery. A city with high daytime temperatures but cool nights may retain opportunities for night ventilation and thermal-mass discharge. A city with warm, humid nights may face much greater indoor danger even at a similar daytime maximum.

Land-surface temperature can help map spatial differences but should not be used as the sole climatic-exposure variable. Most existing urban-heat studies rely heavily on remotely sensed surface temperature, yet surface heat does not directly measure indoor temperature or pedestrian exposure. The reviewed literature stresses that outdoor exposure must be distinguished from indoor thermal conditions, which depend on the building envelope and cooling access. Air-temperature observations, weather-station data, mobile measurements, or validated urban-climate models should therefore complement satellite products.

The built-form and materials domain represents the degree to which housing and neighbourhood morphology amplify or moderate external heat. Variables may include roof material, roof insulation, wall material, wall thickness, glazing, building age, floor position, roof exposure, surface reflectance, ventilation potential, building density, sky-view factor, tree cover, impervious surface, courtyard presence, and proximity to anthropogenic heat sources.

Roof variables deserve particular attention in low-rise and informal housing. Corrugated metal, asbestos-cement sheeting, uninsulated concrete slabs, tiles, earth roofs, insulated assemblies, and cool coatings produce different indoor conditions. Where direct thermal data are unavailable, roof material can serve as a proxy, but the uncertainty associated with that proxy should be reported. A metal roof beneath a shaded and ventilated cavity differs from exposed metal sheeting, while an insulated concrete roof differs from an uninsulated slab.

Wall material should likewise be interpreted as part of an assembly. Earth, stone, fired brick, hollow block, timber, concrete, and mixed construction vary in thickness, moisture condition, surface finish, insulation, and thermal storage. A simple binary variable such as “traditional” versus “modern” would conceal more than it reveals.

Neighbourhood density can increase mutual shade while restricting ventilation and nighttime heat release. It should therefore be accompanied by variables for building height, street width, orientation, vegetation, and exposed roof area. Informal density, historic compactness, and high-rise density should not be treated as thermally equivalent.

The cooling-access domain measures the extent to which households can obtain and sustain safe thermal conditions when passive measures are insufficient. Variables include electricity connection, daily supply duration, outage frequency, voltage quality, air-conditioner ownership, fan ownership, appliance efficiency, access to repair, fuel or electricity cost, cooling expenditure as a share of income, tariff protection, solar or battery backup, and proximity to public cooling centres.

Electricity connection should not be used as a complete proxy for cooling access. The literature shows that households may remain exposed because supply is intermittent, voltage is inadequate, appliances are inefficient, or operation is unaffordable. Cooling ownership also requires disaggregation. A household with one old room air conditioner used for two hours per day differs from one with efficient whole-house cooling, insulation, photovoltaic power, batteries, and redundant systems.

Public infrastructure belongs in the same domain. Variables may include the number, capacity, opening hours, accessibility, and backup power of cooling centres; the availability of shaded public space; distance to healthcare; and the reliability of cooling in schools, clinics, and care facilities. The presence of a cooling centre several kilometres away should not be coded as full access for people with limited mobility or unsafe transport conditions.

The adaptive-capacity domain represents the resources and constraints that determine whether households can act on heat risk. Income and poverty are central but insufficient. Relevant variables include household crowding, tenure, housing affordability, mobility, vehicle access, social isolation, employment, caregiving, age structure, disability proxies, chronic illness proxies, education, language, migration or displacement status, access to healthcare, and participation in community organisations.

Disability and health indicators should be used only where ethically and legally appropriate. Publicly mapped data should be aggregated sufficiently to protect privacy. The purpose is to identify unmet service needs, not to label individuals. Where direct disability data are unavailable or inappropriate, accessible-housing needs, mobility limitations, care-service use, or age-related indicators may be used cautiously and documented as proxies.

Tenure is a major adaptive variable because renters and households with insecure occupancy often cannot alter roofs, install insulation, cut new ventilation openings, or invest in permanent equipment. Overcrowding increases internal heat gains, reduces access to cooler rooms, and can prevent households from concentrating cooling in one protected space. Existing reviews identify private renting and overcrowding as significant but underused indicators of heat vulnerability.

Every variable should be accompanied by metadata recording year, source, spatial resolution, missingness, uncertainty, and whether it is measured directly or used as a proxy. The index should prioritise variables with clear relationships to thermal exposure or adaptive capacity rather than adding indicators simply because they are available.

3. Index Construction, Weighting, and Uncertainty

Composite indices are useful because they condense multiple variables into interpretable patterns. They are also dangerous because they can create false precision. A PCGI score of 0.78 is not inherently more meaningful than a score of 0.73 when the underlying data come from different years, resolutions, and levels of reliability. Index construction must therefore preserve uncertainty and show how methodological choices affect results.

The first step is directionality. Every indicator should be coded so that a higher value represents a larger passive cooling gap. More hot nights, higher cooling degree-days, greater crowding, less vegetation, poorer roof quality, less reliable electricity, and greater cooling burden should all move the score in the same direction.

The second step is normalization. Variables measured in different units may be transformed to percentile ranks, z-scores, min–max scales, or policy-relevant thresholds. Percentile ranking is easy to communicate but describes relative position rather than absolute risk. A country in which nearly all neighbourhoods face extreme heat will still contain a lowest-risk percentile. Threshold-based normalization can retain more physical meaning but requires defensible limits.

Outliers require explicit treatment. Extremely high income, unusually large buildings, or rare climatic values can dominate min–max scaling. Winsorisation, robust scaling, or transformation may be justified, but each procedure should be documented and tested.

The third step is weighting. An equal-weight model provides a transparent default because it does not claim that one domain is inherently more important. Alternative schemes may use expert judgement, community priorities, analytic hierarchy processes, principal component analysis, regression against health outcomes, or policy priorities. Each method answers a different question.

Statistical weighting techniques such as principal component analysis identify patterns of covariance rather than causal importance. A variable can receive a low weight because it is uncommon or poorly correlated with others even when it is critical for a small vulnerable population. The literature documents considerable variation in index weighting and shows that removing particular indicators can unintentionally cause one domain, such as environmental exposure, to dominate the final score.

The preferred PCGI approach is to publish at least three versions: equal domain weighting, empirically derived weighting where health or indoor-temperature data permit, and locally informed weighting developed through community and stakeholder consultation. Areas that remain high across all versions can be described as robust priorities. Areas whose ranking changes substantially should be flagged for further investigation rather than assigned a confident position.

Missing data should never be silently replaced by a neutral score. Each unit should receive a data-completeness flag. Where imputation is necessary, the method and uncertainty should be reported. Multiple imputation is preferable to single substitution when the statistical assumptions are defensible. In contexts with severe data scarcity, a partial profile may be more honest than a complete but artificial index.

Uncertainty intervals can be estimated through Monte Carlo simulation. Indicator values can be sampled within measurement-error or imputation ranges, while weights vary across plausible schemes. The distribution of resulting PCGI scores shows whether an area remains consistently high or shifts widely. The literature notes that measurement error can substantially affect heat-vulnerability indices and that validation against health outcomes remains uneven.

Sensitivity analysis should test alternative spatial units, weighting systems, normalization procedures, climate periods, and indicator selections. Results should be recalculated with and without land-surface temperature, air-conditioning ownership, poverty, disability proxies, and other influential variables. Domain-level maps should always accompany the composite map.

Validation can occur through several pathways. The PCGI may be compared with heat-related mortality, emergency calls, hospital admissions, indoor monitoring, thermal simulations, cooling-energy arrears, outage impacts, or household surveys. No single validation outcome is complete. Health records may undercount illness, while indoor simulations depend on building assumptions. Agreement among multiple forms of validation is therefore preferable.

The PCGI remains a screening tool even after validation. A correlation with hospital admissions does not prove that changing one indexed variable will cause a proportional reduction in illness. Causal evaluation requires intervention studies, longitudinal analysis, matched comparisons, or quasi-experimental designs.

4. Overlooked Households and Unequal Time in Heat

Conventional building design often assumes a mobile, able-bodied occupant with control over windows, appliances, clothing, schedule, and room choice. Many people do not possess these adaptive opportunities. The amount of time spent in hot indoor environments is socially structured by housing, employment, care work, mobility, tenure, gender, age, disability, and displacement.

Informal settlements frequently combine high climatic exposure with low-quality materials, crowding, insecure tenure, weak infrastructure, limited vegetation, and restricted access to healthcare. Residents may live beneath metal or uninsulated concrete roofs and have few safe alternatives during peak heat. Informal neighbourhoods may also be absent from official databases, making them appear as data gaps rather than priority areas.

Borah, Das, and Kumar (2026) link heatwaves in Indian informal settlements with illness, mortality, income loss, and food and housing insecurity. Such outcomes depend on housing, infrastructure, livelihoods, and access to services. Upgrading should therefore be evaluated for health protection as well as physical improvement, with effects established through local evidence.

Renters face different constraints. They may be prohibited from altering the roof, adding external shade, installing efficient appliances, or changing windows. Landlords may have little incentive to invest when tenants pay energy bills. Renters with insecure or informal agreements may avoid reporting unsafe conditions. The PCGI should therefore measure both tenure type and the strength of tenant protection or retrofit rights.

Self-built housing is also heterogeneous. It can use climatically appropriate local knowledge, or it can reproduce exposed concrete and metal construction because these materials symbolize permanence or are available incrementally. Incomplete buildings may remain unplastered, uninsulated, or structurally prepared for future floors, leaving roofs and walls highly exposed. The index should not assume that self-building is either inherently vulnerable or inherently adaptive.

Internally displaced households may occupy camps, temporary structures, unfinished buildings, rented rooms, or informal settlements. Their housing may be designed for short-term shelter despite long-term residence. Legal status, mobility, documentation, and political exclusion may limit access to electricity subsidies, public cooling, healthcare, or formal upgrading.

The homes of outdoor workers require particular attention. Workers may experience intense occupational heat and then return to overheated housing without nighttime recovery. Their vulnerability arises from cumulative exposure rather than from either workplace or housing alone. Income loss during heatwaves can also reduce their ability to pay for electricity, water, transport, or healthcare.

Older adults often spend more time indoors and may have reduced sweating, mobility, cardiovascular reserve, or ability to operate cooling systems. Social isolation can delay assistance. Upper-floor and roof-adjacent rooms are particularly dangerous where older residents cannot move easily. Young children have limited physiological heat regulation and depend on caregivers for hydration, clothing, movement, and access to cooling.

People with disabilities may face inaccessible cooling centres, difficulty opening windows or shutters, reliance on electrically powered medical equipment, sensory barriers in warning systems, or dependence on caregivers. Disability should not be coded merely as individual sensitivity; the index should measure whether infrastructure and services are accessible.

Gender shapes indoor exposure through the distribution of paid work, domestic work, caregiving, mobility, and housing rights. In some settings, women spend more time in poorly ventilated homes because of childcare, elder care, food preparation, home-based employment, or social restrictions on movement.

Women may also face less access to property ownership, credit, appliances, and household decision-making. A household income indicator can therefore conceal unequal control over cooling resources. Gender-sensitive profiling should examine who occupies the hottest rooms, who performs cooking and care during peak heat, who controls electricity expenditure, and who can travel to public cooling.

These groups should not be represented only as demographic multipliers applied to an outdoor-temperature map. Their risk is produced through the interaction between bodily sensitivity, time spent in heat, housing quality, control over resources, and institutional support.

5. From Risk Profiles to Intervention Profiles

The purpose of the PCGI is not merely to identify high-risk places. It is to determine why the passive cooling gap is large and what intervention is appropriate. Two neighbourhoods with similar composite scores may require entirely different responses.

A place with high climatic exposure, exposed roofs, and relatively reliable electricity may benefit most from roof insulation, cool-roof treatment, external shade, efficient appliances, and demand management. Appliance subsidies alone would reduce operating cost but leave the heat-amplifying envelope unchanged.

A dense neighbourhood with low tree cover, high impervious surface, and strong pedestrian exposure may require shaded routes, arcades, street trees, public-space redesign, and cool or permeable surfaces. The intervention should be selected from the built-form domain rather than from a generic heat-risk label.

A settlement with adequate housing but unreliable electricity may require grid reinforcement, solar-plus-storage, protected circuits for fans or refuge rooms, and emergency outage planning. Efficient appliances have limited value when power is absent during the hottest hours.

A low-income district with high cooling-energy burden may require tariff support, appliance replacement, envelope retrofits, and tenant protection. Tariff assistance without efficiency improvement can lock public budgets into rising electricity subsidies. Envelope retrofits without tariff protection may still leave vulnerable households unable to operate cooling during extreme events.

A humid coastal city with high hot-night frequency may require efficient heat pumps, dehumidification, ceiling fans, insulated envelopes, and protected refuge rooms. Natural night ventilation or direct evaporation may be inappropriate despite their historical association with passive cooling.

A dry inland settlement with cool nights but low electricity access may benefit from secure night ventilation, fans, shaded roofs, thermal mass, ventilated courtyards, and mechanically assisted night purge powered by small solar systems. The same intervention would not be appropriate in a polluted or dust-prone city where outdoor air cannot be introduced safely.

City and country profiles should therefore include a domain dashboard rather than only a composite rank. A minimum profile should show:

- climatic exposure and hot-night trajectory;
- dominant roof and wall types;
- vegetation, density, and neighbourhood morphology;
- electricity access, reliability, appliance efficiency, and cooling burden;
- income, tenure, crowding, age, disability, displacement, and care indicators;
- public cooling, healthcare, transport, and emergency infrastructure;
- data quality and uncertainty;
- recommended interventions and responsible institutions.

Intervention selection can be formalised through a decision matrix. High built-form scores direct attention towards shade, roofs, walls, ventilation, and settlement upgrading. High cooling-access scores direct attention towards efficient appliances, electricity reliability, tariffs, solar backup, and public cooling. High adaptive-capacity constraints require healthcare outreach, tenant support, accessible transport, social-care networks, and targeted communication. High climatic-exposure scores strengthen the urgency and design standard applied to all other domains.

Informal settlement profiles should prioritize upgrading rather than clearance. The literature shows that settlement upgrading can reduce heat-related mortality by improving infrastructure and living conditions, while displacement may destroy social networks and move households to equally exposed peripheral sites.

Public cooling centres should be treated as emergency infrastructure, not a substitute for housing reform. Their profiles should include walking distance, transport, disability access, cultural acceptability, operating hours, backup power, water, staffing, and capacity. A nominal centre that cannot be reached during extreme heat provides limited protection.

Healthcare outreach should be targeted where older adults, people with disabilities, chronic illness, social isolation, and unreliable cooling overlap. Programmes may include heat-health checks, medicine guidance, hydration support, backup power for medical devices, and transport to protected facilities.

Country profiles can guide national codes, appliance standards, electrification, tariff policy, housing finance, and climate-adaptation funding. City profiles can direct neighbourhood investment. Local profiles can identify specific buildings, streets, schools, clinics, or rental sectors requiring intervention.

4.4 Institutions That Produce Heat: Codes, Finance, Land Markets, and Heritage Governance

1. Building Codes and the Marginal Status of Passive Cooling

Thermally poor buildings continue to be produced not because passive cooling principles are unknown, but because the institutions governing construction frequently treat them as supplementary rather than fundamental. Solar control, roof protection, natural ventilation, thermal mass, shaded circulation, cool surfaces, and mixed-mode operation may appear in design manuals, voluntary rating systems, or demonstration projects without becoming enforceable requirements. The result is a regulatory distinction between what designers are encouraged to consider and what developers are legally required to deliver.

Many building codes emerged from primary concern with structural stability, fire safety, sanitation, minimum ventilation, and protection against immediate hazards. These functions remain essential. Thermal performance was often added later through energy-efficiency provisions focused on calculated transmittance, equipment efficiency, or annual energy demand. In hot-arid regions, however, codes can remain shaped by temperate-climate assumptions: heating-oriented insulation logic, standardized comfort set points, limited treatment of solar radiation, and insufficient attention to roofs as the most exposed element of low-rise housing.

A code may set a maximum wall U-value while allowing large unshaded east- and west-facing windows. It may regulate glazing performance without requiring external shade. It may require roof insulation but ignore roof colour, ventilated cavities, secondary shade structures, or the effect of rooftop mechanical equipment. It may define minimum window area for light and ventilation while offering no method for evaluating whether those openings admit useful air or extreme heat, dust, noise, and pollution.

Prescriptive requirements can also produce unintended design outcomes. A requirement for a fixed window-to-wall ratio may increase solar gain in a climate where smaller, shaded openings would be more appropriate. Minimum setback rules can separate buildings that historically protected one another through party walls and mutual shade. Parking standards and road-width regulations can enlarge exposed asphalt and reduce the feasibility of shaded pedestrian circulation. Fire-access rules can be interpreted in ways that eliminate narrow, climate-protective urban forms even where alternative emergency-access strategies are possible.

Natural ventilation is often disadvantaged because mechanical ventilation has standardized testing, equipment ratings, and inspection procedures. A designer can demonstrate compliance by specifying a known fan capacity. Proving that courtyards, windcatchers, pressure differences, secure night ventilation, or mixed-mode controls will maintain adequate air quality is more complex. When codes provide no recognized calculation or testing pathway, mechanical systems become the administratively safer choice.

The reviewed literature notes that contemporary regulatory systems rarely credit natural or mixed-mode operation adequately and often prescribe mechanical ventilation without equivalent compliance routes for passive or hybrid systems. This does not mean that natural ventilation should be accepted without verification. It means that codes should provide performance-based methods through which airflow, indoor air quality, heat safety, filtration, and control can be demonstrated.

Local materials face related barriers. Earth, unstabilized masonry, lime, timber–earth composites, and other regional systems may lack approved-material status, standard test values, certified suppliers, or familiar engineering procedures. In Saudi Arabia, the cited literature reports that mud and clay blocks are absent from the approved material framework despite evidence supporting the thermal value of mass. Once a material falls outside the regulatory list, architects, lenders, insurers, and contractors avoid it because approval becomes uncertain.

Some barriers are legitimate. Unreinforced adobe can fail in earthquakes; timber can present fire, insect, or moisture risks; heavy roofs can increase seismic loads; and poorly maintained earth walls can erode. Codes should not romanticize local construction or exempt it from life-safety requirements. The avoidable barrier arises when regulations define safety through material identity rather than verified performance. Reinforced earth, engineered timber–

earth systems, hybrid frames, ring beams, compatible renders, and tested wall assemblies can address many risks.

Codes for heritage buildings create another problem when they apply new-construction requirements without recognizing existing fabric. Full compliance may require destructive changes to wall thickness, openings, stairs, services, or setbacks. Exemption may leave residents without safe electrical systems, fire protection, accessibility, insulation, or cooling. The literature describes this binary problem in Beirut, where planning and building regulations insufficiently account for the condition and characteristics of heritage buildings.

A climate-responsive code therefore requires several parallel compliance routes: prescriptive minimums for common construction, performance-based modelling for innovative systems, tested assemblies for local materials, and proportionate pathways for existing and heritage buildings. Passive cooling should be treated as part of minimum health and resilience performance rather than as architectural enrichment.

2. Finance, Appraisal, and the Preference for Standardized Floor Area

Construction finance values what can be priced, compared, insured, sold, and completed predictably. Passive cooling often creates benefits over decades, while development finance operates through short construction schedules, loan periods, sales cycles, and payback expectations. This temporal mismatch explains why technically effective measures are omitted even when they reduce lifecycle cost.

Developers typically receive income from the sale or lease of floor area. Thick walls, arcades, deep balconies, courtyards, ventilation shafts, shaded setbacks, and service spaces may reduce saleable or rentable area on a given plot. Their thermal benefit accrues later to occupants, utilities, public-health systems, or governments. From the developer’s accounting perspective, they can appear as costs that consume land without producing equivalent immediate revenue.

A courtyard illustrates this valuation problem. Environmentally, it may provide shade, controlled light, ventilation, privacy, and adaptive outdoor space. Financially, it may be recorded as unbuilt land within an expensive plot. A narrow internal corridor generates more enclosed floor area than a generous court. A shallow decorative atrium can preserve a marketable image while minimizing the perceived loss of rentable space, even if it no longer performs as a climatic device.

Thick walls face a similar disadvantage. Appraisal systems commonly value gross or net internal area rather than thermal mass, durability, or indoor stability. Replacing a thick earth or stone wall with a thinner concrete-block assembly may increase internal floor area. The benefit appears immediately in the sales plan, while higher cooling demand is transferred to future occupants.

Mortgage systems prefer buildings with standardized documentation and predictable resale value. A house built from reinforced concrete and conventional masonry can be compared with thousands of similar properties. A reinforced-earth or hybrid building may require specialist appraisal and can be treated as unusual even when it meets structural and thermal standards. Lenders respond by lowering valuations, increasing equity requirements, or refusing finance.

Insurance reproduces this preference. Standard materials have familiar fire, moisture, structural, and repair profiles. Local materials may be perceived as uninsurable because underwriters lack data or approved repair networks. This creates a circular problem: materials are not used because they lack insurance data, and data remains scarce because the materials are not used.

Developer finance also rewards construction speed. Interest accumulates while land and construction loans remain outstanding. Standard blocks, concrete frames, aluminium windows, proprietary membranes, and packaged air-conditioning systems reduce scheduling uncertainty. Local materials that require curing, seasonal work, craft coordination, soil testing, or repeated finishes can be penalized even when their lifecycle environmental performance is better.

The reviewed literature shows that conventional financial decision-making often prioritizes upfront cost over lifecycle thermal performance. It cites substantial additional costs and long payback periods for some high-performance options, while hybrid vernacular-modern approaches can require lower premiums but still exceed the short horizons favoured by investors. A measure with a thirty-year societal benefit may be rejected by an actor expecting recovery within five years.

Low electricity tariffs can deepen the distortion. When cooling energy is subsidized or priced below system cost, future savings from shade, insulation, airtightness, and thermal mass appear financially smaller. The literature links low tariffs with weak incentives to improve envelopes even where retrofit packages can deliver substantial energy reductions.

Public procurement can produce the same outcome. Housing agencies, schools, hospitals, and municipal projects may be awarded primarily on lowest initial bid or maximum unit count. Standardized designs are repeated across different climates because they simplify tendering and oversight. Shade, landscape, passive ventilation, durable finishes, and post-occupancy monitoring are treated as optional costs.

Affordable housing is particularly vulnerable. Political success is often measured by the number of units delivered, not by indoor operative temperature, cooling burden, public shade, or transport access. The reviewed research describes housing programmes in which peripheral siting, weak infrastructure, limited shade, and inadequate green space reproduce thermal vulnerability despite increasing formal housing supply.

Reform requires valuation methods that recognize lifecycle energy, heat resilience, maintenance, embodied carbon, and health. Mortgages can reward lower expected cooling costs. Appraisals can recognize verified performance. Insurance can support tested local assemblies. Procurement can evaluate cost over service life rather than construction price alone. Without such changes, passive cooling remains financially invisible even when it is physically effective.

3. Split Incentives and Fragmented Responsibility

A chain of actors in the thermal performance process incur various expenses and obtain different returns. Therefore, developers, owners of rental properties, tenants, home owners, public service providers, governmental agencies, insurance companies, employers and health care organizations have no common interests.

There are thermally poor homes still standing today due to the many parties responsible for each other's contributions toward the overall thermal performance of a structure.

The developer pays for external shading, better wall insulation, glazing (windows), thick walls, roof protection and construction that performs well.

The future occupants get the benefit of less expensive electricity bills and greater comfort. If they don't understand these potential benefits and if they don't compensate the developer for them; he will be reluctant to invest more than necessary to meet minimum government standards.

For example, in rental properties, the landlord provides for the "building envelope" and the renters pay for all of their utilities. To insulate a roof or to buy an energy-efficient window would result in cost savings to the renter as a result of lower utility charges. However, since the landlord incurs the initial cost of either option, it is likely that he/she would opt for a lower-cost alternative. As such, the renter would then purchase separate units to cool individual rooms at his/her expense.

The split can operate in reverse when utilities or governments subsidize electricity. Households receive cheaper cooling, but public budgets and electricity systems bear generation and peak-capacity costs. Developers and owners face even less pressure to reduce demand because neither construction price nor operating tariff reflects the full system burden.

Utilities may benefit financially from greater electricity sales while simultaneously facing costly peak demand, grid congestion, and outage risk. Their incentive depends on regulation. A utility rewarded for selling kilowatt-hours may have limited interest in passive retrofits. A utility operating under performance-based regulation may support demand reduction, efficient appliances, cool roofs, or thermal storage because avoided peak capacity has value.

Governments receive diffuse benefits from passive cooling: lower infrastructure investment, fewer heat-related illnesses, improved productivity, and reduced emissions. Yet the government department paying for housing may not receive the savings experienced by the health ministry or electricity utility. Budget silos weaken integrated investment.

Healthcare systems may bear the consequences of poor housing without having authority over building codes, landlord standards, electricity tariffs, or urban planning. Schools may experience heat-related learning losses but depend on municipal construction departments for retrofits. Employers benefit when workers sleep safely and recover from heat, but domestic cooling remains treated as a private household matter.

Heritage owners face another split. Society benefits from preserved cultural fabric, shaded streets, tourism, identity, and embodied-carbon savings. Individual owners bear maintenance, regulatory delay, specialist labour, and restrictions on redevelopment. Without grants, tax relief, technical support, or transferable development rights, demolition or neglect may be financially rational.

Split incentives also occur within households. One member may control expenditure while another spends more time in hot rooms. Land tenure, gender, age, and caregiving can determine who benefits from a cooling device or who is allowed to operate it. A household-level energy calculation can conceal these internal inequalities.

Short payback expectations intensify every split. Energy and health benefits over twenty years are discounted heavily by actors focused on immediate sales, annual budgets, or electoral cycles. Measures such as external shade or thick walls may last for decades but appear less attractive than replacing an air conditioner with a more efficient model that produces a clearer, shorter-term calculation.

Correcting split incentives requires assigning cost and benefit more deliberately. Minimum codes can prevent developers from transferring avoidable heat loads to buyers. Rental-efficiency standards can require landlords to provide basic thermal protection. On-bill or property-linked finance can spread retrofit cost over the period of benefit. Utility programmes can fund demand reduction where it is cheaper than new generation. Public-health budgets can support cooling access and housing upgrades for vulnerable groups.

Performance disclosure can improve market recognition, but information alone is insufficient where tenants lack bargaining power or affordable housing is scarce. Mandatory standards, finance, and enforcement must accompany labels and certificates.

The persistence of thermally poor buildings is therefore not evidence that passive cooling lacks value. It shows that the actor able to implement it is often not the actor receiving the largest return.

4. Heritage Governance, Adaptation, and Resident Rights

Heritage governance must balance several objectives that can conflict: preserving material authenticity, maintaining urban form, enabling climate adaptation, introducing safe services, sustaining traditional skills, protecting resident rights, and avoiding displacement. A policy that maximizes only one objective can damage the others.

Strict fabric preservation can restrict roof insulation, solar panels, secondary glazing, ventilation equipment, fire systems, lifts, shading devices, or moisture interventions. These restrictions may protect visual authenticity while leaving buildings uncomfortable, unsafe, or too expensive to occupy. Residents then abandon them, and preservation produces vacancy rather than continuity.

Unregulated adaptation creates the opposite risk. Cement render can damage earth or lime walls. Air-conditioning condensers can disfigure façades and heat courtyards. Sealed glazing can eliminate ventilation. Courtyards may be covered, roofs subdivided, and internal arrangements destroyed. A building remains occupied but loses the material and spatial relationships that justified its heritage value.

Traditional skills are central to this balance. Earth repair, lime plastering, timber joinery, stonework, roof drainage, shading screens, and passive ventilation require knowledge. If heritage rules demand traditional materials but provide no training, supply chains, or financial support, compliance becomes expensive and uncertain. Owners may use incompatible materials or defer maintenance.

Safe modern services are necessary for living heritage. Electrical wiring, plumbing, fire detection, structural reinforcement, accessible circulation, cooling, filtration, and communications must be integrated without unnecessary destruction. The correct standard is not zero change, but compatible, reversible, and evidence-based change.

The Historic Urban Landscape approach offers a useful shift from isolated monuments to the wider relationships among buildings, streets, landscape, community, economy, and cultural practice. Shehata (2022) describes its regulatory, community, planning, and financial tools as a potential framework for integrating climate adaptation with heritage management, while noting limited adoption across many Arab conservation systems.

District-scale protection is especially important for climate-responsive heritage. Narrow streets, mutual shade, shared walls, rooflines, courtyards, vegetation, water systems, and wind paths cannot be preserved through façade rules alone. A listed house loses part of its environmental logic when neighbouring buildings are replaced by towers, roads are widened, or shaded markets are demolished.

Heritage-led displacement presents another tension. Restoration can increase property values, tourism, commercial rents, and investor interest. Residents may be removed from buildings that are then converted into hotels, museums, luxury apartments, or entertainment venues. The physical fabric is preserved while the social practices, maintenance knowledge, and everyday occupation that sustained it disappear.

Tourism-oriented restoration may also prioritize visual authenticity over thermal adaptation for residents. A courtyard is restored as a photographic space but no longer supports domestic use. Traditional screens become decoration. Air conditioning is concealed for visitors while neighbouring households remain unable to afford repairs or cooling.

The reviewed literature emphasizes that conservation imposed without participation produces dissatisfaction and resistance, and that adaptive reuse should involve owners and local populations while addressing their needs. Resident participation must therefore concern more than consultation over colours or façades. It should include tenure security, rent protection, service upgrades, cooling needs, maintenance finance, access to employment, and the future use of buildings.

Climate adaptation in heritage areas should follow a hierarchy. First, repair and restore passive features already present: shading, shutters, courtyards, ventilation paths, roofs, lime finishes, and seasonal spaces. Second, add compatible low-visibility measures such as roof insulation, efficient fans, secondary glazing, filtered ventilation, or reversible shade. Third, integrate efficient mechanical cooling where necessary without concentrating waste heat in public or courtyard spaces. Fourth, monitor indoor conditions and resident outcomes.

Heritage should remain a living form of climate knowledge rather than a visual commodity. Its governance succeeds when buildings remain safe, inhabited, adaptable, and socially meaningful.

5. Comparing Policy Environments Through a Readiness Matrix

National and municipal policy environments differ not only in the wording of their building codes but in their capacity to convert policy into construction practice. A jurisdiction may have an advanced energy code but weak enforcement. Another may permit earth construction but lack trained engineers, finance, or material testing. A third may run an effective cool-roof programme without integrating it into ordinary housing standards.

A policy-readiness matrix can make these differences visible. The matrix should assess at least ten dimensions: codes, enforcement, professional training, material standards, finance, public procurement, cooling plans, heritage rules, data systems, and community participation.

Codes should be assessed according to whether they address roof exposure, solar gain, external shade, airtightness, thermal mass, natural ventilation, mixed-mode operation, overheating, and power-outage resilience. The matrix should distinguish mandatory requirements from voluntary guidance.

Enforcement should assess municipal staffing, plan review, site inspection, testing, penalties, third-party verification, and post-occupancy checks. Code adoption without implementation should not receive a high readiness score. India's ECBC experience demonstrates that professional familiarity, municipal authority, compliance tools, and administrative capacity are necessary to turn standards into practice.

Professional training should cover architects, engineers, energy modellers, contractors, masons, inspectors, valuers, insurers, and heritage professionals.

The reviewed research repeatedly identifies training deficits as a major barrier to implementation. Universities and professional licensing systems should be assessed alongside short courses and certification.

Material standards should evaluate whether earth, lime, local stone, timber, recycled materials, and hybrid systems have recognized testing and approval pathways. A jurisdiction should receive credit not merely for permitting local materials, but for publishing structural, moisture, fire, and seismic guidance that makes safe use practical.

Finance should assess green mortgages, retrofit loans, insurance access, guarantees, grants, tax incentives, property-linked finance, and support for low-income households. It should also examine whether appraisal recognizes verified energy and thermal performance.

Public procurement should determine whether tenders reward lifecycle performance, indoor comfort, peak-demand reduction, embodied carbon, maintenance, and monitoring, or merely lowest initial cost and maximum floor area. Governments can create markets for climate-responsive materials through schools, clinics, housing, and municipal buildings.

Cooling plans should assess whether national or city strategies integrate appliance standards, passive buildings, equitable cooling access, refrigerants, electricity reliability, heat-health plans, and emergency refuge. A plan focused only on efficient air conditioners should rank below one that addresses the full cooling system.

Heritage rules should evaluate adaptive-reuse pathways, district-scale protection, resident participation, compatible service upgrades, maintenance grants, anti-displacement safeguards, and support for traditional skills.

Data systems should include building-stock characteristics, roof and wall materials, energy use, indoor-temperature monitoring, heat-health outcomes, permit compliance, cooling ownership, outage data, and public reporting. Without data, policies cannot be evaluated or updated.

Community participation should assess whether residents, tenants, informal-settlement representatives, disability groups, women's organisations, craftspeople, and local businesses influence standards, projects, and monitoring. Participation should affect decisions and resource allocation rather than operate as symbolic consultation.

Each dimension can be scored through a four-stage scale: **absent**, **emerging**, **established**, and **implemented with verification**. "Established" should mean that policy exists; the highest category should require evidence of enforcement, uptake, and measured outcomes.

The matrix should also distinguish national and municipal responsibilities. National governments often control material standards, appliance efficiency, professional accreditation, finance, and electricity policy. Municipalities control planning permission, local enforcement, streets, shade, public buildings, heritage districts, and community engagement. Effective policy requires alignment across levels.

CHAPTER 05

From Inheritance to Implementation

A Climate-Adaptive Design and Policy Toolkit

5.1 Translate Principles, Not Appearances

1. The VCPF as a Disciplined Design Sequence

The Vernacular Cooling Performance Framework, or VCPF, provides a method for converting historical and locally developed environmental knowledge into contemporary design decisions. Its purpose is not to classify buildings as vernacular or modern, nor to prescribe a catalogue of traditional forms. It organizes design as a six-stage sequence: characterize Exposure; shape Form; specify Fabric; organize Flow; support adaptive Practice; and test Translation through cost, codes, skills, maintenance, safety, equity, and future climate. Each stage asks a different question, and each must be completed before a strategy is accepted as suitable.

Exposure identifies the environmental problem that the building must manage. It includes peak dry-bulb temperature, solar radiation, mean radiant temperature, humidity, diurnal range, hot-night frequency, wind direction and reliability, dust, pollution, drought, water availability, seasonal extremes, urban heat, and power reliability. Exposure must be described at the scales relevant to the project: regional climate, neighbourhood morphology, site microclimate, building envelope, room, and occupant. A design response derived from a dry inland settlement cannot be transferred safely to a humid coastal city merely because both are described as hot.

Form determines how geometry redistributes environmental exposure before material or equipment is selected. It includes orientation, compactness, building height, street or block relationship, courtyards, depth of plan, roof geometry, external shade, transitional space, shared walls, and the position of openings. Form should first reduce direct solar access and unnecessary external surface area while preserving useful daylight, ventilation, access, privacy, and emergency movement.

Fabric concerns the physical assemblies through which heat is reflected, absorbed, stored, transmitted, released, or resisted. It includes roof and wall materials, thermal mass, insulation, surface absorptance, glazing, airtightness, moisture behaviour, durability, embodied carbon, and repairability. Fabric decisions should distinguish between the functions of resistance and storage. A thick wall may provide time lag but inadequate insulation; a lightweight insulated wall may resist transmission but offer little buffering during power loss.

Flow organizes air, heat, moisture, and, where appropriate, water. It includes cross-ventilation, stack effect, wind pressure, night purge, fans, filtered ventilation, mechanical cooling, evaporative systems, drainage, and the movement of occupants between thermal zones. Flow must be controlled rather than assumed. An opening is useful only when pressure, temperature, air quality, security, and occupancy permit it to perform its intended function.

Practice recognizes that vernacular performance was frequently produced by operation rather than by form alone. Shutters were opened or closed at particular hours, rooms changed function by season, roofs were occupied at night, courtyards were watered selectively, and household members moved between spaces. Contemporary design must support realistic adaptive actions without depending on constant attention, unpaid labour, physical strength, or social arrangements that exclude vulnerable occupants.

Translation is the final test. A technically effective mechanism must also comply with structural, fire, accessibility, health, and heritage requirements; fit available skills and supply chains; remain affordable; be maintainable; distribute benefits equitably; and continue to work under future climate conditions. The reviewed literature similarly argues that successful practice extracts bioclimatic principles rather than copying geometry and that traditional and modern systems should be combined where this improves performance, durability, and contemporary use.

The VCPF is therefore sequential but iterative. A proposed form may fail the fabric test, a ventilation concept may fail the air-quality test, or an effective strategy may fail translation because maintenance skills are unavailable. The designer then returns to an earlier stage and revises the proposal. This discipline prevents cultural symbolism, environmental claims, or advanced modelling from substituting for a complete design argument.

2. Mechanism Before Appearance

The central rule of translation is that environmental mechanisms must be separated from architectural appearance. A historical element may carry cultural, social, and aesthetic meaning, but its thermal value arises through specific relationships among geometry, material, climate, operation, and occupancy. Copying its outline does not reproduce those relationships.

A courtyard is not environmentally effective because a space is labelled a courtyard or placed at the centre of a plan. It is a controlled shaded void whose dimensions, orientation, sky exposure, wall height, openings, materials, vegetation, water use, and daily operation influence solar gain, air movement, radiant temperature, and heat storage. A narrow glazed atrium may resemble a courtyard in plan while trapping heat. A large exposed court may increase solar load. Translation requires the designer to specify what the void must accomplish: daytime shade, secure night ventilation, stack exhaust, protected outdoor use, daylight distribution, or connection among rooms.

A windcatcher is an air-pressure and buoyancy device, not a tower-shaped ornament. Its performance depends on wind direction, pressure coefficients, inlet height, shaft area, surface roughness, internal resistance, outlet position, temperature difference, and urban obstruction. A decorative roof projection without a continuous air path captures no useful air. A contemporary windcatcher may need dampers, filters, acoustic treatment, low-energy fans, insect protection, condensate control, and sensors. Its form may differ substantially from the historical precedent while preserving the same pressure and flow logic.

A thick wall is a time-dependent thermal system. Thickness alone does not guarantee comfort. Performance depends on conductivity, density, specific heat, diffusivity, surface absorptance, insulation, internal gains, climate, and the ability to discharge stored heat. In a climate with cool nights, exposed internal mass may delay daytime peaks and release heat during ventilation. During successive hot nights, the same wall may accumulate heat and raise bedroom temperatures. Translation therefore requires a specified time lag, decrement factor, U-value, surface treatment, and night-recovery strategy rather than a generic requirement for “thermal mass”.

A mashrabiya, jali, screen, or lattice is not merely a regional motif. It is a calibrated interface among solar control, privacy, daylight, view, and airflow. Its depth, porosity, orientation, pattern, position relative to glazing, and material determine whether it blocks high-angle sun, reduces glare, admits useful air, or creates visual privacy. A printed pattern applied to sealed glass may preserve appearance while losing shade and ventilation. A contemporary external screen may use different materials and geometry yet remain more faithful to the original environmental principle.

The same distinction applies to arcades, domes, vaults, roof terraces, fountains, elevated floors, and seasonal rooms. Each should be translated into a performance statement. An arcade must provide measurable shade during occupied hours. A dome must demonstrate how its geometry affects solar exposure, stratification, or ventilation. A fountain must justify water use through measured thermal benefit. A roof terrace must remain accessible, safe, private, and cooler than alternative spaces during its intended period of occupation.

Literature supports this mechanism-based interpretation. It identifies ventilation, shading, thermal mass, rainwater management, elevated floors, and spatial organization as transferable principles while warning that modernization can retain a cultural image yet replace climate-responsive materials and configurations with less effective systems.

Mechanism-based translation also protects against unsupported sustainability claims. A project should not be described as passive because it contains a courtyard, nor vernacular-inspired because it uses earth-coloured finishes. The claim should identify the mechanism, baseline, expected effect, method of verification, and conditions under which it will cease to work. Appearance can remain culturally important, but it cannot serve as evidence of thermal performance.

3. Climate- and Occupancy-Led Strategy Selection

Strategy selection should begin with the environmental and social problems, not with a preferred architectural icon. The first design task is to classify the climate subtype and then describe the conditions that matter for the building's operation. Hot-arid, semi-arid, coastal-arid, high-altitude arid, cold-desert, and composite climates should not receive identical passive-cooling packages.

A large daily temperature swing allows for better use of both thermal mass as well as nighttime heat loss (purge). A small day-to-day temperature difference reduces opportunities to lose the built-up heat. A high rate of occurrence of very hot nights will demand particular emphasis on the bedroom area, where the stored heat will need to be removed using some combination of mass storage (thermal mass), mechanical equipment and strategies to allow the house to survive an extended outage.

Whether evaporative cooling is effective depends entirely on humidity levels. If the humidity levels are too high, it is difficult to provide any beneficial physiological relief with either increased air flow speeds, or evaporative cooling.

Wind has many characteristics besides just velocity that need to be evaluated when considering ventilation. These include direction, time-of-occurrence, consistency, particulate matter concentration, sound levels generated, and pollutants present. Therefore, evaluating wind based solely on mean annual values would not adequately represent its total impact.

Air quality and particulate matter concentrations can make certain types of ventilation unworkable. For example, although a windcatcher or open courtyard could have positive thermal effects, they are often hazardous during dust storms, wildfires, automobile exhausts and other forms of industrial pollution. In this case, a mechanically ventilated space with filters and a safe closed-mode would be required.

The availability of water will determine whether features such as fountains, wetted surfaces on rooftops and walls, green roofs, plantings in courtyards and irrigation systems are feasible throughout the duration of the project. Systems that work only while water is continuously supplied through pipes may be unsuitable in regions that experience significant droughts.

Density of urbanization influences both the amount of shading provided by buildings in a city as well as the amount of ventilation possible. While compact neighborhoods may limit the amount of radiant energy received from the sun during the day, they tend to retain much more heat overnight than less densely developed areas. Conversely detached homes may receive significantly more wind than compactly arranged homes; however they may also receive greater amounts of radiant heating energy from the sun.

Building type changes priorities. A school requires daytime shade, air movement, air quality, and robust controls that teachers can operate. A hospital requires filtered air, reliable cooling, redundancy, and strict safety thresholds. Housing requires nighttime recovery, privacy, cooking-heat control, and affordable operation. A market may prioritize shaded circulation and short-duration comfort. A care home requires lower risk thresholds and dependable mechanical backup.

Occupancy schedule is equally important. Night ventilation is valuable only if it can cool the building before the next occupied period and can operate securely. A daytime office may tolerate nighttime mechanical purge without disturbing occupants. A residence may require quiet fans, insect protection, privacy, and manual overrides. A building occupied continuously cannot depend on aggressive purge cycles that create drafts or noise.

Vulnerability should be included at the beginning of selection. Older adults, children, people with disabilities, those with chronic illness, and occupants unable to operate windows or move between spaces cannot be treated as average adaptive users. Strategies requiring roof access, frequent manual operation, water carrying, or strong airflow may exclude some residents. Passive design should expand adaptive opportunity rather than transfer environmental labour to those least able to perform it.

The literature proposes different priorities in different climates: ventilation and shade in humid settings, thermal mass and carefully managed evaporation in hot-dry settings, and a general sequence in which passive measures precede fans and efficient active systems. These are starting principles rather than universal prescriptions.

The strategy-selection process should therefore produce a climate-and-use brief before design begins. It should record beneficial and hazardous hours for ventilation, available nighttime cooling, solar-critical orientations, water constraints, dust events, occupancy patterns, vulnerable users, mechanical-system expectations, and future-climate changes. Only then should architectural options be compared.

4. A Hierarchy of Action

VCPF uses a hierarchy of action to prevent designers from selecting an energy-intensive or operationally complex response before simpler heat-control opportunities have been addressed. The sequence is: avoid heat gain; reduce absorbed heat; delay transmission; dissipate stored heat; increase safe air movement; support adaptive comfort; and provide efficient active cooling for residual loads and life safety.

The first priority is to avoid heat gain. This includes orientation, compactness, party walls, shaded streets, external roof shade, deep overhangs, arcades, screens, reduced east- and west-facing glazing, shaded courtyards, and control of internal loads. Avoidance is generally more robust than removing heat after it enters. External shade is especially valuable because it intercepts radiation before glazing, walls, roofs, and occupants absorb it.

The second priority is to reduce absorbed heat. High-reflectance roofs, appropriate façade finishes, ventilated roof cavities, secondary skins, low-solar-gain glazing, and shaded vegetation reduce the fraction of incident energy stored in the building or ground. Reflectance must be evaluated by surface type: highly reflective roofs can be beneficial, while bright walls and paving may increase pedestrian radiant exposure.

The third priority is to delay transmission through insulation, thermal mass, earth contact, cavities, and layered construction. Delay is valuable when the shifted heat can be released during a cooler period or when mechanical systems can operate more efficiently later. It is harmful when the delayed peak moves into sleeping hours. Time lag must therefore be linked to occupancy and nighttime recovery.

The fourth priority is to dissipate stored heat. Night ventilation, stack exhaust, roof radiation, controlled flushing, earth coupling, and thermal storage management prevent daily accumulation. Dissipation should be conditional on outdoor temperature, humidity, air quality, security, and noise. Mechanically assisted purge may be justified where fan energy is small relative to the cooling load avoided.

The fifth priority is to increase safe air movement. Cross-ventilation, ceiling fans, personal fans, stack devices, and wind-assisted systems increase convective and evaporative heat loss. Air speed should be delivered to occupied zones rather than measured only at an opening. Outdoor air exchange and occupant-level air movement should be distinguished: fans can improve comfort without admitting hot, polluted, or dusty air.

The sixth priority is to support adaptive comfort. Occupants should be able to control shade, fans, openings, room choice, clothing, and schedule within safe limits. Buildings can provide thermal diversity rather than one uniform condition. Transitional spaces, cooler rooms, shaded courts, and seasonal zones allow people to select environments appropriate to activity and time.

The final priority is efficient active cooling for residual loads and life safety. Passive-first does not mean passive-only. High-efficiency heat pumps, dehumidification, zoned cooling, thermal storage, renewable power, and protected refuge rooms are necessary when climate, health, occupancy, or outdoor air quality exceeds passive limits. Active systems should be sized after passive load reduction so that equipment and peak demand remain as small as safely possible.

This hierarchy prevents the common error of placing evaporation, wind devices, or thermal mass into every project because they are associated with vernacular architecture. It also integrates contemporary requirements for indoor air quality, accessibility, privacy, durability, and structural safety. The reviewed research emphasizes that traditional mechanisms must be supplemented where necessary by monitoring, adaptive controls, filtration, accessibility measures, and more durable structural systems.

5. Performance Specifications for Translated Strategies

Translation becomes credible only when strategies are expressed as measurable performance requirements. Specifications should identify the target, baseline, test method, operating conditions, uncertainty, responsible party, and post-occupancy verification procedure. Architectural description alone is insufficient.

For shade, the specification should state the required percentage of critical façade, glazing, roof, courtyard, or pedestrian area shaded during defined dates and occupied hours. Solar analysis should report annual and peak-period incident radiation before and after the intervention. A mashrabiya-derived screen, arcade, or canopy should therefore be evaluated through shade hours, solar heat-gain reduction, glare, daylight, view, privacy, and airflow.

For roofs and walls, specifications should include U-value, solar absorptance or reflectance, thermal capacity, time lag, decrement factor where relevant, airtightness, moisture behaviour, and surface-temperature limits. Massive assemblies should demonstrate that stored heat can be discharged under expected and future nighttime conditions. Roof specifications should include dust ageing, access, drainage, maintenance, and performance after coating degradation.

For ventilation and air movement, the designer should specify required air-change rates for indoor air quality separately from occupant-level air-speed targets for comfort. Natural-ventilation performance should be tested across wind directions and calm conditions. Night-purge specifications should identify the minimum useful outdoor–indoor temperature or enthalpy difference, required airflow, control logic, noise limits, filtration, and security provisions.

For courtyards and transitional spaces, targets should include shade duration, maximum operative or mean radiant temperature during intended use, nighttime cooling rate, airflow path, daylight, and occupied-hour comfort. A courtyard should also be tested for future neighbouring obstruction, vegetation maturity, condenser heat, and water restrictions.

For thermal comfort, annual percentage compliance alone is inadequate. Specifications should include peak operative temperature, overheating degree-hours, hot-night exposure, bedroom conditions, adaptive comfort compliance, and vulnerable-occupant thresholds. Extreme heat and power-outage scenarios should be tested separately from ordinary weather.

For energy, targets should include cooling-energy intensity in kilowatt-hours per square metre per year, peak electrical demand, equipment efficiency, fan energy, water use, and the fraction of occupied hours served through passive, fan-assisted, and mechanical modes. Baseline assumptions must be explicit. A claimed 30 per cent saving is meaningless without the reference building, set point, occupancy, weather, and mechanical schedule.

For maintainability, the specification should identify cleaning frequency, replacement intervals, access requirements, local skill availability, water and energy consumption, spare parts, and responsibility for operation. Screens that cannot be cleaned, fans that cannot be repaired locally, and coatings that fail under dust should not qualify as successful translations.

For safe operation, every passive strategy requires a failure mode. Ventilation systems need closure and filtration during smoke or dust. Evaporative systems need hygienic water management and a dry operating mode. Heavy shading devices require structural verification. Roof occupation requires safe access, guardrails, privacy, and load capacity. Mixed-mode controls must prevent mechanical cooling from operating wastefully against open windows.

Literature supports sensor-based verification and context-specific performance indicators while warning that real-building savings are often lower than simulation estimates. Post-occupancy monitoring should therefore be included within the project scope, with corrective action required where measured performance differs materially from the design claim.

5.2 A New-Construction Design Matrix for Arid Climate Subtypes

1. A Common Method for Climate-Specific Design

Climate-responsive design in arid regions should begin with a local performance brief rather than a universal checklist. The first task is to identify the subtype of aridity, the seasonal and diurnal structure of heat, the reliability of wind, the occurrence of hot nights, the level of humidity, the availability of water, the condition of outdoor air, and the building's occupancy pattern. These variables determine whether mass, ventilation, evaporation, fans, insulation, or mechanical cooling will be beneficial. The same courtyard, wall, or ventilation opening can perform well in one arid city and fail in another. The reviewed literature likewise concludes that integrated packages must be matched to climate subtype and that many apparently general design variables including window-to-wall ratio, ventilation rate, evaporative potential, and phase-change temperature require local calculation rather than universal prescription.

The design process should coordinate urban and building decisions from the beginning. At neighbourhood scale, block orientation, street width, building height, connected walls, tree or canopy placement, paving, public-space shade, and district energy affect the microclimate received by each building. At building scale, roof, wall, glazing, courtyard, ventilation, fans, and active systems modify that microclimate further. A building-level strategy that rejects heat into an enclosed courtyard or street can worsen neighbourhood exposure. Conversely, a compact block that provides shade but eliminates useful airflow can raise nocturnal temperatures. Integrated analysis should therefore move from urban microclimate modelling to whole-building analysis and then to renewable and mechanical-system sizing, so that system sizing reflects the reduced building load.

General targets can be defined even when their values require local calculation. Critical pedestrian routes, waiting areas, façades, and roofs should be shaded during peak exposure. Glazing heat gain should be controlled through orientation, external shade, and appropriate glass. Naturally ventilated zones should be assessed through operative temperature, overheating degree-hours, air speed, air quality, and nighttime recovery. Cooling-energy intensity should be normalised by floor area and use, while peak demand should be tested under extreme weather.

Occupied-zone air-speed targets should be assessed using an applicable comfort model, activity level, clothing, and access to individual control. Ventilation for air quality should be distinguished from air movement for comfort. Outdoor-air cooling should respond to temperature, moisture, and air quality, while maintaining required fresh-air provision; a fan circulating indoor air does not supply ventilation.

Overheating targets should use both adaptive and protective criteria. Ordinary occupied hours in free-running buildings may be assessed against an appropriate adaptive comfort band, but bedrooms, clinics, schools, older occupants, and extreme events require stricter limits. Project specifications should report the proportion of occupied hours within the selected comfort category, annual and seasonal overheating degree-hours, maximum operative temperature, hot-night exposure, and the time required to reach unsafe conditions during power loss. No design should be declared successful solely because indoor temperature remains below the outdoor afternoon maximum.

Building type and occupancy schedule must be incorporated from the outset. Low-income housing requires low capital and operating costs, repairable materials, secure ventilation, and protected sleeping space. Detached houses need stronger control of their exposed envelope, while apartments must protect top floors and west-facing units. Schools require shade, air movement, and fresh air; clinics require filtration, redundancy, and backed-up cooling; offices require strict solar and internal-gain control; markets require continuous public shade; and heritage-compatible infill must preserve street shade, courtyard relationships, scale, and wind paths.

The following pathways apply this common method to five major climate subtypes. They should be read as design sequences rather than fixed style guides. Each pathway begins with the climatic mechanism, then defines priorities for form, fabric, flow, operation, active systems, and neighbourhood coordination.

2. Inland Hot-Arid Climates with Cool Nights

In inland hot-arid climates with a large diurnal range, the central design opportunity is to prevent daytime heat gain and use cool nights to discharge stored heat. Compact urban form, attached buildings, shaded lanes, controlled courtyards, and low external surface area are generally advantageous. Blocks should be oriented to limit east–west façade exposure while preserving access to prevailing evening or nighttime winds. Street proportions should be calculated from solar geometry so that principal pedestrian routes and lower façades remain shaded during critical afternoon hours without creating stagnant nocturnal conditions.

Courtyards should be treated as timed environmental spaces. Their height-to-width ratio, orientation, openings, materials, and vegetation should produce substantial daytime shade while retaining a clear nighttime path for long-wave loss and purge ventilation. Overly narrow courts can trap heat and restrict air movement; overly broad courts can behave as exposed solar collectors. Their dimensions should therefore be derived through seasonal shade simulation, airflow analysis, and nighttime cooling tests rather than copied from a historic precedent. Water features may be used only where wet-bulb depression and water availability justify them.

Roofs are the primary exposed surface in most low-rise housing. The preferred sequence is external shade or a ventilated secondary roof, high solar reflectance where glare is controlled, adequate insulation, and interior thermal mass where night discharge is reliable. Flat roofs may support solar panels, shaded outdoor use, or night-purge equipment, but the thermal and social functions must not conflict. Photovoltaic canopies can combine generation and roof shade, while batteries or thermal storage can support fans and limited cooling during evening peaks or outages.

Walls should combine solar protection, resistance, and controlled mass. Externally insulated earth, stone, brick, or concrete can preserve interior buffering while preventing excessive daytime charging. Large uninsulated mass is inappropriate where several hot nights occur consecutively. Glazing should be limited on east and west façades, externally shaded, and selected for low solar heat gain. Daylight should be admitted through shaded openings, courtyards, light shelves, or high-level apertures rather than large exposed glazing.

Night ventilation is the defining operational strategy. It should activate only when outdoor air is sufficiently cooler than indoor air and exposed mass, moisture conditions are acceptable, and when dust, smoke, noise, and security permit opening. Natural cross-flow can be supplemented by low-energy fans or mechanically assisted purge. The reviewed research identifies mass effect with night ventilation as one of the principal strategies for hot-desert climates and emphasises that the mechanism depends on cooling the building fabric with lower nighttime temperatures. Design should target complete or substantial recovery of the interior mass before morning rather than a nominal air-change rate.

Ceiling fans should be included as standard infrastructure. During shoulder periods they may maintain comfort without refrigeration; during hotter periods they can support higher thermostat settings. Direct evaporative cooling can be effective where wet-bulb depression is large, but its performance should be specified through achievable supply temperature, water use per cooling-hour, and hygienic operation. Vegetation should prioritise shade per unit of water through drought-adapted canopy and non-potable irrigation where feasible.

Low-income housing should emphasise shaded roofs, party walls, secure night ventilation, fans, and one efficiently cooled refuge room. Detached housing can use courtyards and zoned systems but should limit exposed façade. Schools and offices should pre-cool mass at night, while markets require continuous shade and clinics require filtered ventilation with active backup.

Performance targets should include critical-area shade for most peak-sun hours; a low effective solar heat gain through east and west glazing; nighttime purge sufficient to prevent day-to-day heat accumulation; occupied-zone air speed in the locally acceptable warm-condition range; and cooling-energy intensity substantially below a code-minimum reference building. The exact targets should be derived from local weather and use, but the package should demonstrate lower daytime peaks, lower overheating degree-hours, and adequate pre-dawn recovery.

3. Extremely Hot Climates with Persistently Hot Nights

Extremely hot climates with persistently hot nights require a different pathway because the environmental sink used by traditional mass and night-ventilation strategies is weakened or absent. The priority shifts from storing daytime heat for later release to preventing heat from entering at all. Buildings should use highly effective roof and façade shade, continuous insulation, airtightness during extreme periods, low-solar-gain glazing, minimised internal loads, and efficient mechanical cooling sized after envelope reduction.

Urban compactness remains valuable for daytime shade, but excessive enclosure can intensify nocturnal heat. Block design should therefore combine mutual shade with deliberate ventilation corridors, protected courtyards, and low-heat public surfaces. Shared walls reduce envelope area, yet condenser placement and district waste heat must be managed. Trees or tensile canopies should protect pedestrian routes, transit stops, schools, clinics, and markets, while irrigation demand is assessed against long-term water availability.

Courtyards in this subtype should not be assumed to become cool-air reservoirs at night. Their primary roles may be shade, daylight, privacy, and protected circulation. Operable roof screens, high-level exhaust, reflective or low-capacity surfaces, and condenser-free design can reduce heat trapping. Deep massive walls should be used cautiously unless externally insulated and actively or mechanically discharged. Lightweight, highly insulated assemblies may outperform exposed mass during long heatwaves because they absorb less heat and respond more quickly to controlled cooling.

Roofs require the strongest protection: high reflectance or a shaded secondary layer, continuous insulation, reduced thermal bridges, airtight service penetrations, and space for photovoltaic generation. Wall assemblies should prioritise low heat transfer and low solar absorption. Glazing area should be tightly controlled, particularly on east and west orientations, with external shading sized for local sun angles. Daylighting should be delivered through shaded apertures and high-efficiency systems that avoid glare and internal heat.

Natural ventilation should be treated as an opportunistic mode, not the default. Controls should compare outdoor and indoor temperature, humidity, enthalpy, particulate matter, and security conditions before opening. Where nights remain hotter than the interior, ventilation may increase heat gain. Fans remain valuable because they improve air movement at low electrical demand, but they cannot guarantee safety at extreme temperature and humidity. Direct evaporation may provide relief in very dry inland conditions, yet water use and indoor humidity must be controlled; in severe water stress it should be reserved for limited zones or indirect systems.

Efficient heat pumps, zoned cooling, thermal storage, solar-plus-storage, and demand response become central rather than residual. Thermal storage should shift electrical demand and protect critical rooms during outages, but storage temperature and capacity must be designed for the expected heat-wave sequence. District cooling may be appropriate in dense developments, hospitals, campuses, or commercial zones if distribution losses, resilience, pricing, and condenser heat are managed.

The reviewed research shows why passive-only packages are inadequate in the most severe cases: Basrah achieved very low baseline comfort under simple mechanical ventilation, and future natural-ventilation potential may approach zero during peak summer months in some climates. The design objective is therefore load minimisation plus guaranteed life-safety cooling.

Low-income housing should receive roof and wall upgrades, efficient fans, high-efficiency room cooling, tariff protection, and backup for a refuge room. Apartments should exploit shared walls while protecting top floors. Schools require shade, fans, and peak-hour backup; clinics require filtration and redundant power; offices require low internal gains and storage; markets require large-scale shade with active cooling in critical zones.

Performance specifications should prioritise maximum operative temperature, hot-night exposure, outage survivability, peak electrical demand, and cooling-energy intensity. Natural-ventilation hours should be counted only when outdoor conditions are genuinely beneficial. The building should demonstrate safe changeover among closed passive mode, fan-assisted mode, and mechanical cooling without simultaneous wasteful operation.

4. Composite or Monsoon-Influenced Arid Climates

Composite and monsoon-influenced arid climates alternate among hot-dry, hot-humid, dusty, rainy, and sometimes cool seasons. Their design pathway must be reversible. A building optimised only for dry-season ventilation may admit excessive humidity during the monsoon; a sealed air-conditioned building may waste the substantial natural-ventilation potential available during shoulder seasons. Form, envelope, and controls should support multiple seasonal states.

Urban form should provide shade and drainage while preserving seasonal airflow. Blocks can remain moderately compact, but streets and courtyards should be aligned to useful winds without creating channels for dust or driving rain. Covered walkways, verandas, arcades, recessed entrances, and shaded public transport are valuable throughout the year. Vegetation should be selected for seasonal water availability, canopy shade, and resistance to drought or waterlogging.

Courtyards should combine shade, cross-ventilation, drainage, and rain protection. Adjustable canopies, verandas, covered edges, and high-level exhaust can allow open dry-season use and protected monsoon operation. Roofs require insulation, solar control, reliable waterproofing, drainage, and overhangs that protect walls and openings. Ventilated roof cavities can reduce heat gain but must prevent wind-driven rain, pests, and moisture accumulation.

Walls should balance mass, insulation, and moisture tolerance. Internal mass can moderate dry-season swings, but assemblies require drying potential during humid periods. Airtightness should be controllable: leakage must be reduced for mechanical cooling and humid conditions, while deliberate openings provide ventilation when outdoor air is favourable. Glazing should remain externally shaded and protected from driving rain. Daylight design must account for bright overcast conditions as well as clear-sky glare.

Ventilation should operate through a seasonal control matrix. In dry shoulder periods, cross-ventilation and fans can provide most cooling. During hot-dry nights, purge ventilation can discharge mass. During humid monsoon conditions, outdoor air may need to be limited, filtered, or dehumidified. Educational buildings illustrate the conflict: opening windows can reduce carbon dioxide, yet cross-ventilation alone may be unable to offset high external and internal heat. Mixed-mode systems must therefore coordinate air quality, humidity, and temperature rather than use one threshold.

Fans are highly valuable because they extend acceptable conditions during dry and moderately humid periods at low energy. Evaporative cooling should be limited to dry-season operation and automatically disabled when humidity rises. Efficient heat pumps should provide cooling and dehumidification during monsoon peaks. Solar generation can support daytime school, office, and market loads, while batteries protect fans, controls, and refuge rooms during outages.

Low-income housing needs shaded verandas, insulated roofs, protected openings, fans, drainage, and affordable cooling during humid extremes. Apartments require fire-safe and rain-protected cross-ventilation. Schools should combine shaded outdoor space with fan-assisted classrooms; clinics require filtration and humidity control; heritage-compatible infill should retain shaded streets and courtyards while adding drainage and safe services.

Targets should be seasonal. Natural-ventilation availability, acceptable air-speed ranges, window-opening schedules, and cooling-energy benchmarks should be calculated separately for hot-dry, monsoon, and shoulder periods. Overheating and indoor humidity should be reported together. A design that reduces temperature by increasing moisture may not improve health or comfort.

5. Coastal-Arid Climates with Higher Humidity

Coastal-arid climates combine strong solar radiation and limited rainfall with higher humidity, warmer nights, sea-breeze effects, and salt exposure. Their priority is to reduce radiant and conductive heat while using air movement for physiological cooling and reserving mechanical systems for humidity control and severe periods. Thermal mass and direct evaporation are generally less reliable than in dry inland climates.

Urban form should preserve sea-breeze access through aligned streets, ventilation corridors, stepped heights, and porous block edges. Compactness should still provide shade, but continuous barriers perpendicular to prevailing breezes should be avoided. Public-space design should prioritise deep shade because air temperature may remain high even when wind is available. Tree canopies, arcades, colonnades, and roofed markets can reduce mean radiant temperature, while salt-tolerant planting and low-water systems address coastal exposure.

Courtyards should be relatively open to useful breezes and should avoid excessive thermal storage. High-level outlets, shaded surfaces, low internal heat rejection, and porous connections to surrounding spaces are important. Enclosing a courtyard with glazing or placing multiple condensers within it can create a humid heat trap. Water features offer little advantage when wet-bulb depression is small and can increase humidity or maintenance burdens.

Roofs should combine shade, high reflectance, insulation, corrosion-resistant detailing, and secure attachment under coastal winds. Lightweight ventilated roofs can work well where moisture is controlled, while insulated mass roofs require careful night-performance testing. Walls should resist moisture and salt while limiting heat transfer. Airtightness is important during air-conditioned and dehumidified operation, but the building should retain a controlled open mode for favourable breezes.

Glazing must have low solar heat gain and strong external shade. Operable windows should be designed for rain, salt, insects, noise, and security. Daylighting should be diffuse and shaded. Fans are a first-line technology because air movement can improve comfort without the water penalty of evaporation.

Fan performance depends on air temperature, humidity, activity, and individual physiology. Air movement can aid comfort in humid conditions, but it cannot guarantee protection during extreme heat.

Natural ventilation should be based on enthalpy and air quality, not temperature alone. Sea breezes may provide useful air movement while carrying high moisture. Mixed-mode systems should change to closed, mechanically cooled or dehumidified operation when outdoor humidity would increase latent loads or sleep discomfort. Efficient heat pumps should be selected for high-ambient and high-humidity performance, with condensate managed as a possible non-potable water source.

Low-income housing requires shaded roofs, corrosion-resistant fans, secure openings, and efficient room cooling for humid nights. Apartments should preserve cross-breezes without uncontrolled humid-air infiltration. Schools and markets benefit from shaded, fan-assisted semi-open space; clinics require filtered dehumidification; offices require low glazing, controlled daylight, and efficient latent cooling.

Performance targets should include mean radiant temperature reduction, shaded fraction, indoor humidity, air speed, nighttime operative temperature, and latent as well as sensible cooling energy. Direct evaporative systems should not be specified without psychrometric proof of benefit. Cooling-energy benchmarks should distinguish dehumidification from temperature control, since a coastal building may consume substantial energy even when dry-bulb temperature is moderate.

5.3 Retrofit Pathways for Existing Buildings and Informal Settlements

1. A Tiered Retrofit Ladder for Buildings That Must Remain Occupied

Most buildings that will expose people to heat during the coming decades have already been constructed. Their roofs, walls, windows, plots, tenure arrangements, and infrastructure cannot be redesigned as if they were new projects. Retrofit policy must therefore work incrementally, distinguish between immediate protection and deeper transformation, and account for who owns the building, who occupies it, who can authorize changes, who pays, and who remains responsible for maintenance. The appropriate framework is a four-tier retrofit ladder: immediate low-cost measures; moderate envelope and ventilation upgrades; major spatial or structural retrofits; and neighbourhood-scale interventions.

The ladder is not a rigid sequence in which every building must complete one tier before entering the next. It is a method of matching intervention intensity to heat risk, available finance, building condition, tenure, skill, disruption tolerance, and expected service life. A severely exposed clinic may require immediate active-cooling and power-resilience work while its envelope retrofit is being designed. A rented dwelling may be limited initially to reversible shading and fans because the tenant lacks legal authority to alter the roof. A heritage building may require specialist diagnosis before apparently simple insulation is installed. A self-built settlement may achieve greater benefit from a coordinated cool-roof and shade programme than from isolated household retrofits.

Each tier should be evaluated across six implementation dimensions. **Cost** includes capital, operation, finance, and replacement. **Disruption** includes temporary relocation, loss of rooms, noise, dust, and interruption of services. **Tenure** determines who can consent to physical change and who is protected from displacement after improvement. **Skill** concerns the labour, testing, and supervision required. **Maintenance** covers cleaning, recoating, repair, replacement, and occupant operation. **Thermal benefit** includes indoor peak reduction, nighttime recovery, overheating degree-hours, cooling-energy reduction, and safe performance during heatwaves or power failure.

The evidence indicates that roofs deserve early priority in low-rise arid-region stock. In the cited Saudi context, much existing housing lacks insulation and consists predominantly of one- to three-storey buildings, giving the roof a large influence on indoor heat. Reflective roof treatments in Egyptian simulations produced larger whole-building savings than other individual envelope measures, although the reported values varied by city and should not be generalized without local calculation. Roof-first policy is therefore often justified, but not universally: in tall apartment blocks, roof treatment benefits top floors more than lower units, and roof-to-floor ratio can make the whole-building energy effect relatively small.

Integrated packages usually outperform isolated measures. The reviewed literature reports that combinations of insulation, improved glazing, shade, ventilation, and fans produced substantially greater savings than the same measures used individually. Yet packaging must remain diagnostically disciplined. Insulation without heat-release pathways can retain internal gains. Night ventilation can introduce hot, humid, dusty, polluted, or insecure outdoor air. Reflective surfaces can lose performance through dust. Courtyard planting can create maintenance and water burdens. Efficient heat pumps can increase total electricity use if households respond by cooling more rooms or operating for longer hours.

The retrofit ladder should therefore begin with a pre-retrofit diagnosis rather than a list of products. The diagnosis identifies the dominant heat pathway: direct roof gain, west-wall exposure, solar gain through glazing, air leakage, internal gains, poor ventilation, nighttime heat retention, condenser heat, overcrowding, or unreliable electricity. The intervention is then selected to interrupt that pathway with the least disruptive, most maintainable, and most socially secure measure.

2. Tier One: Immediate Low-Cost Heat Protection

Tier One consists of reversible or minimally invasive measures that can be delivered quickly, often while buildings remain occupied. These measures are particularly important before and during heat seasons, in low-income housing, rental units, schools, clinics, informal settlements, and buildings awaiting deeper retrofit. Their objective is to reduce immediate exposure, improve air movement, and establish a basic heatwave response without requiring major structural alteration.

Exterior shade is usually preferable to interior solar control because it intercepts radiation before it reaches glazing or opaque surfaces. Low-cost applications include awnings, shade cloths, bamboo or timber screens, external blinds, temporary roof canopies, shaded verandas, and screens over west-facing windows. Devices must be secured against wind, designed not to block emergency escape, and placed so that they do not transfer reflected heat into neighbouring windows or public paths.

Roof coatings are among the most scalable Tier One measures for exposed low-rise roofs. They can lower solar absorption with limited structural disruption and are particularly suited to public programmes covering many similar buildings. Their actual performance depends on initial roof colour, insulation, roof area, climate, dirt accumulation, waterproofing condition, and coating durability. A reflective coating should not be applied over a leaking or structurally deteriorated roof without repair. Programme budgets must include cleaning, inspection, and recoating rather than treating application as a permanent one-time intervention.

Reflective coatings can reduce roof solar absorption, but the effect on whole-building energy use depends on insulation, roof area, building height, climate, and operation. A large roof surface-temperature reduction does not imply an equally large indoor-temperature or energy benefit. Expected savings should be tested against a stated local baseline.

Ceiling fans provide high benefits relative to cost and electrical demand. They should be installed in bedrooms, living rooms, classrooms, waiting areas, and other occupied zones with adequate ceiling clearance and safe mounting. Fans improve occupant-level air movement but do not necessarily exchange indoor and outdoor air. They can therefore remain useful when windows must be closed because of dust, smoke, security, noise, or extreme outdoor heat. Fans should not be represented as sufficient life-safety protection under all temperature and humidity conditions, but they can extend acceptable conditions and reduce compressor use.

The reviewed research identifies natural ventilation enhanced by ceiling fans as part of an integrated package that achieved high annual comfort and large reductions in heating and cooling requirements in a Mediterranean house. The result belongs to a particular building and package; it should support fan inclusion, not a universal savings claim.

Thermal curtains, blinds, reflective internal screens, and movable partitions are tenant-compatible measures where exterior work is prohibited. Internal curtains are less effective than external shade because solar energy has already passed through the glazing, but well-fitted reflective or insulated curtains can reduce radiant exposure and nighttime heat exchange. They must not block necessary ventilation or create condensation risks.

Window and door adjustment can include weather-stripping, repair of operable sections, insect screens, louvres, door undercuts for cross-flow, and secure opening restrictors. In hot daytime conditions, uncontrolled air leakage can increase cooling loads; during cooler nights, deliberate cross-ventilation may be valuable. Tier One work should therefore distinguish leakage from controllable ventilation.

Secure night ventilation is an operational retrofit as much as a physical one. Security grilles that preserve free area, lockable louvres, high-level vents, screened transoms, and low-energy extract fans can allow night purge without requiring occupants to leave doors or windows fully open. The system should operate only when outdoor conditions are cooler and cleaner than indoors.

Internal zoning can create one protectable room rather than attempting to cool the entire building. Doors, curtains, temporary partitions, and revised occupancy arrangements can concentrate fans or air conditioning where older adults, children, ill occupants, or sleeping household members need protection. In clinics and schools, zoning can prioritize treatment rooms, medicine storage, examination areas, nursery rooms, or the most densely occupied classrooms.

Tier One measures have low to moderate expected thermal benefit individually, but they can be installed quickly and combined. Maintenance is generally simple, though not negligible. Fans require cleaning and electrical safety checks; screens tear; coatings weather; curtains accumulate dust; and movable shade must be operated. Programmes should provide instructions in accessible languages and avoid if occupants can perform frequent manual adjustments.

3. Tier Two: Moderate Envelope and Ventilation Upgrades

Tier Two measures require greater investment and skilled installation but can usually be completed without fundamental changes to the building structure. They include roof insulation, ventilated roof layers, exterior wall improvements, more substantial window and door modification, permanent shading screens, controlled ventilation, and efficient heat-pump replacement.

Roof insulation is frequently the most effective moderate retrofit in low-rise stock. Exterior placement is generally preferable where technically and legally feasible because it protects the roof mass from direct external temperature fluctuations and reduces thermal bridges. Interior ceiling insulation may be more practical in rented, occupied, or heritage-sensitive buildings, but it can reduce room height, create moisture or fire concerns, and leave the roof structure exposed to extreme temperature cycling.

Insulation thickness should be optimized through climate, material, energy price, roof geometry, and service-life analysis. Al-Tamimi (2021) reports diminishing financial returns beyond particular thicknesses in selected Saudi studies, but the cited optimums should not be transferred directly to other locations. The appropriate specification is the thickness or assembly that meets the project's roof heat-flow, overheating, cost, moisture, and resilience targets.

A **ventilated roof layer** places an air cavity or secondary roof above the weatherproof structure. The upper layer shades the primary roof, while airflow removes part of the absorbed heat before it reaches the interior. This can be created through raised metal, tile, timber, or photovoltaic canopies. The cavity requires clear inlet and outlet paths, pest control, drainage, corrosion resistance, and inspection access. It should not become a dust reservoir or be sealed inadvertently during later repairs.

Roof insulation and ventilation can be complementary. The ventilated layer reduces the external heat load, while insulation limits residual transmission. In heritage buildings, reversible secondary shading may be preferable to altering significant roof fabric. In informal settlements, lightweight ventilated roof overlays may provide greater practical benefit than adding heavy materials to structures of uncertain capacity.

Wall improvements include external insulation, ventilated façades, compatible renders, reflective or shaded finishes, cavity injection, internal insulation, and targeted treatment of the most exposed orientations. External insulation usually preserves interior floor area and keeps existing mass within the protected zone, but it changes façades, boundaries, drainage details, and sometimes heritage character. Internal insulation may be more permissible but can reduce area and create interstitial moisture risks.

The reviewed research reports annual energy reductions from wall insulation in hot-arid simulations and notes that exterior placement generally produced better thermal performance. It also documents heritage-compatible proposals using internal or injected insulation while retaining exterior appearance. Every wall retrofit should therefore begin with moisture, salt, structural, and material-compatibility assessment.

Permanent shading screens can improve glazing and wall performance without full window replacement. Their depth, porosity, orientation, daylight effect, privacy, cleaning, and wind loading must be calculated. Where windows are replaced, solar heat-gain coefficient may matter more than U-value for exposed hot-climate glazing. The reviewed research specifically identifies solar transmittance as a major determinant of window heat gain. Replacement should not produce sealed rooms without adequate ventilation or emergency escape.

Controlled ventilation upgrades include solar chimneys, wind-assisted shafts, high-level exhaust, whole-house extract, filtered supply, and fan-assisted night purge. In classrooms, measured window-opening interventions produced modest temperature reductions and substantial carbon-dioxide improvement, demonstrating that ventilation retrofits can support both thermal and air-quality goals. However, classroom results should not be applied directly to bedrooms, clinics, or dusty urban locations.

Efficient heat pumps belong in Tier Two when existing units are old, oversized, high-emitting, or unable to maintain safe conditions. Replacement should follow envelope and shading diagnosis so that capacity can be reduced where possible. High-ambient performance, part-load efficiency, refrigerant, filtration, condensate drainage, noise, and maintainability are more important than the nominal efficiency label alone.

Tier Two measures usually require owner or landlord authorization. In rental housing, public subsidy should be tied to rent stabilization, tenant consent, and continued occupancy. Public housing authorities can standardize roof and fan packages across similar stock but should validate them on representative units before mass rollout. Schools and clinics require phased construction, dust control, child and patient safety, and commissioning outside critical operating periods.

4. Tier Three: Major Spatial and Structural Retrofit

Tier Three includes interventions that reorganize the building's environmental logic. They can produce large and durable benefits but involve higher cost, specialist skill, structural review, temporary relocation, or loss and reallocation of space. Measures include courtyard recovery, removal of heat-trapping additions, major roof reconstruction, wall replacement or deep overcladding, new ventilation shafts, reconfigured circulation, internal thermal zoning, structural shade, and comprehensive mechanical-system redesign.

Courtyard recovery is appropriate where an original court has been roofed, filled, subdivided, or converted into an unventilated service space. Recovery should not assume that simply reopening the centre will produce cooling. The design must assess solar exposure, aspect ratio, sky view, airflow, privacy, drainage, vegetation, water use, condenser placement, and links to occupied rooms. Partial opening, adjustable shade, high-level exhaust, planted edges, or conversion of a glazed atrium into an operable mixed-mode court may be more appropriate than full historical reconstruction.

In heritage buildings, courtyard recovery can restore environmental and cultural functions simultaneously, but it may displace kitchens, bathrooms, storage, commercial uses, or additional households added over time. Residents must be involved in deciding which uses are relocated and whether the recovered court remains accessible to them rather than becoming a visitor space.

Major internal zoning can separate high-gain daytime uses from protected sleeping or treatment areas. In housing, kitchens and heat-producing equipment can be isolated and ventilated. In schools, heavily occupied classrooms can be separated from naturally ventilated circulation and shaded outdoor teaching space. Clinics can create a cooled and filtered core surrounded by lower-energy support zones. Offices can relocate server rooms, equipment, and high-gain activities away from naturally ventilated areas.

Structural roof reconstruction may combine waterproofing, insulation, ventilated layers, photovoltaic shade, solar hot water, accessible maintenance paths, and emergency electrical support. Structural capacity must be checked before adding concrete, soil, water, batteries, panels, or occupied roof decks. Self-built and informal structures require particular caution because drawings and reinforcement details may be unavailable.

Wall reconstruction or deep façade retrofit may be justified when hollow-block, metal, or deteriorated walls cannot meet heat, moisture, or safety requirements through lighter measures. Hybrid assemblies can preserve useful mass while adding insulation, shade, and ventilation. In heritage buildings, original material should be repaired where possible, with incompatible cement layers removed only under specialist supervision.

Tier Three also includes replacement of fragmented room air conditioners with zoned high-efficiency heat pumps, central systems, or district connections. System redesign should prevent condenser heat from being rejected into enclosed courtyards or narrow alleys. Electrical panels, wiring, and backup circuits may require upgrading to support safe cooling.

Major interventions must be assessed against remaining building life. It is difficult to justify deep retrofit of a structurally unsafe building without simultaneous stabilization. Conversely, demolition should not be assumed to be preferable merely because retrofit is complex; replacement can cause displacement, embodied emissions, heritage loss, and years of delay.

Formal owner-occupiers may finance major work through mortgages, property-linked loans, grants, or phased construction. Landlords should not receive public retrofit finance without enforceable affordability conditions. Public housing requires resident relocation plans, right of return, and staged work. Schools and clinics require continuity plans. Heritage projects need conservation approval and resident protections. Informal settlements require community-scale structural assessment rather than enforcement that converts technical improvement into a pretext for eviction.

5. Tier Four: Neighbourhood Intervention, Delivery, and Anti-Displacement Safeguards

Some heat problems cannot be solved by building. Unshaded roads exposed public space, unreliable electricity, dense condenser discharge, tree loss, weak healthcare access, and insecure tenure require neighbourhood intervention. Tier Four includes cool-roof programmes, tree and canopy networks, shaded mobility, settlement upgrading, grid reinforcement, public cooling, district energy, drainage, water systems, and coordinated heritage improvement.

A **cool-roof programme** can reduce procurement cost, standardize quality, map priority roofs, train local applicators, and monitor performance. It should differentiate roof material and structural condition rather than applying one coating to every surface. Tenants should not be displaced during work, and landlords receiving subsidies should be prohibited from converting the improvement into immediate rent increases.

Tree and canopy systems should protect routes between homes, schools, clinics, markets, transit, and cooling centres. Trees provide shade and evapotranspiration but require water, soil, maintenance, and time to mature. Engineered canopies can deliver immediate shade with less water but require structural inspection and repair. Combined systems can provide early and long-term protection.

Settlement upgrading should integrate shade, roofing, electricity, drainage, water, paths, public space, tenure, and emergency access. Heat should not be treated as an isolated technical defect. Upgrading can raise land values and attract redevelopment pressure. Without tenure security, residents may be displaced after public investment improves the area.

Nevertheless, any socially responsible programme should include several minimum safeguards: advance notice; meaningful resident participation; temporary relocation support where necessary; right of return; prohibition of retaliatory eviction; rent stabilization or affordability covenants linked to public subsidy; transparent eligibility; inclusion of renters and undocumented or informal occupants; grievance procedures; and public reporting of displacement outcomes.

Heritage improvement requires similar protection. Grants for façades, roofs, courtyards, and services can make historic areas more attractive to tourism and higher-income residents. Funding should therefore be tied to continued residential use, local employment, maintenance support, and protection of existing tenants. Restoration should improve residents' thermal conditions rather than preserve a tourism-oriented image while households remain exposed.

Authorization and payment vary by sector. Owner-occupiers can authorize most work but may lack capital. Tenants possess direct knowledge of heat exposure but usually cannot approve permanent alteration. Landlords control the asset but may not pay energy bills. Public housing agencies control both building and programme budgets but can impose standardized measures without adequate resident input. Schools and clinics require institutional approval and safeguarding. Informal residents may improve dwellings physically but lack legal security.

Maintenance responsibilities must be allocated in writing. Municipalities may maintain street shade and public cooling; utilities maintain grid infrastructure; landlords maintain roof and envelope systems; tenants operate fans and windows; heritage agencies support specialist repairs; community organizations may monitor public assets. Programmes fail when maintenance is assumed to occur without budget, training, authority, or spare parts.

5.4 Governance, Finance, and the Arid Cooling Observatory

1. Institutional Mandate, Structure, and Independence

The framework developed throughout this book requires an institution capable of maintaining evidence after publication, translating new climate and building data into policy, and identifying when previously effective cooling strategies approach failure. The proposed **Arid Cooling Observatory** would perform this role as an independent public-interest institution or federated research network. Its mandate would be to monitor the evolving relationship among climate exposure, passive cooling capacity, active cooling access, building performance, electricity reliability, social vulnerability, and future-climate thresholds across arid and semi-arid regions.

The observatory should not be designed as a conventional architectural archive. Nor should it function solely as a meteorological agency, energy regulator, public-health unit, or building-research centre. Heat risk crosses all these domains. An institution concerned only with outdoor temperature would overlook housing and infrastructure. One concerned only with energy use might reward efficient air conditioners while ignoring buildings that absorb avoidable heat. A heritage-focused institution might document traditional cooling systems without measuring whether they remain operational, affordable, or safe under future climates. The observatory must therefore combine environmental, architectural, infrastructural, economic, health, and social evidence.

The reviewed literature identifies useful precedents in climate services, public-health surveillance, building-performance disclosure, utility regulation, and energy-data platforms. Climate and health early-warning systems demonstrate how meteorological observations can be linked to injuries, illness, and mortality. Building-disclosure programmes demonstrate how visible performance information can influence markets. Energy regulators demonstrate how utilities can be required to report system conditions and respond to demand. Open-data platforms show how technical information can be made accessible beyond the institution that originally collected it.

A federated structure is preferable to a single centralized organisation attempting to collect all data directly. A small international or regional secretariat could establish indicators, methods, publication standards, conflict-of-interest rules, and interoperability protocols. National nodes could maintain country-level climate, housing, energy, finance, and code information. City or university partners could produce neighbourhood-scale profiles, field monitoring, case documentation, and local policy analysis. Community organisations could participate in diagnosis, interpretation, and verification.

This polycentric model will provide an opportunity to develop some degree of commonality in standards and practices, without losing important elements of local specificity. In addition, this model will decrease reliance upon a single governmental body, donor organization, university, or consulting firm. Local organizations have specific knowledge about their own context as well as access to municipal records and databases. Regional networks can compare approaches, identify inconsistencies among nodes, ensure continuity if one national node is politically hampered.

The observatory should be formally established with a legal or institutional charter defining its mission and public interest mandate. The governance structure of the observatory should comprise a diverse range of members including climate scientists, building scientists, health professionals, energy regulators, housing experts, heritage professionals, finance professionals, trades people (e.g., contractors), tenant and settlement associations, organizations representing persons with disabilities and other community based organizations. No single professional or commercial organization/constituency should comprise a majority of the membership.

In terms of funding, it may be possible for government funding to be used to support the establishment and operation of the observatory. However, the findings produced by the observatory should be protected from political interference by ministers. Funding for core operations of the observatory should be multi-year and distributed across multiple donors/sources so that no individual donor/funding source has the ability to restrict the dissemination of findings that are not consistent with their interests. Project funding from such additional funding sources as development banks, climate funds, utility companies, private foundations and research councils should be disclosed publicly, and donors should agree to restrictions on influencing methodologies employed by the observatory for ranking buildings or publications resulting from the research activities of the observatory.

Although the observatory must operate independently, it does not need to maintain a distance from policy making. The observatory should be authorized to request data from utility providers, building authorities, housing authorities, publicly funded retrofit programs and national meteorological services. Although the observatory can make formal recommendations regarding best practices for improving building performance, ultimately the responsibility for establishing standards and enforcing compliance rests with governments and regulatory bodies. Therefore the role of the observatory is to measure, compare, warn, evaluate and advise – not to usurp decision making authority in democracies or enforce regulations by statute.

Its primary unit of concern should be the **cooling service required for safe and dignified habitation**, not the number of passive features or air conditioners installed. A building with a courtyard but dangerous bedrooms should not receive a favourable assessment. A city with high appliance ownership but frequent outages should not be treated as having secure cooling access. A low-energy building that becomes unsafe during a heatwave and power failure should not qualify as resilient.

2. Core Products and an Updateable Indicator System

The observatory should produce a recurring set of products that translate complex evidence into comparable but context-sensitive forms. These products should be updated on defined schedules and should retain historical versions so that changes in climate, policy, building stock, and vulnerability can be traced over time.

The first product would be **country and city cooling profiles**. A country profile would include climate trends, cooling degree-days, hot-night frequency, building-stock characteristics, roof and wall materials, air-conditioner and fan access, electricity reliability, cooling-related peak demand, building-code provisions, enforcement capacity, retrofit policy, heritage regulation, climate finance, and Passive Cooling Gap indicators. City profiles would provide greater spatial detail on urban form, vegetation, roof exposure, informal settlement, public shade, cooling access, grid stress, healthcare, and neighbourhood vulnerability.

Profiles should not culminate in a single unexplained rank. They should show separate domains, data quality, uncertainty, and the interventions most relevant to the observed gap. One city may require roof retrofit and tariff support, another grid reinforcement and efficient cooling, and another shaded public space and protection of ventilation corridors.

The second product would be an **open indicator dashboard**. This would publish current and historical values for climatic exposure, Passive Cooling Gap domains, building-code readiness, cooling access, passive-design adoption, retrofit delivery, grid reliability, and future-climate thresholds. Users should be able to view country, city, neighbourhood, and building-type information where privacy and data quality permit.

The dashboard should distinguish observed data from modelled estimates and proxies. A measured indoor-temperature series should not be displayed as equivalent to a roof-material estimate. Every indicator should include a source, date, spatial resolution, uncertainty statement, and revision history. Where data are missing, the interface should show missingness rather than silently treating it as average performance.

The third product would be a **vernacular cooling case registry**. This registry would document historical, contemporary, and hybrid examples through climate, form, fabric, flow, practice, translation constraints, measured performance, maintenance, and future-climate suitability. It would apply the VCPF rather than cataloguing visual styles.

Each registered case should identify what mechanism was claimed, how it was tested, what baseline was used, who operated and maintained it, what failures occurred, and whether performance persisted. Cases should include ordinary dwellings, settlements, retrofits, public buildings, schools, clinics, markets, and contemporary reinterpretations, not only celebrated monuments.

The registry should also identify knowledge contributors. Communities, builders, craftspeople, and local researchers should retain attribution and, where commercial applications arise, access to agreed economic or institutional benefits. Data on culturally sensitive buildings or practices should not be published without consent.

The fourth product would be a recurring **code and policy comparison**. This would assess whether national and municipal systems address roof heat gain, external shade, glazing, insulation, thermal mass, natural ventilation, mixed-mode operation, overheating, power-outage safety, local materials, heritage adaptation, appliance efficiency, cooling access, and retrofit finance. The comparison should distinguish formal code text from enforcement, training, market readiness, and measured compliance.

The fifth product would be an **independent retrofit evaluation series**. Public and privately subsidised programmes should be assessed through pre-retrofit diagnosis, implementation quality, indoor-temperature change, energy use, maintenance, affordability, tenant outcomes, and displacement. Evaluations should compare predicted and measured performance and should continue long enough to detect degradation, non-use, and rebound.

The sixth product would be **early-warning reports**. These would identify short-term and structural risks associated with hot nights, heatwaves, electricity-grid stress, water shortages, dust or smoke, and declining passive-cooling potential. A warning system should combine meteorological forecasts with building and infrastructure conditions.

Relevant indicators include forecast hot-night sequences, wet-bulb or humidity stress, expected cooling demand, grid reserve margin, outage probability, transformer loading, water restriction, dust or smoke forecasts, and the share of vulnerable housing lacking safe cooling. The reviewed literature supports combining climate, health, building, and grid indicators and highlights the importance of real-time grid analytics and locally relevant climate information.

Longer-term threshold reports should assess whether night ventilation, direct evaporation, outdoor sleeping, passive courtyard cooling, vegetation, or thermal mass are losing effectiveness under observed and projected climates. Thresholds should be expressed through ranges and proportions of models rather than one deterministic date.

The seventh product would be **guidance for practitioners and communities**. Professional guidance should include subtype-specific design packages, retrofit protocols, code pathways, procurement templates, monitoring methods, and performance specifications. Community guidance should explain heat diagnosis, roof and shade options, safe ventilation, appliance selection, tariff programmes, heatwave action, tenant rights, and available finance in accessible formats and local languages.

3. Responsibilities Across the Cooling System

The observatory can reveal gaps, but it cannot close them alone. Responsibilities must be distributed explicitly across public authorities, market actors, professional bodies, utilities, heritage institutions, researchers, and communities. Without such allocation, every actor can claim that thermal protection belongs to someone else.

National governments should establish minimum building, appliance, health, and life-safety protections. Their duties include climate-specific building codes, material standards, appliance-efficiency requirements, refrigerant policy, national cooling plans, housing finance, social protection, grid investment, and integration of heat into health and disaster policy. Governments should define minimum thermal conditions for rental, public, educational, and healthcare buildings and should prohibit the transfer of avoidable heat risk to occupants.

Municipalities should regulate urban form, street shade, building orientation, setbacks, plot coverage, roof use, public-space design, vegetation, parking, local heritage, and construction enforcement. They should preserve ventilation corridors without sacrificing mutual shade, map local heat exposure, maintain public cooling centres, and coordinate neighbourhood upgrading. Municipal planning permissions should require evidence that new development will not increase heat exposure through excessive glazing, paving, condenser discharge, loss of trees, or obstruction of wind.

Developers should deliver buildings that meet thermal-performance and resilience standards rather than relying on future occupants to purchase larger cooling systems. Disclosure should include predicted and measured cooling intensity, peak demand, overheating, and envelope performance. Developers receiving public land, tax benefits, or planning concessions should meet higher affordability and monitoring obligations.

Landlords should provide a basic thermally safe envelope, maintain roof and ventilation systems, permit approved efficiency improvements, and avoid retaliatory eviction or rent escalation following public retrofit. Tenants should not be expected to compensate indefinitely for poor roofs, unshaded windows, or defective cooling infrastructure.

Utilities should support efficient and resilient cooling through demand-side management, appliance replacement, weatherisation, tariff design, demand response, grid reinforcement, distributed energy, storage, and protection of critical facilities. They should report cooling-related demand, outage, voltage, and peak-stress data to the observatory.

The literature identifies utilities as crucial actors because building efficiency, urban heat, and grid reliability form one connected system. It also describes performance-based regulation and demand-response programmes as precedents for rewarding outcomes rather than electricity throughput.

Professional bodies should train and certify architects, engineers, energy auditors, contractors, valuers, inspectors, and facility managers. Certification should include passive cooling, overheating, mixed-mode control, local materials, future climates, post-occupancy evaluation, and ethical community engagement. Professional liability should apply to unsupported performance claims and negligent omission of foreseeable heat risk.

Heritage institutions should enable sensitive adaptation rather than forcing a choice between fabric preservation and safe occupation. Their responsibilities include compatible retrofit pathways, support for traditional skills, grants, technical advice, district-scale shade protection, reversible service integration, and safeguards against heritage-led displacement.

Researchers and data providers should maintain transparent methods, disclose uncertainty, publish negative and inconclusive results, and avoid overstating simulation findings. Research institutions should document funding, commercial relationships, data limitations, and model assumptions. The observatory should maintain peer-review and reproducibility requirements for indicators and case-registry claims.

Communities should participate in diagnosis, priority setting, programme design, implementation monitoring, and post-retrofit evaluation. Participation should not transfer statutory responsibility to residents or treat unpaid community labour as a substitute for public investment. Residents should be able to challenge inaccurate data, report failed interventions, and influence the interpretation of vulnerability profiles.

The reviewed research supports this distribution of responsibility by emphasizing government coordination, utility participation, building disclosure, research infrastructure, and community involvement. The observatory should publish a responsibility map for every major indicator and programme so that identified failures are connected to actors with authority to respond.

4. Finance for Buildings, Households, and Neighbourhoods

Cooling adaptation requires finance, but poorly designed finance can create unaffordable debt, landlord windfalls, or displacement. Financial mechanisms should be matched to income, tenure, building condition, public benefit, and the distribution of savings.

Concessional retrofit loans can support owner-occupiers, housing cooperatives, small landlords, schools, clinics, and community organisations. Interest rates and repayment periods should reflect the long service life of shade, insulation, roofs, and ventilation systems. Loan eligibility should be based on verified technical packages rather than product marketing.

Debt is inappropriate for households that cannot safely absorb repayment risk. **Grants** should therefore fund vulnerable households, public housing, low-income renters, informal settlement upgrading, care facilities, schools, and clinics. Grant programmes should prioritize life safety, roofs, fans, efficient appliances, protected refuge rooms, and outage resilience. Eligibility should not depend exclusively on formal title where insecure tenure is widespread.

On-bill finance can allow repayment through utility bills, but it requires safeguards. Monthly repayments should not exceed verified savings or an affordable share of income. Disconnection for retrofit debt should be prohibited. Responsibility when tenants move should be defined clearly, and landlords should not receive asset improvements while tenants bear all repayment without rent protection.

Public procurement can create demand for climate-responsive materials, craft systems, monitoring services, and high-performance construction. Governments should procure schools, clinics, housing, and offices through lifecycle thermal and energy performance rather than lowest initial cost. Contracts should include commissioning, post-occupancy monitoring, maintenance, and remedies when measured performance falls below the promised range.

Climate funds and green bonds can finance national roof programmes, passive public buildings, district cooling, urban shade, workforce training, and open-data infrastructure. The reviewed literature identifies green bonds and blended finance as relevant precedents but emphasizes the need for stable revenue, credible project design, and transparent climate governance.

Insurance incentives can reward verified roof protection, safe electrical systems, resilient cooling, and reduced heat-related business interruption. Insurers can also support approved local and hybrid material systems by developing evidence-based underwriting rather than excluding unfamiliar construction automatically. Incentives should not become penalties that make insurance unaffordable in high-risk communities.

Results-based finance can release part of project funding after verified outcomes such as reduced overheating degree-hours, maintained affordability, improved grid performance, or functioning public shade. Results should include social and maintenance indicators, not energy savings alone. A programme that lowers electricity use by restricting cooling access should not qualify as successful.

Cooling-as-a-Service and energy-service models can shift equipment ownership, maintenance, and performance risk from households to providers. The service contract should guarantee thermal conditions, efficiency, maintenance, and affordability. It should also prevent providers from locking users into opaque long-term charges or collecting excessive operational data. The reviewed research presents service-based cooling and energy-performance contracting as potential ways to redistribute upfront cost and operational responsibility.

Material and craft-sector support is necessary because local and hybrid construction cannot expand without testing facilities, accredited producers, training, tools, insurance, and procurement demand. Grants and concessional finance can support reinforced-earth production, lime, timber and screen fabrication, local insulation, shade structures, repair workshops, and apprenticeships. Such support should include quality standards so that cultural recognition does not substitute for safety.

Blended finance for neighbourhood upgrading can combine public grants, climate finance, development-bank loans, utility investment, municipal budgets, and community-controlled funds. Projects may include roofs, shade, trees, paths, public cooling, electricity reliability, drainage, water, and healthcare access. Finance agreements should include tenure protection, right of return, affordability covenants, local employment, and independent displacement monitoring.

No subsidy should be awarded without identifying who receives the asset value and who pays over time. Landlord subsidies should require rent stabilization and continued tenancy. Utility-funded programmes should include households with irregular billing or informal connections where legally possible. Public finance should publish distributional outcomes by income, tenure, gender, disability, settlement type, and neighbourhood.

5. Implementation Sequence and Political Feasibility

The observatory and its policy system should be introduced through a staged sequence. Attempting to create a complete multinational data platform, new building codes, retrofit finance, professional certification, and community governance simultaneously would risk institutional paralysis. Yet a narrow pilot without a path to statutory integration could remain an isolated research exercise.

The **immediate phase**, approximately the first one to three years, should establish governance, baseline data, and minimum reforms. A founding charter, independent board, conflict-of-interest policy, data protocol, and public methods register should be adopted. Existing climate, housing, code, grid, public-health, and cooling-access datasets should be mapped. Initial country and city profiles should be produced using transparent data-quality flags rather than waiting for complete information.

Governments should simultaneously review roof, solar-control, ventilation, overheating, local-material, rental-safety, and heatwave provisions in existing codes. Immediate reforms should focus on obvious no-regret gaps: roof protection, external shade, minimum appliance efficiency, fan readiness, safe mixed-mode operation, and public-building heat plans. Utilities should begin reporting cooling-related peaks, outages, and demand-response capacity.

The immediate phase should also launch representative monitoring in vulnerable housing, schools, clinics, and heritage buildings. A small number of carefully measured cases is more valuable than a large unverified catalogue. Community agreements should define consent, data use, compensation, and the right to review local interpretations.

The **medium-term phase**, approximately three to seven years, should develop demonstration programmes, workforce capacity, finance, and enforcement. Demonstration projects should cover different climate subtypes, building types, tenure conditions, and intervention tiers. They should include unsuccessful and conditionally successful cases so that the registry does not become promotional.

Professional bodies should establish certification for passive design, retrofit, mixed-mode control, local materials, heat resilience, and monitoring. Technical colleges and craft programmes should support roof applicators, insulation installers, fan and ventilation technicians, earth builders, lime workers, energy auditors, and building operators. Municipal inspectors require equivalent training so that new skills are recognized during approval and enforcement.

Finance programmes should move from pilots to standardized products. Retrofit loans, grants, on-bill schemes, public procurement, and neighbourhood funds should use observatory data to target need and evaluate outcomes. Anti-displacement and affordability requirements should become standard contractual provisions rather than optional social components.

The **long-term phase**, beginning around seven to fifteen years, should integrate cooling into routine planning, housing, energy, health, and climate-adaptation systems. Building permits should use current climate and future-overheating files. Housing policy should treat thermal safety as a basic quality standard. Health surveillance should incorporate indoor heat and cooling access. Electricity planning should include passive load reduction and household cooling need. Heritage policy should fund climate adaptation and resident continuity.

Political feasibility depends on framing. Passive cooling should not be presented solely as environmental restriction or nostalgia. It can reduce peak infrastructure investment, household bills, health burden, outage risk, and import dependence while improving comfort and local employment. Mechanical cooling should not be portrayed as an enemy; the objective is to deliver necessary cooling with lower loads, higher efficiency, and greater resilience.

Potential opposition will come from actors benefiting from current practices: developers prioritising saleable area, utilities rewarded for energy throughput, equipment suppliers resisting stricter standards, professionals defending established methods, landlords opposing tenant protections, and heritage or planning agencies reluctant to share authority. Reform packages should combine minimum requirements with transitional support, training, finance, clear timelines, and public disclosure.

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